SUBSIDENCE CAUSED BY HIGH EXTRACTION COAL MINING IN THE SASOLBURG AND SECUNDA AREAS : PREDICTION THEREOF AND THE MITIGATION OF ITS EFFECTS

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DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Doctor of Philosophy in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

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Jacob Nielen van der Merwe

Date: 3/7/91......

ABSTRACT

The thesis describes the results of research which was done over the period 1985 to 1990 in the Sasolburg and Secunda areas into the effects of underground high extraction coal mining on the surface, surface structures and agriculture.

Legal restrictions on the undermining of structures potentially sterilize more than 30% of the coal reserves in the study area. The basic motivation for doing the research was that most of the restrictions could be overcome if methods could be developed to undermine structures safely and economically.

For subsidence data analysis, a computerised three dimensional method of analysis, the Surface Element Analysis (SEA) approach, was developed and implemented. Using the results of the analyses and analytical considerations, a subsidence profile prediction method was developed. The prediction method incorporates a new approach to the prediction of strain, based on the shape of the subsidence profile and the thickness of deformable layers on surface.

The reactions of various commonly occurring structures in the study area, namely bituminised roads, gravel roads, pipe lines and conveyor belts, to subsidence were analysed. It was found that although no consideration to subsidence was given in the design of the structures, most could withstand the effects thereof safely with only minor and relatively inexpensive precautionary and repair measures.

With regard to agriculture, it is shown that while there are mining induced effects, they are in general not severe. There is, however, reason for concern regarding the long term and not immediately apparent effects. Further work is thus very necessary.

Overall, it was found that while a very cautious approach to high extraction undermining had merits in the past, most of the restrictions can be relaxed in the light of the knowledge which is now available.

The important provision is that careful and detailed prior investigations are necessary for each individual case, and that a sound and responsible engineering approach must be followed. Mines can derive substantial economical benefit from the mitigation methods which are described.

A very important aspect is the administrative handling of the undermining of structures. A coordinated multi disciplinary approach, catering for communication and joint planning of mining and infrastructure, is proposed. It contains the essential elements of the Australian approach with modifications for local South African conditions.

This work is dedicated to my family,

Hantie, Melani, Hein and Nielen,

and the memory of my late father,

H. A. van der Merwe.

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LIST OF SYMBOLS, UNITS AND CONVENTIONS

Except where indicated otherwise, the following symbols and units are used in the thesis:

	Symbol
strain, expressed in mm/m.	ϵ
compressive strain, expressed in mm/m.	ϵ_-
tensile strain, expressed in mm/m.	ϵ_+
maximum strain, expressed in mm/m.	ϵ_m
maximum tensile strain, expressed in mm/m.	ϵ_{m+}
maximum compressive strain, expressed in mm/m.	ϵ_{m-}
mining height, expressed in m.	h
mining depth (i.e. from surface to floor of coal seam) expressed in m.	H
subsidence, expressed in m.	S
maximum subsidence, expressed in m.	S_m
tilt, expressed in mm/m.	T
maximum tilt, expressed in mm/m.	T_m
panel width, expressed in m.	W
critical panel width, in m	Wc
distance from panel edge to any point on surface, expressed in m.	X
distance between two points on surface, expressed in m.	x

Conventions

Tensile strains are positive.

Compressive strains are negative.

Angles measured in a clockwise direction are positive.

Angles measured in an anti-clockwise direction are negative.

1 INTRODUCTION

1.1 PRIMARY MOTIVATION FOR PREDICTING THE EFFECTS OF HIGH EXTRACTION COAL MINING ON THE SURFACE

It is widely known that high extraction coal mining at relatively shallow depth, such as commonly practised in South Africa, results in surface deformation. Very few structures are designed specifically to withstand this type of deformation, with the result that the undermining of structures with high extraction mining could not be done without careful investigation.

The regulations of the Mines and Works Act of 1956 specifically prohibit the undermining of any structure on surface, except with the permission of the Government Mining Engineer (GME). The GME usually gives exemption from the prohibition on the basis of two basic requirements: firstly the safety of people may not be jeopardized, and secondly the owner of the structure must agree to the undermining.

On closer inspection, the first requirement is revealed to be of a technical nature, while the second implies some form of formal agreement. Guaranteeing the safety of people using a structure or being in a position to be affected by its condition, implies that the effects of the undermining on the structure must be predicted. This can only be done after the nature of the subsidence itself has been predicted. It can then be seen that the ability to predict subsidence resulting from high extraction coal mining is a prerequisite for the undermining of that particular structure.

Subsidence prediction is not in itself a new science and several prediction models, which are valid for a wide range of mining methods and geological conditions, exist world wide. When preliminary examination showed that the existing prediction models were not suited to the conditions prevailing in the Sasolburg and Secunda areas, it became clear that if structures were to be undermined, a suitable method for prediction would have to be developed.

Faced with the position just described, the cost and effort of developing a prediction model had to be weighed against the possible benefits of undermining structures. A survey was then conducted to determine the amount of coal sterilised by the prohibition of undermining. As will be shown later in more detail, the restriction on mining affects the coal directly underneath the structure plus a surrounding area. It was found that in total, more than a third of the total coal reserves owned by Sasol in the Sasolburg and Secunda areas was potentially sterilised.

Assuming a uniform areal distribution of structures, this implied that some 9 million tonnes of coal per year would be affected by the restriction. Should undermining then be restricted to bord and pillar mining with high safety factors, it meant that approximately 4,5 million tonnes of coal would not be available for mining each year. This would result in an effective annual loss of some R50 million (in 1989 monetary terms).

Therefore, the potential benefit of doing the necessary research to be in a position to predict the effects of subsidence on various structures amounted to R50 million per year. This is a conservative estimate as it excludes any additional coal losses which may result from the position of the restricted areas leaving smaller blocks of coal in difficult to reach locations. Also, the cost estimate is based not on the sales value of in situ coal, but on the money lost by creating a position to mine a block of coal and then not extracting it.

High extraction coal mining in South Africa is relatively young. The first mechanised longwall was only introduced in the country (at the Sigma Colliery) in the mid 1970's. Therefore, the opportunity to study the effects of high extraction coal mining only arose in the last decade. By 1980, the annual production from high extraction methods by the Sasol Company (currently the major proponent of high extraction coal mining in

South Africa) was around 2,5 million tonnes. By 1990 that figure had increased to around 7,5 million tonnes.

The increase in the application of high extraction mining had a twofold effect: firstly it increased the need for undermining structures with high extraction methods, and secondly it provided the opportunity to do the required research to satisfy the requirements for undermining.

1.2 INTER DEPENDENCE OF MINING, AGRICULTURE AND INFRASTRUCTURE

The discovery of minerals in South Africa in several instances preceded the population settlement. South Africa owes the existence of several towns and cities to mining. Johannesburg and virtually the whole of the Witwatersrand are possibly the best examples, while cities like Welkom, Witbank and several others had similar origins.

In spite of the high profile of the mining industry, South Africa also remains a farming country to a very large extent. It is by far the continent's most important supplier of most agricultural products. Modern, mechanised farming practices require fuels, fertilizers, and many more products manufactured from materials which were extracted from the earth in the first place. The world over, the farming community is one of the most protected ones of all, which proves the importance of that community to society.

Thus: many roads, railway lines, power lines, even cities, would not have existed had it not been for the mining industry. Without infrastructure, the mines cannot operate. Farmers need the products made from mined materials to produce food for the population, and they also benefit from the affluence of the population, to which the mining industry is a major contributor. It is ironical that for instance in the Secunda area, the high density of surface structures which now restricts mining, is at least partially due to the existence of the mines and is certainly necessary to enable the mines to operate.

Mining, infrastructure and agriculture are thus economically inter dependent. They are also physically linked by the process of high extraction coal mining, as subsidence has at least some effect on both artificial structures and agriculture. The immediate losses incurred by a blanket prohibition on the undermining of structures have been shown to be significant. The longer term consequences, resulting in an effective loss of a major portion of the country's coal reserves, may be even more serious.

While absolute protection of surface structures by not allowing any undermining at all is therefore not in the overall interest, an absolute protection of mining by allowing undermining to take place regardless may be equally undesirable. In the very worst case it may be self destructive in that it may destroy a mine's own ability to produce coal.

The inter dependence of the three elements manifests itself in several areas: economical, social and physical. This study is concerned with the physical interaction of mining with infrastructure, consisting of physical structures on surface such as roads, pipe lines, power pylons, etc., and with agriculture. It will be shown that the physical interaction is severe enough to warrant structured and formal cooperation, yet not anywhere near severe enough to warrant serious restrictions on the application of high extraction mining methods.

Prior to the research described in this thesis, there was insufficient knowledge to allow undermining of structures to proceed unhindered. A further motivation for the research was thus to establish a balance between the interests of underground coal mining and surface utilization, bearing in mind the importance of preserving the integrity of the surface utilization.

Once mining has been carried out, and subsidence taken place, the process cannot be reversed. The sought after balance can thus only be obtained by knowing whether damage will occur, and the extent to which it will, before mining takes place. This, in turn, can best be done by observing historical cases and then devising some means of predicting subsidence effects for new areas.

Subsidence does not necessarily result in damage. Experience has shown, for instance, that of the 3000 ha of farming land undermined by Sasol by high extraction methods up to 1989, only 100 ha (less than 4%) were no longer suitable for the original agricultural application. Of the 100 ha, some portions at least were still suitable for an alternative farming activity, for instance maize lands turned into grazing.

From this very simple example it should be clear that the simplistic solution to the problem which will guarantee protection for the farming community, which would be not to allow high extraction mining, is both unrealistic and unnecessary.

The human element cannot be ignored. Before subsidence caused by high extraction coal mining received much attention, the country was shocked by a number of disastrous incidences of dolomitic sink holes, with loss of life, on the far West Rand.

Gold mining was basically responsible, as dewatering of geological compartments in order to protect gold mine workings, eventually resulted in the formation of the sink holes. The phenomena of dolomitic sink holes and the handling thereof has been described by a number of authors, one of the most comprehensive being Wagener (1982).

Even the most superficial of comparisons will immediately yield the conclusion that dolomitic sink holes, being sudden and largely unpredictable occurrences, are completely different from coal mining subsidence, which can be described as gentle and predictable, and orders of magnitude less severe than dolomitic sink holes. Yet, in the minds of the uninformed public, the occurrences are identical.

In Australia, Holla and Hughson (1986) made the statement "Change this state of equillibrium by underground mining and the surface strains are minimal when compared to the sociological ones", referring to mining induced subsidence. In South Africa the mental association of mining induced subsidence with dolomitic sink holes would appear to magnify the sociological "strains" by at least an order of magnitude.

The only way to allay those fears is to give factual reassurance, based on scientifically recorded histories and sound reasoning. Fruitful negotiations leading to successful cooperation can only take place once all parties are free of the fear of the unknown. Knowledge of the effects of subsidence caused by high extraction coal mining will thus also relax the sociological strains, allowing a better atmosphere in which to negotiate more fruitfully, to exist.

1.3 OBJECTIVES

From the previous sections, it is clear that the primary objective of the research was to establish whether it would be possible to undermine surface structures safely. If that could be done, it would still be necessary to develop a formal method, which had to be acceptable to the relevant authorities, by means of which subsidence could be predicted.

These two steps would then satisfy the GME's requirement that undermining could be allowed only if it could be shown that no danger would result therefrom. In turn, and provided that the necessary agreements with the owners of surface structures could be reached, the potential financial gain would be some R50 million per year - provided of course that the costs incurred by preparatory and repair work would be sufficiently low.

The main objective was sub divided into the following sub objectives:

- Observe subsidence in the Sasolburg and Secunda areas.

- Analyse the gathered data and determine whether suitable relationships with measurable, predetermined parameters could be found so that a prediction model could be developed.

- Observe damage resulting to undermined structures and to agriculture.

- Find methods by which the observed damage could be lessened.

- Determine the cost of the required preparatory measures and final repairs or replacement of structures so that decisions whether or not to undermine can be taken on a rational cost basis.

1.4 PROCEDURE WHICH WAS FOLLOWED

It was impractical to follow an action plan which would allow the objectives listed in the previous section to be reached step by step. Opportunities had to be used when they arose - for instance, when mine planning required a road to be undermined, it could not be postponed until after a suitable subsidence prediction model was available. Therefore, some of the work had to be done concurrently or in the "wrong" order.

A further restriction was the nature of surface utilisation. Cultivated lands are not ideal for monitoring purposes, and detailed investigation was only done in such areas in highly exceptional cases. Nevertheless, the high rate of mining and the number of underground sections allowed all the required data to be gathered in the relatively short time span of five years, from 1984 to 1989. During this period, it became apparent that observing subsidence along a line only did not always yield the required information.

In many cases it is sufficient to simplify the characteristics of the subsidence trough by only viewing the subsidence profile, i.e. a section across the subsidence trough at a position perpendicular to the long axis of the trough sufficiently far from the edges not to compromise the two dimensional nature of the profile. There are at least two situations where this simplification is misleading. One is where the structure under consideration is of a planar as opposed to a linear nature - as for instance a road. The second exception, perhaps the most important one, is where any long structure does not cross the panel at right angles or where the structure is situated near the corners of the trough. Because mining and surface infrastructure are planned independently, this situation arises more often than not.

In such cases, subsidence has to be analysed three dimensionally. In order to do that, an alternative method of data collection is required. The methods of data collection and analysis which were developed, and which are explained in greater detail later, essentially entailed measuring subsidence at the corners of small adjoining square areas and then calculating principal strains and major tilts.

In all cases where any danger could arise to people, structures which were undermined experimentally were taken out of commission for the duration of undermining until such time as suitable repairs were effected. In other cases, where the possible disruption of serviceability could result in financial losses only, contingency plans in case of emergency were made.

It was found extremely difficult to obtain scientific data relating to the effects of subsidence on agriculture. Among the reasons for this were the complexity of non-mining related factors affecting crop yields and the very sensitive nature of the issue. Nonetheless, some data at least was found and is presented later.

1.5 SUMMARY OF FINDINGS

While more detailed descriptions of the research results are given in the various following chapters of the thesis, it can be stated here in broad terms that the objectives were reached. Sufficient data was collected to enable a prediction model to be developed. Especially with regard to strain, a unique approach based on observations which shed light on the process by which strain develops could be devised.

All the structures which commonly occur in the study area could be observed during undermining. It was found in all cases that the structures displayed more flexibility than they were designed for, and could withstand the deformations accompanying subsidence with only minor pre-subsidence modification. Permanent repairs were also found to be much less costly than the value of the extracted coal. Consequently, no technical grounds for not undermining most structures under the conditions prevailing in the Sasolburg and Secunda areas could be found. The important provisions are that each case has to be individually investigated and then decided upon, and that the precautions, although minor in most cases, have to be taken.

1.6 APPLICABILITY OF RESULTS TO OTHER AREAS

This study is involved primarily with the effects of underground coal mining on the surface and surface structures. It is restricted in area to the Sasolburg and the Secunda areas. The reason for the areal restriction is that the areas chosen are those where the Sasol company operates and where data was thus accessible to the author. It is the stated mining policy of the company to optimise its utilization of coal reserves, Cox (1988). Of all the coal mined in South Africa by underground high extraction methods, Sasol produces an estimated 80%.

The effects described in this study are by no means tied to that one company. As the long and short term economics of high extraction mining methods become apparent to the other major mining houses, and as the need to preserve South Africa's finite energy sources become more pressing, the other companies are bound to follow suit and deploy high extraction methods on a much bigger scale. Some of the other mines already implement high extraction methods on a meaningful scale, and they experience the same effects.

Therefore, the effects described here will be experienced much more widely and in time to come, the importance of the effects described here for predictive purposes will grow. Obviously, as time and the scale of observations increase, so will the quality of the predictions improve. Many of the observations presented here are first observations. Later, time may well prove them to be incomplete. However, the engineer cannot wait for all the possible observations before doing his work. That which is available, has to be used until methods can be improved, which is when they must be improved. There is much value in the often heard saying that incremental improvement is better than delayed perfection.

1.7 STRUCTURE OF THE THESIS

This chapter is followed by three more of an introductory nature - two covering work previously done by other researchers and then one describing the physical area where this research was conducted. The previous research is described in two separate chapters, one devoted to subsidence prediction per se and the other to the physical effects of subsidence on structures and the handling of those effects. Due to the fact that subsidence in South Africa is closer akin to that in the USA and Australia than Europe, the literature study was confined to the USA and Australia.

Thereafter, the SEA (Surface Element Analysis) approach to data analysis, which is essentially the three dimensional analysis of subsidence data, is explained. The suite of computer programs (called VERA, after the Afrikaans "Versakkings-Analise" for subsidence analysis) which was written to facilitate the SEA approach is also briefly described. The VERA suite of programs is contained on a computer diskette inside the back cover.

Then, the results of the subsidence analysis culminating in a prediction model are presented. The model consists of the prediction of maximum subsidence, upon which a subsidence profile is then based. Induced tilt and strain are then calculated. The prediction model uses the actual pre-mining topography as a basis, not a hypothetical flat surface.

The effects of subsidence on structures and agriculture are given in five separate chapters. Bituminous roads were found to behave differently from gravel roads and are thus treated separately. The effects of subsidence on an overland conveyor belt, a burried water pipe line and agriculture are then discussed separately.

In the final chapter the conclusions reached in the previous chapters are briefly repeated and combined to arrive at the overall conclusion, which is basically that all the structures studied could be undermined with simple precautions and relatively inexpensive repair work. Areas where further work is required or would be beneficial are also identified.

2 OVERVIEW OF SUBSIDENCE PREDICTION IN THE USA, AUSTRALIA AND SOUTH AFRICA

2.1 INTRODUCTION

The prediction of subsidence is the first step in predicting the effects of high extraction coal mining on surface structures. Before embarking on research to arrive at a position from which subsidence could be predicted, it was necessary to find out what had already been done in this regard elsewhere and to evaluate the applicability of that work in conditions similar to those in the study area.

This chapter will summarise the work done elsewhere with regard to research into coal mining induced subsidence, and will also describe very briefly what has already been accomplished in South Africa to date. Overseas comparisons will be restricted to the USA and Australia, where the nature of the overburden and mining depths are comparable to those in South Africa.

2.2 THE CLASSICAL ELEMENTS OF SUBSIDENCE

A number of elements related to mining induced subsidence have gained universal recognition. They will therefore not be defined here, but are shown in Figure 2.1.

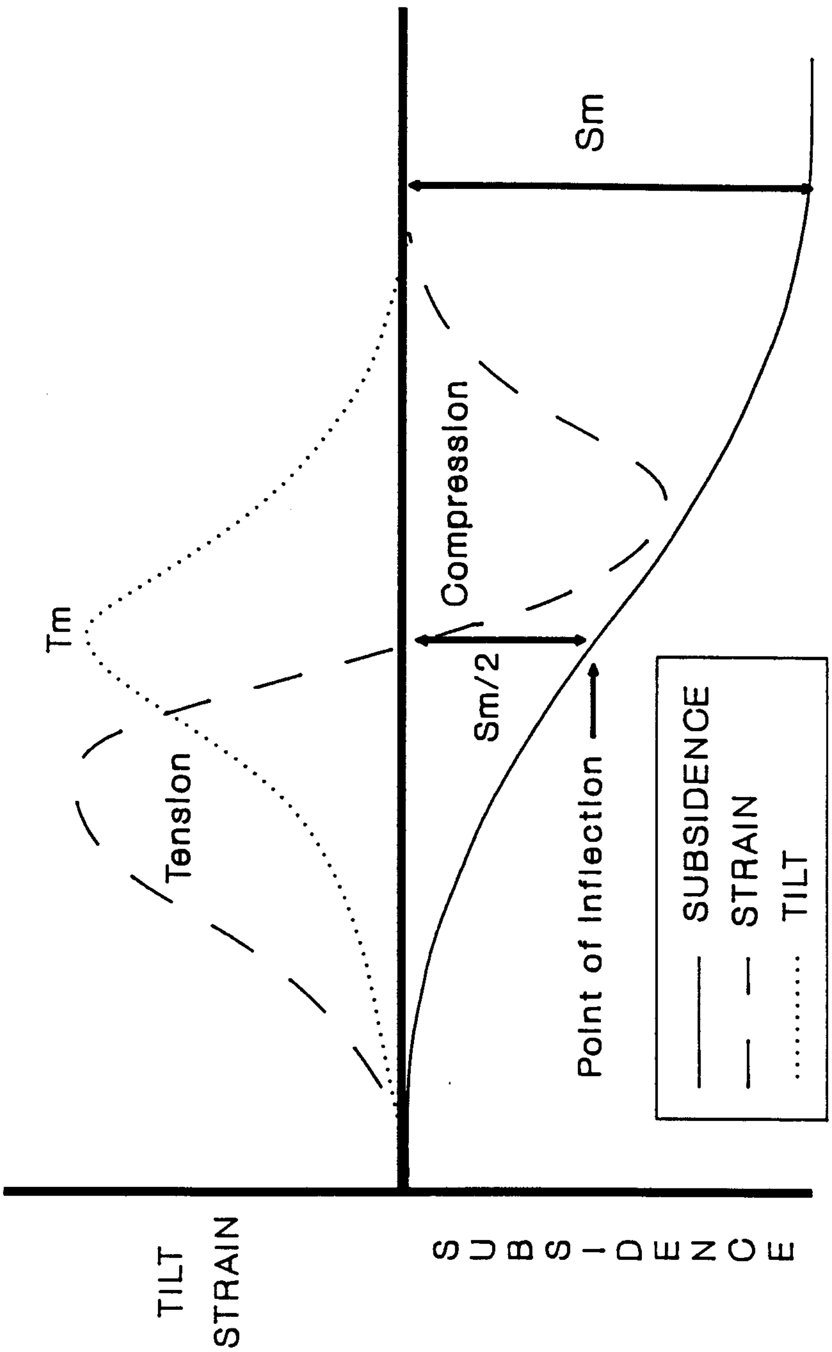


Figure 2.1 The classical elements of subsidence.

However, the term "strain" needs to be precisely defined in order to differentiate between the various methods by which strain can be calculated. Strain is defined as the ratio of change of length between any two points on the surface to the original length. Where the total length between points is considered, the term "strain" will be used. When only the horizontal projections of distances are used, the term "horizontal strain" will be used. The term "principal strain" will apply where three dimensional analysis is done, and will thus comply with the usual definition.

2.3 RELATIONSHIPS BETWEEN THE SUBSIDENCE ELEMENTS

Subsidence is the result of a process which is initiated by mining. Before subsidence occurs, there are no induced tilts or strains. Subsidence and its accompanying effects are therefore linked. The success of a subsidence prediction method depends on the success of the way in which the various elements are mathematically linked.

2.3.1 Tilt relationships

By definition, tilt is the rate of change of subsidence and curvature is the rate of change of tilt. The link from subsidence to tilt to curvature is therefore definite. The relationship of maximum tilt to the maximum subsidence and cover depth, H, is governed by a constant, k_1, which is usually determined empirically:

$$Tm = k_1 Sm/H. \tag{2.1}$$

2.3.2 Strain relationships

Strain and curvature

Viewing a subsided surface as a beam undergoing bending, the greatest magnitude of strain should coincide with the greatest curvature (or smallest radius of curvature). Accordingly, the point of inflection should be strain free, as the curvature there has to be zero. Also, the point of inflection, being the point at which the curvature changes from positive to negative, should mark the position at which the strain changes from tensile to compressive. Therefore, diagrams indicating the relationships between the various subsidence elements traditionally indicate a tensile zone and a compressive zone, the transition occurring at the point of inflection. The maximum values of strain then also coincide with the positions of highest curvature.

In practice, the relationship between tilt and curvature, being governed by definitions and calculated from the same sets of data, is always correct.

However, strains are calculated from different data (differential horizontal displacement) and the relationship between strain and curvature is characterised by anomalies. The National Coal Board (1975) recommends that strain be calculated rather than measured, which is salient confirmation of the fact that deviations from the expected frequently occur. In fact, subsidence prediction methods are in general poor predictors of strain.

It is the author's belief that the real cause of the inability to predict strain lies in the imperfect nature of the surface material. Once a crack has formed, large horizontal displacements occur across the crack. Further stressing of the surface will not lead to proportional and evenly distributed strains, but merely to further large displacements across the existing fracture.

By this mechanism, cracking of the surface will have an overriding effect on the distribution of strain; once the distribution is affected, the relative magnitudes of strains at given positions are obviously also affected. Since the curvature is not affected by crack formation to the same extent, the relationship between curvature and strain will be disrupted.

Taking this argument further, it follows that the scattering of strains will be worse as the frequency and magnitudes of cracks increase. This in turn, will be more prevalent at more "severe" subsidence areas, i.e. shallower mining exhibiting greater magnitudes of tilt, thinner soil covers (less of a cushioning effect) and stronger, more brittle rock types. Therefore, strain prediction based on curvature will be less successful in South Africa, the U S A and Australia than for instance in Great Britain or Europe.

It has been the author's experience that the correlation between curvature and strain is an evasive one, an observation that is confirmed by Schümann (1988a). It has also been reported by Adamek and Jeran (1982) that strains appear to be random variables in the Northern Appalachian coal field in the U S A, although the authors suspected that variations in surface topography were the cause of the inconsistancies.

The effect of topography on strain cannot be neglected. The author has often observed that larger surface cracks appear on one side of subsidence trough than the other, even at gently sloping subsidence terrains. The National Coal Board (1975) actually supplies a strain adjustment method to compensate for the effects of sloping topographies. In Australia, Kapp (1980) reported that strains were aggravated by severe topography. Once it is recognised that strains are affected by topographical features, it is also implied that the mechanism giving rise to strain does not depend only upon geometrical considerations based on the subsidence profile.

The significance then of uneven topography and the forming of cracks is that strain is the subsidence element most likely to deviate from its expected value and therefore the most difficult element to predict. Notwithstanding the foregoing remarks, several authors have attempted to correlate strain to other, easier to measure subsidence elements.

Several authors related maximum strain to the Sm/H ratio,

$$\epsilon_m = k_2 Sm/H. \qquad (2.2)$$

2.4 SUBSIDENCE PREDICTION METHODS

Subsidence prediction methods can be broadly classified into empirical or analytical methods. Most of the empirical methods have at least some analytical elements and vice versa: a purely empirical method would predict subsidence only for uniquely defined conditions for which an exact example exists, while a purely analytical method would not require any adjustment at all "for practical reasons", but rely only on calculation based on first principles. The classification thus relies on where the bias of the method lies, and not on an absolute distinction.

2.4.1 Empirical methods

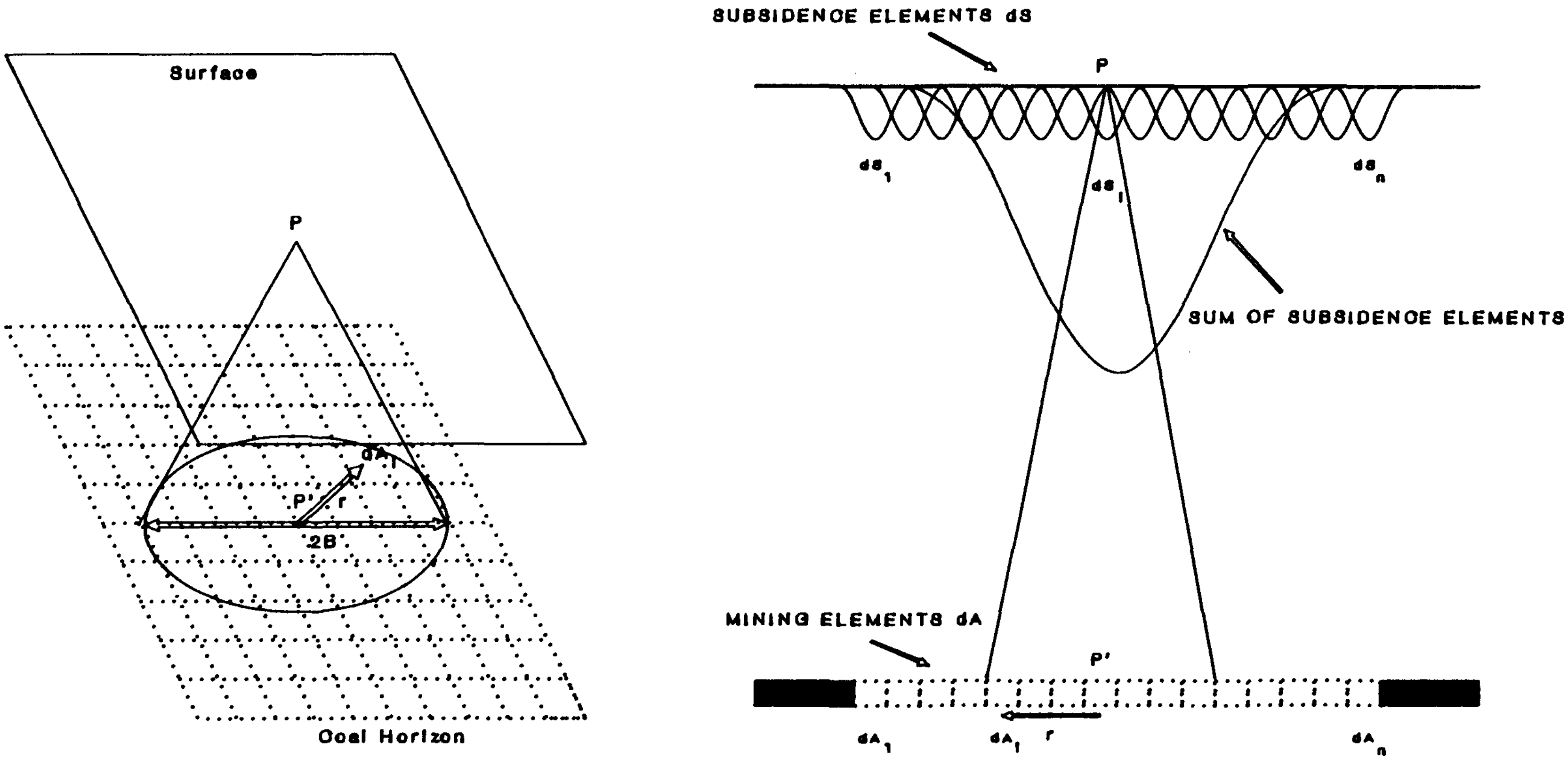
According to Salamon and Oravecz (1976), the initial attempts world wide at predicting subsidence were based on the Influence

Function method. Later, Profile Function methods became popular. Both will be only briefly explained, as several well documented explanations are available, such as Brauner (1973) and Bell and Coulthard (1988).

Influence Function Methods

Essentially, any Influence Function method relies on the assumption that the extraction of an element of rock, dAi, underground results in elemental subsidence, dSi, of the surface. This is shown in Figure 2.2. Summation of the elemental subsidences results in the definition of the complete subsidence profile. The shape of an elemental subsidence profile is described by the Influence Function. Most of the Influence Functions require at least two parameters to be determined empirically: the radius of influence, B, and the maximum subsidence, Sm.

A point on surface, P, is influenced by all the elements contained in a circle on the mining horizon, with radius B and centre directly underneath P. The amount of influence of any element dAi on point P is directly proportional to the size of the element and inversely proportional to the square of the horizontal distance of the element to point P.



3 Dimensional view   2 Dimensional view

Figure 2.2 Simplified diagram showing the principle of the Influence Function method.

From this it follows that maximum subsidence will occur at the centre of a panel with width 2B, as under those conditions the full circle of influence will consist of extracted elements. Also, the subsidence over the ribside has to equal 0,5Sm, as the circle with its centre exactly on the ribside will consist of one half mined out elements and one half solid elements.

A panel with width, W, greater than 2B will result in a subsidence trough with a flat central portion - such panels are termed super-critical. Sub-critical panels, on the other hand, have a width less than 2B and exhibit less subsidence. Panels with a width equal to 2B are termed critical. The critical span is not constant, but increases with increasing depth, H.

One of the major criticisms against Influence Function methods is that it does not allow for cases where the superincumbent strata is sufficiently strong to exhibit bridging. Where this happens, subsidence over the ribsides is significantly less than 0,5Sm. The majority of South African subsidence troughs fall within this class, Schümann (1988b).

Oravecz (1986) suggested the use of different angles of influence for mined and solid elements in order to compensate for the observation that less subsidence occurs over ribsides. In this way, surface points located towards the solid edges would be influenced by greater areas of solid, and hence less subsidence would be predicted.

Bell and Coulthard (1988) advocate the use of Complementary Influence Functions, a suggestion previously made by Sutherland and Munson (1983). The method of Complementary Influence Functions utilises the concept that the subsidence of surface points are influenced by seperate influence functions for mined and solid elements, and that the total subsidence is the sum of the results of the two influence functions.

To date, nothing has been published regarding the application of Complementary Influence Functions in South Africa. The concept, however, appears to be sound.

Profile Function Methods

Profile Function methods are more empirical in nature than Influence Function methods, as the method relies only on observed characteristics of subsidence profiles, and do not require explanation of deviations from the expected characteristics. Their application is therfore also more restricted than Influence Function methods, as the effects of changes in geological structure cannot be easily estimated beforehand.

Profile Function methods commonly entail the prediction of the shape of the subsidence profile based on previously gathered data from cases where mining and geological conditions are similar. Figure 2.3 is an example of a Profile Function. The figure shows the more important points on the subsidence profiles which are predicted. These are the magnitude of maximum subsidence, its position of occurrence relative to the panel edge, the position where subsidence begins and the position where half of the maximum subsidence occurs.

The British Coal model, described in detail by the Subsidence Engineer's Handbook (1975), is probably the most complete Profile Function of all. It is also frequently the first model to be tested in a new mining area and the literature abounds with examples where subsidence is compared to the British Coal prediction. It almost appears to be the first task of many subsidence analysts world wide to prove that the British Coal model is not valid for a particular new area.

In the U S A, Karmis et al (1984) developed a profile function for their Eastern coalfields based on an analysis of 34 case studies. The authors anticipate that the subsidence model may change as more data is gathered, but already claim that the model is "accurate" (not defined) for the Appalachian region.

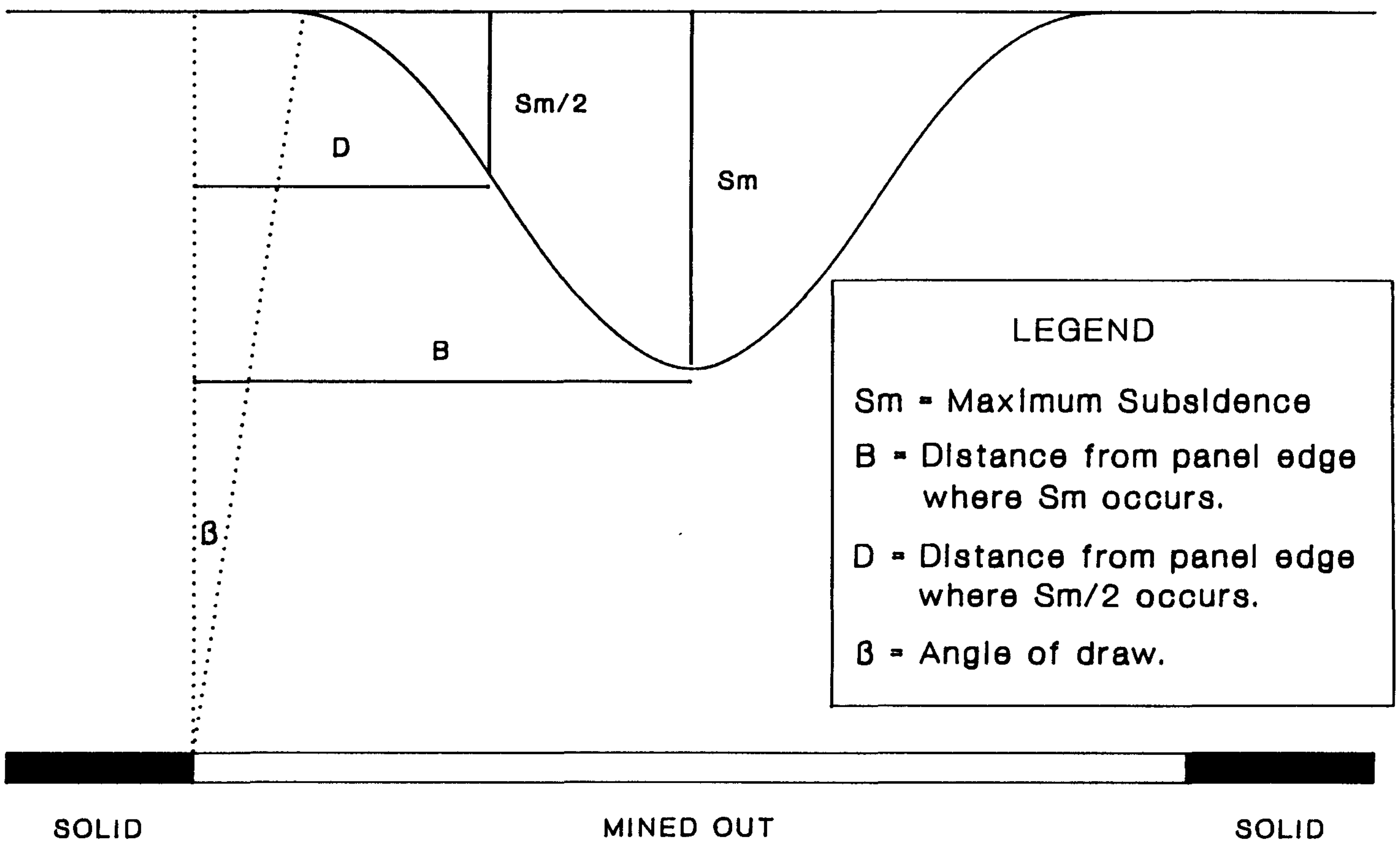


Figure 2.3 Simplified diagram explaining the Profile Function.

In Australia, Holla (1985) developed a Profile Function for the Southern coalfield of New South Wales while the same author, Holla (1986) provided a different one for the Newcastle coalfield where different geological conditions rendered the first model less applicable.

Their ease of application is the major advantage of Profile Functions; the requirement of a relatively large data base for their development and restricted application are their major disadvantages.

2.4.2 Analytical methods

The disadvantages of empirical subsidence prediction methods, which are by their nature largely unrelated to the subsidence process, can be overcome by modelling the causes of subsidence. This analytical approach presupposes a knowledge not only of the subsidence process, but also of the mechanical properties of the rock mass involved in that process. The lack of knowledge of these mechanical properties, and to some extent of the subsidence process, are the major reasons why analytical methods have so far not met with appreciable success.

Salamon et al (1972) supplied an equation for the prediction of maximum subsidence, based on the caving height, the bulking factor of the immediate roof and the compressibility factor of the goaf material. This is one of the very few purely analytical models available.

Ishijima and Toxhira (1973) described efforts to utilize finite element methods, with promising results. Gurtanca and Schümann (1986) reported some success with a two dimensional, transversely isotropic, linearly elastic boundary element model developed by Crouch (1976).

Both the finite element model and the boundary element model, however, essentially ignore the true nature of the subsidence process. The large displacement behaviour of the jointed rock mass is approximated by "softening" the overburden rock. The true analytical content of such attempts may thus be justifiably questioned.

It would appear that models capable of simulating the displacement of discrete blocks, such as that described by Cundall and Marti (1979), may be more correct. The elastic models may be useful for simulating subsidence where dolerite failure did not occur.

2.5 RESULTS FOR SUBSIDENCE PREDICTION OBTAINED IN AUSTRALIA, THE U S A AND SOUTH AFRICA

2.5.1 Australia

The emphasis in Australian subsidence prediction is on empirically derived profile functions.

For the Newcastle coalfield in New South Wales, Holla (1986) found the following:

$$S_m = 0{,}55h, \quad (2.3)$$

$$W_c = 1{,}6H, \quad (2.4)$$

$$T_m = 1{,}8h/H, \quad (2.5)$$

$$\epsilon+ = 0{,}4h/H, \quad (2.6)$$

$$\epsilon- = 0{,}6h/H. \quad (2.7)$$

For the Southern coalfield, Kapp (1980) quotes a slightly smaller critical span, 1,5H, and a slightly higher value of Sm = 0,65h.

2.5.2 United States of America

In the U S A, Karmis et al (1984) deduced the following expression to describe subsidence profiles in the Appalachian regions:

$$S(x) = 0,5\ Sm\ [1 - \tanh (cx/B)], \quad (2.8)$$

where

S (x) = subsidence of a point on surface

x = distance from the inflection point to a point on surface,

Sm = maximum subsidence for the profile,

B = distance from the inflection point to the position of S_m,

c = constant, 1,4 for sub-critical panels and 1,8 for critical and super critical panels.

The critical width, although not explicitly stated by the authors, appears to equal 1,3H from the data.

They also determined the following empirical relationship between strain and curvature:

$$\epsilon = 0,92\ (\Gamma)^{0,5}. \quad (2.9)$$

Furthermore, strain was found to be related to the geometrical elements as follows:

$$\epsilon = 0,92\ C/B\ [Sm\ \text{sech}^2\ ({}^{cx}/B)\ \tanh (cx/B)]^{0,5}. \quad (2.10)$$

The subsidence factor was found to decrease linearly from 0,62 to 0,2 with an increase in the percent hardrock (sandstone and limestone) in the overburden from 0% to 80%.

Trevits et al (1987) describe an influence function, for the Northern Appalachians, based on the well known Bals (1932) theory. Their model does not yet predict strain, but a high degree of accuracy is claimed for the subsidence profile. The work is described as preliminary.

2.5.3 South Africa

Failed dolerite sill

The most comprehensive overview of subsidence elements in South Africa is given by Wagner and Schümann (1985).

They quote the following empirically derived elements:

$$W_c = 2{,}0H, \tag{2.11}$$

$$Sm = 0{,}65h, \tag{2.12}$$

$$T_m = 1{,}5h/H, \text{ and} \tag{2.13}$$

$$\epsilon_{x,m} = 0{,}43h/H. \tag{2.14}$$

Note that the maximum strain referred to in equation (2.14) is the maximum <u>horizontal strain</u>.

It is evident from the data that the ratio of critical width to mining depth, given as 2,0, could not be determined with certainty, but had to be found by extrapolation. This is due to the scarcity of data relating to panels with a W/H ratio greater than 2. It was deduced by van der Merwe (1986a) that the critical width may be as high as 2,5. However, this deduction was based on observations at very shallow mining depth (50 m below surface) and it has been shown by authors like Kapp (1982) that at shallow depth, the critical width may be greater. Therefore, the value of 2,5 may represent an upper limit, and the W/H ratio for critical width is probably between 2,0 and 2,5 for depth of mining ranging from 150 m to 50 m below surface.

Intact sill

For the situation where a dolerite sill is present in the overburden, Galvin (1983) supplied an equation to determine the panel width necessary to result in dolerite failure. (To avoid confusion, the term "critical width" shall refer to the underground panel width which is required for maximum surface subsidence to occur, while the term "critical span" shall refer to the panel span, or width, required to result in dolerite failure). According to Galvin (1983), the critical span, S_c, is given by:

$$S_c = \sqrt{1165t_d - \frac{935t^2_d}{D}} + 2\ t_p \tan\alpha, \qquad (2.15)$$

where

t_d = thickness of sill,

t_p = parting thickness,

D = depth from surface to base of sill, and

α = goaf angle.

Should the dolerite fail, it no longer restricts the surface subsidence and the situation is the same as where the dolerite is absent. However, if the dolerite sill does not fail, the maximum subsidence is substantially decreased, as observed by several authors such as van der Merwe (1984). It has often been remarked, inter alia by Salamon et al (1972) that the intact sill then acts as a plate, undergoing elastic deflection.

Schümann (1988b) attempted to correlate the deflection of an intact sill to the theoretical elastic deflection, without much success. He did, however, find a good correlation between the maximum observed subsidence and the square of the panel width to dolerite thickness ratio.

As the ratio of the length of the plate to its width is normally in the region of five to ten, thus greatly in excess of two, the deflection of a beam instead of a plate may be considered without appreciable error, according to Obert and Duvall (1967). Fundamentally, then, the maximum deflection of the beam is given by the expression:

$$Z_{max} = \frac{L^4 \Omega}{32\ Et^2}, \qquad (2.16)$$

where

Ω = evenly distributed unit load on beam,

L = length of beam (or width of cavity underneath dolerite),

E = modulus of elasticity, and

t = thickness of beam.

According to Galvin (1983) the width of the cavity underneath the sill is given by:

$$W_d = W_p - 2\ t_p \tan \alpha \qquad (2.17)$$

where

W_p = panel width,

t_p = thickness of parting between base of sill and extracted coal seam, and

α = goaf angle, commonly taken as 15°.

Using equations (2.16) and (2.17) for a 30 m thick sill occurring midway in an overburden overlying a coal seam at 180 m below surface, a 130 m wide panel should result in maximum subsidence of 45 mm, while a 150 m wide panel under the same conditions should result in subsidence of 100 mm.

These conditions at Coalbrook Collieries resulted in measured maximum subsidences of 230 mm and 250 mm respectively, as reported by van der Merwe (1984). These observed maximum subsidences can only be obtained by calculation if the modulus of elasticity, which was taken at the laboratory value of 75 GPa, is reduced to 15 GPa and 30 GPa respectively for the two situations.

While it is granted that the elastic constants of an imperfect, jointed rock mass will differ from the laboratory values obtained from small specimens, the differences in the required adjustments indicate that relating the behaviour of an intact sill to a classical elastic deflection example may be an over simplification. However, it remains a more accurate estimate of subsidence than comparing it to subsidence at areas with a failed sill.

2.6 APPLICABILITY OF RESULTS

The foregoing sections have indicated that a significant amount of work has already been done, both locally and overseas where the subsidence pheonomena appear to be somewhat similar. There are significant similarities between mainly the Australian observations of Holla (1985) and the observations made by Wagner and Schümann (1985) in South Africa.

Those observations deal mainly with the relationships between tilt and strain and vertical subsidence. For the purposes of predicting the effects of subsidence on structures, the need for predicting strain and tilt is self evident - therefore emphasis will be placed on those parameters.

Especially in the South African context, some issues which determine the success of making a reliable prediction of strain and tilt remain. The first one is that both strain and tilt are sometimes calculated from the vertical subsidence. In the work of Wagner and Schümann (1985), the vertical subsidence is given as 0,35h to 0,65h (where h is the mining height) which is a very wide range. Although, for structures, vertical subsidence per se is sometimes less important, this same range is then applicable to the derived values for strain and tilt, which may then vary almost by a factor of two.

Secondly, the stated relationships represent the best fit to the available data. There is unfortunately no mention of the degree of scatter in the data.

Visual examination of Figures 14 and 16 from Wagner and Schümann (1985), reproduced here as Figures 2.4 and 2.5, indicate the amount of variation in the data. For example, at a mining height to depth ratio of 0,025 the horizontal strain can vary from less than 5 mm/m to more than 10 mm/m - a factor greater

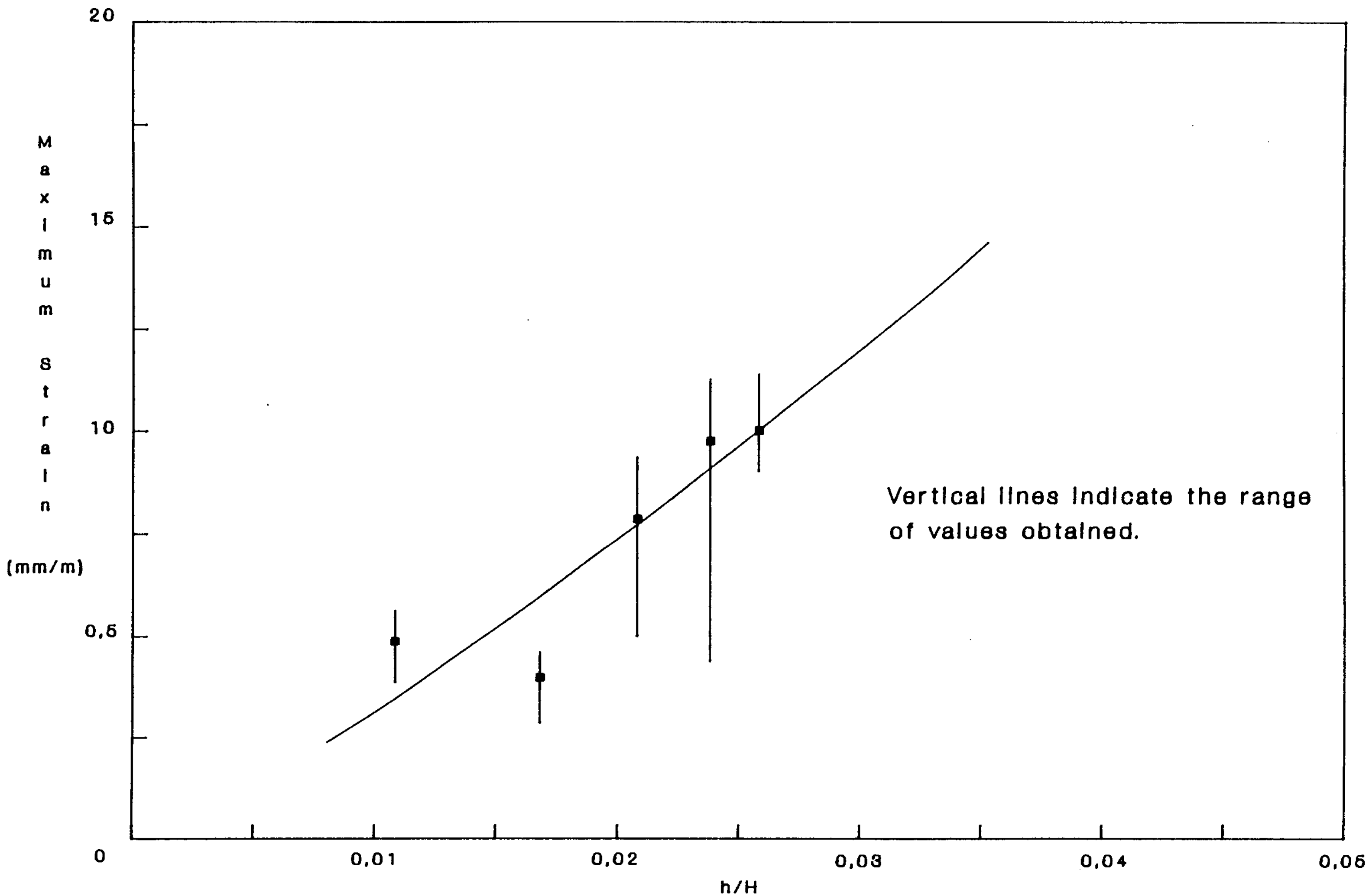


Figure 2.4 Relationship between h/H and Maximum Strain, after Wagner and Schümann (1985).

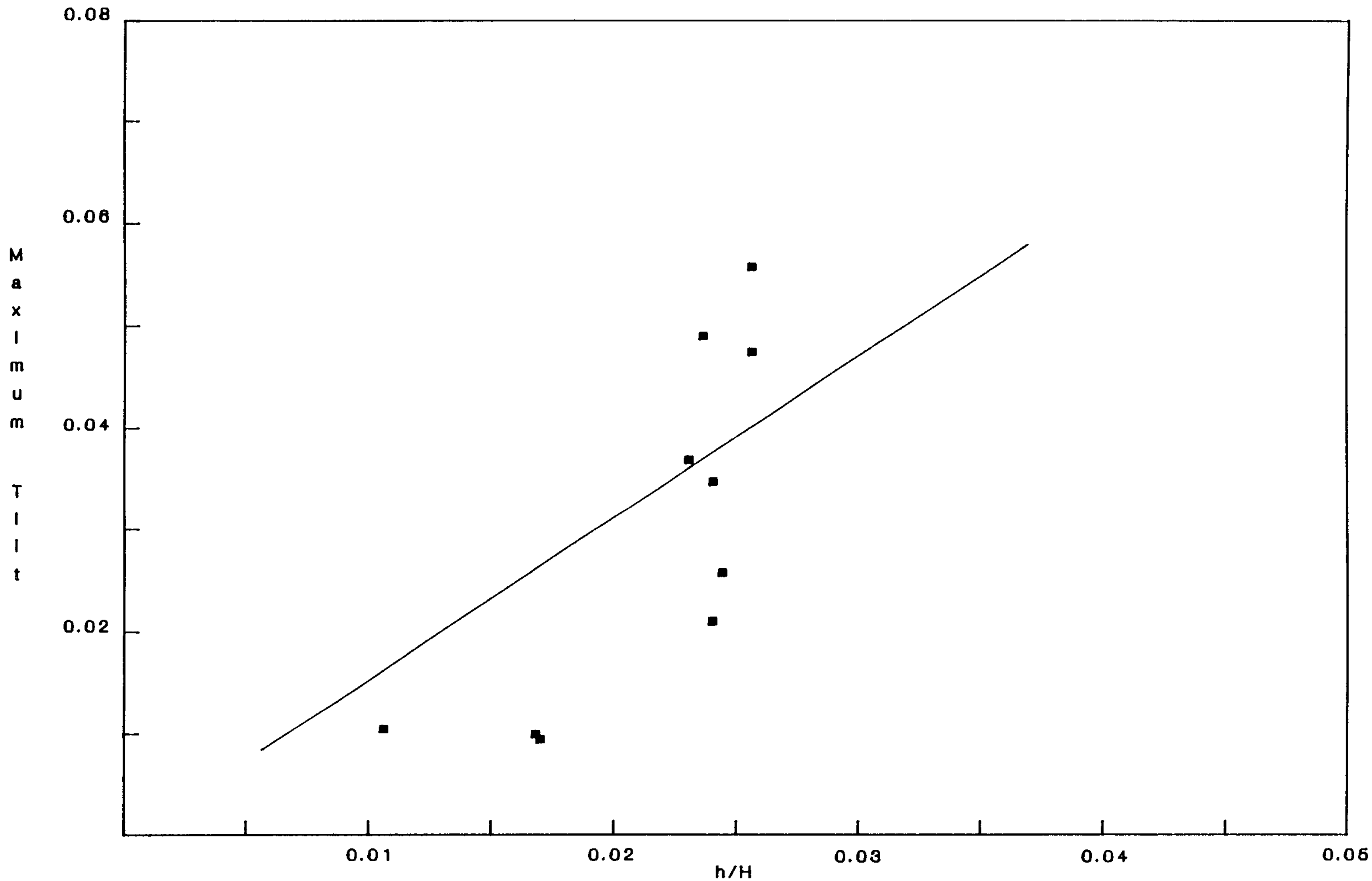


Figure 2.5 Relationship between h/H and Maximum Tilt, after Wagner and Schümann (1985).

than two. Similarly, the induced tilt at the same mining height to depth ratio can vary from 20 mm/m to over 50 mm/m, which is again a factor of variation greater than two.

It is significant that these variations are displayed at a mining height to depth ratio of 0,025, as that ratio corresponds to a mining height of 3 m at a depth of 120 m. This is a very common South African coal mining situation, and therefore also the situation for which the most data is available.

It is suspected that the variation is primarily due to variations in geological structure within the broad classification, and also to the blocky nature of the relatively strong overburden strata. These causes of the variation are also present at other mining height to depth ratios for which less subsidence data is available. There is therefore reason to suspect that the variation in strain and tilt will also be present at other configurations, but that the variation is hidden due to lack of data.

Therefore, the proportionality constants of 0,43 and 1,5 contained in equations (2.13) and (2.14) are not questioned as being the best fit to the available data, but the opinion is held that they are poor predictors of strain and tilt due to the small amount of data on which they are based and the scatter in the data which is available.

Another reason for the variation is the following:
Wagner and Schümann (1985) relate maximum tilt and strain magnitudes to the ratio of mining height to mining depth, ignoring the panel width. The relationship is certainly valid for super critical panels, where the maximum subsidence is no longer a function of panel width. The same authors state that the critical W:H ratio is probably in the region of 2, which means that the great majority of high extraction panels in South Africa fall in the sub critical class. Cognisance must therefore be taken of the panel width. The author suspects that the only reason why there is some correlation between strain and tilt and the h:H ratio, is because the panel widths of the studied cases were more or less constant. However, as this will not always be the case, the simplification of Wagner and Schümann's approach cannot always be valid.

Unfortunately, Wagner and Schümann (1985) make no distinction between tensile and compressive strain. The magnitudes of maximum tensile and compressive strains have been found to be different by overseas researchers, which is confirmed by the author's own experience in South Africa.

It can thus be concluded that although much good work has already been done, and the broad parameters determined, much more work is required before a suitably accurate subsidence prediction model will be available for South Africa.

3 OVERVIEW OF WORK PREVIOUSLY DONE WITH REGARD TO THE EFFECTS OF SUBSIDENCE ON STRUCTURES AND AGRICULTURE

3.1 INTRODUCTION

While the previous chapter dealt mainly with the prediction of coal mining induced subsidence, this chapter is devoted to the reaction of structures to the displacements associated with subsidence. A further complication is thus introduced: the type and quality of the construction, or the purpose which the surface serves. If subsidence can be seen as the first consequence of the act of high extraction mining, then the effects of that subsidence may be seen as a second order consequence.

In a very broad sense, two classes of surface utilisation may be distinguished. Firstly, the surface itself may be used. In this class, a number of sub divisions exist. Agricultural use may mean the utilisation of the natural veld for grazing or the cultivation of land for crop production. Surface may also be used for storing water in the form of a dam, or be registered as a landing strip for aircraft.

The second class of utilization includes all the forms of artificial structures. Structures may be sub divided into tall, narrow based structures such as transmission towers, low broad based structures such as houses or long, thin structures such as pipe lines.

It will be shown that each type of structure is affected by different elements of subsidence. Further complicating factors are the differences in quality even of the same type of structures, and the differences in construction materials, eg. steel versus asbestos cement pipes.

In the design of an empirical prediction method, the amount of data required is directly proportional to the number of variables involved and the variation of each variable when all the causitive factors appear to be constant. The variations in the characteristics of the rock mass involved in the subsidence process and the topographical features of the surface already introduce restrictions on the accuracy of the prediction of the subsidence elements. Taking into consideration the variations of the structures on surface, it is clear that the creation of an empirical method to predict the effects of subsidence on structures will require a massive amount of data.

Very little data is actually available in South Africa, as not many structures have been undermined. This is because firstly South Africa is not a densely populated country and consequently fewer structures exist than for instance in Europe, and secondly because permission from the Government Mining Engineer is required to undermine any structure. Mining companies tend to plan underground layouts such that the minimum of surface structures have to be undermined.

Ironically, permission to undermine a structure is often considered on the basis of projections of damage likely to result from subsidence. In the absence of examples, such projections cannot be made. This approach cannot be faulted, as owners of surface structures have a right of protection of their property. The stalemate can only be broken by experimental undermining of structures, which can be costly.

The alternative to the empirical approach is to adopt an analytical approach to the prediction of the effects of subsidence. This, however, will require knowledge of those characteristics of structures - and not only the materials comprising the structures - likely to be affected by subsidence, such as flexural limits. Structures are seldom designed with a view to accommodating the magnitude of displacements induced by mining and consequently the design tolerances are usually very small.

Also, because large displacements were usually not considered in the design of structures, the prediction of the effects of subsidence is as difficult for the original designer as for the subsidence analyst.

Due to the variations already explained, it will be seen that specific guidelines are seldom readily available, and the available literature often tends to be vague. Different methods of dealing with the conflict of interest of mineral and surface owners exist in different countries of the world; these will also be referred to.

In a commercial environment, the level of knowledge available on a subject is governed by the commercial need for that knowledge. For instance, if no benefit can be derived from undermining a structure on surface, the best mining policy would be to avoid undermining that structure and it would then not be necessary to know what effect subsidence would have on the structure. Also, if statutory controls are of such a nature that absolutely no undermining of any structure can ever be permitted, little can be gained from researching the effects of subsidence on structures. If, however, predicting the effects of subsidence on a structure is required as a prerequisite for obtaining permission to undermine that structure, knowledge of the effects of subsidence has significant commercial value.

It is therefore to be expected that there is a correlation between statutory requirements or the method of resolving the conflict of interest between surface and mineral owners, and the level of knowledge of subsidence effects.

In the next sections, a brief overview will be given of how subsidence conflicts are handled in certain states of the USA and Australia. The information is also valuable in order to evaluate the South African systems and possibly to develop a more satisfactory local system.

3.2 WORK DONE IN AUSTRALIA

3.2.1 Methods of dealing with the effects of subsidence

According to Kapp (1986) the conflict between maximising coal reserves and preserving the integrity of the surface environment, which has always existed, is becoming even more evident in the coalfields of the Sydney Basin, from which most of the Australian coal production has come. He also states that when structures are to be undermined, there are either legislative requirements or there is agreement following consultation between the various parties concerned.

A concise yet comprehensive overview regarding the legislative measures applicable in Australia is given by Ramsland and Holla (1986). The Coal Acquisition Act, 1981, enabled the New South Wales Government to vest the ownership of all coal in the Crown. Although the Act was aimed primarily at obtaining royalties from all coal mining in the state for the Crown, it had the additional effect of unifying all coal mining operations under the same Acts.

There are basically four Acts that embody specific subsidence provisions and associated matters. Firstly, coal mining leases are granted under the Coal Mining Act, 1973 (NSW Government, 1984) which is administered by the Minister for Mineral Resources. Under this Act, the only permissable mining method is bord and pillar and it provides for due consideration to be given to the integrity of surface improvements and features.

Secondly, the Coal Mines Regulation Act, 1982 (NSW Government 1982) makes provision for the safety of operations in coal mines. This Act is administered by the Minister for Industrial Relations, and mining methods other than bord and pillar can only be applied with his permission. He acts on the recommendation of the Chief Inspector of Coal Mines. The Minister may require a mine operator to leave a protective pillar or pillars to protect the position of the mean high water mark of tidal waters or surface improvements or features, whether natural or artificial. Generally, when consideration is given to the undermining of structures, the owner of the structure is asked to investigate the structure's integrity under the influence of additional stresses caused by subsidence. Restrictions on undermining may or may not then be required, according to the structural integrity of the development under consideration.

The third Act is the Mine Subsidence Compensation Act, 1961 (NSW Government 1983) which has two main functions. It provides for compensation to be paid, where applicable, by the Mine Subsidence Board and for the Board to regulate surface development within proclaimed mine subsidence districts. The regulation of surface development implies not as much restricting development, but ensuring that structures (schools, houses, pipe lines, etc.) are constructed in such a fashion that they may tolerate the expected magnitudes of subsidence.

The Board consists of six members. These include the Secretary, Department of Mineral Resources, the Chief Inspector of Coal Mines and four other members appointed for a term of three years by the Governor. It derives its income primarily from contributions by the owners of colliery holdings. The contributions are based on the land value of the colliery holding. Other sources of income include interest on investments and fees for the issue of certificates provided for in the Act.

It has been the policy of the Board to recommend proclamation of only selected coal bearing areas, i.e. those that are likely to have potential for subsidence damage and are likely to experience substantial surface development.

The Dams Safety Act, 1978 (NSW Government, 1978) addresses coal mining in and around stored waters. In essence, it regulates the protection of certain dam walls from mining induced subsidence by the prohibition of mining in defined zones underneath and around wall structures, and the restriction of mining under storage areas.

It appears that for the purposes of protection, an angle of draw of 35° is usually assumed. The sizes of pillars required for protection appear not to be governed by specifically calculated safety factor considerations, but are based on fractions of the cover depth or multiples of the mining height.

The Chief Inspector of Coal Mines plays a very important role in the implementation of all four the mentioned Acts. Although various Ministers may bear the legal responsibility, applications to implement particular mining methods or to undermine structures are considered pending the advice of the Chief Inspector. He plays a coordinating role, gathering all the information relative to the need for and degree of surface protection required against the background of the responsible development of the available coal reserves. An important condition which is normally incorporated in the approval for high extraction mining methods is that subsidence monitoring should be undertaken. This is a valuable source of information for the development of subsidence prediction models.

Although not explicitly stated by Ramsland and Holla (1986), it was learnt from Kapp (1986a) that the Chief Inspector of Coal Mines is assisted in his duties regarding surface effects by a qualified subsidence engineer. The appointment of a qualified subsidence engineer followed on a recommendation of the report compiled by the Honourable Mr R G Reynolds, Judge of Appeal of the Supreme Court, into coal mining under or in the vicinity of stored waters. The motivation for this suggestion by Reynolds (undated) was to decrease Australia's dependence on foreign expertise in subsidence related matters.

It is difficult for an outsider to assess the real value and success of the Australian method of handling the effects of subsidence, as any such system is ultimately handled by people. However, the system itself appears to cater for the interests of all the parties involved. While one Act is aimed at protecting existing structures, another protects the coal reserves by controlling the construction of structures. The decision whether or not to allow the undermining of existing structures is based on the tolerance of the structure to subsidence and a comparison of the cost of repairing or replacing the structure to the value of the coal which will be sterilised by not undermining it.

Different Ministers are responsible for administering the different Acts, but all act on the recommendation of the Chief

Inspector of Coal Mines, who has expert assistance available. He is thus in a position to take sensible and realistic decisions. Compensation for damages arising from subsidence is catered for by a formal system and funds are available. The funding is based on the value of the overlying surface underneath which coal mining takes place.

It would appear that the system overall may be cumbersome due to the number of Acts and different Ministers involved in the process, but it also appears to cater for all the aspects related to mining induced subsidence.

3.2.2 Work done with regard to the effects of subsidence on structures

Guidelines stating the maximum tolerable limits of subsidence elements like tilt, strain, etc. for various structures do not exist in Australia. Specific guidelines only exist for the undermining of dams, which is provided for by the Dams Safety Act, 1978 (NSW Government, 1978). In that case, maximum subsidence elements are not prescribed, but mining parameters are.

Undermining of dams

Permission to undermine dams is granted by the Minister of Public Works acting on a recommendation of the Dams Safety Committee. According to Ramsland and Holla (1986), the Committee usually imposes restrictions, which generally include the following:

(a) No mining is allowed under dam structures and their restricted zones, based on a 35° angle of draw.

(b) Underneath the storage area and an area 1,2 times the depth horizontally around the storage area, bord and pillar mining is allowed if the cover depth exceeds 60 m. The bord widths may not exceed 5,5 m and pillar widths must be at least the greater of fifteen times the mining height or one-tenth of the depth of cover.

(c) In some instances, where the cover depth exceeded 120 m, high extraction mining has been allowed. In such cases, the panel width is restricted to one third of the cover depth, and inter panel pillars must have a width equal to at least the greater of one-fifth the cover depth or fifteen times the mining height.

Regular monitoring of subsidence, water seepage and geotechnical features are required and compared to predictions by the Committee. Deviations are investigated.

Williamson (1978) commented on the principle that dams may be undermined and on the restrictions. Based on measurements of water inflows into mines as well as the hydrogeological properties of the overburden strata, he came to the conclusion that both bord and pillar and high extraction mining, under the conditions normally laid down by the Dams Safety Committee, can be carried out and that dam water losses can be kept to acceptable limits (less than 22,3 Ml/day).

Observations made by Wilson (1985) at two sites in New South Wales support the opinion of Williamson. Wilson found that water leakage into mines from reservoirs overlying high extraction panels was unlikely at cover depths greater than 120 m.

Kapp and Kennerly (1986) studied pillar stability, subsidence and hydrological aspects at two mines which mined underneath dams according to the Dams Safety Commission guidelines. They came to the conclusion that the guidelines were too conservative, and could be relaxed without risk to the long term stability of the pillars or the superincumbent rock mass.

Undermining of other structures

Kapp (1982a) describes the effects of subsidence resulting from longwalling at a depth of 500 m on a number of houses over an area of 9 km^2, including two churches of historical value, constructed of sandstone. With regard to the churches, maximum tilts of 2 mm/m and compressive strain of 0,5 mm/m (of which half was transferred to the building), accompanied by maximum subsidence of 530 mm, did not result in effects different from those caused by seasonal changes. Overall in the area, the maximum subsidence was 730 mm, the maximum induced tilt was 3,6 mm/m and the maximum tensile and compressive strains were respectively 0,5 mm/m and -1,2 mm/m. Even though the area was a Declared Subsidence District, and surface owners thus eligible for compensation for damage caused by subsidence, no damage was reported in the area. Consequently, the stated magnitudes of the subsidence elements can be regarded as being less than the threshold values for houses, roads and general services in that area.

Holla and Hughson (1986) described the undermining of a number of structures in New South Wales. Their findings are briefly summarised in the following sections.

Pipelines

A high pressure natural gas pipeline, diameter 864 mm, subsided by 700 mm without suffering damage. Two other pipelines, both of which underwent less subsidence, were also reported to have been undermined without being damaged.

Roads

The F6 Southern Tollway was undermined by longwalling at a depth of 470 m and subsided by 1,67 m. The maximum recorded tensile and compressive strains were respectively 2,5 mm/m and -2,8 mm/m. Some damage did occur on the road, but the trafficability of the road was never impaired as continuous maintenance was carried out. In another instance, a road was reported to have suffered major cracking due to high extraction undermining at a depth of 120 m. Traffic safety was ensured throughout the mining operation by temporary repairs. The road was under traffic during undermining.

Holla (1988) describes the undermining of three roads. The most notable of these is the undermining of the Pacific Highway by the Wyee Colliery. The road subsided by 2,23 m and a maximum compressive stain of -8,1 mm/m was recorded, the maximum tensile strain being 2,5 mm/m. The maximum induced tilt was 18,5 mm/m and maximum horizontal displacement was 265 mm. Tilts and strains were measured along a single line running parallel to the road, which traversed the longwall panel at roughly 45°. It can thus be concluded that the strains and tilts mentioned were only components of the principal strains and major tilt, which could have been significantly greater.

Severe cracking and compressional ridging, 25 mm to 50 mm high, occurred on the road. However, the road (two lanes in either direction) was kept under traffic all the time. The normal speed restriction of 100 km/h was maintained. Continuous maintenance was provided.

Transmission towers

Two cases of undermining transmission towers are mentioned by Holla and Hughson (1986). The first one subsided by 1,6 m and a maximum strain of 3 mm/m was recorded. The second one subsided by 250 mm. Neither tower was structurally designed for subsidence, but no damage was reported.

3.3 WORK DONE IN THE U S A

3.3.1 Methods of dealing with the effects of subsidence

Except where indicated to the contrary, the information in this section was obtained from DuMontelle et al (1980).

Federal measures

The Federal Government only started active participation in mining induced subsidence related matters in 1977, with the passing of the Surface Mining Control and Reclamation Act (SMCRA). Prior to 1977, this was considered as a matter to be dealt with by the individual States.

The SMCRA requires regulation of both open cast and underground mining. The individual States are expected to adopt programmes for the implementation of the SMCRA provisions. Where this does not happen, or where State programmes are not approved, the Secretary of the Interior is directed to enforce a Federal programme.

Underground coal mine operators are required to adopt measures consistent with known technology, to prevent subsidence causing material damage and to maintain the value and reasonably foreseeable future use of surface lands, except where the mining technology used results in planned subsidence in a predictable and controlled manner.

Steps must thus be taken to either prevent subsidence, or subsidence must take place in a controlled and predictable manner. The essence of the Act appears to be prevention of material damage, and not prevention of subsidence per se.

Prevention of damage is not restricted to current land usage, but includes "reasonably foreseeable land usage"; it also does not exclude farming land by restricting the terms to structures.

The regulations implementing the Act, which were published in 1979, require mine operators to notify surface users of their mining schedules. Steps aimed at preventing material damage due to subsidence have to be implemented - these steps could include leaving protective pillars, causing controlled subsidence or back filling to minimise or prevent subsidence.

Mine operators have to provide a survey to the regulatory authority (a State authority) indicating whether structures or "renewable resource land" exists in the area to be undermined. If it does, then the mine operator has to file a plan indicating a description of the mining method to be used, a detailed description of the steps aimed at damage prevention, a description of the measures to be taken to mitigate damage if it occurs and also a description of the methods to be used to determine the degree of damage.

If damage occurs, whether it could be foreseen or not, and whether or not approved damage prevention steps were taken, the mine operator is responsible to repair the damage. He must either restore, replace or rehabilitate the structure, feature or value to its pre-subsidence condition, or he must purchase the damaged structure or feature for its fair-market pre-subsidence value and restore the land surface to the extent technologically and economically feasible to a condition capable of supporting the purchased structure and other foreseeable uses.

The regulatory authorities are also empowered to regulate or prohibit mining underneath public buildings, urbanized areas, dams, perennial streams or aquifiers serving as major sources of water to public water systems.

State measures

The individual States have different methods of dealing with the effects of subsidence, mostly within the framework of the SMCRA. The SMCRA provides essentially for the prevention of subsidence damage in the future, or for methods of compensation in the event of damage occurring.

A number of States have to deal with the additional problem of subsidence occurring now, as a result of mining which was done several decades ago. In older times, partial extraction was done. Pillars of varying dimensions were left in place in a disorganised fashion. It is evident from an observation by Allen (1978), that there was no relation between mining depth and pillar dimensions, that pillars were not scientifically designed with a view to supporting the overburden strata. With the deterioration of pillar strength and the occurrence of roof falls over time, pillar collapses and, in the case of very shallow mining, bord collapses to surface, are now occurring.

Very often, surface owners have no means of claiming damages as many of the mine owners have either disappeared or are no longer solvent. Due to differences in the magnitude of the problem and historical factors, the different States approach the problem differently.

The State of Illinois has perhaps the most unique approach. In Illinois, insurance companies are obliged to offer Subsidence Insurance to home owners at a premium prescribed by State law. In areas where there is a high risk of subsidence damage, the cover is automatic and home owners, while not forced to take out the insurance, have to absolve themselves from the insurance in writing if they do not want it. In areas with a smaller risk of subsidence damage (determined by the extent of mining) the cover is not automatic, but is nevertheless available for owners who want to be covered.

The Insurance is covered by a fund set up by the State Government. In the event of a short fall, insurance companies may borrow from the fund, and repay at a later stage. The motivation for the fund was to ensure that the scheme should not fail in its early stages of existence.

While surface structures damaged by subsidence are commonly catered for in most arrangements all over the world, it is very seldom that agriculture is specifically addressed. This is possibly due to the fact that it is more difficult to attach economic value to damage done by subsidence. The construction or replacement cost of most structures can be easily determined, but how does one calculate the loss in value of agricultural land realistically? In most instances, farming activities continue after subsidence has taken place, which proves that the loss is usually not total. While it is relatively easy to determine magnitudes of subsidence, it is very difficult to determine crop losses, explicitly due to subsidence, in isolation of the other factors governing crop yields.

In Illinois, this problem is currently being addressed in a scientific manner. The Illinois State Geological Survey (ISGS) is engaged in orderly research to determine the economical effects of mining induced subsidence on agriculture. One of the aims of the research program is to decide whether or not agriculture should be included in the insurance scheme.

In Pennsylvania, insurance is also available for home owners. Unlike in Illlinois, though, the scheme is wholly funded and administered by the State Government. A novel aspect of the Pennsylvanian approach is that surface owners who do not have the right of subjacent support (i.e. cases where it has been waived or sold by previous owners) have the opportunity to purchase that support from mine owners. Determining the amount of minerals to be bought for subjacent support or the price to be paid, especially in the light of the effect of protective pillars on the layout of adjacent areas, may sometimes prove difficult.

Mining of coal resulting in subsidence underneath certain structures is absolutely prohibited. Included in such structures are public buildings, residences and cemetries in existence prior to 1966, when the Pennsylvania statutes were enacted.

Maryland was one of the first States to react to the SMCRA. It has adopted regulations along the lines required by the SMCRA, with the provision that structures covered by the regulations must be in place at the date of issue of the mining permit. Prior to being granted a permit, a mine operator has to file a surety bond which is adequate to cover among other things the estimated total costs for preventing or reclaiming subsidence damage.

3.3.2 Work done in the U S A with respect to the effects of subsidence on structures and agriculture

One of the provisions of the SMCRA is that controlled and predictable mining induced subsidence is seen as a subsidence control measure. The SMCRA also implies that the effects of subsidence on structures should be predictable in order for subsidence to be considered as controlled. Agricultural land is not excluded from these provisions.

There has therefore recently been a lot of emphasis on subsidence damage related research in the U S A. Various Federal, State and other agencies are involved in this research.

Buildings

A very useful summary of criteria for subsidence damage to buildings, based on a survey of published material, is given by Bhattacharya and Singh (1984). The survey covered 62 sources, of which the greatest number (21) was from the U S A.

The authors classified buildings into four groups, as indicated in Table 3.1.

Table 3.1: Classification of buildings, after Battacharya and Singh (1984)

Description	Category
Brick and masonry structures/brick bearing walls/low rise structures	1
Steel and reinforced concrete frame structures	2
Timber frame structures	3
Massive structures of considerable rigidity/ central core design	4

Three classes of damage were identified, as follows:

Architectural - onset of architectural damage, characterized by small scale cracking of plaster and sticking of windows and doors.

Functional - onset of functional damage characterized by instability of some structural elements, jammed doors and windows, broken window panes, building services restricted.

Structural - onset of structural damage characterized by impairment of primary structural members, possibility of collapse of members, complete or large-scale rebuilding necessary. May be unsafe for habitation.

The conclusions of the authors are summarized in Table 3.2.

Table 3.2: Recommended damage criteria for buildings, after Battacharya and Singh (1984)

Category	Damage Level	Angular distortion (mm/m)	Horizontal strain (mm/m)	Radius of curvature (km)
1	Architectural	1,0	0,5	-
	Functional	2,5 - 3,0	1,5 - 2,0	20
	Structural	7,0	3,0	-
2	Architectural	1,3	-	-
	Functional	3,3	-	-
	Structural	-	-	-
3	Architectural	1,5	1,0	-
	Functional	3,3 - 5,0	-	-
	Structural	-	-	-

In the table, the term "angular distortion" refers to the tilt, from which is subtracted the rigid body tilt of the building. The angular distortion is therefore that portion of the tilt which caused bending of the building.

Yokel (1979) gives certain recommendations for housing developments in subsidence prone areas. These include that the long axis of buildings should be parallel to induced tilt contours, dimensions should be restricted to 25 m (or 30 m across any diagonal), buildings should be seperated by at least 2 m, basements should be protected by trenching, backfilled with a soft material and structures should generally be flexible.

Singh (1984) recommends similarly, with the added precaution that buildings should not traverse different soil types as these may settle differently. There appears to be general consensus in the literature that small, flexible buildings with allowance for clearances at windows and doors are preferable in subsidence prone areas.

Bruhn et al (1983) analysed subsidence damage at 163 buildings above active and abandonded mines in an attempt to determine the influence of ground surface conditions on damage resulting from subsidence. They observed that basements were the most sensitive parts of houses with regard to subsidence damage, and that basements usually suffered more damage than the rest of the house. They devised an index describing the severity of damage, which they also related to repair costs, according to observations in the basements. While the system appears to have significant merit for the U S A, it is not directly usable in South Africa as very few South African houses have basements.

In all but a few of the cases they studied, reliable subsidence data was not available. It was therefore not possible to determine a relationship between subsidence elements and damage, or to determine the effects of soil types on subsidence damage.

Marino et al (1986) described damage to three houses, a radio station and three radio transmitting towers due to partial extraction (70%) of a 2 m high seam at a depth of 43 m. Maximum tilts ranged from 20 mm/m to 70 mm/m. All the structures were severely to very severely damaged. The houses were demolished, while the radio station and transmitting towers were repaired.

3.4 HANDLING THE EFFECTS OF SUBSIDENCE IN SOUTH AFRICA

The statutory measures related to dealing with the effects of undermining in South Africa are expected to change in the very near future, with the publication of the Minerals Act which is aimed at unifying the various Acts dealing with mining which exist at the moment.

The current situation is that mining related subsidence is dealt with mainly by two acts, namely the Mines and Works Act of 1956 and the Mineral Laws Supplementary Act of 1975. A third act, the Mining Rights Act of 1967, prohibits prospecting in a manner which will disturb the surface of a township, road or railway, areas reserved for Government or public use or land of which the surface rights belong to another mineral holder.

Essentially, section 5 of the Mines and Works Act of 1956 prohibits mining underneath or within a horizontal distance of 100 m or a horizontal distance equal to the depth of mining below surface divided by 2,7 (whichever is the greater), except with the permission of the Government Mining Engineer (GME). This relates only to structures, farming land being excluded. The GME thus has the power to decide whether or not undermining will be allowed and to impose whatever restrictions he may see fit.

In practice, the modus operandi is for a mine desiring to undermine a structure to approach the Chief Inspector of Mines of the relevant district with such a request. The Chief Inspector of Mines then usually recommends to the GME that permission be granted on condition that a safety factor of 2 to 2,5 be used for pillar design, with sometimes the additional requirement that the bords be filled once the mining entries are no longer required. Depending on the nature of the structure, permission is usually not too difficult to obtain and the conditions not unduly onerous when bord and pillar mining is contemplated.

When it comes to high extraction methods, however, there is usually the additional requirement that the owner of the structure should also agree to the undermining. This requirement often leads to some or other form of contractual agreement relating mainly to compensation for damages between the mine owner and the owner of the structure.

For example, if a farm dwelling is to be undermined, the house is usually vacated prior to undermining and the owner compensated in such a way that he can build a similar house in another location. This is not a legal requirement, but a matter to be negotiated between the mine owner and the owner of the structure. The agreement so reached usually forms part of the conditions imposed by the GME.

Section 6 of the Mineral Laws Supplementary Act of 1975 deals with the situation where a farm may become an uneconomical unit as a result of mining activities. While the Act was really drawn up with open cast mining in mind, it has been written such to apply also to underground total extraction base mineral mining. Essentially, the Act provides for a farmer to approach the Minister of Mineral and Energy Affairs if he feels that his farm will become uneconomical due to mining activities. The

Minister will then investigate the matter, and, if he finds that this will indeed be the case, the Government may then purchase that farm from the farmer. If, however, it is considered not to be in the Government's interest to buy the farm, the Minister may order the mine owner to purchase the farm. The price is to be settled by agreement, or, failing that, by arbitration. From the time that the approach has first been made to the Minister, the farmer forfeits his right to obtain an interdict prohibiting further mining against the mine for a period of nine months. Should the matter not be settled within that period, the mine owner may prevent the farmer from obtaining an interdict by lodging security with the registrar of the court.

Legally, therefore, structures may not be undermined except with the permission of the Government Engineer while farming activities are only addressed if a farm as a whole will become uneconomical.

Lesser damage to farming, in other words where certain farm lands will be subjected to mining induced subsidence without causing the whole farm to become uneconomical, is catered for by common law. According to Shipman (1983) it is the duty of mineral rights holders to provide subjacent support for the soil of the land owner, while Kaplan (1983) explains very clearly that the mineral rights holder has the right to remove his minerals from the earth. Both parties thus have a right to exploit and enjoy their assests. Where this mutual exploitation is irreconcilable, the matter is generally resolved in favour of the mineral rights holder, according to Kaplan (1983).

However, it is seldom that conflicts of this nature result in litigation. Perhaps mainly in order to prevent the possibility of an interdict, the mines usually prefer to negotiate terms of damage compensation with surface owners prior to high extraction mining.

It thus appears that most situations are catered for, either formally or informally. There is adequate legal protection for the owners of surface structures and for farm owners facing the possibility of their farms becoming uneconomical. Farm owners facing a lesser degree of damage are protected by their right to obtain an interdict to prevent possible losses, which usually encourages mine owners to enter into negotiation prior to subsidence taking place.

Still, the system has several shortcomings. Firstly, the Mines and Works Act specifies that "structures" should be protected by prohibiting mining underneath them without differentiating between various types of structure or different magnitudes of subsidence. Therefore, a derelict farm outhouse is afforded the same protection as a nuclear power plant. While it may be argued that the current approach of the Government Mining

Engineer (to insist on an agreement between the owner of the structure and the mine) compensates for this fact, it also places the mine owner at the mercy of the owner of the structure. The mine does not have the statutory opportunity to demonstrate that his actions may only lead to insignificant damage.

The emphasis is on the agreement between the two parties, which means that the treatment of subsidence effects cannot always be uniform or consistent. This is demonstrated by the fact that in the Secunda district transmission towers are undermined with a minimum of bother, while gravel roads may not be undermined while under traffic, even though it has been shown that no danger arises. In fact, several gravel roads had been successfully undermined in the past while under traffic in the same area, but permission to do so was withdrawn without technically motivated reasons.

In the absence of differentiation between either types of structure or magnitudes of subsidence, relatively little research into the effects of subsidence on structures has been done. In a commercial environment one's actions have to be restricted to what will result in financial gain. In fact, the research that has been done was done in the hope of supplying sufficient information to change the rules.

3.5 CONCLUSIONS

The USA, Australia and South Africa have different approaches to the problems caused by mining induced subsidence. While a more sophisticated approach requires the availability of more information, it can also be said that the opportunities offered by a more flexible approach will encourage more research to be done and thus more information to be generated. This in turn will pave the way for an even more flexible approach.

In the USA and in Australia, there is encouragement for research as an engineering approach is already in use. By contrast, the South African approach is somewhat archaic. It is granted that the South African legislation was drawn up at a time when the effects of subsidence on any type of structure were largely unknown and the only safe approach was the conservative one. By this time, however, a number of structures have been undermined successfully and the time has perhaps arrived to adopt an engineering approach.

An engineering approach will only have merit if it will indeed be economical to undermine surface structures safely. In the following chapters, this aspect will be investigated.

4 MINING CONDITIONS IN THE STUDY AREA AND THE DATA WHICH WAS GATHERED

4.1 LOCALITIES OF THE MINING DISTRICTS

4.1.1 The Sigma district

Sigma Colliery is located at the town of Sasolburg, some 80 km South of Johannesburg. It is situated on the Northern boundary of the Orange Free State Province, the Vaal river. The mine was established in 1955 to supply coal to the Sasol I factory for the production of synthetic fuels and related chemicals. The location is shown in Figure 4.1.

4.1.2 The Secunda district

The Secunda district is situated in the South East of the Transvaal province, approximately 150 km East of Johannesburg. The location is also shown in Figure 4.1.

Sasol Coal operates four underground mines in the Area: Middelbult Colliery in the North West, Brandspruit Colliery in the South West, Bosjesspruit Colliery in the South East and Twistdraai Colliery in the North East, as shown in Figure 4.2.

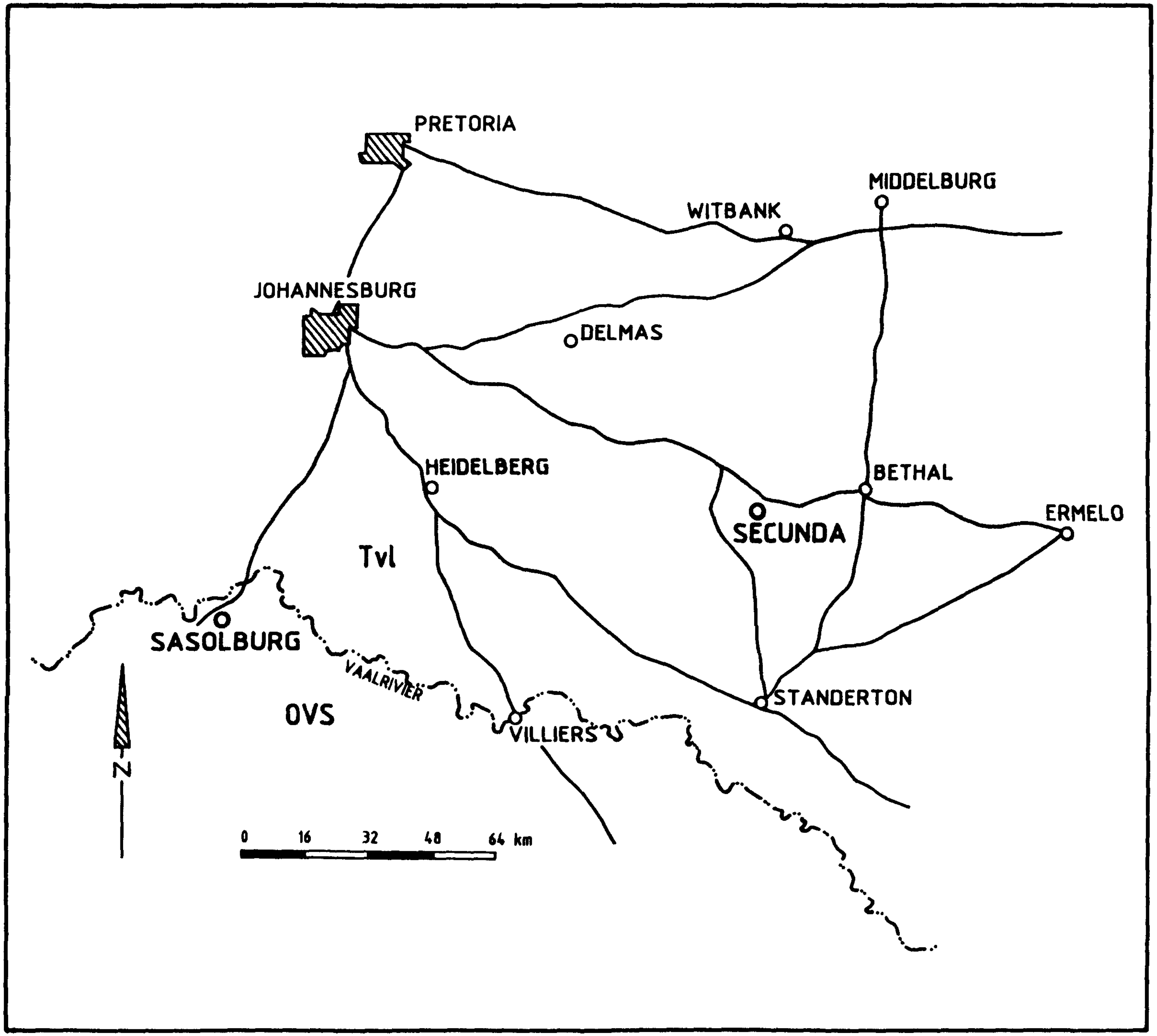


Figure 4.1 Localities of Sasolburg and Secunda.

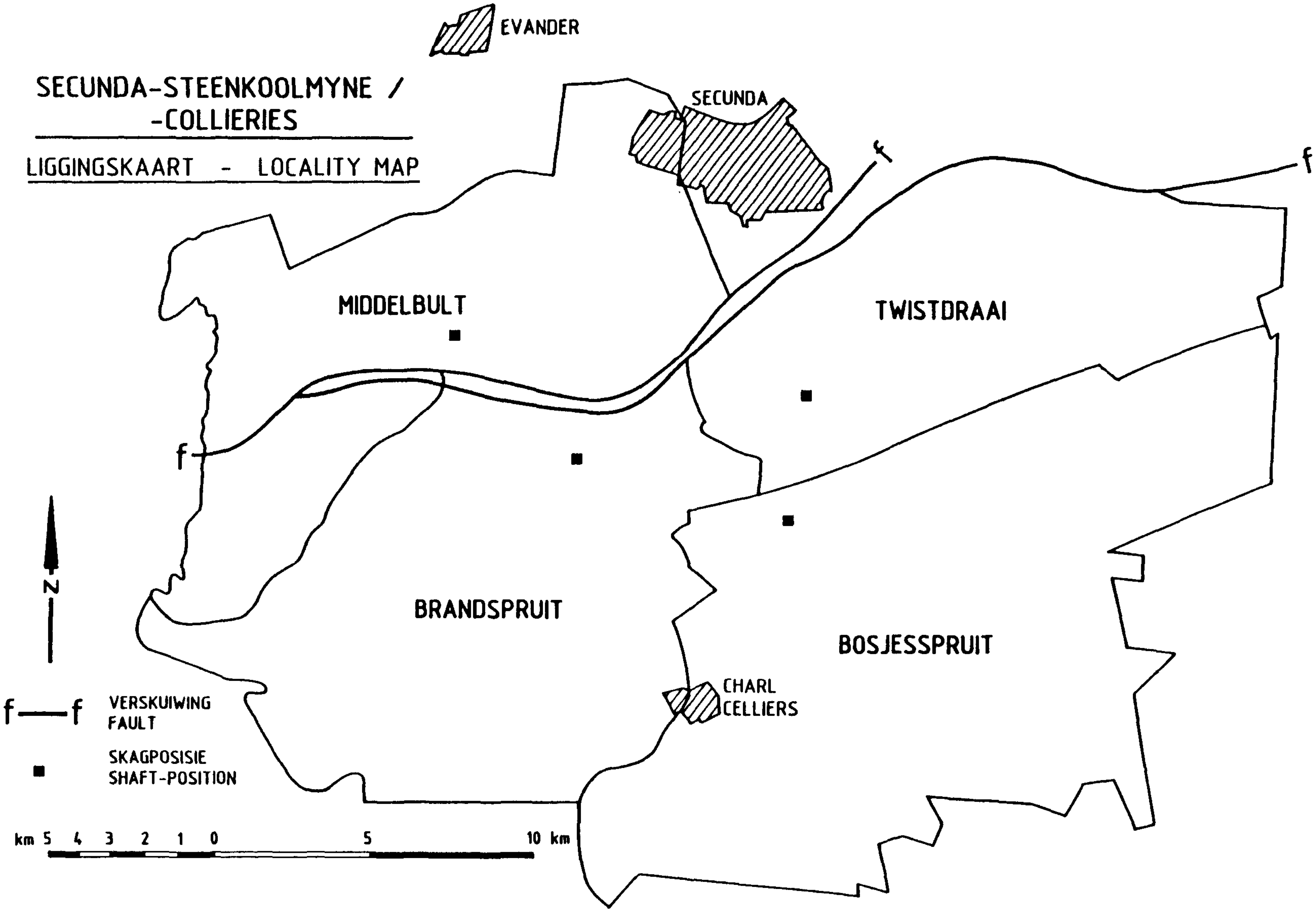


Figure 4.2 Relative locations of the four underground mines at Secunda.

The mines were established between the late seventies and early eighties to supply coal to the Sasol II and Sasol III factories for the production of synthetic fuel and related chemicals. The factories were provided to overcome the oil embargo against South Africa.

4.2 GEOLOGY AND TOPOGRAPHY

4.2.1 Secunda district

The coal in the Secunda District belongs to the Vryheid Formation of the Ecca Group of the Karoo Sequence and is of Permian age, according to The South African Committe for Stratigraphy (1980). Only one seam, the No. 4 Lower Seam, is generally mined although the No. 4 Upper Seam has been mined in small, isolated areas. The other coal seams are not well developed in the area. The mining height is nominally 3 m with heights of up to 4,5 m in small areas in the North West of the current reserve area.

The coal deposit is generally flat, with local inclinations of 4° to 5° in places. The depth below surface varies from 90 m in the North West to approximately 200 m in the South East. The average mining depth is approximately 120 m.

The overburden consists of horizontally bedded massive sandstones, shales and siltstones, the sandstones accounting for roughly 80% of the sequence. Dolerite dykes and sills, discordant intrusions, are common in the area. The dolerite sills generally occur in the Eastern areas, close to surface with thickness varying from 10 m to approximately 50 m. The dolerite sills tend to be vertically jointed. A generalized stratigraphical section is shown in Figure 4.3.

The topography can be described as gently undulating, typical of the Transvaal Highveld. The soil cover is generally thin, seldom exceeding 3 to 4 m, and consists predominantly of a tough black turf.

Surface activity is mainly farming, with maize, sorghum and sunflower the most popular crop types. Where the soil cover is too thin to plow or the soil too weak to sustain economical planting, the land is given over to grazing for cattle. Grazing accounts for roughly 75% of the surface area.

4.2.2 Sasolburg District

The coal seams in the Sasolburg District also belong to the Vryheid Formation of the Ecca Group of the Karoo Sequence and is of Permian age. Up to four mineable seams are present, from the bottom upwards known as the No. 1, No. 2A, No. 2B and No. 3

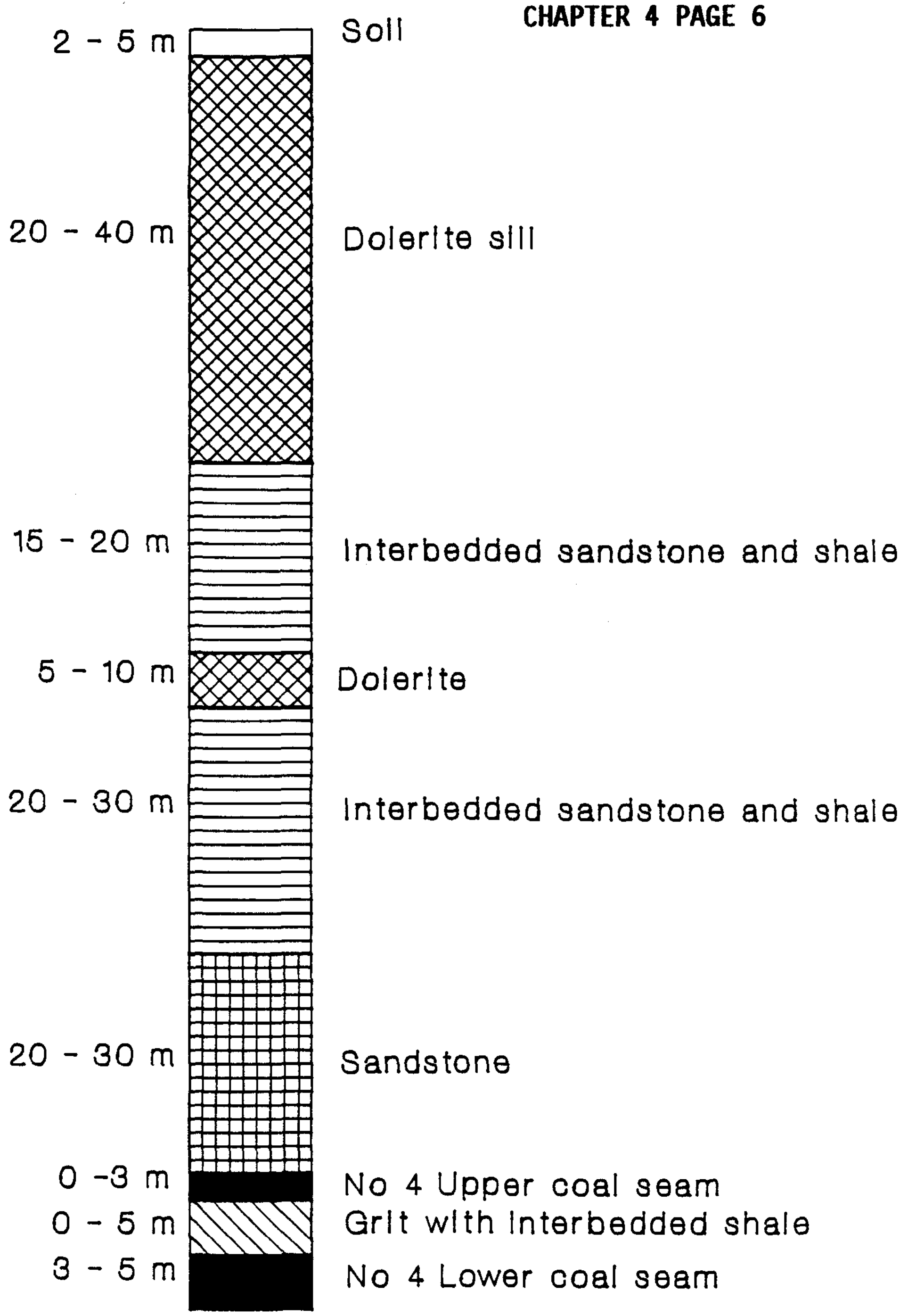


Figure 4.3 Simplified general stratigraphy of the Secunda area. The dolerite sill is not always present.

Seams. The majority of the coal is mined from the No. 2B and the No. 3 Seams, at an average mining height of 3 m. Limited mining has also been done on the No. 1 Seam (discontinued due to the uneven floor and inconsistent seam thickness) and the No. 2B Seam (discontinued because of unsuitable composition).

The overburden, shown in Figure 4.4, generally consists of mudstones, shales, siltstones and sandstones. In the Southern and Western parts of the current reserve area a dolerite sill, 10 to 50 m thick, intruded the sandstones at depths ranging from 15 m to 60 m. Sandstones account for approximately 80% of the overburden.

The mining depth varies from 50 m below surface in the Northern area to some 150 m below surface in the South. The average mining depth is approximately 115 m below surface.

The surface topography can be described as flat, a typical Northern Orange Free State landscape. The soil cover is thick, 10 to 20 m of loose sand with interbedded thin clay layers. It was deposited by the ancient river beds of the Vaal river.

Maize farming is the predominent surface activity, with some 25 % of the land used for cattle grazing.

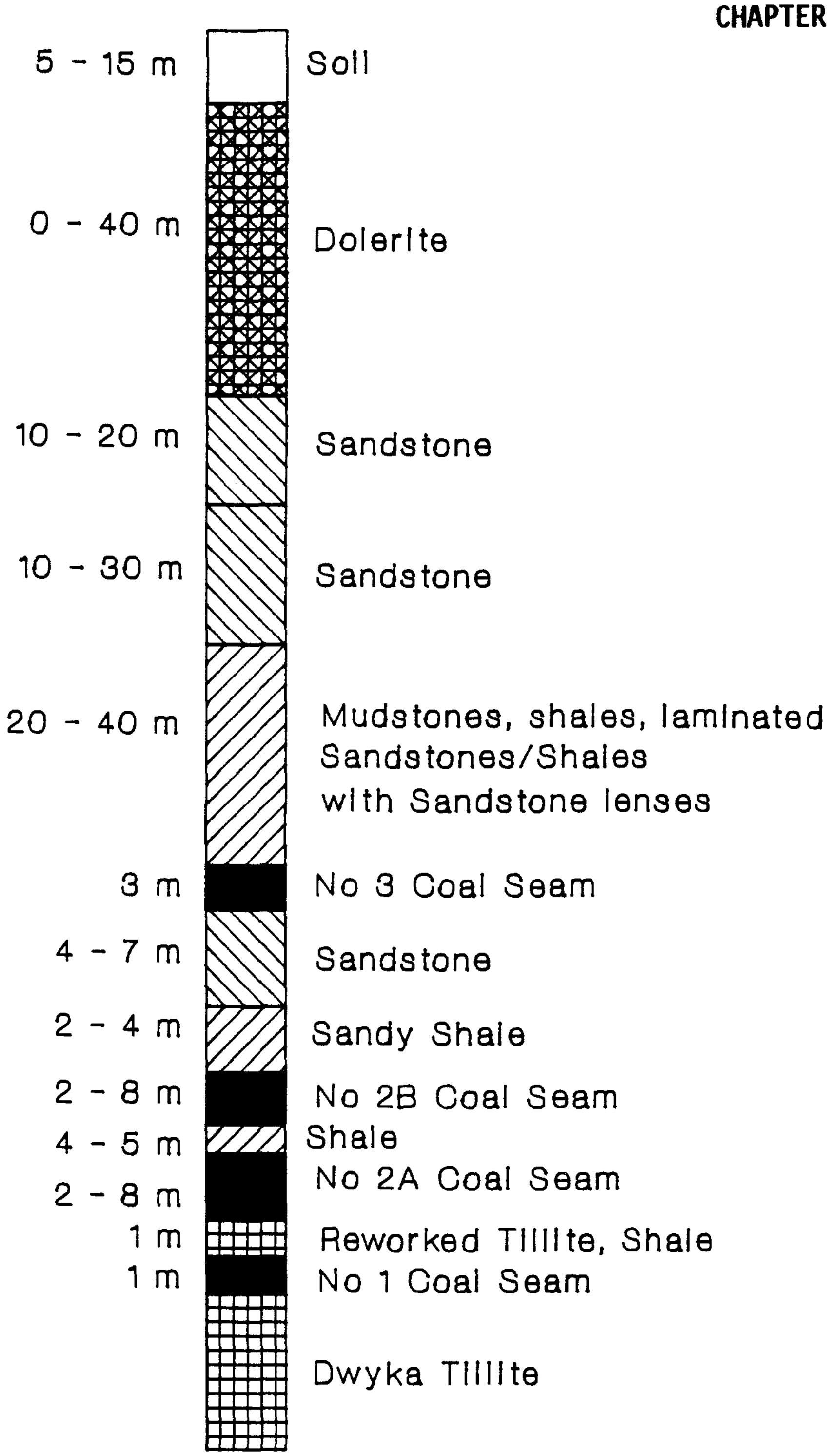


Figure 4.4 Simplified general stratigraphy of the Sasolburg area. The dolerite sill may be absent, or may occur deeper down in the sequence.

4.3 MINING METHODS

4.3.1 Background

The Sasol Company is committed to high extraction coal mining methods. In order to achieve the required annual production of 36 million tonnes from the five underground mines while maintaining the cost of geographical expansion at minimum levels, high extraction mining methods have to be employed. The company has also adopted a policy to maximise reserve utilization, in order to preserve as much coal as possible for later generations.

The emphasis on high extraction methods is evidenced by the fact that the Company pioneered mechanized longwalling in South Africa. It was also the first to implement the rib pillar extraction method in the country.

4.3.2 High Extraction Mining Methods

The brief descriptions in the following paragraphs relate to the applications of the mining methods by the mines of Sasol Coal.

Longwalling

Retreat longwalling is practised. Two or three road entries are developed nominally 200 m apart with 20 to 30 m wide inter panel pillars. This is shown in Figure 4.5. The mining height is on average 3 m. No stowing or backfilling is installed. The roof is allowed to collapse freely. During the study period, eight longwalls were in operation in the Sasol Company.

Pillar Extraction

Pillar extraction as practised in the study area essentially entails the predevelopment of pillars by either conventional drill and blast methods or continuous miners, followed by the removal of the pillars by continuous miners.

In general, pillars are 18 m square and road widths are nominally 6 m. A typical layout is shown in Figure 4.6. Although it is very difficult and often impossible to measure, due to the collapse of the roof, it is estimated that roughly 80% of the pillars are removed.

No backfilling or stowing is provided. Immediate roof support consists of timber breaker lines, mobile hydraulic supports or roof bolts only.

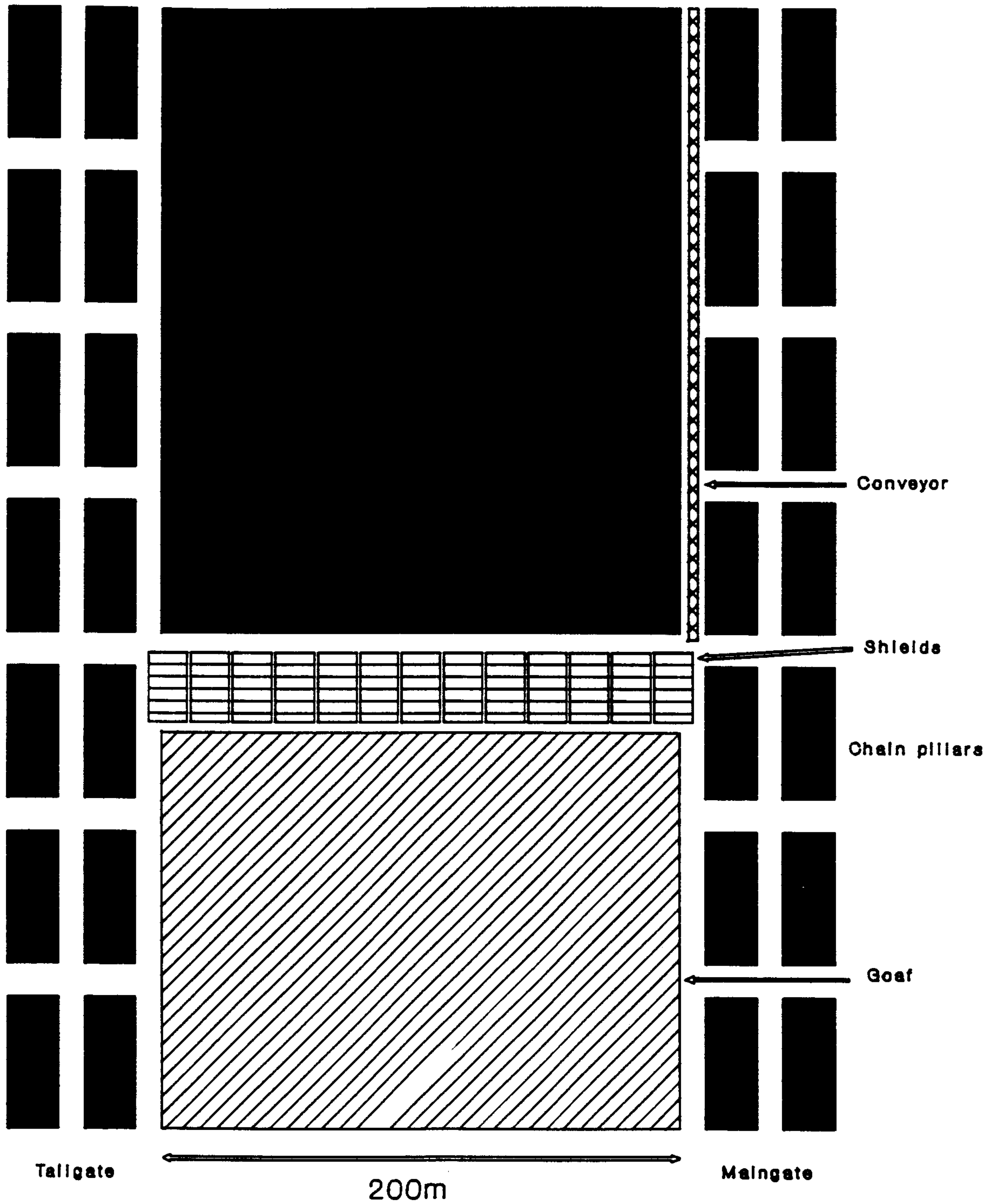


Figure 4.5 Simplified layout of a Longwall installation.
The chain pillars are not usually mined out.

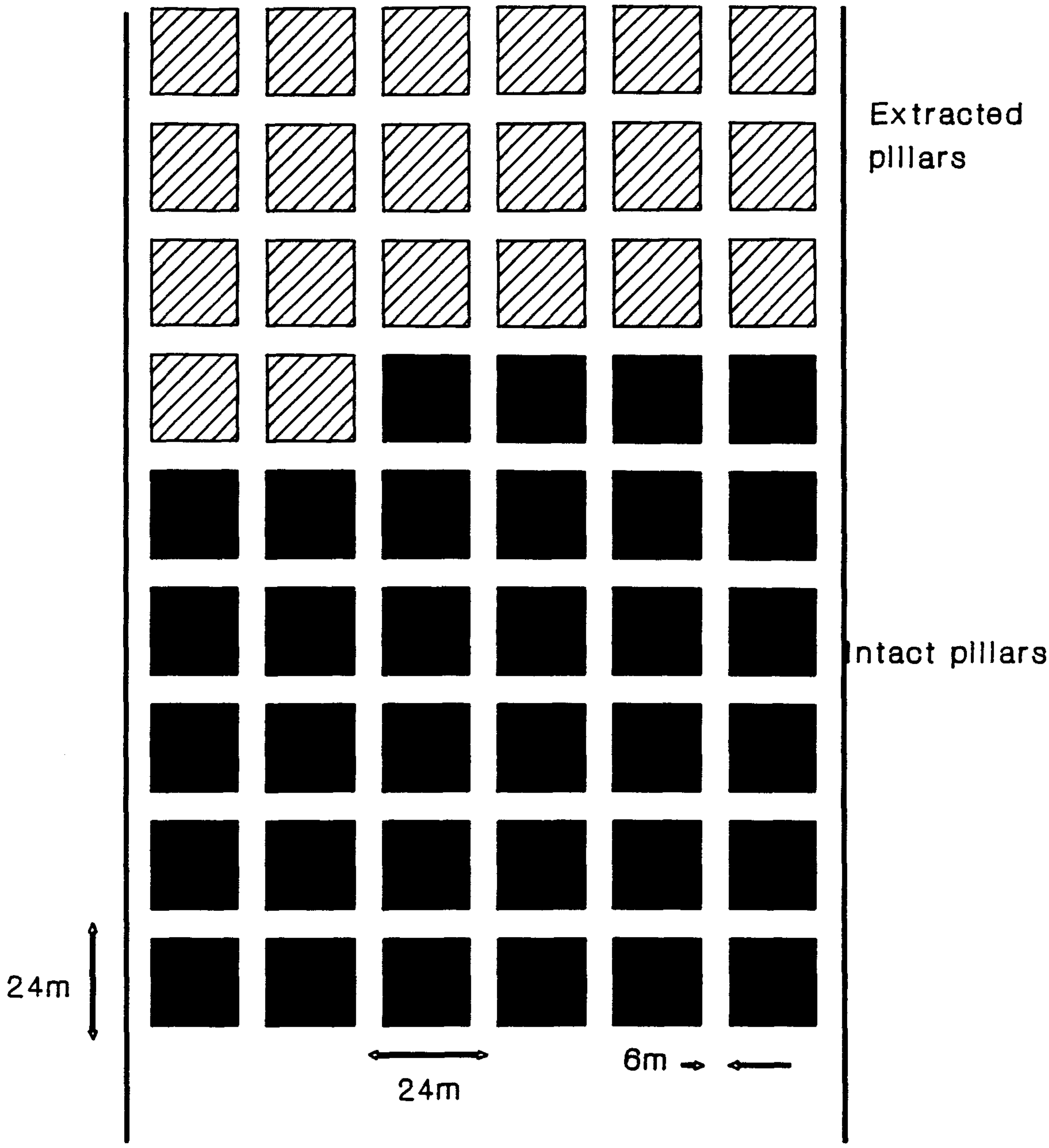


Figure 4.6 General layout of a pillar extraction panel. Roadways are nominally 6m wide and pillar centres are 24m.

At irregular intervals it is sometimes necessary, due to poor roof or floor conditions, to leave portions of pillars or in extreme cases, whole pillars behind as remnants.

Rib pillar extraction

Rib pillar extraction entails the predevelopment of three road entries adjacent to an intact block of coal nominally 48m wide. The intact block of coal is extracted concurrently with the extraction of the development pillars. In order to extract the intact block, 6 m wide roadways at 6 m intervals are developed into it. The 6 m wide pillars are then extracted in a retreat fashion. The roof is allowed to collapse unhindered. No backfilling or stowing is installed. The basics of the method are shown in the typical layout sketch in Figure 4.7.

4.4 DESCRIPTION OF THE DATA BASE

4.4.1 Introduction

To date some 3 500 ha of high extraction mining has been done in the study area. Not all the areas were suitable for data gathering by measurement, due to the locations of sight restricting structures, or, in the majority of cases, agricultural activity. Grazing areas posed no restrictions, while worked lands could only be used in exceptional cases. In

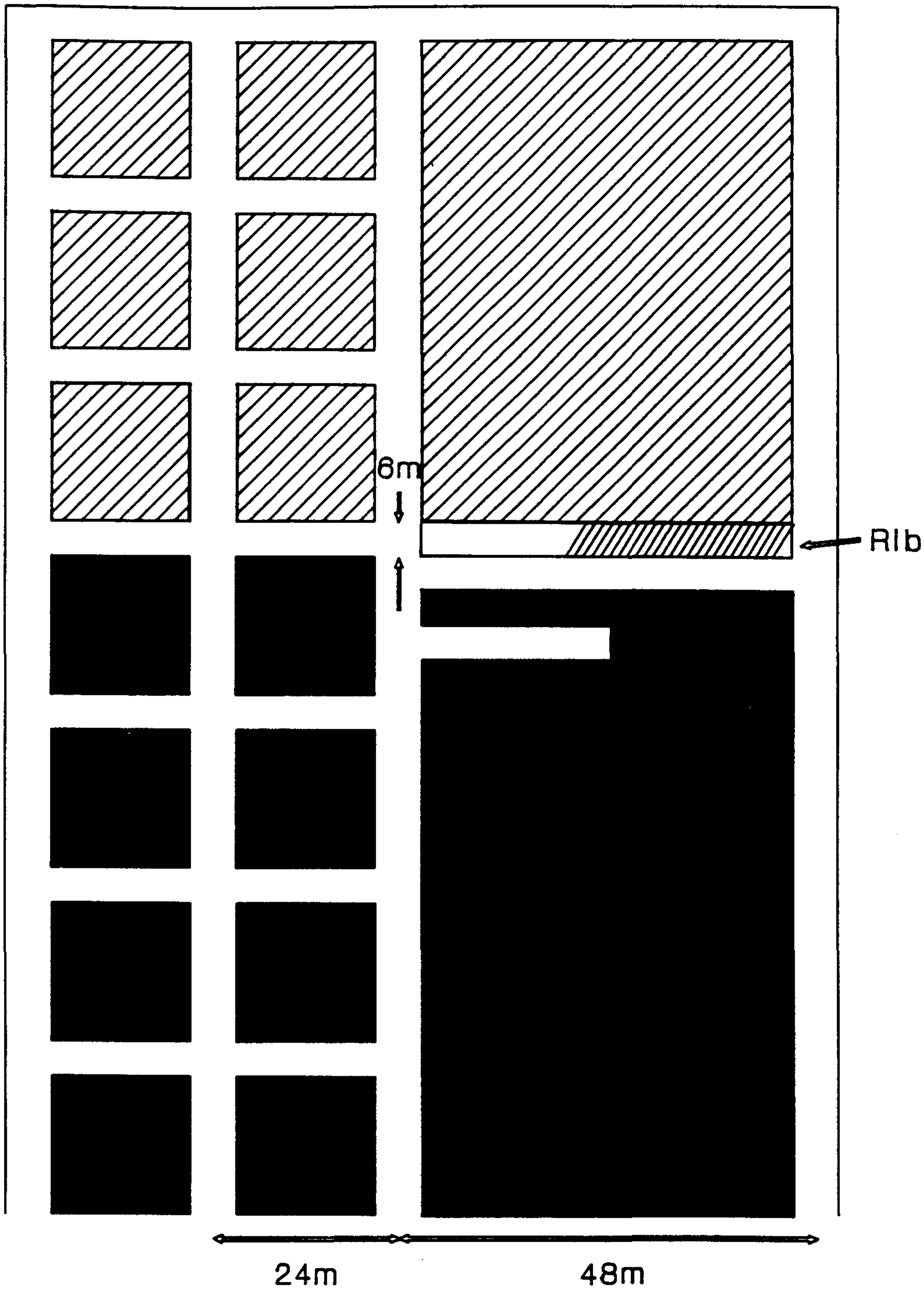


Figure 4.7 Simplified layout of a Rib Pillar Extraction panel. Ribs, 6m wide, are cut into the solid block on the right, and then extracted in a fashion similar to slicing a loaf of bread.

cultivated lands, entry by farming machinery would have had to be prohibited during data gathering, which would have placed restrictions on farming activities. This could not always be done.

The majority of the measured data was collected at the sites where structures were undermined. In those cases it served the double purpose of yielding data for subsidence prediction per se and also subsidence data relevant to the reaction of the structure to subsidence.

Most of the subsided areas, whether measurements were taken or not, were available for visual inspection. The exceptions were one or two cases where permission to enter farms could not be obtained from farmers. The surface is owned by independent farmers.

4.4.2 Method of measurement

A Wild T2000 theodolyte with an infra red distomat was the basic tool used for observations. The method required a stable base station to be surveyed in from official Government beacons, and the X, Y and Z coordinates of the monuments, installed over the high extraction panel to be determined before, during and after subsidence.

The directions of the lines in which the monuments were installed were such that they were parallel to the structure being undermined. The directions of the lines were not very important, as major dips and principal strains were calculated, as explained in Chapter 5. The spacings of the monuments were constant for each experiment, varying between 5 m and 7 m.

Concurrently with the measurements, visual inspections were carried out and the positions and descriptions of cracks, ridges and noticeable effects on the various structures were noted and reported by the surveyor. At pertinent stages, usually after the subsidence had stabilised, more scientific investigations such as X-ray inspections on pipes, were done to determine the degree of damage to the structures.

The first survey, to determine base readings, was usually done not less than a month before the face reached the position of the survey monuments. Thereafter, measurements were taken according to the rate of subsidence. During the period when most of the subsidence took place, measurements were taken two to three times per week (daily in the event of the first undermining of a particular type of structure), to taper off to weekly and then monthly measurements as the rate of subsidence decreased.

4.4.3 List of cases measured

Detailed measurements were obtained during the course of the study at the following:

(a) Subsidence data per se (no structures involved):

- (i) Sigma Colliery Boschbank Shaft shallow longwall (50 m below surface),
- (ii) Sigma Colliery double seam staggered longwalls,
- (iii) Sigma Colliery Rib Pillar Extraction, and
- (iv) Twistdraai Colliery standard longwall.

(b) Road undermining:

- (i) Road P185/1 gravel deviation (plus control measurement next to road), and
- (ii) Road P185/1 bituminized road with slots and yield pillar (plus control measurement next to road).

(c) Conveyor belt undermining:

- (i) Twistdraai standard panel undermining, and
- (ii) Twistdraai widening panel undermining.

(d) Pipe line undermining:

- (i) Bosjesspruit first partial undermining, and
- (ii) Bosjesspruit first complete undermining.

In addition, subsidence data gained at greater benchmark spacings was available from at least twenty further areas.

4.4.4 Special precautions

In order to ensure that the best possible accuracy was obtained during measurements, a number of small but important precautions were implemented.

Firstly, the instruments were checked regularly by a qualified surveyor other than the one responsible for data gathering. Primary calculations to determine the coordinates of the monuments were done in the field with the aid of a hand held programmable calculator and deviations were investigated promptly.

Secondly, a qualified and experienced senior mine surveyor with a crew of assistants were dedicated to the task of data gathering at all the sites. The particular surveyor and his crew quickly became specialists in subsidence data gathering. Thirdly, the sighting distance for measurements was restricted to 50 m. This was done after it was found that the number of anomalies decreased significantly when intermediate base stations were used.

Fourthly, the period of measurement was between first light in the morning and 11:00 when at all possible. This was done to decrease the difficulties posed by heat simmer. It was also found, mainly in Secunda, that the winds usually came up at around 11:00. The equipment was capable of measuring angles to an accuracy of 1 second and distances to an accuracy of 10 mm per 1000 m. Over a measuring distance of 50 m the maximum error was therefore less than 1 mm.

4.4.5 Other observations

Mainly with regard to structures, the assistance of suitably qualified specialists was obtained to record and evaluate observations relevant to the particular structure. For instance, on road matters the Division for Roads and Transport Technology of the CSIR was consulted; on pipes the maintenance and design engineers of the Department of Water Affairs; on power pylons Eskom's design engineers, etc.

The most difficult observations to evaluate objectively were the ones related to agriculture as it involved not only a great number of uncontrollable and controllable variables, but also the attitudes of farmers, who being the land owners, could be expected to be subjective. Several interviews and informal discussions with farmers were held, as well as with agricultural experts of fertilizer suppliers, Universities and Government Departments.

5 METHODS OF ANALYSIS USED FOR THE STUDY

5.1 INTRODUCTION

Traditionally, subsidence is analysed two dimensionally along a subsidence profile. This means that strains and tilts in the direction of the observation line only are considered. This implies inter alia that only a single component of strain can be calculated for each position.

As shown in Plate 1, the two dimensional profile approach is not sufficient in all cases. Plate 1 is a very clear demonstration of an instance, of which further examples abound in practice, where both tensile and compressive strains are present in the same locality. The situation shown in the photograph cannot be realistically reflected by attaching a single value for strain to that particular area. An alternative approach is thus called for. The need for an alternative is most pressing in situations where information is gathered obliquely across a subsidence trough or near the corners of the trough, where the simplification of representing the trough by a two dimensional profile is not valid.

The approach which was adopted for subsidence analysis is called the Surface Element Analysis (SEA) approach. Instead of

PLATE 1 The photograph shows a compression ridge on an untreated road. The green line crossing the ridge at approximately right angles is an open tension crack. The existence of both tensile and compressive strains in the same area illustrates the deficiency of the linear approach to strain analysis.

Photograph courtesy of EHR Schümann.

considering surface as a two dimensional line, it calls for considering the subsided area as a three dimensional surface. Where the conventional approach bases the analysis on the changes caused by subsidence to the inclination and length of short sectors of lines comprising the profile, the SEA approach is based on the changes caused to elemental surfaces. Therefore, selected areas (in most cases, strips) of the subsidence trough are analysed three dimensionally.

As each elemental line is defined by survey monuments at either end, so the elemental surface is defined by four survey monuments, one at each corner. This is achieved by doubling the number of survey monuments installed, so that a line of adjoining elemental surfaces is formed. It was found in practice that monument spacings of 5 to 7 m yielded the best results, so that essentially square elements measuring 5 x 5 m to 7 x 7 m are formed.

As will be shown in the following paragraphs, the calculations that are performed are basically similar (albeit extended) to the calculations performed for the two dimensional linear analysis. Therefore, the same restrictions and assumptions apply. The most important assumption is that the differential displacements are relatively small, so that the mathematical expressions used for the calculations may be simplified by ignoring the squares of differential displacements.

The SEA approach was applied selectively in the study. Apart from finding correlations between maximum induced tilt and strain and maximum subsidence, it was not used for the development of the subsidence prediction method described in Chapter 6. The reason this was not done is because it was found that the development of a true three dimensional prediction model will require observations over wider surface areas than just a single line of surface elements. Due to the practical limitations with regard to data gathering, it could not be done.

The SEA approach was primarily applied to evaluate subsidence effects on planar, as opposed to linear, structures. Of the structures investigated, only the pipe line can be described as truly linear. Roads, buildings, conveyor belts and power pylons are structures with planar bases and were therefore well suited to be analysed with the SEA approach.

5.2 TWO DIMENSIONAL PROFILE ANALYSIS

Usually, subsidence is measured and analysed along two perpendicular lines over a high extraction panel. The one, the longitudinal line, would be situated along the long axis of the panel, in the centre of the panel. The other, the transverse line, would cross the longitudinal line perpendicularly and be situated in a position where it would not be subjected to the corner effects of the trough. The traditional layout is shown in Figure 5.1.

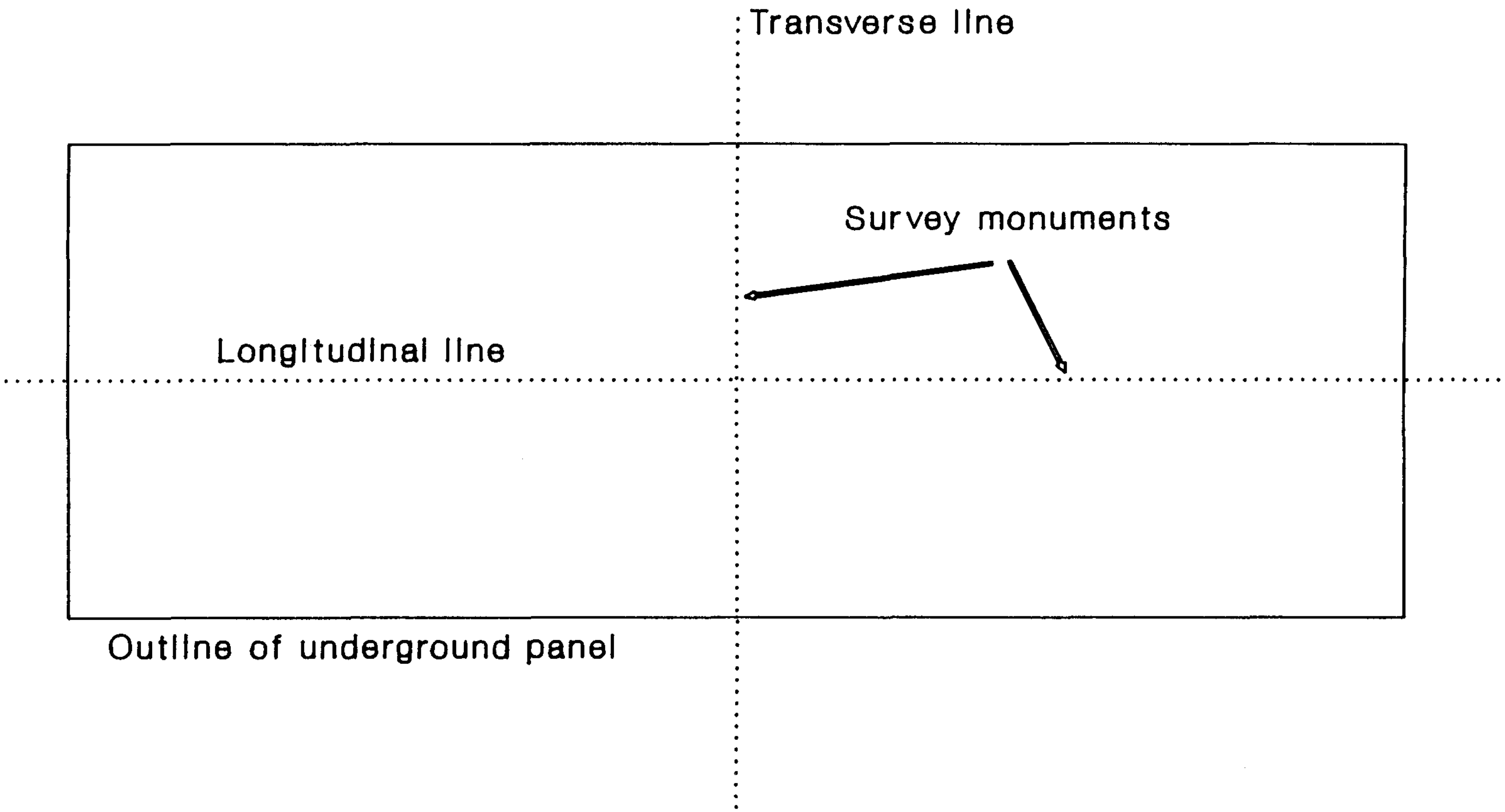


Figure 5.1 Traditional layout of a subsidence data gathering exercise. The survey monuments over the ribsides are often installed at a higher density.

Tilt, T, is then derived by the simple relationship:

$$T = \frac{dz}{dx}, \tag{5.1}$$

where dz is the difference in height between two points which are dx apart horizontally. The induced tilt is then found by simply determining the difference between the original tilt and the post subsidence tilt.

By determining coordinates of monuments or measuring by tape, strain is usually found by the relationship of the change in horizontal distance to the original distance, or

$$\epsilon = \frac{dx}{X}, \tag{5.2}$$

where the distance X between two points changed by a magnitude dx after mining. With the analysis being done along a single straight line, only certain components of those displacements can be measured and thus analysed, which are those components occurring in the direction of the observation line.

Strain is often prone to misrepresentation: certain researchers consider only the horizontal components of displacement in the calculation. The "horizontal strain" then quoted is in fact no more than a component (i.e. the horizontal component of the strain component in the direction of the observation line) of a component of the actual strain, which cannot in any way be related to the three dimensional strain situation. Relating ground strain to damage suffered by surface structures can therefore be misleading.

5.3 THE SURFACE ELEMENT APPROACH

The optimum solution, from an academic point of view, for the problem would be to observe and analyse displacements over the entire surface area overlying the panel. As this solution is impractical, the next best is to analyse a sample series of small surface elements, which are defined by closely spaced survey monuments. A diagrammatic layout is shown in Figure 5.2. Note that this approach requires twice as many survey monuments to be observed, as compared to the layout for the two dimensional approach shown in Figure 5.1.

The analysis is then done by considering each group of four monuments as a surface element, and then analysing the behaviour of that small surface. Figure 5.3 shows the detail of a single surface element and explains the symbols which will be used in the following paragraphs. Table 5.1 may also be helpful in this regard.

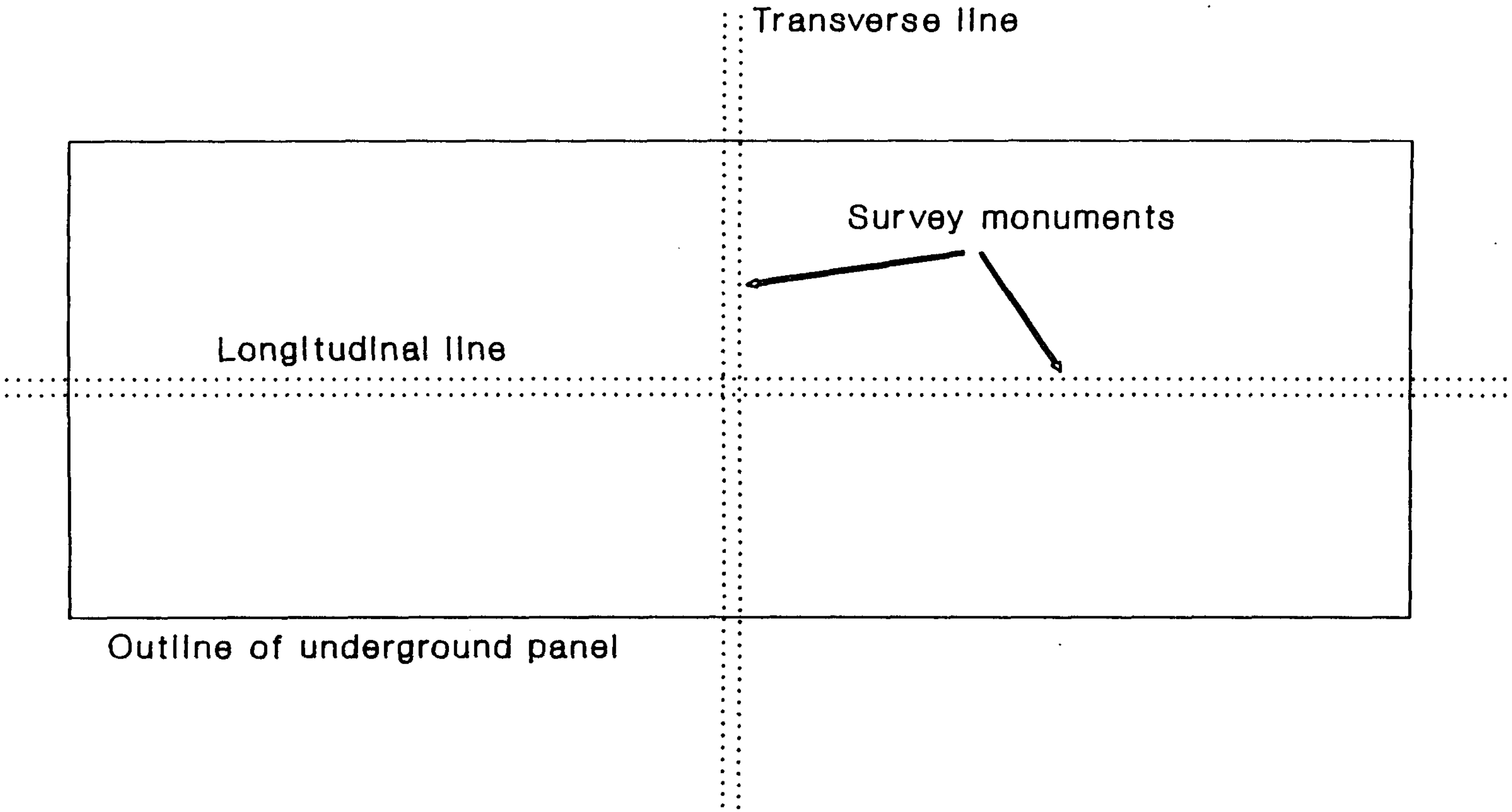


Figure 5.2 Data gathering layout to cater for the SEA analysis. Although two sets of lines are shown in the figure, they may be replaced by a single set running diagonally across the panel at any angle.

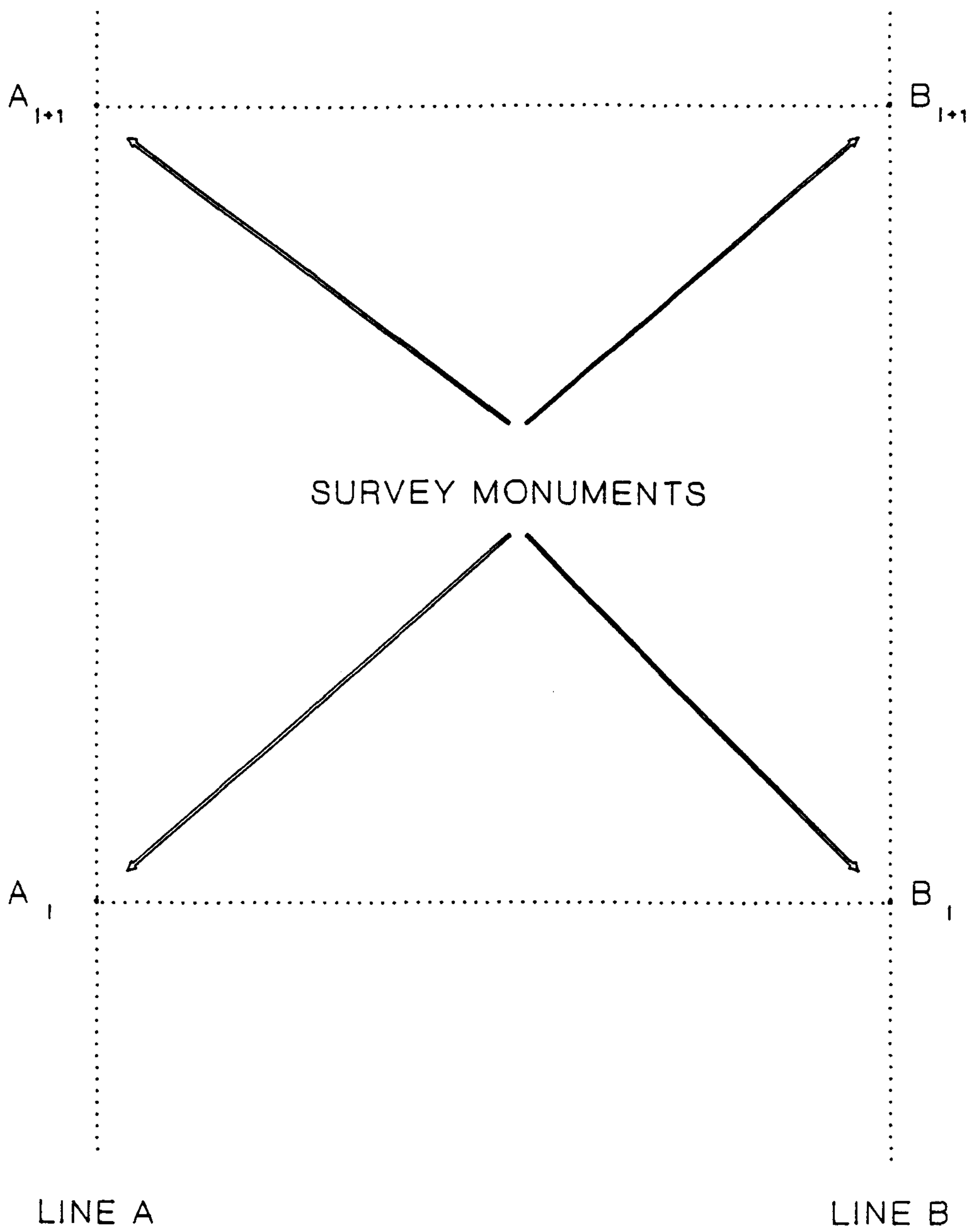


Figure 5.3 Detail of a single Surface Element, formed by four adjoining survey monuments from the two parallel lines.

5.3.1 Calculation of induced tilt

A method to calculate the major tilt by using two minor tilts has been a standard survey technique for a very long time. The

Table 5.1: Symbols used in the derivation of subsidence elements

	ORIGINAL COORDINATES	NEW COORDINATES
Line A		
X-Coordinate	$X_{A(i)}$	$X'_{A(i)}$
Y-Coordinate	$Y_{A(i)}$	$Y'_{A(i)}$
Z-Coordinate	$Z_{A(i)}$	$Z'_{A(i)}$
Line B		
X-Coordinate	$X_{B(i)}$	$X'_{B(i)}$
Y-Coordinate	$Y_{B(i)}$	$Y'_{B(i)}$
Z-Coordinate	$Z_{B(i)}$	$Z'_{B(i)}$

same method is applied here: two tilts, obtained directly from the measurements, are considered as the minor tilts and the major tilt is then calculated for the pre-mining situation. Figure 5.4 shows the directions in which the components are calculated, while Figure 5.5 indicates the various elements in their spatial orientation.

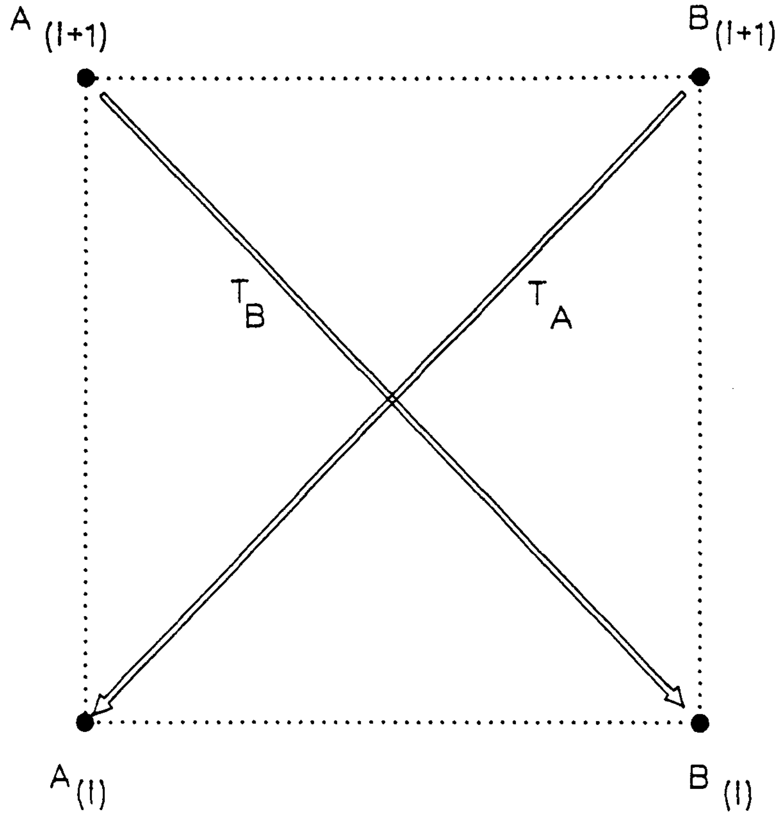


Figure 5.4 The directions in which the two minor tilt components are calculated.

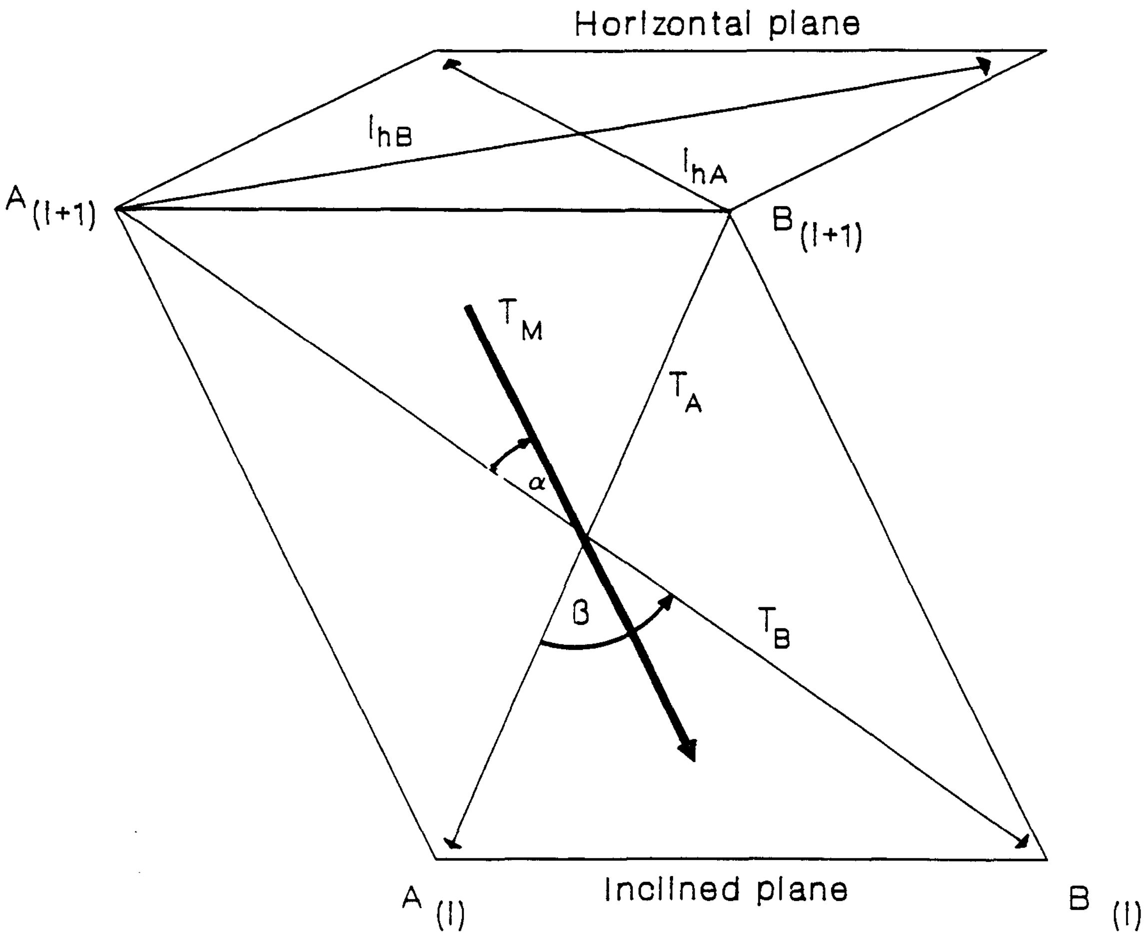


Figure 5.5 Spatial orientation of the tilt components which are used for the calculation of the Major Tilt before subsidence. Similar calculations are used to determine the Major Tilt after subsidence. The Induced Tilt is then calculated from the two Major Tilts.

The two original minor tilts are those from point $A_{(i)}$ to $B_{(i+1)}$ and from point $B_{(i)}$ to $A_{(i+1)}$, denoted T_A and T_B respectively:

$$T_A = \frac{Z_{B(i+1)} - Z_{A(i)}}{l_{hA}}, \qquad (5.3)$$

where l_{hA} is the original horizontal distance between points $A_{(i)}$ and $B_{(i+1)}$. Similarly, the component T_B is:

$$T_B = \frac{Z_{A(i+1)} - Z_{B(i)}}{l_{hB}}, \qquad (5.4)$$

where l_{hB} is the horizontal distance between points $B_{(i)}$ and $A_{(i+1)}$.

The direction, α, of the Major Tilt relative to the direction of a Minor Tilt component, say T_B, is found by:

$$\mathrm{Tan}\alpha = \mathrm{Cosec}\beta . \frac{(T_B - \mathrm{Cos}\beta)}{T_B}, \qquad (5.5)$$

where

α = angle between T_B and the Major Tilt, and

β = angle between T_A and T_B.

The angle β is again found by:

$$Tan\beta = \frac{M_2 - M_1}{1 + M_2M_1}, \tag{5.6}$$

$$\text{where } M_2 = \frac{Y_{A(i)} - Y_{B(i+1)}}{X_{A(i)} - X_{B(i+1)}} \tag{5.7}$$

$$\text{and } M_1 = \frac{Y_{B(i)} - Y_{A(i+1)}}{X_{B(i)} - X_{A(i+1)})}. \tag{5.8}$$

The magnitude of the original Major Tilt, T_M, is found by the relationship:

$$T_M = \frac{T_B}{COS\alpha}. \tag{5.9}$$

By substituting new coordinates for original coordinates in equations (5.3) to (5.9), the direction and magnitude of the new Major Tilt, T'_M, can also be found. Both the original and new Major Tilts, T_M and T'_M, are vector quantities, having magnitude and direction.

The quantity which will affect a structure on surface, is the Induced Tilt, T_I, which is defined as the vector required to change the magnitude and the direction of T_M to that of T'_M. Simple vector algebra is used to determine the direction and magnitude of T_I. This is shown in Figure 5.6.

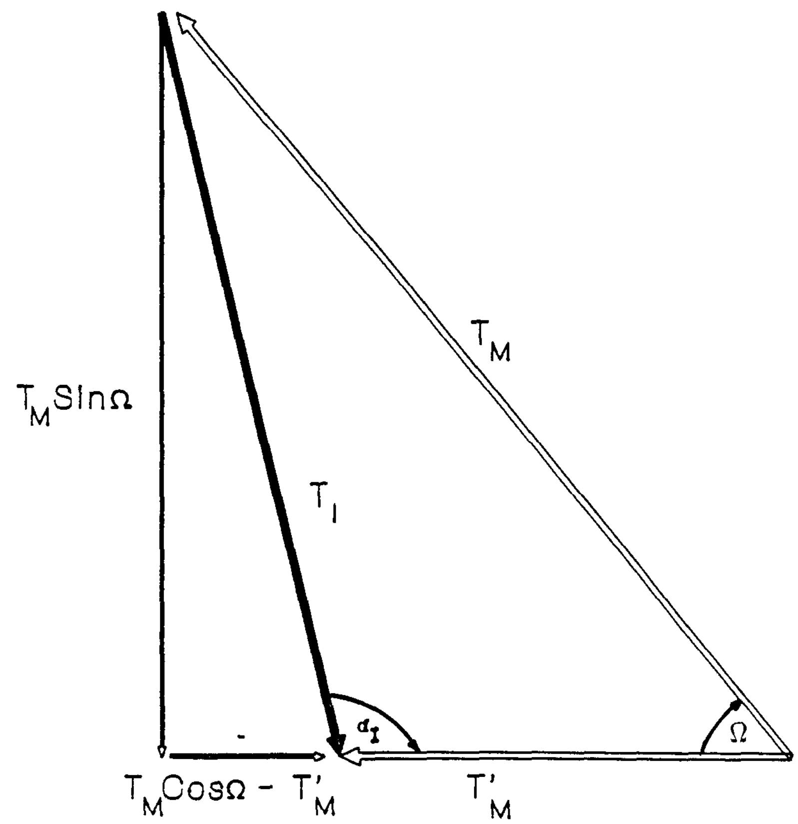


Figure 5.6 Calculation of the Induced Tilt.

The magnitude of T_I is found by the relationship:

$$T_I = \sqrt{[T_M \cos\Omega - T'_M]^2 + [T_M \sin\Omega]^2}, \tag{5.10}$$

where Ω= angle between T_M and T'_M,

The direction of T_I relative to the direction of T'_M, α_I, is found by:

$$\tan \alpha_I = \frac{T_M \sin\Omega}{T_M \cos\Omega - T'_M}. \tag{5.11}$$

Having determined both magnitude and direction, the Induced Tilt is thus fully described.

For recording purposes, the analyst should take care to describe all directions relative to a common base. This merely entails addition or subtraction of known directions. These are simple operations, not shown here. Using the direction of the mining face is recommended as a common base as it facilitates direct comparison with other subsidence analyses.

5.3.2 Calculation of strain

The calculation of strain is merely the application of well established engineering principles to the calculation of strain resulting from subsidence. The underlying principle is that the surface should be regarded as a planar surface undergoing deformation, and that the principal strains should be considered. There are several methods of performing the calculations. The very simple case will be presented here, where it is assumed that the survey monuments are installed equidistantly and perpendicularly.

Firstly, as shown in Figure 5.7, two strain components are calculated. By virtue of the simplification introduced in the previous paragraph, the two components will also be perpendicular. From these components, the magnitudes and directions of the principal strains may be obtained.

The two strain components, denoted ϵ_A and ϵ_B, are those between points $A_{(i)}$ and $B_{(i+1)}$ and between points $B_{(i)}$ and $A_{(i+1)}$ respectively:

$$\epsilon_A = \frac{l_{OA} - l_{NA}}{l_{OA}}, \tag{5.12}$$

where

l_{OA} = original true distance, not merely horizontal, between points $A_{(i)}$ and $B_{(i+1)}$ and

l_{NA} = new true distance, not merely horizontal, between points $A_{(i)}$ and $B_{(i+1)}$.

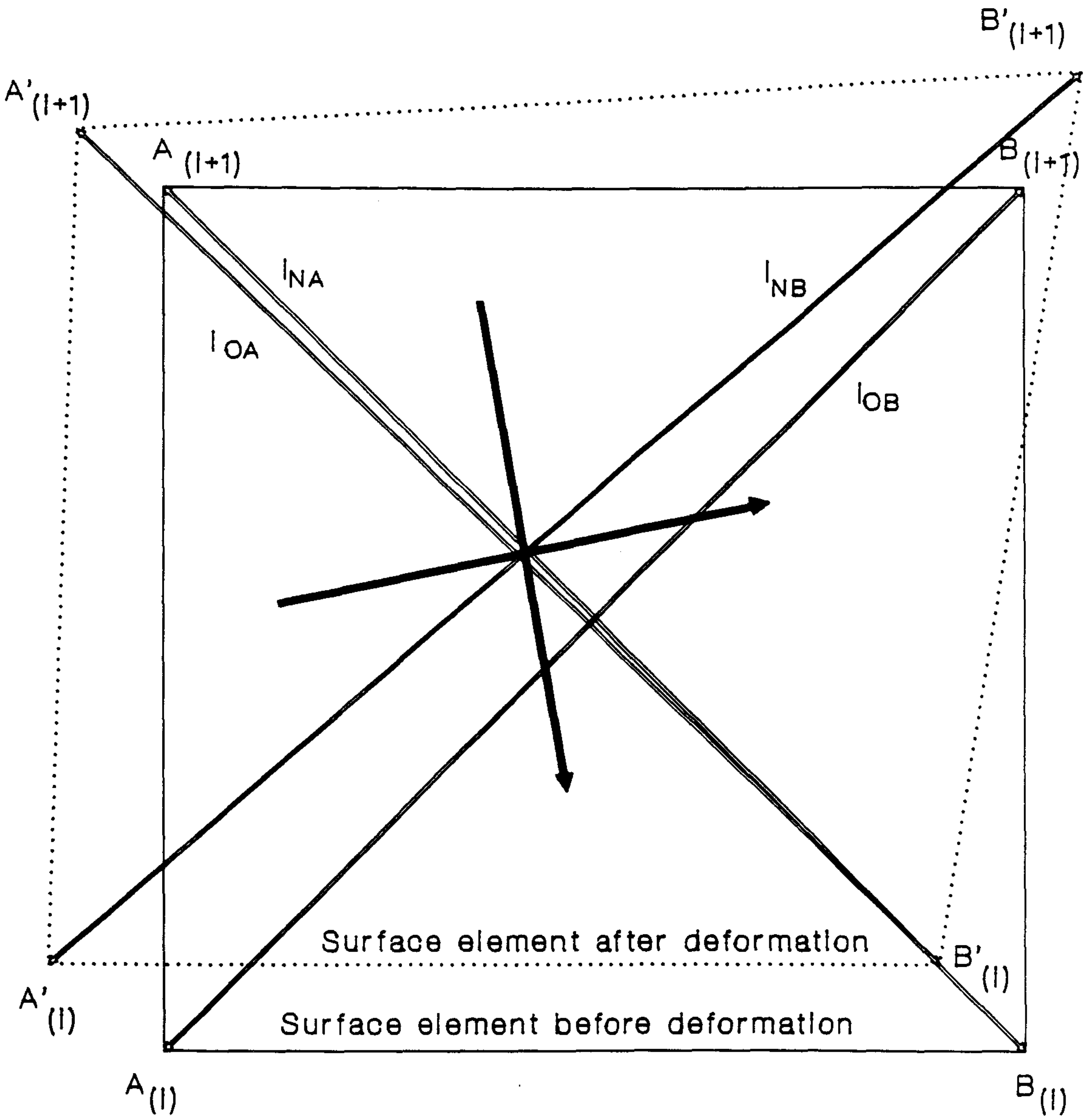


Figure 5.7 Locations of the lines of which the lengths are determined for the calculations of the Principal Strains.

Similarly,

$$\epsilon_B = \frac{l_{OB}-l_{NB}}{l_{OB}}, \qquad (5.13)$$

where:

l_{OB} = original true distance between points $B_{(i)}$ and $A_{(i+1)}$ and

l_{NB} = new true distance between points $B_{(i)}$ and $A_{(i+1)}$.

The magnitudes of the Major and Minor Principal Strains, ϵ_1 and ϵ_2, are then:

$$\epsilon_1, \epsilon_2 = [\epsilon_A+\epsilon_B] \pm \sqrt{2\Gamma + [\epsilon_A-\epsilon_B]^2}, \qquad (5.14)$$

where $\Gamma = \frac{1}{2}\mathrm{Tan}\Phi$, and Φ is the angular distortion, measured in radians, calculated as the difference between the original and new angles between ϵ_A and ϵ_B. The calculation of the angles between lines defined by known coordinates is a well known standard procedure, not shown here.

The directions of the Principal Strains are found by:

$$\mathrm{Tan}\ 2\theta = \frac{2\Gamma}{\epsilon_A - \epsilon_B}. \qquad (5.15)$$

A very useful parameter is the areal strain, A_S, which is the proportion by which the area of the surface element either increased or decreased. Very simply,

$$A_S = \epsilon_1 + \epsilon_2 = \epsilon_A + \epsilon_B . \quad (5.16)$$

More background to the determination of Principal Strains can be found in Jaeger and Cook (1979).

Note that the computer program which is used for subsidence analysis briefly described in the next section, calculates more than one value for each of the parameters described here by using alternative directions. Mean values are then obtained for the various parameters.

5.3.3 Computer program

The analysis of tilt and strain according to the procedures explained in the previous paragraphs would be prohibitive if done by hand. An "average" project may require 60 surface elements to be analysed for 10 or more consecutive survey occasions. A total number of over 10 000 calculations will have to be performed, merely to obtain magnitudes and directions of strain and tilt. Add to this the simpler calculations of horizontal displacements and directions of individual points, and the total number of calculations increase to roughly 15 000.

To overcome this problem the calculation procedures were computerised. The program suite is called VERA, from "VERsakkings-Analise", the Afrikaans for "subsidence analysis".

The suite of programs consists of three main sections. The first section deals with the creation of data files containing the coordinates of survey monuments, the second is the main analysis module and the third section is used for comparing analysed data at various stages of a project. The following paragraphs briefly outline the various sections of the program. The layout of the programmes is shown in Figure 5.8.

SECTION A: Data Capturing Modules

VERAKS: Manual input of coordinates, survey monuments in both lines numbered in rising order.

VERAKD: Manual input of coordinates, one line of survey monuments numbered in rising order and the other in declining order.

VERAAS: Manual input of distances and angles - the program calculates coordinates. Both lines of survey monuments numbered in rising order.

VERAAD: Manual input of distances and angles - the program calculates coordinates. One line of survey monuments numbered in rising order and the other in declining order.

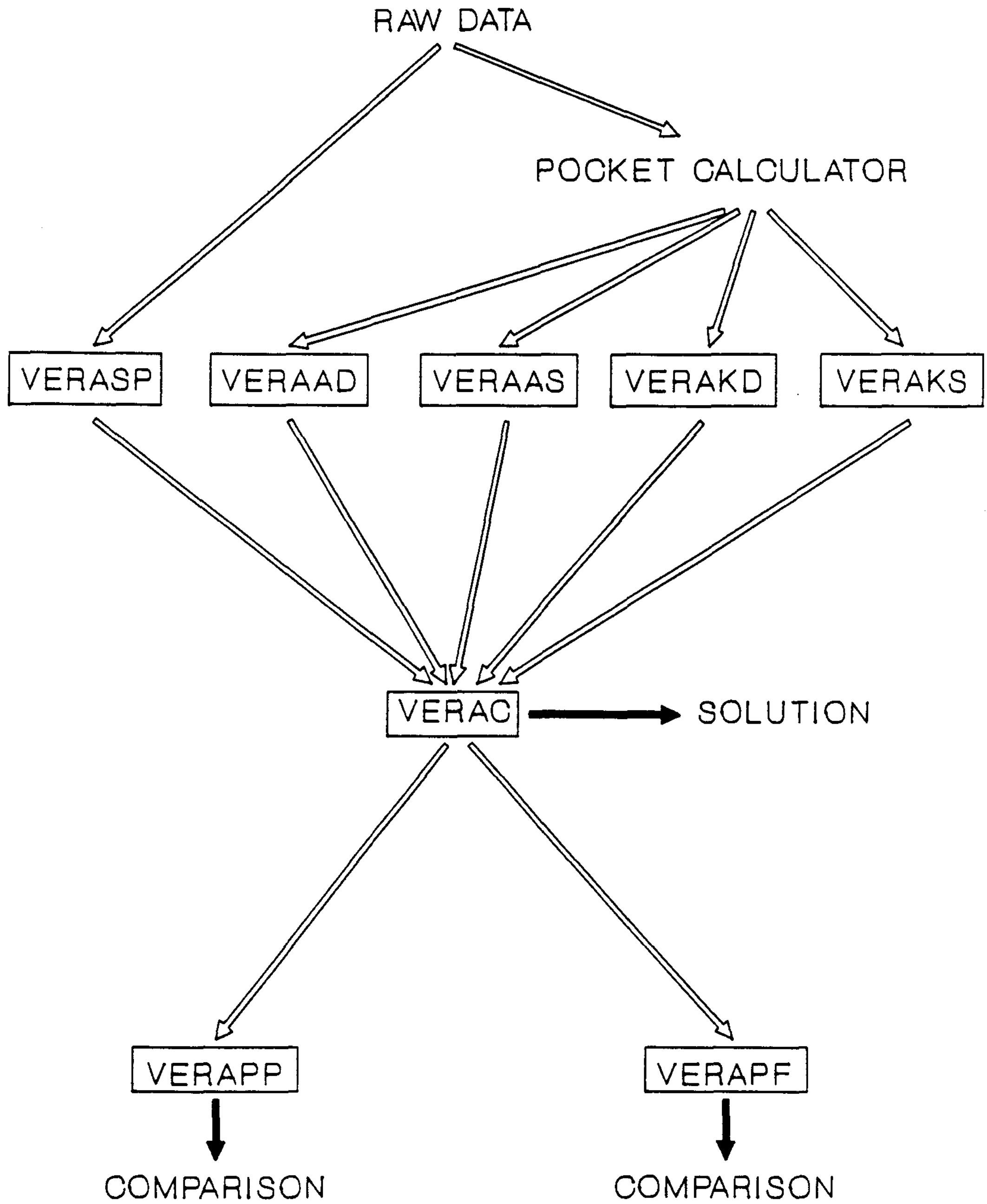


Figure 5.8 Schematic layout of the more important modules of the VERA suite of programs. The route to be chosen is decided on the basis of the format of the available data.

VERASP: This program reads a "Surpac" file. No manual input of data is required.

All these programs create and store data files which are used by the next program. They are all similar, the differences are only there to cater for the exact form and sequence in which raw data is available. Errors in computerised analysis only occur during input of data, and by providing the right program, the probability of making an error is greatly reduced. Additionally, all the programs contain compulsory data checking procedures to further enhance the quality of the data. In order to be protected against the potential disaster caused by a damaged base station, all the work is done in global coordinates.

SECTION B: Main Analysis Module

VERAC: Uses the data files created by the programs in section A to calculate the following:

(i) Vertical, horizontal and total displacements of individual points.

(ii) Original, new and induced tilts and their directions.

(iii) Major, minor and areal strains and their directions.

(iv) Rotation and displacement of the surface elements.

(v) Radii of curvature.

This program stores the analysed data in a solution file. It also contains a graphics section, which allows any combination of the results to be plotted on paper. Previously obtained solution files may also be called up for the graphics section.

Figure 5.9 is an example of a plot of the principal strains and induced major tilt of a project. The positions of axes are automatically determined by the program, according to the number of variables to be plotted, to optimize the clarity of the diagram.

SECTION C: Comparison Section

VERAPP: Reads up to 10 solution files obtained in Section B to compare the behaviour of specified individual surface elements. Therefore, the development of any element (vertical subsidence, any tilt or strain parameter, etc.) at specified positions may be compared with increasing face advance. Figures 5.10 and 5.11 illustrate some of the plots that may be obtained.

(iv) Rotation and displacement of the surface elements.

(v) Radii of curvature.

This program stores the analysed data in a solution file. It also contains a graphics section, which allows any combination of the results to be plotted on paper. Previously obtained solution files may also be called up for the graphics section.

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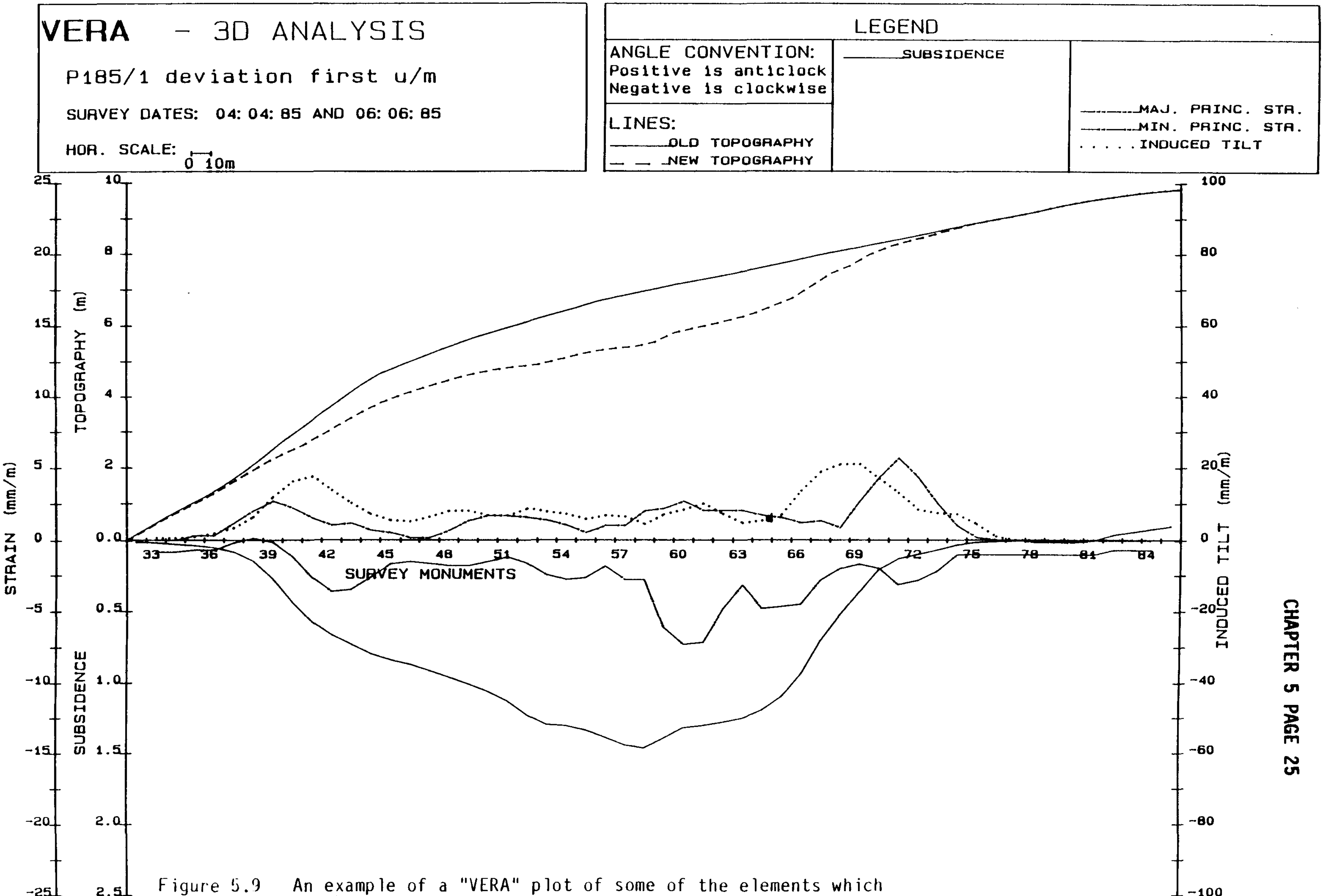

Figure 5.9 An example of a "VERA" plot of some of the elements which may be graphically represented by the programme.

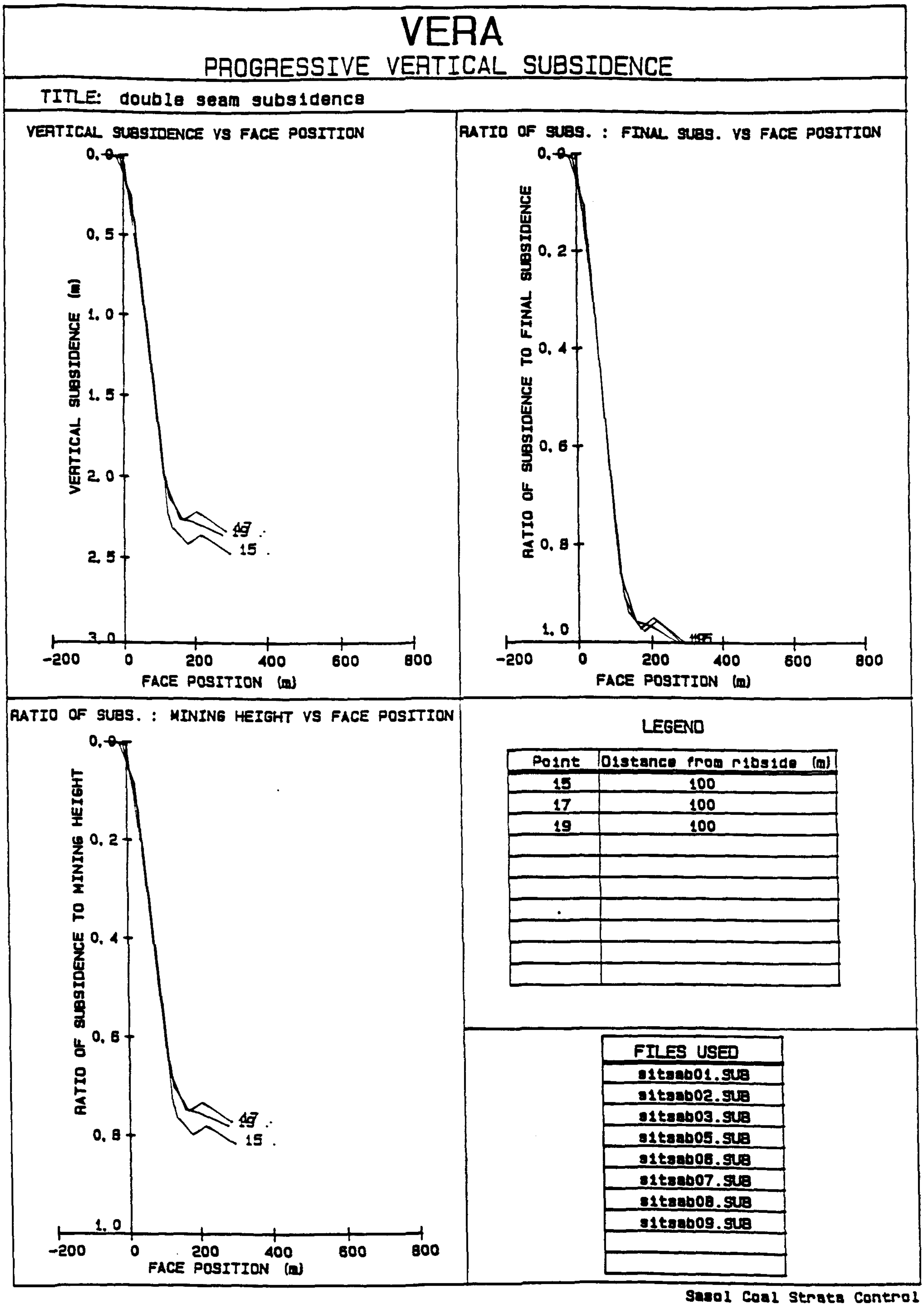

Figure 5.10: Example of "VERA" output for the study of progressive subsidence of selected points on surface.

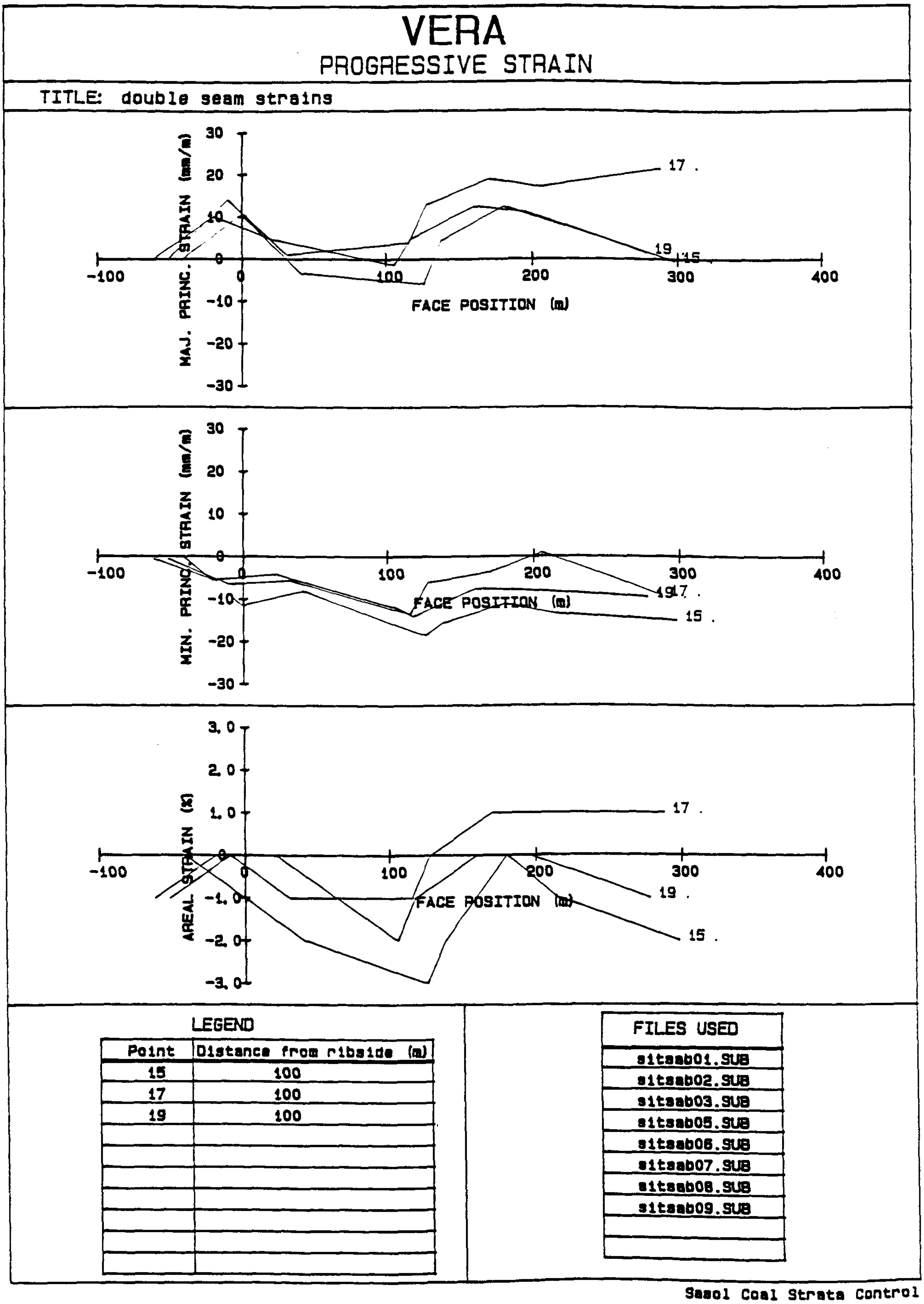

Figure 5.11: Example of "VERA" output for the study of progressive strain at selected surface points.

VERAPF: Reads up to 10 solution files to compare the development of any single element (strain, tilt, subsidence, etc.) over the entire observation area. Figure 5.12 illustrates, as an example, the development of Major Principal Strain for a particular project. The development of trends can be easily studied with this program.

In addition to the VERA suite of programs, a program to analyse the effects of subsidence on linear structures (eg. pipe lines) has also been written and now forms part of the suite of programs. This program will not be discussed here, as it is based on equations (5.1) and (5.2), which are very simple and do not require further enlightment.

5.4 SIGNIFICANCE OF THE SURFACE ELEMENT ANALYSIS AS OPPOSED TO THE TWO DIMENSIONAL PROFILE ANALYSIS

The Surface Element Analysis, being more comprehensive, and thus requiring the gathering of more data and also more involved analysis of data, is a more expensive method to apply than the two dimensional one. If more practical benefit cannot be derived from it, there is very little reason to use it.

To highlight the difference between the two methods, a case of subsidence analysis was taken at random from the available observations. Results for tilt and strain calculations using

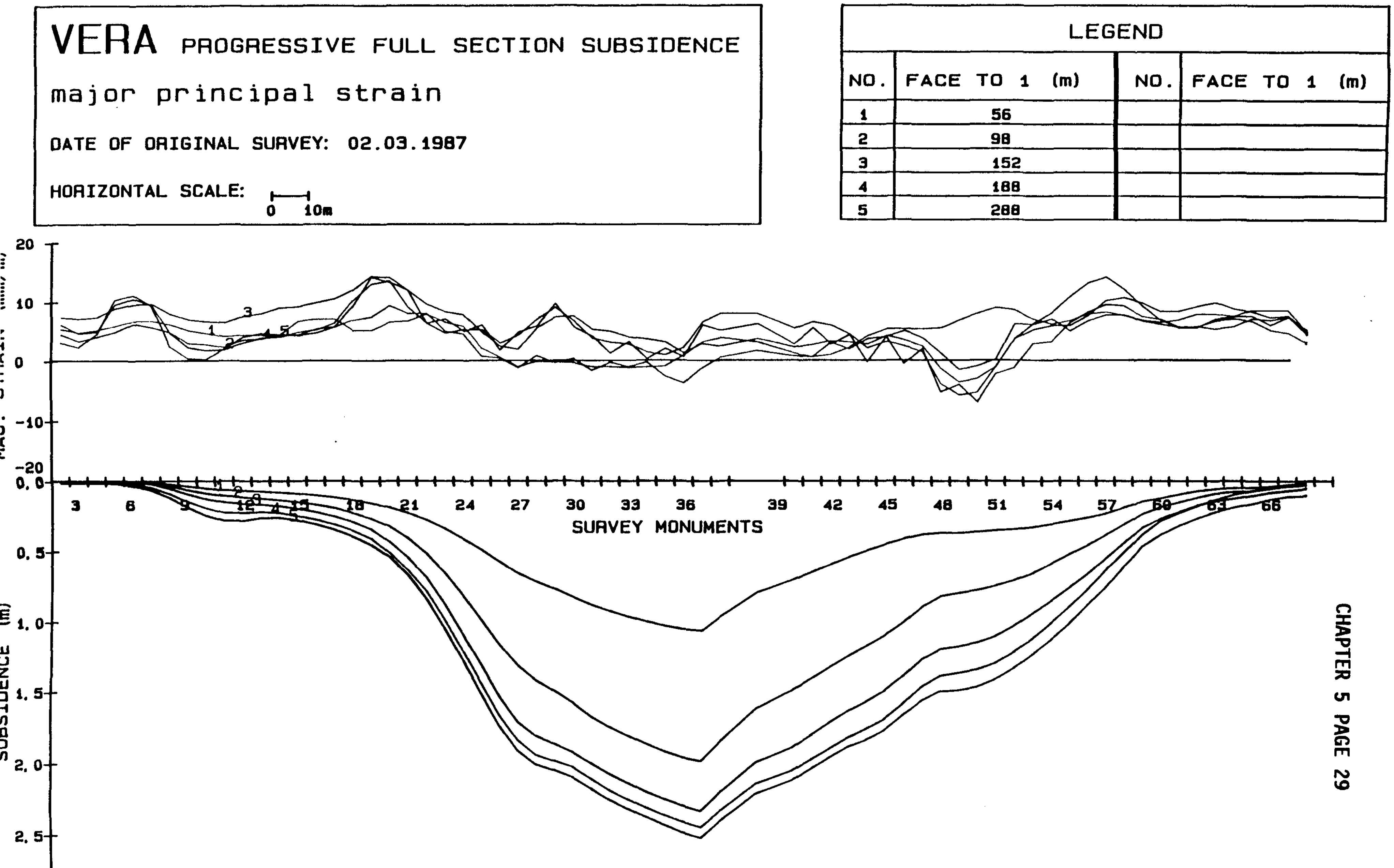

Figure 5.12 Example of "VERA" output, showing progressive subsidence and Major Principal Strain over the whole panel.

both the profile analysis and the SEA approach, were compared. The next two sections deal with the comparison of those results.

Figure 5.13 is a simplified view of the observation area. Note that the observation lines did not cross the panel at right angles. The reason for this is that the observation lines were installed parallel to the structure which was undermined and which required monitoring.

Lest it be argued that this is a special case, consider that as underground layouts and surface structures are planned independently of one another, the probability of any linear structure being installed at right angles to an underground panel is virtually non existent. The converse is therefore true: any long structure (road, pipe line, railway line, etc.) which crosses an underground panel at right angles is an extremely rare occurrence and therefore a very special case.

For the comparison, the same data was used. For the profile analysis, only the data from one of the two lines of monuments were used.

5.4.1 Comparison of induced tilts

Figure 5.14 shows the comparison of the induced Major Tilt and the tilt calculated along the two dimensional profile. Only the magnitudes of the induced tilts are considered.

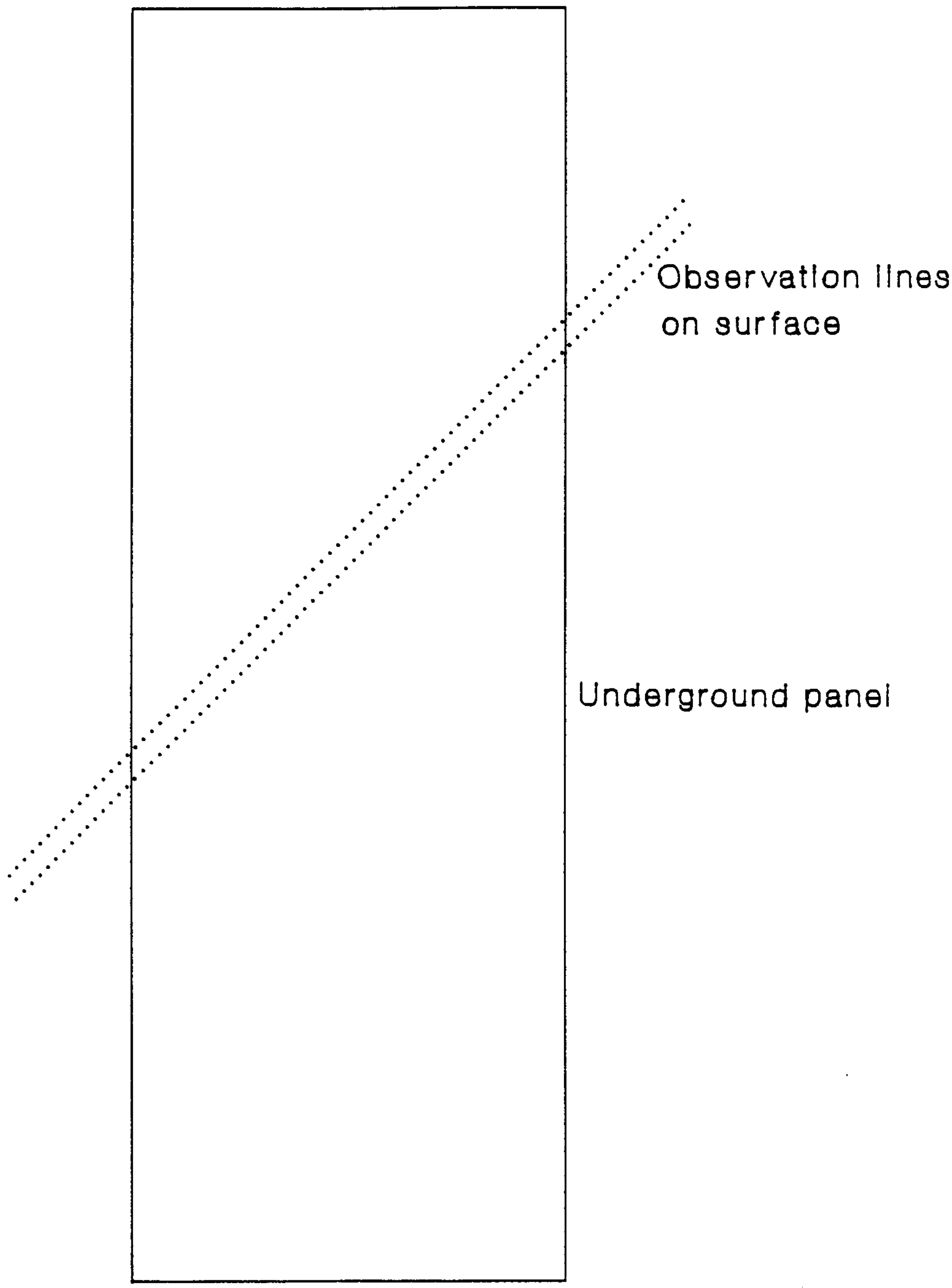

Figure 5.13 Position of the observation lines relative to the underground panel.

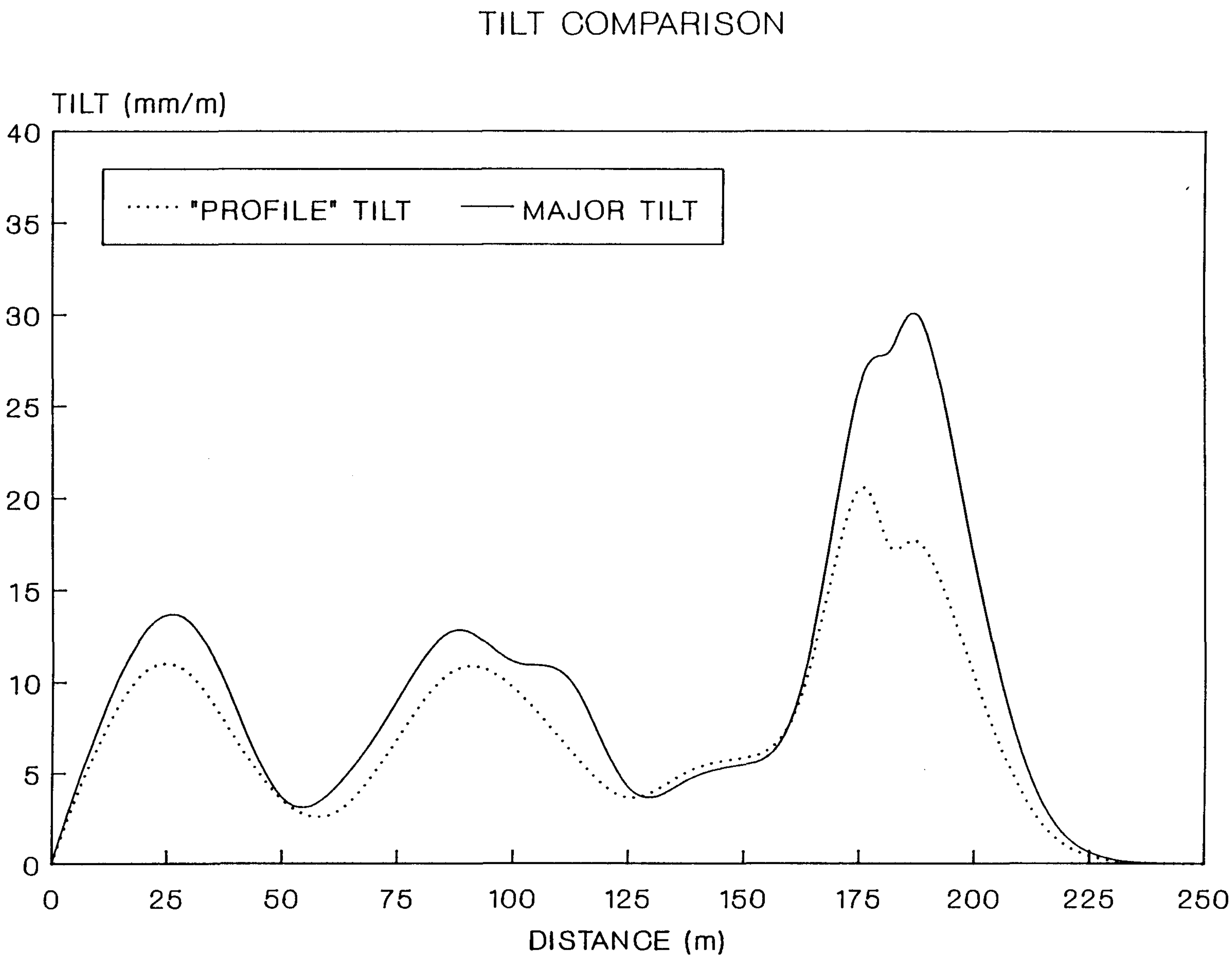

Figure 5.14 Comparison of the Tilts obtained by analysing the same data two and three dimensionally.

It is clear that the two dimensional profile analysis yields induced tilts of significantly smaller magnitude than the Major Tilt. The reason for this is perfectly clear: the profile analysis only allows the calculation of a minor tilt. The real maximum tilt at any position is thus hidden. By calculating the Major Tilt, the maximum value is in fact derived.

In this specific example, which is a practical one, it is also clear that there is no relationship between the two tilts. If subsidence along this structure was thus analysed in the conventional profile manner, attempts to correlate the induced tilt with observed damage on the structure, may either have failed or been subjected to imaginative explanations. When it comes to damage to structures, the damage which would have occurred in the "wrong" locations, would probably have been erroneously blamed on poor construction.

It is hard to imagine any structure which would be affected by tilt in a specific direction only. Roads, railway lines, etc., which may be considered as "linear" structures, are not truly linear in the sense of being two dimensional. A road, for instance, is affected by tilt in its travelling direction as much as in its cross direction.

The approach advocated here, that of deriving the Major Tilt, and its direction, has the added advantage of allowing the Minor Tilt in any desired direction to be calculated.

5.4.2 Comparison of strains

The strains as derived in the two dimensional profile analysis and the Principal Strains are graphically compared in Figure 5.15. The deficiencies of the two dimensional strain analysis are immediately apparent.

Firstly, the true maximum value of strain at any point is hidden. Once more, this has to be so: the two dimensional strain can only be a component of the Principal Strains at any point.

Secondly, the two dimensional approach only recognises a single mode of strain: either tension or compression. It completely ignores the co-existence of compression and tension (albeit in different directions) in the same area. The subsidence analyst who takes the trouble of travelling to subsidence sites and visually inspecting those areas, will know that tension and compression certainly do exist in the same areas, as shown in Plate 1.

This has important bearing on the definition of the areas of a subsidence trough previously defined as "tensile" (the edges of the subsidence trough) and "compressive" (the central zone of the subsidence trough). Previously, the two dimensional approach led to the erroneous belief that only tensile strains

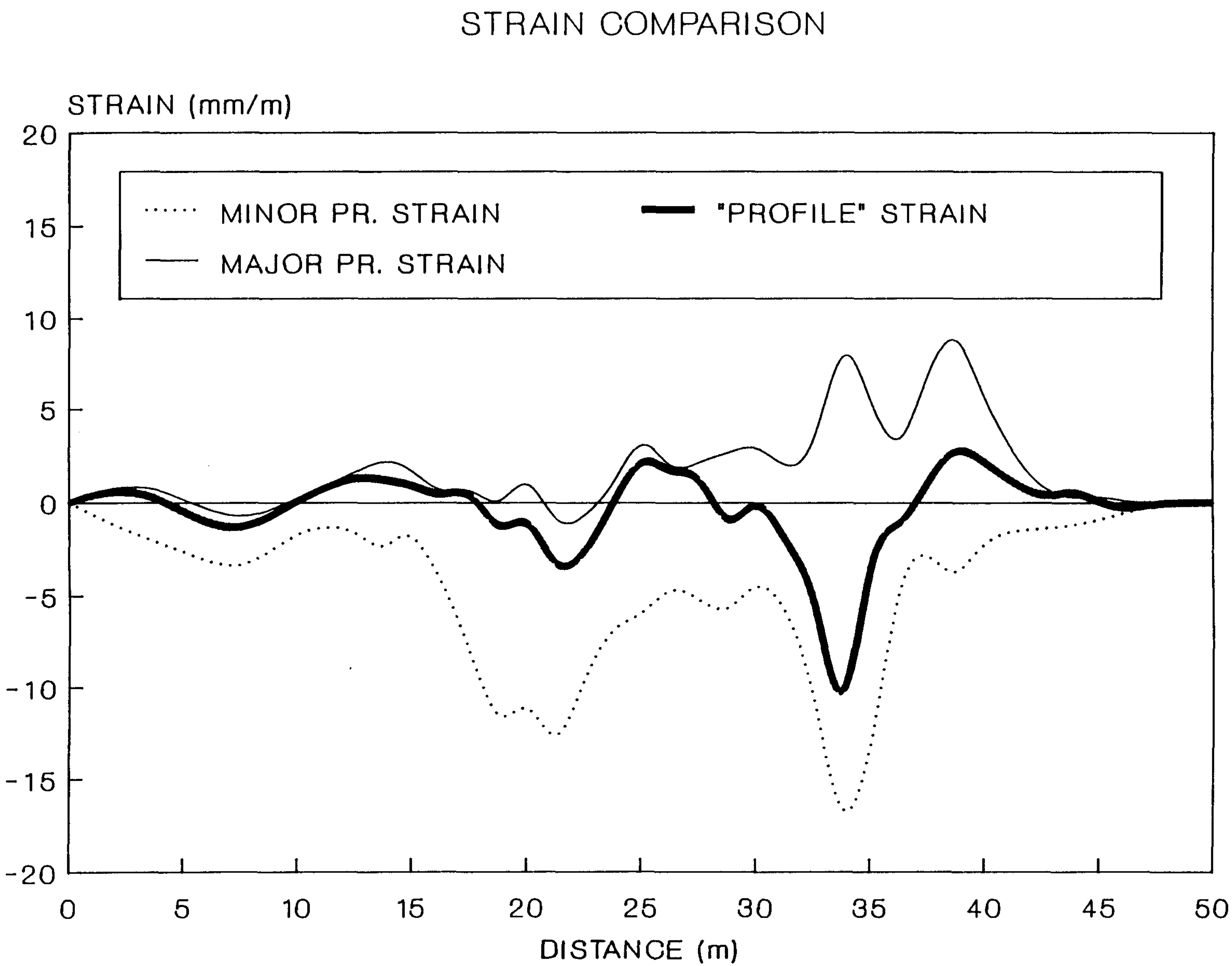

Figure 5.15 Comparison of the results obtained by analysing strains two dimensionally. The same base data was used.

existed in the "tensile" zones and only compressive strains existed in the "compressive" zones. This is not true. What is true is that the "tensile" zones are characterised by higher magnitudes of tensile strains than compressive strains, and vice versa. While both Principal Strains in the "tensile" zone may be tensile, one of the two may very easily be compressive. The converse is true for the "compressive" zone, where a smaller magnitude of tension very often occurs in the same area as the greater magnitude of compression.

Thirdly, it is seen from Figure 5.15 that the two dimensional strain component is not consistant in its prejudice, but favours the greater magnitude of Principal Strain in a rather fickle fashion. It cannot be relied upon to give an indication of the magnitude of either principal strain, although it may possibly hint at whether tensile or compressive strains are dominant in any particular area.

5.5 CONCLUSIONS

Previous paragraphs already outlined most of the advantages of the surface element approach. In summary, it firstly yields the maximum values of either induced tilt or strain in any area, which the two dimensional approach cannot do.

Secondly, it considers both tilt and strain as vector quantities and consequently allows the direction of either maximum parameter to be known.

Thirdly, it allows the calculation of any component of tilt or strain in any direction to be done.

Fourthly, with regard to strain, it recognises the co-existence of compressive and tensile strains in any particular position.

Fifthly, it allows more flexibility with regard to the location of the observation areas, as the magnitudes of the derived parameters are independent of the direction of the observation lines.

The major disadvantage of the approach is that it requires more data to be gathered and significantly more calculations to be done. However, this advantage is largely overcome by computerisation of the calculations. Even data gathering can be speedily done if electronic means - the so called "total station" concept - is adopted.

As an example, the total procedure was timed at Sigma Colliery. From the time the surveyor left his office to obtain the coordinates of 140 survey monuments, to the time a set of fully analised results was available, took less than three hours.

6 THE PREDICTION OF SUBSIDENCE IN THE SECUNDA AND SASOLBURG AREAS

6.1 INTRODUCTION

6.1.1 Motivation for predicting subsidence

When confronted with the option of undermining a structure on surface with high extraction mining or not, sound engineering practice requires that a number of basic steps be taken in sequence. Firstly, the subsidence elements have to be predicted. Secondly, the reaction of the structure to the subsidence elements has to be forecast. Then, by taking cognisance of the required steps for damage prevention or reduction, repair costs and safety risk and the benefit to be gained by undermining, a logical and sound decision can be taken.

This chapter is devoted to the first step in the decision making process, namely the prediction of the subsidence elements in the study area. As the approach was primarily empirical, the prediction method presented will only be valid for the study area or areas with similar geological and geometrical features.

Later chapters will deal with the reactions of various types of structures to subsidence.

In the context of this thesis, the term "subsidence" refers not only to vertical displacement of the surface as a result of high extraction mining, but to the suite of elements occurring in sympathy with the vertical displacement. These elements include tilt, horizontal displacement and strain.

In everyday terms, the "severity" of subsidence is often expressed by the magnitude of vertical displacement. This is not strictly correct, because vertical displacement per se is seldom the cause of serious damage to a structure. However, on its own it may result in ponding on farming lands or affect the sight distance along a road.

It will also be shown that the other elements are related to vertical displacement. It is thus a very important parameter, and its use a first order indicator of the severity of the total change caused by subsidence may be justified.

Induced tilt, or the first derivative of vertical displacement, is on its own perhaps more important with regard to damage to a structure than vertical displacement. This is especially true for high structures like transmission towers or walls.

Horizontal displacement is again important for long, continuous structures like conveyor belts, where the horizontal alignment is a prerequisite for its smooth functioning. As a separate subsidence element, it thus has to be considered.

Strain, caused by differential horizontal displacement, is possibly the most important parameter where the integrity of structures is concerned. Tensile strain may cause cracks in walls or roads or stretch the bases of transmission towers, leading to undesirable loads on structural members. Compressive strain may result in ridging on roads, damage to walls, squashing of the bases of transmission towers, etc.

Depending on the nature of a structure, i.e. tall and slender, long and flat or broad based, different subsidence elements may have different relative importance to its integrity. In all cases, the limiting magnitudes of the different elements depend primarily on the condition and the construction method (i.e. monolithic vs modular building construction) of the structure at hand. While generalisations may therefore be very dangerous, the decision making process has to begin with a prediction of the magnitudes of the various subsidence elements.

6.1.2 Methods used for deriving the subsidence prediction model

Vertical Displacement

An empirical approach was adopted to predict the maximum magnitude of vertical displacement as well as the shape of the subsidence profile. The latter is defined as the magnitude of vertical displacement at various positions along the profile.

The method used was firstly to determine a relationship between maximum vertical displacement, S_m, normalised with respect to the mining height, h, and the ratio of panel width, W, to mining depth, H. The shape of the profile was determined by calculating average values for vertical displacement, S, normalised with respect to S_m, at various intervals along the profile from a number of observations. Only comparable observations were used - some observations had to be rejected because the profiles were influenced by the presence of crush pillars, or because double seam mining was done.

Dolerite failure

Galvin (1983) gave a formula for predicting dolerite failure. His work did not primarily deal with subsidence, and the formula, based on the limited information which was then available, was used more in the spirit of obtaining additional information than being an essential component of the work. The formula is, however, widely used as there has thus far not been an alternative.

The formula was re-evaluated in the light of the vast amount of information which has become available since it was derived. Certain deficiencies were found, and an alternative formula was derived and will be shown to be more effective.

Induced tilt

As induced tilt along the profile is a direct function of the shape of the subsidence profile, it follows that this parameter is also taken care of once the shape of the profile has been defined. No additional work was thus required for this parameter.

For the prediction of maximum induced tilt, T_m, a correlation was found between T_m and S_m, based on observations. T_m for the various cases was found from the three-dimensional analysis explained in Chapter 5. In this way, the problem presented by the fact that most of the observations were taken in lines running obliquely across the panels (to coincide with the positions of monitored structures) was overcome.

If two-dimensional analyses were done, the data would not have been suitable for comparison as only components of tilt and strain would have been derived. With the SEA analysis (see Chapter 5), the maximum magnitudes of the subsidence elements could be calculated and compared.

Strain

For the prediction of strain along the profile, a new concept was developed and tested. As will be explained later in the chapter, it essentially links the magnitude of strain to the shape of the subsidence profile and a parameter which is a function of the thickness of the deformable layer on surface. The prediction method correlates well with observations, as well as a slightly modified British Coal prediction method.

With regard to the prediction of maximum magnitudes of tensile and compressive strains, relationships were found between those parameters and S_m. For the same reasons as explained in the section dealing with induced tilt, the three-dimensional SEA approach was used to determine the maximum magnitudes of the two strain parameters.

6.1.3 Nature of the prediction method

The prediction method explained in this chapter is a two dimensional profile method. There was insufficient data to determine the full subsidence trough characteristics near the beginning and end positions of the troughs.

The method is therefore only valid for those positions on the subsidence trough which are not influenced by the beginning and end positions of the troughs. However, as it represents the worst case (i.e. maximum magnitudes of the induced subsidence elements), it is valid.

The three dimensional analysis method described in Chapter 5 was used to determine the magnitudes of the various parameters in the cases where the observations were not taken in a direction perpendicularly to the long axes of the underground panels. It was thus used to overcome what would otherwise have been a deficiency in the data.

6.2 MAXIMUM SUBSIDENCE

6.2.1 No dolerite sill present, or sill in a failed state

The relationship between the ratio of Maximum Subsidence to Mining Height (S_m/h) and the ratio of Panel Width to Mining

Depth (W/H) for longwalling is shown in Figure 6.1. Although it is apparent from the figure that there may be some justification for differentiating between the Sasolburg and Secunda subsidences, the differences are small enough to be contained within the range of observations. It was therefore decided to lump the data together.

It can also be seen from the figure that at the lower range of W/H, a cluster of points are plotted which appear not to correlate with the rest. Those cases, marked separately on the figure, represent instances where the dolerite sill in the overburden apparently did not fail. In the determination of a mathematical expression of the relationship between S_m/h and W/H, those cases were ignored.

It was found that the expression:

$$S_m/h = 0{,}39\ (W/H)^{0{,}32}, \qquad (6.1)$$

best expressed the relationship between S_m/h and W/H. The correlation coefficient between the values of S_m/h obtained with equation (6.1) and field measurements was 0,74.

Equation (6.1) is only valid for the range of observations indicated in Figure 6.1. As consideration of mining geometries indicated that the range is not likely to be extended in the near future, no attempt was made to cater for an extended range.

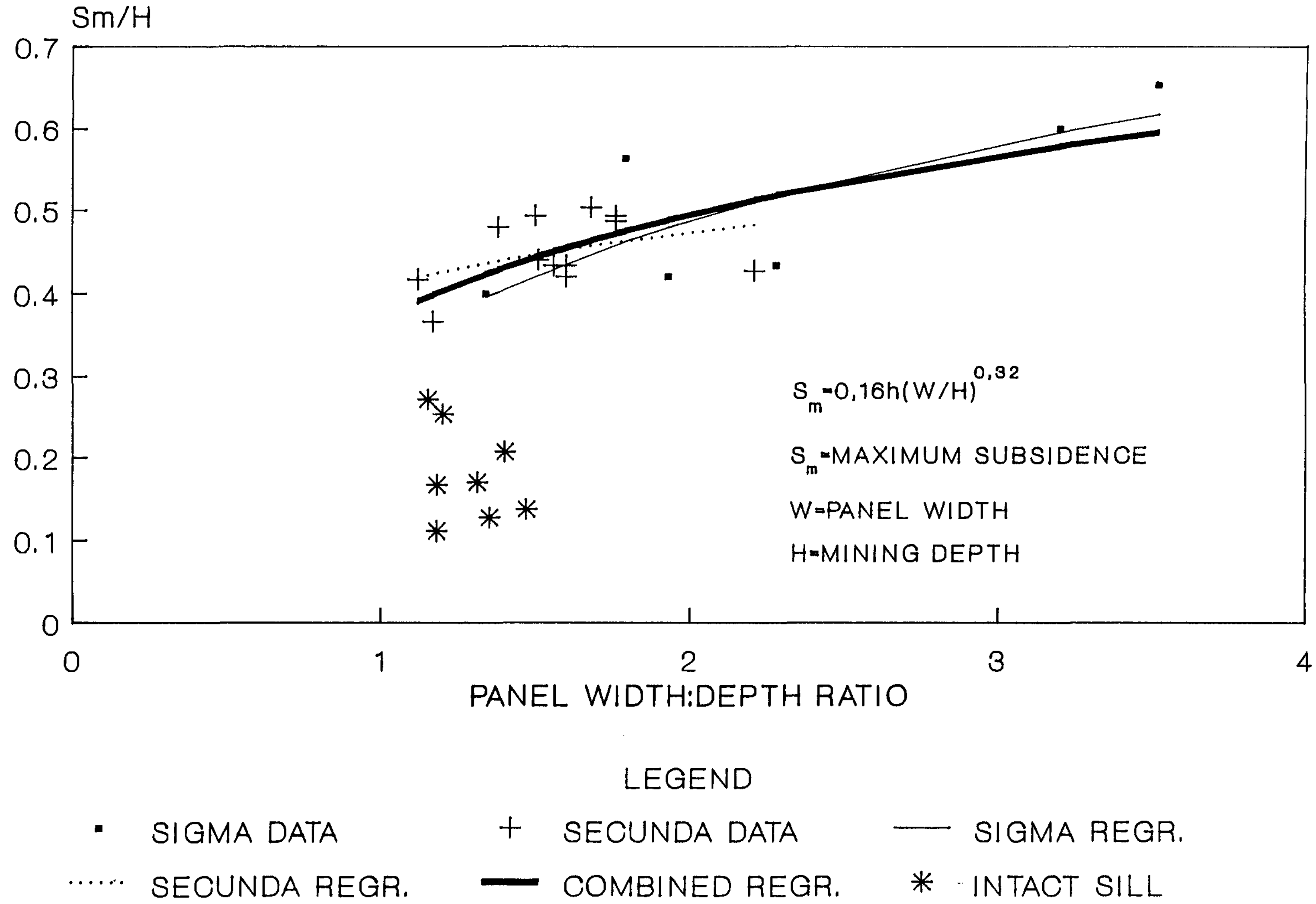

FIGURE 6.1 Maximum subsidence as a function of the Panel Width to Mining Depth ratio.

6.2.2 Effect of the dolerite sill

Equation (6.1) is only valid for instances where the dolerite sill had failed, or is absent. Previously, the relationship given by Galvin (1983), based on limited data, was used to predict whether or not the sill would fail. As mentioned in Chapter 1, the decade 1980/90 saw a dramatic increase in the application of high extraction underground coal mining. As case histories beyond the limits of the data available to Galvin became available, certain deficiencies in the Galvin formula came to light.

Galvin states that the critical span for dolerite failure, L_c, can be calculated as follows:

$$L_c = \sqrt{1165t_d - \frac{935t^2_d}{D}} + 2t_p\tan\alpha, \qquad (6.2)$$

where

t_d = dolerite thickness,

D = depth of dolerite base,

t_p = parting thickness between dolerite base and coal seam and

α = goaf angle.

It was seen in practice that the formula is a poor predictor of dolerite failure when the dolerite occurs close to surface. This is especially true for the Eastern part of the Secunda coal field.

The shortcomings of the Galvin formula are illustrated in Figure 6.2. In the figure, the ratio of actual subsidence to predicted subsidence (using equation (6.1)) is plotted against the ratio of critical span (calculated with equation (6.2)) to actual span. If equation (6.2) was a good predictor of dolerite failure, then the dolerite should not fail when the critical span is greater than the actual span, or where the ratio of critical span to actual span is greater than one. Therefore, the actual subsidence should then be significantly less than the predicted subsidence, and consequently the ratio of actual to predicted subsidence should be less than one.

It is seen from Figure 6.2 that this is not the case. It can therefore be concluded that equation (6.2) is not valid for predicting failure of the dolerite sill in the study area.

The reason for this observation may be found in closer scrutiny of the Galvin formula. The only term in the formula related to the loading of the sill is the negative portion in the square root sign:

$$\frac{935t^2d}{D}.$$

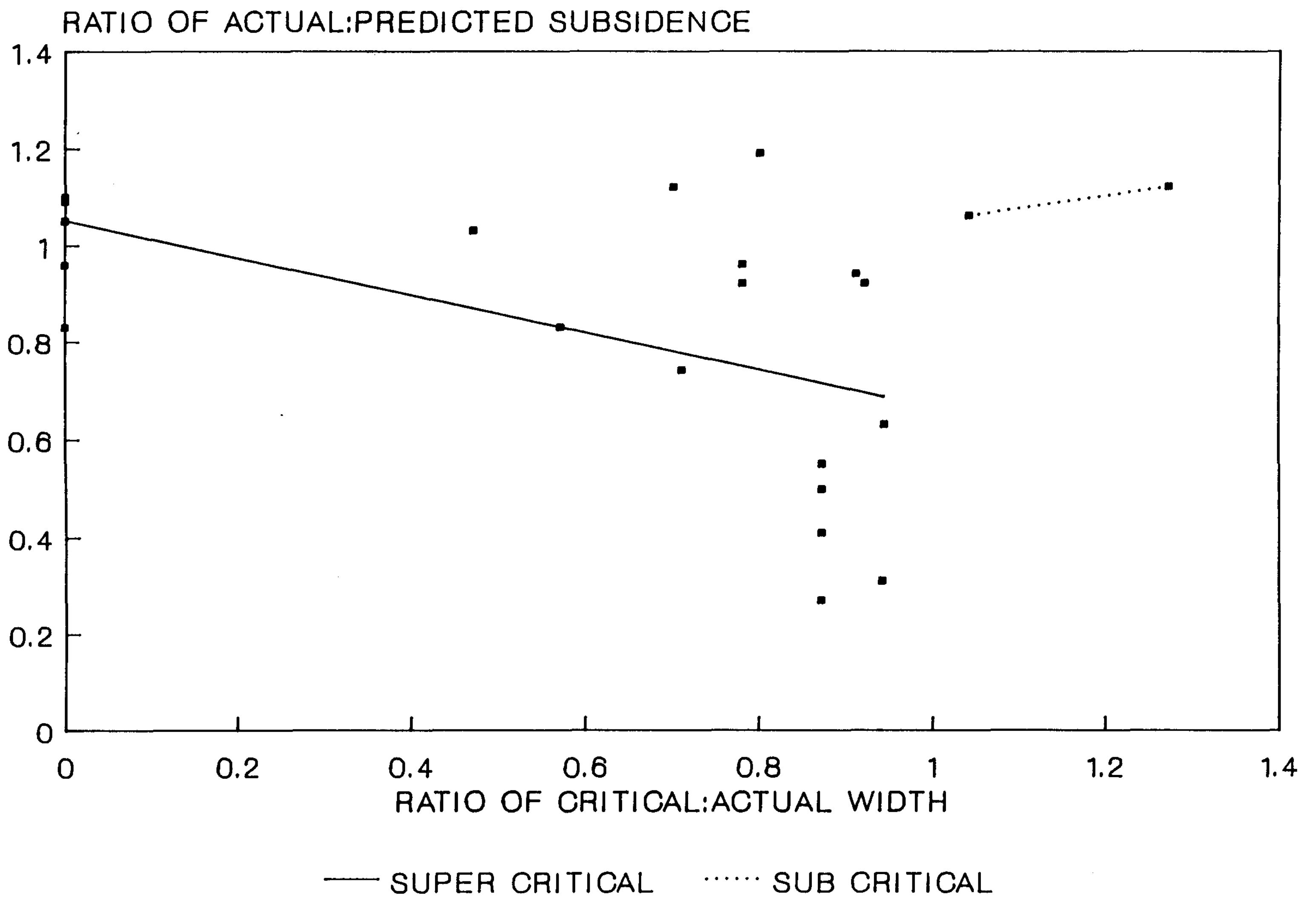

FIGURE 6.2 The ratio of actual to predicted maximum subsidence vs the ratio of critical to actual panel width, using Galvin's formula for the prediction of critical width.

As the sill occurs deeper, or as D increases, the predicted L_C becomes greater. But, as D increases, the load on the sill increases and logically it should then fail at a smaller span. L_C should therefore decrease with increasing D, which is contrary to the Galvin formula.

An alternative model was then sought. Based on the concept that the dolerite will fail when the horizontal compressive stress across vertical discontinuities is reduced sufficiently by bending of the rock mass to permit gravity induced sliding of distinct blocks, an alternative formula was developed. After simplification, it had the following form:

$$L_C = \sqrt{\frac{3{,}25td\ (d - t/2)}{(d - t)}} + 2p\ \tan\alpha, \qquad (6.3)$$

where

t = dolerite thickness,

d = depth of dolerite base,

p = parting thickness between base of dolerite sill and coal seam and

α = goaf angle.

The effectiveness of the alternative formula is illustrated in Figure 6.3, where it is subjected to a similar test with the same data as was done for the Galvin formula in Figure 6.2. It

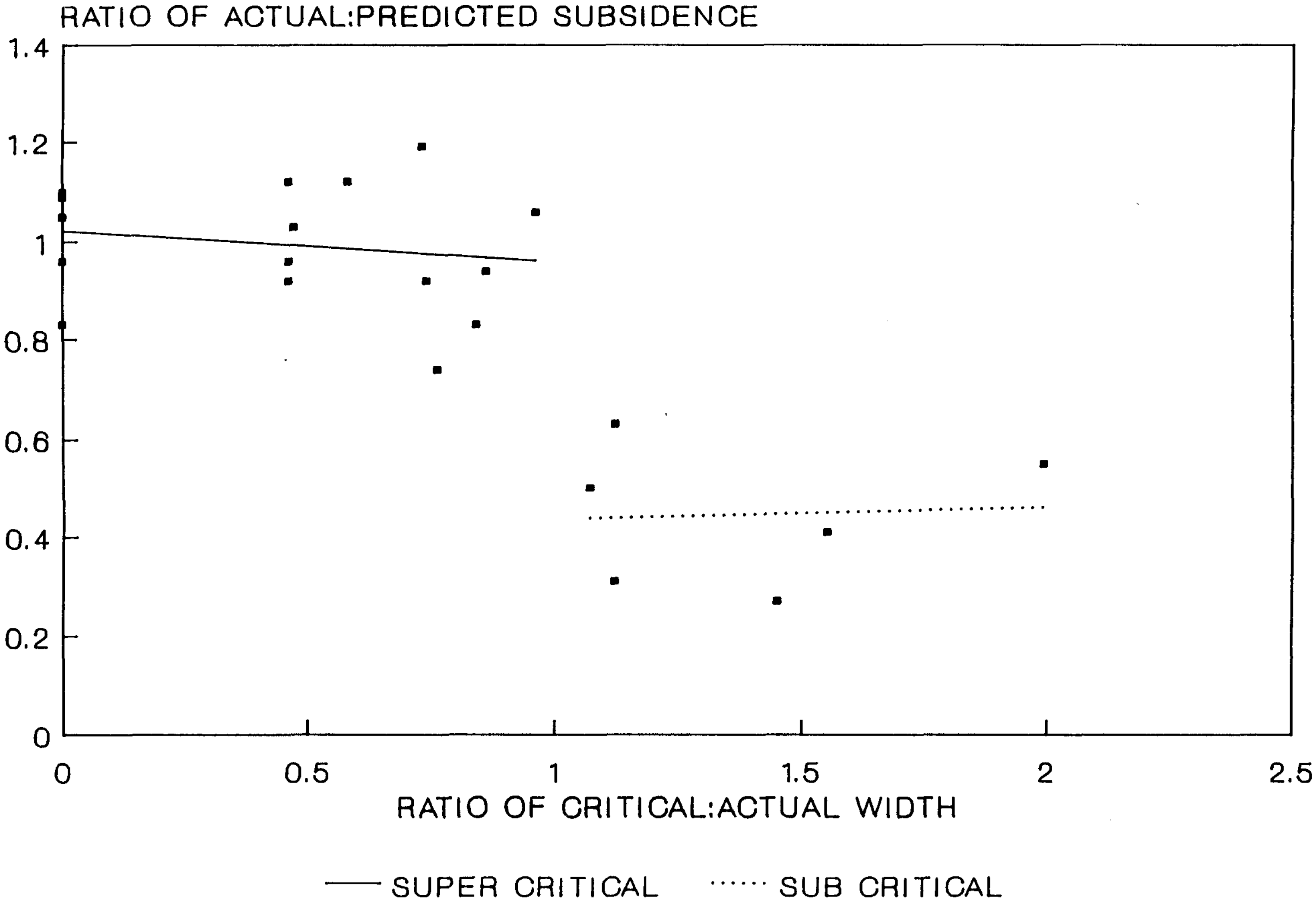

FIGURE 6.3 The ratio of actual to predicted maximum subsidence vs the ratio of critical to actual panel width, using the new formula for the prediction of critical width.

is immediately apparent that equation (6.3) is a good predictor of dolerite sill failure for the conditions in the study area. The sub critical panel widths are characterised by significantly reduced magnitudes of maximum subsidence.

6.3 SHAPE OF THE SUBSIDENCE PROFILE

Eight subsidence profiles were found suitable for comparison to find a representative profile. Several had to be rejected.

Some were unsuitable as they were influenced by crush pillars or by increasing panel widths, or because the dolerite sill remained intact. Others related to double seam extraction. The chosen profiles are nonetheless considered to be representative, as they cover the Sigma area and both the Eastern and Western Secunda fields.

Figure 6.4 shows the chosen profiles and the average profile. All the profiles are plots of the ratio of subsidence to maximum subsidence (S/S_m) against the ratio of distance from the panel edge to panel width (x/W).

The expression:

$$S/S_m = 0{,}5\ [\tanh\ (7x/W - 1{,}645) + 1] \qquad (6.4)$$

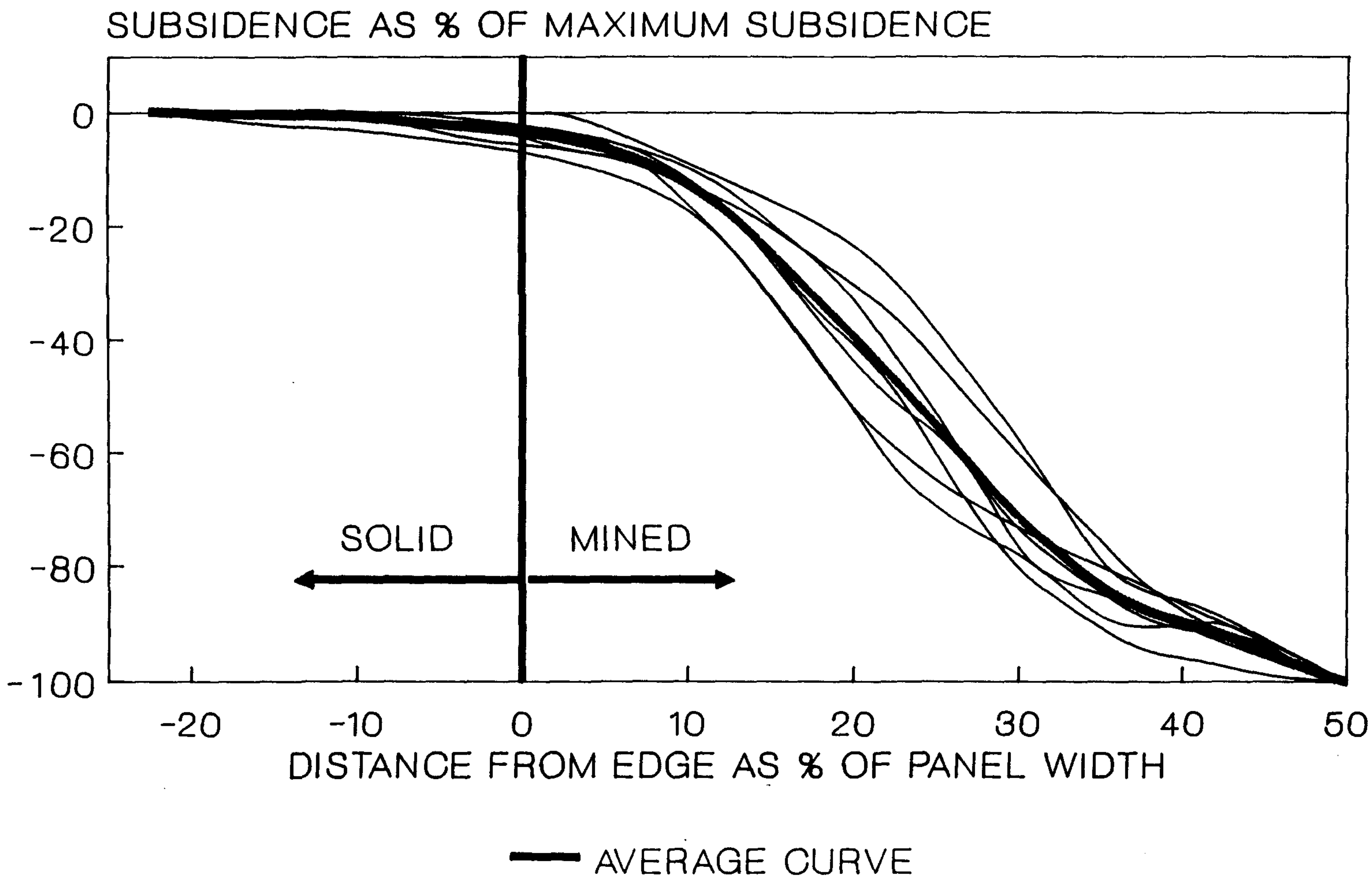

Figure 6.4 The various Subsidence Curves that were used to derive the average curve.

was found to describe the average curve with a correlation coefficient of 1,0.

Subsidence over the ribsides amount to approximately $0,04S_m$ and the point of inflexion occurs at 0,23W.

6.4 PREDICTION OF INDUCED TILT

6.4.1 Prediction of tilt along the subsidence profile

By definition, induced tilt is the quotient of differential vertical displacement between two points on a subsidence profile and the horizontal distance between the two points. Therefore, once the shape of the subsidence profile has been defined, the calculation of induced tilt is very simple.

6.4.2 Prediction of maximum tilt

There was very little variation in the data with regard to panel width, mining depth and mining height, which were nominally 200 m, 120 m and 3 m. The data was therefore not suitable for determining a relationship between T_m and the ratio of mining height to mining depth.

From a geometrical point of view, however, there should be a correlation between T_m an S_m for constant panel width, irrespective of whether the dolerite sill failed or not. This relationship was investigated and the results are shown in Figure 6.5. It is clear that a linear relationship does exist, and is expressed as:

$$T_m = 21{,}6\ S_m + 7, \qquad (6.6)$$

where the units of T_m are mm/m and S_m is measured in metres.

For a 200 m wide panel with a mining height of 3 m and a mining depth of 120 m, S_m according to equation (6.1) is 1,37 m and T_m according to equation (6.6) would then be 37 mm/m. According to the maximum tilt prediction of Wagner and Schümann (1985), equation (2.14), T_m should be 38 mm/m. The two predictions are in good agreement.

6.5 PREDICTION OF STRAIN

6.5.1 Prediction of maximum strain

Due to the same reason as explained in section 6.4.2, no attempt was made to correlate maximum strain to the ratio of mining height to mining depth. Instead, a correlation was sought between observed maximum strain and maximum subsidence.

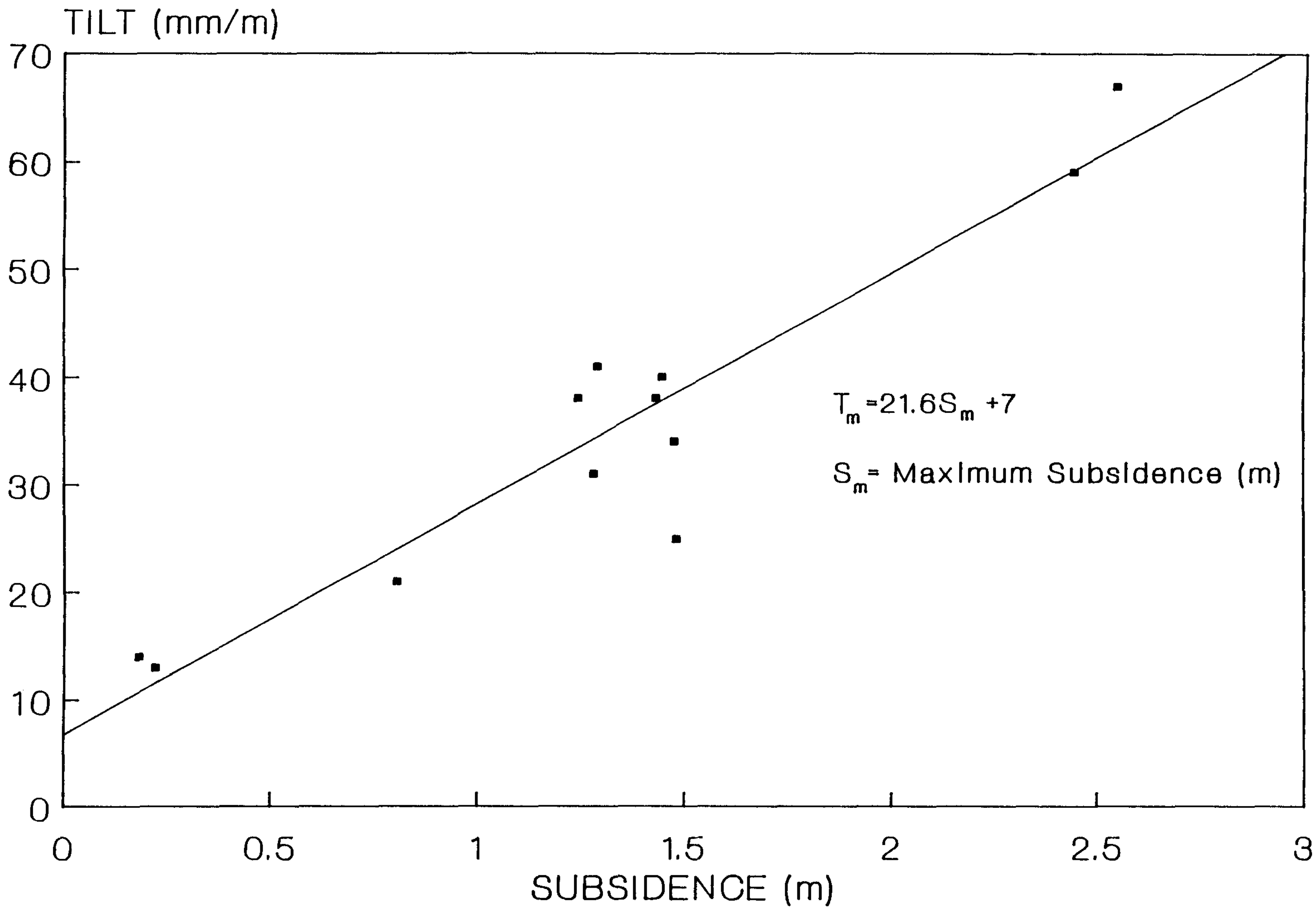

FIGURE 6.5 Maximum Tilt as a function of Maximum Subsidence.

As shown in Figure 6.6 reasonable correlations exist between both compressive and tensile maximum strains and maximum subsidence.

The relationships are mathematically expressed as follows:

$$\epsilon_{m+} = 4,2S_m + 1,7 \text{ and} \quad (6.7)$$

$$\epsilon_{m-} = - 9,1S_m - 2,8, \quad (6.8)$$

where S_m is measured in metres and the strains are given in mm/m.

For a 200 m wide panel with 3 m mining height at 120 m depth, it is predicted, by equations (6.7) and (6.8), that the maximum tensile strain should be 7,5 mm/m and the maximum compressive strain -15,3 mm/m. Wagner and Schümann (1985) unfortunately do not differentiate between tensile and compressive strains, but predict according to equation (2.15) that the maximum horizontal strain should be 10 mm/m for the same conditions.

According to Holla (1986) the maximum tensile and compressive strains should be respectively 10 mm/m and -15 mm/m, which is in good agreement with the results from equations (6.7) and (6.8).

It is noteworthy that in Figure 6.6, the magnitudes of compressive strains are greater than those of tensile strains, which is a characteristic of sub critical panel widths. The

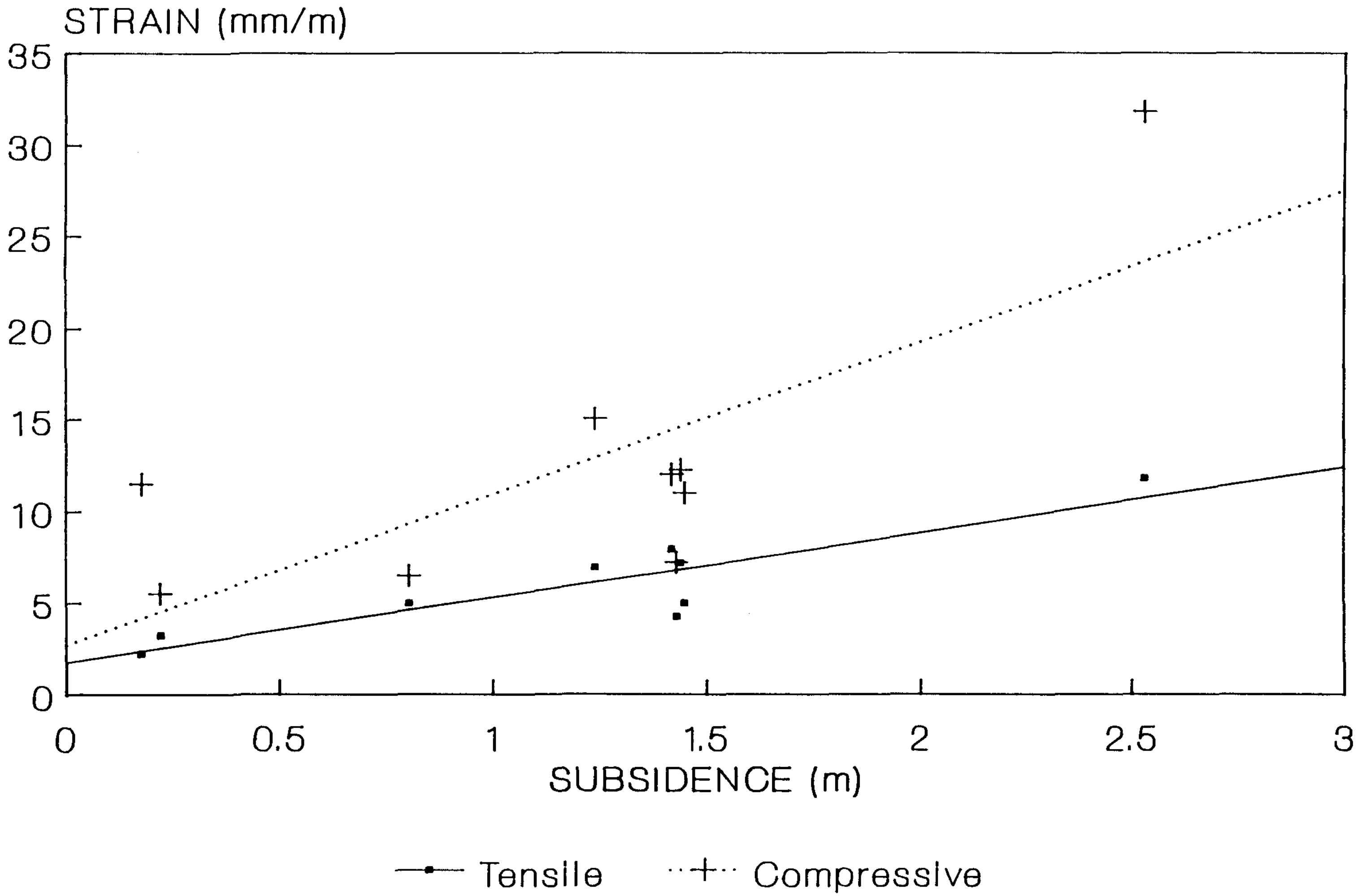

FIGURE 6.6 Maximum Tensile and Compressive strains as a function of Maximum Subsidence.

maximum panel width to mining depth ratio of the data represented in Figure 6.5 was 1,7. This observation confirms the remarks made in Chapter 2, section 2.4.3, that the critical W:H ratio for South African conditions appears to be in the region of 2 - 2,5.

6.5.2 Prediction of strain along the subsidence profile

Of all the subsidence elements, the prediction of strain along the subsidence profile appears to be the most difficult and also the least accurate. This is understandable, as neither the rock nor the overlying soils are continuous. Therefore, even a single factor like the formation of cracks will affect the distribution and the magnitude of strain. Once a crack has opened on the surface, the tendency with further subsidence would be for that crack to open wider in preference of further distribution of strains.

Attempts to develop a strain prediction model based on the elastic bending of a continuous beam are thus not likely to be successful when surface cracks are a feature of subsided areas. This is indeed the case in South Africa. Based on observations during 1986, a unique strain prediction model was developed. In the following paragraphs, the development of the strain prediction method and its validation will be described.

(a) Development of strain prediction method

Observations at shallow longwall in 1986

During 1986, a longwall face suffered a severe collapse at a shallow depth (60 m below surface) at Sigma Colliery. During the six months period of extraction of the equipment, the amount of rock which was loaded out from underground was sufficient to result in a 30 m deep doline on surface. This afforded the unique opportunity of visually inspecting a cross section of the strata overlying a longwall at the edge of the subsidence trough. Unfortunately, the sides of the doline appeared to be unstable and a close examination was therefore not possible.

Viewed from the top, a number of important observations could still be made. The most significant observations (see Plate 2) were the following:

(i) the rock mass was not a solid beam,

(ii) discrete blocks of rock appreared to have been differentially displaced vertically and

(iii) the upper blocks appeared to have tilted.

PLATE 2 This photograph shows a cross section through rock which has subsided. Note that the rock did not deflect as a solid beam, but rather as discrete blocks that subsided and tilted relative to one another.

These observations confirmed that the mechanism of subsidence at shallow depth was not bending of a continuous beam, but rather differential displacement of discrete blocks. The postulated mechanism is consistent with the fact that in South Africa, meaningful subsidence only occurs within the extremities of the underground panel. There is no bending of a beam: blocks can only be displaced where material is removed from underneath. Also, the total amount of subsidence will increase with increasing distance away from the ribside, due to incremental vertical displacement of the blocks relative to one another.

Of all the analytical models available for analysing rock behaviour, the discrete element model of Cundall and Marti (1979) should be best suited for predicting subsidence. The model was tested and indeed found potentially suitable for the prediction of the subsidence profile. The test was done with several assumptions regarding rock characteristics and more work is required to turn the method into a reliable engineering tool. It was concluded, however, that the postulated subsidence mechanism was confirmed by the analysis.

Strain and the subsidence mechanism

The explanation in the foregoing section was given as background to the development of the strain model.

If there is no beam mechanism then compressive strain can only arise by tilting of near surface blocks and the compression of soil or other compressible material on the surface. The mechanism by which strain is then postulated to be created, is shown in Figure 6.7. The Figure shows a model which is made up of two distinct layers near the surface: an incompressible layer underneath, representing the upper layer of unweathered rock, overlain by a compressible layer of thickness t which represents soil and weathered rock. The incompressible layer is dissected by joints or fractures, turning it into discrete blocks. The model examines the effects of tilting of the blocks relative to one another.

As the blocks tilt, the material comprising the compressible layer is either compressed or stretched, depending on whether the bending is of a concave or convex shape. It is seen from Figure 6.7 that for the tensile strain situation, the pivot point about which tilting occurs is not the same as for compressive strains.

Note that in the figure, there are two important features: there must be differential tilting of discrete blocks, and there must be a compressible layer of thickness t, conceivably consisting of soil and weathered rock, overlying a relatively incompressible layer, the unweathered rock.

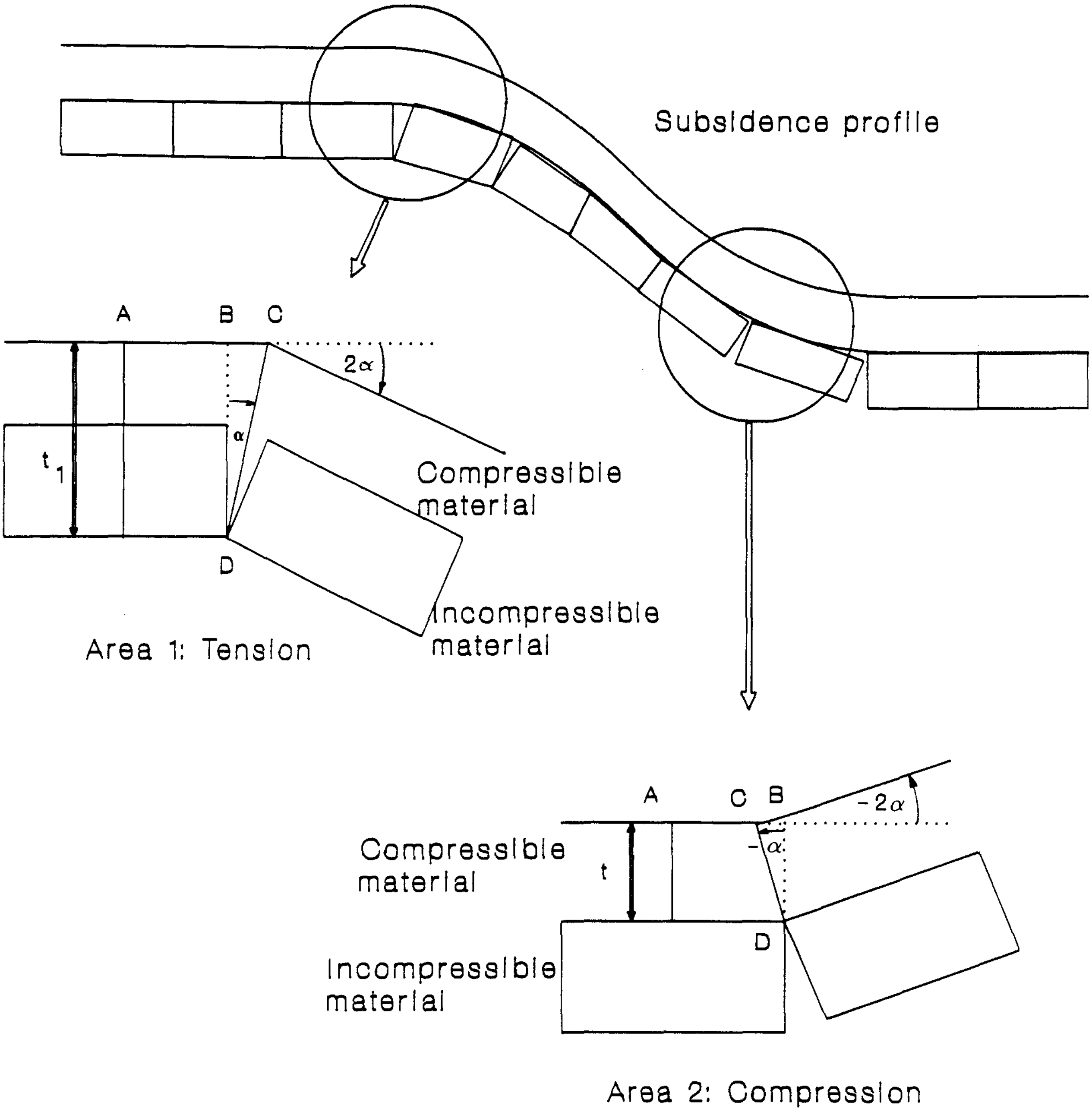

Figure 6.7: A typical subsidence profile, showing the upper incompressible rock layer overlain by compressible material (soil, weathered rock). Typical situations at respectively the tensile and compressive zones are enlarged.

In Figure 6.7, area 1, it is seen that for the tensile zone,

$$\epsilon_{+} = \frac{BC}{AB}$$

$$= \frac{t_1 \tan\alpha}{AB} \qquad (6.9)$$

Similarly, from area 2, it is seen that for the compressive zone,

$$\epsilon_{-} = \frac{-t \tan\alpha}{AB} \qquad (6.10)$$

Note that equations (6.9) and (6.10) only differ in two respects: firstly they are of opposite signs and secondly, the parameters reflecting the depth to which the strain mechanism is confined, t and t_1, is greater for tensile than for compressive strains.

Quantification of t and t_1

This attempt at an analytical approach to explain the strain phenomenon is not complete, as the parameter t or t_1 should logically also be influenced by the stiffness of the upper layers. It therefore stands to reason that it should be area specific. Attempts to correlate measured strain to strains calculated from induced tilts by using equations (6.9) and (6.10) showed that this is indeed the case.

As will be shown later, very good correlations between measured and calculated strains were found, while the slopes of the correlation curves, indicating the ratios of the magnitudes of measured to calculated strains, were prone to greater variation. The magnitudes of the calculated strains vary directly with variations in t and t_1, which indicates that better correspondence between the strains would occur by employing site specific values for t and t_1.

It was found by back analysis of a number of profiles representing a wide variation of conditions, that using values of t = 3,5 m and t_1 = 4,7 m yielded the best results.

Quantification of parameter α

In Figure 6.7, the parameter α is shown to be half of the difference between induced tilts of adjoining sections of the subsidence profile. However, it was found that the correlation between calculated and measured strains improved by using the actual topography as a base, as opposed to using a hypothetical flat and level surface. The reason for this is shown in Figure 6.8.

The two subsidence profiles in Figure 6.8 have identical magnitudes of subsidence at corresponding positions. If both were constructed from level surfaces, they would be identical.

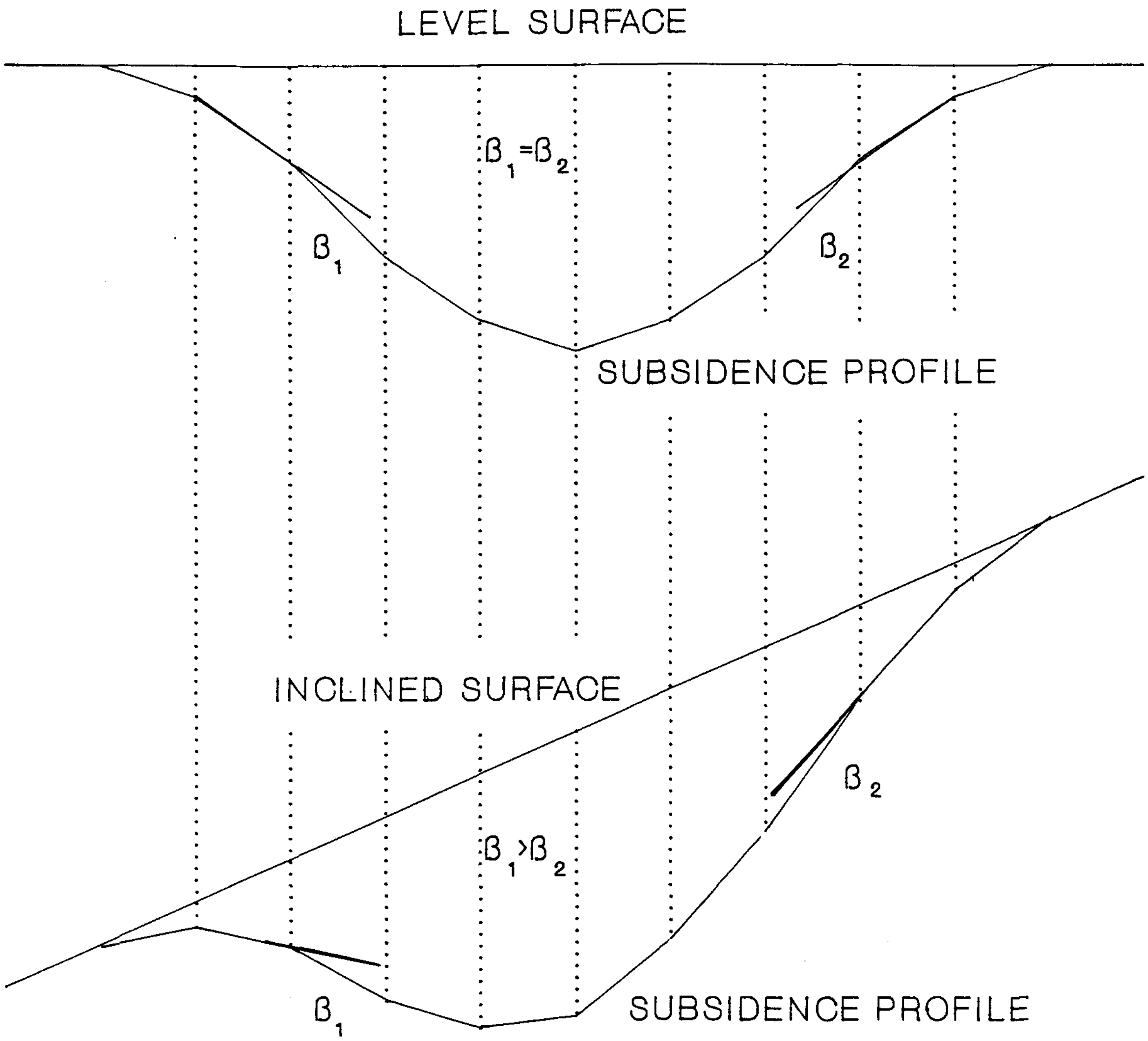

FIGURE 6.8 The effect of pre-mining topography on the subsidence profile. Although the two profiles have identical vertical subsidence at corresponding positions, the subsidence profiles are not identical. The diagram shows the effect of the pre-mining topography on the differential tilt angles, and consequently on the magnitudes of strain.

To illustrate the effects of the initial topography on strain, the bottom profile is constructed from an inclined surface, the inclination of which is exaggerated.

Strain has been shown to be directly proportional to differences in induced tilt between adjoining sections. The figure then indicates that when the initial surface is inclined, the induced strains are not equal to those using the level original surface at corresponding positions. Also, the strain profiles of the two half profiles are not symmetrical.

The parameter α is therefore defined as being half of the change brought about of the difference between the actual tilt angles of adjoining sections on the subsidence profile before and after subsidence.

(b) Validation of strain prediction method

In order to validate the proposed strain prediction method, the strains calculated from equations (6.9) and (6.10) were compared to measured strains over a wide range of conditions. It was also compared to a modified National Coal Board (now British Coal) (1975) method.

Comparison to measured strains

Nine profiles, chosen to represent the widest possible range of conditions, were selected for the comparison. "Measured" strains were calculated by comparing the distance between survey monuments after mining to those before mining. "Calculated" strains were calculated by applying equations (6.9) and (6.10) to the same profiles.

The results of the comparison are contained in Table 6.1. The table lists the correlation coefficients between measured and calculated strains and the slopes of the correlation curves.

A high correlation coefficient indicates a good linear relationship between compared parameters, while the slope of the correlation curve indicates the agreement in magnitudes. A correlation coefficient of 1 would thus indicate a perfect linear relationship, while the magnitudes of one data set may all be proportionally smaller or greater than those of the other data set. A slope of 1 would indicate that the magnitudes of the data are identical for all the pairs which are compared.

The table indicates that there is a good correlation between measured and calculated strains, even though widely different conditions existed at the selected sites. It also shows the variation in the slopes of the correlation curves, which is probably due to different stiffnesses of the upper rock and or soil layers.

Table 6.1: Correlation coefficients between measured and calculated strains, and the slopes of the correlation curves, for selected profiles.

Site	Correlation Coefficient	Slope of Correlation curve	Remarks
Sigma pillar extraction	0,88	1,29	Uneven profile
Sigma shallow longwall	0,84	1,11	Shallow mining
Sigma double seam	0,67	0,65	High magnitude of subsidence (2,5 m)
Secunda pipe line	0,6	0,41	Restricted subsidence (0,8 m)
Secunda conveyor 1	0,91	1,54	Across corner of trough
Secunda conveyor 2	0,65	1,17	Inconsistant panel width
Secunda longitudinal	0,91	1,40	Longitudinal section, 250 m wide panel
Road 1	0,88	1,05	Contained crush pillar
Road 2	0,79	0,77	No crush pillar

Comparison with modified National Coal Board (now British Coal) method

When the measured strains were compared to the National Coal Board (1975) method, they were found not to compare very well. However, when the constant 0,08 in the formula was replaced with 0,025, a significant improvement was noticed.

The formula then had the form:

$$\epsilon = \sqrt{\frac{0,025\Delta T}{l}}, \qquad (6.11)$$

where

ΔT = difference in induced tilts of adjoining sections and
l = bay length.

Comparisons of the correlation coefficients of measured to calculated strains for the National Coal Board (1975) method and equations (6.9) and (6.10) are shown in Table 6.2. The same data which was used for Table 6.1 was used for the calculated strains, and the same profiles as contained in Table 6.1 were selected.

Table 6.2: Comparison of correlation coefficients and slopes of correlation curves between measured and calculated strains, using the National Coal Board (1975) method and equations (6.9) and (6.10)

Site	Eqns (6.9) & (6.10)		National Coal Board	
	Correlation Coefficient	Slope	Correlation Coefficient	Slope
Sigma pillar extraction	0,88	1,29	0,91	0,58
Sigma shallow longwall	0,84	1,11	0,8	0,59
Sigma double seam	0,67	0,65	0,7	0,42
Secunda pipe line	0,6	0,41	0,56	0,55
Secunda conveyor 1	0,91	1,54	0,88	1,07
Secunda conveyor 2	0,65	1,17	0,67	1,35
Secunda longitudinal	0,91	1,40	0,88	0,98
Road 1	0,88	1,05	0,93	2,25
Road 2	0,79	0,77	0,81	1,44

Table 6.2 shows that in both cases, good correlations were found with measured strains, the averages for both being 0,79. The difference between the two methods are found in the slopes of the correlation curves, which indicate the ratio of the magnitudes of measured to calculated strains.

For equations (6.9) and (6.10), the average of the slopes is 1,04 while it is 1,03 for the National Coal Board method. The former method, however, is more consistant. The standard deviation of the slopes is 0,37 (or 36% of the average) for equations (6.9) and (6.10) while it is 0,59 (or 57% of the average) for the National Coal Board method.

Two conclusions can be reached from the foregoing. Firstly, the principle of relating strain to the severity of bending is correct. Secondly, equations (6.9) and (6.10) will predict the magnitudes of strains better more frequently than will the National Coal Board method.

6.6 SUMMARY AND CONCLUSIONS

6.6.1 Comparison with other subsidence prediction models.

The magnitudes of S_m, T_m and ϵ_m are in fair agreement with the results obtained by Holla (1986) for the NSW Coalfield in Australia. It also agrees reasonably well with the results published by Wagner and Schümann (1985) for South Africa.

An alternative approach to strain prediction, based on first principles, was developed. It was found to correlate well with observed strains as well as the British Coal predicition when applied to observed subsidence profiles. The proposed method was shown to yield accurate magnitudes of strain more consistantly in unknown areas.

6.6.2 Dolerite failure.

It was shown that the formula by Galvin (1983), for predicting the panel width at which the dolerite sill should fail, is not valid for the conditions prevailing in the study area. An alternative formula was developed and shown to be better suited to that area, which includes a wider range of conditions than that on which the Galvin formula is based.

6.6.3 Summary of prediction model

The conclusions of the previous paragraphs can now be summarised to form a complete subsidence prediction model for the study area. It can be broken down into the following steps:

(a) Maximum Subsidence

$S_m = 0{,}39h\ (W/H)^{0{,}32}$,

(b) Maximum Tilt:

$T_m = 21,6\ S_m + 7,$

(c) Maximum Tensile Strain

$\epsilon_{m+} = 4,2\ s_m + 1,7,$

(d) Maximum Compressive Strain

$\epsilon_{m-} = -9,1\ S_m - 2,8,$

(e) Subsidence at any point on the subsidence profile:

$S = 0,5S_m\ [\tanh\ (7x/W - 1,645) + 1],$

(f) Tilt along the subsidence profile:

$$T = \frac{S_1 - S_2}{\Delta x},$$

(g) Strain along the subsidence profile:

$$\epsilon_+ = \frac{4,7\ \tan\alpha}{\Delta x}.$$

$$\epsilon_- = \frac{-3,5\ \tan\alpha}{\Delta x}$$

6.6.4 Significance of the prediction model

The application of the model described in 6.6.3 will enable the subsidence engineer to take the first step in predicting the effects of subsidence on a structure, which is to predict subsidence and its related elements. Without this first step, no sound decisions regarding the undermining of structures with high extraction methods can be made.

Based on the prediction of the subsidence elements, an estimate of the likely damage to various types of structures, as described in the following chapters, can be made. This then means that decisions regarding steps to prevent damage, if deemed necessary, can be made - as can estimates of repair work and the associated costs. Therefore, decisions regarding the undermining of structures can then be taken based on the considerations of safety risk and economics.

6.6.5 Restrictions of the prediction method

As the method was derived empirically, it will only be valid for the Sasolburg and Secunda areas and areas with similar geological and geometrical features. Strain prediction is primarily based on the geometry of the subsidence profile, and as such may be more universally applied once that shape is known. However, local knowledge of the magnitudes of parameters t and t_1, relating to the thickness of compressible layers on the surface, is also required.

Furthermore, as the method yields a two dimensional profile, it is bound by the same restrictions as any other profile method. It is thus only valid for areas far enough from the beginning and end positions of subsidence troughs not to be influenced by them.

Although the model only predicts the two-dimensional profile and the elements associated therewith, it is a valid tool as it represents the worst case.

7 THE EFFECTS OF SUBSIDENCE ON A BITUMINIZED ROAD AND MEASURES TO REDUCE THE SEVERITY OF DAMAGE

7.1 INTRODUCTION

7.1.1 Background

Of all the structures undermined experimentally during the course of the study, roads were by far the most sensitive from a statutory point of view. There are several good reasons for this.

Provincial roads in the Transvaal province are under the protection of custodians, the Transvaal Provincial Administration (TPA), who are remote from mining and were never explicitly informed about coal mining induced subsidence. After having provided the roads in the first place to stimulate the economy, the Provincial authorities are charged with the protection of the roads, to ensure both the safety and the comfort of road users.

South Africa has by no means a good road safety record. It is understandable that any action which may result in dangerous deterioration of the physical condition of the road, would be approached with great apprehension by the Provincial authorities.

Furthermore, before the experiment virtually nothing was known about the possible effects of subsidence on a bituminized road.

While a subsidence profile could be predicted rather accurately by using previous experience gained in the vicinity of the road, the effects of induced strains on the artificially constructed road surface were unknown. Broadly speaking, the serviceability of a road could be impaired by two factors: induced strain could damage the road surface and induced titlt could alter the vertical alignment of the road to such an extent that it no longer conforms to the standard required for the designed permissible traffic speed.

The road under consideration was the provincial bituminized road number P185/1, running from Kinross in the North to Standerton in the South, as shown in Figure 7.1. Due to the reasons stated before, a deviation beyond the perimeter of the underground panel was provided to accommodate traffic during the undermining of the main road.

Subsequent to the first undermining, both the main road and the deviation were undermined on two further occasions. No road was ever under traffic during undermining. This was achieved by shuttling traffic between the main road and the deviation. The sequence of mining and the layout of the underground panels relative to the road are shown in Figure 7.2.

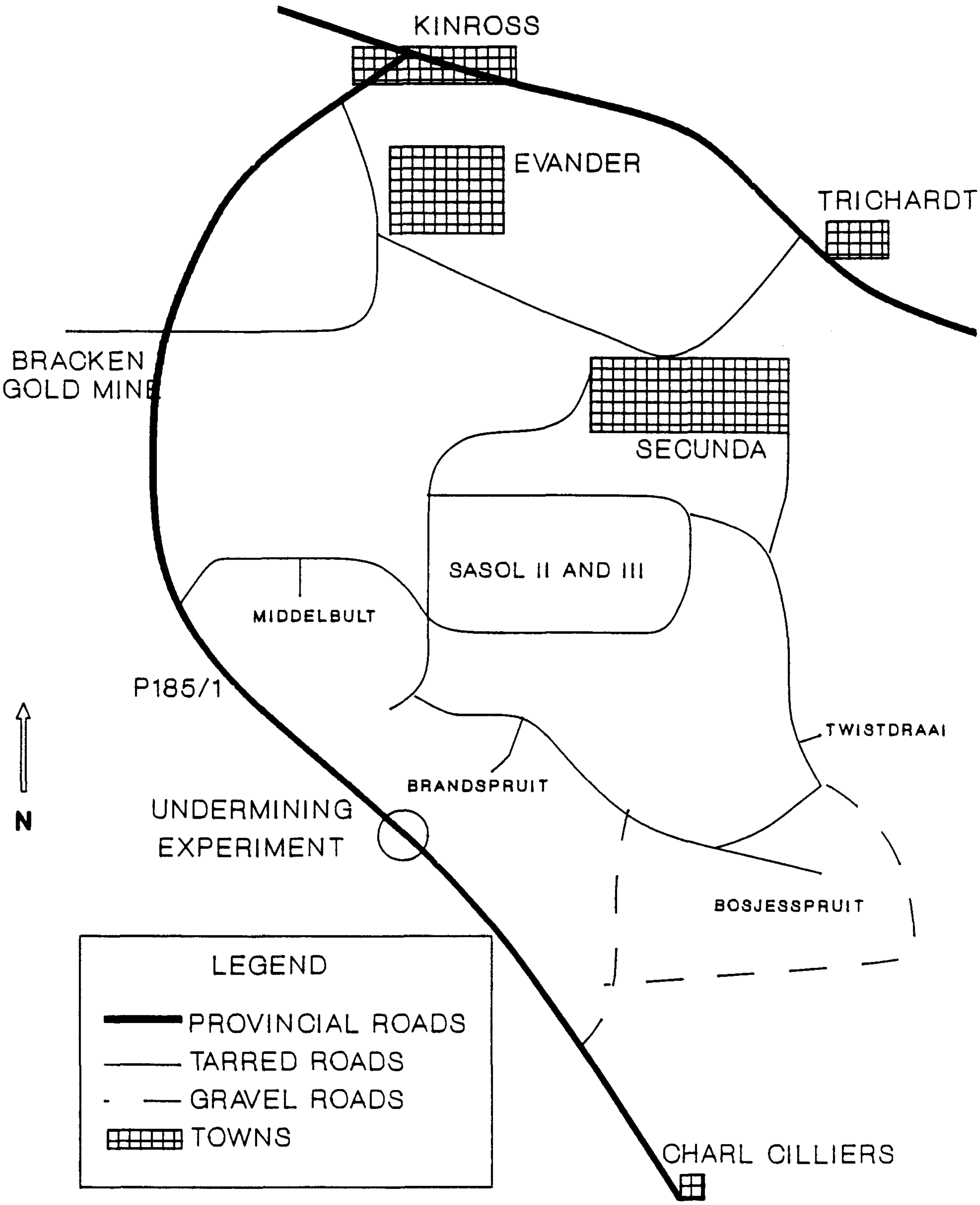

Figure 7.1 Locality map showing the position of the road undermining.

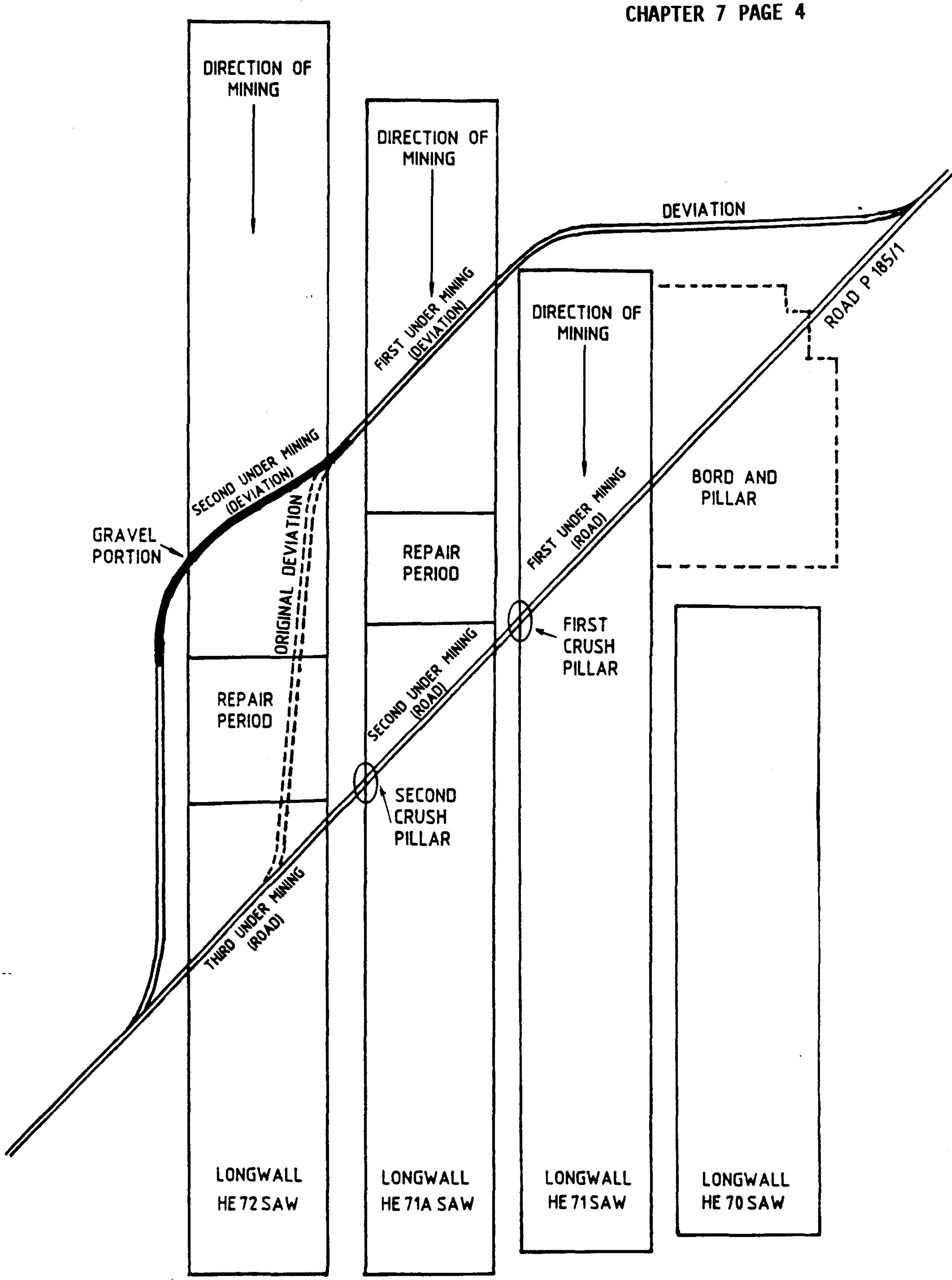

FIGURE 7.2: Diagram showing the locality of the road and the deviation relative to the underground panels, and the sequence of undermining.

Detailed monitoring was carried out by the Division of Roads and Transport Technology of the Council for Scientific and Industrial Research (CSIR), the Chamber of Mines Reasearch Organisation (COMRO) and Sasol. The Department of Mineral and Energy Affairs and the Branch: Roads of the TPA were informed of progress, and inspected the experimental area at selected times.

7.1.2 Objectives

The main objective of the undermining experiment was to find a method or methods whereby the coal underneath a road could be totally extracted safely and economically. The main objective was sub divided into three sub-objectives, namely:

(a) to determine the effects of subsidence on a bituminized road;
(b) to find means of reducing whatever harmful effects were found by adapting the mining method (longwall); and
(c) to find means of constructing a road to accommodate the effects of subsidence.

7.1.3 Requirements

STATUTORY REQUIREMENTS

Initially, the main requirement set by the Government Mining Engineer for exemption from Regulation 5.3 of the Mines and

Works Act No. 27 of 1956, which prohibits the undermining of structures, was that no traffic shall be allowed on the road until such time as the road had been proven to have stabilized and that afterwards the road shall be repaired to the satisfaction of the Roads Division of the TPA. The deviation had to be built to standards set by the TPA, who basically required a bituminized deviation with curves designed to accommodate traffic at a maximum speed of 80 km per hour.

Later, when permission was sought to mine a further two panels underneath the road, a further requirement was set:

As no absolute guarantee could be supplied that the inter panel pillars between longwall panels would be stable ad infinitum, they had to be removed. No pillars were allowed to be left underneath the road. As will be shown, this requirement posed serious problems to the underground mining operations and perhaps introduced greater risk to the stability of the road than leaving an intact inter panel pillar would have.

TECHNICAL REQUIREMENTS

Technically, for a road to be considered serviceable the road surface has to conform to a certain minimum degree of comfort as expressed by the Drivability Index, and the vertical alignment has to conform to certain standards laid down for various classes of road. Furthermore, the condition of the road foundation has to be such that it can sustain traffic using that road.

The Drivability Index is often expressed in PSI units, which are obtained by driving an instrumented vehicle over the road at a predetermined constant speed. For bituminized roads of the class which was undermined, the scale varies from >2,5 (sound) to <2 (Severe), according to the National Institute of Transport and Roads Research (1984).

For gravel roads, a different scale, measured in QI (Quarter-car Index) units is usually used. According to Paige-Green and Netterberg (1988), QI values of 0 - 40 can be considered as excellent while >200 is unacceptably poor at 80 km/hr. Netterberg (1991) stated that at 50 km/hr, somewhat higher values (respectively 0 - 50 and >250) can be used.

The strength of the road foundation is determined by measuring the energy required to drive an inverted cone into the road to a predetermined depth. The test is commonly referred to as a Dynamic Cone Penetrometer (DCP) test.

7.1.4 Duration of the project

The first undermining commenced in February, 1984, and the last undermining ended in December, 1986. Allowing for final settlement of the road and final repairs, the rehabilitated road was finally reopened to traffic in January, 1989.

7.2 DATA GATHERING

Subsidence data was gathered and analysed by following the procedures set out in Chapter 5. On each occasion, a set of observations on the road was complemented by a control set in the veld next to the road.

On each occasion, a zero measurement was obtained by determining the arithmetic mean of two consecutive surveys taken at a time when the face was at least 50 m away from the road. Thereafter, measurements were taken at weekly intervals until such time as the first subsidence occurred. The measuring frequency was then increased to daily observations (Saturdays and Sundays excluded) until the rate of subsidence decreased. Then the schedule returned to weekly surveys for one month and finally to monthly surveys until the time when the monuments were destroyed by road repairs. Whatever monuments remained accessible, were and will continue to be monitored at annual intervals in an attempt to determine the long term behaviour of the road.

The procedure as described in Chapter 5 was only developed in 1985, and consequently the data, gathered prior to 1985, i.e. the first main road undermining, was analysed according to the two dimensional profile approach and not according to the SEA approach. Unfortunately, the data was not gathered in a manner which could allow SEA analysis. Therefore, the derived elements, tilt and strain, are not directly comparable. In the traditionally analysed case these parameters were obtained for a direction parallel to the road, which was at 45° to the long axis of the panel. These results are thus unfortunately not directly comparable to most other subsidence analyses. Detailed observations at the first undermining were published by Schümann (1988).

Observations relating to the reaction of the road to subsidence, were carried out by the CSIR and subsequently published in summarised form by Netterberg (1988). The observations consisted primarily of investigations of the road pavement before and after undermining, visual observations and the determination of Drivability Indices by means of an instrumented vehicle.

7.3 MINING LAYOUTS AND GEOLOGICAL STRUCTURE

7.3.1 Mining layouts

The three panels involved in the undermining had the dimensions indicated in Table 7.3.1.

Table 7.1: Dimensions of the longwall panels which undermined Road P185/1.

PANEL	WIDTH (m)		MINING HEIGHT (m)	DEPTH (m)	
	MAIN ROAD	DEVIATION		MAIN ROAD	DEVIATION
HE 71 SAW	172	-	3	120	-
HE 71A SAW	197	181	3	124	121
HE 72 SAW	225	194	3	126	126

7.3.2 Geological structure

A generalised stratigraphic section for the area is shown in Figure 7.3. There was only insignificant variation in the geological structure overlying the coal seam. As Figure 7.3 indicates, 84% of the overburden rock consisted of sandstone. The 11 m thick dolerite sill did not play a significant role in the subsidence process.

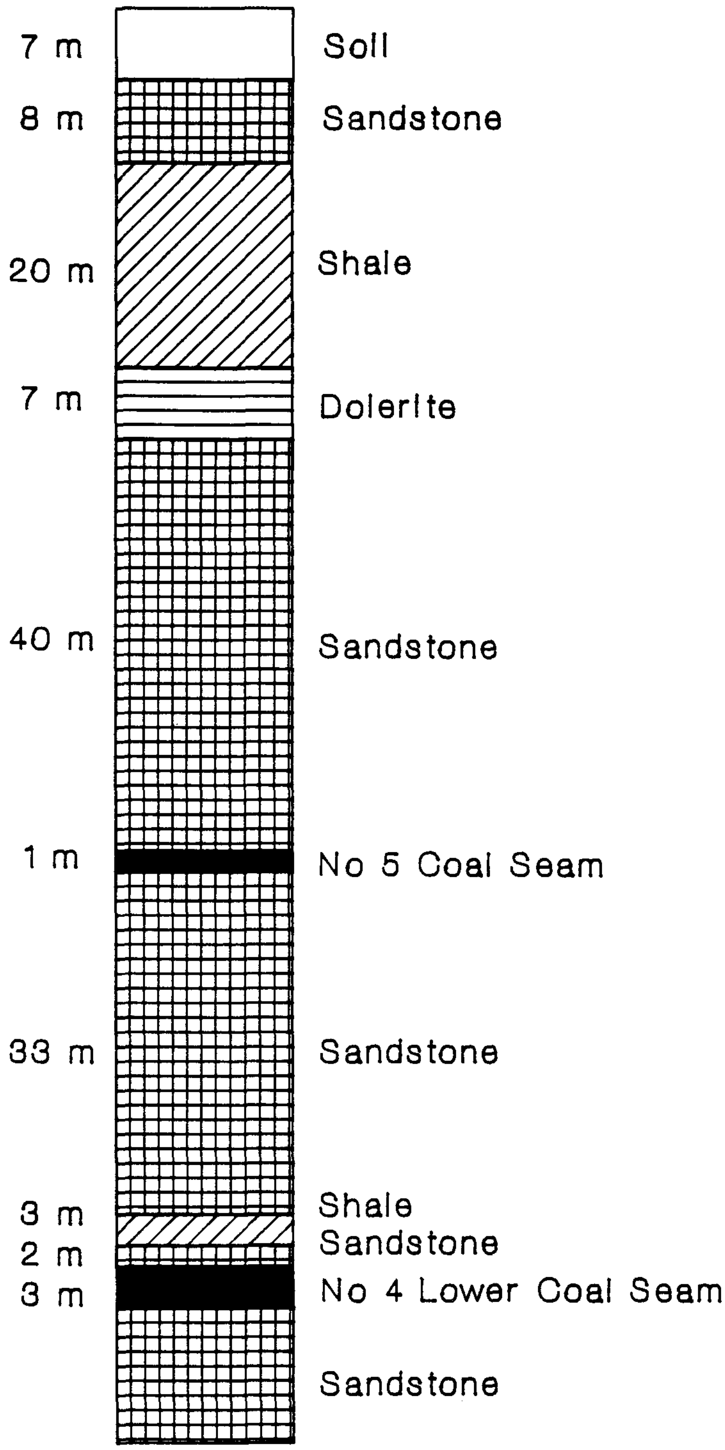

Figure 7.3 Simplified stratigraphy of the road undermining site. The dolerite sill was too thin to influence the subsidence characteristics.

7.4 EFFECTS OF SUBSIDENCE ON AN UNTREATED BITUMINIZED ROAD

7.4.1 General overview

The first undermining of the road yielded sufficient information to satisfy the requirements of the first sub aim of the project, namely to determine the effects of subsidence on the road. Essentially, it was learnt that under the prevailing conditions, compressive strains resulted in damage so severe as to render the road unserviceable.

The further underminings of the road saw two major innovations: the provision of strain relief slots across the road and the implementation of crush pillars between adjacent longwall panels underground. These innovations were aimed at the remaining two sub aims of the project, namely to find means of road construction and mining methods to alleviate the harmful effects of subsidence on the road.

7.4.2 Description of observations

As described by Schümann (1988) and Netterberg (1988) the portion of road involved in the first undermining was severely damaged. Compressive ridges developed across the road in a number of localities. The largest one was approximately 100 mm high with a base of approximately 1 m and is shown in Plate 1, Chapter 5. Severe cracking of the road surface occurred. The cracks varied in width, from 1 mm or less to approximately 40 mm. The crack spacings varied from 1 to 4 m and their directions from transverse to diagonal across the road.

A detailed description of the subsidence elements is given by Schümann (1988). He found that the maximum vertical subsidence was 1,27 m, or 42% of the mining height. The maximum compressive strain was -7,9 mm/m in the longitudinal direction and -2,4 mm/m in the transverse direction. The maximum tensile strains were 7 mm/m and 6 mm/m in the longitudinal and transverse directions respectively. Note that these are not principal strains. Maximum induced tilts were calculated and found to be 28 mm/m and 36 mm/m respectively for the two sides of the profile.

7.4.3 Conclusions

Although cracking of the road surface was the most common damage, the compressive ridges were considered to be the most serious. Whereas cracks in a road can be repaired fairly easily, the ridges had to be dug out and refilled even for temporary repairs. This was both expensive and time consuming, resulting in a longer period during which the road was unserviceable.

Having then learnt that under the stated conditions subsidence resulted in severe damage to the road, meaning that a bituminized road under the study conditions could not safely be under traffic while being undermined, the attention focussed on the remaining two objectives of the project. These dealt respectively with finding means of road construction and underground layouts which would minimise the adverse effects of subsidence.

These conclusions were confirmed by further underminings of a disused strip of bituminized road in the same vicinity, by rib pillar extraction. The said underminings were not monitored. According to visual inspections, however, the vertical subsidence of estimated 1-1,5 m was again accompanied by compression ridges, as shown in Plate 3.

7.5 THE DESIGN AND IMPLEMENTATION OF A CRUSH PILLAR

7.5.1 Background

The crush pillar experiment was aimed at the second sub objective of the project, namely to find means whereby adaptation to mining methods could alleviate the effects of subsidence on a road.

PLATE 3 A compressive ridge which formed on an unused section of a tarred road.

Solid inter panel pillars between adjacent longwall panels, while serving a most useful purpose underground, have the detrimental effect on surface of forming humps between adjoining subsidence troughs. When road P185/1 was to be undermined by Longwall Section 64 of Brandspruit Colliery, the humps on surface were not seen as the major problem caused by the solid pillar, as this could be overcome by cutting through the humps to obtain a suitable vertical alignment for the road.

Rather, the problem was that the Transvaal Roads Department could not be convinced that the pillars would be stable forever. It was feared that failure of the pillars at a later stage could result in secondary subsidence of portions of the road. This attitude evoked some controversy, as there was no objection to the bord and pillar undermining of the same road in the area immediately adjoining the longwall mining.

Permission to undermine the road was then granted by the Government Mining Engineer on condition that no inter panel pillars were left underneath the road. As it was considered impractical and dangerous to mine out the inter panel pillar completely, the option of mining out the pillar partially and leaving a crush pillar behind was adopted.

The crush pillar had to conform to two main requirements: at the face position, it had to be stable - for reasons of safety - and

10 m behind the face, it had to be in a failed state. If the pillar was still solid 10 m behind the face, there was a distinct possibility that lateral goaf pressure on the pillar could strengthen the pillar to such an extent that failure would be delayed to an unknown time or even prevented altogether.

7.5.2 Design procedure

At the time, no analytical method which could yield all the answers required was available. Therefore, a combination of analytical methods and comparative visual observations had to be followed.

It was estimated that an eventual pillar safety factor of 0,5 or less would be required to ensure pillar failure. The pillar safety factor could be obtained by calculating the pillar load for an isolated pillar with an overhanging overburden, as shown in Figure 7.4. The pillar strength could be obtained by using the well known formula of Salamon and Munro (1967):

$$S = 7{,}2 \frac{w^{0,46}}{h^{0,66}} \text{ MPa} \qquad (7.1)$$

In equation (7.1), the term "w" refers to the width of square pillars. As these pillars were rectangular, the width was estimated according to the suggestion made by Wagner (1980), i.e. by dividing four times the cross sectional area of the pillar by its circumference.

Therefore, obtaining the safety factor (strength divided by load) was a simple matter.

Determining the height of the pillar for use in the formula required some consideration, as the "pillar" as shown in Figure 7.4 was no longer a structure with a well defined geometry, but in fact a structure some 120 m high. One part of that entire structure was the loading system, and the rest could be considered as the pillar on which the load was imposed. The coal portion was considered to be the "pillar", as it represented the weakest part of the structure.

In calculating the load, the angle of overhang in Figure 7.4, β, was clearly of prime importance. Figure 7.5 shows safety factors for different pillar widths at various angles of overhang. The sensitivity of the system to variations of β is clearly seen.

Observations of surface subsidence profiles relative to underground workings, indicated that an angle of 15° for β would be a realistic value. From Figure 7.5, it is seen that a safety factor of 0,4 for an overhang of 15° would require a 6 m wide pillar.

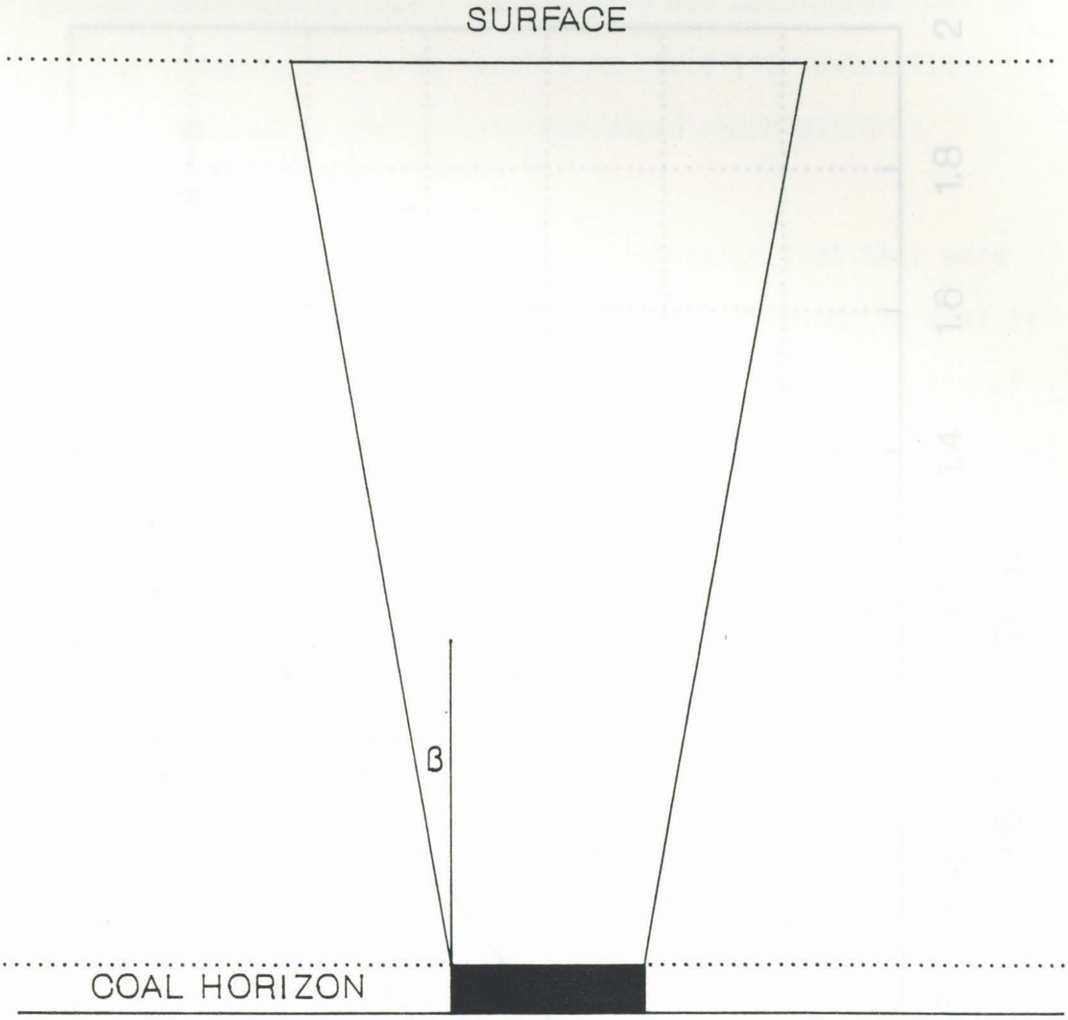

Figure 7.4 Simplified section through an isolated pillar, with total extraction on either side. The sides of the column are assumed to have no contact with the surrounding rock mass and are thus stress free.

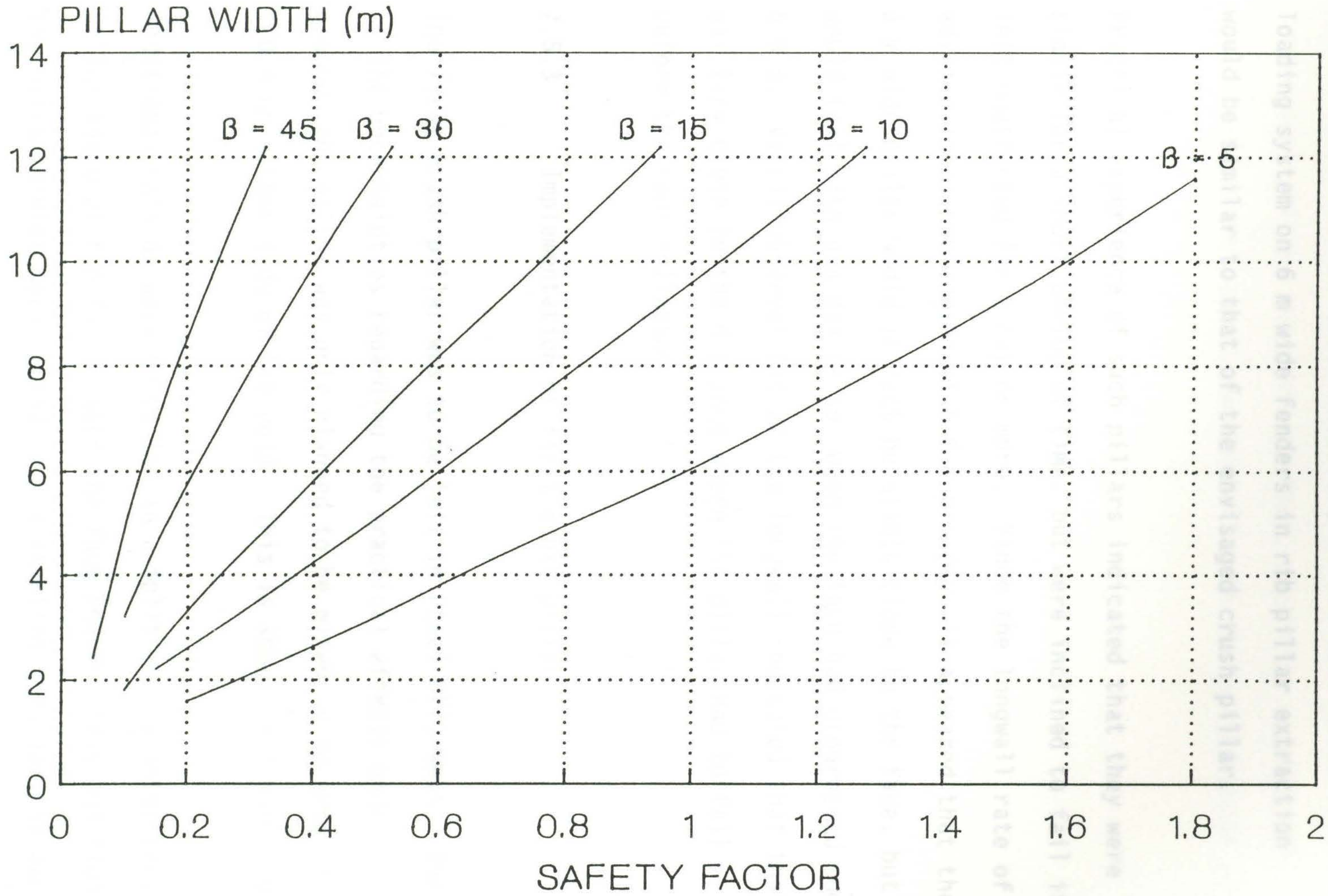

Figure 7.5 Safety Factors vs Pillar Sizes for various angles of overhang.

To evaluate the stability of a 6 m wide pillar in the area near the face, where it had to be stable, available analytical methods could not be used. However, it was considered that the loading system on 6 m wide fenders in rib pillar extraction would be similar to that of the envisaged crush pillar.

Practical experience of such pillars indicated that they were stable for a short period of time, but were inclined to fail if left unattended for a day or more. Since the longwall rate of advance is in the region of 6-8 m per day, it appeared that the 6 m wide pillar would in fact be stable close to the face, but would fail within a day or so, when the face had progressed some 6-8 m. Visual observations at the longwall indicated that that was very close to the distance where the pillar had to fail before the roof collapsed.

7.5.3 Implementation of first crush pillar

The first crush pillar was to be left in Panel HE71 West. Due to the uncertainties regarding the practical effects underground, the pillar was only planned to be mined in an area of 100 m on either side of the road. This is shown in Figure 7.6.

Additional shields were installed in a split in the inter panel pillar ahead of the face. When the face reached this position, the extra shields were linked to the existing ones and the pan line was extended. The entire installation was then long enough to increase the face length so that all but 6 m of the inter panel pillar could be extracted. To prevent failure of the inter panel pillars ahead of the face, each time a split was approached, stick support was installed in the splits ahead of the face.

7.5.4 Observations at the first crush pillar

The first crush pillar behaved satisfactorily. Visual observations underground indicated that it was stable at the face position, but appeared to be failing immediately behind the shields. Surface subsidence measurements also indicated that the pillar crushed and that the desired effect was achieved on surface. Figure 7.7 shows the effect of the crush pillar on the topography. The area of the road above the pillar subsided by 0,7 m, as compared to 1,2 m elsewhere. The "subsidence loss" of 0,5 m is attributed to the fact that even though the pillar failed, the crushed material was not removed but remained in place.

7.5.5 Implementation of the second crush pillar

The crush pillar implementation at Panel HE72 West was more complex than the first one, due to two factors. Firstly, the three road development resulted in a double set of chain

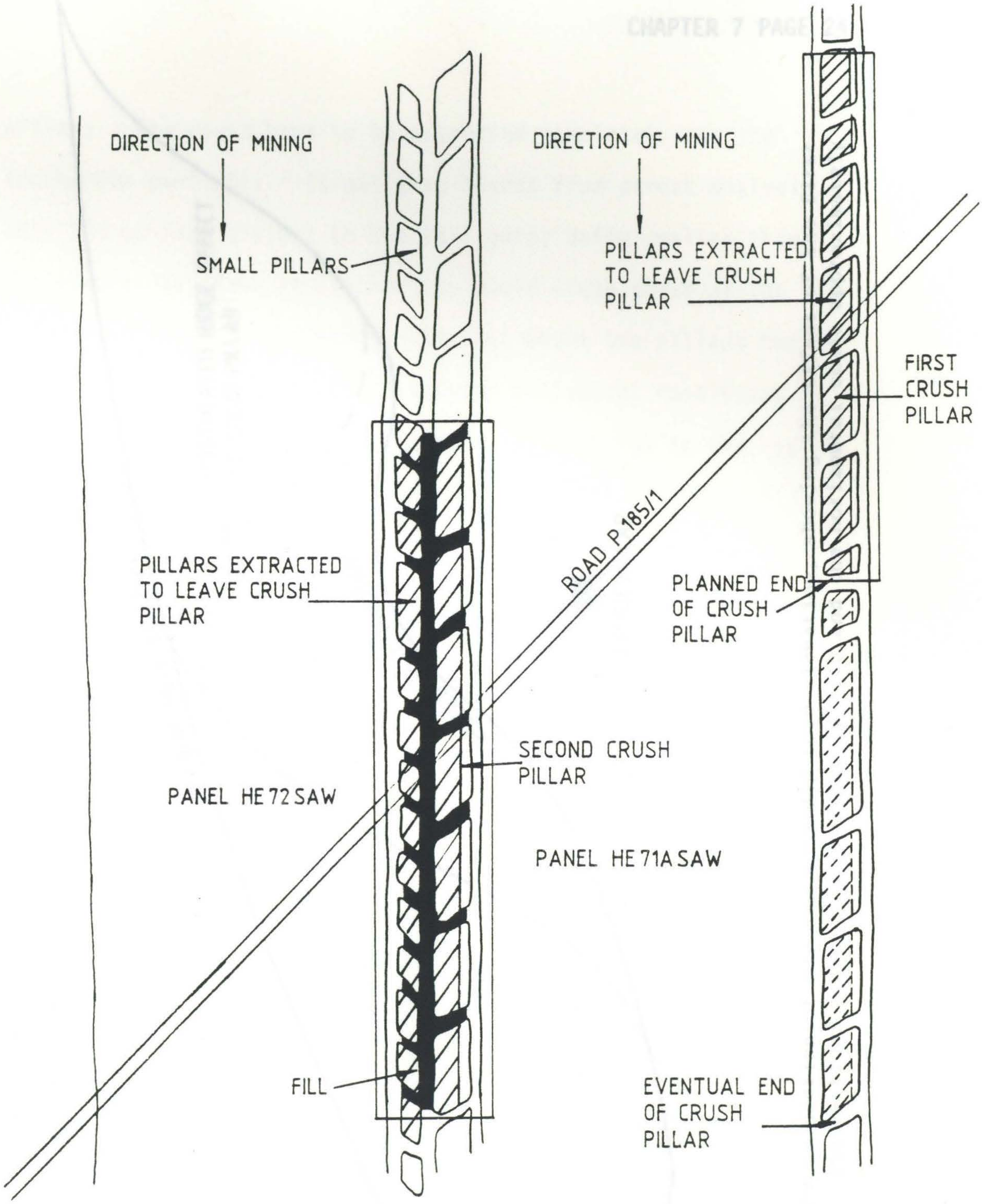

FIGURE 7.6: Localities of the two crush pillars relative to the road position. The first crush pillar had to be extended, as adverse geological conditions prohibited stopping the longwall face to extract the additional shields used for cutting the pillars.

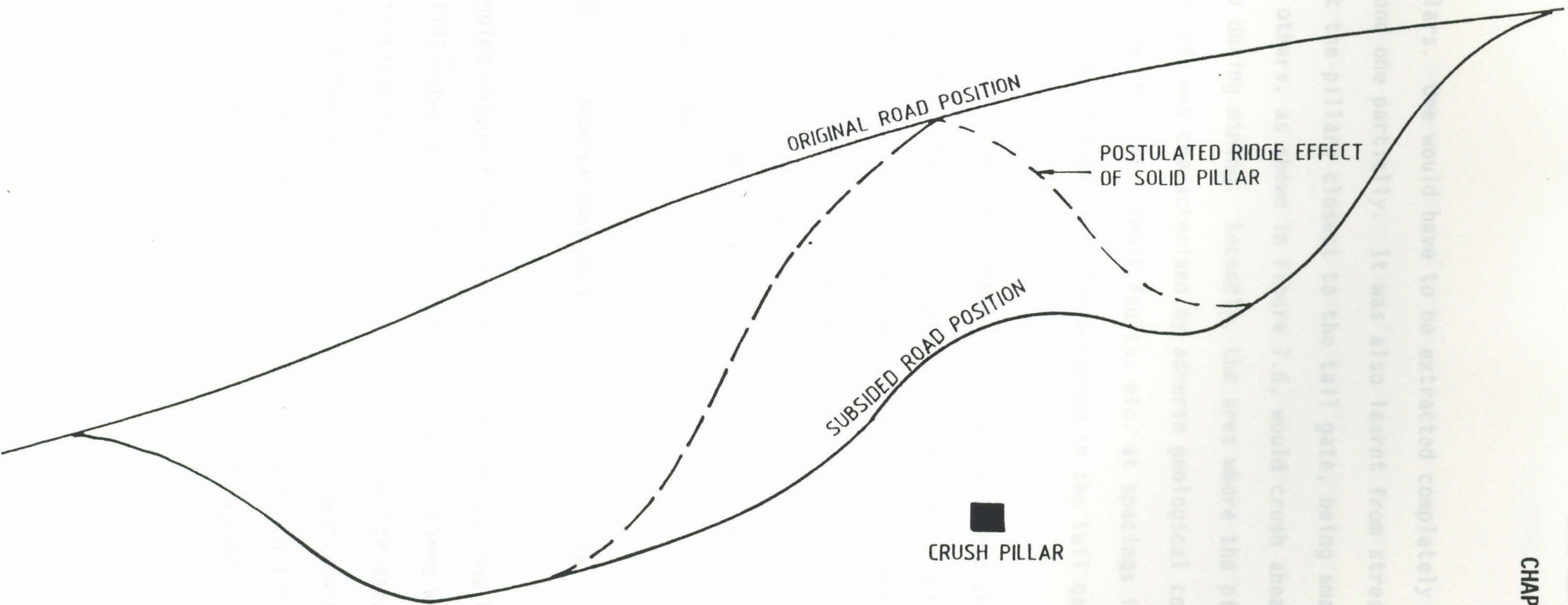

FIGURE 7.7: Smoothed out Cross section of old and subsided road elevation, showing the effect of the first crush pillar. The vertical scale is approximately 1:40 and the horizontal scale approximately 1:1400.

pillars. One would have to be extracted completely and the second one partially. It was also learnt from stress analysis that the pillars closest to the tail gate, being smaller than the others, as shown in Figure 7.6, would crush ahead of the face during mining. Secondly, the area where the pillars had to be mined, was characterised by adverse geological conditions in the form of joints, small faults, etc. at spacings in the region of 1 m. Roof falls had also occurred in the tail gate.

In the light of these problems, it was considered unwise to mine the pillars in that area. Instead, it was decided to fill the tail gate companion and all the splits in the area to form a very large artificial pillar which could be partially extracted safely. Following the filling operation, the now combined pillar was partially extracted in the same fashion as on the first occasion.

7.5.6 Observations at the second crush pillar

A problem unique to the second crush pillar was the hardness of the fill material. Due to time constraints, there was insufficient time to allow full hardening of the ash/cement mixture before mining was to take place. The mixture was then strengthened by the addition of cement, to reach the required strength (5-8 MPa) at the time when mining was estimated to take place. However, the geological discontinuities, observed in the tail gate, extended into the face and mining progressed at a slower rate than anticipated. The fill then became harder than required, and difficult cutting conditions were encountered. Plate 4 shows the fill material in place underground, during its extraction.

A second, minor, problem was the difficulty in precise control of the crush pillar width. An uneven or bent face meant that more shields were required on the face and a shorter length was then available to cut into the pillars at the tail gate end. Consequently, the crush pillar was sometimes slightly wider than anticipated. Reference to Figure 7.5 indicates that this is not a serious problem, as even a pillar of more than 10 m wide still resulted in a safety factor of less then 0,8.

At the second crush pillar, both underground observations and subsidence measurements indicated that the pillar failed satisfactorily. The subsidence profile is shown in Figure 7.8.

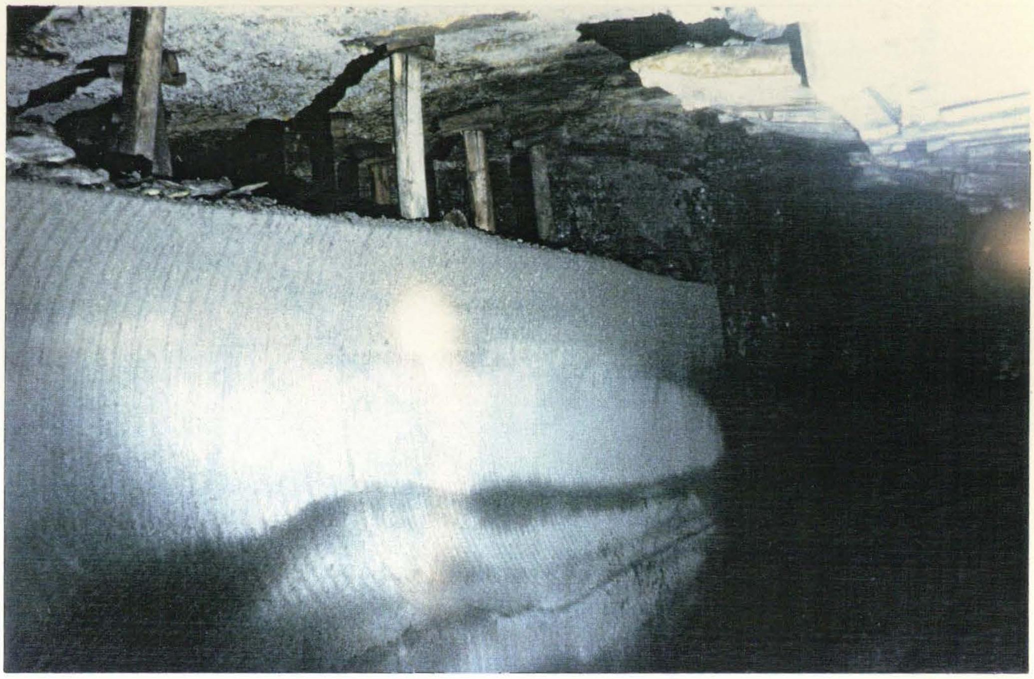

PLATE 4 The fill material which was placed in the roads before mining to stabilize the area, shown here during the mining operation.

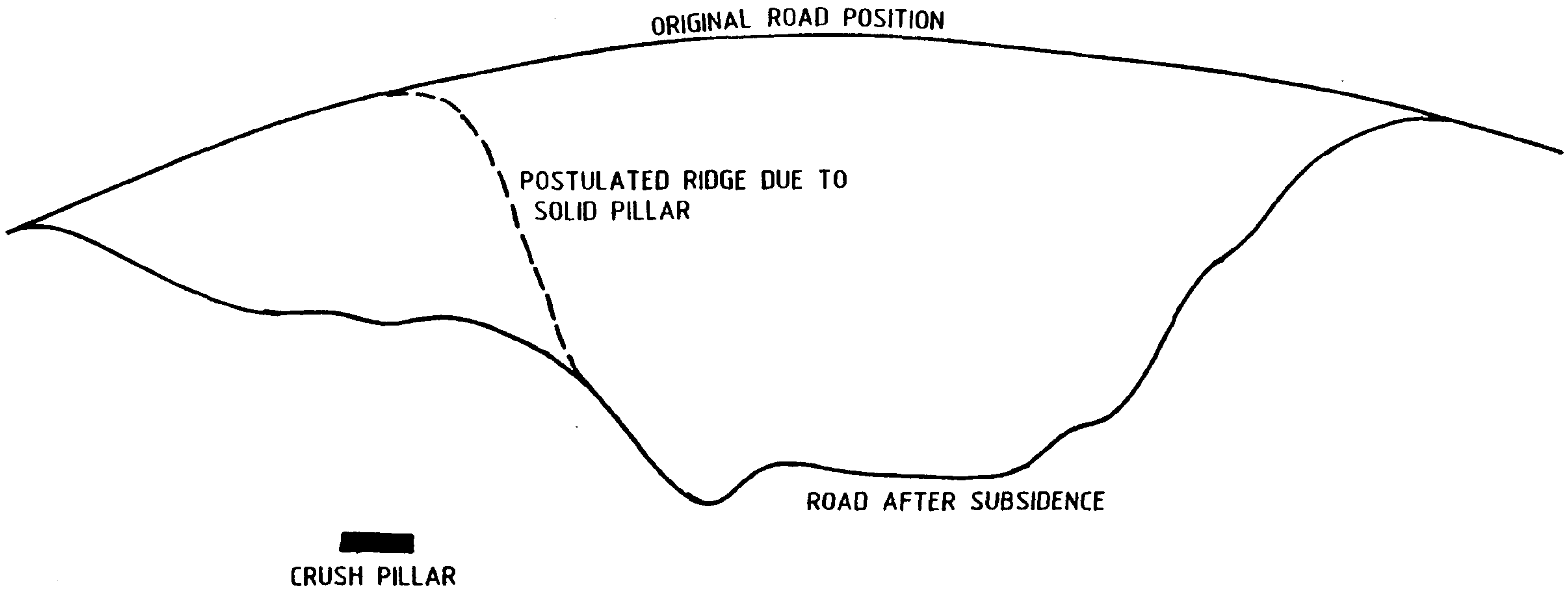

FIGURE 7.8: Original and new road position after subsidence, showing the effect of the second crush pillar. The horizontal scale is approximately 1:2200 and the vertical scale 1:22

7.6 ANALYSIS OF SUBSIDENCE ON ROAD FITTED WITH COMPRESSION RELIEF SLOTS AND WITH A CRUSH PILLAR UNDERNEATH

7.6.1 Background

Having observed that compressive ridging occurred on the road during undermining, and realising that the reason for the ridging was due to the relative incompressibility of the paving material, it was attempted to accommodate the compressive strains by the provision of compression relief slots on the road. The initial idea was to cut thin slots through the road foundation, say 25 mm wide, and fill them with a compressible material such as bitumen.

As the road foundation was usually some 500 mm thick (up to 1 m in places), and no equipment could be found which could cut a thin slot to that depth, it was decided to provide whatever slots could be cut in an attempt to prove the validity of the concept. The initial trials were done on the tarred road deviation, with positive results. It was found that no compressive ridging took place and measurements indicated that the slots had in fact closed up.

The results which are presented in this section were obtained at a repetition of the experiment. The site was the final undermining of the main road, where, by virtue of the dome like topography, shown in Figure 7.8, greater magnitudes of compressive strain were expected than on the previous occasions. The configuration of the slots is shown in Figure 7.9. Slot dimensions were 300 mm wide by 500 mm deep.

To facilitate the SEA analysis, additional survey monuments were installed to form grids as described in Chapter 5. A grid was also installed in the veld next to the road. The slot behaviour was monitored by measuring the distances between pegs installed on either side of the slots, as shown in Figure 7.10.

Figure 7.11 shows the area which was monitored relative to the underground panel. On the Northern side, the monitoring was extended to include the area where movement was anticipated due to the crushing of the crush pillar.

Detailed survey monitoring commenced on 16 July 1986 and continued through to 26 January 1987. The panel passed underneath the road from 25 August 1986 to 20 December 1986. The slow rate of advance was due to geological difficulties and the hardness of the fill material. A number of elevation checks to determine longer term subsidence was done at irregular intervals until August 1988.

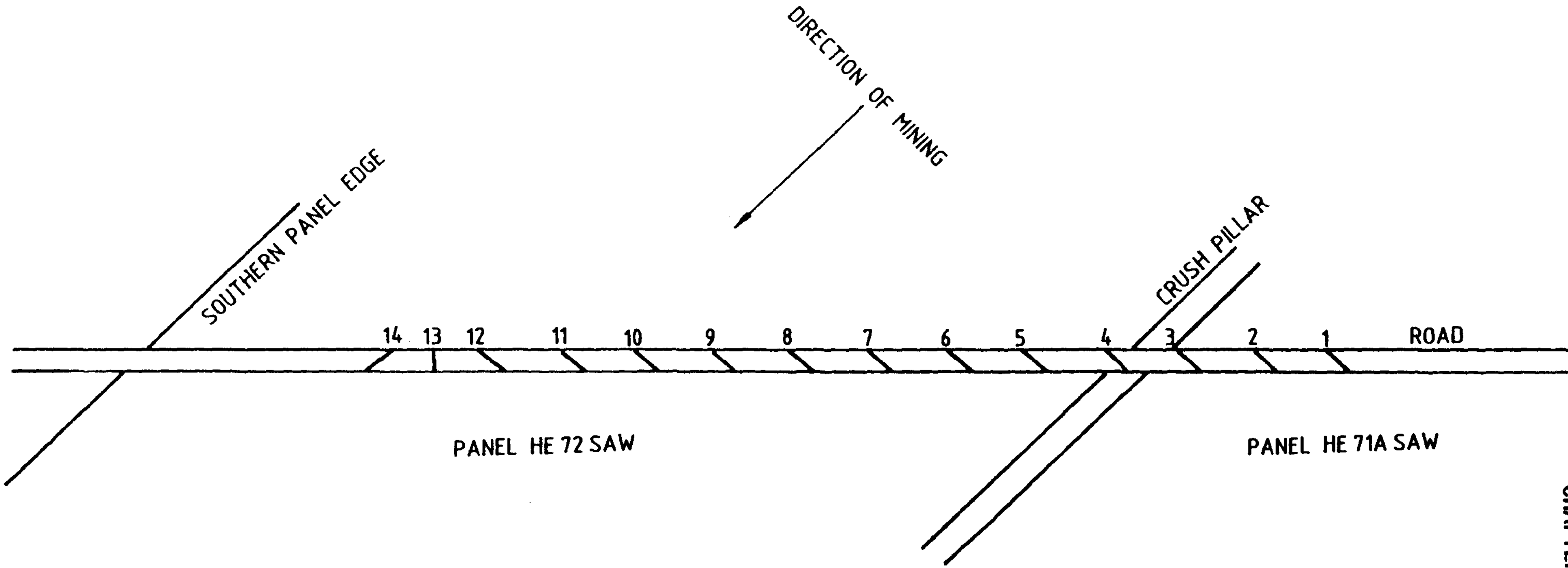

FIGURE 7.9: Detail of the slot layout. The slots were 300 mm wide, and cut to a depth equal to the road foundation thickness, i.e. 300 mm - 500 mm deep.

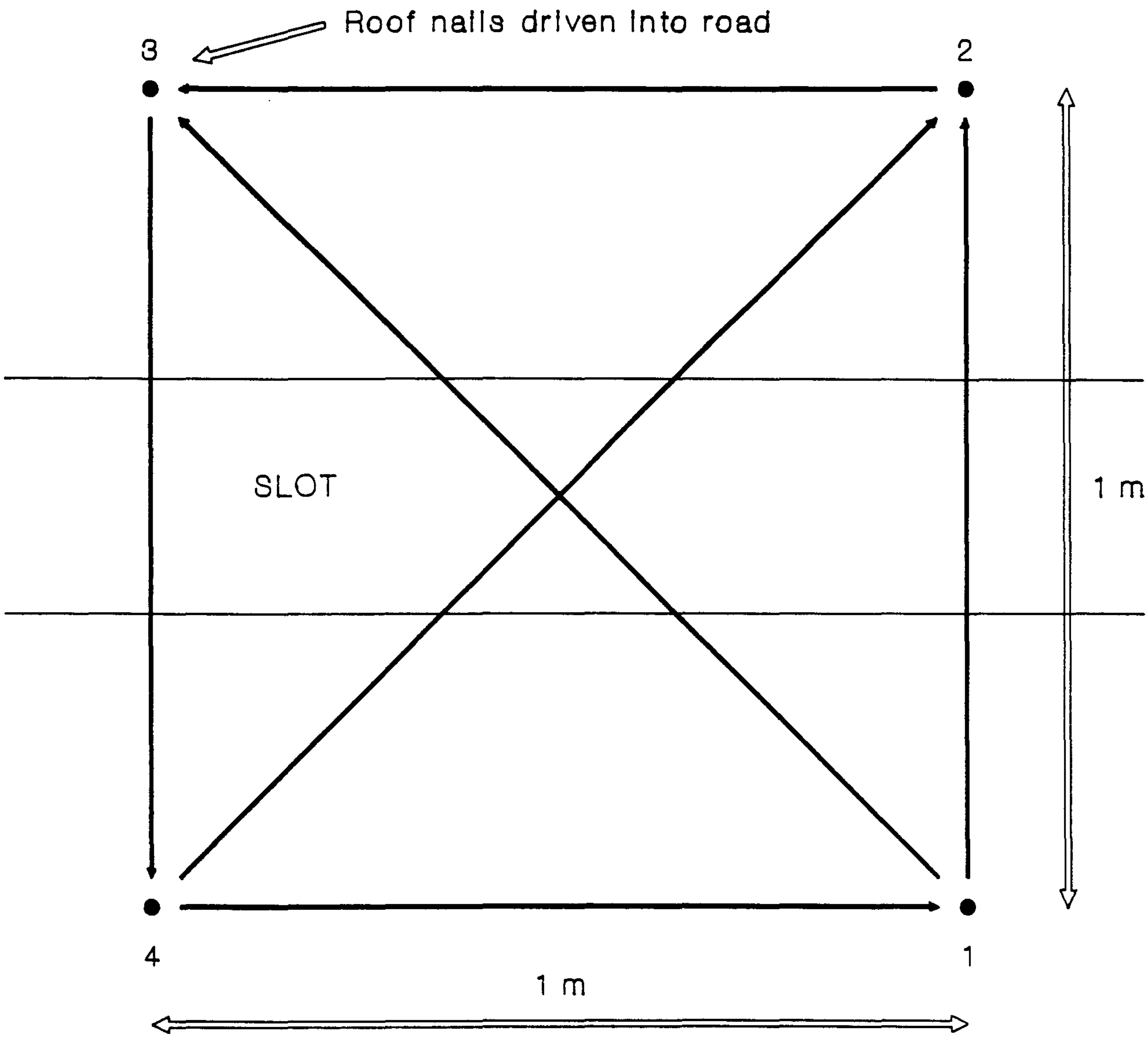

Figure 7.10 Detail of the measurements which were taken to monitor displacements across the slots.

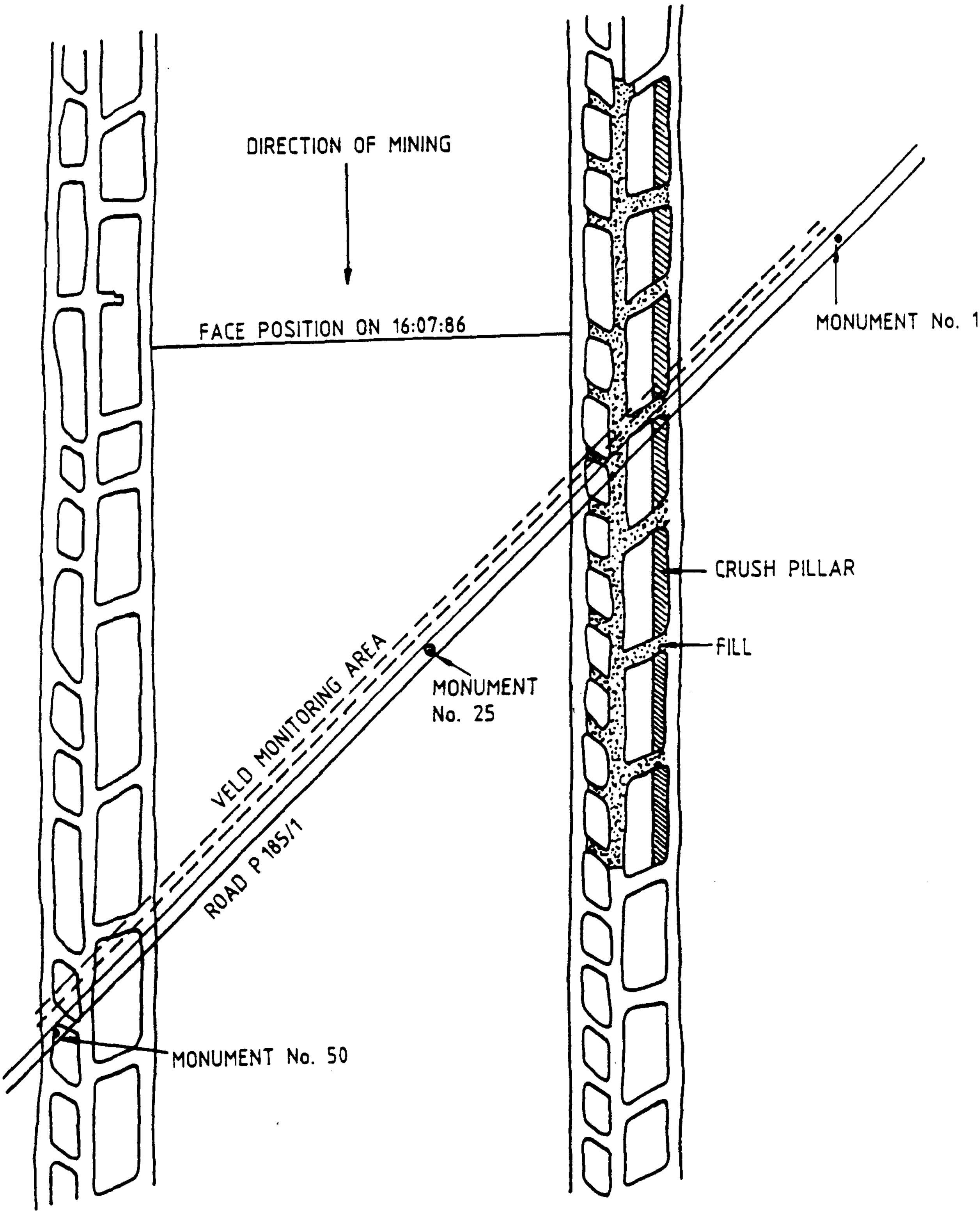

FIGURE 7.11: Diagram showing the monitoring area for the final undermining relative to the underground workings. On the final measuring date, the face was 300 m away from Monument No. 25.

The panel width was 194 m measured from solid edge to solid edge before the inter panel pillar was mined, and 223 m wide in the area where the crush pillar was left. The depth of mining was 123 m and the mining height was nominally 3 m.

7.6.2 Subsidence Results

In this section, where positions are quoted, distances will be measured normal to panel edges to facilitate comparison with other subsidence profiles.

Vertical Subsidence

The maximum vertical subsidence on the road was 1,44 m, and in the veld next to the road it was also 1,44 m. Over the crush pillar, the subsidence on the road was 0,75 m and in the veld it was 0,78 m.

Progressive subsidence profiles for the road and the veld are shown in Figures 7.12 and 7.13 respectively. Both Figures exhibit a compressive ridge, which was also observed at the deviation. This ridge, being both wide and smooth, was not readily discernable to the naked eye. It was quite unlike the sharp ridging shown in Plates 1 and 3. The vertical subsidence at the crest of the ridge was 1,34 m on the road and 1,35 m in the veld. On the road, a much smaller ridge also developed in

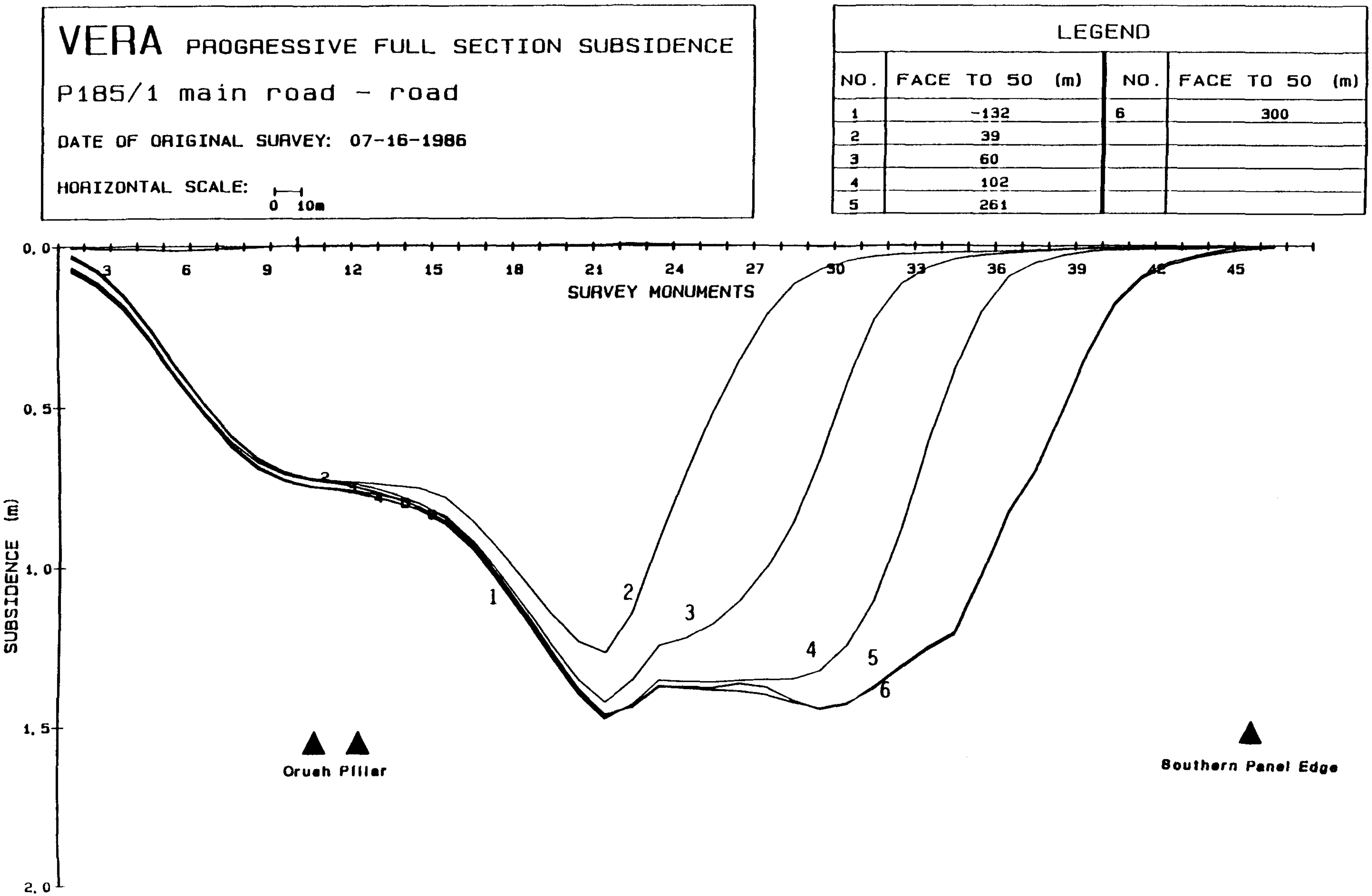

Figure 7.12 Progressive vertical subsidence of the road at selected stages of undermining. The distance between the longwall face and monument Number 25 for the various stages are shown in the legend.

VERA PROGRESSIVE FULL SECTION SUBSIDENCE

P185/1 Main road - control

DATE OF ORIGINAL SURVEY: 07-16-1986

HORIZONTAL SCALE: 0 10m

LEGEND

NO.	FACE TO 50 (m)	NO.	FACE TO 50 (m)
1	-142	6	290
2	29		
3	50		
4	110		
5	251		

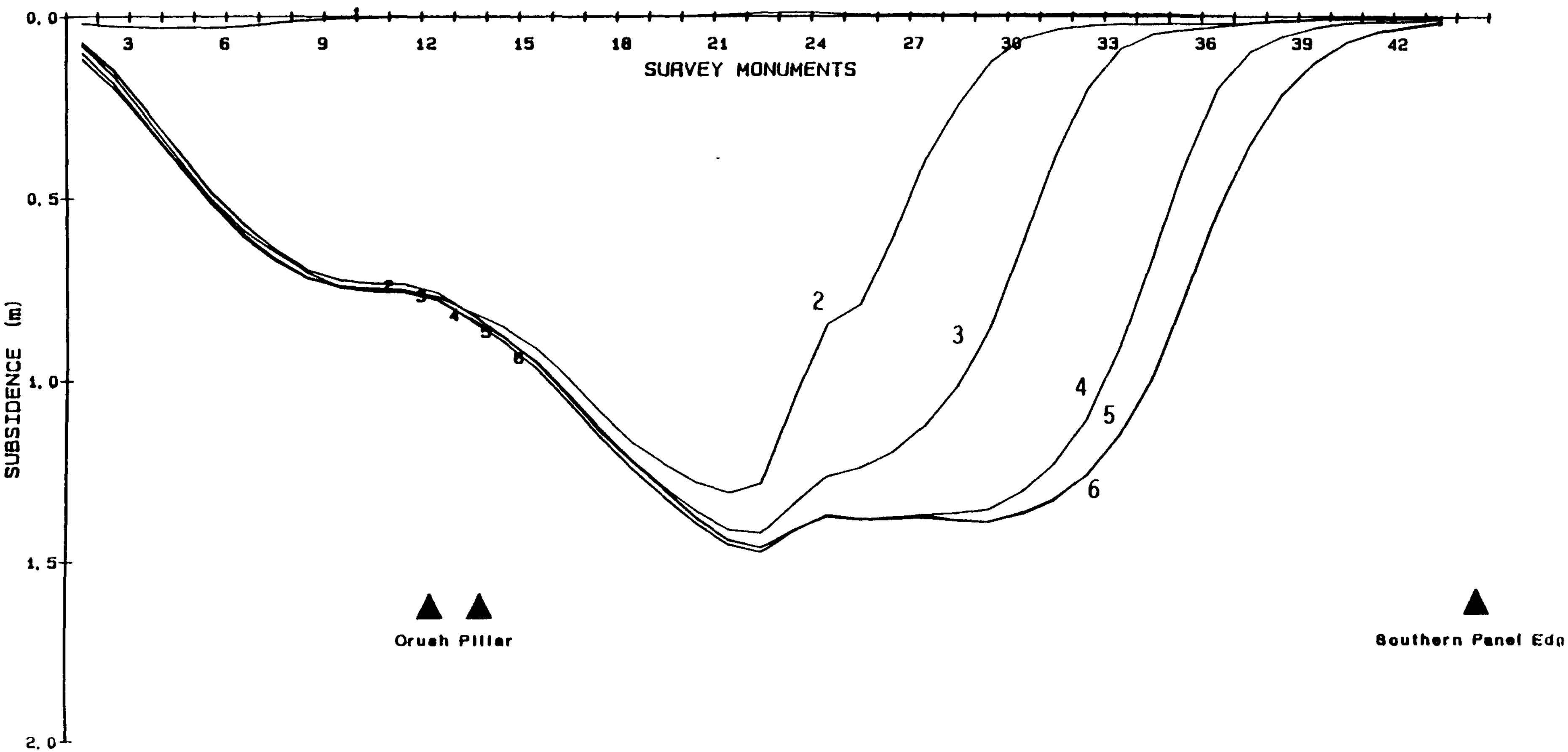

Figure 7.13 Progressive vertical subsidence of the veld next to the road. The distance between the face and monument No. 25 are shown in the legend.

the region of monuments 36 - 37. This ridge is of interest as it was clearly visible on the road, having a noticable incline on the Northern side. This incline is not shown on any of the curves, as it was a small feature which could not be detected with the monument spacing which was used.

The measurement of elevations in the period July 1986 to August 1988 provided the opportunity to study the longer term subsidence behaviour. The opportunity was even more ideal in the sense that the survey monuments were all firmly fixed to the road, and were undisturbed for the whole period as neither cattle nor any type of vehicle entered the monitoring area. The only remaining outside influence was clay swell.

Table 7.2 contains the longer term subsidence data for three points on the subsidence profile in the road. The three points are characteristic of the following areas: overlying the crush pillar, in the centre of the panel and on the Southern slope. A negative subsidence rate indicated downward displacement.

The table indicates that after approximately one year, vertical displacements tend to fluctuate between positive and negative. The displacements of the three widely spaced points appear to be more in sympathy with one another than to correlate with their relative age after undermining: the fluctuations thus appear to be more due to clay swell than the effects of mining.

Table 7.2: Long term subsidence of selected characteristic points on the subsidence profile. For each area, the start of the time scale is taken at three months after the point had been undermined. Additional subsidence as from that date is taken into account.

AREA	OVER CRUSH PILLAR	IN CENTRE	ON SOUTHERN SLOPE
Time (months)	14	11	9
Subsidence (mm)	-8	-10	-8
Rate (mm/mnth)	-2	-2,5	-2
Time (months)	18,5	15,5	13,5
Subsidence (mm)	-8	-6	-7
Rate (mm/mnth)	-1,8	-1,3	-1,6
Time (months)	21,5	18,5	16,5
Subsidence (mm)	+7	+3	-1
Rate (mm/mnth)	+2,3	+1	-0,3
Time (months)	23,5	20,5	18,5
Subsidence (mm)	-6	-5	-5
Rate (mm/mnth)	-3	-2,5	-2,5

Induced Tilt

On the Southern slope of the subsidence trough on the road, the maximum induced tilt was 40 mm/m and it occurred at a position 64 m North of the Southern edge. On the Northern slope, two maxima were found, on either side of the crush pillar. At a position 45 m North of the crush pillar it was 28 mm/m and at a position 51 m South of the crush pillar it was 27 mm/m. These are shown in Figure 7.14, as curve "b".

In the veld, the maximum on the Southern slope was 46 mm/m at a position 60 m North of the Southern edge. On the Northern slope, the maximum was 25 mm/m at a position 41 m North of the crush pillar and 22 mm/m at a position 33 m South of the crush pillar. These are shown as curve "b" in Figure 7.15.

Horizontal Displacements

Horizontal displacements for various stages of subsidence on the road and in the veld are shown in Figures 7.16 and 7.17 respectively. In both instances, the maximum displacements occurred on the Southern slopes.

On the road, the maximum was 383 mm at a position 50 m North of the Southern edge in a direction normal to the face and towards the mined out area. There was also a minor peak of 318 mm at a position 66 m South of the crush pillar in a direction of 60° from the face. The Northern edge of the compression ridge was characterized by an abrupt decrease in horizontal displacement.

In the veld, the maximum horizontal displacement of 342 mm, in a direction normal to the face and towards the mined out area,

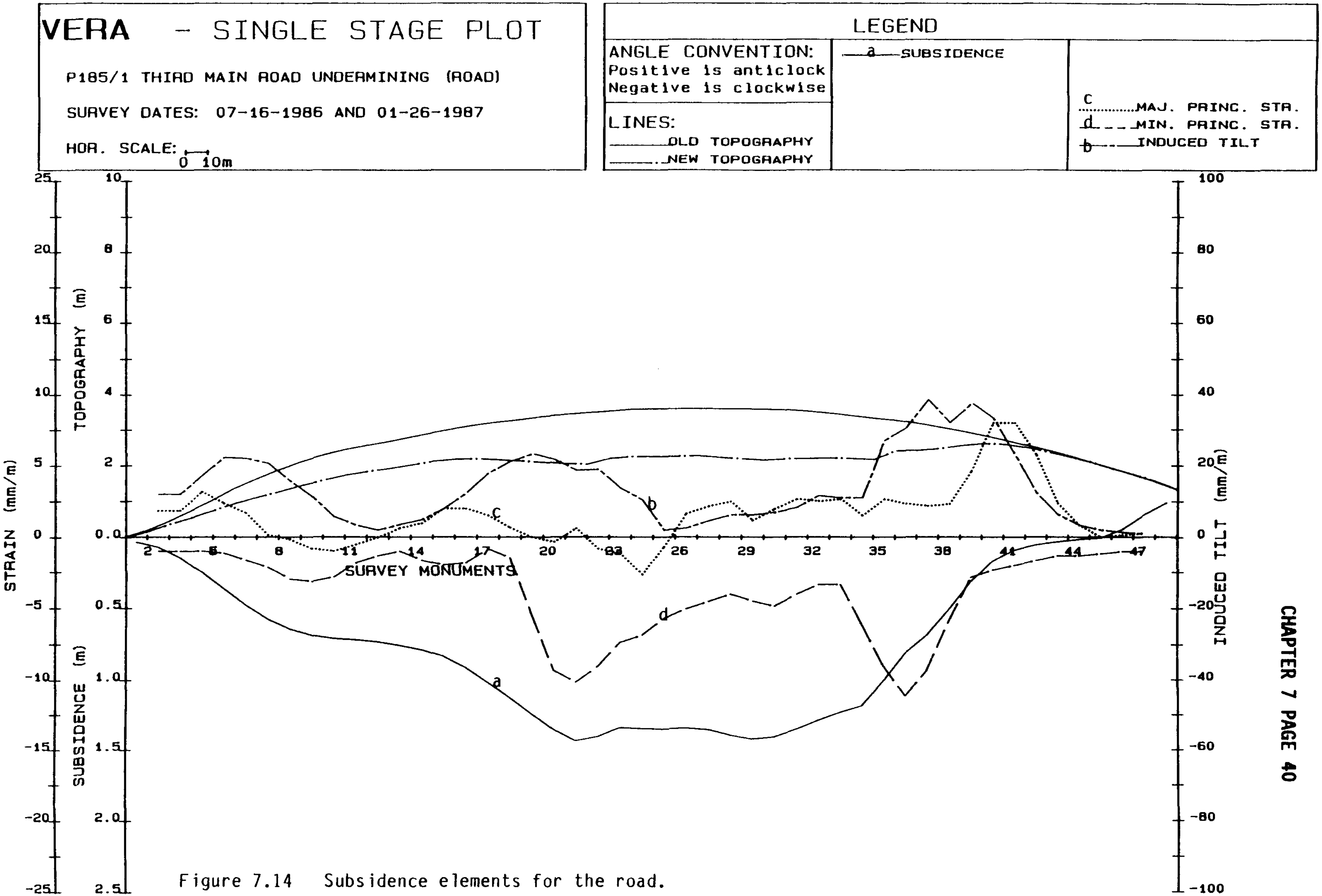

Figure 7.14 Subsidence elements for the road.

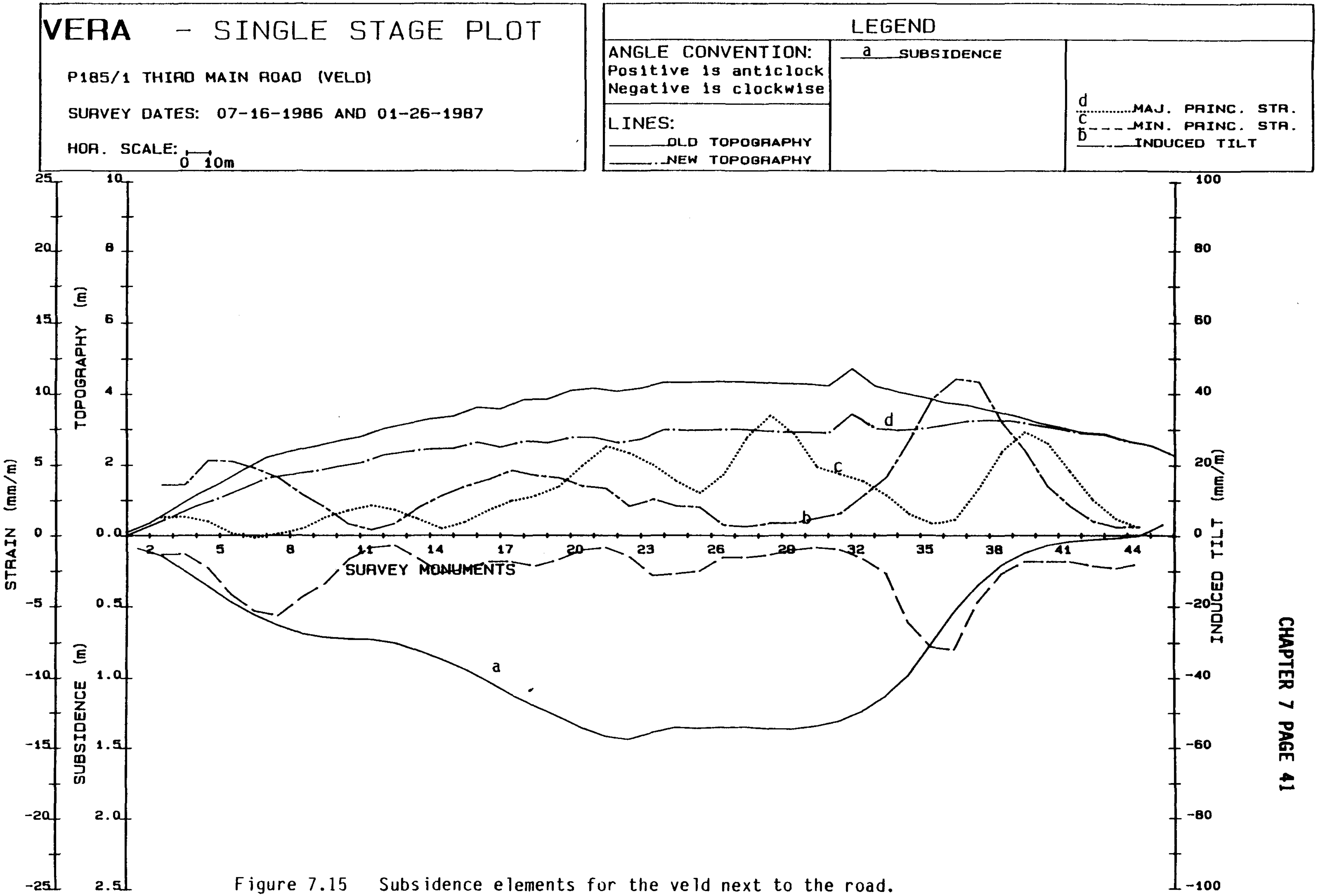

Figure 7.15 Subsidence elements for the veld next to the road.

VERA PROGRESSIVE FULL SECTION SUBSIDENCE

P185/1 Main road - road

DATE OF ORIGINAL SURVEY: 07-16-1986

HORIZONTAL SCALE: 0 10m

LEGEND			
NO.	FACE TO 50 (m)	NO.	FACE TO 50 (m)
1	-132	6	300
2	39		
3	60		
4	102		
5	261		

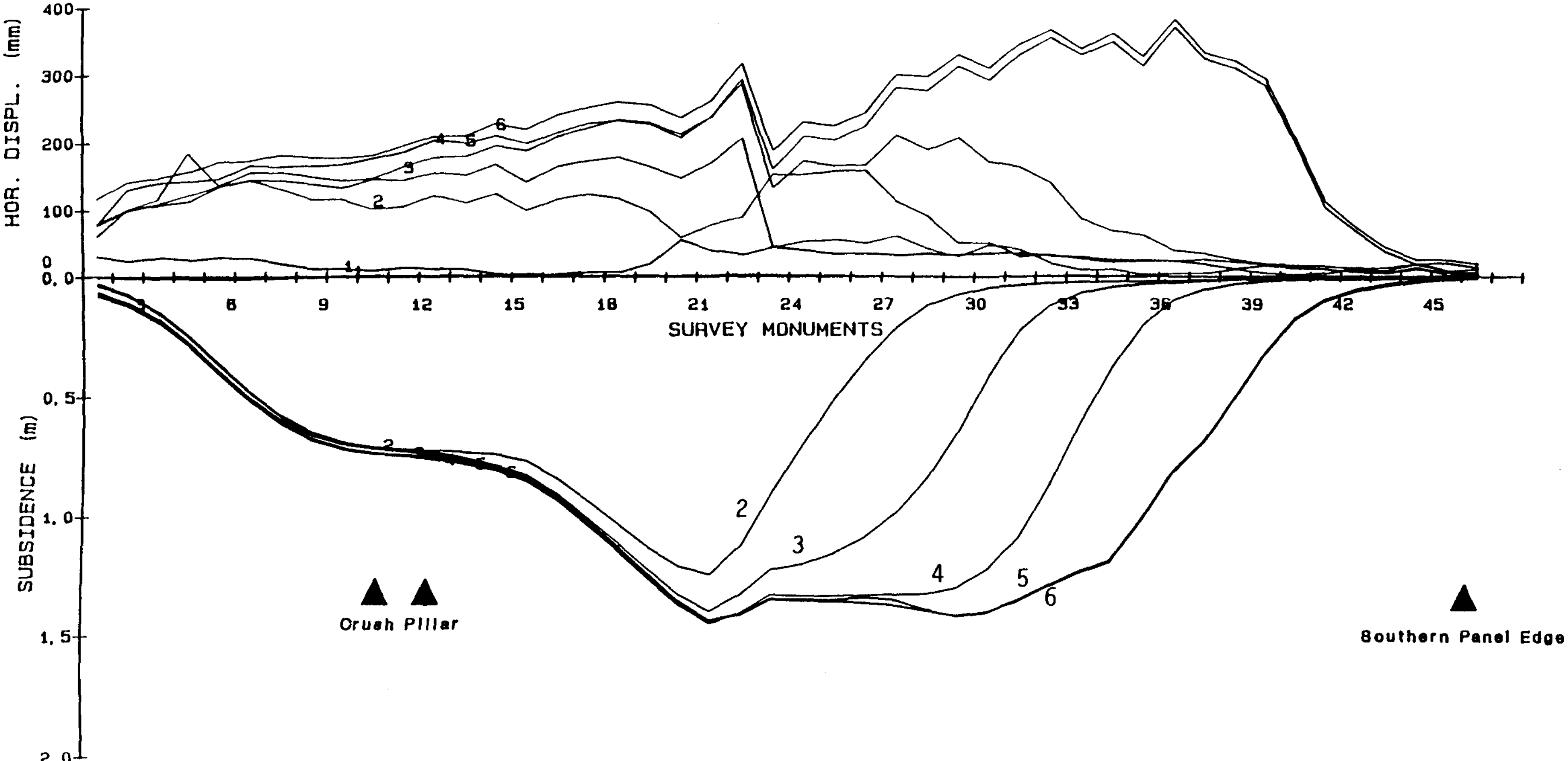

Figure 7.16 Progressive horizontal displacements for various stages of subsidence of the road.

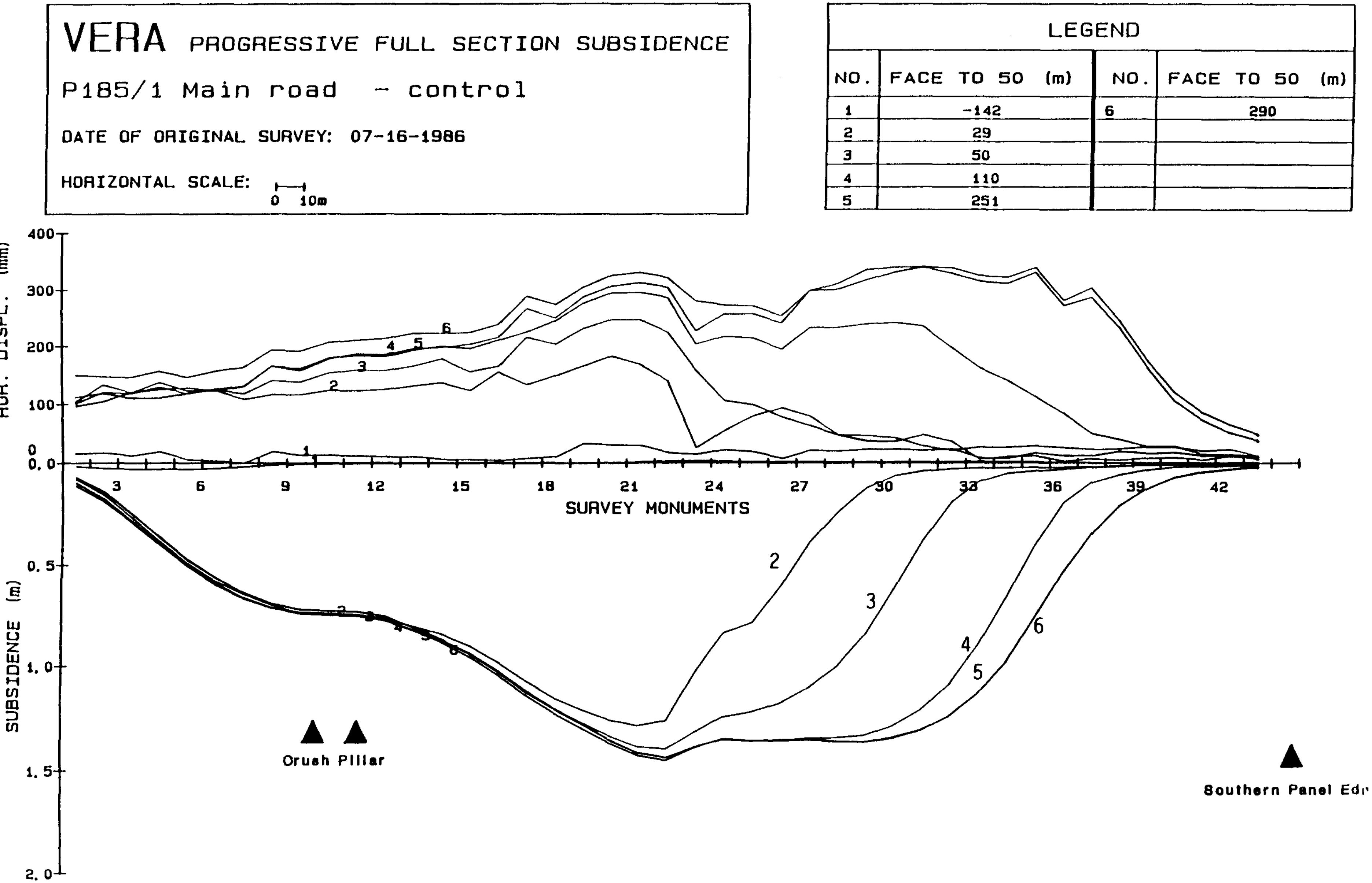

Figure 7.17 Progressive horizontal displacement for various stages of subsidence of the veld next to the road.

occurred at a position 90 m North of the Southern edge. The minor peak was also evident: 331 mm, also directed towards the mined out area and normal to the face, at a position 64 m South of the crush pillar. As was the case on the road, the compressive ridge was again characterised by a sharp, though less marked, decrease in horizontal displacement. The horizontal displacements did not occur in a continuous manner. Rather, it appeared as discrete small displacements across cracks. This is shown in Plate 5.

Surface Strain

The discussion of strain will be divided into two sections. The Minor Principal Strain (usually compressive) will be discussed seperately from the Major Principal Strain (usually tensile). Compressive strains may result in ridging while tensile strains may cause open cracks. It is not unusual for a specific surface element to be in compression in one direction and in tension in another direction. Following the first undermining, Schümann (1988), also refers to open tension cracks being orientated at right angles to compressive ridges.

(i) Major Principal Strain

The maximum Major Principal Strain on the road had a peak with magnitude of 8,5 mm/m at a position 29 m North of the Southern

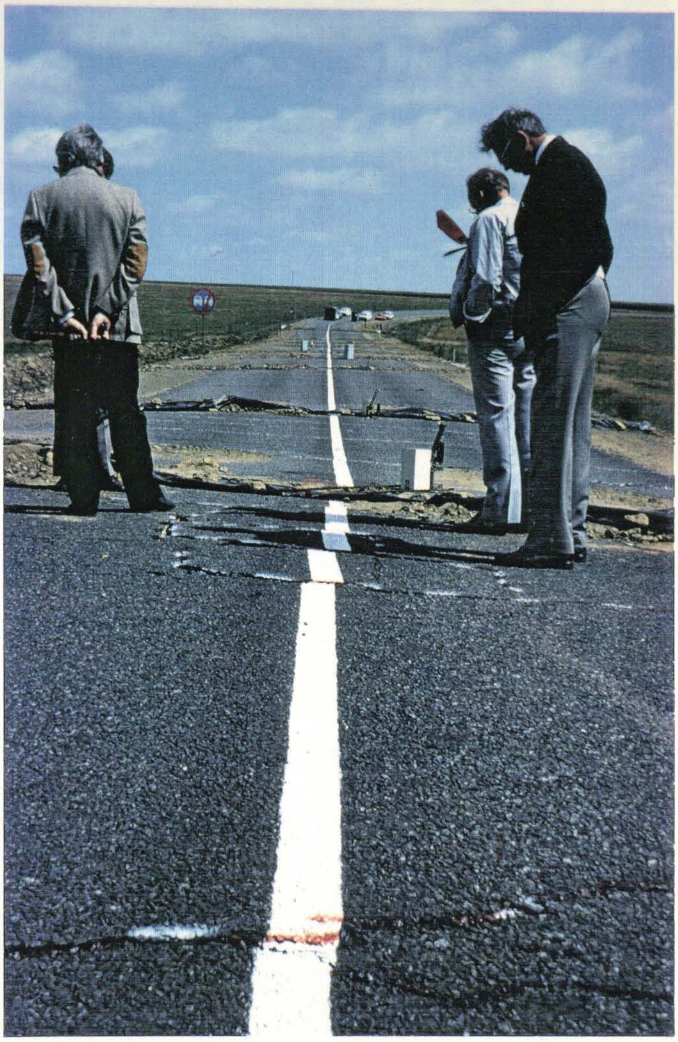

PLATE 5 Horizontal displacement of the road. Note that the displacement was not continuous, but rather in the form of discrete displacements across the tension cracks.

panel edge. Much smaller strains were apparent on the Northern slope. The maximum in that area was 2,5 mm/m at a position 19 m South of the crush pillar and 3 mm/m at a position 14 m South of the Northern edge of the panel. The progressive Major Principal Strains are shown in Figure 7.18, from which it is apparant that no greater strains were observed during the intermediate phases. These strains are somewhat smaller than those normally encountered.

In the veld next to the road, the maximum Major Principal Strain had a magnitude of 8,5 mm/m and it occurred at a position 64 m North of the Southern edge. At 25 m North of the Southern edge, a peak with magnitude 7,5 mm/m occurred. On the Northern slope, peaks of 1,5mm/m, 2,5 mm/m and 6,5 mm/m occurred at respectively 7 m, 39 m and 78 m South of the Northern edge.

(ii) Minor Principal Strain

The minimum Minor Principal Strain on the road had a magnitude of -11 mm/m and it occurred at a position 64 m North of the Southern panel edge. It coincided with the position of the smaller compression ridge which was described in the previous section. There was a second peak of magnitude -9,5 mm/m which

VERA PROGRESSIVE FULL SECTION SUBSIDENCE

P185/1 Main road - road

DATE OF ORIGINAL SURVEY: 07-16-1986

HORIZONTAL SCALE: 0 10m

LEGEND

NO.	FACE TO 50 (m)	NO.	FACE TO 50 (m)
1	-132	6	300
2	39		
3	60		
4	102		
5	261		

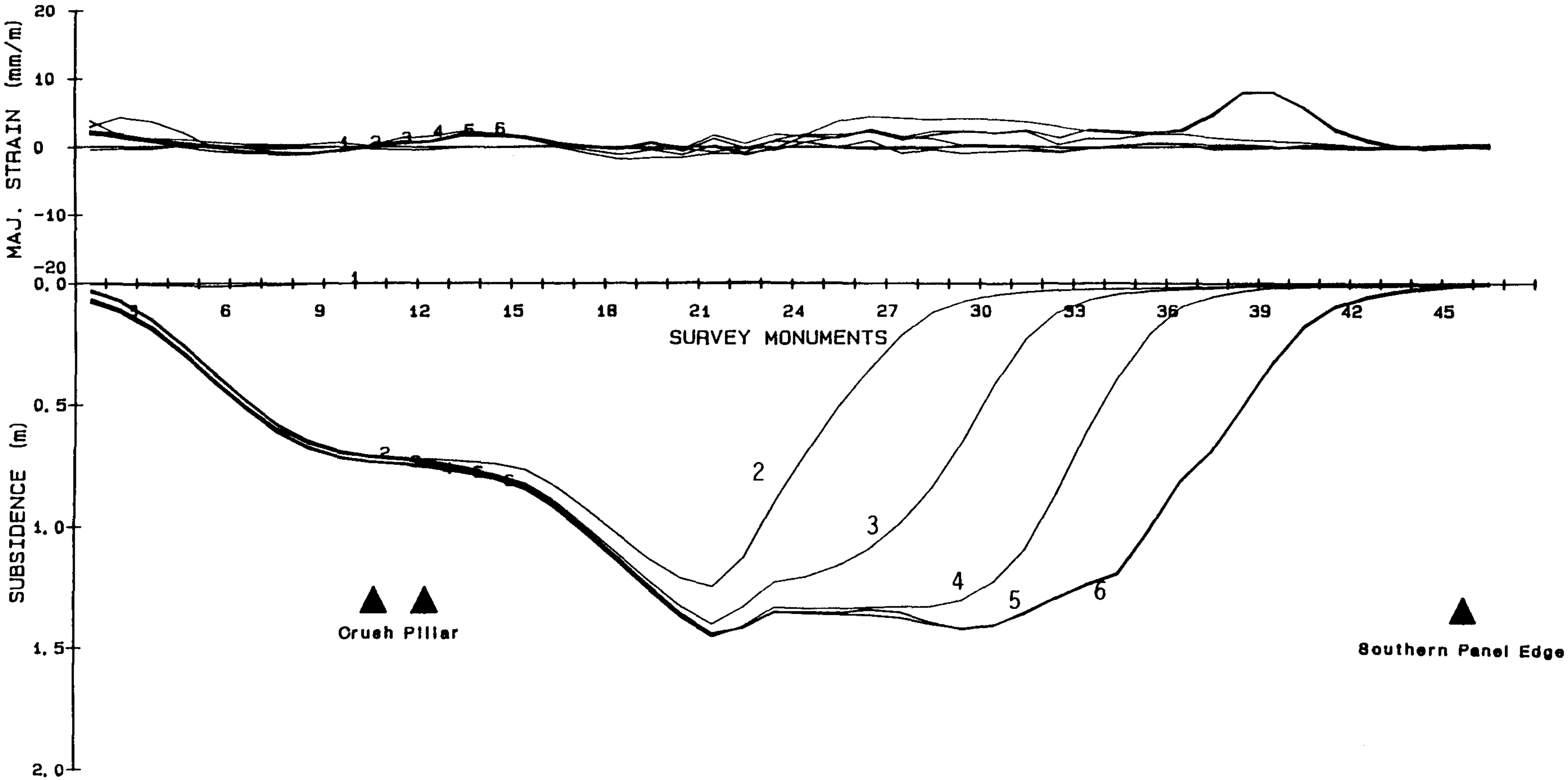

Figure 7.18 Progressive Major Principal Strain for various stages of subsidence of the road.

VERA PROGRESSIVE FULL SECTION SUBSIDENCE

P185/1 Main road - control

DATE OF ORIGINAL SURVEY: 07-16-1986

HORIZONTAL SCALE: 0 10m

LEGEND			
NO.	FACE TO 50 (m)	NO.	FACE TO 50 (m)
1	-142	6	290
2	29		
3	50		
4	110		
5	251		

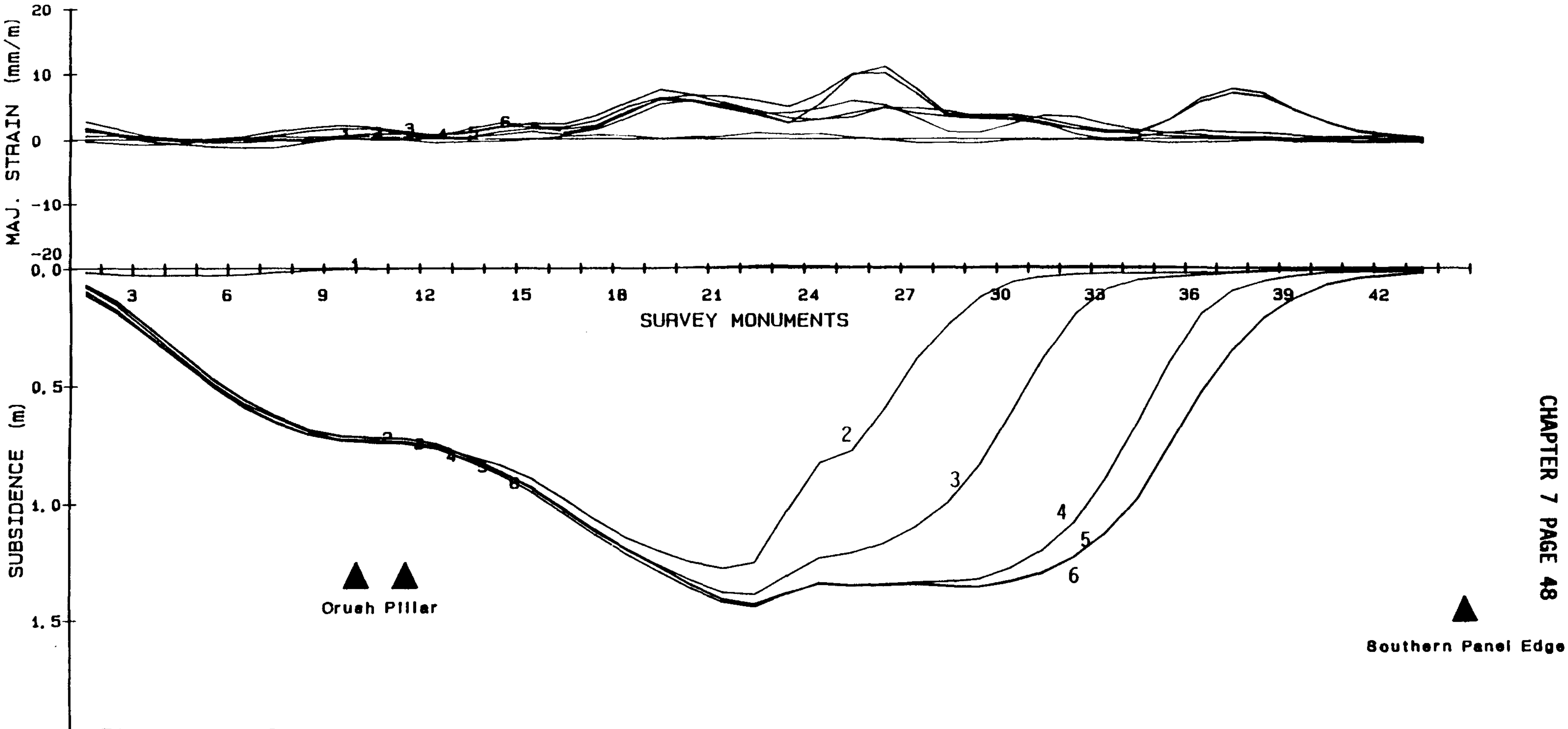

Figure 7.19 Progressive Major Principal Strain for various stages of subsidence of the veld next to the road.

was located at a position 70 m South of the crush pillar. It coincided with the deepest part of the trough and could perhaps be associated with the compressive ridge. Progressive Minor Principal Strains on the road are shown in Figure 7.20. The final strain profile is shown in Figure 7.14, as curve "c", together with certain other parameters.

In the veld next to the road, the Minor Principal Strain characteristics were somewhat different. These are shown in Figure 7.21 for different stages of subsidence. The final strain profile is shown as curve "C" in Figure 7.15. The most significant differences are that firstly, the Northern edge of the trough experienced more compression than that which occurred on the road. In the veld, the minimum strain was -6,5 mm/m at a position 42 m North of the crush pillar.

Secondly, the peak magnitude at the compression ridge was much smaller, being -2,5 mm/m. The compression at the position coinciding with the smaller compression ridge on the road, at a position 60 m North of the Southern edge of the panel, was -10,5 mm/m.

Comparing curves "C" in Figures 7.14 and 7.15 shows that overall, the road experienced more compressive strain than did

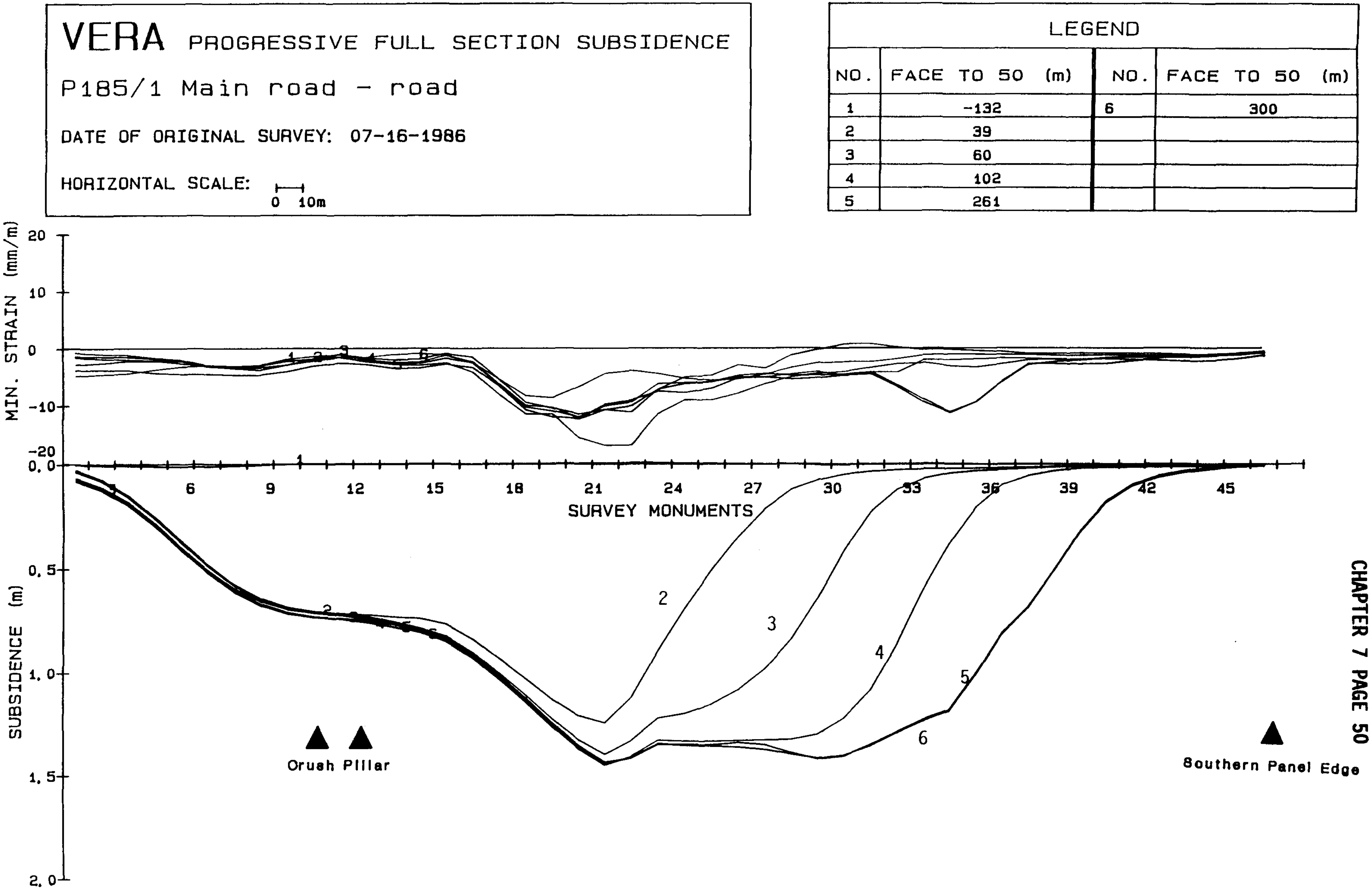

Figure 7.20 Progressive Minor Principal Strain for various stages of subsidence of the road.

VERA PROGRESSIVE FULL SECTION SUBSIDENCE

P185/1 Main road - control

DATE OF ORIGINAL SURVEY: 07-16-1986

HORIZONTAL SCALE: 0 10m

LEGEND

NO.	FACE TO 50 (m)	NO.	FACE TO 50 (m)
1	-142	6	290
2	29		
3	50		
4	110		
5	251		

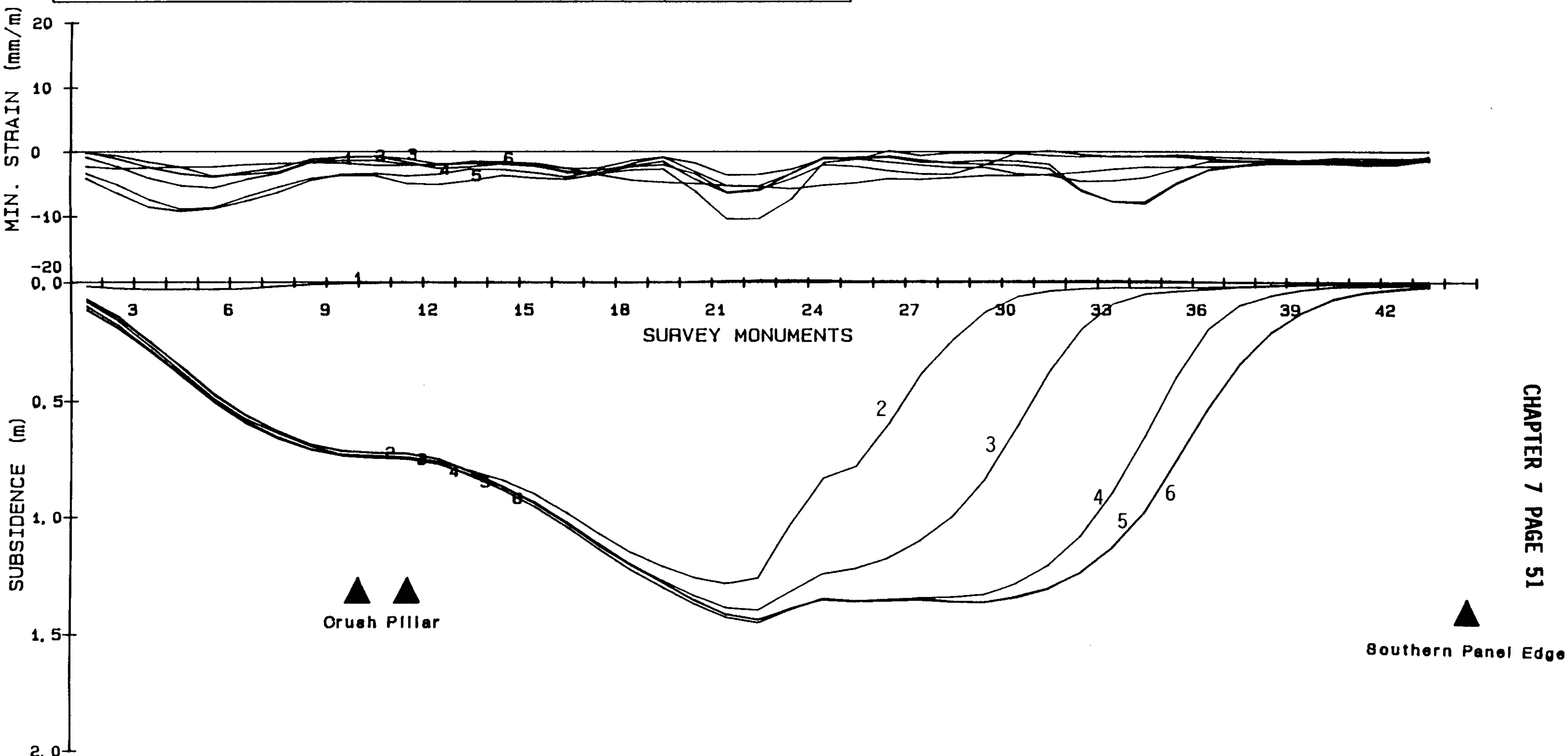

Figure 7.21 Progressive Minor Principal Strain for various stages of subsidence of the veld next to the road.

the veld next to the road, while the veld again experienced more tensile strain. The differences are large enough to be termed significant. It is difficult to ascribe the differences to chance, or due to normal variations caused by different localities of measurement. The observation areas were only 5 m apart.

Strain is at least to some extent dependent on the mechanical properties of the soil on which the survey monuments are located. These differed significantly for the two areas of observation: the veld was an untreated black turf, while the road was a cemented, compacted structure divided into blocks by the slots cut across it. The road had more opportunity to be displaced by virtue of the space created by the slots.

Due to the greater freedom, more displacement would then occur on the road if the driving forces behind the strains were of the same nature. The road, being a very rigid structure, would probably have exhibited significant ridging, had the slots not been provided. This is shown in Plate 6.

As it is, the two readily apparent ridges on the road gave rise to some concern as to the possible existence of cavities underneath the road surface. Three boreholes were put down to a depth of 20 m to investigate this possibility. The borehole sides were visually examined with a closed circuit TV camera, but no cavities were found.

PLATE 6 A slot which had undergone closure. Note the absence of ridging on the tarred road surface itself, while the untarred road shoulder, which was also underlain by compacted material, ridged significantly. The slot did not traverse the road shoulder.

7.6.3 Behaviour of the compression relief slots

Displacements across the slots

Displacements across the slots were measured by tape at regular intervals from 15 July 1986 through to 26 January 1987. Table 7.3 summarises the displacements of the Northern side of each slot relative to the Southern side, at the final date. The compressive strains measured in the areas of the slots are also shown in the table. In the fourth column, the product of strain and the monument spacings are given.

The direction of displacement in degrees, is given relative to the normal across the slot and is an indication of the success of the directional placing of the slot. Therefore, the smaller the angle, the more correct was the forecast of the direction of displacement across the slot.

All the displacements were negative, i.e. they tended to close the slots and not to pull them apart. Therefore, all the slots were provided in the correct localities. This is especially true of slots 8, 13 and 14, which were located in the zones of maximum compression (see Figure 7.15). Slots 8 to 14 were all located in a zone characterised by high compressive strains. Plates 7 and 8 show the amount of closure which was observed at slot No. 14.

PLATE 7 Slot 14 before mining.

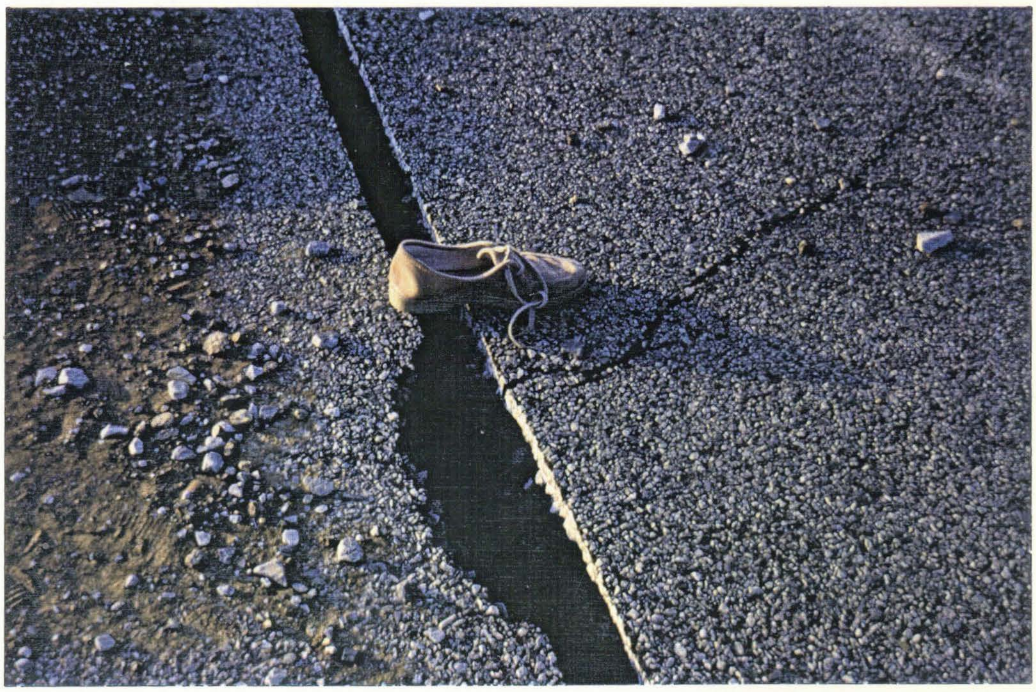

PLATE 8 The same slot after mining, indicating the amount of closure.

Table 7.3: Displacements and directions of displacements of the Northern side of the slots relative to the Southern side.

SLOT	TOTAL DISPLACE-MENT (mm)	COMPONENT OF DIS-PLACEMENT PARALLEL TO SLOT (mm)	COMPONENT OF DIS-PLACEMENT NORMAL TO SLOT (mm)	DIRECTION (degrees)	STRAIN (mm/m)	STRAIN X SPACING (mm)
1	23	22	-2	86	-1,5	-15
2	20	18	-10	64	-2,5	-25
3	18	17	-2	80	-3	-30
4	13	12	-3	74	-1,5	-15
5	37	31	-16	60	-1	-10
6	22	21	-7	72	-2,5	-25
7	76	58	-49	49	-5	-50
8	213	94	-191	26	-11	-110
9	46	37	-26	54	-10	-100
10	64	54	-35	57	-6	-60
11	97	72	-65	48	-4	-40
12	77	62	-45	54	-4	-40
13	104	6	-103	3	-6	-60
14	233	191	-133	56	-15	-150

The significance of the seventh column in the table is that there is fair agreement between the displacements measured by tape across the slots, and the displacements calculated from the strains. The two measuring systems functioned independently.

It can also be seen that all the displacements were smaller than the original slot widths of 300 mm, and therefore all the slots were wide enough.

The directions of placement could have been better, as all but two of the directions of displacement were more than 45° off the normal across the slots. The errors tended to be larger towards the North, where the crush pillar was located. In that area, the displacements were obviously affected by the previously fractured rock mass from the previously mined panel.

7.6.4 Development of cracks in the road

Several cracks, from 1 to 40 mm wide at spacings from 1 to 4 m, developed on the road. In order to study the occurrence of cracks as related to tensile strain, the road was divided into sections for which strain values were available. Sections which included strain relief slots or parts thereof, were excluded.

For each section, the strain was multiplied by the length across the section measured at right angles to the general direction of cracks in that section, to obtain the elongation of the section. This was compared to the sum total of crack openings in the relevant section. The results are contained in Table 7.4.

It is seen from the table that the sum of the total crack widths and the sum of the elongations agree to within 6%. The slight discrepancy is possibly due to inaccurate measurement, mainly of crack widths, as these tended to vary along the length of the cracks.

Table 7.4: Comparison of total crack widths to measured elongation.

SECTION	TOTAL OF CRACK WIDTHS (mm)	ELONGATION (mm)
1	17	35
2	25	20
3	4	6
4	18	18
5	13	15
6	23	6
7	27	24
8	40	46
9	35	20
10	46	26
11	5	5
12	50	60
13	50	59
14	40	30
TOTAL	393	370

As the measured elongation is approximately equal to the total crack width in each section, the correlation coefficient being 0,73, it may be concluded that "stretching" of the road surface was virtually absent and that any tensile strain was directly manifested as a crack on the road. This conclusion highlights the very rigid nature of a bituminized road, and its inherent inability to withstand mining induced strains. It does not, however, by itself indicate the unsuitability of a bituminized road for undermining, as cracks on a road surface are repaired easily and cheaply.

7.7 EFFECTS OF SUBSIDENCE ON THE ROAD

The remarks in this section of this chapter were selected from the report "Undermining of Road P185/1 (Kinross-Charl Cilliers): Summary of finding 1984-1988." by dr F Netterberg of the National Institute for Transport and Road Research of the CSIR.

7.7.1 "Road construction

The road was constructed in 1974 with a 7,6 m wide seal and 4 m gravel shoulders. The pavement construction is as follows: double seal/125 mm graded crushed stone base/125 mm limeslag stabilized weathered dolerite subbase/weathered dolerite selected layer and fill/black clay.

A pavement evaluation carried out before undermining showed that the road was in a very good condition and had not yet been resealed. The average riding quality was about 3,2 PSI units and there was no significant cracking or rutting. The average Lacroix deflection in the outer wheeltrack was about 0,5 mm (range 0,2 - 1,5 mm) and a DCP[1)] investigation showed the base and subbase to possess an average DN[2)] of about 1 - 2 mm/blow. The traffic carried is about 900 vpd[3)] (20% heavy vehicles) or about 100 E80/day[4)] in both directions."

7.7.2 "Damage due to subsidence

Undermining led to maximum vertical displacements ("subsidence") of about 1,3 m and maximum horizontal displacements of 0,25 m, together with horizontal strains of up to about 0,8% in both tension and compression, and tilts of up to 3%. Vertical curvature was also increased in some places resulting in a reduction of 'K'[5)] values down to 9 for one crest and one sag curve.

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1) Dynamic Cone Penetrometer.
2) Average Number of blows per mm over a certain depth.
3) Vehicles per day.
4) Equivalent 80kN standard axle load.
5) "K" values refer to sight distance. For this class of road, K value of at least 60 for crests and 50 for sags are required.

As a result of these effects the road experienced severe damage, mostly in the form of tension cracking, with a lesser amount of shear cracking and compressive ridging. Transverse to diagonal cracks up to 40 mm in width occurred on a spacing of about 1-4 m over most of the undermined length.

A number of protective 'slots' (trenches about 300 m wide and deep) were cut across the road over the panel which succeeded in greatly reducing the compressive damage. Bankelman-beam deflections after undermining averaged about 1,2 mm (range 0,2 - 2,7 mm) and were especially high within about 0,5 m of cracks and ridges. In many cases the road cracked into apparently otherwise intact blocks some 4 m square. In such cases DCP work suggested that the pavement structure in the central position of the blocks was undamaged. However the beam deflections in such places were always high.

The road developed two smooth, gradual 'steps' up to about 0,4 m high over distances of about 10 m which did not occur elsewhere on the road, deviation, or in the veld. These were investigated by means of DCPs to a depth of 2,6 m, rotary percussion drilling to a depth of 20 m and by borehole camera to a depth of 15 m. (The latter was carried out by the Geological Survey.) No cavities were found and these sections are considered to be safe from the risk of sudden subsidence. It must be concluded that they simply represent a type of compression damage possibly influenced by the subsurface geology or the rate of undermining.

Subsidence and the accompanying damage was at all times gradual, and no crown holes, significant sharp faulting across the cracks, or sudden drops in level occurred. In the opinion of those involved in the investigation the road (without slots) could probably have been kept open to traffic provided that speeds could have been kept low, say below 50 m/h. Traffic compaction would have prevented the ridging from rising as high as it did, but would have resulted in potholing in such areas and spoiling of the edges of the cracks. Test runs over the two 'steps' on the road shoulders over the third panel showed that they could be safely negotiated at speeds of up to about 50 km/h. However, experience shows that in practice it is very difficult to induce the travelling public to drive at a safe, low speed. Moreover, the wider cracks, and the two steps over the third panel, may have alarmed some drivers and led to their taking dangerous (though unnecessary) evasive or braking action."

7.7.3 "Permanent rehabilitation

Before the road can be permanently rehabilitated it must be shown that any possible further movements will both not constitute a danger to the travelling public and will also result in negligible damage to the road. It is considered that the former contraint has been met. With respect to the latter, the last available level result suggests that the northern half of the undermined section of road may now have practically ceased subsiding. However, the southern half (i.e. that affected by the third panel) appears to have subsided an average of about 10 mm between October 1987 and March 1988. The remaining long-term residual subsidence is estimated at a maximum of about 20 mm in the case of the northern half of the undermined section and about 50 mm in the case of the southern half. According to overseas evidence movements should cease entirely in about 1989 and 1991, respectively. It is considered that such movements will cause no or negligible damage to the road and that permanent rehabilitation can now proceed.

Factors which must be considered in the design of the rehabilitation include the 'steps' over the third panel, the relatively high Lacroix deflections measured over some parts of the repaired first and second panels and therefore expected over the third panel, crack and slot filling, and the remaining slight residual subsidence. Some attention to side drainage and to culvert remains is also required. Vertical realignment will be necessary in several places in order to restore the required sight distances.

It is recommended that a minimum number of level pegs be reinstated after rehabilitation and that measurements be taken once a year (at the same time of year) until it is certain that all movement attributable to the undermining has ceased."

7.7.4 "Conclusions

Undermining of a surfaced road by the longwall method has resulted in relatively smooth and predictable damage which largely ceased once the longwall face had moved away from the road.

Under the conditions at this site the effects were relatively smooth and gradual, without the occurrence of crown holes, sharp faulting across the cracks or sudden drops in level.

A surfaced road can probably be safely undermined under traffic under conditions similar to those studied together with some maintenance provided the maximum speed can be limited to about 40 km/h. However, to achieve this in practice will be difficult.

The whole section of road undermined by longwall can now be safely rehabilitated. Any damage which may be caused by future residual subsidence will be negligible.

The technique of placing slots across the road to minimise compressive damage can be further refined, but is at the moment already sufficiently well developed to absorb compressive displacements under most conditions.

The provision of slots, by minimising damage to the road, will shorten the period required for repairs. The provision of a short term gravel deviation therefore becomes more attractive."

7.8 CONCLUSIONS

Only the conclusions relevant to the experimental work described in this chapter, will be discussed. A broader perspective dealing with an overall strategy for the undermining of roads in general will be given in Chapter 12.

7.8.1 Effects of subsidence on an untreated bituminized road

It was seen very clearly, on a number of occasions, that subsidence of the order of 1,3 - 1,5 m with the accompanying compressive strains of -8 mm/m or more, resulted in severe damage. Ridges developed on the road which may have caused dangerous driving conditions.

However, this does not totally preclude undermining a bituminized road while under traffic, even under the stated conditions of mining geometry and magnitude of subsidence. Two very important facts have to be borne in mind before reaching a final conclusion: the road was not under traffic during undermining, and no maintenance was done.

It remains a fact that Holla (1988) described the undermining of the Pacific Highway in Australia while under traffic. The strains and horizontal displacements were of the same order as the elements found for Road P185/1, and several compression ridges formed, but the highway was kept open to traffic all the time. Continuous maintenance was provided.

The locally untested possibility thus exists that the effect of traffic on a road would be to prevent or at least restrict the development of compression ridges. Heavy rollers can be used to flatten ridges as part of a continuous maintenance programme.

It is granted that there will be some effect on a road, caused by subsidence. It will not be possible to prevent all damage altogether. The question which has not been answered is how much damage to a road can be tolerated.

It is clear that further experimentation in this regard is not only required, but essential. If the further work is not done, the present conclusion that bituminized roads should not be undermined under conditions similar to those described here while under traffic, may become an unnecessarily harsh and costly restriction.

With regard to the formation of ridges on a road, it demonstrated very clearly the role of the stiffness of the upper surface layer in the visible effects of compressive strains. The ridges as shown on Plate 1, were only visible on the road surface. Next to the road, where the upper surface layer was a much more compressible soil, the ridges did not develop.

The author has witnessed ridges in the veld on several occasions, each time where the soil cover was of the order of 20 cm or less. In those instances, the upper surface layer can be considered to consist of relatively incompressible rock, and compressive strain can only be accommodated by buckling of the upper rock layers.

With regard to the materials used for road construction, it leads to the conclusion that the ideal material would be transversely isotropic. It should be stiff enough in the vertical direction to ensure durability under traffic, but soft enough in the horizontal direction to accommodate horizontal compression.

7.8.2 The effect of the crush pillar

Although it was clearly demonstrated on two occasions that it was possible to design crush pillars to behave in a predetermined manner, and that the desired effects on surface were achieved, the matter needs to be put into perspective. The ultimate aim with regard to inter panel pillars underneath roads should be to ensure long term stability on the surface and to maintain minimum standards of vertical alignment of the road in the most cost effective manner.

Providing crush pillars is only one way of achieving this aim. It is not necessarily the most cost effective. The mining cost and potential danger to the underground workings should also be considered.

Direct costs are incurred as a result of modifications to the coal mining equipment and installation of additional support. Indirect costs are incurred due to production delays caused by the changes in length of the face.

Technically it may not always be possible to leave only a crush pillar between two panels. For instance, if the inclination of the coal seam is such that the second panel is mined at a lower elevation than the first, there is a real risk that the second panel, the one being mined, may be flooded by water accumulated in the goaf of the previous panel. Adverse local geological conditions, which are often unpredictable, may cause premature failure of the crush pillar with subsequent danger to people working underground.

The practice of leaving crush pillars between longwall panels is therefore a high risk practice. It is not one that can summarily be regarded as standard practice. The most obvious alternative, to leave a sufficiently large pillar underneath a road, should receive serious consideration. It will cancel all the cost disadvantages to the mine, while ensuring long term stability of the road. Any adverse effects on the vertical alignment of the road can be overcome by surface construction.

The experiment described in this chapter did not prove an exclusive method for the handling of inter panel pillars underneath roads. It proved the technical possibility of one alternative.

A choice between the various options regarding the underground layout should be based on the considerations of safety of both the road user and the underground worker and on costs.

7.8.3 Compression relief slots

The compression relief slots were primarily intended to decrease the damage done by compressional ridging of a bituminized road during undermining. It thus had the effect of artificially decreasing the lateral stiffness of the paving material to absorb the compressive strains.

In the experimental work, the slot dimensions were a function of the slot cutting method, which was done by equipment which could not cut a slot thinner than 30 cm. This meant that no traffic could be allowed on the road.

The benefit derived from providing the slots was that the repair cost and the time taken to do the repair work were decreased. This meant that the total time during which a road would be out of commission was shortened, which in turn made the provision of a gravel deviation instead of a bituminized deviation a more attractive alternative.

The ultimate aim would still be to cut much thinner slots at denser spacings. This would still prevent compressive ridging of the road while keeping the road under traffic.

The combination of the benefits of providing thin slots and keeping the road under traffic, would almost certainly preclude the necessity of providing any sort of deviation for the road, except perhaps for the provision of a low cost emergency by-pass should a really unexpected event occur.

8 THE EFFECTS OF SUBSIDENCE ON AN UNPAVED GRAVEL ROAD

8.1 INTRODUCTION

By the time of the experimental undermining of a gravel road, the following progress with regard to the undermining of roads in general had been made:

(i) It was found that severe damage was done to the untreated bituminized road, by compressive strains.

(ii) It was shown that the provision of slots across the road had the beneficial effect of absorbing compressive displacements, and that damage to the road could be minimised by the provision of slots.

(iii) A procedure had been developed to alleviate the detrimental effects of a solid inter panel pillar between adjacent longwall panels, by adapting the mining method such that the inter panel pillar was partially extracted, leaving only a crush pillar in situ.

By that time, therefore, all three sub divisions of the main objective had been addressed and meaningful progress could be shown on each one.

In broad terms, however, the results could not yet classify the project as having been successful. An expensive bituminized deviation, causing inconvenience to the owners of land adjoining the road, still had to be provided to the road to be undermined. Prior to 1987, gravel roads had been undermined by high extraction on several occasions in Secunda with the permission of the Government Mining Engineer. From 1987 the Government Mining Engineer also required the mine to obtain the permission of the roads authorities as custodians of the roads, before he would allow a road to be undermined. The roads authorities refused to allow any road to be undermined under any circumstances while under traffic.

In view of evidence obtained from the undermining of gravel roads elsewhere in Secunda in the past, and observations at road P185/1, it was felt that the construction of a high quality deviation was unnecessary. It was felt that as it could be shown that the subsidence process was not sudden, but was yet practically completed in the space of three months, and that the process was predictable, a gravel deviation within the road reserve would be sufficient.

However, tightly controlled scientific observations were not yet available. As the existing deviation had to be extended to allow further undermining of the main road P185/1, this was identified as an opportunity to gain high quality scientific

data on the effects of subsidence on a gravel deviation. A decision was taken to construct the extension of the deviation as a gravel road initially. The sequence of the various underminings is schematically shown in Figure 7.2 in Chapter 7. The gravel portion would then be undermined, allowed to settle and be repaired and surfaced before traffic would be allowed on. This chapter concerns the effects of undermining of the gravel road, as constructed (no slots) and without traffic.
The underground panel was 192 m wide measured from solid edge to solid edge. Mining was done at a depth of 126 m and the mining height was nominally 3 m. The other geological and geometrical parameters are as given in Chapter 7.

8.2 DATA GATHERING

Two classes of data were to be gathered: that dealing with the elements of subsidence and that dealing with the effects of that subsidence on the road.

8.2.1 Subsidence data

A grid of survey beacons spaced at 5 m apart was installed. A grid was also installed in the veld next to the road to serve as a comparative base. The survey monuments were installed and measured at regular intervals. Data gathering and analysis was based on the SEA approach as described in Chapter 5. Figure 8.1

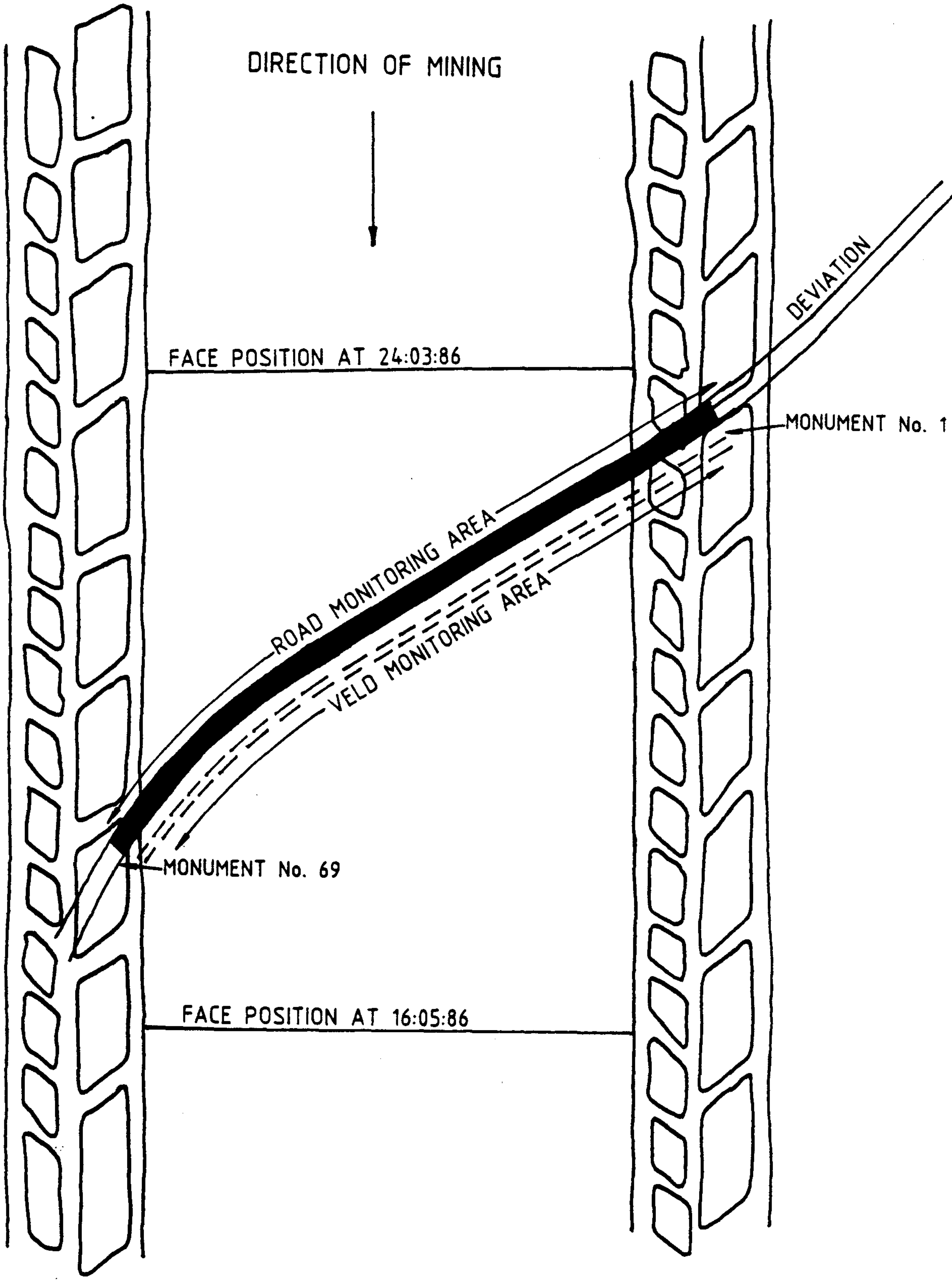


FIGURE 8.1: Detail of the monitoring area, showing face positions of the underground panel at the beginning and end of the monitoring period.

shows the detail of the data gathering area.

Measurements started on 24 March, 1986, and continued through to 16 May, 1986, at which time the road repairs started. The longwall face passed underneath the road between 31 March, 1986, and 1 May, 1986.

8.2.2 Road behaviour data

Data pertaining to the behaviour of the road was gathered by Dr F Netterberg of the CSIR. Data gathering consisted essentially of visual observations and the determination of riding qualities before and after undermining.

8.3 RESULTS

8.3.1 Subsidence results

Vertical Subsidence

On the road, the maximum vertical subsidence was 1,24 m. The progressive vertical subsidence is shown in Figure 8.2. The ridge in the region of Monument No. 35 was caused by compressive strain, and is not an uncommon feature. At the very top of this primary ridge (which is not easily discernable by the naked eye) a secondary ridge, which was visible to the naked eye, developed

VERA PROGRESSIVE FULL SECTION SUBSIDENCE

P185/1 UNPAVED DEVIATION 1986

DATE OF ORIGINAL SURVEY: 24/03/86

HORIZONTAL SCALE: 0 10m

LEGEND

NO.	FACE TO 35 (m)	NO.	FACE TO 35 (m)
1	15	6	165
2	39		
3	75		
4	84		
5	102		

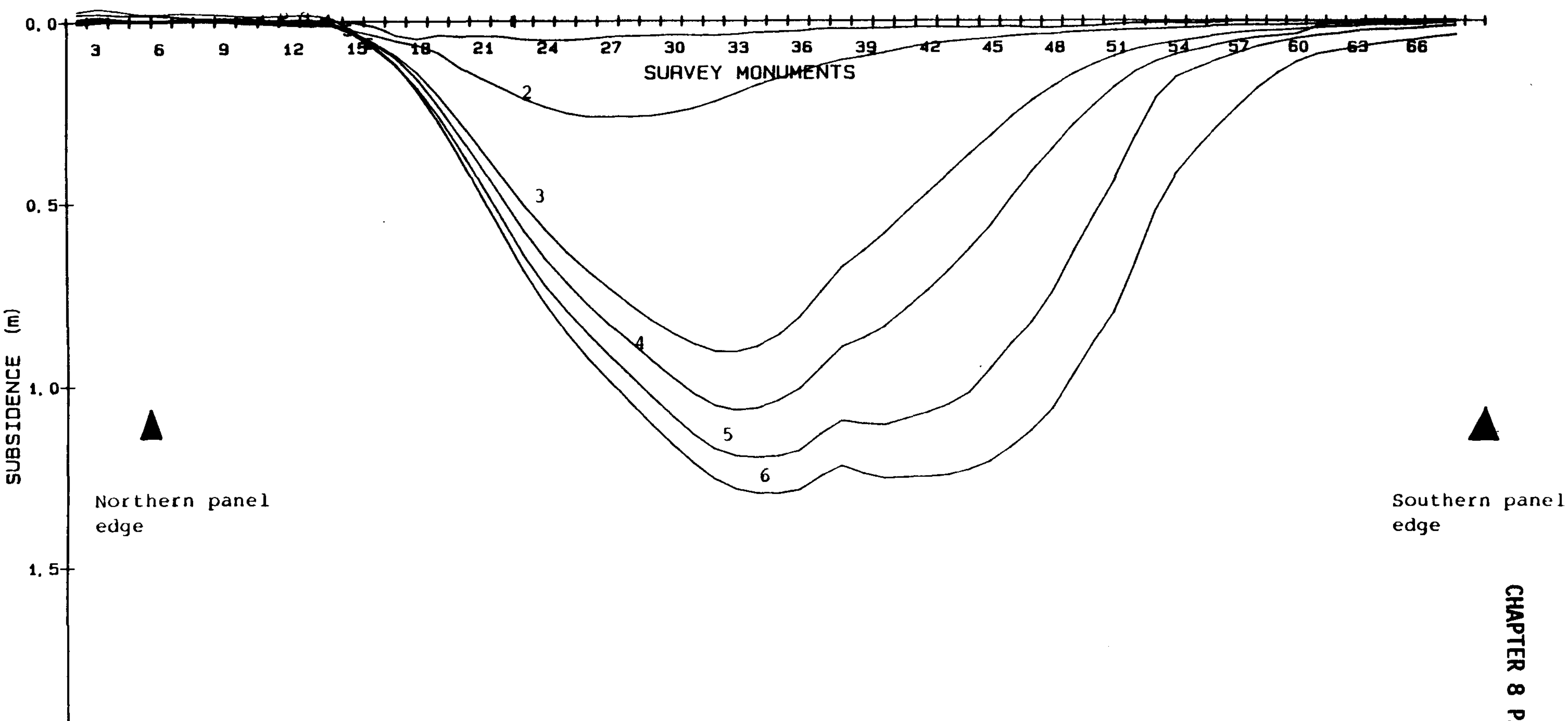


FIGURE 8.2: Progressive vertical subsidence of the unpaved deviation. The ridge, in the region of Monument No. 37, is a compression feature. The distance between the longwall face and Monument No.35 are given in the legend.

on the road. The secondary ridge was approximately 40 mm high over a lateral distance of 1 m. It was seen that a single pass of a motor car over the road flattened the ridge where the wheels of the car crossed it.

Similar data for the veld next to the road is shown in Figure 8.3. It can be clearly seen that the primary ridge in the veld was higher and more pronounced than the one on the road. However, the secondary ridge at the tip of the primary one did not develop in the veld.

Both Figures 8.2 and 8.3 confirm previous observations that the subsided zone is confined to within the edges of the underground panel. The diagrams may be misleading at the Southern positions, where it appears that a smaller subsidence gradient exists than at the Northern end. This is due to distortion, as the observation lines were curved at the Southern end to follow the road - see Figure 8.1.

Induced Tilt

The maximum Induced Tilt on the Northern slope of the subsidence trough was found to be 33 mm/m, on the Southern slope it was 31 mm/m and the maximum Induced Tilt associated with the ridge was 11 mm/m. In the veld next to the road, the corresponding Induced Tilts were 28 mm/m, 46 mm/m and 11 mm/m. Overall,

VERA PROGRESSIVE FULL SECTION SUBSIDENCE

P185/1 UNPAVED DEVIATION (VELD)

DATE OF ORIGINAL SURVEY: 24/03/86

HORIZONTAL SCALE: 0 10m

LEGEND

NO.	FACE TO 35 (m)	NO.	FACE TO 35 (m)
1	23	6	173
2	47		
3	83		
4	92		
5	110		

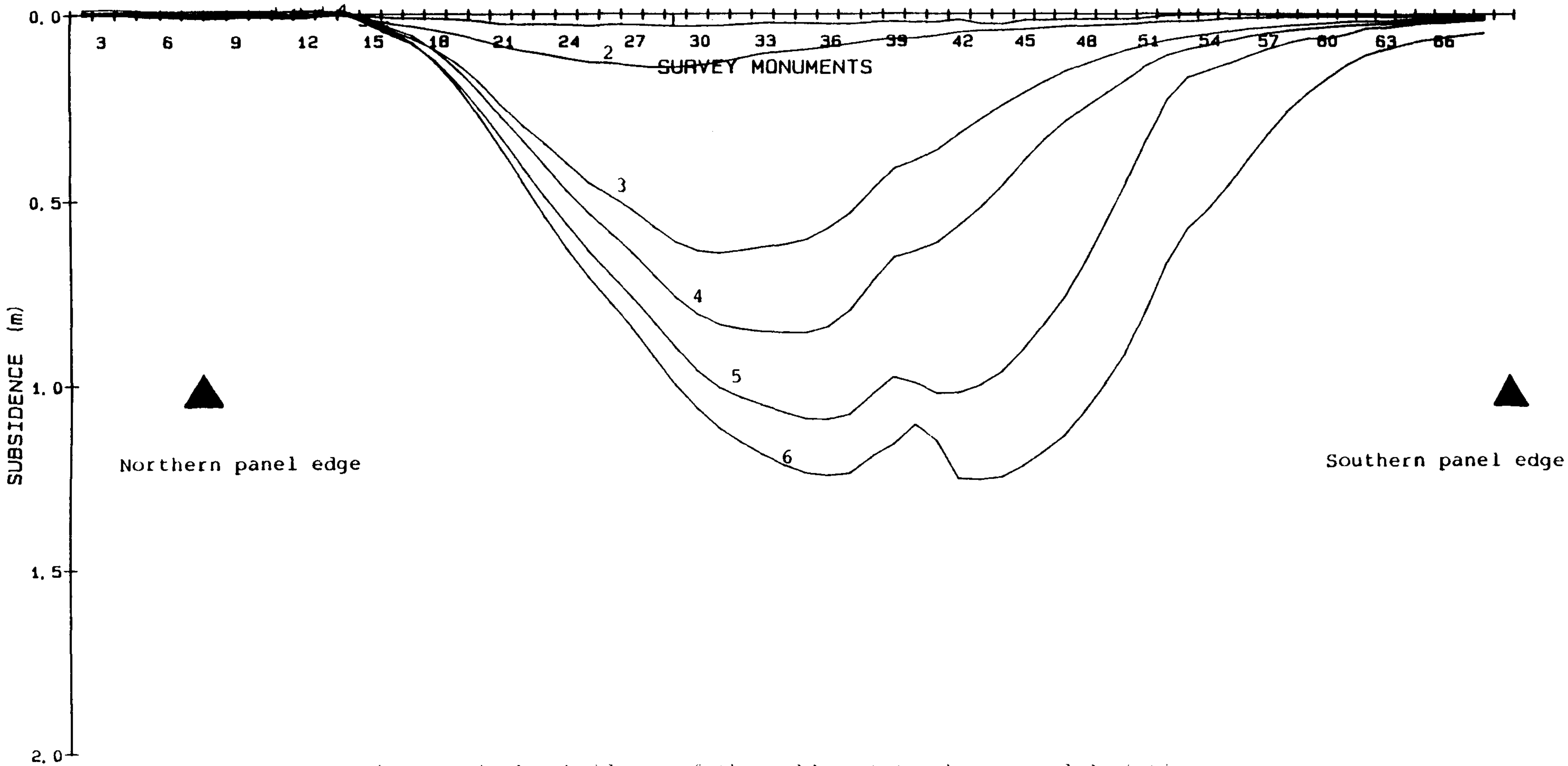


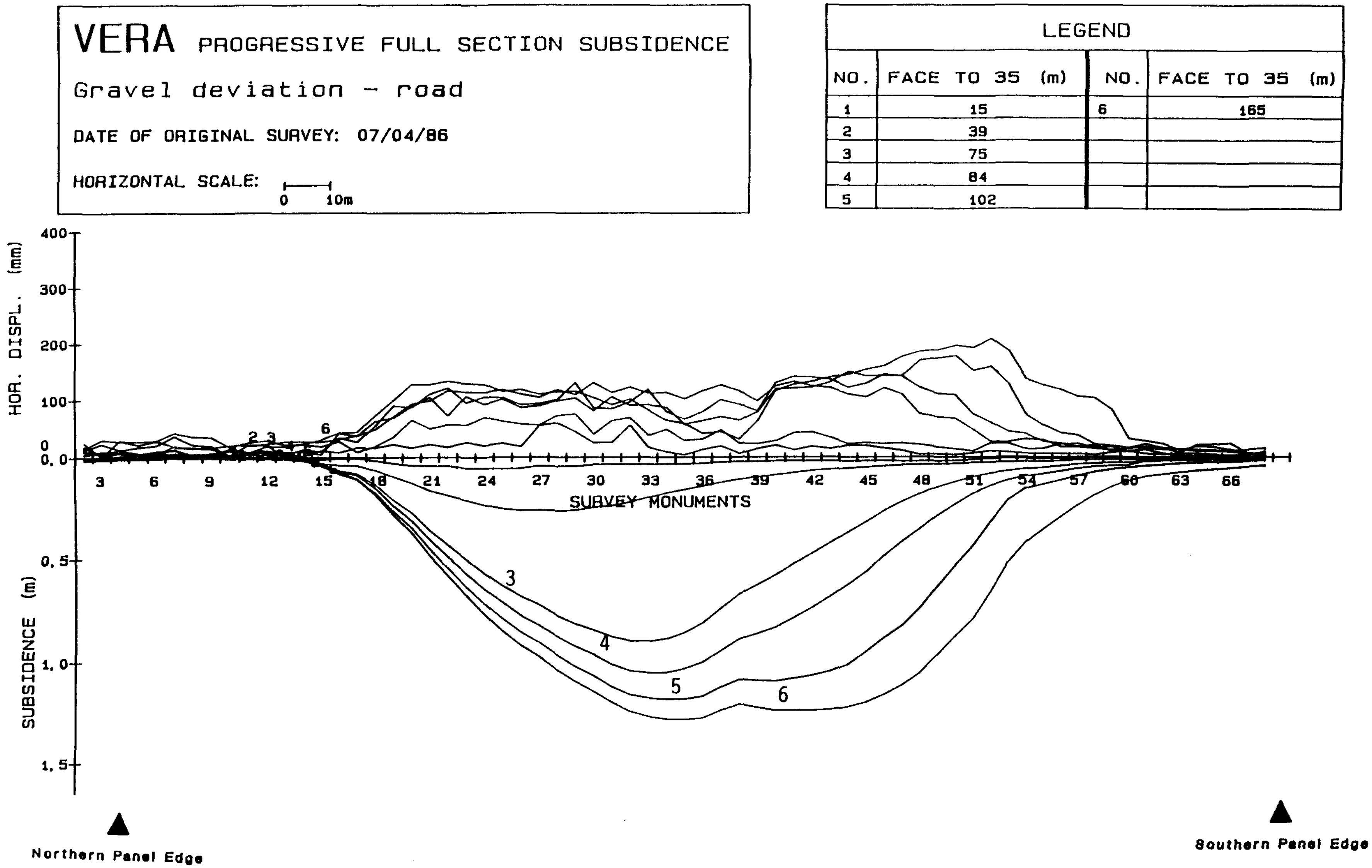
FIGURE 8.3: Progressive vertical subsidence of the veld next to the unpaved deviation.

the maximum Induced Tilt was thus 46 mm/m and it occurred on the Southern slope of the subsidence trough.

Horizontal Displacements

The horizontal displacements for various stages of subsidence of the road are shown in Figure 8.4. The same data for the veld next to the road is shown in Figure 8.5. The figures indicate that horizontal displacement increased with increasing subsidence, and that the maximum residual horizontal displacements occurred on the sloping edges of the subsidence profiles. In the case of the road, the maximum horizontal displacement on the Southern edge was 211 mm, in a direction parallel to the longwall face and towards the centre of the panel, at a point 74 m from the Southern edge of the panel. On the opposite slope the maximum horizontal displacement was 134 mm, also towards the centre of the panel, at a point 60 m South of the Northern panel edge.

In the veld, the maximum horizontal displacements were 148 and 163 mm on the Northern and Southern slopes respectively. On the Northern slope, the maximum occurred at a position 50 m South of the Northern panel edge in a direction 15° from the face line. On the Southern slope it occurred at a position 54 m North of the Southern panel edge in a direction 16° from the face line.



NO.	FACE TO 35 (m)	NO.	FACE TO 35 (m)
1	15	6	165
2	39		
3	75		
4	84		
5	102		

Figure 8.4 Horizontal displacements for various stages of subsidence of the deviation.

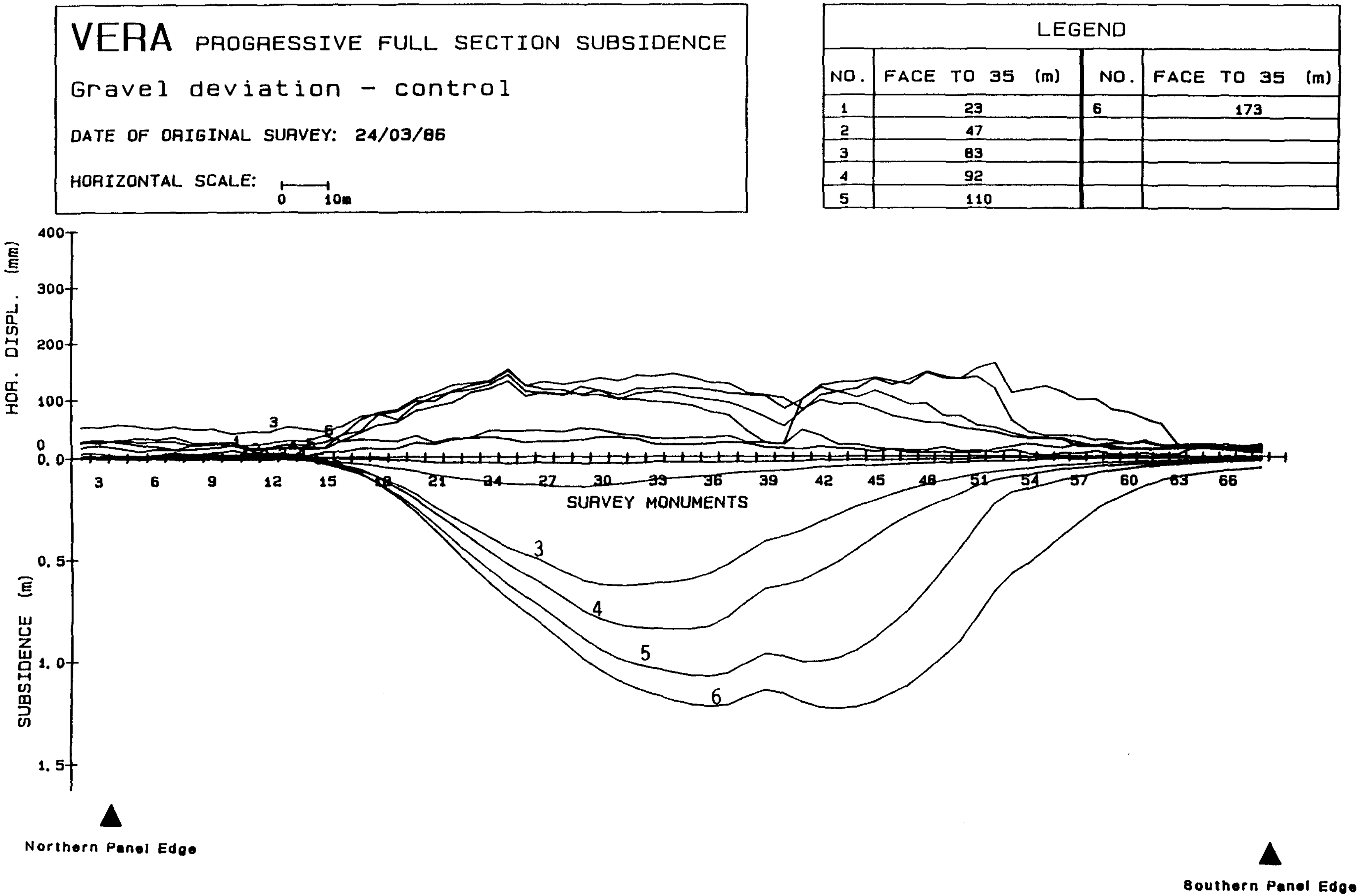


Figure 8.5 Horizontal displacements for various stages of subsidence of the veld next to the road.

Strain

The maximum Major Principal Strain on the road was found to be 8 mm/m (tension) and it was located near the top of the Northern slope, 53 m from the solid panel edge.

The Major Principal Strain is shown graphically as curve "C" in Figure 8.6 together with certain other parameters. Note that in Figure 8.6, the normal convention of plotting a moving 3 point average for strain values was followed. Figure 8.7 shows the progressive Major Principal Strains for various stages of undermining. It is learnt from Figure 8.7 that the position of the maximum Major Principal Strain shifted as undermining progressed, but that the magnitude of the maximum did not vary significantly.

The Minor Prinicipal Strain, shown as curve "D" in Figure 8.6, reached a minimum value of -11 mm/m in the region of the compressive ridge. Figure 8.8, comparing Minor Principal Strains for various stages of subsidence of the road, shows that no abnormal deviations occurred during the process of undermining.

Comparative data for the veld next to the road indicates that no significant differences in strain occurred. Curve "C" in Figure 8.9 shows the Major Principal Strain of the veld next to the

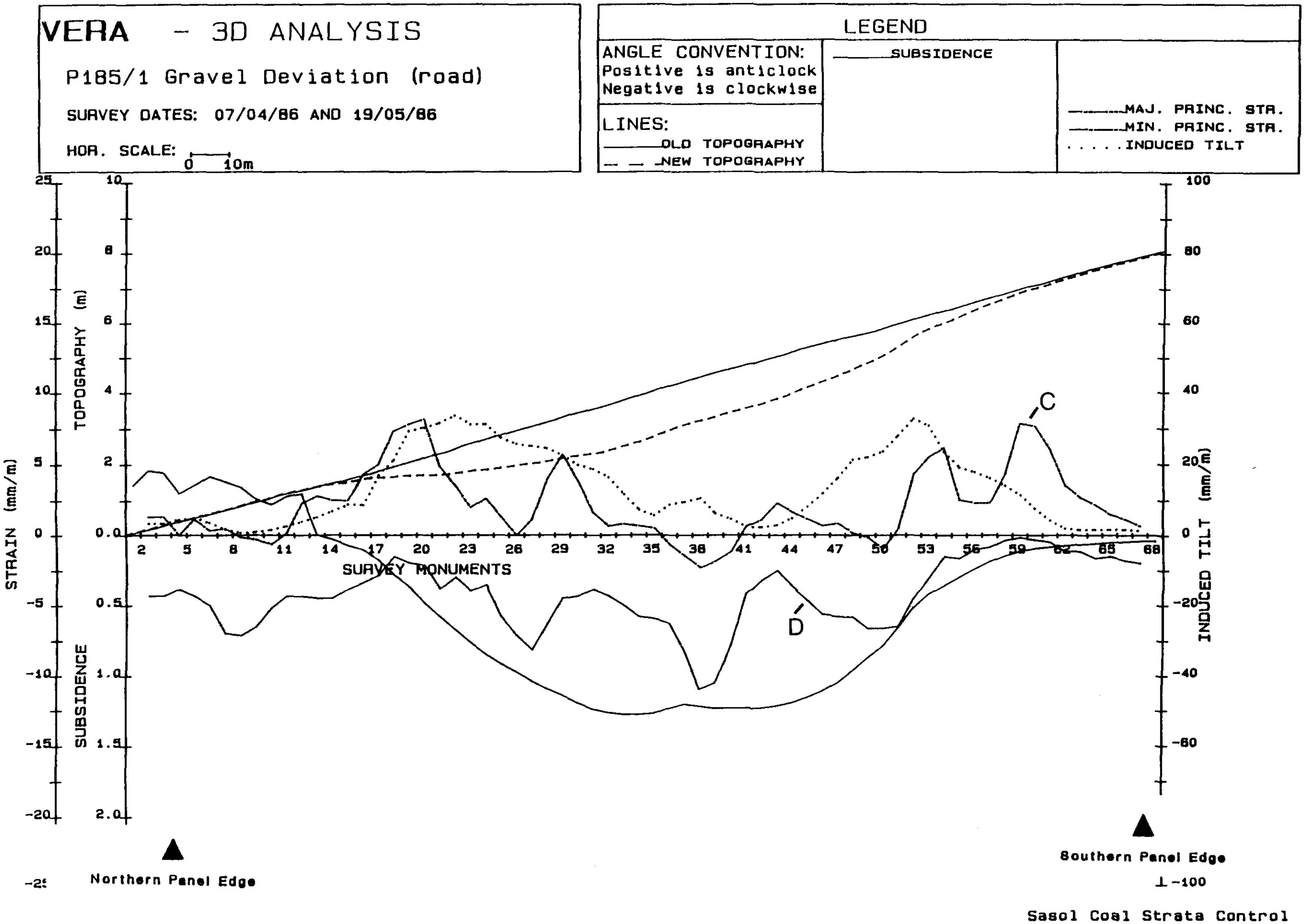


Figure 8.6 Final profile topographical change, Subsidence, Horizontal Displacement, Major Principal Strain and Minor Principal Strain

VERA PROGRESSIVE FULL SECTION SUBSIDENCE

Gravel deviation - control

DATE OF ORIGINAL SURVEY: 24/03/86

HORIZONTAL SCALE: 0 — 10m

LEGEND

NO.	FACE TO 35 (m)	NO.	FACE TO 35 (m)
1	23	6	173
2	47		
3	83		
4	92		
5	110		

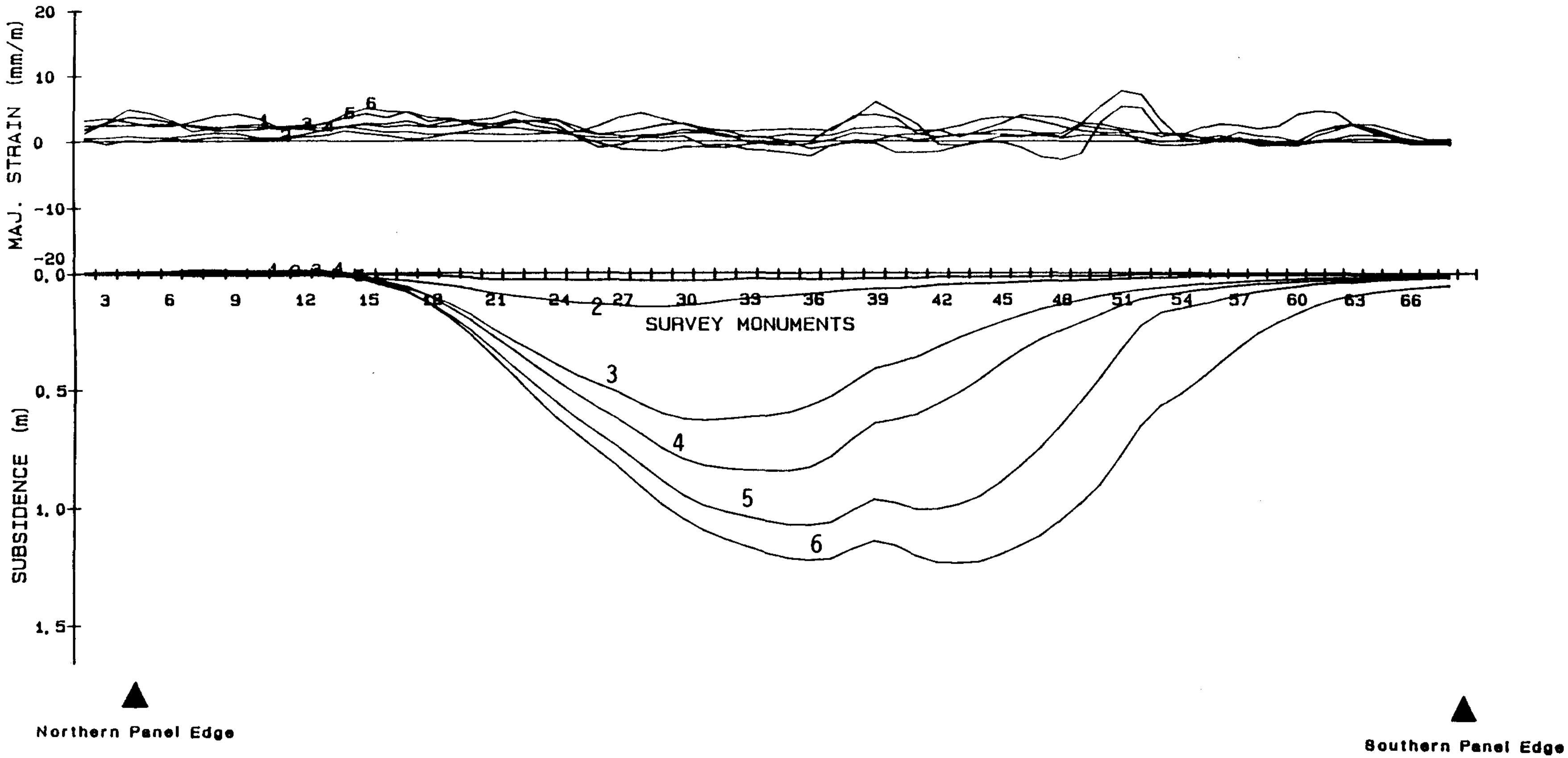


Figure 8.7. Major Principal Strains for progressive stages of subsidence of the road. Tensile strains are positive.

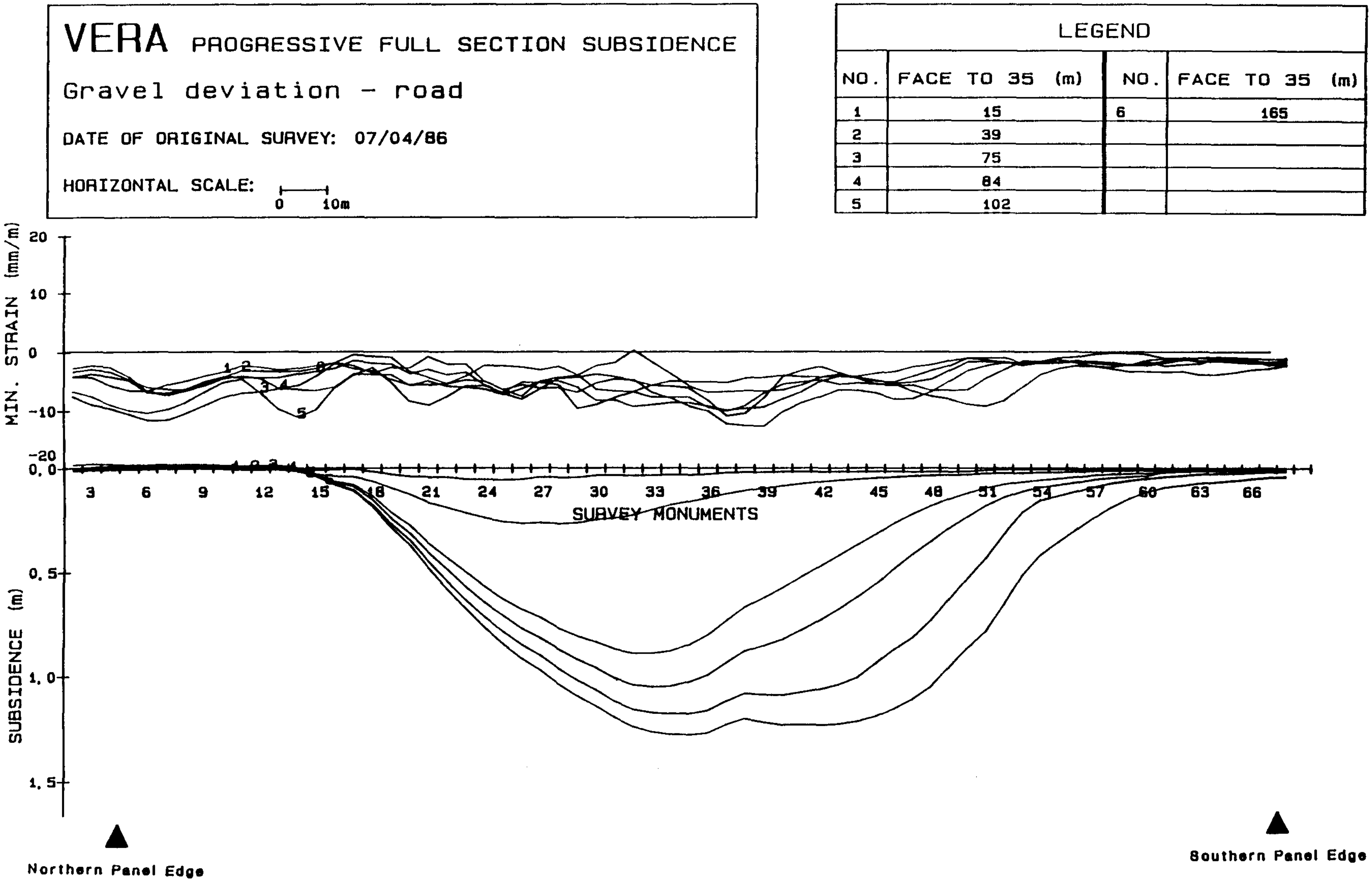


Figure 8.8 Minor Principal Strains for progressive stages of subsidence to the road. Compressive strains are negative

road, while curve "D" in the same Figure shows the Minor Principal Strain. It can be clearly seen that the compressive ridge can be regarded as a strain "hot spot".

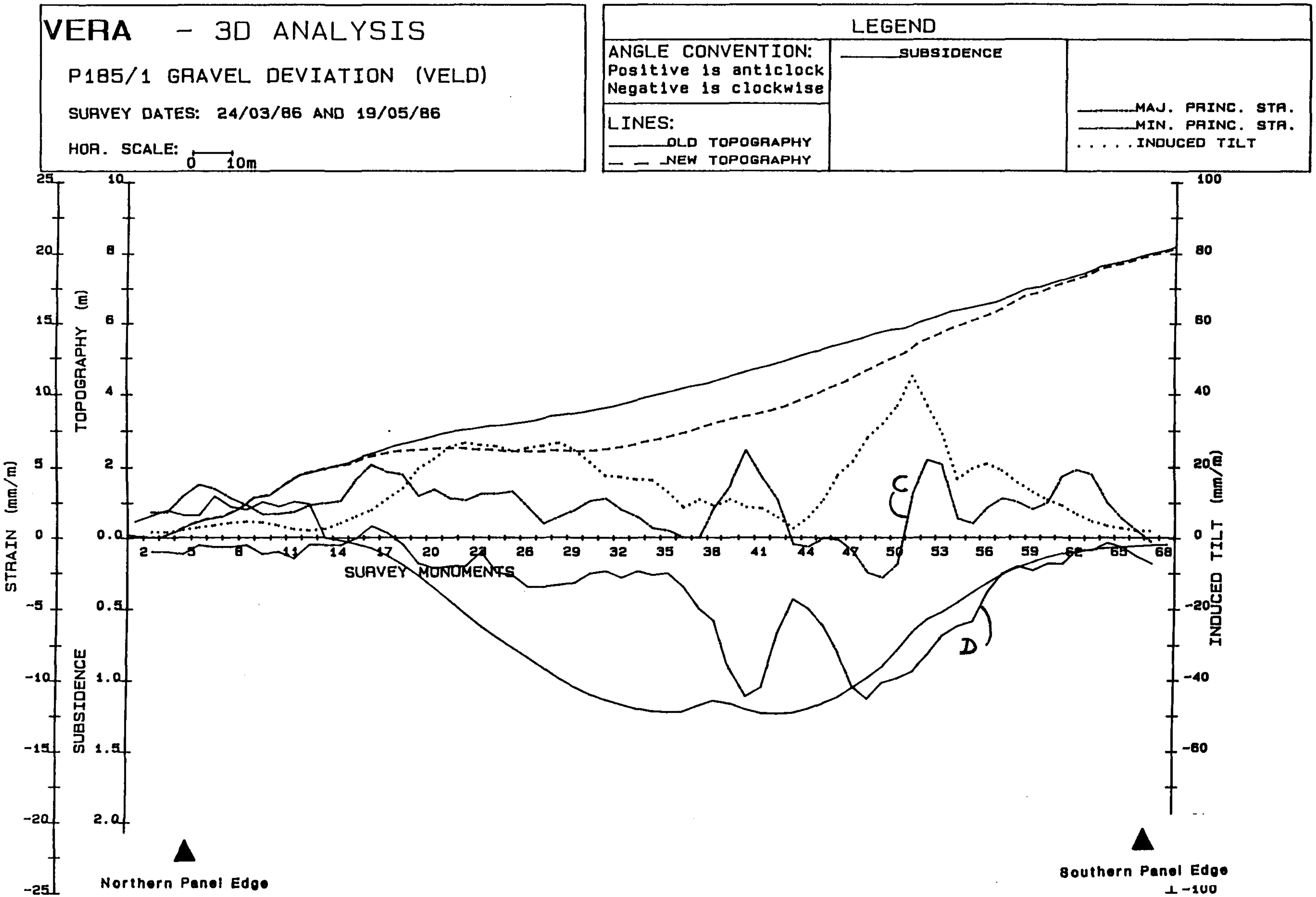
The greatest magnitude of Major Principal Strain associated with the edges was 6,5 mm/m at a position 57 m North of the Southern panel edge, while the greatest magnitude of Minor Principal Strain was -11,5 mm/m which occurred in the region of the ridge.

Figures 8.10 and 8.11 are graphical representations of Major and Minor Principal Strains for various stages of undermining. It can be seen from the figures that no strains of magnitudes greater than those already mentioned, occurred during the process of undermining.

Summary of Subsidence Elements

The subsidence elements described in the previous paragraphs are summarised in Table 8.1 below.

The locality in each case is measured perpendicularly to the panel edge, from the edge toward the centre of the panel. The distances pertaining to the compressive ridge are measured from the Southern edge.



Sasol Coal Strata Control

Figure 8.9 Final profile Topographical change, Subsidence, Horizontal Displacement, Major Principal Strain and Minor Principal

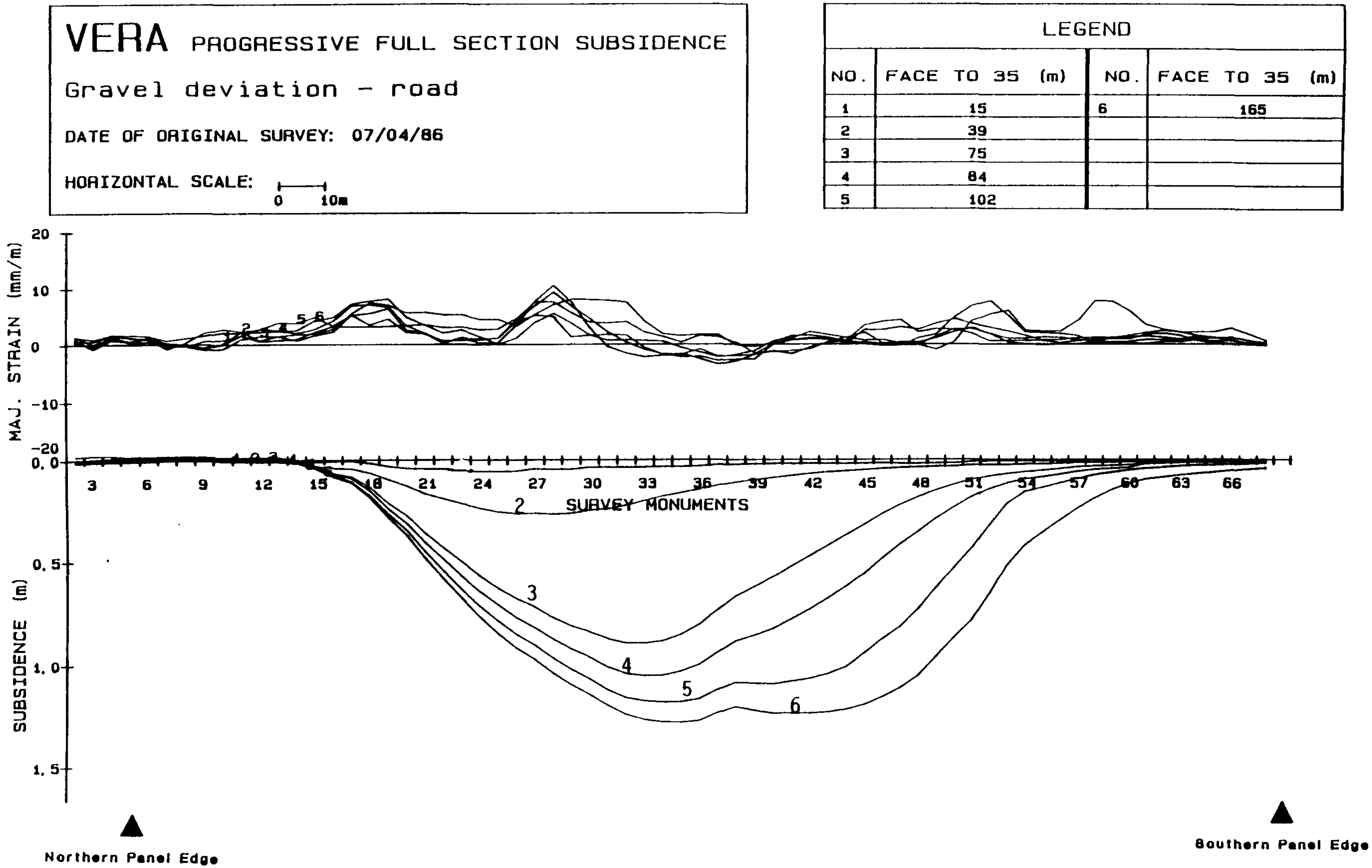


Figure 8.10 Major Principal Strains for various stages of subsidence of the deviation.

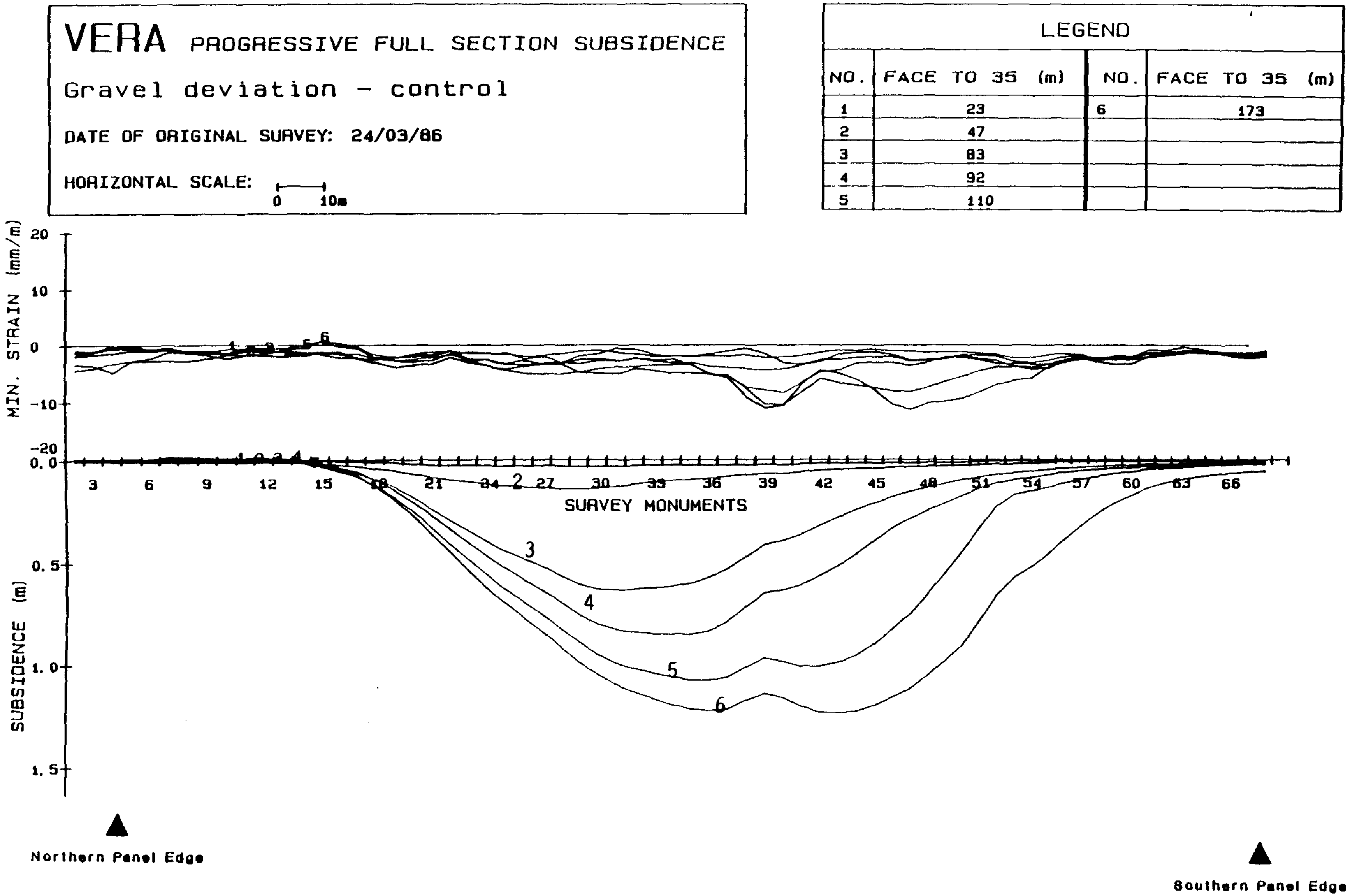


Figure 8.11 Minor Principal Strains for various stages of subsidence of the veld next to the deviation.

Table 8.1: **Summary of maximum Vertical Subsidence, maximum Induced Tilt, maximum Horizontal Displacement, maximum Major Principal Strain and maximum Minor Principal Strain for the Northern and Southern Slopes and the compressive ridge of the deviation and the veld next to the deviation.**

ELEMENT	DEVIATION			VELD		
	NORTH	SOUTH	RIDGE	NORTH	SOUTH	RIDGE
SUBSIDENCE (m)	-	1,24	1,21	-	1,24	1,09
LOCALITY (m)	-	89	97	-	82	94
TILT (mm/m)	33	31	11	28	46	11
LOCALITY (m)	40	45	90	78	60	92
HORIZONTAL DISPLACEMENT (mm)	134	211	110	148	163	95
LOCALITY (m)	60	74	90	50	54	92
MAJOR PRINCIPAL STRAIN (mm/m)	8	7,8	-2	5	6,5	7
LOCALITY (m)	53	32	95	39	57	96
MINOR PRINCIPAL STRAIN (mm/m)	-8	-6,0	-11	-3,5	-11,5	-11,5
LOCALITY (m)	78	67	90	74	70	57

The only significant difference between the subsidence elements found for the road and those in the veld is the magnitude of Major Principal Strain on the Northern slope, where a group of three wide cracks (each approximately 40 mm wide) were observed. This is believed to be a feature associated with the blocky nature of the underlying dolerite sill. The soil cover in the region was only some 1 - 2 m thick. The cracks were only 10 - 20 mm wide in the veld.

8.3.2 Effects on the road

The following is an extract from paragraph 6, pertaining to the undermining of the gravel deviation, of the report "Undermining of Road P185-1 (Kinross-Charl Cilliers): Summary of findings 1984-1988" by Dr F Netterberg of the National Institute for Transport and Road Research.

"Tension cracks up to about 40 mm in width occurred together with one transverse compression ridge up to 40 mm in height and 1 m in width. The gravel on this ridge was loosened to a depth of 350 mm.

Test runs in an ordinary car showed that the road, including the transverse ridge, could be safely negotiated at speeds of at least 80 km/h at all stages of undermining. Measurements of riding quality before and after undermining showed a decrease of

0,3 - 0,6 PSI units due to the undermining. However, the riding quality remained within acceptable limits. It was considered that a safe speed for the general public would be 60 km/h if the change in superelevation and loss in sighting distance were also taken into account. It was considered that the transverse ridge would have been compacted and would not have risen to such a height had the road been subjected to traffic during undermining. As the maximum damage also only occurred over a relatively short and predictable period of time it was also considered that an unpaved gravel road could be easily maintained to a high standard without the risk of wide cracks or significant ridging causing alarm to the travelling public.

After undermining had taken place the damage was repaired, the subbase, base and seal constructed, and the deviation reopened, in time for the main road to be closed in preparation for its undermining by the third panel. Apart from some slight, initial loss of surfacing, possibly due to carbonation during construction, this extension to the deviation has performed well, and no further damage due to subsidence or other causes has occurred."

8.4 CONCLUSIONS

There were no significant differences between the subsidence elements derived on the road and those in the veld next to the road. On both the road and the veld next to the road, a compressive ridge developed at the centre of the underground panel.

On the road, an easily discernable secondary ridge developed on the crest of the compressive ridge. The secondary ridge was observed to be flattened by a single pass of a motor vehicle. It may therefore be concluded that the ridge would not have developed if the road had been under traffic.

Regarding the effects of undermining on the gravel road, dr F Netterberg concluded as follows:

"Undermining of an untrafficked gravel deviation resulted in damage generally similar to that experienced by the main surfaced road and the surfaced portion of the deviation.

An un-maintained gravel deviation under conditions similar to those studied can probably be safely undermined under traffic provided the maximum speed can be limited to about 60 km/h. With maintenance a greater speed would be permissable."

The essence of these conclusions is that gravel roads may be undermined safely while under traffic. This conclusion is confirmed by the experience of undermining several gravel roads in the Secunda area in the past, which did not cause a single accident.

9 THE EFFECTS OF SUBSIDENCE ON AN OVERLAND CONVEYOR BELT

9.1 INTRODUCTION

9.1.1 Function and description of the conveyor belt

The conveyor belt which was experimentally undermined on two occasions, transports the total coal production of the Twistdraai Collliery (some 8 million tonnes per year) to the Sasol III coal storage yard. The belt runs continuously, being fed by a 12 000 tonne storage bin at the pit head. It is only stopped for routine maintenance and in the event of a breakdown.

The conveyor is 7,9 km long and is divided into three sections, each with an independant drive motor. The belt is 1,35 m wide and it runs at an average speed of 3,2 m/s under an average load of 2 000 tonnes/minute.

It is suspended on a steel structure which is held together by bolts, indicating that there is some flexibility in the structure. It is supported on steel legs spaced at 4 m. The legs are supported on circular concrete foundation blocks, 500 mm diameter by 500 mm deep. The belt is covered by cover plates to prevent dust pollution of the environment and wetting of the coal in the event of rain. A cross section of the structure is shown in Figure 9.1.

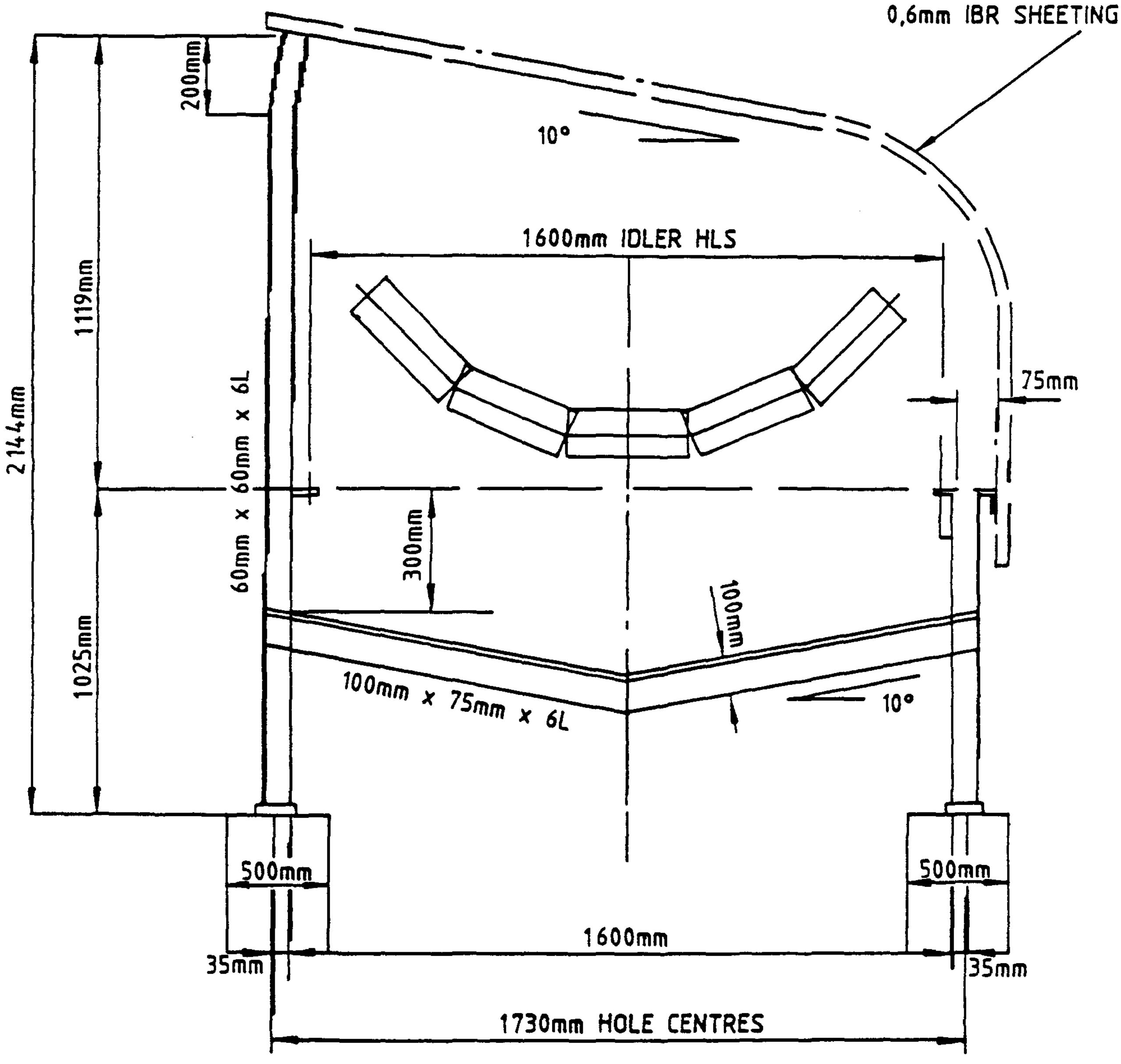


FIGURE 9.1 Typical cross section of the conveyor belt structure.

9.1.2 Benefit to be derived from undermining

The total amount of coal potentially sterilised by overland conveyor belts in the Secunda area alone is approximately 20 million tonnes. With longwalling, the loss would be significantly more as longwalling is not a sufficiently flexible mining method to allow for selective mining within a panel. Therefore, portions of potentially mineable longwall panels significantly greater than the area sterilized by the legal requirement would be lost if conveyor belts could not be undermined.

The seriousness of an unexpected breakage due to subsidence was lessened somewhat by the fact that only the factory and the mine would be affected. The loss in revenue would still be substantial, but at least other parties would not be involved. Also, there was no question of a risk of safety to people, as in the case of public roads.

9.2 REQUIREMENTS AND PRECAUTIONS

9.2.1 Requirements

As in the case of the design of most other structures, no thought was given to the possible effects of subsidence on a conveyor belt. Conveyor belts are primarily designed for a relatively static environment, yet are fairly robust structures and can tolerate at least some displacement. The tolerances are not readily quantifiable, but can accommodate seasonal changes in elevation caused by clay swell, easily.

The major requirements for the alignment of a conveyor belt are that it must remain straight longitudinally, that inclinations must not exceed 18° (325 mm/m) and that it must be level in the transverse direction, the maximum allowed lateral tilt being 5° (87 mm/m). As for changes in length due to undermining, the limits could not be ascertained. Due to the fact that the changes caused by subsidence were relatively small, they ought to be easily catered for by the latitude allowed by the take-up spools at the ends of the belt sections, where several meters of length change can be accommodated.

9.2.2 Precautions

Horizontal displacement was identified as the single parameter most likely to cause a disruption in the availability of the conveyor. It was catered for by cutting the bolts attaching the legs of the structure to the foundation blocks. Thereby the ground surface would be allowed to move freely underneath the structure, which was expected to have sufficient rigidity in the longitudinal direction to maintain itself in a straight line.

Subsidence was measured daily, and apart from that an engineering inspection was carried out at eight hour intervals during the period of active subsidence.

Maintenance was done as required. It consisted mainly of welding plates onto the bottoms of the legs of the structure to maintain contact with the foundation blocks, in order not to place excessive strain on the structure. An example of such a leg is shown in Plate 9.

9.3 MINING PARAMETERS

The layout of the underground panels relative to the conveyor belts are shown in Figures 9.2 and 9.3. It can be seen that in the case of Panel 1, maximum lateral tilting of the belt was expected as the belt cut across one corner of the panel.

In the case of Panel 2, the lateral tilt was expected to be less, but spread over a longer distance. The panel width was increased in two steps from 125 to 230 metres, to make allowance for a dyke on the Eastern side of the panel.

The mining height was 3 m in both instances. Panel 1 was 130 m deep and 230 m wide. Panel 2 was also 130 m deep and the width respectively 125 m, 180 m and 230 m for the three stages shown in Figure 9.3. The stratigraphy is shown in Figure 9.4.

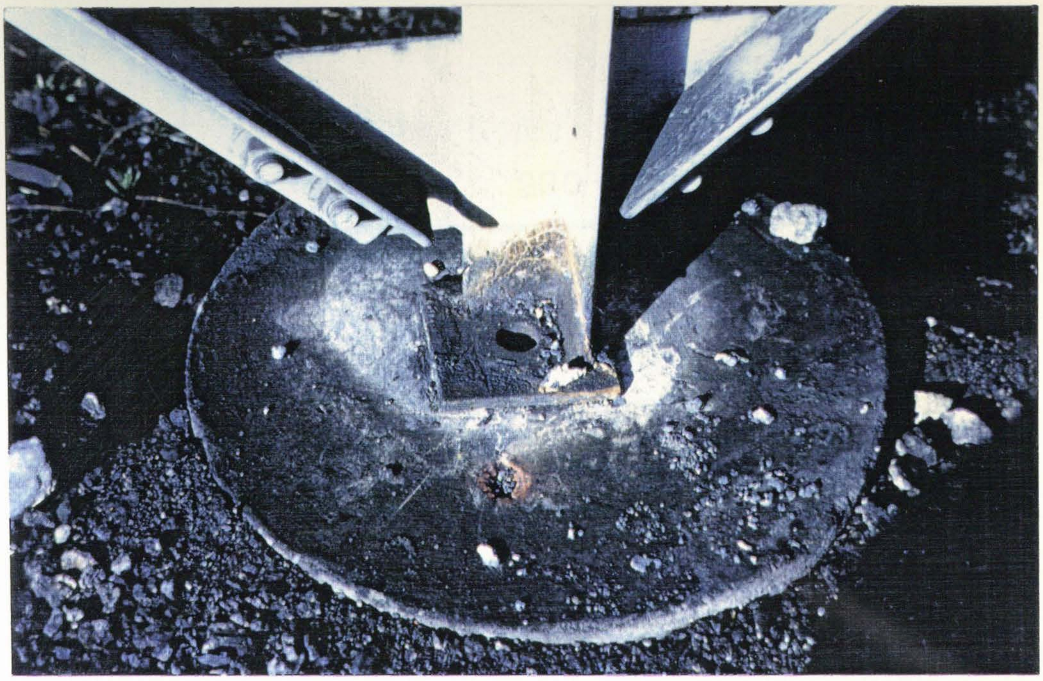


PLATE 9 The leg of the conveyor belt structure after the bolt attaching it to the concrete foundation block had been cut loose.

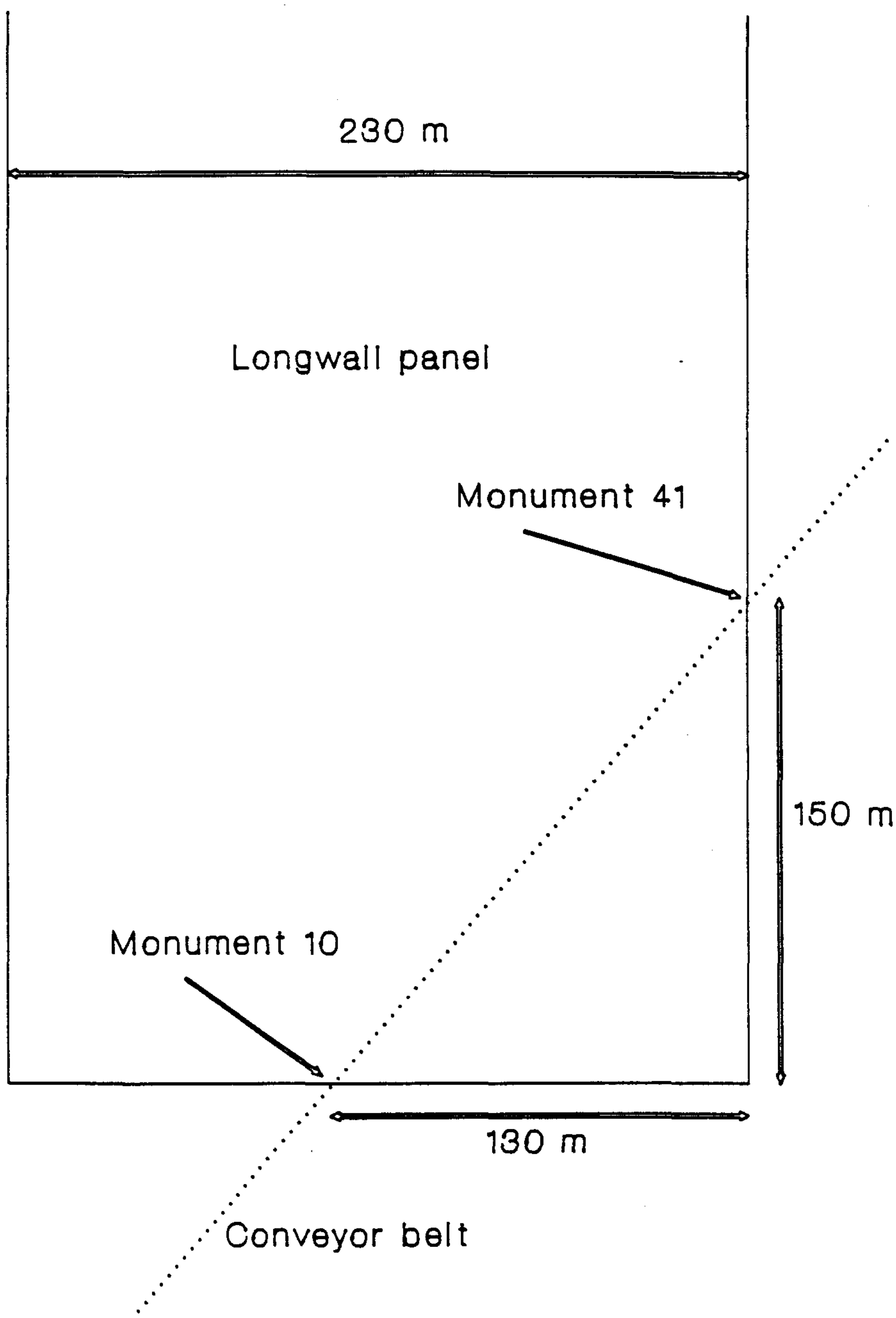


Figure 9.2 Position of the conveyor belt relative to the longwall panel.

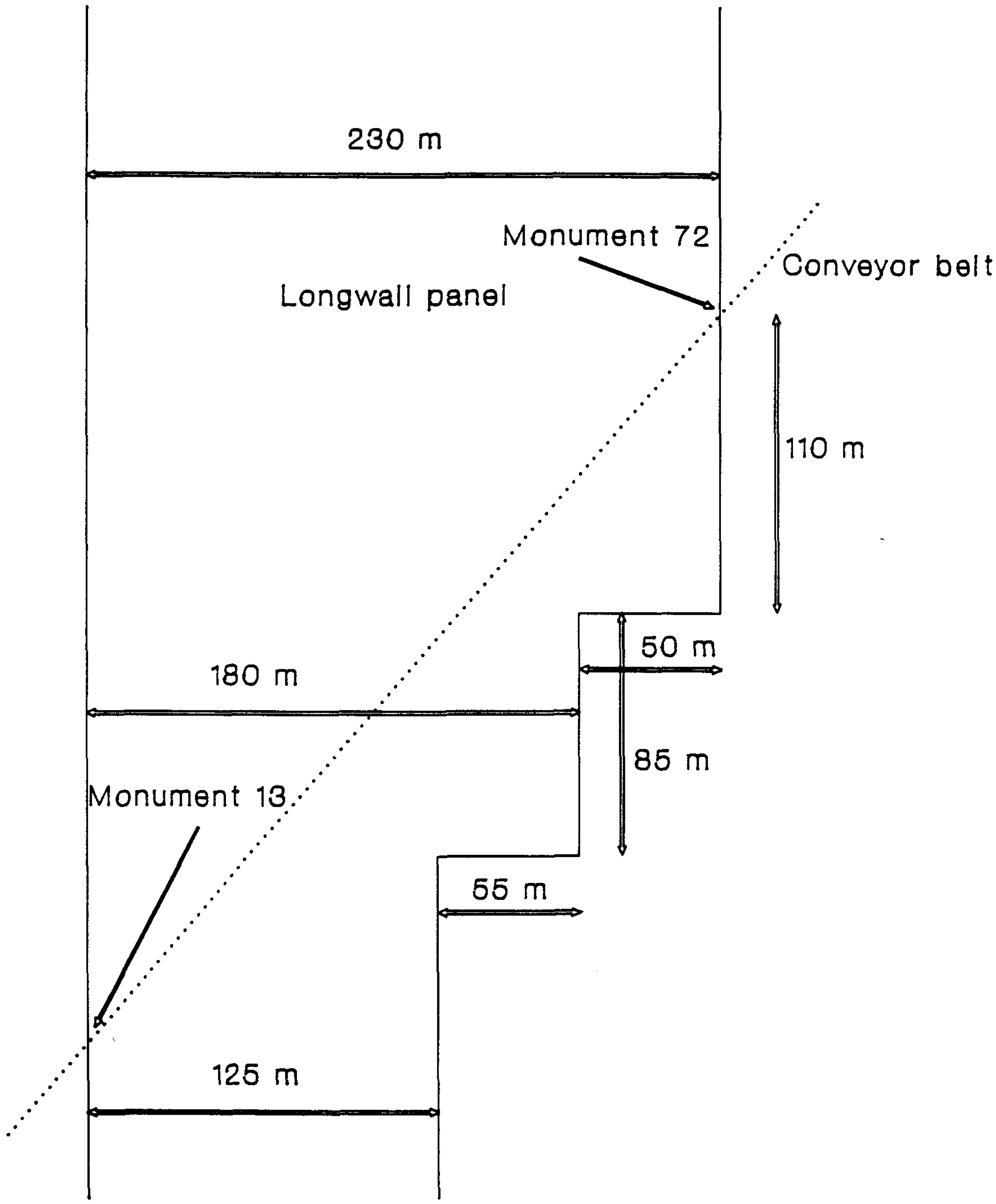


Figure 9.3 Position of the conveyor belt relative to the longwall panel during the second undermining of the conveyor. The increase in panel width in two stages is also shown.

9.4 OBSERVATIONS

9.4.1 Subsidence measurements

Maximum magnitudes of subsidence elements

The maximum magnitudes of the various subsidence elements are summarised in Table 9.1. Note that Principal Strains and Major Tilts are quoted.

Due to the difficulty of obtaining measurements on both sides of the conveyor belt simultaneously, the measurements were obtained in the veld immediately adjacent to the conveyor belt. In that position the survey monuments could not be damaged by maintenance work on the conveyor, which was an added advantage of measuring in this way.

Although the vertical subsidence in the two cases were similar, Panel 1 was characterised by significantly greater magnitudes of the other subsidence elements when compared to Panel 2. The reason for this observation is believed to be that in the case of Panel 1, the conveyor was situated over the beginning of the panel. It has often been seen that the first subsidence on a panel usually exhibits greater induced tilts and strains, which are manifested in wider surface cracks.

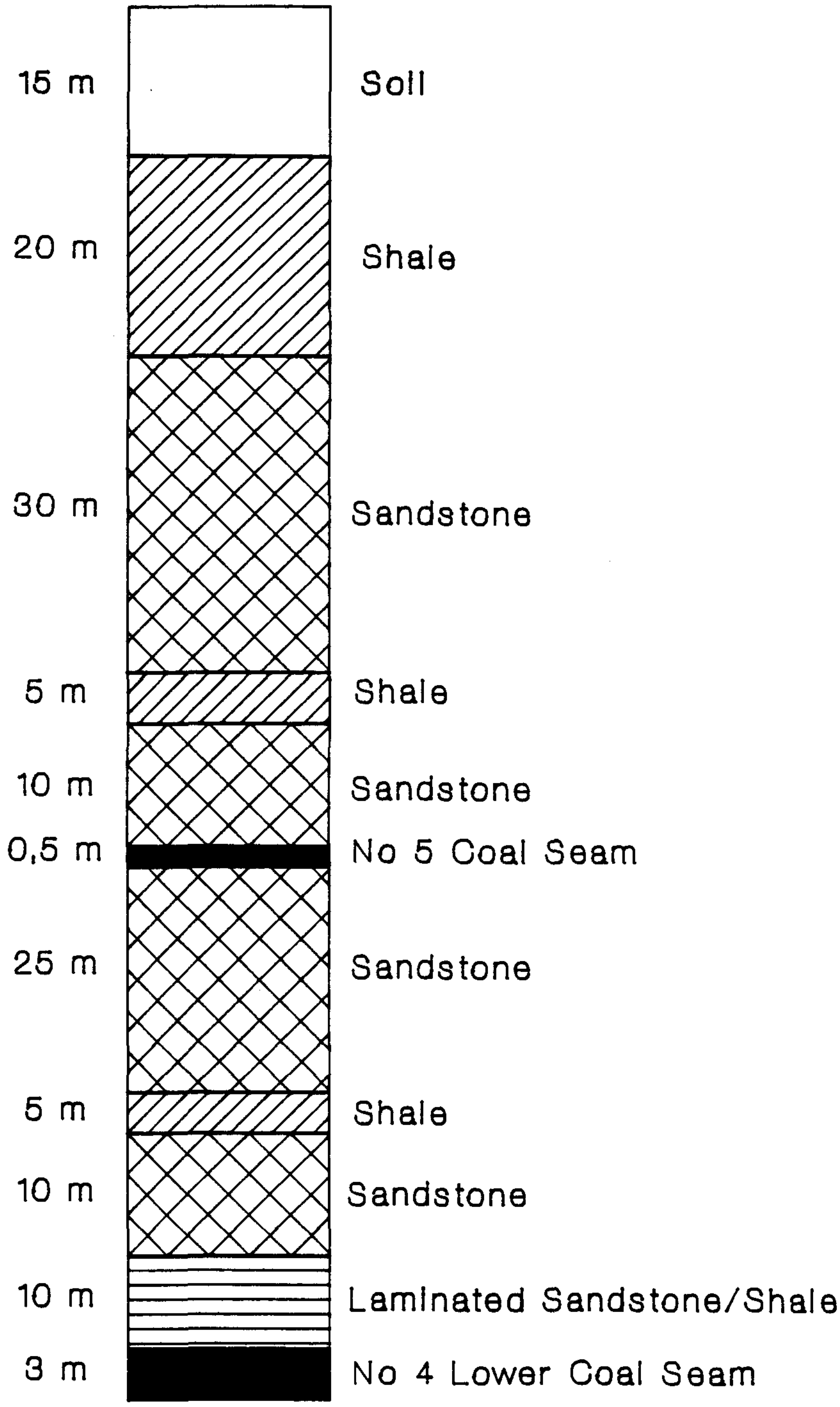


Figure 9.4 Simplified stratigraphical section of the overburden at the undermining of the conveyor belts.

Table 9.1: Maximum magnitudes of the subsidence elements for the two underminings of the conveyor belt

SUBSIDENCE ELEMENT	PANEL 1	PANEL 2
Vertical subsidence	1,46 m	1,43 m
Horizontal displacement	375 mm	132 mm
Major Principal Strain	16 mm/m	3,5 mm/m
Minor Principal Strain	-18,5 mm/m	-7,5 mm/m
Major induced tilt	65 mm/m	46 mm/m
Longitudinal tilt	60 mm/m	31 mm/m
Transverse tilt	50 mm/m	35 mm/m

Distribution of subsidence elements

The subsidence profile, induced Major Tilt and Major and Minor Principal Strains for Panel 1 are shown in Figure 9.5. Figure 9.6 contains similar curves for Panel 2.

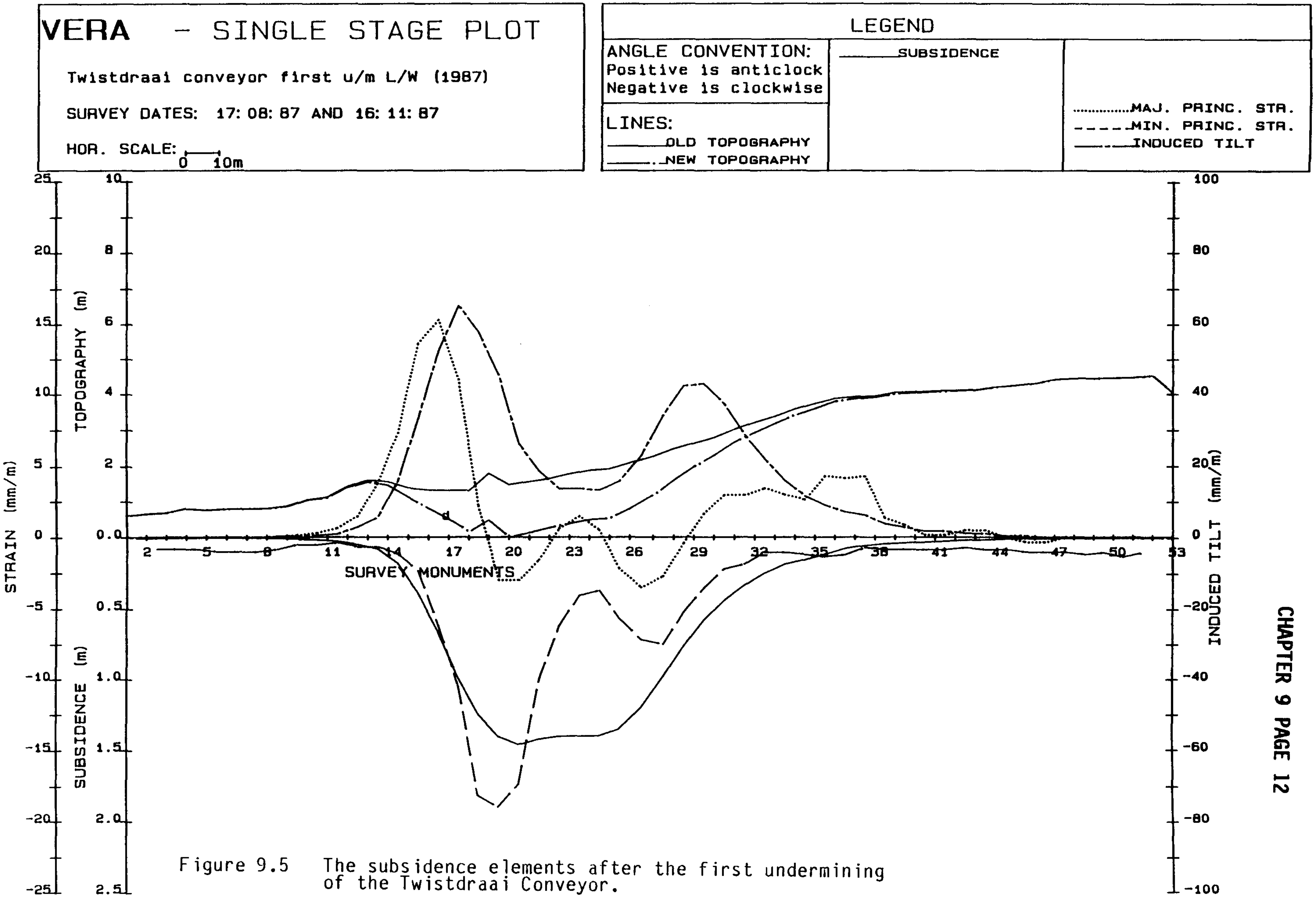


Figure 9.5 The subsidence elements after the first undermining of the Twistdraai Conveyor.

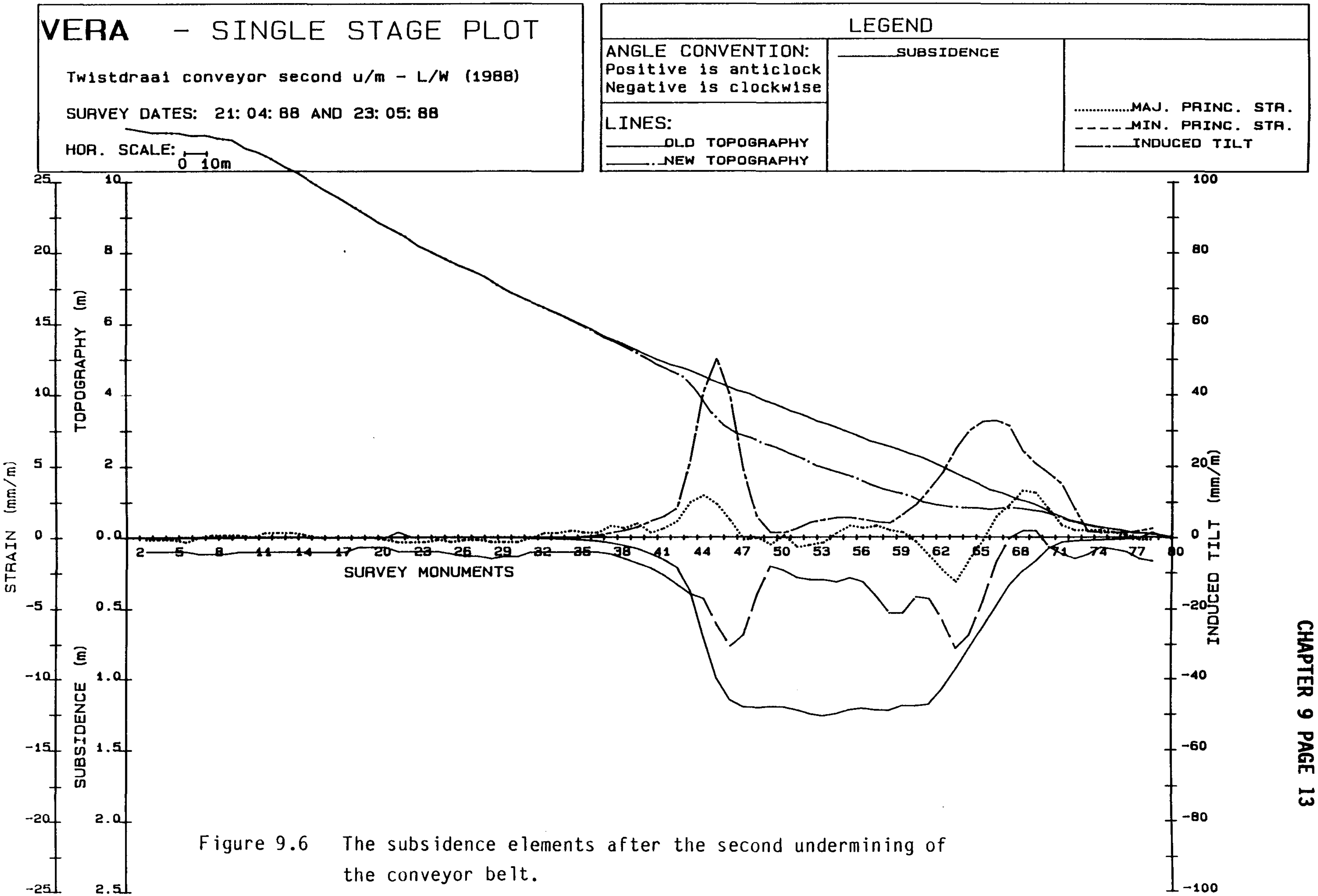


Figure 9.6 The subsidence elements after the second undermining of the conveyor belt.

Comparison of the two curves confirms that the magnitudes of the subsidence elements for Panel 1 generally exceed those for Panel 2. Furthermore, no out of place trends are observed.

Figures 9.7 and 9.8 show plan views of the horizontal displacements (exaggerated) of the individual measurement beacons over Panels 1 and 2 respectively.

It can be seen that in both cases, the soil underneath the structures underwent snaking - in the case of Panel 1, double snaking is even observed. Figures 9.7 and 9.8 also indicate very clearly, by observing the paths traced for the individual monuments, that the final destination of a point on surface does not necessarily represent the point of maximum displacement. Surface points are not displaced in a straight line horizontally. As the structures were loosened from the soil, however, the horizontal displacements did not affect them. The figures indicate that no abnormally large horizontal displacements were present during the interim phases.

9.4.2 Visual observations

Several cracks were observed on the ground surface. The largest cracks over Panel 1 were approximately 70 mm wide, but the average width was 20 - 50 mm. Over Panel 2 the widest crack was approximately 40 mm, the general trend being 10 - 30 mm.

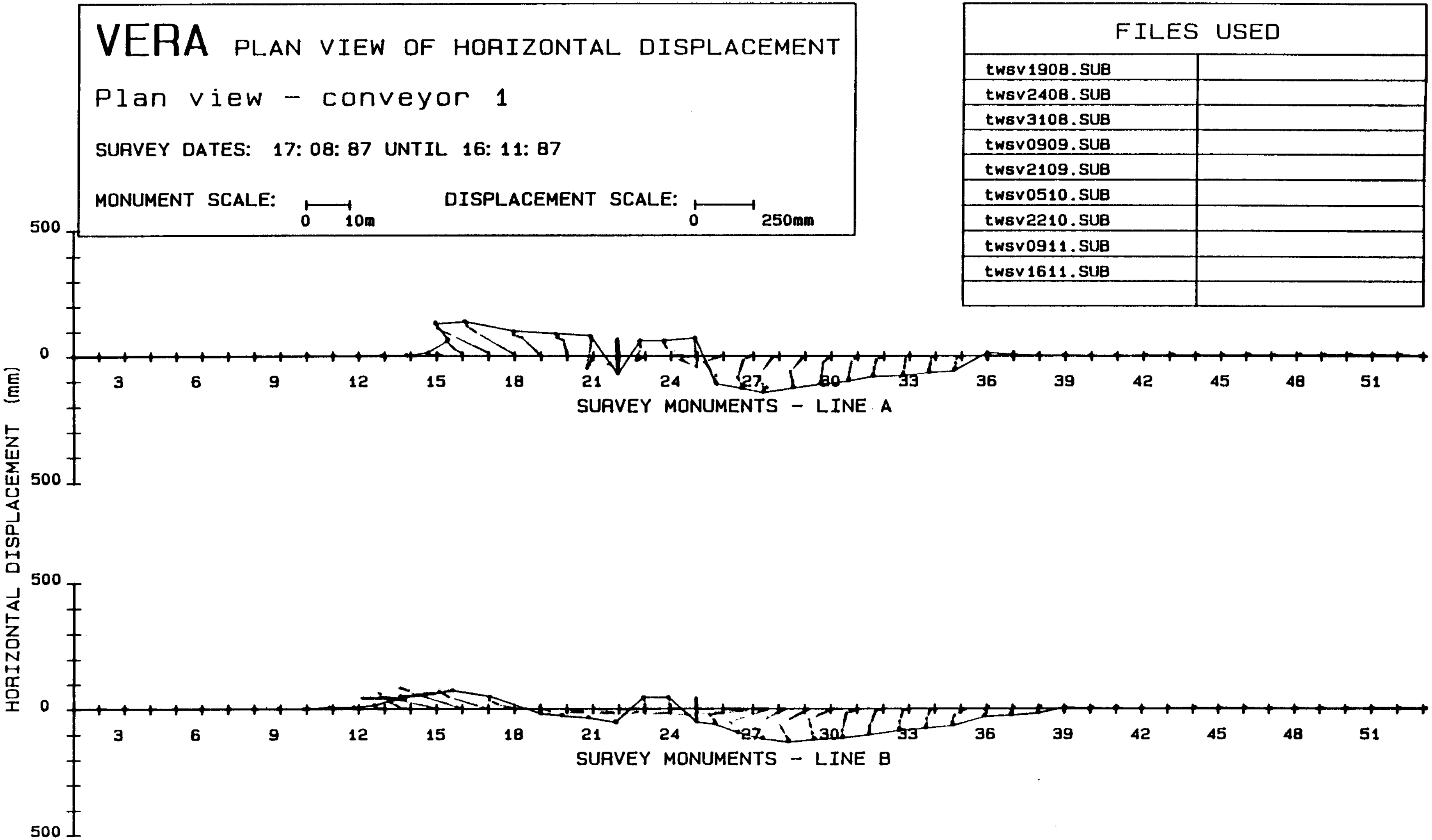


Figure 9.7 Plan view of the horizontal displacement of the ground next to the conveyor during the first undermining.

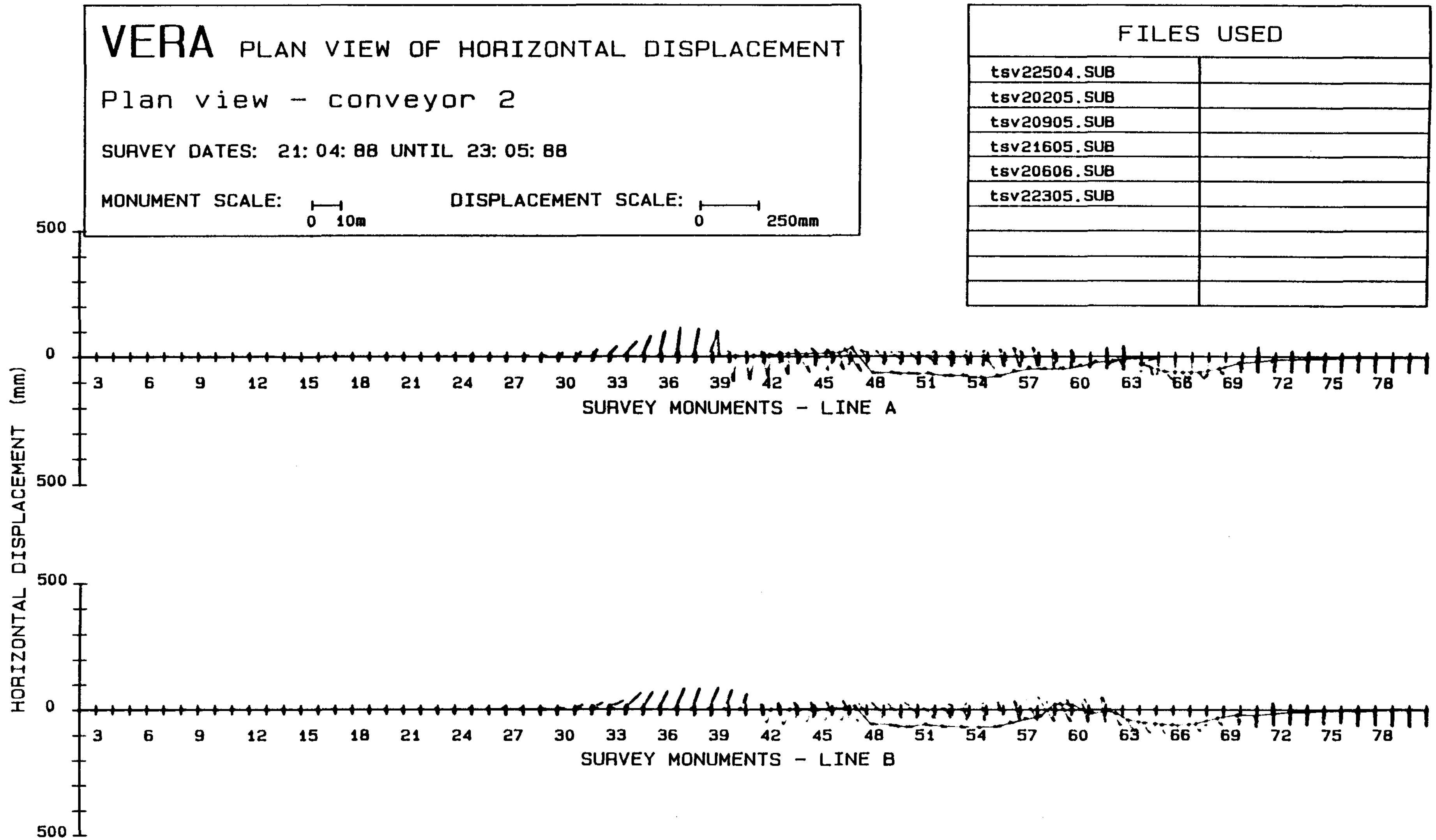


Figure 9.8 Plan view of the horizontal displacement (exaggerated) of the ground next to the conveyor during the second undermining. Note that in the region of monuments 32 to 47, the monuments returned to their original positions.

Horizontal displacement was seen where the foundation blocks had been laterally displaced underneath the legs of the structure. Compressive strain was manifested in the buckling, in a single location, of the cover plates of the structure. This is shown in Plate 10. The damage was of a cosmetic nature, and did not warrant urgent repair. The damage occurred in the only position where the compressive strain was less than -15 mm/m. Over Panel 2, where the compressive strain was never less than -7,5 mm/m, no such damage occurred.

9.5 EFFECTS ON THE STRUCTURE

Apart from the buckling of the cover plates, no adverse effects occurred on the structure at either panel. The belts were never stopped due to subsidence or maintenance work caused by subsidence.

In one instance, the foundation block underneath a leg was displaced to the extent that a substitute foundation had to be supplied. This was done by placing a steel beam next to the foundation block. The leg of the structure then came to rest on the beam after it had moved off the concrete block. This occurrence was foreseen, following from the regular inspections. No disruption was thus caused. At Panel 2 the horizontal displacement was small enough not to require substitute foundations.

PLATE 10 Compressive strain caused the buckling of the cover plates shown in the photograph.

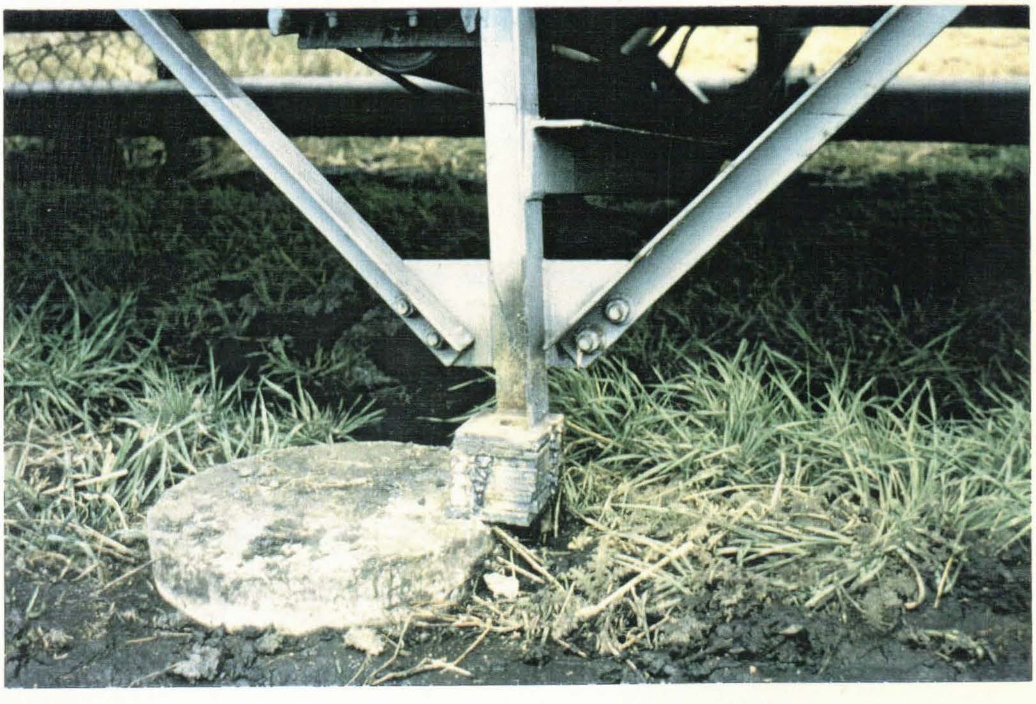


PLATE 11 Detail of a leg of the conveyor belt structure, showing the plates which were welded on and the amount of horizontal displacement.

The welding of steel washers onto the legs to compensate for vertical subsidence was required to a far lesser extent than expected. At the position of maximum subsidence at Panel 1, the total thickness of washers supplied was less than 300 mm. At Panel 2 no washers were required. Plate 11 illustrates a leg with washers welded onto it, and the extent of relative horizontal displacement between the structure and the foundation.

Differential height adjustment of corresponding legs to compensate for induced transverse tilt was done in ten instances, all at Panel 1. Although this was strictly speaking not required according to the allowable tilt limits, it was nonetheless done at the same time as providing washers for height adjustment to restore the transverse inclination of the belt to zero.

No other structural damage occurred. No bolts were sheared or had to be replaced, and no beams were visibly bent.

Three years after the underminings, both conveyors were still functioning smoothly.

Subsequent underminings

Subsequent to the two cases described here, similar conveyor belt structures were undermined by pillar extraction on three occasions. On all three occasions, less subsidence than described here occurred, due both to narrower panels and the mining method. The same precautions - with the exception of detailed subsidence monitoring - as described in previous paragraphs were taken on all three occasions.

No anomalies were observed. To date, the buckling of the cover plates and the necessity to provide a substitute foundation, both of which occurred over Panel 1, remain the most serious damage caused by subsidence on a conveyor belt. Similar types of effects, but of a smaller magnitude, were observed on all three occasions.

9.6 CONCLUSIONS

(a) The slight nature of the maintenance which was required is indicative of the inherent flexibility of the structure, notwithstanding the fact that it was not designed to accommodate mining induced subsidence.

(b) Conveyor belts of construction similar to the one described here (which is a fairly typical construction), can be safely undermined without costly precautions like telescopic legs. Loosening the structure from its foundation temporarily, coupled with ongoing monitoring and maintenance, are sufficient precautions.

(c) As shown by the difference between the observations at Panels 1 and 2, the position and direction of the conveyor relative to the panel layout are very important. The position of the conveyor over Panel 1 was probably the worst possible, as shown by the magnitudes of induced tilt and strain.

The importance of the direction of the conveyor belt relative to the underground panel is emphasized further by the differences in the longitudinal and transverse tilts and the Major Induced Tilt. It is purely by virtue of the position of the structure that the Major Induced Tilt did not occur transversely across the belt.

It is unlikely that induced tilt in the longitudinal direction will have a serious effect on a conveyor belt, except in instances where the topography is such that pre-mining inclinations close to the limit of 325 mm/m are present. In such cases the tilt induced by mining may result in a final tilt in excess of the limit.

However, in the transverse direction problems may arise easier. It is therefore important that a direction of the conveyor belt parallel to the long axis of a panel, at the positions of excessive induced tilt, be avoided. If it cannot be avoided, planning to compensate for the tilt is required. If a conveyor belt is situated such as to run perpendicularly across a panel, excessive lateral tilts may only be induced temporarily by the passing subsidence wave. No permanent adjustments should be required in those cases, the worst inconvenience probably being temporary spillage from the belt if no adjustments are made.

The most important conclusion to be reached is that the subsidence elements as well as the effects on the conveyor belt are predictable and can be accommodated. The knowledge exists to enable effective maintenance plans to be made beforehand. There is no reason for the availability of a conveyor belt to be disrupted by mining induced subsidence.

(d) It can be safely concluded that the following magnitudes of the various subsidence elements can be tolerated without causing structural damage to a conveyor belt structure of the type which was monitored:

Tensile strain: 16 mm/m,

Compressive strain: -18,5 mm/m,

Transverse tilt: 87 mm/m,

Longitudinal tilt: such that the total inclination does not exceed 325 mm/m, Horizontal displacement: Half the width of the foundation block, provided the structure can be kept straight.

(e) When designing to accommodate greater magnitudes of subsidence, the following modifications to a conveyor belt structure may be considered:

Floating foundations

Corresponding legs of the conveyor should be fastened to a single raft-like floating foundation. This will prevent the legs being forced open. Horizontal displacement can be compensated for by pushing the individual rafts into position with a dozer.

Telescopic legs

The structure should be supported on legs capable of individual adjustment. This will enable vertical adjustment to compensate for vertical subsidence to be made, as well as re-aligning the level of the belt in the transverse direction. Excessive transverse tilts may lead to spillage of coal off the belt and excessive wear of the rollers.

10 THE EFFECTS OF SUBSIDENCE ON A BURIED WATER PIPE LINE

10.1 INTRODUCTION

The provision of water is an essential element of infrastructure. Water is also one of the main requirements of the Sasol factories and the mines. In Secunda, the water is primarily supplied by the Department of Water Affairs. The water is piped from the Grootdraai Dam to the Bosjesspruit Dam, from where it is distributed to the various mines and factories.

The pipe line from the Grootdraai Dam to the Bosjesspruit Dam is underlain by coal reserves of the Bosjesspruit Colliery. It is situated such that if it was not undermined, a number of longwall panels would have had to be shortened to the extent that their profitability was in the balance. It had previously been undermined by longwalling, but in that instance it just crossed a corner of a panel and no subsidence occurred at the pipe. This chapter is concerned with the second undermining, where meaningful subsidence was expected and did occur.

10.2 DESCRIPTION OF PIPE

The pipe diameter was 1 140 mm, with a 9 mm wall thickness. It was a steel pipe, SABS Mild Steel 719 Gr A, consisting of 9 m sections welded together. The pipe was covered on the inside as well as outside with a 10-15 mm layer of bitumen for protection against corrosion.

The pipe was buried to a depth of 2 m to 3 m, depending on the depth of soil and the nature of the topography. The ditch was excavated 1 m deeper than required and filled with dolerite gravel to form a bed for the pipe. After the pipe was lain, the ditch was covered to surface. Covered inspection openings were provided at 500 m intervals.

10.3 MINING PARAMETERS

The mining height was 3 m and the depth 183 m. The panel width was 210 m. Figure 10.1 shows the underground layout and the position of the pipe line.

The stratigraphy is shown in Figure 10.2. Of importance is the 55 m thick dolerite sill near the surface. According to the Galvin formula, equation (2.16), it was expected to fail, as it was close to the critical span for dolerite failure -197 m as compared to the actual span of 210 m. Even though doubts regarding the validity of equation (2.16) existed at the time, it was assumed that the sill would fail and that subsidence of the order of 1,2 - 1,3 m had to be expected.

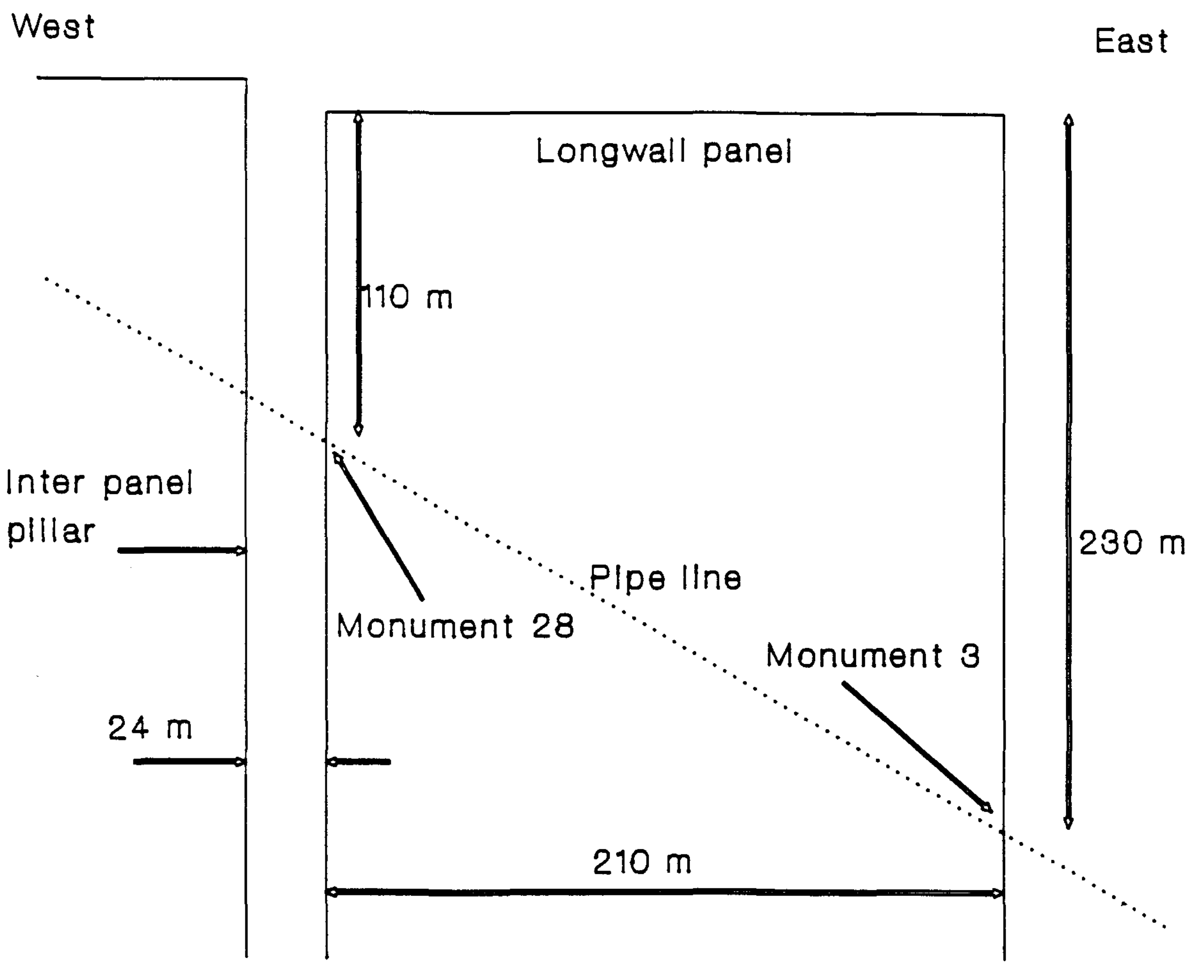


Figure 10.1 Position of the Pipe line relative to the longwall panels. No subsidence was recorded at the pipe over the panel on the Western side, presumably due to the position of the pipe and the fact that the dolerite sill did not fall.

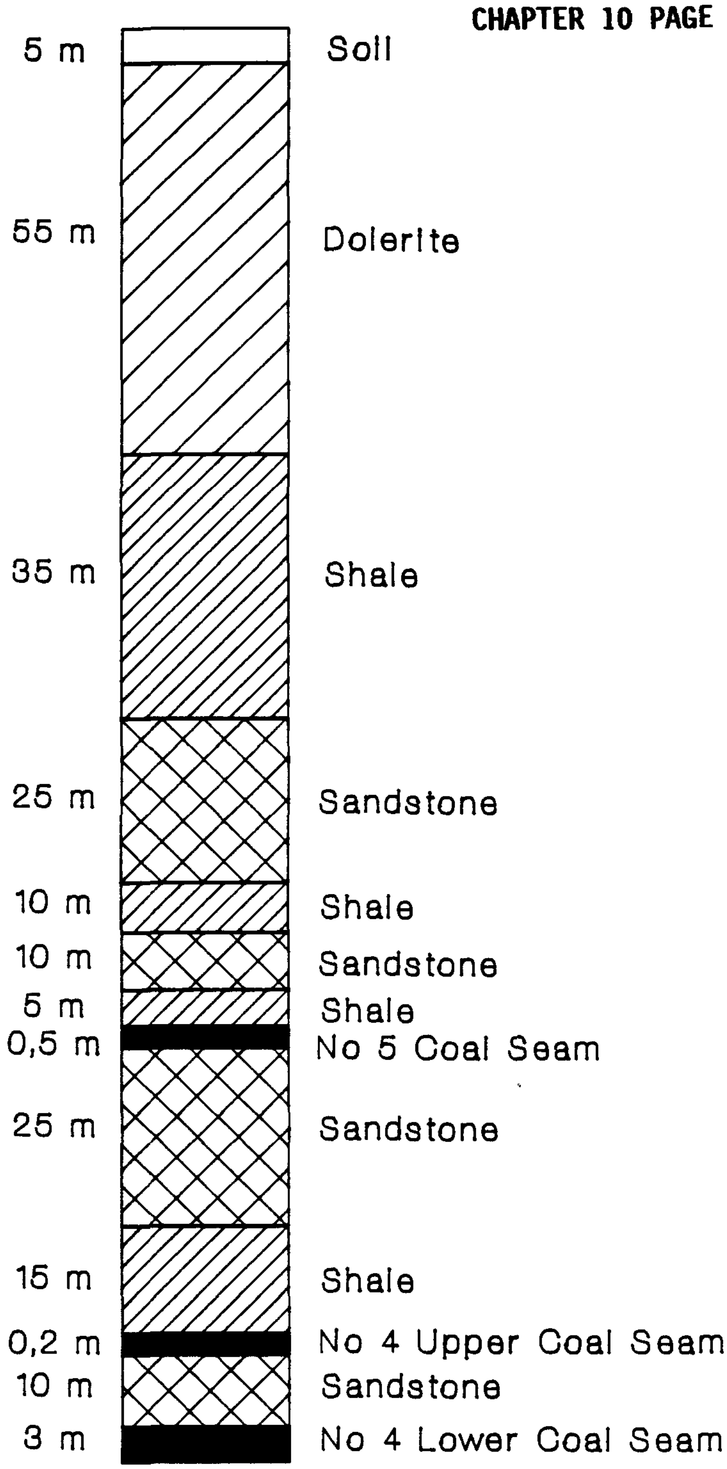


Figure 10.2 Simplified stratigraphy at the site of the pipe undermining.

10.4 PRECAUTIONS

Although it was considered pertinent to uncover the pipe line, thereby loosening it from its environment and allowing free displacement, the officials of the Department of Water Affairs felt that it would not be necessary. Their opinion was that the pipe would be able to withstand the predicted displacements without being damaged. The main concern was that the bitumen insulation material would be damaged in the excavating process, giving rise to corrosion problems later.

The pipe was therefore not uncovered completely. Inspection pits were dug down to the pipe at 10 m intervals, with the intention of attaching strain gauges to the pipe. However, several heavy rainstorms resulted in frequent flooding of the pits and that part of the monitoring could not be done.

The contingency plan consisted of two aspects. Firstly, the Bosjesspruit Dam would be maintained at full levels all the time, thereby ensuring a minimum of 10 days' water supply to the mines and factories. Secondly, spare pipe sections and excavating equipment was kept on site to effect emergency repairs, should it be required.

Subsidence monitoring was done daily during the period of active subsidence. Daily inspection for signs of water leakage and constant monitoring of water flow by Water Affairs to detect leakages also formed part of the contingency system.

10.5 SUBSIDENCE OBSERVATIONS

10.5.1 Maximum magnitudes of subsidence elements

The magnitudes of the maxima of the various subsidence elements which occurred in the veld adjacent to the pipe are listed in Table 10.1. It can be seen by the relatively small magnitude of subsidence, 0,81 m, that the dolerite sill did not fail completely. The other elements similarly display low maximum magnitudes.

10.5.2 Distribution of the subsidence elements

Figure 10.3 shows the distribution along the subsidence profile of the Linear Strains and the Induced Major Tilt. The figure shows that no significant anomalies were present.

The only noticeable feature is the amount of subsidence over the Western ribside, which did not take place over the Eastern ribside. This is believed to be due to the weight of the overburden compressing the inter panel pillars on that side of the panel. As the dolerite sill did not fail, higher abutment loads would be encountered underground. On the Eastern side,

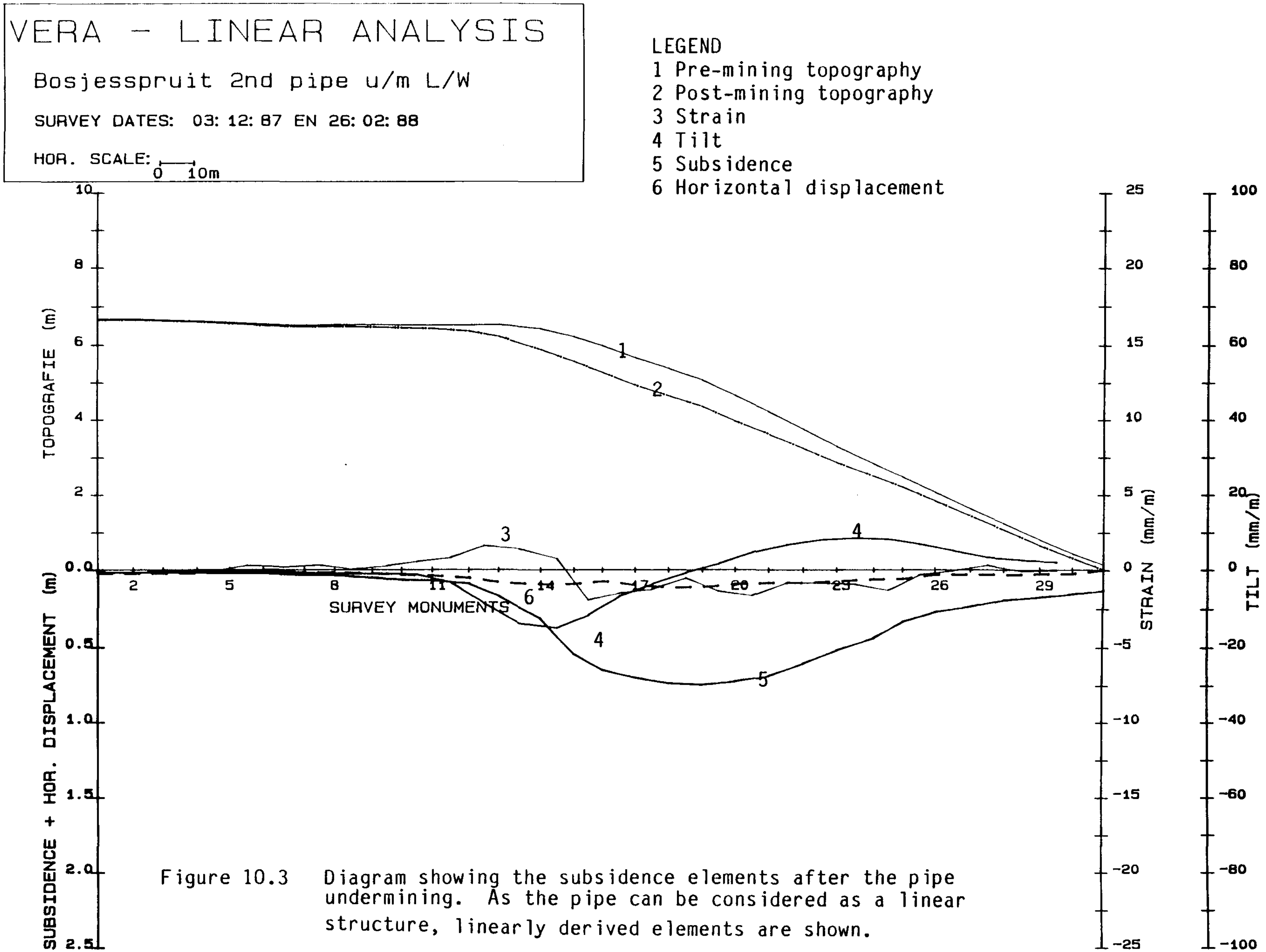


Figure 10.3 Diagram showing the subsidence elements after the pipe undermining. As the pipe can be considered as a linear structure, linearly derived elements are shown.

Table 10.1: Maximum magnitudes of the subsidence elements at the undermining of the water pipe line.

SUBSIDENCE ELEMENT	MAGNITUDE
VERTICAL SUBSIDENCE	0,81 m
HORIZONTAL DISPLACEMENT	135 mm
INDUCED MAJOR TILT	21 mm/m
MAJOR PRINCIPAL STRAIN	7 mm/m
MINOR PRINCIPAL STRAIN	-8 mm/m

the higher loads would be supported on the solid coal. On the Western side, however, the high loads would result in higher stresses on the single line of chain pillars and the pillars would then be compressed.

10.6 OBSERVATIONS ON THE PIPE LINE

The most important observation was that the pipe did not fail and suffered no noticeable distress.

The bitumen insulation however, was damaged in several spots. The first one was noticed in one of the inspection pits towards the end of the active subsidence period. The whole pipe was subsequently uncovered and several areas of damage were found, although the greatest damage was done during the excavation process. Typical types of tensile and compressive damage to the insulation material are shown in Plates 12 and 13.

Excluding instances where the insulation was obviously damaged during the uncovering process, a total of 17 cracks and 13 compression zones were found. Their relative positions are indicated in Figure 10.4, where the subsidence profile is also included for reference.

Two dimensional ground strains (not Principal Strains from the SEA approach) were calculated and compared with the types of damage observed on the pipe. The reason for doing this was that a pipe can be considered as being two dimensional with regard to its function. The flow of water through a pipe cannot be affected by tilts in the transverse direction, only in the longitudinal direction. The important tilt component is therefore the one in a direction parallel to the pipe itself. It would be misleading to compare the performance of the pipe with greater magnitudes of tilt, occurring in any direction, than those in a direction parallel to the pipe.

PLATE 12 A tension crack in the bitumen insultation on the pipe.

PLATE 13 Compressive ridging of the insulation material on the pipe.

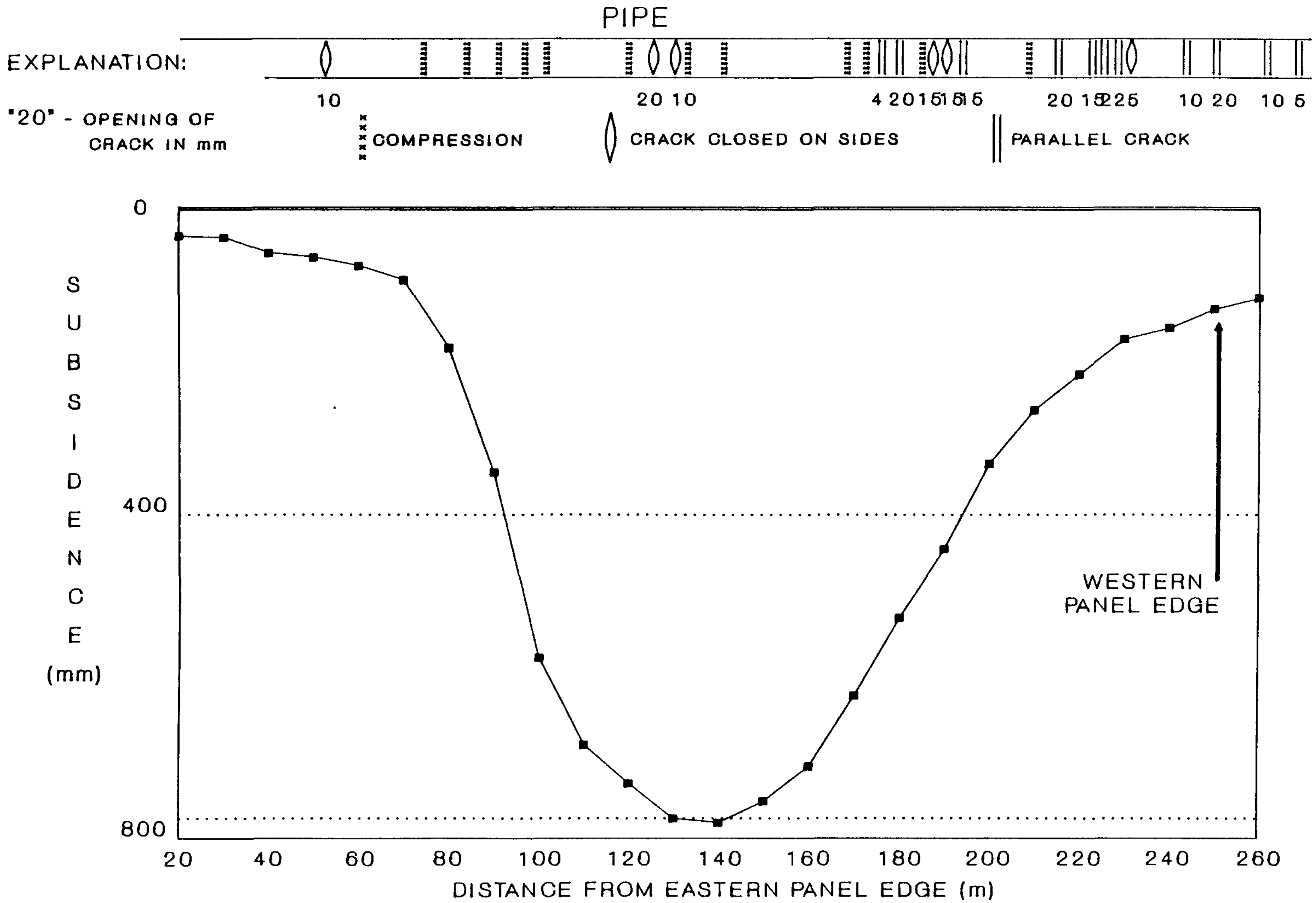


Figure 10.4 Observations of the types and positions of occurrence of damage on the pipe. The subsidence profile is added for reference.

Similarly, the diameter of the pipe was very small compared to its length and it was a monolithic structure. It could not be damaged by strain in the transverse direction, while it could be affected by strain in the longitudinal direction.

As the pipe did not cross the panel at right angles, the subsidence elements could not be considered as being related to the classical two dimensional subsidence profile. The subsidence elements derived for this particular analysis were thus two dimensional components of the major tilt and principal strains, occurring in a direction parallel to the pipe.

For each section, the strain was multiplied by the bay length to arrive at the change in length. This is compared, in Figure 10.5, to the sum of the crack widths on the insulation around the pipe for corresponding bay lengths. Little reliance can be placed on the exact magnitudes of the two variables in Figure 10.5, as there was no measure of the negative length change due to compression which was observed on the insulation material. For calculating the increase in length, maximum crack widths were considered.

Comparing the extent to which the sign of the length changes correspond, it is found that the correlation is 79%. This means that over 79% of the area, an increase in length on the ground surface is accompanied by a corresponding nett opening of

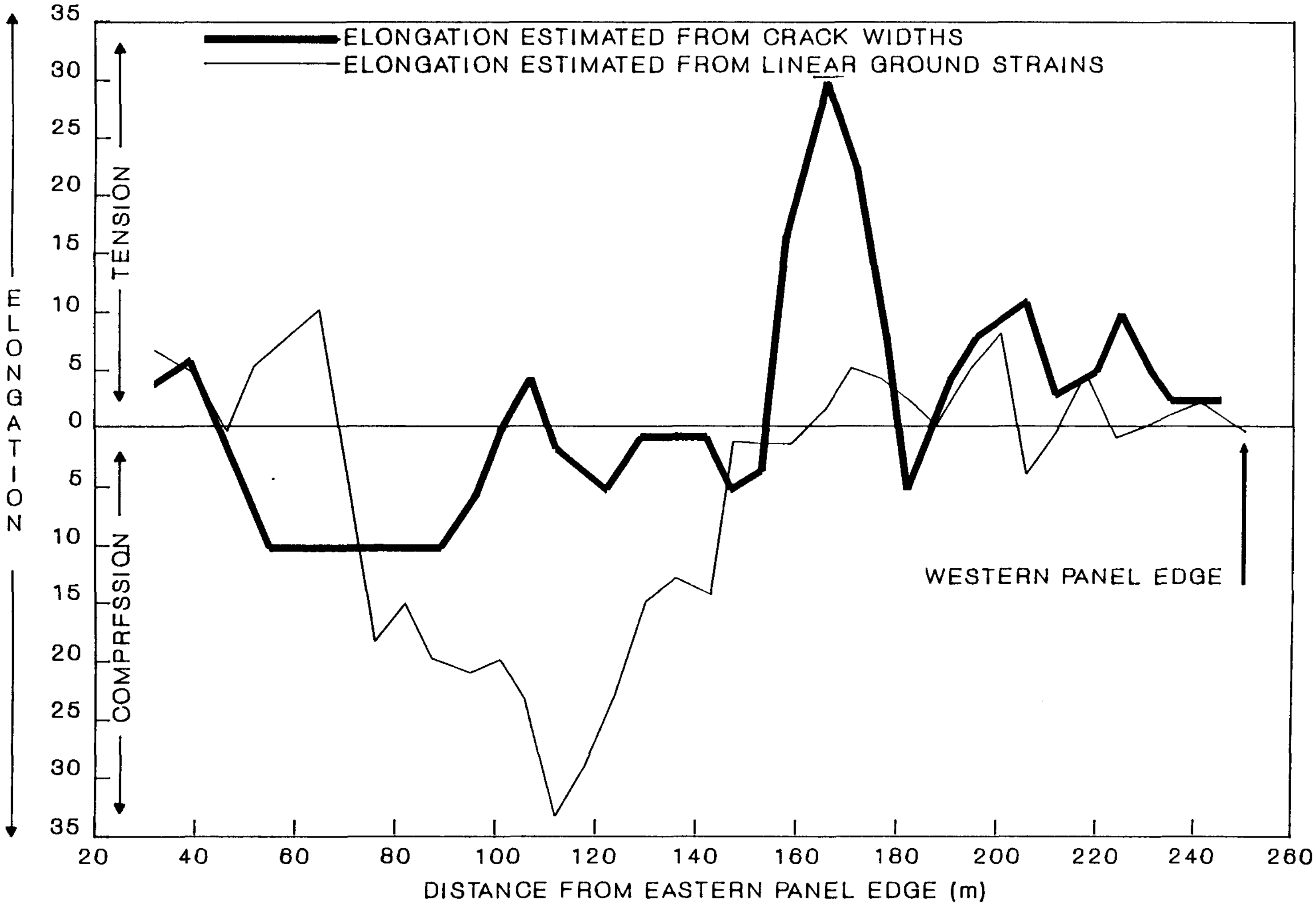


Figure 10.5 Comparison of elongation estimated from crack widths and elongation calculated from linear ground strains. Moving two point averages are shown.

cracks on the pipe insulation and vice versa for a decrease in length and indications of compression on the pipe insulation.

At a convenient time the pipe line was isolated and drained to allow internal examination. On the inside, three instances where the insulation had become detached from the pipe were found. All were located at the positions of the welded joints.

The opportunity was also used to do an X-ray examination of the pipe and to check the internal dimensions to determine whether the pipe had become oval. The deviations from circularity which were found, were well within the limits for a pipe of that nature. No cracks or other weaknesses could be found in the pipe walls.

According to Grobler (1988) the damage to the insulation material inside the pipe could not be positively connected with subsidence. It may also have been due to poor workmanship, as the only areas where damage was observed, was where the insulation was fixed to the pipe on site, after welding. The rest of the insulation is fixed to the pipe during the manufacturing process. The same type of damage was also found up to 100 m beyond the panel boundaries.

10.7 OBSERVATIONS AT OTHER SITES

On a number of occasions, pipes of smaller diameter, 300 mm or less, have been undermined and allowed to subside. Steel pipes were undermined without any precaution other than regular inspection. Asbestos cement pipes were provided with steel bypass pipes laid on surface.

No leakages or any other problems were ever encountered with the steel pipes. The other pipes were broken or had become detached at the joints in all instances.

10.8 CONCLUSIONS

10.8.1 Cause of damage

On the balance of the evidence, it is fair to conclude that the damage to the insulation material was caused by subsidence. However, the slight nature of the damage is indicated by the fact that some doubt existed as to whether the damage was caused by subsidence or poor workmanship.

The only damage was to the insulation material, which was repaired within less than two days. The pipe itself was not damaged.

It is believed that if the pipe had been uncovered, the damage to the insulation would have been less. Two mechanisms could have caused the damage: the shearing action of the soil against the pipe and bending of the pipe.

Two observations rule bending out as the only cause of the damage. Firstly, the insulation inside the pipe was not damaged to the same extent or in the same positions as outside. Secondly, if bending did cause the problem then tensile damage on the top of the pipe should always have been accompanied by compressive damage on the bottom at the same position. This was not the case. Where the damage was tensile, indicated by an open crack, eleven out of seventeen cracks were circular, open all the way around the perimeter of the pipe. The damage in those cases is believed to have been caused by the shearing action of the horizontal ground displacement against the stationary pipe.

Had the pipe been uncovered, the damage caused by shearing would have been prevented. While it is true that the excavation process possibly would have caused more damage than shearing, it is also true that after undermining the pipe has to be opened anyway for inspection and repair purposes.

10.8.2 Precautions

Another argument in favour of uncovering a pipe beforehand is that if it should develop a leak, it would be visible and accessible immediately. If a covered pipe should develop a leak, the position of the leak would only be betrayed by dampness on the surface. Reaching the leak will then require digging through saturated soil, a very difficult task.

In summary then, the most important conclusion is that the pipe was not damaged by subsidence, while minor and easily repairable damage occurred to the bitumen insulation. It is better to uncover the pipe before subsidence commences. If a pipe is made of asbestos cement or similar material, a steel bypass pipe should be provided.

11 THE EFFECTS OF SUBSIDENCE ON AGRICULTURE

11.1 INTRODUCTION

The effects of subsidence on artificial structures have received much attention in several countries of the world. By contrast, agriculture has been virtually excluded from investigations into subsidence effects.

There may be several good reasons for this. Firstly, when farm lands are undermined, experience has shown that due to the gradual and gentle nature of subsidence, no danger to farm workers results. In the absence of danger, the matter then reduces to one of economics, and the remaining question is to what extent the economic potential of the agricultural activity is changed, if at all.

In the South African experience, farming has not had to cease altogether as a result of subsidence in a single instance. In the vast majority of cases, farming continues after subsidence as though nothing had happened. Plate 14 is an example of an instance where subsidence of approximately 4 m, caused by double seam longwalling, did not prohibit the continuation of farming. This and several other similar examples, serve to indicate that in general the subsidence effects do not seem to be very serious.

Where the pre-mining topography is flat, ponding (such as shown in Plate 15) has been seen to result. The severity of the ponding effect is also a function of rainfall, as the problem would be more serious in wet seasons than in dry seasons.

In most instances, any damage resulting from subsidence is compensated for by mining companies by paying a mutually acceptable sum of compensation money to farm owners, replacing water which is lost from dried up wells, etc. By satisfying individual farmers in this manner, it has thus far not been necessary to do research into the effects of subsidence on agriculture.

It has also been found extremely difficult to quantify the effects of subsidence on agriculture, due to the great number of external variables which also affect crop yields. These include controllable variables such as the amount of fertilizer used, the farmer's judgement relating to the exact time of planting, the type of crop planted, etc. There are also variables which cannot be controlled such as temperatures, the amount of rainfall at specific times during the various growth stages of plants, etc.

The variables mentioned make it virtually impossible to isolate the effects of subsidence on changes in crop yield measured before and after subsidence.

Plate 14: A mealie land which had been subjected to subsidence of approximately 4 m, caused by double seam longwalling. The surface was more or less flat before subsidence occurred.

Plate 15: A pond, caused by subsidence of approximately 1,5m. A 200 m wide longwall panel mined from the top right hand side of the land through to the bottom left hand corner. Discolouration of the mealies can be seen all along the line of mining.

In addition, the issue as a whole is an emotional one and it would be dangerous to rely only on the opinions of individual farmers to arrive at a conclusion. It is thus very difficult to determine the effects of subsidence on agriculture.

In recent years, the State of Illinois in the USA has embarked on a comprehensive study of the effects of subsidence on crop yields. Mining induced subsidence, crop types and rainfall in Illinois are comparable to those in South Africa and it would therefore be useful to at least take cognisance of the work done there. The preliminary conclusion of the ongoing study with regard to crop losses is that longwalling leads to yield reductions of less than 5% and pillar extraction to losses of less than 2%. These figures correspond with the areas which have been found to have been severely affected by subsidence in South Africa.

In South Africa, the Cabinet appointed a Commission of Inquiry into the effects of high extraction mining on agriculture in 1988. The final report was published in 1990, with the main finding that not enough information was available to arrive at any definite conclusions, and that certain research should be done into the matter. The only concrete outcome of the work was the appointment of a committee to oversee the required research and improve communications between the mining and agricultural communities.

In this chapter, the work done in Illinois will be briefly reviewed and compared with the approach to the problem in South Africa. From that, recommendations regarding the handling of the problem in South Africa will be made.

11.2 OVERVIEW OF WORK DONE IN ILLINOIS

11.2.1 Background

As described in Chapter 3, subsidence damage in Illinois is handled by an insurance scheme. When the question arose as to whether agriculture should be included in the scheme, the risk to insurers first had to be quantified, which meant that the effects of mining induced subsidence on agriculture had to be quantified.

In order to do that, the Illinois Mine Subsidence Research Program (IMSRP) was formed in 1985. The IMSRP functions under the leadership of the Illinois State Geological Survey, and its main aims are to determine the extent of subsidence effects, to define the mechanism and character of subsidence and to review mitigation efforts, DuMontelle (1988). Four universities in Illinois participate actively in the program, as do the US Bureau of Mines, the Illinois State Geological Survey and industry. The research is done by a highly qualified team of experts in the mining, geological and agricultural fields.

11.2.2 Overview of results

The work done in Illinois is designed to cater for the local conditions, and includes the subsidence mechanisms due to pillars punching into the floor, pillar stability, etc. Also, the very important subject of hydrological changes are not yet at the stage where meaningful conclusions can be drawn. Those matters will be excluded here, and attention will focus on the quantification of crop losses due to high extraction mining induced subsidence.

(i) Method of investigation

Essentially, the method employed is to compare crop yields in areas subjected to subsidence to yields in unaffected areas under the same non-mining related conditions. In most cases, subsidence will not affect an entire land during the same mining exercise. Crop yields were then monitored in a subsidence affected area and compared to a control area in an area of the same land which has not subsided. In this way, the effects of non mining related variables were excluded from the comparison.

The comparisons were only done for the first crop season following subsidence. Subsided areas were identified by means of areal photography.

Great care was taken to include respresentative samples of areas with the same topographical features, such as tilt. Records of rainfall were also kept. The comparisons were done for three consecutive years, 1985 to 1987. The three years represented periods of less than normal, normal and greater than normal rainfall.

A total area of 40 000 ha, covering 150 mining panels, was investigated over the three year period. Maize was chosen as an indicator crop as it was by far the most common agricultural product.

(ii) Results

As was to be expected, different results were recorded for the three different years (due to variations in rainfall) and for longwalling and pillar extraction. Pillar extraction is usually characterized by less subsidence than longwalling under the same conditions.

Based on information supplied by Darmody et al (1988), Table 11.1 was constructed. The table contains comparisons of areas investigated, rainfall and crop losses for the period 1985 to 1987.

Table 11.1: Comparison of investigated areas, rainfall and crop losses for longwalling and pillar extraction during the period 1985 to 1987

	Area (ha)	Rainfall (mm)	Departure from average rain-fall (mm)	Longwall crop loss (%)	Pillar extraction crop loss (%)
1985	11 000	940	+50	7,4	2,4
1986	13 000	800	-60	4,2	2,2
1987	16 000	560	-290	2,4	0,9
Average	13 333	770	-100	4,7	1,8

Note that the crop losses were calculated over the entire undermined areas in each case.

The two most important conclusions to be drawn from the table are that firstly, higher rainfall results in greater crop losses (presumably due to the greater extent of ponding), and secondly that longwalling leads to greater crop losses than pillar extraction. Both conclusions are understandable and conform to expectations.

Other information supplied by the same authors indicate that the crop losses are not uniformly distributed over the undermined areas. The reason for this is that the same amount of subsidence will have different effects on different pre-mining topographies. For instance, where the pre-mining topography is flat, more ponding will occur than where severe inclinations existed before mining.

Based on infra red photographs taken at various times of the year before and after mining, different classes of Subsidence Induced Effects (SIE) were distinguished. These are indicated in Table 11.2, with crop losses within such demarcated areas. This is in contrast to the information in Table 11.1, where the respresentative losses over the entire panels were considered.

Table 11.2: Crop losses according to SIE (Subsidence Induced Effects) class.

SIE Class	Description	Crop loss (%)			
		1985	1986	1987	Average
None	No change	-	-	-	-
Slight	Topographic change without dark infra red signature	-	-	-	
Moderate	Dark infra red signature	52	56	22	43
Severe	Ponding or black infra red signature	95	99	91	95

Table 11.1 shows very clearly that subsidence alone does not account for the observed damage. Changes in the moisture content of the soil caused by subsidence, are also influenced by factors like the pre-mining topography, the moisture retention characteristics of the soil and the amount of rainfall. In estimating the amount of damage done by subsidence, those factors therefore also have to be considered.

The table also indicates that most of the crop losses occur over a small portion of the undermined area. It appears that where conditions are such that surface water is not contained, i.e. allowed to drain, very little crop losses are encountered.

Comparison of damage in Illinois to observations in South Africa

In South Africa, no observations which can be directly compared to those in Illinois have been made. It may be possible, however, to make an indirect comparison based on the areas of land for which compensation has been paid to farm owners.

According to information received from one mining company, a total area of 3 500 ha has been undermined by high extraction mining until June 1990. Of that total area, compensation paid to farm owners because the potential agricultural activity has had to change due to mining induced subsidence, covered a total of 148 ha, or 4,2% of the total area. The mining methods employed were approximately 75% longwalling and 25% pillar extraction.

The proportionate area which had been affected by mining to the extent where the original potential application had to change (i.e. maize lands changed to grazing or flooded due to ponding), are in good agreement with the Illinois crop loss figures. This is especially so when it is borne in mind that it was found in Illinois that losses are virtually confined to "wet" areas, the same for which the mining company paid compensation.

If the Illinois figures of 4,7% loss due to longwalling and 1,8% loss due to pillar extraction are applied to the mix of mining methods in this case, it would yield an average crop loss of 4,0%. This appears to correspond very closely to the 4,2% quoted by the South African mining company.

This comparison, coupled to the fact that the same crops are grown and that average annual rainfall are comparable (770 mm in Illinois vs. approximately 700 - 800 mm for the Transvaal Highveld) seem to indicate that there may be considerable merit in closer cooperation with the IMSRP. It is also known that mining geometries and the extents of subsidence are comparable.

11.3 FORMAL INVESTIGATIONS IN SOUTH AFRICA

11.3.1 Background

Formal, coordinated research into the effects of subsidence on agriculture has not yet been done in South Africa. The increasing popularity of high extraction coal mining, including strip mining, prompted the South African government to appoint a commission of inquiry into the matter in 1988. The commission was formed to determine the extent of the problem caused by the interaction of high extraction coal mining and agriculture, and not to conduct scientific research into the problem.

According to the report issued by the Management Committee of the commission, "An investigation into the long term effects of high extraction coal mining on agriculture in the Eastern Highveld of the Transvaal", published in August 1990 (henceforth called the Report), the following goals were set:

(a) to study the problem areas which could be stumbling blocks in the balanced development of the agricultural and mining industries;

(b) to find obvious solutions to the problems, or to initiate further investigations and research where the solutions were not obvious, and

(c) to recommend suitable organisational structures to function as an informal forum between mining, agriculture and all other instances which may be involved in the development of resources in the area.

11.3.2 Magnitude of the interaction between mining and agriculture

Set against the background of the delicate relationships between the farming community, the mining industry and various government departments, the Report is a very carefully worded document. It appears that the interest of all the parties concerned are well served and no culprits are identified. However, it contains very little in the form of useful scientific information. Under the term "high extraction coal mining" both strip mining and underground high extraction mining are jointly included without making distinction. From a scientific point of view, the effects of strip mining rehabilitation and subsidence are very different.

With regard to the overall magnitude of the problem, certain important facts can however be learnt from the Report. The study area included four major coal fields of South Africa, together comprising some 49% of the country's total minable reserves. In 1988, the area produced approximately 70% of the total South African sales tonnes. The income from agriculture in the area was 8,8% of the national agricultural income for the same period.

The Report states that of the total study area, some 21,1% is underlain by potentially minable coal. Of that, approximately 41% (or 8,6% of the total area) may be mined by high extraction methods. Based on the finding that of the total area mined by high extraction methods, less than 5% is severely damaged, and assuming that the total strip mined area is severely damaged, it may be expected that less than 2% of the total study area may eventually be severely damaged if no mitigation is done. This figure is grossly pessimistic as it is based on the unlikely assumption that strip mining rehabilitation will be a total failure.

With regard to agricultural potential, approximately 50% of the area can be classified as high potential. A further 30% is classified as medium potential, and the remaining 20% as low potential. Of the high and medium potential land, only 33% is permanently worked.

It may appear curious to refer to the effects of high extraction coal mining as a problem when it appears that less than 2% of the total area (which contains a high concentration of coal mining) may be severely damaged, while 66% of the high and medium potential land is not permanently under cash crops. Other factors must, however, also be borne in mind.

Firstly, the effects on groundwater may be very serious. Apart from changing the hydrological characteristics of the sub surface, it is possible that the quality of the ground water source may be affected over a wide area by being enriched in sodium chloride content from the marine shales overlying the coal seam.

Secondly, even if the overall effect based on the total area may be very small, it could still be serious to individual farmers. Even a small change in agricultural potential can be disastrous to a marginally economical farming unit. While it is clear that a significant improvement can be brought about by more intensive farming methods, mining induced damage should be minimized in the light of the emotional aspects. For these reasons, the Committee functioned from a base of affording equal importance to mining and agriculture.

The Report, while not overtly stating it, leads to the conclusion that a significant proportion of the problem is of an emotional nature. Even though the investigation, according to its title, dealt primarily with the effects of high extraction mining (therefore the physical aspects) it also addressed social questions, such as theft in the vicinity of townships, control over workers, etc. The problem therefore encompasses much more than just the physical or economical interaction between mining and agriculture.

11.3.3 Findings of the commission

In summary, the commission found that not enough was known about the specific nature of the interaction to come to a definite conclusion. It also came to the important conclusion that a lack of communication was an important factor in creating the problem.

The Report recommends that research be conducted into the effects of mining on the agricultural potential of land and on the agricultural engineering aspects. It also calls for the determination of economical norms for the size of farming units and an investigation into the suitability of alternative agricultural activity.

Other recommendations include that the Minister of Agriculture be involved in rehabilitation programmes and that the reduced value of land in the study area (if it is in fact found to be reduced) be considered in the application of Article 42 of the Minerals Law. Article 42 regulates the purchase of land by mining companies, should such land become uneconomical due to mining activities.

The only direct action taken thus far by the committee was to create a Liaison Committee. The Liaison Committee, a non statutory body, consists of the same membership as the

Management Committee which was responsible for the investigation and the Report, i.e. respresentatives from the Departments of Agricultural Development, Water Affairs, Agriculture, Mineral and Energy Affairs, Planning and Provincial Affairs and the Environment, as well as the Chamber of Mines, Eskom, the South African Agricultural Union and Sasol.

The Liaison Committee will be charged with providing a forum for communication between the mining and agricultural industries. It will also ensure close liaison between organisations responsible for conducting research recommended by the Report and advise those organisations with regard to the planning, structuring and execution of the required or implied research.

The Report also recommends that a centre for agricultural development of the Highveld region be founded, and that specific information centres regarding the effects of high extraction mining be created. One such centre, the Sasol Mining Centre for Ground Conservation, was in fact established before the Report was published.

11.4 COMPARISON OF THE ILLINOIS AND SOUTH AFRICAN APPROACHES TO THE PROBLEM

The South African and Illinois approaches cannot yet be compared directly. Thus far, an attempt has only been made in South

Africa to define the problem and identify research areas, while in Illinois the research is already well under way. It would appear, though, that the emphasis in Illinois is more on scientific matters, while in South Africa it tends to be more socio-political than in Illinois.

In South Africa, the research will be guided and controlled by the Liaison Committee, which has a very broad, representative base. While this should ensure a balanced result, the danger also exists that it may be inconclusive, in trying to satisfy too many diverse interests simultaneously. A very necessary pre-requisite for the success of the South African attempt will be to minimise the "political" influence and control over the research scientists.

With regard to the scientific methods employed by the IMSRP, the similarities in conditions in Illinois and South Africa seem to indicate that cross polination will be beneficial. From a scientific point of view, the Illinois approach appears to be very sound. Savings in money and time may be achieved by studying the methods developed in Illinois in more detail.

11.5 CONCLUSIONS

11.5.1 Magnitude of the problem

Considering the fact that in the Eastern Highveld, where there is a high concentration of coal mining, preliminary work suggests that less than 2% of the area may suffer severe damage as a result of high extraction coal mining, while 66% of the high and medium potential agricultural land is not permanently under cash crops, it appears that overall the problem is not serious. The preliminary conclusions in South Africa correspond well with more detailed work in Illinois, where the nature of subsidence, crop types and rainfall are similar. There is therefore reason to believe that the estimated extent of crop losses are reasonably accurate.

However, in both South Africa and Illinois the groundwater aspects have not yet been satisfactorily researched. It is suspected that the hydrological characteristics of the sub surface will change over a wide area as a result of high extraction coal mining. There is also at least a possibility that the quality of ground water may be affected. The effects on ground water may thus be significantly more serious than the effects on immediate crop yields.

Also, the long term effects on erosion patterns, caused by changes in surface water drainage patterns, have not yet been researched. It is not yet known how this will affect crop yields over the longer term.

While it therefore appears that the magnitude of the problem is not very great, there are still several unknowns. Especially the longer term effects, which may conceivably survive the life spans of most mines, are not known at this stage.

11.5.2 Identified research areas

Following on the remarks in the previous paragraphs, it is clear that especially the longer term effects on agriculture need to be investigated. Hydrological changes, the quality of ground water and surface erosion are aspects that will have to be researched.

The extent of immediate crop losses will also have to be quantified more scientifically than merely considering the areas for which compensation has been paid, as the latter consideration contains too strong a subjective element. In doing this investigation, the effects of pre-mining topography, rainfall, soil type, etc. will have to be considered.

11.5.3 Methods of research

At this stage, it is certain that the research efforts will be controlled by a body with a very broad base, representing all the interested parties. While this will contribute towards a balanced result, care will have to be taken to minimise the "political" influence on research results.

With regard to the exact methodology of specific research areas, a more detailed study of the methods developed and applied by the IMSRP will be beneficial. The IMSRP has been in operation since 1985 and has already produced meaningful results. There are strong similarities in both the mining and agricultural conditions. Savings in both time and money may be achieved by learning from the IMSRP effort.

12 CONCLUSIONS

This chapter will refer to the conclusions reached at the end of the foregoing chapters. While some repetition is therefore inevitable, the focus will be on reaching a synthesis of the separate conclusions.

12.1 SUBSIDENCE PREDICTION

12.1.1 Current position

It is now possible to predict subsidence as a result of high extraction coal mining to what can be described as a fair degree of accuracy. The required "degree of accuracy" cannot have a single answer, as it is determined by the sensitivity of the structure to be undermined, which varies for different structures.

For the undermining of man made structures, the accurate prediction of the subsidence elements of induced tilts and strains in a relatively small area are of prime importance. Vertical subsidence per se is only important as it governs the magnitudes of the other elements.

For agriculture, the post mining subsidence characteristics of a wide area comprising several high extraction panels are important. The exact magnitudes of induced tilts and strains are not as important as for structures. What is important, is to predict new height contours after subsidence over a wide area. This requires that induced vertical subsidence at a number of positions over each high extraction panel be superimposed on the pre-mining topography. Only when this has been done can the effects of subsidence on a farm unit be predicted.

The methodology to predict subsidence to the required accuracy, exists. However, there is still room and also a need for improvement.

12.1.2 Summary of prediction model

The sequence to be followed to arrive at the prediction of all the subsidence elements over the subsidence profile in the Sasolburg and Secunda areas is as follows:

(a) Maximum Subsidence

$S_m = 0,39h\ (W/H)^{0,32}$,

(b) Maximum Tilt:

$T_m = 21,6S_m + 7$,

(c) Maximum Tensile Strain

$$\epsilon_{m+} = 4,2\ S_m + 1,7,$$

(d) Maximum Compressive Strain

$$\epsilon_{m-} = -9,1S_m - 2,8,$$

(e) Subsidence at any point on the subsidence profile:

$$S = 0,5S_m[\tanh(7x/W - 1,645)+1],$$

(f) Tilt along the subsidence profile:

$$T = \frac{S_1 - S_2}{\Delta x},$$

(g) Strain along the subsidence profile:

$$\epsilon_{+} = \frac{t_1 \tan\alpha}{\Delta x},$$

$$\epsilon_{-} = \frac{-t \tan\alpha}{\Delta x}.$$

If there is no prior knowledge of the values of t and t_1, they should be set equal to respectively 4,7 and 3,5 m, which are the average values found over a wide range of conditions.

12.1.3 Further work

The most meaningful improvement on the prediction model presented in Chapter 6, would be to the shape of the subsidence profile. The one presented is the best that could be empirically derived from the available data. The subsidence profile holds the key to the prediction of induced tilt and strain as well as the post mining topography. It is therefore the single aspect which will contribute most to the overall prediction model.

From preliminary work done by the author, it would appear that using a distinct element computer model will yield the best results for predicting the subsidence profile. It will certainly be the most realistic model to use and should therefore be the best suited to area specific predictions.

The emphasis in the work has been on subsidence induced by longwalling, reference occasionally being made to pillar extraction. It has been seen that pillar extraction results in less subsidence than longwalling. It has also been shown that the relationship between the angular distortion of the surface and induced strain holds true for pillar extraction. However, there was insufficient data to derive a model which could predict a subsidence profile for pillar extraction.

Longwalling entails the removal of relatively thin strips of coal (0,5 m - 1,0 m wide) from a 200 m long face. The excavation is thus enlarged in small increments in the same direction all the time.

By contrast, pillar extraction entails the sudden removal of the support of a roof area measuring 500 m^2 to 600 m^2. It has been observed underground that the roof usually only collapses when an entire pillar has been extracted. The mode of extraction is then to remove the support of relatively large areas in a direction perpendicular to the overall direction of advance. Furthermore, the collapses of these large areas take place suddenly and the process is less continuous than in the case of longwalling.

There is therefore reason to believe that the subsidence profile for pillar extraction may differ from that for longwalling. If the subsidence profile is different, the other subsidence elements will differ accordingly. It is suggested that further work should address this aspect. There are strong indications that in certain areas, especially those characterised by a high frequency of dolerite intrusions, pillar extraction may be preferred over longwalling as a high extraction mining method.

12.2 THE EFFECTS OF SUBSIDENCE ON STRUCTURES

12.2.1 Introduction

It has been shown that a number of structures, not necessarily designed to accommodate the effects of subsidence, can withstand these effects rather well. In certain instances, at least some precautionary work is required on the structure to enhance its flexibility. In other cases, hardly anything is required. In virtually all the cases, the cost of the steps required plus the cost of whatever repairs are required, is a fraction of the value of the extracted coal. The only exception is the undermining of a tarred road, where it is required that a tarred deviation be provided. As it has been shown that this is a technically unnecessary requirement under the study conditions, it may be concluded that it is also possible to undermine tarred roads economically.

12.2.2 Summary of precautions and effects on different structures

(a) Tarred roads

It has been shown that under the conditions described for the study area, an unmaintained tarred road which is not under traffic during undermining, will be adversely affected by cracks up to 40 mm wide at an average spacing of 4 m. While the cracks may be easily repaired, possibly more serious damage is caused by compression ridges up to 100 mm high on the road surface.

It was also shown that the provision of compression relief slots on the road surface inhibits the development of compression ridges. However, this can only be done if the road is not under traffic during undermining.

Partial extraction of inter panel pillars, leaving only crushable portions behind, resulted in a better post subsidence topography where several adjoining panels are mined. It will not always be possible to do this, due to local conditions underground, and a number of practical mining problems remain to be solved.

(b) Gravel roads

In contrast to bituminized roads, gravel roads suffered only negligible damage under the same conditions. The difference is believed to lie in the more flexible nature of the surface of a gravel road. The experimental road withstood 1,24 m of vertical subsidence, 46 mm/m tilt, 7,8 mm/m of tensional and -11,5 mm/m of compressional strain and 240 mm horizontal displacement without suffering functional loss.

The conclusion that gravel roads are in general less susceptible to subsidence damage than bituminized roads, is confirmed by previous experience in the Secunda area. Several gravel roads had been undermined in the past while under traffic, without noticeable ill effects.

(c) Proposed strategy for the undermining of roads in the study area

Combining the conclusions described in (a) and (b), it appears that the provision of a gravel deviation in the road reserve will be sufficient for the undermining of a bituminized road. During the active subsidence period, traffic may safely be accommodated on the gravel deviation while compression relief slots on the bituminized road will prevent ridging and thereby reduce both the time and the cost of repair work. Gravel roads may be undermined while under traffic without providing any deviation.

While the above conclusion is based on facts, the author holds the opinion that even under the study conditions, it may be possible to undermine bituminized roads while under traffic. The impact of vehicle wheels on the road surface, aided by continuous maintenance, could prevent the forming of dangerous ridges on the road. This opinion is based on the description by Holla (1988) of the undermining of the Pacific Highway by the Wyee Colliery in Australia. The road subsided by over 2 m while under traffic.

Notwithstanding the comments in the previous paragraphs, any road undermining should be approached with the necessary caution. A comprehensive investigation is required in all cases. The effects of subsidence on the existing topography should be considered. For instance, if the vertical road alignment is such that the horizontal sighting distance is close to the limit, the induced tilts may have highly undesirable consequences. Subsidence on a bend in the road may also have consequences which were not noticed in the study.

It is essential that precautions be drawn up in close collaboration with the roads authorities. The subsidence engineer can predict the effects of subsidence on any road, while matters like speed restrictions, etc. should be the responsibility of the roads authorities.

(d) Conveyor belts

It was found that the conveyor belts described in Chapter 9, were successfully protected against subsidence of nominally 1,5 m by merely detaching the structure from its foundations. The maximum induced tilt was 65 mm/m, while compressive strain of up to -18,5 mm/m were found. The maximum horizontal displacement of the ground was 375 mm.

After the bolts holding the structure to its foundations had been loosened, the structure still had sufficient lateral rigidity to maintain itself in a straight line, while it was also still flexible enough to accommodate the strains.

The maximum tilt which can be induced onto a conveyor belt is a function of both the design parameters and the pre-mining nature of the topography. Therefore, comprehensive investigation is once more required before subsidence can be allowed to take place. The induced tilt on the conveyor should be evaluated against the spare capacity in the pre-mining state, taking cognisance of the exact position of the conveyor relative to the underground panel. It is important to predict the magnitude of the post subsidence tilt of the conveyor along its entire undermined length in both its transverse and longitudinal directions.

(e) Pipe lines

The study showed that a buried water pipe of 1 140 mm diameter was not damaged by subsidence of 0,81 m, while minor damage was done to the bitumen insulation, mainly on the outside of the pipe line. By considering the nature of the cracks in the insulation and the magnitude and positions of the ground strains, it was concluded that the shearing action of the ground being displaced against the pipe, contributed significantly to the damage. It would therefore be better to uncover a pipe prior to undermining.

It was also found that non steel pipes, like asbestos cement, were easily broken by subsidence. Such pipes should therefore be replaced by steel pipes before subsidence takes place.

(f) Agriculture

The available information indicates that while subsidence has at least some effect on agriculture, there is insufficient information to attempt to quantify that effect. It has nonetheless been shown that the upper limit of the area where the farming application has had to change due to subsidence, is less than 5% of the total area mined by high extraction methods. There is reason to suspect that the actual area which was so damaged is less than the upper limit.

12.2.3 Importance of position of structure relative to underground panel

Structures with square base outlines, such as houses and transmission towers

Although not entirely free of the permanent effects of subsidence, the centres of high extraction panels are the areas where the permanent magnitudes of strain and tilt are at minimum and often negligible levels. To avoid the high cost of permanent re-alignment of structures, it is thus desirable to locate structures in the centres of high extraction panels. Where the structures exist prior to planning the mine, attempts should be made to arrange the planning of the underground panels such that the same effect is achieved.

With regard to transmission towers, Otto (1986), concluded that the direction of mining should be at either 0° or 90° to the direction of the power line to minimise the loads transferred to the structure by stretching or compression of the legs of the tower. A direction of 45° is the least desirable.

Linear structures, such as roads, conveyor belts and pipe lines

The best orientation is for the structure to cross the underground panel at 90° to its long axis. In this way the distance of the structure to be undermined is minimised, as well as the areas on the sloping edges where permanent deformations are manifested.

A direction of mining parallel to the direction of the structure means that the structure will be subjected to the repeating cycle of tensile and compressive strains for a long distance, even if the structure is located along the centre of the panel.

The worst condition would be for a structure to be orientated parallel to the long axis of the high extraction panel, and be situated off the centre of the panel. Under those conditions, the disadvantage of a permanent lateral tilt would be added to that mentioned in the previous paragraph.

12.3 STRUCTURES NOT INCLUDED IN THE THESIS

The effects of subsidence on houses and power pylons were excluded from the thesis, as the relevant research has been done previously.

For tranmission towers, Otto (1986), found that subsidence caused the safety factor of a tower undermined by longwalling to decrease temporarily from 2,5 to 1,35. The decrease was caused by additional loads transferred to the legs of the structure during the phase of active subsidence. His recommendation to isolate the tower from the conductors and earthwires by temporarily suspending them on rollers, has become the standard precaution before undermining a transmission tower. This is shown in Plate 16.

In most rural areas, and certainly in the Secunda and Sasolburg areas, a great variety of types of houses have been built. It would thus be dangerous to generalise the effects of subsidence on houses if the information is based on one or two experiments. In total, four farm houses have been undermined.

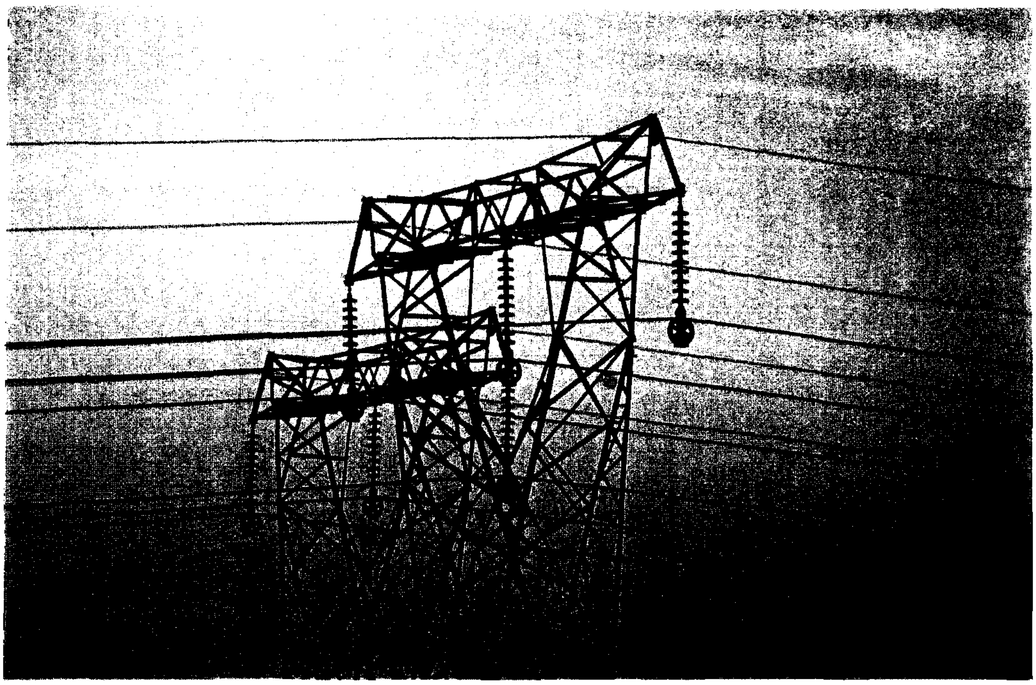


PLATE 16 Photograph showing the pulleys on which conductors are suspended to allow free movement of transmission towers during undermining.

Detailed monitoring was only possible on one occasion. This was done in 1983 under the guidance of the Chamber of Mines Research Organisation. The research report is not available yet, but the most important findings have been made public. After undermining, that particular house was restored by Sasol and now houses the Sasol Mining Centre for Ground Conservation.

The house was situated in the centre of a longwall panel, 200 m wide and 3 m high. The mining depth was 120 m. The maximum induced tilt of 20 mm/m during the active subsidence phase reduced to 2mm/m after stabilization. The major damage was cracking of interior walls. In considering the total repair cost of approximately R70 000, it should be borne in mind that the house was of very sturdy construction, having been well built by most standards.

In one other instance vandalism prior to undermining resulted in structural members of the house being removed, and the house had to be demolished. In the second case the house was built some 70 years before of a mixture of locally made clay brick, timber and stone. The repair costs could not be justified in the light of the poor condition of the house before undermining and it too was demolished. The third house where monitoring was not done is estimated to have been subjected to the same subsidence parameters as the one that was monitored. Being of similar, if only slightly weaker construction, the damage was comparable to that of the monitored house. However, it was situated on the permanently sloping edge of a subsidence trough and correcting the sloping floors and leaning walls, while not considered dangerous, was considered necessary but not cost justifiable. That house was also demolished.

In considering the undermining of houses it is thus clear that several additional factors have to be considered, and no definite general conclusions can be reached on the available information.

Farm houses are widely scattered and the undermining of townships are not considered for the foreseeable future. Therefore the frequency at which houses will be undermined is not high enough at the moment to warrant the high cost of research on specially constructed houses. As opportunities arise, they should nonetheless be used.

12.4 ECONOMIC BENEFIT OF UNDERMINING

12.4.1 Benefit per structure

A comparison of cost estimates of the various precautions which are required for the different types of structures is given in Table 12.1. The figure in the last column is the total cost

Table 12.1: Summary of the costs of undermining various types of structures

STRUCTURE	PRECAUTIONS	COST	REPAIRS	COST	TOTAL COST	(COST/BENEFIT) X 100
Tarred road (with current restrictions)	Tarred deviation Provide slots	R240 000	Re-align, fill slots, fill cracks, resurface. Remove deviation	R417 000	R657 000	98% 3)
Tarred road (with proposed methods)	Gravel deviation Provide slots	R 80 000	Re-align, fill slots, fill cracks, resurface.	R142 000	R222 000	33%
Gravel road with current restrictions	Gravel deviation	R100 000	Re-align, flatten ridges.	R 50 000	R150 000	22,5%
Gravel road with proposed methods	Maintenance during undermining	R 50 000	Effected during undermining	-	R 50 000	7,5%
Conveyor belt	Loosen foundation	R 5 000	Refix foundations	R 5 000	R 10 000	1,5%
Pipe line	Excavate	R 5 000	Repair insulation, fill trench.	R 10 000	R 15 000	2,3%
Transmission tower 1)	Install rollers for conductors	R 1 000	Replace fixed attachments for conductors	R 1 000	R 2 000	0,3%
House 2)	Evacuate, rent alternative	R 15 000	Replace broken windows, bent frames, repair wall cracks etc.	R 70 000	R 85 000	12,7%

1) Precautions are those which are currently taken by Eskom, following research described by Otto (1986).

2) Repair cost estimate based on repair costs to undermined farm dwelling which now houses the Sasol Mining Centre for Ground Conservation, Secunda Mines.

3) With the addition of the extra costs usually incurred in reality, the undermining of bituminized roads with the current restrictions is not economically justifiable.

resulting from protecting and repairing the structure due to the subsidence effects, expressed as a percentage of the value of the coal gained by undermining. To facilitate comparison, the loss of not mining coal which was made available by the provision of infrastructure and entries was taken at R7 per tonne, and the amount of coal as the difference between that which would have been extracted with bord and pillar mining with a safety factor of 2 and that extracted by longwalling.

A standard length of structure of 250 m was assumed, and the mining depth was assumed to be 120 m with a mining height of 3 m and panel width of 200 m. In reality it often happens that more coal than just that restricted by legislation is lost when a structure may not be undermined with high extraction, due to the high cost of moving a longwall installation. Those costs cannot be standardized, and were ignored for the purpose of comparison.

It is clear from Table 12.1 that with the exception of bituminized roads under the current restrictions, all the structures which were investigated can be undermined safely and economically. It has been shown that a bituminized road can be undermined safely by providing a gravel deviation, and it is seen from the table that the economics of doing that will benefit the mining industry.

As stated previously, even the provision of a gravel deviation may not be necessary in all instances. It is therefore clear that additional work in this regard has the potential of even more benefit both to the mining industry and the travelling public.

12.4.2 Direct benefit to be obtained in the immediate future

The results described in this thesis can be applied to all the structures to be undermined in the Sasolburg and Secunda districts. It can also be applied to similar structures in other areas where the subsidence elements can be predicted to the required degree of accuracy.

With regard to direct applicability in the immediate future, the structures as listed in Table 12.2 are planned to be undermined in the Secunda area during the five year period 1990-1994. The table also shows the amount of coal which will be gained by undermining the structures with high extraction methods as opposed to undermining with bord and pillar.

No houses or similar structures are planned to be undermined during this period. It is clear from the table that significant benefit will be derived from the work which was done during the study. More than 11 million tonnes of coal will be gained by the undermining of structures over the next five years by the coal mines in Secunda alone.

Table 12.2: Structures planned to be undermined with high extraction methods and the coal to be gained by doing so during 1990-1994

STRUCTURE	TOTAL LENGTH (m)	COAL GAIN (million tonnes)
Tarred roads	2 200	1,05
Gravel roads	5 090	2,43
Pipe lines	2 850	1,36
Conveyor belts	2 650	1,26
Power lines	(72 pylons)	5,09
T O T A L		11,19

12.5 METHOD OF HANDLING SUBSIDENCE

It was shown in Chapter 2 that the undermining of structures is prohibited by legislation, but that exemption is readily obtained provided that the Government Mining Engineer is convinced that the undermining can be done safely, and that the owner of the structure agrees to the undermining. The experience thus far has been that the Government Mining Engineer can be convinced of the safety of such underminings once the prior investigations have been done to his satisfaction.

In practice, permission to undermine a structure is therefore often in the hands of the owner of the structure. The deciding factor is then the outcome of negotiations between the mine and the owner of the structure.

With regard to single structures, like farm houses, the modus operandi can be regarded as a good one, being generally satisfactory to both parties. Considering the value of the coal to be gained by undermining, most mines are in a position to offer favourable compensation to the owners of structures.

This may not always remain a good method. Should the economics of coal mining change, which is likely to happen when lower grade reserves are mined, the terms which the mines can offer may not be so favourable.

When expanding network structures like roads or pipe lines are considered, the approach based on separate negotiations for individual underminings has distinct disadvantages. It could result in an uncoordinated confusion of different requirements for different companies in different areas for network serving the same purpose.

The approach at the other end of the scale, blanket permission to undermine certain structures regardless, is also not desirable. It has been shown that there are several variables which have to be investigated when undermining is considered. Blanket underminings may therefore be dangerous, especially in the case of smaller mining companies who do not have available the services of in house experts, or who cannot afford the various costs associated with subsidence damage.

It is proposed that a system be adopted which will place the decision whether or not to undermine a structure and the nature of precautionary and remedial work in the hands of a body of experts in a coordinated manner. The essence of the Australian example could be followed in this regard, with the declaration of defined subsidence districts and the appointment of a Subsidence Board to exercise limited control over the underminings in that district.

The main function of the Subsidence Board should be to provide a platform for a joint planning function between the various mines and the structure owners. It is possible that by adjusting the planning for the construction of infrastructure and/or the mines, undermining can in some cases be avoided. Undermining applications should also be decided by the Board. The third function should be to control the erection of structures, with regard to timing, position and construction.

Undermining of structures, although increasing in frequency, do not yet occur frequently enough to warrant the appointment of a full time board of independent experts. The board should therefore consist of members nominated by the mines and the owners of the structures, under the guidance of a full time chairman, who should be the Department of Mineral and Energy Affairs' subsidence expert. The board should not conduct undermining investigations, but should evaluate such investigations presented by the mines.

The essential conclusion of the study is that a number of commonly occurring structures can be undermined safely and economically by high extraction methods. In the light of the inherent flexibility of certain structures and rigidity of others, indicated by the non serious nature of subsidence damage, there does not appear to be too great a need to adapt construction methods of most structures dramatically to accommodate the displacements induced by high extraction coal mining.

It is very important that each contemplated undermining be investigated in detail, as the effects of subsidence are controlled by several independent variables. Each decision on whether to allow undermining or not should be considered on its particular merits.

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