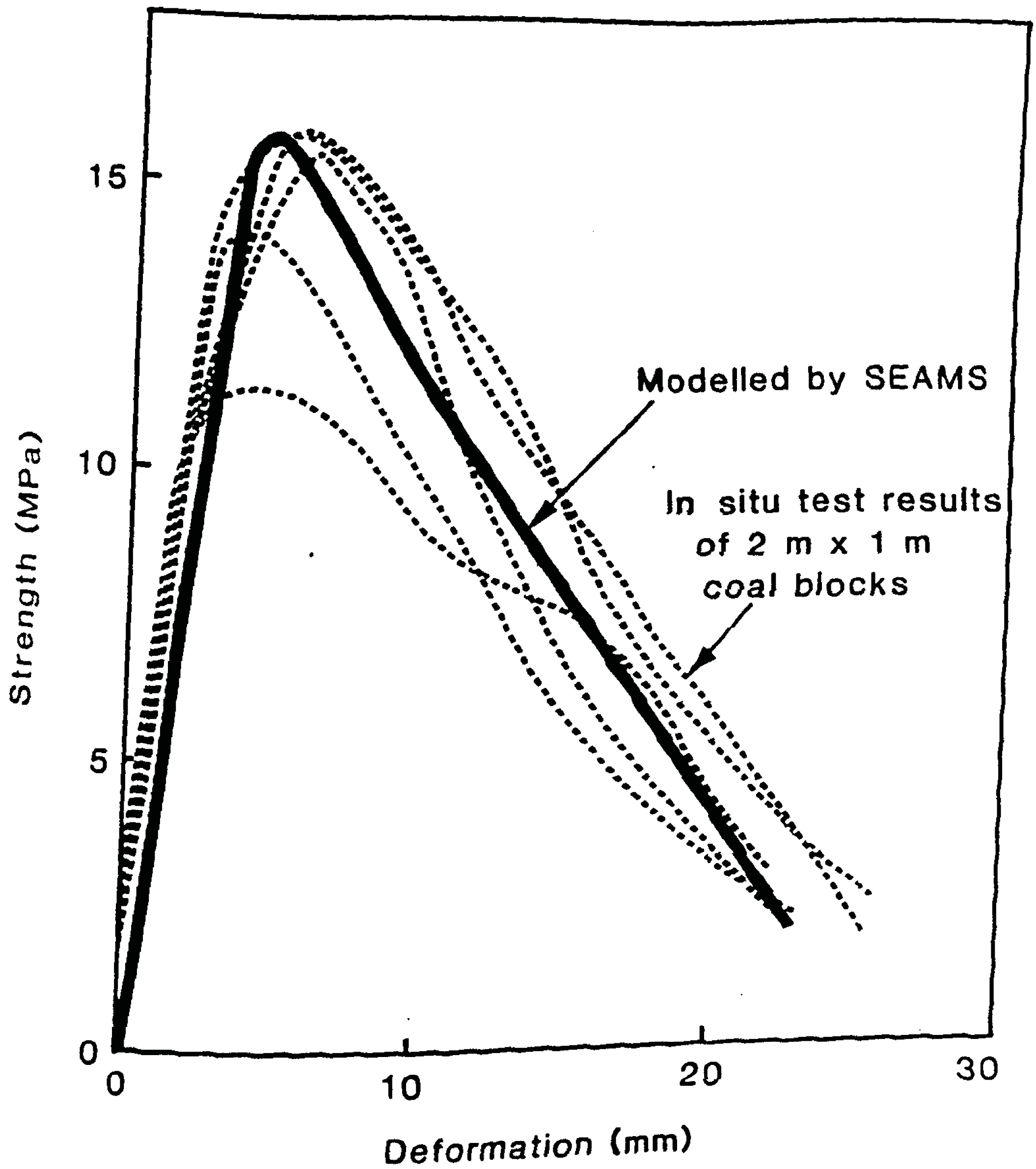

Figure 7.22 Strength-deformation curves obtained using the program SEAMS.

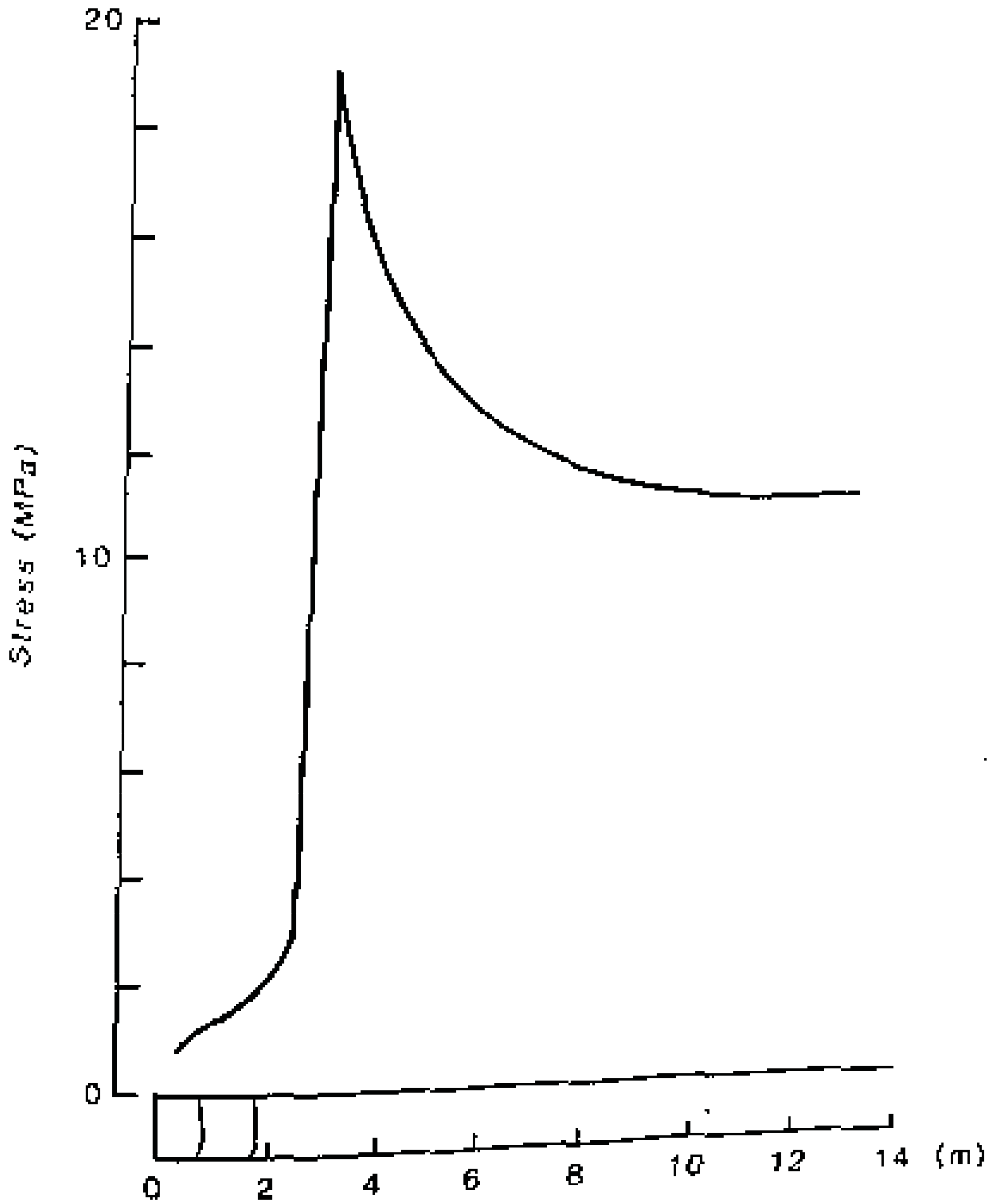

Figure 7.23 Stress profile across pillars obtained using the program SEAMS.

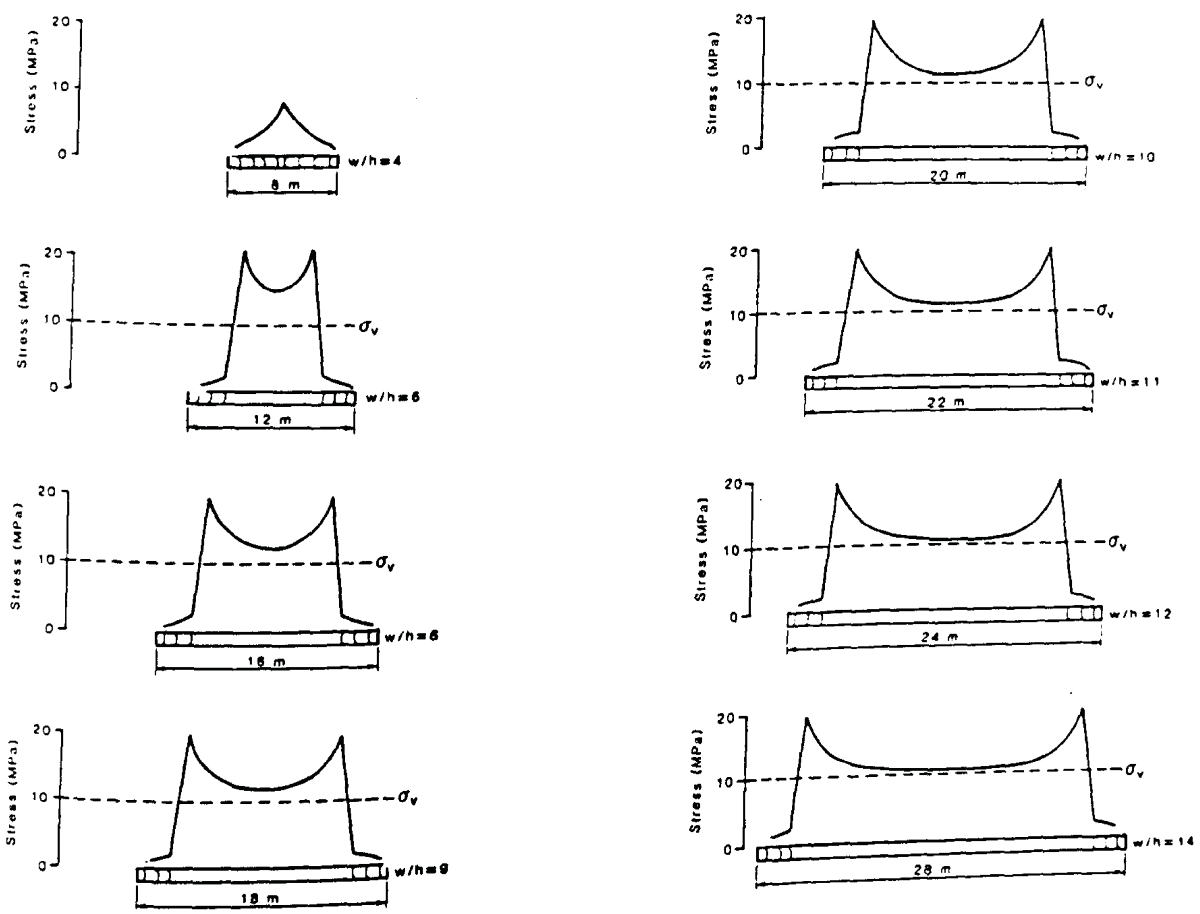

Figure 7.24 Stress profiles across pillars 8,0 to 28,0 m wide obtained using the program SEAMS.

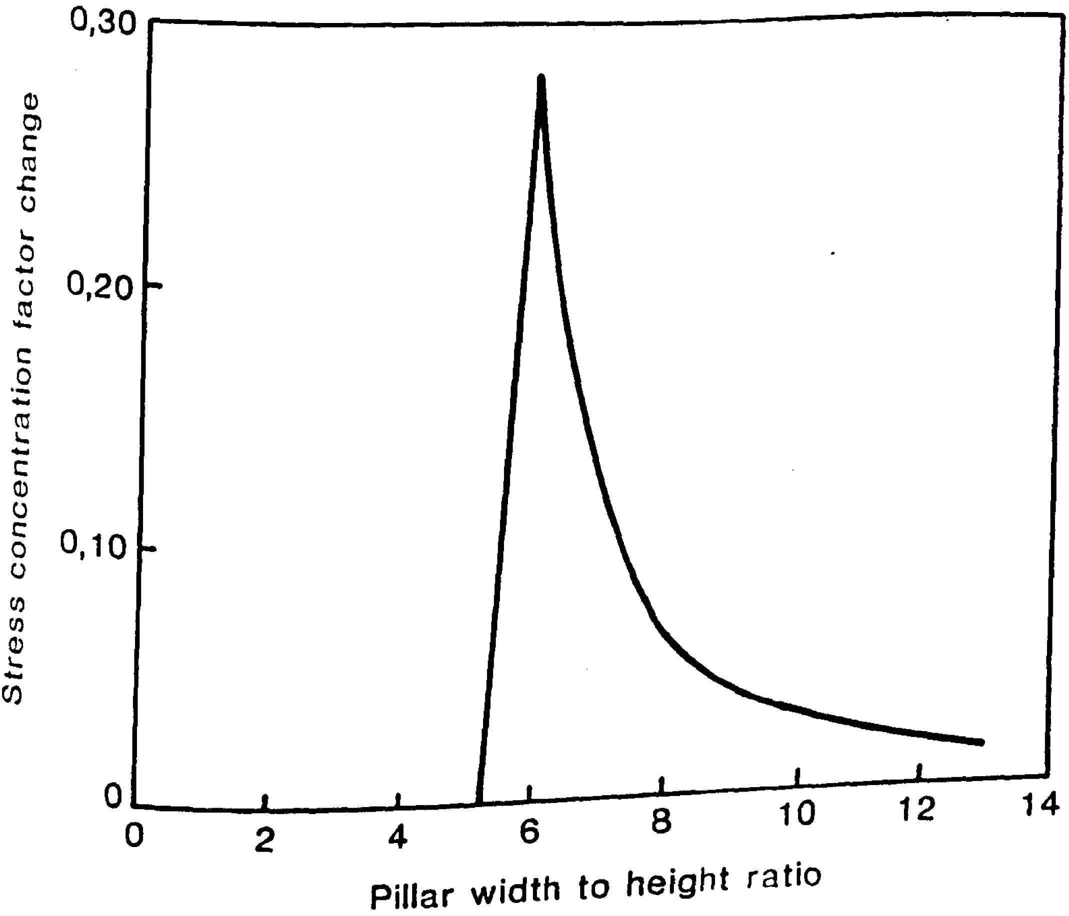

Figure 7.25 Change in stress concentration factor at the centre of the pillar for varying width to height ratios.

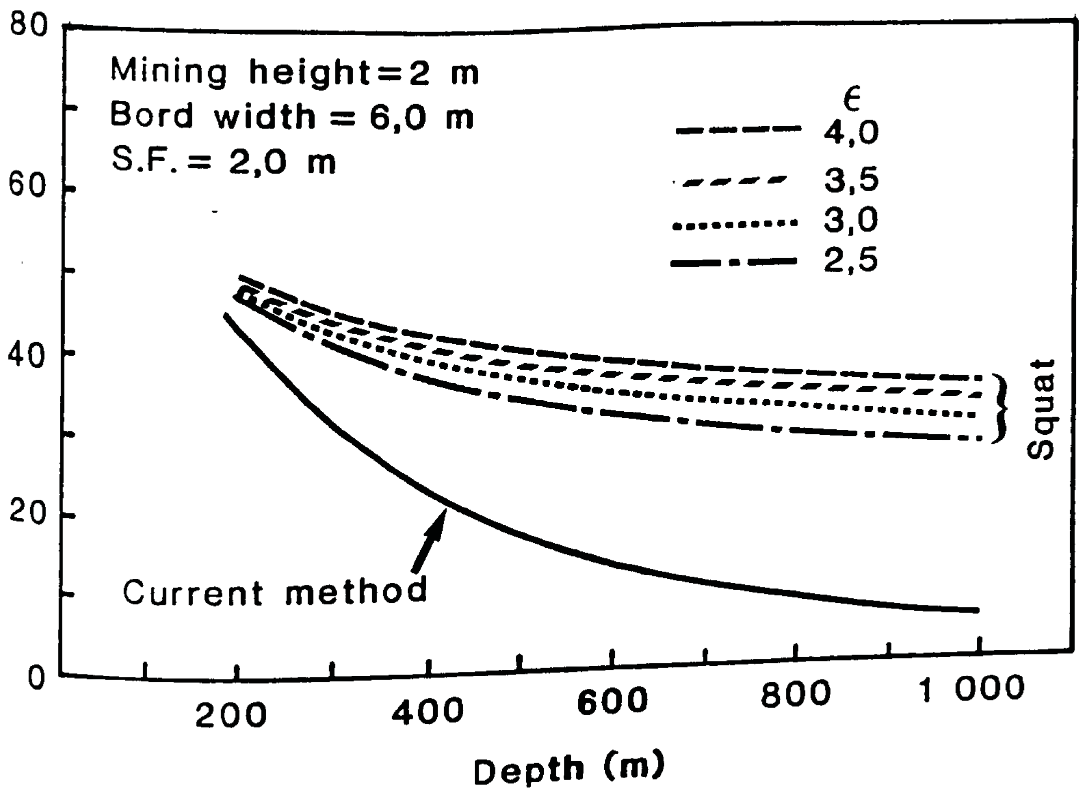

Figure 7.26 Areal percentage extraction versus depth using Salamon and Munro's and squat pillar strength formulae, for different values of ϵ.

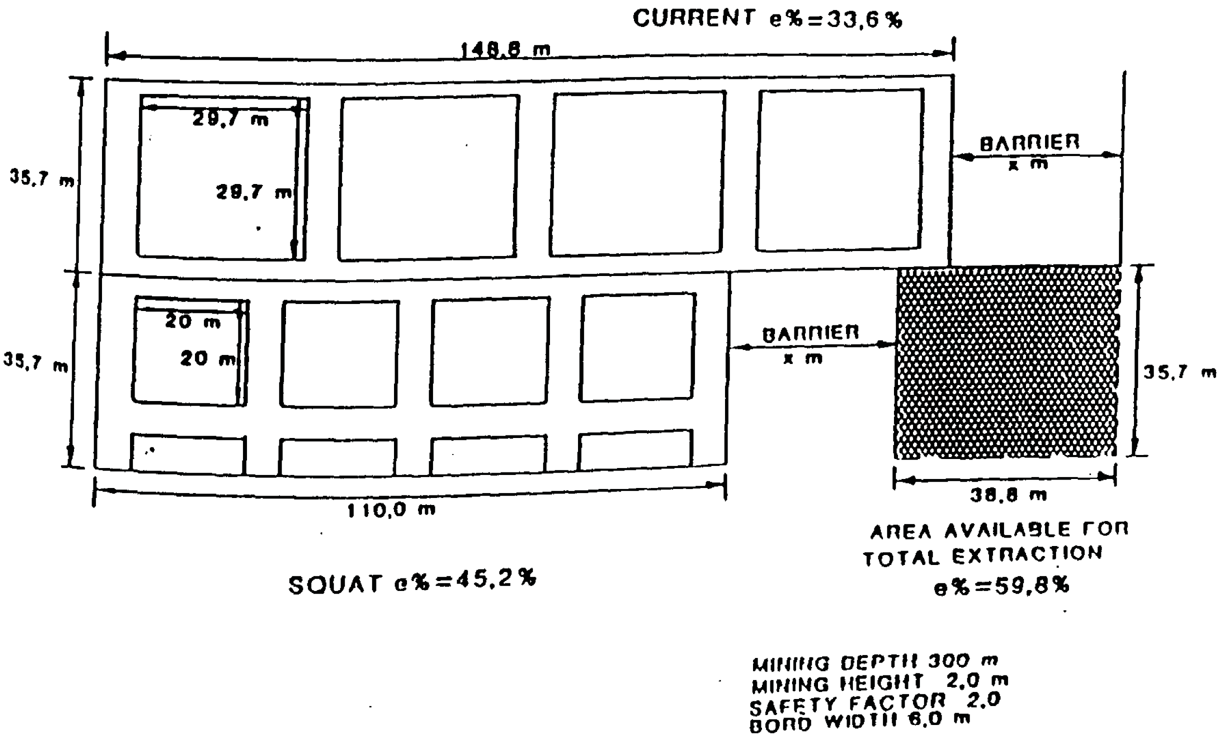

Figure 7.27 Schematic illustration of areal percentage extraction using Salamon and Munro's and squat pillar strength formulae over the same area.

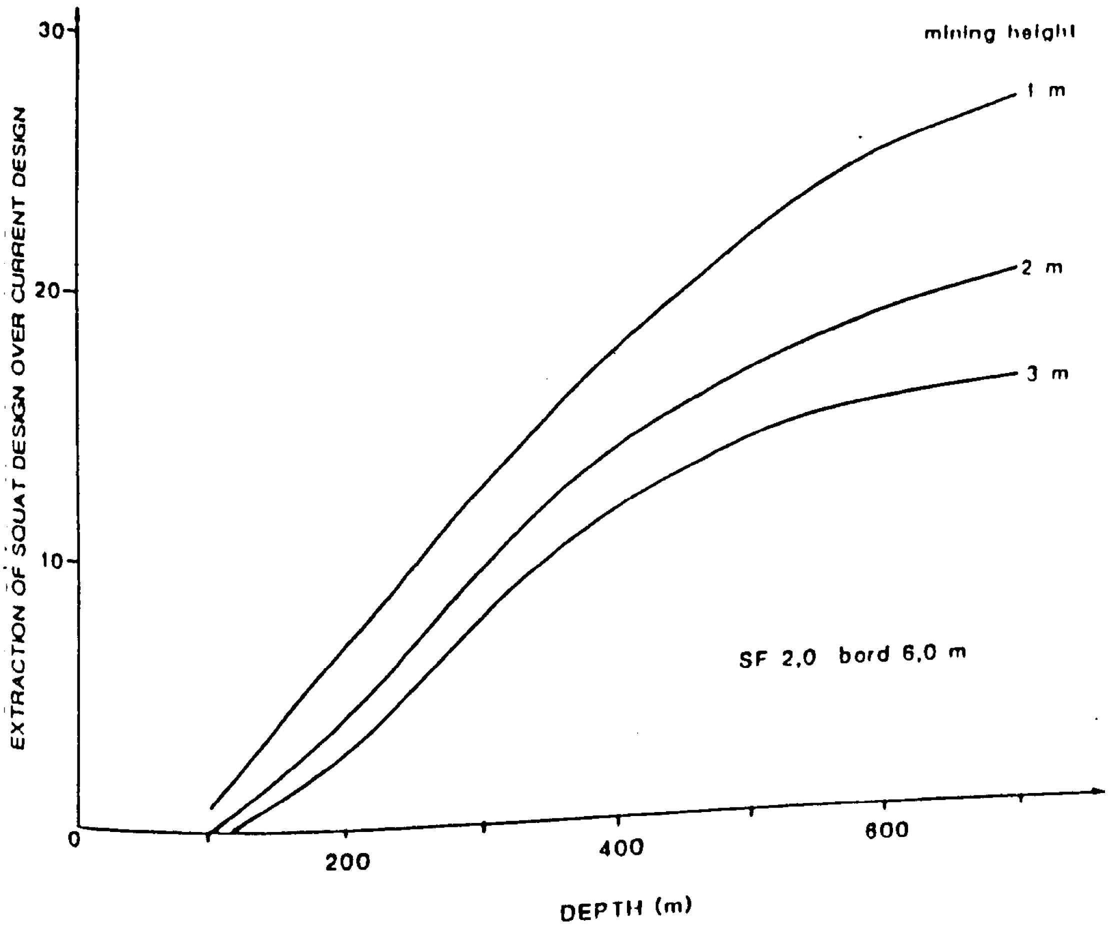

Figure 7.28 Absolute increase in areal percentage extraction of squat pillar strength formula compared to that obtained using Salamon and Munro's strength formula for various depths.

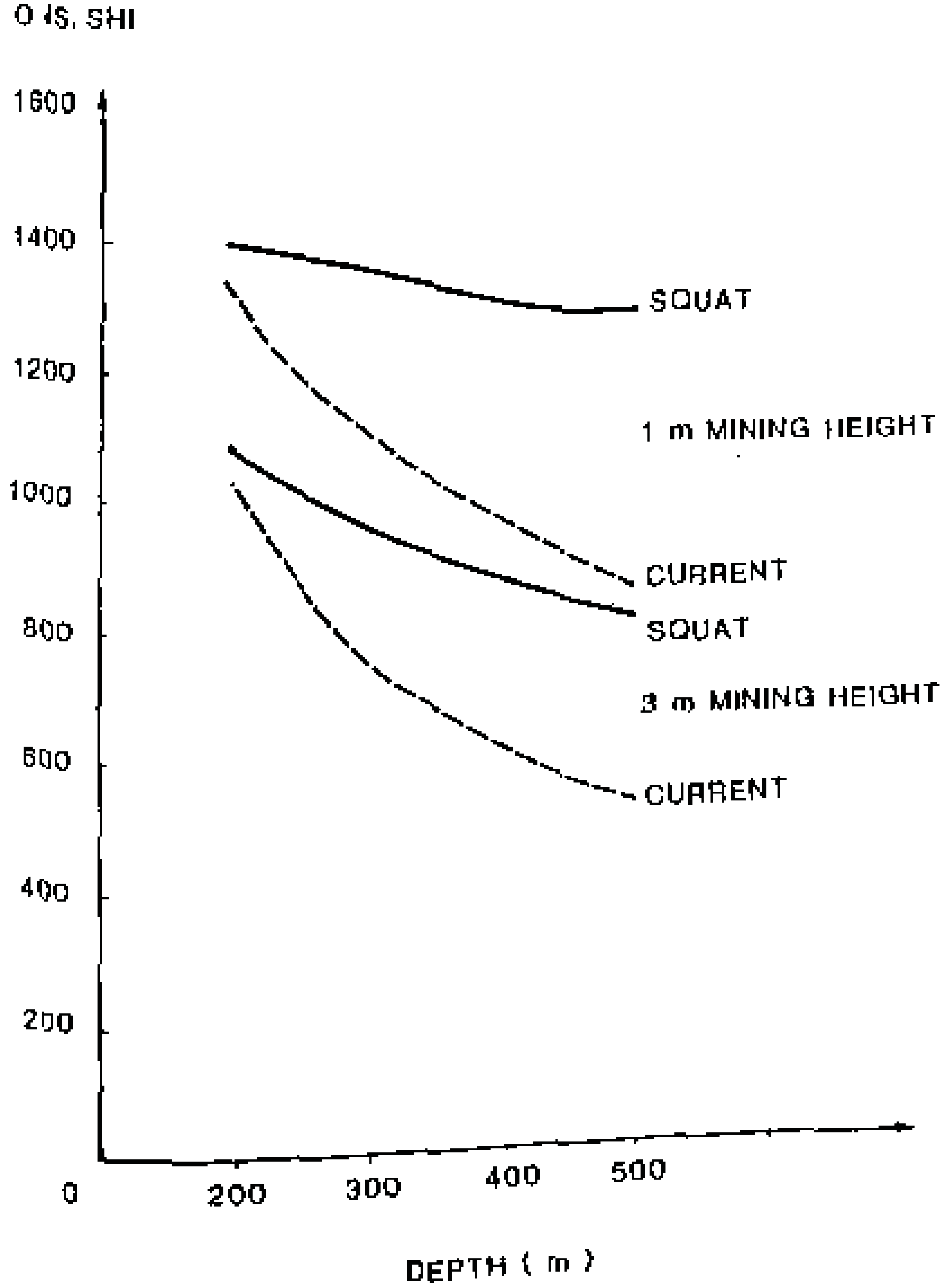

Figure 7.29 Tons per shift for 1 and 3 m mining height at depths between 200 and 500 m.

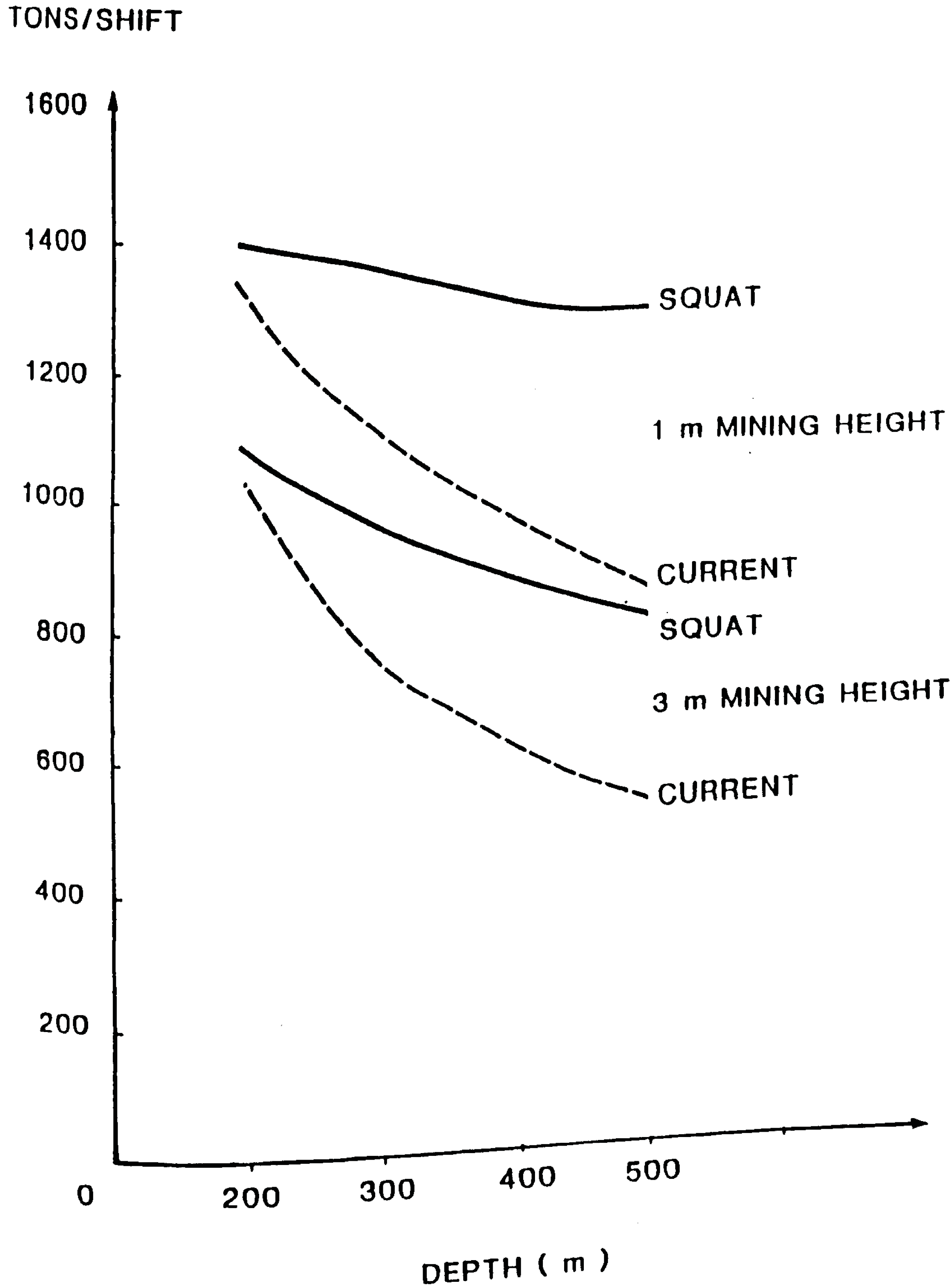

Figure 7.29 Tons per shift for 1 and 3 m mining height at depths between 200 and 500 m.

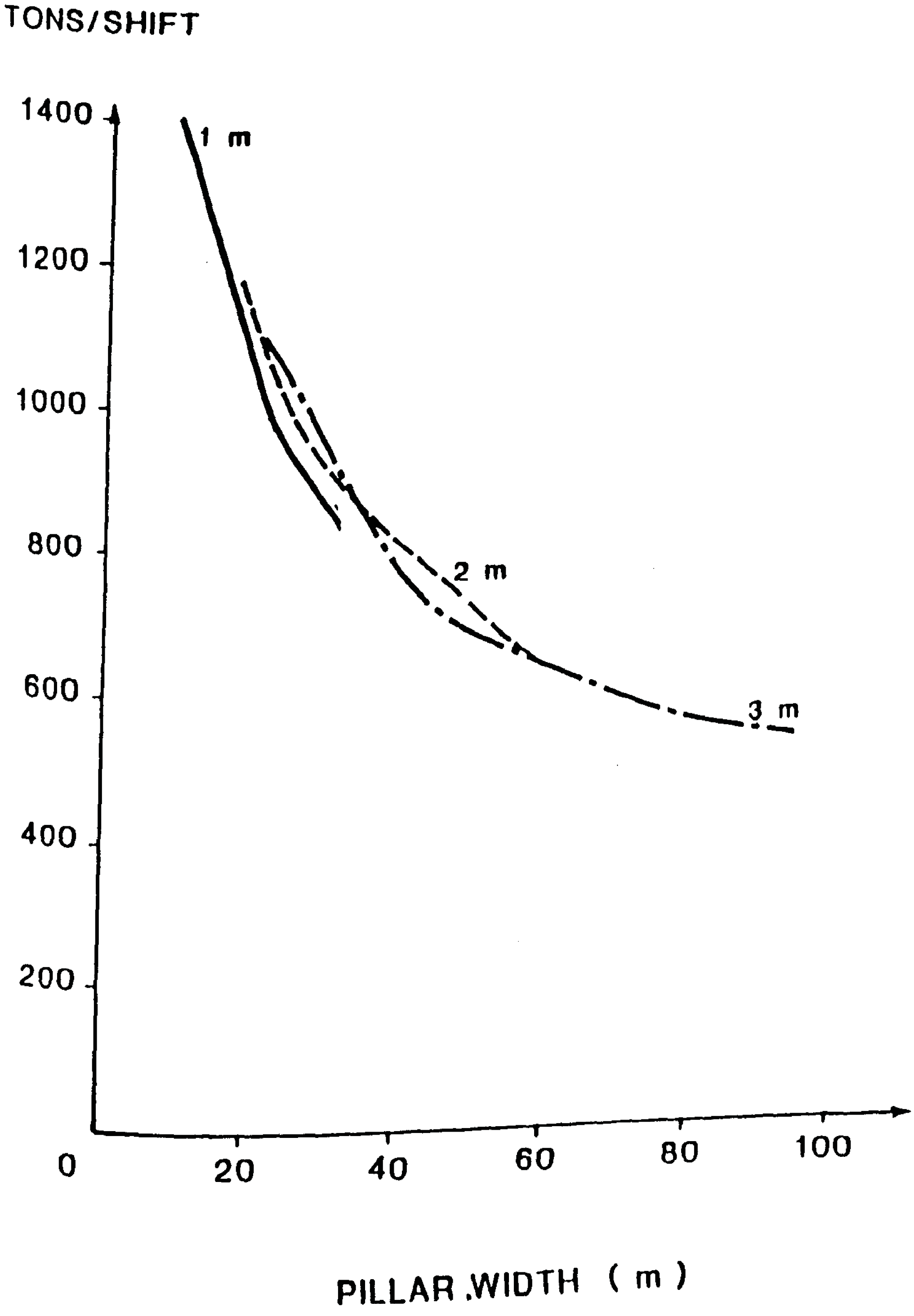

Figure 7.30 Tons per shift for 1 , 2 and 3 m mining height versus pillar width. (For the computer simulations the machine parameters were kept constant for all mining heights.)

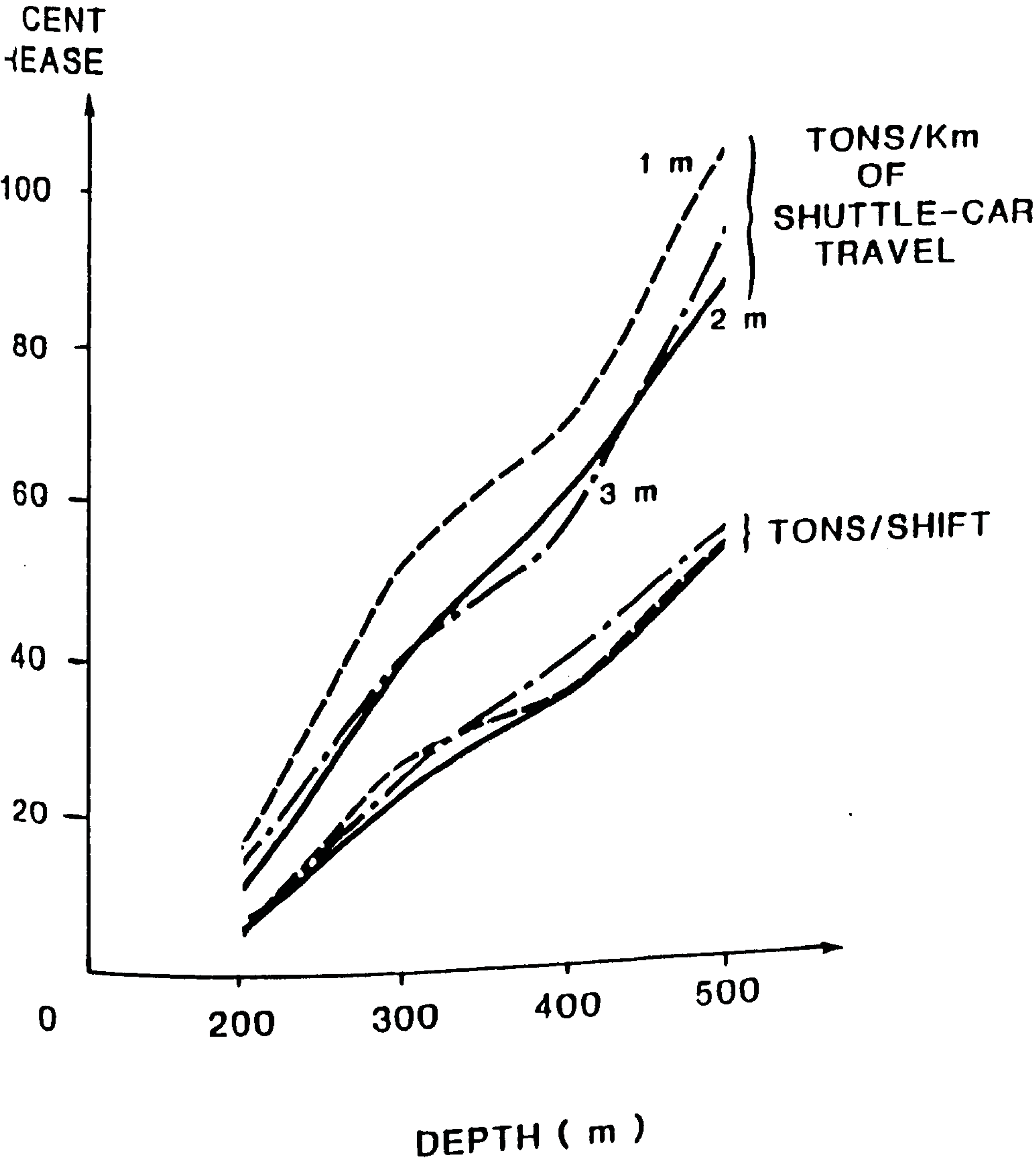

Figure 7.31 Percentage increase in tons per shift and tons per kilometre of shuttle-car travel of squat pillars over pillars designed using Salamon and Munro's strength formula for depths of 200 and 500 m.

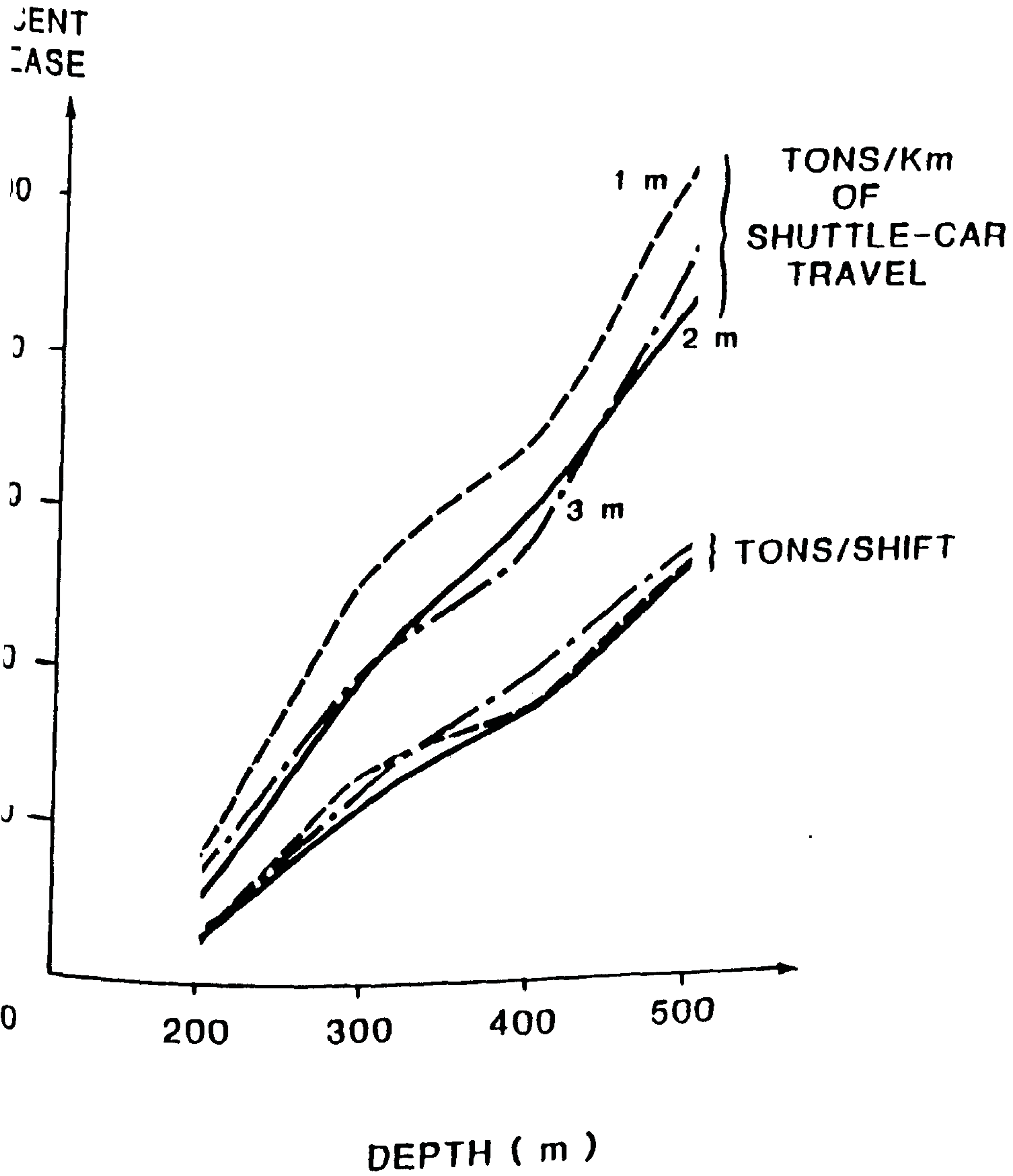

Figure 7.31 Percentage increase in tons per shift and tons per kilometre of shuttle-car travel of squat pillars over pillars designed using Salamon and Munro's strength formula for depths of 200 and 500 m.

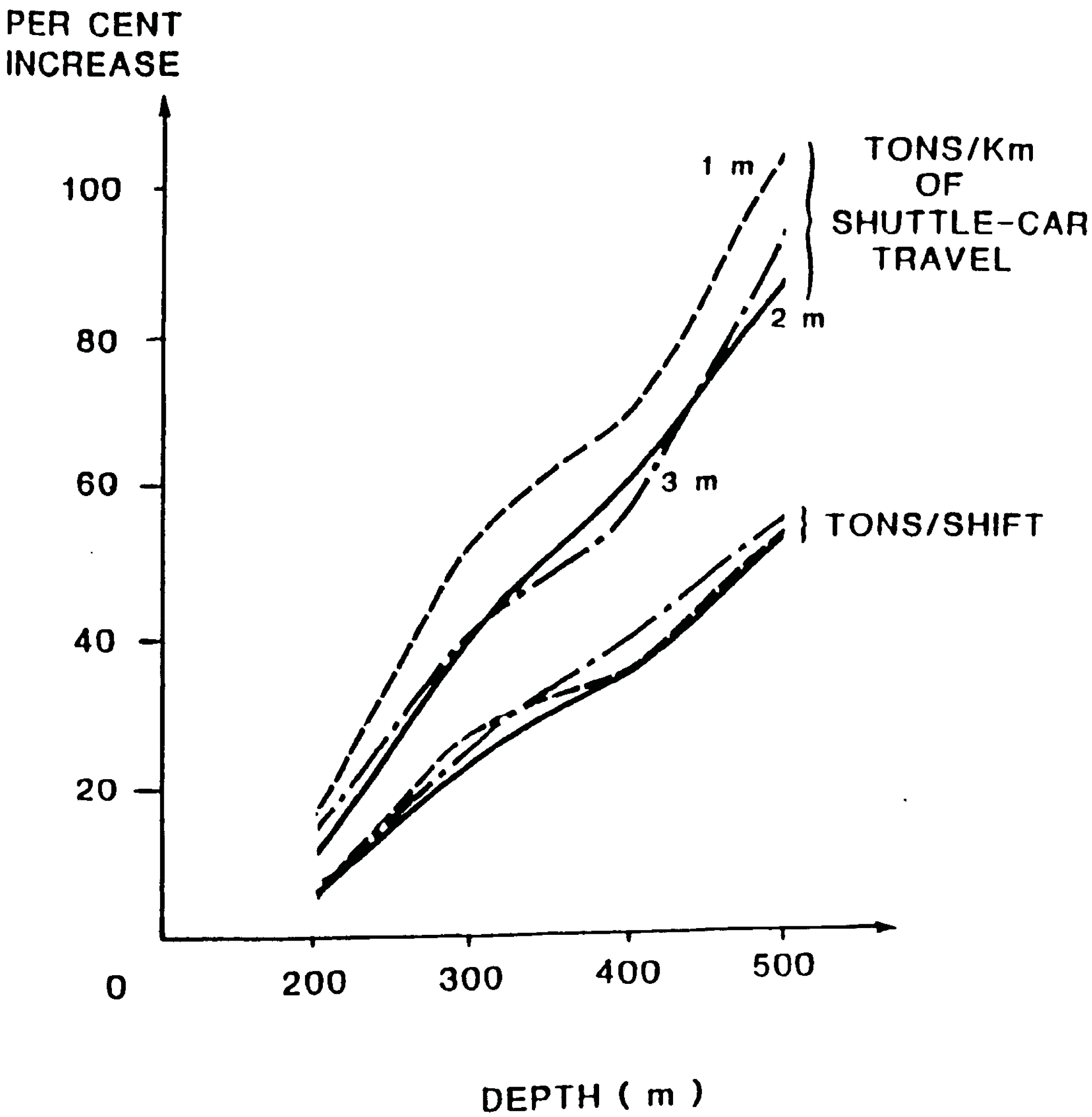

Figure 7.31 Percentage increase in tons per shift and tons per kilometre of shuttle-car travel of squat pillars over pillars designed using Salamon and Munro's strength formula for depths of 200 and 500 m.

CHAPTER 8

CONCLUSIONS AND PROPOSED FURTHER STUDIES.

8.1 SUMMARY AND CONCLUSIONS

This thesis presents the results of investigations into the factors affecting the strength of pillars in South African coal seams with the aim of utilizing rock mechanics principles to improve the extraction of coal reserves in a productive, economic manner without jeopardizing the safety of men and equipment.

A survey of the literature showed that the strength of coal, and the consequent design of stable production pillars, have been researched extensively worldwide since early this century. This has lead to investigations into the effects on shape, size, friction, stress-strain characteristics, material properties, geometry, end constraints and geological discontinuities. Extensive testing programmes in the laboratory and on large sized in situ samples have been conducted, resulting in numerous design formulae proposed by various authors to account for the strength of coal pillars. One problem common to these research efforts, however, was the extrapolation of results, either from laboratory or in situ tests, to the design of full size pillars.

It was not until the back analysis, using statistical methods, of collapsed and intact pillar geometries by Salamon and Munro (1967) that a practical pillar strength design formula based on full size pillars was formulated. This design method has been used to calculate pillar geometries in South African collieries for the past 22 years. During this period the South African coal mining industry has expanded considerably, extending the exploitation of reserves beyond the empirical range used to develop the pillar strength formula. Thus its applicability in these cases required investigation. In addition, the formula assumed one average strength for all seams and this also needed to be investigated.

The first phase of the investigation was to examine the cases of pillar collapse that had occurred after the introduction of Salamon and Munro's pillar strength formula. During the period 1966-1988 31 cases of pillar collapse were reported. Seventeen cases fulfilled the criteria applied by

Salamon and Munro (1967) for their inclusion in the statistical analysis. The remaining 14 were thought to be due to bord collapses inducing pillar failure.

The 17 pillar collapses between 1966-1988 were analysed together with the 27 cases of Salamon and Munro (1967) to examine if new trends emerged. The results of the investigation showed that at very shallow depth, between 15 and 40 m, pillar collapses can occur with high safety factors. This is thought to be a result of small pillar sizes being susceptible to the influence of blast damage, weathering, geological discontinuities, weak layers within the coal seam or a combination of these factors. It is recommended that a minimum pillar size of 5,0 m and width to height ratio of 2,0 , together with a maximum areal extraction of not greater than 75 per cent be maintained when designing pillars at depths shallower than 40 m to ensure long term pillar stability.

The statistical analysis of all collapsed pillar geometries together with the 92 intact cases used by Salamon and Munro showed a variation in all parameters from the original analysis. However, the strength calculations of pillar strength using the two sets of parameters showed very little difference. This proved that the pillar strength formula of Salamon and Munro was effective in designing stable bord and pillar geometries for South African collieries.

Applying the statistical analysis to individual coal seams showed that, although a difference in strength was indicated, the scatter of results was not statistically significant and the assumption of one strength for all coal seams is valid. This result is understandable considering the variation in coal composition, the influence of geological discontinuities and the limited data available.

A pillar classification system based on the visual observation of pillar performance was developed to assess the relative strengths of individual seams. The method of classification accounted for the effects of weaknesses within the pillar, geological discontinuities, the pillar contact between the roof and floor, the effects of water and weathering. These parameters are not directly considered in the pillar strength design formula. The classification rated the effects of these parameters on the ability to withstand deterioration. To this rating was applied a time factor and an overall pillar rating was given to the pillar. This total rating was compared to the skin stress of the pillar. The classification successfully indicated a relative difference between the seams but could not be used to quantify the different seam strengths, as it was particularly sensitive to the skin stress, a small variation resulting in a significant change in rating. This limited the application of the classification system. However, the classification of pillars is useful to determine the pillar condition and has been used to evaluate the stability of old workings as a supplement to the probability of a stable geometry given by Salamon and Munro's design formula.

The effect of mining on pillar strength was investigated as pillars formed by a continuous miner are not subjected to the blast damage of conventionally formed drill and blast pillars. All cases in the statistical analysis of stable and collapsed pillar geometries used to develop the pillar strength formula were formed by drilling and blasting. Hence the pillar strength formula inherently accounts for the effect of the blast damage zone which was quantified as extending 0,25-0,3 m into the pillar side. A continuous miner formed pillar, mined to the same dimensions as a drill and blast formed pillar, has greater strength due to the absence of the blast damage zone. Thus the designed pillar width when using a continuous miner can be reduced by the extent of the blast damage zone without a decrease in the stability of the pillar.

This reduction has practical significance in the increased extraction of reserves. The use of a continuous miner in a 2,0 m seam can increase the areal extraction between 4,75 per cent at 12,0 m centres and 4,22 per cent at 19,0 m centres. The limitation of this application is that in pillar widths of less than 6,0 m a small change in dimension, from a weak layer or geological discontinuities, results in a significant reduction in pillar area. This can result in greater stress on the pillar side initiating slabbing of the sidewall. Stress-induced slabbing also occurs in pillars at depths exceeding about 175 m.

Thus increased percentage extraction is possible when using continuous miners for pillars greater than 6,0 m in width at depths not exceeding about 175 m. This method has been successfully applied at Matla Colliery over the last three years and an estimated 4,5 per cent increase in extractable reserves in panel has been obtained. At Khutala Colliery an estimated 30 million tons of coal has been added to the reserves by applying this method, as the resulting smaller pillar dimensions do not require pillar superimposition in a multi-seam situation.

The examination of the collapsed pillar geometries revealed that no pillar had collapsed with a width to height ratio greater than 3,75. Salamon and Oravecz (1976) suggested that the pillar strength formula of Salamon and Munro underestimates pillar strength when the width to height ratio exceeds five or six. Salamon (1982) proposed an extension to his original pillar strength formula to account for the increased strength of squat pillars.

To examine this concept an extensive series of laboratory tests was conducted. This investigation showed that, beyond a certain critical width to height ratio, there is a marked change in the influence exerted by the width to height ratio of a specimen on its strength. It was not possible to define a strength value for a specimen, but the strength value was identified to be dependent on the compression of the sample. It was found that for the small cylindrical sandstone specimens there existed a gradual transition from a brittle behaviour, at low width to height ratios, to a ductile behaviour at large width to height ratios, with the transition occurring between width to height ratios of 5,0 to 6,0. This finding is of great practical significance as it suggests that sudden unstable pillar collapse is most unlikely in the case of squat pillars.

The results also showed that a small confinement applied to the fractured circumference of the specimen influences the strength and load-deformation characteristics. These laboratory tests showed that the squat pillar formula of Salamon (1982) successfully predicted the strength of specimens with increasing width to height ratios.

It was based on these findings that the Government Mining Engineer was approached to approve field trials to evaluate the suitability of the squat pillar formula for South African collieries. These field trials examined the performance of two panels designed to the squat pillar formula, assuming the critical width to height ratio to be five and the rate of strength increase to be 2,5. From field evidence, as no pillar collapse has occurred with a width to height ratio greater than 3,75, the assumption of the critical width to height ratio being five is considered as being conservative but accurate.

The findings of the field investigation showed that, although severe sidewall fracturing occurred at depths in excess of 250 m, the extent of fracturing was limited to the skin of the pillar with the maximum depth of fracturing observed being less than 2,0 m into the pillar side. There was a large central portion of unfractured coal in pillars at Piet Retief Colliery at a depth of between 450-550 m from the surface. Measurement of stress profiles showed that the coal in the fractured zone was capable of carrying significant load and that in the central part of the pillar the stress had returned to virgin conditions.

At Hlobane Colliery the pillars proved to be stable but severe floor heave resulted in the loss of some pillars. This indicated that the influence of the surrounding strata on the overall stability of the workings must be considered.

Overall, the field trials showed that stable pillars which were designed using the squat pillar formula resulted in a significant reduction in pillar dimensions when compared to the pillar strength formula of Salamon and Munro.

Numerical modelling using the program SEAMS simulated the fracturing within the pillar sides and the results correlated well with the stress profile obtained from in situ tests, after about 6,0 m into the pillar. This model was used to examine the stress profile with varying geometries.

It was not possible to select a rate of strength increase as this value was sensitive to small changes in pillar width. However, the assumption of ϵ equal to 2,5 gives a conservative design.

The squat pillar formula gives substantial improvements in percentage extraction over the current design method, approximately 19 per cent for a 2,0 m high seam at 600 m, the current maximum depth of mining in South African collieries. The reduced pillar sizes result in increased productivity and reduced tramming costs which combine to give lower working costs. This has been shown to occur where squat pillar panels at Hlobane Colliery recorded an average increase in productivity of 15 per cent.

In summary, the re-evaluation of Salamon and Munro's formula showed that this design method is very successful in designing stable bord and pillar geometries within its empirical range. This formula has been modified to account for a continuous miner formed pillar resulting in increased extraction.

The extension of Salamon and Munro's pillar strength formula by the squat pillar formula has been proved, in field trials, to lead to the design of stable pillar geometries. In December 1989 the South African Government Mining Engineer formally approved the squat pillar formula for use in collieries. To date six collieries : Hlobane, Kilbarchan, Piet Retief, Majuba, New

Denmark and Welgedacht, have successfully applied the squat pillar formula. This has resulted in substantial benefits in percentage extraction, productivity and reduced working cost without affecting the safety of men and equipment.

8.2 FURTHER INVESTIGATIONS

To attain the maximum benefit from the squat pillar formula, the strength of full size pillars at various compressions should be investigated. This investigation would have to encompass the stability of the surrounding strata as severe sidewall fracturing would be anticipated. The ability of the roof and floor strata to sustain the strains induced by pillar compression would also require investigation. It was shown in the field trials at Hlobane Colliery that, while pillar stability was maintained, severe floor heave occurred which resulted in the loss of about half the remaining pillars in the section. Therefore, criteria need to be identified for a design method which prevents foundation failure beneath coal pillars. As the depth of mining increases, these factors will influence the capability of obtaining a more efficient and economic design.

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APPENDIX I

CALIBRATION OF CORRECTION FACTOR FOR AXIAL DISPLACEMENT FOR THE TESTING OF SANDSTONE SPECIMENS

The laboratory tests on cylindrical sandstone specimens required a correction factor as the method of measuring axial displacement included the deformation of the platens, the indentation of the specimen into the platens and the deformation of the machine parts.

Thus it is necessary to find the correction factor for the axial displacement. The method used was to record the load displacement curve of a specimen of known material properties, then calculate the ideal deformation using the known material properties and subtract this from the measured result. The resulting correction factor can be applied to a specimen of the same diameter.

Mild steel specimens were prepared for each series size and the load-displacement curve obtained. The ideal deformation of the mild steel specimen could be calculated form

$$E = \frac{\sigma}{\epsilon'} \qquad (I.1)$$

where E = Young's modulus

σ = stress

ϵ' = axial strain;

$$\epsilon' = \frac{\sigma}{E}$$

$$\sigma = \frac{L}{A} \qquad (I.2)$$

where L = load

A = specimen area.

Therefore

$$\epsilon' = \frac{L}{A.E} \qquad (I.3)$$

$$\epsilon' = \frac{\Delta e}{l} \qquad (I.4)$$

where Δl = change in length
l = length of the specimen.

Therefore

$$\Delta l = \frac{l.L}{A.E} \qquad (I.5)$$

Therefore the ideal deformation of the mild steel specimen can be determined for any load, knowing the Young's modulus of mild steel E = 210 GPa, and the dimensions of the specimen tested.

Example:

The calculation of the correction factor for axial displacement for the "E" series diameter 80,0 mm.

Neglecting the settling in of the specimen, the slope of the load displacement curve for the mild steel specimen is shown in Figure I-1, line A.

At a load of 161,35 kN the axial displacement was 0,04002 mm.

Using equation (I.5) the ideal deformation at 161,35 kN can be calculated from

$$\Delta l = \frac{l.L}{A.E}$$

where A = area of specimen
= 0,005026548 m^2
l = specimen length 19,8 mm
E = 210 GPa (mild steel).

Therefore

$$\Delta l = \frac{19,8 \times 161,36}{0,005025648 \times 210 \times 10^6}$$

= 0,00302653 mm.

Thus the ideal slope can be represented by line B.

The correction at 161,35 kN is

0,04002 mm - 0,00302653 mm = 0,03699347 mm.

Line C is the correction that must be applied to obtain the correct axial displacement of the tested specimen. This can be represented as

x = y/k

where x is the axial correction
y is the load
k is the slope of the line C.

Thus

$$k = \frac{161,35 kN}{0,0369934 mm}$$

= 4361,581.

For specimens of diameter 80,00 mm the axial displacement must be corrected by the equation

x = y/k

where x is the displacement correction,

y is the load

k = 4361,581.

This correction applies to a certain configuration for measuring the axial displacement. Each specimen diameter was corrected by its relevant equation.

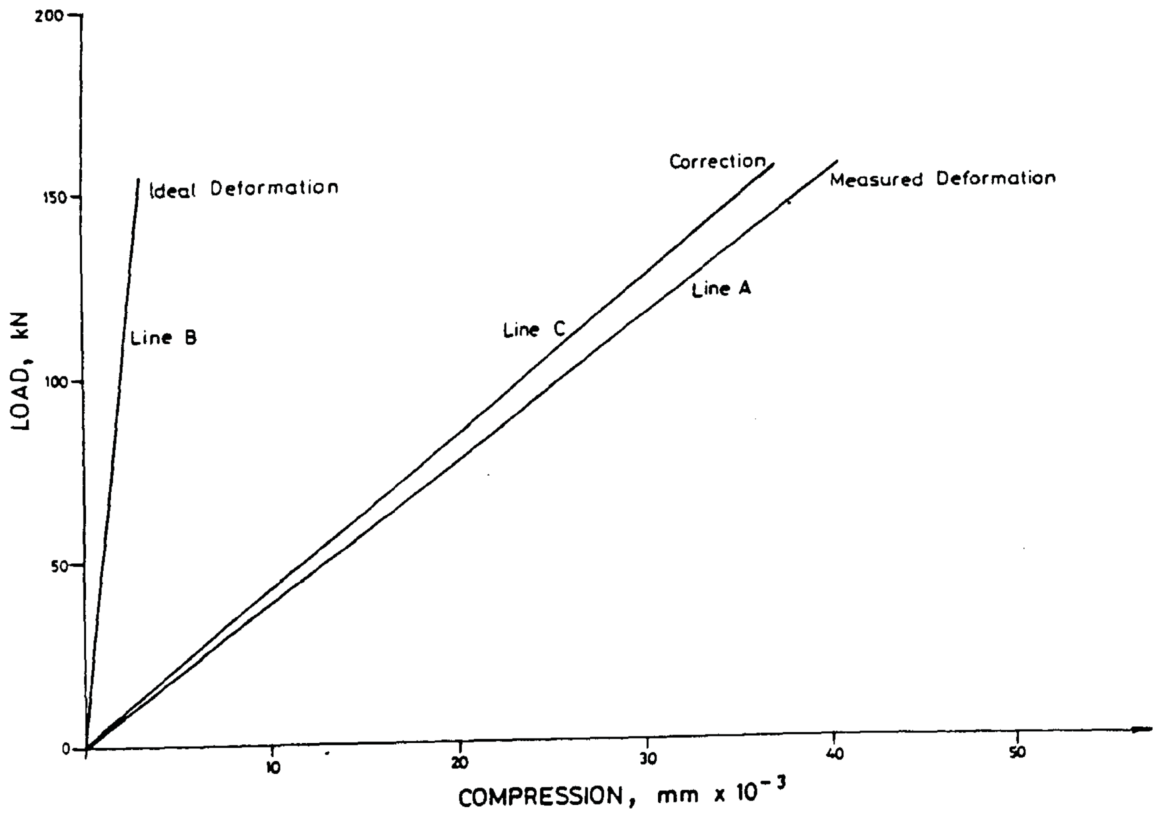

Figure I.1 Correction factor for "E" series 80,0 mm diameter.

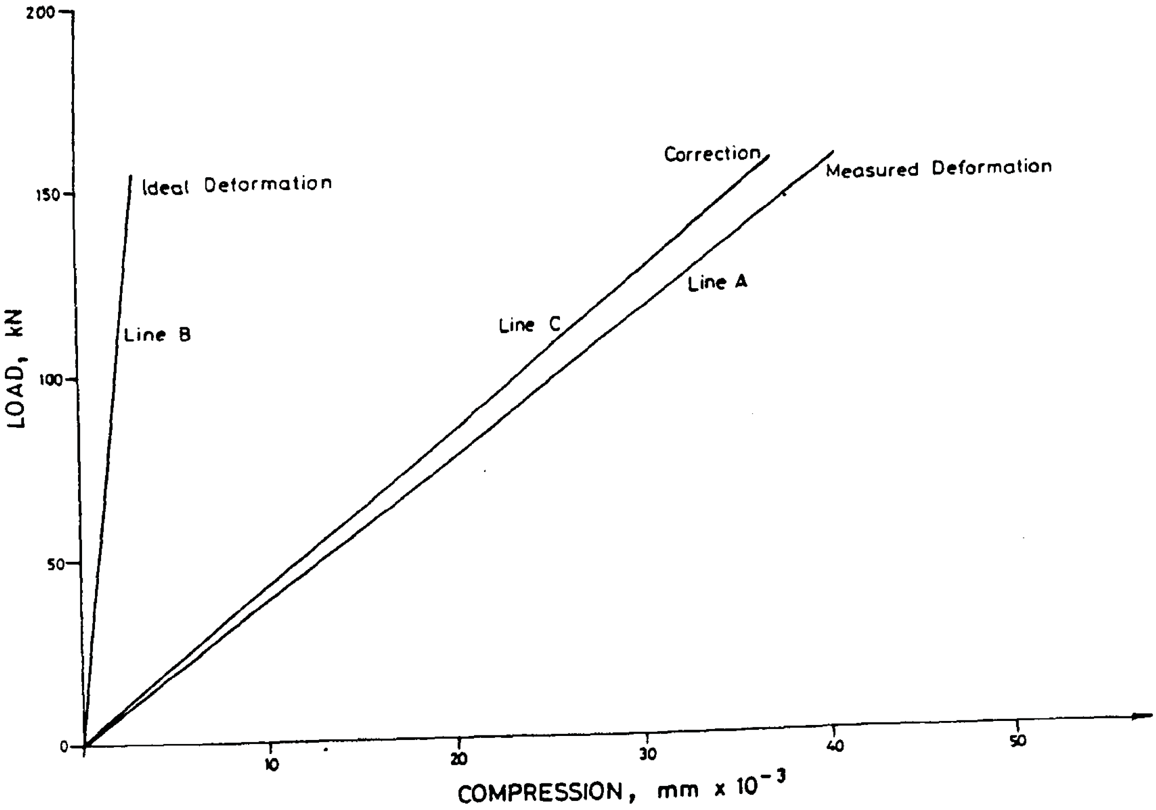

Figure I.1 Correction factor for "E" series 80,0 mm diameter.