NON-LINEAR FINITE STRAIN CONSOLIDATION OF TAILINGS AND WASTE

Fred Werner Gassner

A project report submitted to the Faculty of Engineering, University of the Witwatersrand, Johannesburg, in partial fulfillment of the requirements for the degree of Master of Science in Engineering.

Johannesburg 1997

DECLARATION

I declare that this project report is my own, unaided work. It is being submitted for the Degree of Master of Science in Engineering in the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination in any other University.

(F.W. Gassner)

1 day of September 1997

ABSTRACT

The research report summarises the theory of consolidation, for both linear infinitesimal strain, and for non-linear finite strain. The non-linear finite strain theory is adopted in a computer program to model the building of a tailings dam by thin layers. This program provides the pore water pressure profile over the depth of the deposit, as well as the settlement of the deposit.

Making use of the program and the consolidation properties of five mining residues and two industrial residues, the build-up of excess pore water pressures is modelled for different rates of deposition of the waste products. These results are used in determining how the rate of deposition affects the stability of the outer slope of a tailings dam. Also, the difference in the stored volume in a dam is investigated, based on different drainage conditions and rates of deposition.

ACKNOWLEDGEMENTS

The author wishes to thank Crown Mines Limited and the Department of Water Affairs & Forestry for their permission to use the results of testwork carried out on their projects, for some of this research.

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

Quantity	Symbol
Density of soil or tailings	γ
Void ratio	e
Stress	σ
permeability	k
density of water	γ_w
Length of drainage path	H
pore pressure	u
initial pore pressure	u_o
Gravity	g
applied pressure	p
incremental settlement of a layer	δ_l
change in stress	$\Delta\sigma$
change in void ratio	Δe
effective stress	σ'
metres per annum	mpa

CONTENTS

CHAPTER 1: INTRODUCTION

The recent failure of the Merriespruit Tailings dam has initiated a large number of investigations, with many of the "accepted practices" being revisited and criticised. One of these accepted practices is the concept of maximum acceptable rate of rise of a tailings dam. It is a requirement of the Department of Mineral and Energy Affairs that the owner of a dam submits an annual survey of the top of all tailings dams, with the rate of rise over the previous year. Empirical values of 1 meter per year and 2,5 meters per year, as the maximum allowable rate of rise, are used as guides for tailings dams on clays and free draining soils, respectively.

As a result of a difference of opinion between two prominent Consulting Engineering Companies, as to what is the acceptable rate of rise of three high-risk tailings dams, the present study was initiated by the author. The purpose of the study is to provide a rational basis to address the acceptable rate of rise issue.

There are a number of factors that need to be considered in determining the acceptable rate of rise, some of which are:

- consolidation of the tailings
- drying shrinkage of the tailings
- method of depositing the tailings
- foundation soils and geometry of the dam

Only the first item is addressed by this study. The study addresses the non-linear property of tailings, and the changing boundary effect (i.e. settlement and rate of rise of the surface).

Issues dealing with construction details have been purposely excluded from the study, to ensure that the focus remains on the effect of consolidation. Factors such as rate of placing of tailings being limited by drying shrinkage times have not been considered. Also, recommendations relating to the outer geometry of the dams, to assist in the rehabilitation and closure of the dam have not been considered.

Early in the investigation it became apparent that the results of this study could not be compared to earlier studies carried out for the mining industry by others. The primary reason for this is that the earlier work was based on the assumption of linear tailings properties, and the results were published as a function of those properties (i.e. the value of the coefficient of consolidation namely, c_v). However, a case study of a failed copper tailings dam has been used to verify the accuracy of the analysis presented in this document.

The present study is intended to give an indication of the expected pore water pressure and actual storage capacity of a disposal facility, based on the properties of the specific tailings or waste used in the analysis.

The coding of the Visual Basic ® program used in the analysis is included in the report, to allow analyses to be carried out for specific tailings. The program was written by the author as part of this investigation.

Three of the tailings studied have been selected to demonstrate the impact of various rates of placing on the overall stability of the tailings dam, using the results from the program.

CHAPTER 2: SCOPE OF THE INVESTIGATION

The need was identified to be able to predict the pore pressure and settlement of mine tailings as a function of the deposition cycle being adopted for a dam. The classical theory of consolidation of Terzaghi is not suitable for this analysis, due to the changing boundary conditions, as the tailings are being deposited, as well as the change due to consolidation. Field observations and published values[16, 17] confirm that the magnitude of settlement of tailings deposits vary considerably and in general is large.

The investigation is based on using the finite strain theory, as proposed by Gibson, *et al*,[8, 9 and 17] with incremental time steps of analysis, by way of a computer program, to analyse the pore pressure distribution and magnitude in a tailings deposit, with a fixed deposition cycle.

The analysis of the program is based on the following parameters:

- stepped time increment for deposition
- stepped deposition thickness
- non-linear soil parameters

The effect of decanting seepage from the deposit is also modelled. The results of the analyses have been used in a stability analysis program, to test the effect of the various rates of deposition on the stability of the outer slope of a tailings dam. The lateral extent of the pore pressure zone was determined, based on the experience of the author with tailings dams. The stability analyses are very sensitive to variation of this zone, and therefore the results should be considered as indicative results only.

The calculated consolidation settlement of the dam is considered to be accurate, for the "floor" of a tailings deposit. The floor area of a tailings dam benefits from very limited, if any, consolidation as a result of evaporation and sun drying of the deposit. It is demonstrated in the literature[6, 21 and 22] that the effect of high evaporation can result in large pre-consolidation stresses in the upper crust of a deposit, which is consistent with larger settlements in the upper layers of the deposit. This effect is evident in the "daywall" section of a tailings deposit, that makes use of the drying effect of the sun, in the operational management of the tailings dam.

The result of the investigation produced typical pore pressure profiles for seven different types of mine tailings, as well as two industrial residue products. The results have been compared to published results, and differences in results are investigated and explained.

The program has been written to allow for future development, to include the effect of evaporation from the surface of the deposit. The program can be used as a basis to analyse a two-dimensional effect in the consolidation analysis, so that the outer slope drainage effect of tailings dams can be modelled.

CHAPTER 3: THEORY

3.1 CLASSICAL THEORY OF CONSOLIDATION

The classical theory of consolidation is based on the work by Terzaghi[24], which was originally written to allow the prediction of pore pressures and settlement of stiff layers of clay, subjected to the application of a load. The discussion below is limited to one-dimensional conditions.

The classical theory of consolidation is based on the following assumptions:

- the voids of the soil are completely filled with water
- the water and the soil constituents are completely incompressible
- Darcy's law of fluid flow applies
- the coefficient of permeability of the soil is constant over the entire range of analysis
- the time factor of consolidation is purely a function of the soil permeability.

In addition the following stress strain relationship applies to the soil at every point in the soil mass and over the entire process of consolidation.

$$a_v = \frac{\partial e}{\partial \sigma_v} \text{ is a constant for the soil} \quad \text{......(1)}$$

i.e. The change in void ratio as a result of a change in the state of the soil stress is constant, and is called the coefficient of compressibility.

Another assumption is that the equation of equilibrium applies.

$$\sigma_v = \gamma . z + q \quad \text{......(2)}$$

where σ_v = vertical stress
γ = density
z = depth from the top of the layer
q = applied stress at the top of the layer
e = void ratio

The applied stress is located at the top of the consolidating stratum, and the density of the soil remains constant with depth.

In order to satisfy the conditions of continuity of flow in the soil, the following equation needs to be satisfied.

$$k \frac{\partial^2 h}{\partial z^2} = \frac{1}{(1+e)} \frac{\partial e}{\partial t} \quad \text{......(3)}$$

where k = permeability of the soil

h = hydraulic head

e = void ratio

t = time

To satisfy the above assumptions and equations, the strains that occur due to consolidation must be small.

Based on the above, the following equations have been developed to help predict the rate of consolidation of stiff clays, and the settlement that is associated with the consolidation (Terzaghi[24], Taylor [3]). These equations are summarised below:

$$\left[\frac{k(1+e)}{\gamma_w a_v}\right]\frac{\partial^2 u}{\partial z^2}=\frac{\partial u}{\partial t} \qquad (4)$$

where $u = h.\gamma_w$
γ_w = density of the water

The assumptions above require that the permeability and the coefficient of compressibility remain constant, i.e.

$$\frac{k(1+e)}{\gamma_w a_v}=\text{constant} \qquad (5)$$

This constant is called the coefficient of consolidation c_v, and is assumed to be a unique value for a soil mass under a certain set of stress conditions. Hence equation (4) can be rewritten in the more familiar form below:

$$c_v\frac{\partial^2 u}{\partial z^2}=\frac{\partial u}{\partial t} \qquad (6)$$

Equation (6) is known as Terzaghi's[24] consolidation equation.

The head (h) is equivalent to the hydrostatic excess pore pressure, which will cause a flow gradient and can be replaced by u/γ_w. The above equation can then be rewritten as:

$$c_v\frac{\partial^2 h}{\partial z^2}=\frac{\partial \sigma_v}{\partial t} \qquad (7)$$

Since the left member of this equation does not contain the variable t, its value cannot be altered by a change in t; therefore, if the equality is to be preserved, a change in t must not affect the value of the right member. A similar argument holds true if z is considered variable. Hence each term must be equal to a constant. For convenience, call this constant $-A^2$.

$$\frac{\partial}{\partial z^2} f(z) = -A^2 f(z) \qquad (8)$$

The expression, which satisfies this relationship, is

$$f(z) = C_1 \cos Az + C_2 \sin Az \qquad (9)$$

in which C_1 and C_2 are arbitrary constants. The right member of the equation gives

$$\frac{\partial}{\partial(t)} = -A^2 c_v f(t) \qquad (10)$$

The expression, which satisfies this relationship, is

$$f(t) = C_3 \; e^{-A^2 c_v t} \qquad (11)$$

in which e is the Napierian base and C_3 is an arbitrary constant. Thus the equation becomes

$$u = (C_4 \cos Az + C_5 \sin Az) e^{-A^2 c_v t} \qquad (12)$$

The remaining requirement is the satisfying of boundary conditions. The boundary conditions for the case of one-dimensional consolidation may be expressed as follow:

- Free drainage at top; i.e. at $z = 0$, $u = 0$
- Free drainage at bottom; i.e. at $z = 2H$, $u = 0$ where H is the length of the longest drainage path
- The initial excess pore pressure is constant, i.e. at $t = 0$, $u = u_0$

The first condition is satisfied if $C_4 = 0$. This leaves

$$u = C_5 (\sin Az) e^{-A^2 c_v t} \qquad (13)$$

The second condition will be satisfied if $2AH = n$p, wherein n is any integer. Then

$$u = C_5 \sin \frac{n\pi z}{2H} \; e^{-n^2 \pi^2 c_v t / 4H^2} \qquad (14)$$

The term C_5 is merely an arbitrary constant, and n can assume any integral value whatever. Therefore a series of the form

$$u = B_1 \frac{\pi z}{2H} \; e^{-\pi^2 c_v t / 4H^2} + B_2 \sin \frac{2\pi z}{2H} \; e^{-4\pi^2 c_v t / 4H^2} + \ldots + B_n \sin \frac{n\pi z}{2H} \; e^{-n^2 \pi^2 c_v t / 4H^2} + \ldots \qquad (15)$$

in which $B_1, B_2, \dots B_n, \dots$ are constants. This series may be written in abbreviated form:

$$u = \sum_{n=1}^{n=\infty} B_n \sin \frac{n\pi z}{2H} e^{-n^2\pi^2 c_v t/4H^2} \quad (16)$$

The third boundary condition will be fulfilled if the constants B_n in equation (16) above are determined so that

$$u_0 = \sum_{n=1}^{n=\infty} B_n \sin \frac{n\pi z}{2H} \quad (17)$$

This is a common type of Fourier expansion, and the constants may be readily determined by the use of the following relationships

$$\int_0^\pi \sin mx \sin nx \, dx = 0 \quad (18)$$

and

$$\int_0^\pi \sin^2 nx \, dx = \frac{\pi}{2} \quad (19)$$

where m and n are unequal integers. With change of variable from x to $\pi z/2H$, these expressions become

$$\int_0^{2H} \sin \frac{m\pi z}{2H} \sin \frac{n\pi z}{2H} dz = 0 \quad (20)$$

and

$$\int_0^{2H} \sin^2 \frac{n\pi z}{2H} dz = H \quad (21)$$

If both sides of equation (17) are multiplied by $\sin (n\pi z/2H)\, dz$ and integrated between 0 and 2H, all terms in the series except the nth term will assume the form of the first equation above and vanish; the nth term will be in the form of the second equation and will have a definite value. Thus

$$\int_0^{2H} u_0 \sin \frac{n\pi z}{2H} dz = B_n \int_0^{2H} \sin^2 \frac{n\pi z}{2H} dz = B_n H \quad (22)$$

hence

$$B_n = \frac{1}{H} \int_0^{2H} u_0 \sin \frac{n\pi z}{2H} dz \quad (23)$$

Substituting into equation (16), the solution then becomes,

$$u = \sum_{n=1}^{n=\infty} \left(\frac{1}{H}\int_0^{2H} u_o \sin\frac{n\pi z}{2H}\,dz\right)\left(\sin\frac{n\pi z}{2H}\right) e^{-n^2\pi^2 c_v t/4H^2} \quad \text{.......................(24)}$$

This equation is perfectly general for the conditions assumed, and it enables the hydrostatic excess pressure u to be computed for a soil mass under any initial system of stress u_0, at any depth z, and at any time t.

This equation may be written in a more general form, since time t appears as a multiple of c_v/H^2, which is a constant for a given case. Let

$$T = \frac{c_v t}{H^2} \quad \text{.......................(25)}$$

An analysis of the units of the quantities involved shows that T is a dimensionless number, and it is called the time factor. The insertion of the equation above into the general equation gives the following form, which holds for any homogeneous stratum:

$$u = \sum_{n=1}^{n=\infty} \left(\frac{1}{H}\int_0^{2H} u_o \sin\frac{n\pi z}{2H}\,dz\right)\left(\sin\frac{n\pi z}{2H}\right) e^{-0.25n^2\pi^2 T} \quad \text{.......................(26)}$$

In particular, if u_0 is a constant, the equation becomes

$$u = \sum_{n=1}^{n=\infty} \frac{2u_0}{n\pi}(1 - \cos n\pi)\left(\sin\frac{n\pi z}{2H}\right) e^{-0.25n^2\pi^2 T} \quad \text{.......................(27)}$$

When n is even, $1 - \cos n\pi$ vanishes; when n is odd, this factor becomes 2. Therefore it is convenient to let $n = 2m + 1$, in which m is an integer. The substitution of

$$M = \frac{1}{2}\pi(2m + 1) \quad \text{.......................(28)}$$

is a considerable aid in the simplification of the writing of equations, since M appears frequently. After these substitutions are made the equation for constant initial hydrostatic excess pressure becomes

$$u = \sum_{m=0}^{m=\infty} \frac{2u_0}{M}\left(\sin\frac{Mz}{H}\right) e^{-M^2 T} \quad \text{.......................(29)}$$

Classical consolidation theory assumes that the settlement of any layer is negligible, and hence is not considered further. Hence the drainage path length does not change for the analysis; i.e. H is a constant.

3.2 FINITE STRAIN NON-LINEAR CONSOLIDATION THEORY

Non-linear finite strain theory differs from the classical theory of consolidation in the following way:

- The time dependant factor of consolidation varies, and is a function of the permeability and the void ratio of the soil.
- The void ratio of the soil is not constant, and varies as a function of the soil skeleton's effective stress.
- The coefficient of permeability of the soil varies over the stress range in the soil.
- The consolidation settlement of the soil is limited to the change in void ratio of the soil.

The following assumptions also apply, which is the same as for the classical theory:

- The voids of the soil are completely filled with water.
- The water and the soil constituents are completely incompressible.
- Darcy's law of fluid flow applies.

Non-linear Finite Strain theory allows the modelling of a large strain consolidation process, which incorporates the non-linear functions of permeability and void ratio over the thickness of the consolidating stratum. Hence, this theory is particularly relevant to soft soils and hydraulically placed deposits.

Large strain of the soil layer results in a significant change in the thickness of the layer, and as a result, in the drainage path length of the interstitial water, as a function of time. Therefore, it is necessary to be able to trace soil particles on a relative co-ordinate system within the soil stratum, which varies with time as the consolidation process proceeds.

At any one location, the volume of solids remains a constant, and the volume of interstitial water varies as a function of time and is controlled by the void ratio of the soil. The rate at which the interstitial water leaves the soil dictates the rate of consolidation.

Hence, the permeability of a layer is a function of the void ratio, and the change in volume of a layer is a function of the void ratio. The compressibility of a layer is a function of the void ratio, and hence a_v is a function of void ratio, Therefore $h = h(e)$ and ....(30)

$a_v = a_v(e)$

The development of the governing equations for large strain, non-linear consolidation (see Gibson[9], *et al* 1967) is best-accomplished using Lagrangian co-ordinates z_0 and z, as shown in **Figure 3.1**. The detailed derivation of the equations has not been reproduced, but the following needs to be considered:

$$\frac{k(1+e)}{\gamma_w a_v}\frac{\partial^2 u}{\partial z^2}=\frac{\partial u}{\partial t} \text{ excludes the self weight of a layer} \qquad (31)$$

To include self-weight, another term needs to be added to the equation (Gibson[8], *et al*) namely

$$\frac{k(1+e)}{\gamma_w a_v}\frac{\partial^2 u}{\partial z^2}=\frac{\partial u}{\partial t}-\gamma\frac{dh_t}{dt} \qquad (32)$$

where h_t = distance to the top of the layer
γ = effective density of the layer, and
σ = $\gamma . h_t$

Rewriting equation (32), into another form, in terms of stress σ.

$$\frac{k(1+e_0)}{\gamma_w(1+e)}\cdot\frac{\partial^2 u}{\partial z^2}=\frac{a_v}{1+e_0}\cdot\frac{\partial u}{\partial t}-\frac{a_v}{1+e_0}\frac{\partial \sigma}{\partial t} \qquad (33)$$

where e_0 = initial void ratio

The above equation (33) can be rewritten with the non-liner terms above (equations 30) and the Lagrangian co-ordinates to produce the following equation:

$$\frac{\partial}{\partial z_0}\left[\frac{k(e)(1+e_0)}{\gamma_w(1+e)}\cdot\frac{\partial u}{\partial z_0}\right]=\frac{a_v(e)}{1+e_0}\left[\frac{\partial u}{\partial t}-\frac{\partial \sigma}{\partial t}\right] \qquad (34)$$

rewriting the equation (34) in which e is the dependent variable

$$\frac{\partial}{\partial z_0}\left[\frac{(1+e_0)\cdot k(e)}{\gamma_w(1+e)\cdot a_v(e)}\cdot\frac{\partial e}{\partial z_0}\right]\pm f(e)\cdot\frac{\partial e}{\partial t_0}=\frac{1}{1+e_0}\cdot\frac{\partial e}{\partial z} \qquad (35)$$

$$\text{where } f(e)=-\left[\frac{\gamma_s}{\gamma_w}-1\right]\cdot\frac{d}{de}\left[\frac{k(e)}{1+e}\right] \qquad (36)$$

where f(e) is the self-weight component of the equation and γ_s = unit weight of solids.

Introducing a term called the *Finite Strain Coefficient of Consolidation*, namely g(e)

$$\text{Where } g(e) = -\frac{k(e)}{\gamma_w(1+e)a_v(e)} \quad \text{.......(37)}$$

Allows equation (35) to be rewritten as

$$\frac{\partial}{\partial z}\left[g(e)\frac{\partial e}{\partial z}\right] \pm f(e)\frac{\partial e}{\partial z} = \frac{\partial e}{\partial t} \quad \text{.......(38)}$$

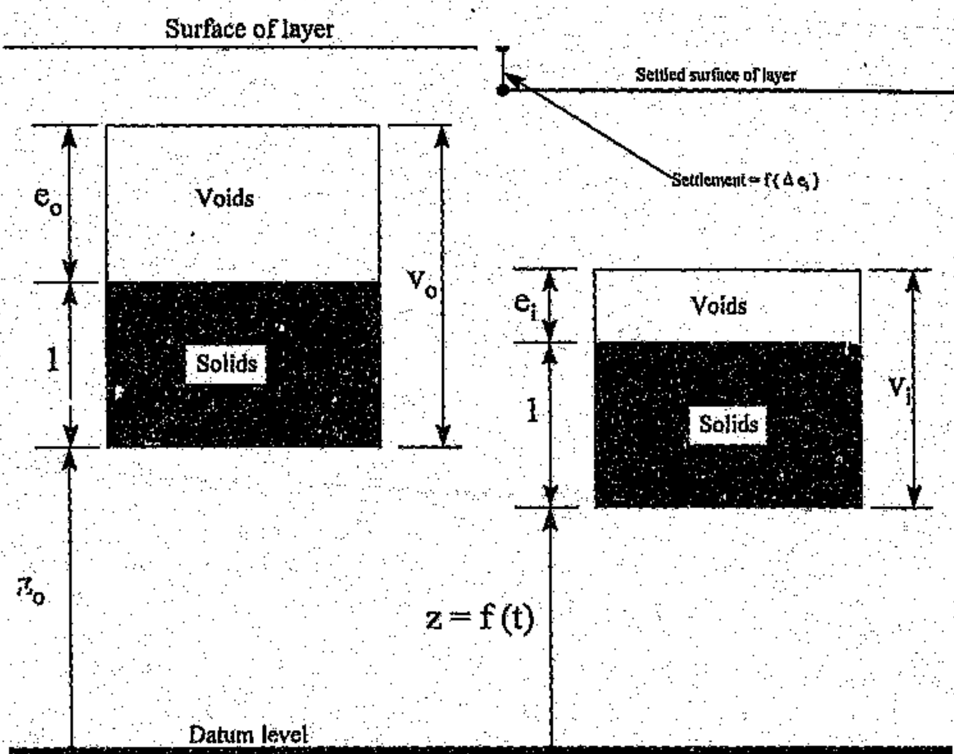
and

$$g(e) = \frac{c_v}{(1+e)^2} \quad \text{.......(39)}$$

Relating the Finite Strain Coefficient of Consolidation to the classical Coefficient of Consolidation allows the adoption of the process of predicting the dissipation of pore-water pressure described in Section 3.1 to the present theory.

The process of finite strain is represented graphically in **Figure 3.1** below, which shows how the drainage length changes with settlement. Also, the settlement is a function of the change in the void ratio, i.e. the soil particles are assumed to be incompressible over the range of analysis.

Figure 3.1: Finite Strain Consolidation



Note: The solids are the same particles for the two time increments.

In all of the above equations, k, which is the permeability, is a function of the void ratio, and hence a function of the effective stress. The variable z is a reduced co-ordinate, which is related to the moving boundary. This variable is defined as the volume per unit area of solids lying between the datum level and the Lagrangian co-ordinate level. The Lagrangian co-ordinate is the initial level of the solids under consideration (z_0).

3.3 Finite Strain Non Linear Theory Applied to a Layer Increasing With Time

The above theory is to be applied to a layer increasing in thickness with time. Closed form solutions have been published by Gibson[7], for constant linear soil properties, under two conditions. These conditions are:

- thickness of deposit is proportional to $\sqrt{t} \cdot k$
- constant rate of deposition

where t = time and k = permeability of the consolidating material.

These solutions do not include the effect of consolidation settlement, or any non-linear properties of the consolidating material.

The present research is aimed at including the non-linear and large strain effect into the analysis of a consolidating body increasing in thickness with time.

This effect is modelled by breaking the consolidating body into numerous thin layers. The characteristics of each of the thin layers is assumed to be constant over the layer thickness. The consolidation process over time is also divided into numerous short-time intervals, and the soil properties over that short-time increment are assumed to be constant for the time interval.

The consolidating body is assumed to increase in thickness in a step-wise fashion. Any increase in thickness is modelled by adding another thin layer to the rest of the consolidating body. The added layer imposes a load onto the underlying layers, and increases the drainage path length.

At each time increment, the soil parameters are changed due to the change in pore pressure. The change in pore pressure results in changes in the permeability, the compressibility, and results in a reduction of the drainage path length due to settlement.

Therefore, the theory of Section 3.2 is applied in a stepped manner, for both time and loads.

The settlement of layers occurs as a result of a reduction of the void ratio, resulting from the dissipation of pore pressures.

$$\text{Settlement} = \sum_{i=1}^{n} f(\Delta e_i) \qquad (40)$$

where n = number of incremental layers
e_i = void ratio of the i the layer

The analysis is carried out on a timestep basis, the interval of which is selected to ensure that the non-linearity of the soil is simulated acceptably. It is evident that the drainage length of each incremental layer varies both with time and location, in the overall consolidating mass. As time proceeds, the drainage length increases by the difference between the thickness of the added layers, minus the settlement as a result of consolidation. The applied pressure on any incremental layer also increases with time, which is a function of the deposition rate at the surface of the consolidating mass.

The process of removing supernatant water from the surface of the consolidating mass results in a reduction of load on the layers. The supernatant water is the interstitial water that has reached the top of the total stratum, as a result of consolidation. Similarly, seepage that leaves the layer through the base results in reduction of load on the consolidating layers. Hence, the applied load on any layer varies with each time increment, if supernatant water is "removed" in the analysis.

CHAPTER 4: HYDRAULIC WASTE DISPOSAL

The mining industry produces large volumes of residue product from the mineral extraction processes. Due to the volumes being so large, the most economical method to transport and dispose of the tailings is by mixing the residue product with water, and pumping it via dedicated pipelines to a tailings dam. These tailings dams are built up incrementally to contain the liquid tailings within the dam. In South Africa, the weather allows the outer walls to be built using dried tailings, while in other parts of the world this outer wall is built with engineered fill.

The tailings is placed in layers of slurry at a low relative density, allowing the solids to settle out, and decanting the supernatant water, after a set period. Each layer of tailings that is placed on the dam loads the lower layers, previously placed. The tailings is usually fine grained from the grinding process, and hence is slow draining. Hence, with each layer placed, the lower layers develop excess pore pressures, which dissipate with time to the nearest free draining surface. The distance to a free draining surface becomes longer with each new layer placed, and reduces as the older layers consolidate.

The outer wall of the tailings dam needs to consolidate adequately, to allow sufficient gain in strength of the tailings material to retain the tailings in the dam. To this end, the Chamber of Mines provided a guideline document, that suggested a limiting rate of rise for tailings dams. This rate of rise was related to the slope of the outer wall, the height of the dam, and the coefficient of consolidation of the tailings. The two graphs presented in the Chamber of Mines document are for a dam on a pervious and on an impervious base for a tailings with a c_v of 180m^2/year.

These graphs were produced on the basis of calculating the stability of the outer slope of a tailings dam. For this analysis the pore pressure of a limited number of thick layers of tailings, placed at a constant time interval, was calculated. The dam outer slope was "formed" by cutting a slope into the layers of normally consolidated tailings. The pore pressure was calculated using the linear theory of infinitesimal strain for consolidation, as suggested by Terzaghi[24].

The above work has the following limitations:

- The change in the soil parameters as a result of consolidation is not taken into account.
- Tailings placed at a high void ratio will result in substantial settlement. This is not taken into account by this document.
- The effect of two-dimensional drainage near the outer slope of the dam is ignored.
- The two graphs relate to tailings with a shear strength of 35°, and a single value of c_v.

When these graphs were produced they were based on the average properties for a particular gold tailings.

Test data from various mine and industrial waste materials show significant non-linear properties. This data is presented in **Appendix A** of this report. Schiffman, *et al*[17], Mitsunari[14] and Glenister and Press[10] also measured non-linear large strain properties of various tailings.

The test data in **Appendix A** and the publications above[17, 14 and 10], all confirm the following trend:

- A decrease in the permeability of the material with increased effective stress.
- A substantial reduction in the void ratio with increased effective stress.

The test data in **Appendix A** for the "Crown" gold tailings and the manganese tailings were obtained from test results carried out using Rowe cell consolidation tests. The reason for selecting this type of test apparatus was two fold:

The Crown tailings was known to be fairly quick draining, and the results from conventional consolidation equipment would be inaccurate. This is due to the short drainage path of the test sample, and the related very short time increment to measure t_{90} for the test.

The manganese tailings properties were also measured in a Rowe cell. Although this test was for another purpose, the results were also used for the consolidation analysis. The manganese tailings consolidates slowly, and hence a conventional consolidation test would probably have been adequate except for the small specimen height.

Due to the non-linear properties the need exists to be able to model the change in the permeability of the soil with the change in applied load, with time. A reduction in permeability results in a higher pore pressure at any time, compared to using a constant average permeability value of the material. Failure to incorporate this effect will result in stability analyses, which will provide unsafe results, due to the under-estimation of the excess pore pressures.

The reduction in the void ratio with applied stress is less critical, in that if this is not included in the analysis, it will have the following effect:

- The total thickness of the tailings will not be reduced due to consolidation settlement, and hence the length of the drainage path will be over-estimated.

- The actual capacity of the tailings dam will be more than what will be predicted, and hence the actual rate of rise of the dam will be lower, and therefore safer. This will however have financial implications for the development of the tailings dam, as the predicted size of a facility will be larger that what is actually required.

In order to accurately predict the pore pressure in the material and to simulate the true height (and hence capacity) of the dam with time, the following requirements have been identified:

- The deposition sequence of the tailings on the dam needs to be simulated as closely as practically possible. Hence, thin layers of material are simulated as being placed on the material already in the dam. Each layer is simulated as a load, plus an increase in the drainage length for all the underlying layers.

- The dissipation of pore pressure from each load increment needs to be traced with time, as the dissipation process is an exponential one, and the drainage length changes with time. The change in drainage length is as a result of consolidation settlement, plus the extra thickness from new layers above.

- The consolidation process needs to be modelled during the time between load applications. If this is not done, and the time interval between load applications is large, large inaccuracies will result in the analysis. This is as a result of the non-linear properties of most tailings. The modelling process needs to be based on a number of short time increments, over which period the soil properties can remain constant for analysis. This should be the basis on which the analysis time increment is selected, and needs to be varied for different tailings.

- To model high tailings dams built by a large number of thin layers, could result in information storage capacity problems, due to the large number of varying properties. It is however not necessary to keep track of information from layers where the pore pressures from early loads have fully dissipated. Hence, the analysis needs to have a process to identify and neglect this "dissipated" information.

- The information must be presented in a format that can be effectively used for the design of a facility.

CHAPTER 5: PORE PRESSURE ANALYSIS PROGRAM

The word "soil" has been used in the discussion of the programme. The analysis equally refers to any consolidating matter, particularly for waste or residue products, to which this type of analysis is relevant.

The analysis of large strain consolidation is a calculation intensive process. The non-linearity of the materials being analysed also results in a large number of constantly changing variables. Every load step results in an additional set of values being added to the variable matrices, whilst all the existing values change for each incremental time-analysis step. The changes in the pore pressure of the consolidating layer are non-linear, being exponential. Also, the laws of superposition can **not** be applied to the pore pressure dissipation process, for different load applications; i.e. the dissipation pressure of load 1 plus the dissipation pressure of load 2 does not equal the dissipation pressure of (loads 1 + 2) added at the start of the dissipation process.

The dissipation algorithm used in the program is based on a uniform initial distribution of pore pressure in each individual consolidating layer.

5.1 Algorithm and Basis of the Analysis

During the development phase of the program, the following requirements were identified, to ensure that the program analysis functioned correctly:

- For each load increment, the dissipation of pore pressure in a particular layer needs to be tracked separately, with the dissipation period being measured relative to the time when the load was applied.
- The change of soil properties needs to be recalculated continuously with time, as the layer under consideration consolidates. These soil property parameters need to be recalculated between as well as during loading stages.
- The dissipation of pore pressure over a unit time increment needs to be calculated as follows:

  1. The soil parameters applicable at the end of time increment t-1, are applicable to the pore pressure dissipation calculation at time = t, for the unit time increment.
  2. Calculate the pore pressure at time = t–1, using the soil parameters of 1, and a dissipation period of t–1.
  3. Calculate the pore pressure at time = t, using the same soil parameters and a dissipation period of t.
  4. Subtract the difference in pore pressure of t-1 and t, from the excess pore pressure stored at the end of the last time increment.
  5. Steps 2 to 4 need to be calculated separately for each load increment, due to the difference in the dissipation time, as a result of loads being applied at different times.

  The above process needs to be repeated for each incremental layer.

- The drainage length of each layer changes with each time increment.
- The soil parameters of the overall consolidating stratum varies with depth, in accordance with the non-linear soil parameters of the soil.
- The point of maximum pore pressure over the soil profile needs to be determined, in order to identify whether the incremental soil layer is draining upwards or downwards.
- Settlement of each incremental layer needs to be calculated for each change in pore pressure, to calculate the change in drainage length. Many residue products are placed at high void ratios, and the magnitude of the resulting settlement is large.

The above points highlight the salient features of the analysis program. For the detailed implementation of these features, the coding of the program should be consulted. A copy of the coding has been attached as **Appendix B** of this document.

The extensive amount of variables that need to be recalculated continuously, lead the author to the decision to write the program in Visual Basic [(R)], using the spreadsheet concept to display the results both numerically and graphically. The Spreadsheet system, Excel, was also used to analyse the input data of the soil, to set up the initial soil layer parameters, as well as to fit equations to the test data, that represent the non-linear behaviour of the soil.

5.1.1 Program Functions

The Visual Basic code has been written to allow any form of non-linear behaviour of the soil to be analysed by the program. Separate functions exist in the program that calculate these parameters. **(Function G, Function void and Function T)**. The default relationship of these functions is as follows:

Function G:

The function calculates:

- the permeability of the soil
- the compressibility of the soil
- the finite strain coefficient of consolidation parameter g(e) of the soil

The *permeability* of the soil is a function of the effective stress of the incremental layer under consideration. For many residue products, a relationship based on the logarithm of the effective stress, results in a quadratic equation, of the form:

$$k = 10^{(a.(\log(\sigma^{\prime}))^{\wedge}2 + b.\log(\sigma^{\prime}) + c)} \quad \text{..........} (41)$$

where a, b and c are constants determined from laboratory tests on the residue.

From the above it can be seen that the applied stress needs to be above 1 kPa, to avoid problems with the log function with respect to the effective stress. If lower stresses are applied, it will be necessary to use a non-log function to relate the soil properties of the consolidating layer. The program code will then have to be modified for this function.

The *compressibility* of the soil is represented as the inverse of the coefficient of compressibility, in the form:

$$M_v = \frac{(\sigma'_i - \sigma'_{i-1})}{(e_{i-1} - e_i)} \quad \text{.......... (42)}$$

where σ'_i is the effective stress at the start and end of the incremental consolidation period, and e is the void ratio at the start and end of the incremental consolidation period.

The *finite strain coefficient of consolidation* parameter g(e) of the soil is similar to the coefficient of consolidation used in the Terzaghi Theory, namely c_v. The relationship of g(e) in the program is as follows:

$$g(e) = \frac{k.M_v}{g.(1+e)} \quad \text{.......... (43)}$$

where e is void ratio,
g = gravity acceleration
k = permeability at the void ratio e

Function void:

The void function calculates the void ratio of the soil, as a function of the effective stress (σ') in the soil, and is of the form:

$$e = d \cdot \log(\sigma')^2 + f.\log(\sigma') + g \quad \text{.......... (44)}$$

where d, f and g are constants determined from laboratory tests on the residue.

Again, it can be seen that this is a log function. This function may be modified, if the log relationship results in an unacceptably low correlation with the laboratory results, or the applied stresses are very low.

Function T:

This function calculates the value of the variable T, which is the *time factor*, and is a function of the time that has lapsed in the dissipation process, since the load has been applied. The relationship of this function is as follows:

$$T = (g(e) \cdot (1+e)^2 \cdot t) / H^2 \quad \text{.......... (45)}$$

where t is the time of dissipation
H is the length of the shortest drainage path

The value of the void ratio (e), and g(e) are variable inputs that are related to the properties of the soil, at the time t being analysed. These variables change at each time increment, due to the changing effective stress in the consolidating soil layer.

A further two functions exist in the program. These functions do not change if the soil functions are changed. These functions are as follows:

Function remain
Function ui

Function remain:

This is a function that has been created for programming purposes, and is not related to the algorithms of the analysis. This function returns the fraction remainder of a division of two numbers, and is used in the display of results.

Function ui:

The function ui returns the residual pore pressure at a selected location in the soil. The variables used by the function to determine the pore pressure are:

- applied load
- function T
- position or location with respect to the drainage path length.

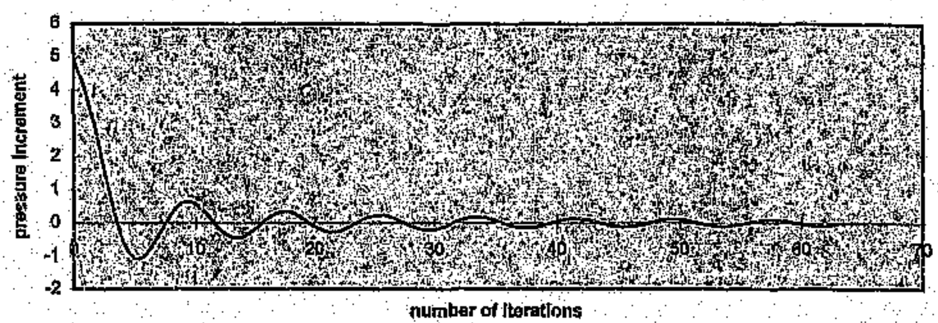
The form of this algorithm is as follows:

$$ui = \sum_{k=0}^{\infty}\left(\frac{2.p}{m}.\left\{\sin(m.\text{position}).e^{(-(m^2 \cdot T))}\right\}\right) \qquad (46)$$

where $m = 0{,}5.\pi.(2.k+1)$
p = applied pressure
T = time function
position = depth ÷ shortest drainage length
k = counting variable for the summation process.

The value of ui is cumulated for each iteration of k, until the value of k reaches 100, or the value of each incremental ui is less than the pressure ÷ 1000. As this is a Fourier series analysis, the function continues calculating until the iteration has continued for a multiple of 2 times the inverse of the "position" variable, to ensure that the iteration cycle has stopped at the end of a closed cycle. This is illustrated in **Figure 5.1** below.

Figure 5.1: Fourier Series Iteration Stability



The graph above shows the dissipation of a pressure applied to a layer of consolidating soil as the iteration process proceeds. To ensure a closed iteration loop, the number of curves above and below the horizontal axis must be equal.

If a different pore pressure dissipation algorithm to the one above is to be used, then the Function ui can be modified to accommodate this.

5.1.2. Analytical Section

The body of the program has been divided into four sections that perform similar calculations. These four sections are as follows:

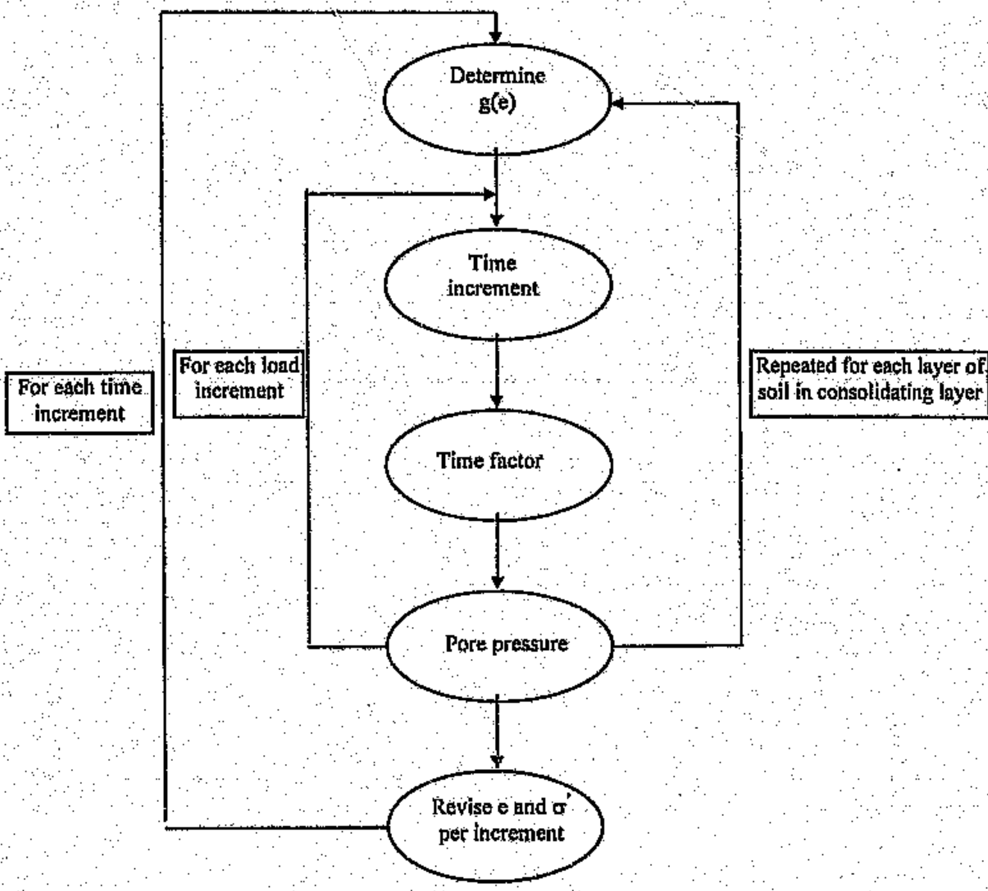
- initial layers, draining upwards
- initial layers, draining downwards
- added layers, draining upwards
- added layers, draining downwards

The initial layer facility allows for the field situation to be modelled where tailings are deposited on the top of an older deposit. This also allows for the modification of the program, to simulate two different types of consolidating soils, one of a fixed thickness, such as a clay deposit, and the second layer, as a layer increasing in thickness with time, such as a tailings dam, embankment or terrace.

The initial conditions for the initial layers are set by the first section of the program, where the initial void ratios and permeability of the layer is set as a function of the effective stress. For this, it is assumed that the layer is at equilibrium, i.e. no excess pore pressure.

The structure of the four sections of the program can be represented as follows:

Figure 5.2: Structure of Program



Pore Pressure:

The change in pore pressure is directly related to the change in effective stress of the layer. The change in effective stress is then used to calculate the change in permeability and void ratio, by way of the Functions void and G .

The change in pore pressure is calculated as follows:

The latest values of the soil parameters of permeability and void ratio are used to calculate the pore pressure of each incremental layer at time equals to t and t-1. This incremental change in pore pressure (Δu) is then subtracted from the last value of pore pressure calculated for time equals t-1. Hence,

$$u_{new\,i} = u_{old\,i} - \Delta u \qquad (47)$$

where Δu is the dissipation of pore pressure calculated for the unit time increment with the latest soil parameters

The process of pore pressure dissipation is repeated for every separate load, applied to each layer by the weight of the above layers. This requires that a separate record is kept of the pore pressure for each load application at each incremental layer, with a record of at what stage the load is applied.

It is not correct to add all the incremental pressures at a layer, and dissipate this summed pressure as if it is at time = 0.

The program has a number of control statements in the pore pressure module to reduce the number of calculations and prevent negative pore pressures being developed, once the pore excess pressure of a load has dissipated to zero.

Settlement:

The incremental settlement of each incremental layer is calculated on the basis of the change in void ratio of that layer over each time increment. The incremental settlements of all the layers are summed, to determine the overall settlement of the consolidating layer. The relationship used for the calculation of the incremental settlement is as follows:

$$\delta_t = \Delta e \, . \, d_1 \, . \, (1 - \frac{1}{(1 - e_1)}) \quad \text{.................................(47)}$$

where Δe	=	change in void ratio between time increments t and t-1
d_1	=	thickness of incremental layer at time t
e_1	=	void ratio of the layer at time t-1

Once the settlement of each of the four sections of the program has been determined, the total settlement is calculated as the sum of the four. The consolidating layer thickness, and hence the shortest drainage path length is calculated as:

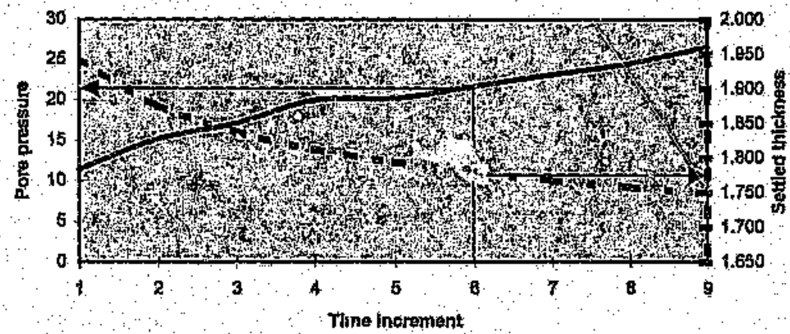
New thickness = old thickness - total settlement (+ new layer thickness, when applicable)

A new layer is not added at every time increment, and hence this addition is determined by way of a control structure in the program.

Each incremental layer thickness is kept in an array, as the soil particles of each layer remain as particles of that layer, i.e. the particles of layer 15 at time increment No. 1, remain the particles of layer 15 at time increment No. 50, but they will be in a tighter matrix, due to the process of consolidation.

The design of the program allows a record to be obtained of the settlement, as well as the pore pressure with time, at any incremental layer. A typical record is given below:

Figure 5.3: Pore Pressure build up and settlement of an incremental layer



The dotted line is the trace of the settlement of an incremental layer, in relation to the overall layer thickness base level, i.e. the trace includes the settlement of the layers below the one being shown. In the graph a soil particle was at elevation 1,94m above the base of the consolidating layer at t = 1, and the same particle settled to a level of 1,75m above the base at time increment 9.

The solid line is read in relation to the left-hand axis of the graph, and represents the increase in pore pressure of the same incremental layer as the settlement trace, as a function of time. The pressure increases as the overall consolidating layer is increasing in thickness with time. The increase in thickness is brought about by the addition of fine-grained soil at the top of the layer, at a faster rate than what the pore pressure can dissipate. The above data is taken from an analysis of a tailings deposit, with the moving co-ordinates having been converted to absolute levels.

The above results may seem contradictory, in that the pore pressure increases, but settlement still occurs. The results are however only for the selected time frame. The pore pressure of the incremental layer is higher when the incremental loads are applied, and some of the pressure dissipates, leading to settlement of the layer.

5.2. Program Input And Output

The extract of the program below is a copy of the main input and output sheet of the program, for the analysis of the pore pressure with respect to location and time.

Figure 5.4: Sample of Program input and output sheet

RESULTS OF PORE PRESSURE ANALYSIS FOR CONTINUOUS LOADING

Time increment for display of results=	276	Days
Load applied at each stage=	4.887	kPa
Time step of loading (every ... days)=	12	Days
Time interval for analysis=	3	unit=days
Initial drainage L=	1.78	m

Number of drainage paths=	2	
Total number of loads applied=	230	No.
Thickness of applied load=	0.296	m
Initial increments in start layer=	6	

Time increment: (day No.) =			276	days	552	days	828	days
Total settlement=			1.636	m	3.461	m	5.409	m
Total load to date (kPa)=			117.29	kPa	229.69	kPa	342.09	kPa
Total applied thickness to date (m) =			7.104	m	13.912	m	20.720	m
Settled thickness=			7.231	m	12.214	m	17.073	m
	Depth from base up	*u*	Depth from base up	*u*	Depth from base up	*u*	Depth from base up	*u*
RELATIVE LEVEL:	m	kPa	m	kPa	m	kPa	m	kPa
17%	0.384	0.00	0.266	1.433	0.258	3.229	0.253	2.767
33%	0.769	0.00	0.530	2.769	0.513	4.021	0.504	4.471
50%	1.148	0.00	0.790	4.687	0.765	6.099	0.751	7.032

The lightly shaded cells are the cells that need input values. The rest of the sheet is used as an output for the analysis.

The following list explains each of the input cells:

Time increment for display of results $[days]$	This determined at what time interval the pore pressure is to be displayed on the output sheet.
Load applied at each stage $[kPa]$	The sheet assumes that the load that is put into this cell is applied at a constant rate of the next cell.
Time step for loading $[days]$	The loading of the above cell is applied at a rate of every xx days. This is the value (xx) for this cell.
Time interval for analysis $[days]$ *	Due to the non-linear nature of the soils, the interval for pore pressure dissipation can be selected. The minimum is one day, and must be an integer.
Initial drainage L $[m]$	This cell reflects the thickness of the initial layer. This layer must have no excess pore pressure. This layer needs to be an even integer multiple of the "thickness of applied load".

Number of drainage paths [*value*]	This value is 1 for one way drainage, or 2 for two-way drainage.
Total number of loads applied [*number*]	The number of loads multiplied by the time step of loading determines the total length of time being analysed for the deposit.
Thickness of applied load [*m*]	The thickness of the applied layer that places the load on the consolidating layer needs to be placed into this cell. This value is used to increase the longest drainage path length.

The appropriate value to be selected for cell marked (*) is a matter of experience. The lowest value, 1, will give the most accurate value of the analysis, but the analysis time may become prohibitively long. One analysis has been run for a copper slime, for a deposit placed over 750 days, at daily intervals. This analysis took 30 hours on a Pentium 133MHz computer, with no other analysis tasking.

The first column of *u* is the column where a static pore pressure can be inserted. The function of this column is for a deposit on a low permeability base, where a permanent water table has developed in the deposit. The value put into this column is subtracted from the effective stress value that is used to determine the initial soil properties with respect to permeability and void ratio.

The workbook includes spreadsheets for the analysis of laboratory data to determine the non-linear relationship of the soil properties, for input into the program. A summary of the Excel procedure to use the curve fitting options is given in the **Appendix C** of this document.

Sheet 2 of Workbook

Sheet 2 is used to start the analysis process by inserting the test results from consolidometer or Rowe cell tests carried out on undisturbed or reconstructed samples of soil or waste. The correct selection of test is important to obtain realistic consolidation results. The laboratory results need to measure the following:

1) Specific gravity of the sample

2) The void ratio as a function of applied stress to the sample. This is determined by measuring the void ratio at the start of the consolidation test, and thereafter is related to the vertical height of the sample being tested.

3) A trace of the time versus settlement of the sample at each stress (load) increment. From the time trace, the coefficient of consolidation (c_v) can be determined, by graphical construction. The coefficient of consolidation is then related to the permeability of the sample at that load increment.

Alternatively, permeability tests can be carried out at different confining stresses of the sample.

$$c_v = \frac{k(1+e)}{\gamma_w} \cdot \frac{\Delta\sigma}{\Delta e} \quad \text{.......................................} (48)$$

hence

$$k = \frac{c_v \gamma_w \Delta e}{(1+e)\,\Delta\sigma} \quad \text{.......................................} (49)$$

Sheet 3 of Workbook

In the **Sheet 3**, charts are created that graphically represent the laboratory results of the **Sheet 2**. This sheet has not been pre-formatted, to allow maximum flexibility to determine the most appropriate equation of the results.

It has been found that a quadratic fit to the laboratory data usually results in a good correlation. The data is usually plotted as follows:

log effective stress vs. log permeability
log effective stress vs. void ratio

The pore pressure analysis program requires a relation of permeability as well as void ratio as a function of stress.

Hence, in this sheet two charts need to be created. These charts can be created anywhere on the sheet. There are no active links from the rest of the workbook to this sheet, except for the shaded cells.

Once the appropriate two formulas have been found, they need to be manually inserted into the shaded cells in **Sheet 3**. If those formulas are calculated outside the spreadsheet, no analysis needs to be carried out in **Sheet 3**, but the appropriate values need to be inserted into the shaded cells.

The program has been further developed to include the effect of removing the seepage and supernatant liquid from the consolidating mass, as the process of consolidation proceeds. This effect results in the applied load at any time being reduced by the amount of seepage that leaves the stratum. This reduced load is equivalent to the settlement of a layer, multiplied by the density of water. Any settlement of the layer is as a result of interstitial water being squeezed out of the consolidating layer. The removal of seepage water is included as an incremental event that occurs every time a load is applied to the layer. This removal of load is simulated as a reduction of the applied load, by an amount equal to the settlement of the entire layer times the density of water, over the time between load applications. Hence, the reduction of load only applies to the present load being applied, and the "older" loads remain unchanged.

If the reduction of load as a result of seepage is applied to all the loads, then this results in problems in the analysis. A future version of the program may include this finer adjustment, but this will require special memory management to prevent the analysis becoming prohibitively time consuming. The removal of seepage has been limited to the case of free seepage to the surface. No allowance has been made for the case where the effect of evaporation can dry out the surface and create negative pore pressure gradients in the surface layers. This will result in an accelerated rate of consolidation of the layer, as reported in Seneviratne[18], *et al*, Fahey and Fujiyasu[6], Swarbrick[21] and A. MacG Robertson[15].

The program can be modified to display any number of variables, as a function of the depth of the deposit. **Figure 5.5** below shows an example where the effective stress at different depths has been included in the output. These values can be used for the stability analysis of a consolidating stratum.

Figure 5.5: Program output including effective stress values

300	days	
1.441	m	
158.69	kPa	
9.240	m	
9.546	m	
Depth from base up	*u(x,t)*	*Effective Stress*
m	kPa	kPa
0.387	3.326	164.721
0.764	5.946	152.703
1.129	9.645	141.879
1.483	12.774	132.658
1.839	15.445	121.278
2.196	17.680	112.443
2.556	20.242	102.695
2.917	22.230	93.760
3.280	23.923	85.230
3.645	25.713	76.053
4.013	26.904	67.947
4.383	27.705	60.541
4.756	27.846	53.414
5.132	27.059	47.409
5.510	26.074	41.449
5.892	24.812	36.166
6.276	22.717	31.584
6.664	20.012	27.337
7.056	17.565	23.007
7.453	15.023	18.640
7.855	11.904	15.162
8.262	7.935	12.242
8.677	4.503	9.018
9.106	1.356	5.393
9.546	0.000	0.000

5.3 Validation of Program Results

Results from the program have been compared to the published results of an analysis carried out by Schiffman, Pane and Gibson (1984)[10], on copper tailings. The analysis was based on a tailings deposit that had been placed over a period of 3000 days, on a dry (i.e. permeable) base. The pore pressure results were published in the form of a graph with a normalised height of the dam i.e. the pore pressure was recorded relative to the total height of the dam at each stage. For the purposes of comparing these results with the results of the authors' program, the height has been converted to the actual thickness of consolidated stratum. The soil properties of the tailings deposit used are represented by the relationships below (which were published in the original paper):

$$e = 1.45 - 0.265 \log(\sigma') \qquad (50)$$

$$\log k = -6.9464 - 0{,}473 \log(\sigma') \qquad (51)$$

where k has units of m/s and σ' has units of kPa.

The placed height of the dam that has been simulated is 80m. This is the total height without any consolidation, called the Lagrangian height. The settled height at the end of 3000 days was calculated by the program as 57.8m, as compared to 66.9m calculated by Schiffman[10], *et al.* There is an explanation for this difference, in that the reference paper reports that the tailings were placed at a void ratio of 1.3, whereas the soil property relationship given indicates a void ratio at zero effective stress of 1.45. The effect of simulating the tailings dam using a void ration of 1.3, is shown graphically in **Figure 5.6.** The settled height of the dam using a void ratio of 1.3 is 66m high, which agrees very well with the results of Schiffman[10], *et al.*

Examination of the pore pressure values also indicates a difference, which is explained by the same discrepancy. If the Lagrangian height is ignored for the purpose of simulation, and the dam is simulated to a settled height of 66.9m, the pore pressure values obtained agree well with the published values of Schiffman[10], *et al.* **Figure 5.6** represents the pore pressure profile of the reference paper and the results of the program written for this report. The comparison is based on the analysis of no seepage water removal. The comparison of the peak pore pressure at 3000 days is as follows:

Schiffman[10] *et al*	:493kPa
Program (e_0=1,45)	:470kPa
Program (e_0=1,30)	:450kPa

The percentage difference of the Schiffman[10] *et al* prediction to the program is a 4,67% and 8,72%, respectively, lower pore pressure from the program. The location of the peak is in the same position for both analyses.

For comparison, the peak pressure at times = 3000 days with seepage water removal is 435kPa at a height of 0,38H.

The relationship of the soil properties is relatively sensitive, as is demonstrated below.

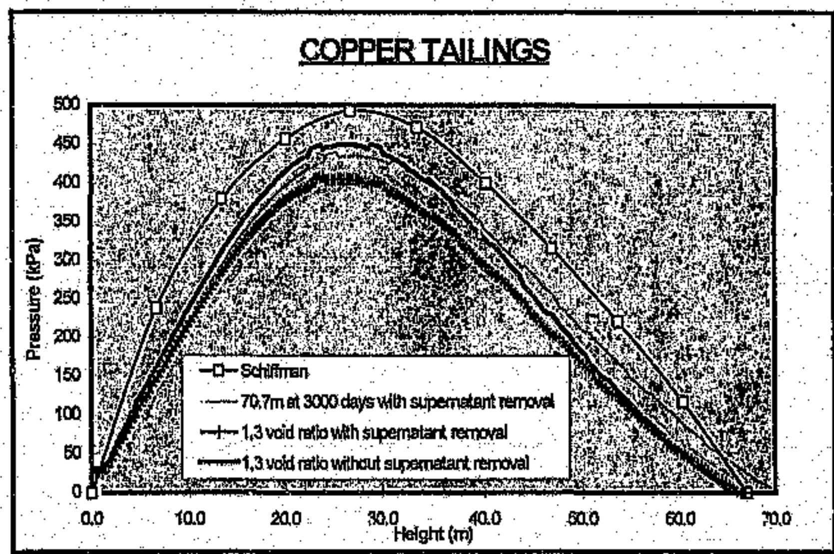
A similar sample of copper tailings was tested by Schiffman[10] *et al*, which resulted in a different relationship of the consolidation properties. These results were also used to run the program to ensure that the sensitivity required would be reflected in the results of the analysis. In **Figure 5.7**, it can be seen that there is a marked difference in the shape and values of the pore pressure compared to the other copper sample, as is expected.

The relationships used for the copper tailings is as follows:

$$e = 1.26 - 0.247 \log(\sigma') \quad \ldots\ldots (52)$$

$$\log k = -7.035 - 0.858 \log(\sigma') \quad \ldots\ldots (53)$$

Figure 5.6: Comparison of program results to Schiffman results

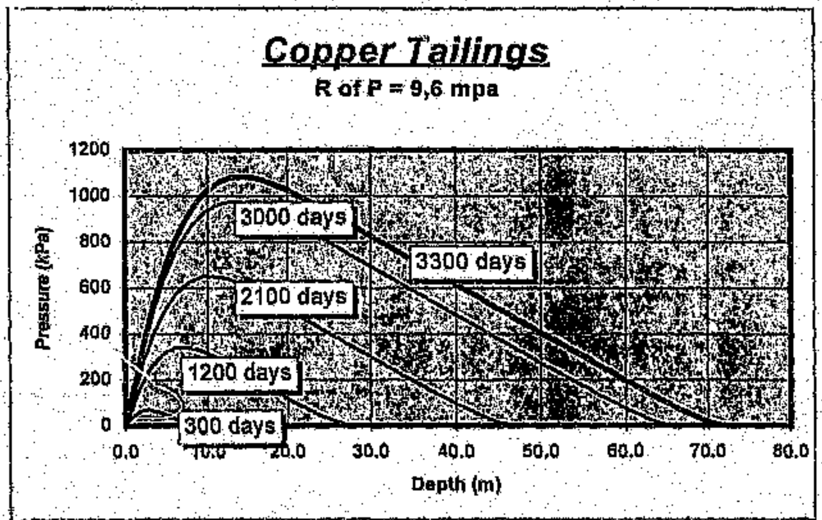


These relationships are taken from the same reference as above of Schiffman[10] *et al.* The reference does not provide the rate of deposition of the tailings, but provides the trend of the pore pressure for the dam at a height of 49.5m at 3390 days, after the top was surcharged for 330 days. Hence, the shape of the pore pressure profile is valid for comparison, but not any of the values. The peak pressure occurred at 0.2H, where H is the height of the dam. The peak pressure quoted is 858kPa. The values obtained from the authors' program is a peak pressure of 1083,74kPa at a position of 0,197H, simulated at a rate of placement of 9,6 metres per annum.

Figure 5.7 below represents graphical results from the program showing the build-up of pore pressure in the copper tailings with respect to time, using the above soil property relationships.

From the above it can be concluded that the program can be considered as being valid, based on the correlation to the published data. It is the authors opinion that the program is more accurate, as the incremental modelling adopted in the program, would have been prohibitively time consuming with respect to computer time, at the time of the publication of the work of Schiffman[10], *et al.* In addition the facility exists in the program to model the removal of the load, simulating the removal of water from the tailings or waste.

Figure 5.7: Graphical Presentation of Results from Program for Copper Tailings (Second Sample)



CHAPTER 6: SCENARIOS AND BASIS OF ANALYSIS

6.1 Residues Analysed

The program has been used to assess what the impact is on the stability of tailings dams, as a function of the rate of placing tailings on the dams. This study has been carried out for soil properties of various types of tailings. These properties have been based on laboratory test results from various projects that the author has been involved in, and published data. The following types of tailings have been analysed:

Gold Slime, from Crown Mines in Johannesburg

Gold Slime, from Boddington Western Australia

Bauxite Residue, from Western Australia

Manganese Residue, from a Beneficiation plant, Mpumalanga

Copper Slime, from Bethlehem

Treated Acid Mine Drainage Residue, from Department of Water Affairs &Forestry Witbank

Coal Slurry, from a Coal Washing Plant, Witbank

6.2 Properties of Residues

The relationships of the properties of the tailings that have been used in the study are listed below. The relationships are those between the void ratio with respect to the effective stress, and the permeability with respect to the effective stress.

The relationship of Gold Slime and Bauxite Residue from Western Australia, and the Copper Slime from Bethlehem are taken from published data [10, 14, 16 & 17]. The remaining relationships are from test data, as described in Chapter 4.

Table 6.1: Properties of Residues and Tailings

Tailings	Properties
1. Crown Mines Tailings	$\log(k) = -0.1514 \log(\sigma')^2 - 0.7169 \log(\sigma') - 5.1854$ $e = -0.01320 \log(\sigma')^2 - 0.0795 \log(\sigma') + 1.056$
2. Boddington Tailings	$\log(k) = 0.5373 \log(\sigma')^2 - 2.9744 \log(\sigma') - 4.7435$ $e = -0.0339 \log(\sigma')^2 - 0.6137 \log(\sigma') + 2.3791$
3. Bauxite Residue	$\log(k) = -0.227 \log(\sigma')^2 - 0.0010 \log(\sigma') - 7.1740$ $e = -0.4764 \log(\sigma')^2 - 0.0010 \log(\sigma') + 2.3428$
4. Manganese Residue	$\log(k) = -0.8009 \log(\sigma')^2 + 1.3044 \log(\sigma') - 8.00$ $e = -0.0497 \log(\sigma')^2 + 0.0116 \log(\sigma') + 1.8987$
5. Copper Tailings	$\log(k) = -0.473 \log(\sigma') - 6.9464$ $e = -0.265 \log(\sigma') + 1.450$
6. Treated AMD	$\log(k) = 0.9487 \log(\sigma')^2 - 4.2641 \log(\sigma') - 3.8031$ $e = -0.0955 \log(\sigma')^2 - 0.0854 \log(\sigma') + 2.7083$
7. Coal Slurry	$\log(k) = -0.1514 \log(\sigma')^2 - 0.7169 \log(\sigma') - 5.1854$ $e = -0.01320 \log(\sigma')^2 - 0.0795 \log(\sigma') - 1.056$

Copies of the curves fitted to the laboratory data, where data was available, are attached in the **Appendix A** to this document. Copies of the laboratory data are also attached.

It is to be noted that the relationships of the data fitting curves are all related to the log of the effective stress, with both quadratic and linear relationships. The permeability relationship dominates the rate of pore pressure dissipation, while the void ratio relationship dominates the settlement of the layers. Their relationships are also inter-related, in that they both are time related, and both are dependent on changes in the applied stress.

6.3 Deposition Scenarios

The following deposition scenarios were modelled for the different tailings:

Table 6.2: Deposition Scenarios

(mpa = metres per annum)

Material	Deposition Scenario
Copper Tailings	3,65mpa Two way and one way drainage. 9,60mpa Two way and one way drainage. 10,7mpa Two-way drainage.
Gold Tailings	3.26mpa One way drainage. 3.90mpa Two-way drainage. 5.20mpa Two-way drainage. 6.50mpa Two-way drainage.
Gold Tailings from weathered rock	2.40mpa Two-way drainage. 3.93mpa Two-way drainage. 7.80mpa Two-way drainage.
Coal Slurry	3.65mpa One-way and two-way drainage. 5.20mpa Two-way drainage. 10.4mpa Two-way drainage.
Bauxite Residue	1.95mpa Two-way drainage. 2.60mpa Two-way drainage. 3.91mpa Two-way drainage. 7.80mpa Two-way drainage. 10.95mpa One-way drainage.
Acid Mine Drainage Sludge	3.65mpa One-way and two-way drainage. 7.30mpa Two-way drainage. 10.95mpa Two-way drainage.
Manganese Tailings	1.83mpa Two-way drainage 3.65 mpa One-way and two-way drainage. 7.30mpa Two-way drainage. 14.6mpa Two-way drainage.

The analysis of a number of selected deposition scenarios was re-run to include the effect of the removal of the supernatant and seepage water. This was done only on the tailings that showed a substantial settlement, which are the tailings that are placed at a high void ratio. If the settlement is small, it means that the amount of seepage that flows from the tailings is small, and hence the change in load is small. The tailings that were selected for this analysis are shown in **Table 6.3**, below with the analyses performed.

Table 6.3: Analyses with removal of supernatant and seepage water

Material	Deposition Scenario
Copper Tailings	3,65mpa Two way and one way drainage. 6.42mpa Two way and one way drainage. 9.60mpa Two-way drainage. 10.7mpa Two-way drainage.
Acid Mine Drainage Sludge	3,65mpa Two-way drainage.
Bauxite Residue	3,65mpa Two-way drainage. 7,82mpa Two-way drainage. 10,95mpa One-way drainage.
Coal Slurry	3,65mpa Two-way drainage.
Gold Tailings from weathered rock	3,65mpa Two-way drainage.

For comparison purposes the gold tailings from hard rock mining, was also analysed for a rate of placing of 3,65mpa and 6,5mpa.

6.4 Basis of Stability Analysis

The pore pressure program has been used to obtain pore pressures over the profile of a dam. The stability of the tailings dam was then determined using a commercial stability program, called Prokon[25]. This program uses Bishop's Modified Method of analysis, which is based on the ratio of mobilising to resisting moments, by the method of slices, to determine the factor of safety. A second module of the program has also been used, which is a non-circular analysis method. This module of the program was used to analyse a dual wedge failure of the tailings dam.

The profile of the slope that has been analysed was based on accepted practise in the industry. All the analyses are based on the same assumptions, which are listed in **Table 6.4** below:

Table 6.4: Assumptions for stability analysis.

1. The foundation soils are stable, and have higher shear strength than the tailings.
2. A failure of the slope constitutes a failure surface into the body of the tailings, i.e. excludes surficial sloughs.
3. No phreatic surface is present in the tailings, i.e. the pore pressure from the program is the total pore pressure.
4. The depth of the pool of water at the surface of the tailings is very shallow, and hence free drainage occurs at the surface of the deposit.
5. No cohesion has been included in the analysis.
6. The tailings has been assumed to be homogeneous.

The pore pressure contours near the outer slope have been defined, based on experience with tailings dams. The location of these contours, to simulate the two dimensional effect of drainage, is shown in **Figures 6.1 and 6.2** below. A "drain" was placed 30m inwards from the toe irrespective of slope height, to ensure a consistent analysis. This dimension was decided upon by trial and error, in order to get stability results that focus on the effect of the varying pore pressure. A dimension of 30m from the toe of the dam is a realistic position for a drain.

Figures 6.1 and 6.2: below represent the typical geometry of the slope that was used in the study.

The slopes have the following features:

- Horizontal ground surface
- Single consistent outer slope (i.e. no 'step-backs')
- No phreatic surface

Figure 6.1: Geometry for circular failure surface

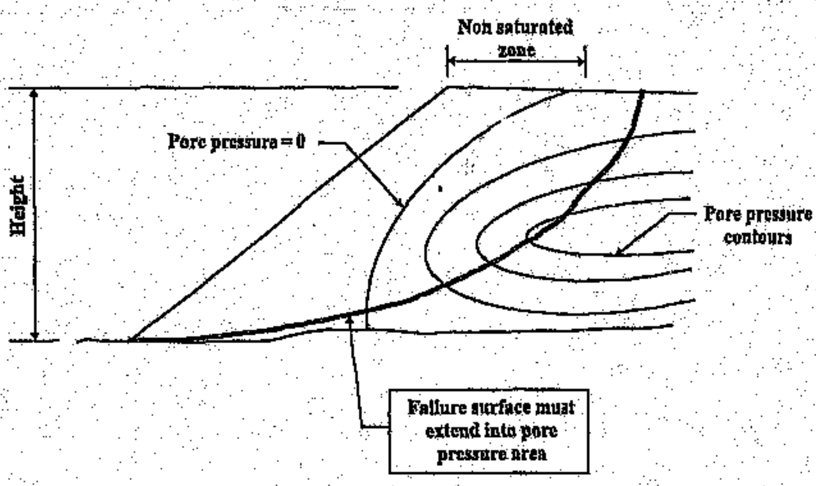
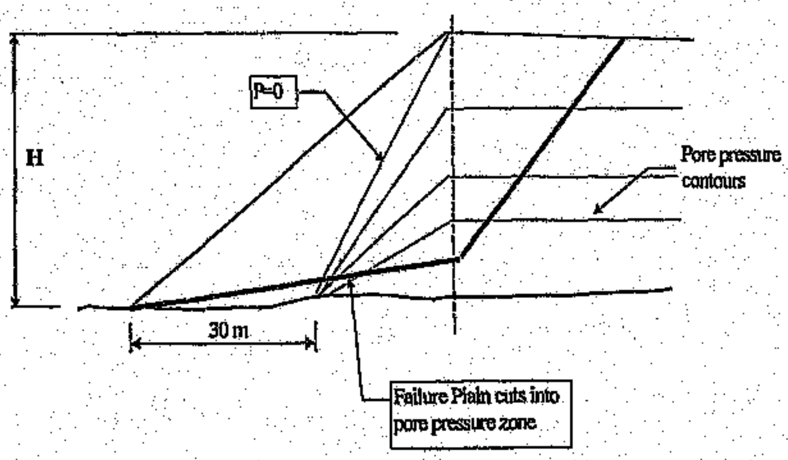


Figure 6.2: Geometry for dual wedge failure surface



For the dual wedge analysis, the pore pressure contours deflected below the crest level, and ended at a point 30m in from the toe. To analyse the slope, the junction point for the pore pressure contours was located 5m below natural ground level, which resulted in an acceptable spread of pore pressure near the failure surface. Also, the failure surface was fixed with the following criteria:

- Exit at toe of the dam.
- First wedge ends below the crest at a height of 5m above the toe.
- The second wedge slope is at ($45° + \phi.0,5$) to the horizontal.

The factor of safety of a pre-defined failure surface was determined.

CHAPTER 7: RESULTS AND DISCUSSION

7.1 Pore Pressure Results

A series of detailed plots of the pore pressure profiles for the various deposition scenarios have been included in Appendix D of this document. Some of the results of the analysis exclude the removal of supernatant from the surface of the dam, or removal of seepage from the base, and some include the effect of the removal of the supernatant liquid from the consolidating mass. Each plot that includes the removal of liquid, as been marked as such.

Some of the more salient results have been summarised in the following eight tables.

The information that has been summarised is the actual rate of rise of the dam, compared to the rate of placing of the tailings. The magnitude of the settlement, as well as the peak pore pressure has been recorded. The location of the peak pore pressure, as a percentage of the dam height, is also given. The data has been summarised for selected height intervals of the dam, to allow the results to be compared.

Table 7.1 to 7.8 show the summarised data for the seven different waste products.

The general trend of the results for each waste product is discussed below:

A trend that was observed in all the analyses, is that the rate of rise of all the dams is substantially lower than the rate of placing of the material, and the rate of rise also reduces as the height of the dam increases.

- **Copper Tailings: (Table 7.1 and 7.2)**

  The settlement of the tailings is substantial, with settlements varying from 10% to 40% of the placed height of the dam. The settlement also increases with the reduced rate of placing at the same height of the dam, i.e. at a dam height of 26m, the settlements at a rate of placing of 3,65mpa and 9,6mpa are, 36% and 24% respectively, of the height of the dam. These settlements have been calculated as at the end of the deposition of the last layer of tailings. Further settlement will occur in the dam, as the consolidation process continues with time.

  The peak pore pressure within the tailings also exhibits a trend, which is presented in Figure 7.1. It is evident that the peak pore pressure increases non-linearly with the height of the dam, and the rate at which the peak pressure increases with height, increases, as the rate of deposition is increased.

TABLE 7.1: WASTE PRODUCT - COPPER TAILINGS (TWO-WAY DRAINAGE)

Rate of placing	Height	Rate of rise	Settlement	Settlement as a percentage of height	Peak pore pressure	Position of peak from bottom	Peak position as percentage of height	Comments
Mpa	m	mpa	m	%	kPa	m	%	
3.65	9.22	2.95	2.37	26%	8.0	5.25	57%	two way drainage with supernatant removal
	26.24	2.70	9.35	36%	37.8	13.90	53%	two way drainage with supernatant removal
6.42	10.93	6.38	1.83	17%	21.8	5.78	53%	two way drainage with supernatant removal
	27.46	5.57	6.41	23%	75.5	13.64	50%	two way drainage with supernatant removal
	39.52	5.28	10.19	26%	125.7	18.02	46%	two way drainage with supernatant removal
	67.26	5.08	19.41	29%	269.5	31.26	45%	two way drainage with supernatant removal
9.60	8.60	8.90	1.39	16%	23.0	4.26	50%	two way drainage
	27.47	7.99	6.52	24%	114.0	12.28	45%	two way drainage
	45.77	7.75	12.22	27%	234.0	19.16	42%	two way drainage
	63.88	7.63	18.11	28%	375.0	25.64	40%	two way drainage
10.79	9.28	9.10	1.55	17%	28.1	4.53	49%	two way drainage
	29.95	8.98	7.28	24%	141.8	13.32	44%	two way drainage
	50.03	8.62	13.61	27%	292.3	19.85	40%	two way drainage
	69.91	8.45	20.12	29%	467.5	27.31	39%	two way drainage
10.70	9.55	8.99	2.31	24%	26.0	4.47	47%	two way drainage with supernatant removal
	28.49	8.05	9.78	34%	115.4	12.84	45%	two way drainage with supernatant removal
	46.88	7.81	17.72	38%	230.8	19.42	41%	two way drainage with supernatant removal
	65.12	7.69	25.94	40%	365.0	28.71	44%	two way drainage with supernatant removal
9.60	8.51	8.68	1.48	[illegible]	68.0	2.65	31%	two way drainage, different soil parameters
	27.56	8.26	6.42	23%	341.3	7.05	26%	two way drainage, different soil parameters
	46.51	8.01	11.47	25%	651.4	10.49	23%	two way drainage, different soil parameters
	65.40	7.96	16.59	25%	1083.5	14.44	22%	two way drainage, different soil parameters

TABLE 7.2 WASTE PRODUCT: COPPER TAILINGS (ONE-WAY DRAINAGE)

Rate of placing	Height	Rate of rise	Settlement	Settlement as a percentage of height	Peak pore pressure	Position of peak from bottom	Peak position as percentage of height	Comments
Mpa	m	mpa	m	%	kPa	m	%	
3.65	9.32	3.61	1.48	16%	22.8	2.34	25%	one way drainage with supernatant removal
	26.08	3.12	5.92	23%	102.0	4.36	17%	one way drainage with supernatant removal
	39.89	3.00	10.12	25%	183.8	6.08	15%	one way drainage with supernatant removal
	46.49	2.95	12.31	26%	225.0	7.23	15%	one way drainage with supernatant removal
6.42	8.64	6.22	1.05	21%	41.6	2.32	27%	one way drainage with supernatant removal
	29.63	5.85	6.46	22%	194.7	4.20	14%	one way drainage with supernatant removal
	49.92	5.43	12.57	25%	392.3	6.75	14%	one way drainage with supernatant removal
	73.93	5.23	20.23	27%	665.5	8.60	12%	one way drainage with supernatant removal
9.40	7.14	7.95	1.74	24%	39.7	1.48	21%	one way drainage
	23.84	7.08	8.20	34%	203.0	3.29	14%	one way drainage
	39.99	6.85	15.21	38%	411.4	4.81	12%	one way drainage
	55.94	6.74	22.42	40%	647.9	5.27	9%	one way drainage
9.60	8.38	8.50	1.62	19%	127.7	0.74	9%	one way drainage, different soil parameters
	27.36	7.80	6.64	24%	529.4	0.73	3%	one way drainage, different soil parameters
	46.11	7.72	11.89	26%	935.8	0.73	2%	one way drainage, different soil parameters
	70.89	7.69	19.11	27%	1477.6	0.73	1%	one way drainage, different soil parameters

TABLE 7.3: WASTE PRODUCT: GOLD TAILINGS - CROWN MINES

Rate of placing	Height	Rate of rise	Settlement	Settlement as a percentage of height	Peak pore pressure	Position of peak from bottom	Peak position as percentage of height	Comments
Mpa	m	mpa	m	%	kPa	m	%	
3.90	16.00	3.59	1.54	10%	4.1	6.34	40%	two way drainage
	23.70	3.55	2.57	11%	11.3	9.70	41%	two way drainage
	33.74	3.50	4.06	12%	26.4	12.47	37%	two way drainage
6.50	15.81	6.08	1.44	9%	4.6	7.67	49%	two way drainage
	24.70	5.97	2.57	10%	13.9	9.10	37%	two way drainage
	33.40	5.89	3.80	11%	28.1	11.87	36%	two way drainage
	50.88	5.82	6.37	13%	72.6	17.80	35%	two way drainage
	63.80	5.78	8.40	13%	119.7	20.93	33%	two way drainage
5.20	16.90	4.80	1.64	10%	5.6	6.46	38%	two way drainage
	34.50	4.68	4.11	12%	31.0	11.56	34%	two way drainage
	51.80	4.63	6.76	13%	79.3	16.78	32%	two way drainage
3.65	16.72	3.34	1.58	9%	19.8	0.28	1%	one way drainage with seepage removal
	36.52	3.26	4.28	12%	107.9	0.27	1%	one way drainage with seepage removal
	49.60	3.24	6.21	13%	203.2	0.27	1%	one way drainage with seepage removal
	69.02	3.21	9.29	13%	388.4	0.27	1%	one way drainage with seepage removal
6.50	20.24	6.07	1.92	10%	46.2	0.34	2%	one way drainage with seepage removal
	35.87	5.89	4.10	11%	151.5	0.33	1%	one way drainage with seepage removal
	51.60	5.84	6.36	12%	304.8	0.33	1%	one way drainage with seepage removal
	67.23	5.81	8.73	13%	492.2	0.32	0%	one way drainage with seepage removal

TABLE 7.4: WASTE PRODUCT: GOLD TAILINGS - BODDINGTON

Rate of placing	Height	Rate of rise	Settlement	Settlement as a percentage of height	Peak pore pressure	Position of peak from bottom	Peak position as percentage of height	R_u	Comments
Mpa	m	m/pa	M	%	kPa	m	%		
2.40	7.40	1.39	6.55	89%	23.3	3.32	45%	0.17	two way drainage
	15.30	1.25	16.65	109%	76.0	6.56	43%	0.28	two way drainage
	23.70	1.19	28.10	119%	145.0	10.40	44%	0.34	two way drainage
3.93	7.62	2.07	7.06	93%	33.9	2.95	39%	0.25	two way drainage
	15.76	1.85	17.81	113%	110.0	6.24	40%	0.39	two way drainage
	24.00	1.80	28.48	119%	203.0	9.25	39%	0.47	two way drainage
	33.70	1.72	43.08	128%	339.0	13.30	39%	0.56	two way drainage
7.80	21.30	3.61	25.47	120%	274.0	6.80	32%	0.71	two way drainage
	39.20	3.36	52.55	134%	666.0	11.98	31%	0.94	two way drainage
3.65	9.20	2.10	7.39	80%	25.8	3.13	34%	75.20	two way drainage with supernatant removal
	15.15	1.98	13.44	89%	60.6	5.30	35%	110.85	two way drainage with supernatant removal
	20.84	1.90	19.75	95%	101.6	6.92	33%	145.45	two way drainage with supernatant removal

TABLE 7.5: WASTE PRODUCT: COAL SLURRY

Rate of placing	Height	Rate of rise	Settlement	Settlement as a percentage of height	Peak pore pressure	Position of peak from bottom	Peak position as percentage of height	R_u	Comments
Mpa	m	mpa	m	%	kPa	m	%		
3.65	5.96	3.41	0.64	11%	1.2	3.00	50%	0.01	two way drainage
	14.57	3.25	2.03	14%	5.2	6.67	46%	0.03	two way drainage
	22.98	3.18	3.61	16%	12.2	9.25	40%	0.04	two way drainage
	33.00	3.15	5.62	17%	25.1	13.30	40%	0.05	two way drainage
5.20	6.30	4.85	0.68	11%	2.4	3.17	50%	0.03	two way drainage
	14.92	4.64	2.08	14%	7.3	6.49	43%	0.03	two way drainage
	23.35	4.55	3.65	16%	17.3	9.76	42%	0.05	two way drainage
	39.99	4.46	7.01	18%	50.0	16.37	41%	0.09	two way drainage
10.40	5.96	9.59	0.63	11%	1.1	3.01	51%	0.01	two way drainage
	14.59	9.23	2.01	14%	11.1	5.98	41%	0.05	two way drainage
	23.03	9.07	3.56	15%	28.3	9.10	40%	0.09	two way drainage
	33.74	8.94	5.63	17%	59.7	13.48	40%	0.13	two way drainage
	43.40	8.91	7.62	18%	99.5	16.35	38%	0.16	two way drainage
3.65	5.98	3.42	0.62	10%	1.1	3.00	50%	0.01	two way with removal of supernatant
	14.61	3.26	1.98	14%	4.6	6.51	45%	0.02	two way with removal of supernatant
	23.07	3.19	3.53	15%	10.6	9.79	42%	0.03	two way with removal of supernatant
	33.10	3.15	5.50	17%	22.0	13.68	41%	0.05	two way with removal of supernatant
3.65	5.97	3.42	0.63	11%	3.5	0.17	3%	0.04	one way drainage only
	14.60	3.25	1.99	14%	17.8	0.17	1%	0.09	one way drainage only
	23.06	3.19	3.54	15%	43.1	0.17	1%	0.13	one way drainage only
	34.80	3.14	5.82	17%	95.0	0.17	0%	0.19	one way drainage only

TABLE 7.6: WASTE PRODUCT: BAUXITE RESIDUE

Rate of placing	Height	Rate of rise	Settlement	Settlement as a percentage of height	Peak pore pressure	Position of peak from bottom	Peak position as percentage of height	R_n	Comments
Mpa	m	mpa	m	%	kPa	m	%		
1.96	2.87	0.40	2.06	72%	2.5	1.08	37%	0.05	two way drainage
2.60	5.93	1.19	7.41	125%	19.4	1.48	25%	0.19	two way drainage
3.91	6.01	1.81	7.33	122%	26.5	1.55	26%	0.26	two way drainage
7.82	6.21	3.76	7.13	115%	44.4	1.47	24%	0.42	two way drainage
7.82	6.61	4.42	5.67	86%	17.4	1.84	28%	0.15	two way drainage with supernatant removal
	12.10	3.63	14.63	121%	51.4	3.16	26%	0.25	two way drainage with supernatant removal
10.95	6.03	7.48	3.27	54%	69.9	0.14	[illegible]	0.68	one w[illegible]age with supernatant removal
	7.17	7.18	4.23	59%	89.9	0.14	[illegible]	0.74	one way [illegible]ainage with supernatant removal
3.65	6.34	1.93	6.25	99%	8.5	2.09	33%	66.39	two way drainage with supernatant removal
	12.02	1.57	16.57	138%	30.3	3.56	30%	147.45	two way drainage with supernatant removal
	16.28	1.49	24.31	149%	58.1	4.60	28%	214.20	two way drainage with supernatant removal

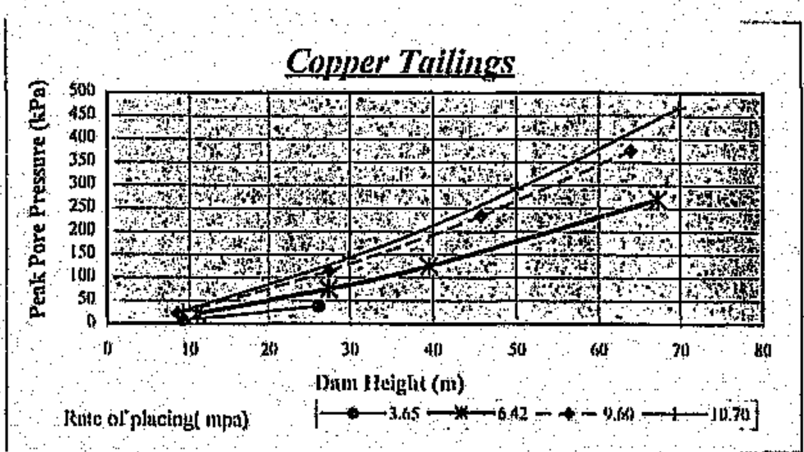
TABLE 7.7: WASTE PRODUCT: ACID MINE DRAINAGE SLUDGE

Rate of placing	Height	Rate of rise	Settlement	Settlement as a percentage of height	Peak pore pressure	Position of peak from bottom	Peak position as percentage of height	R_u	Comments
Mpa	m	mpa	m	%	kPa	m	%		
3.65	4.91	2.91	1.38	28%	7.8	1.71	35%	0.11	two way drainage
	6.43	2.79	2.07	32%	13.1	2.26	35%	0.14	two way drainage
	10.92	2.63	4.38	40%	37.3	4.08	37%	0.23	two way drainage
7.30	4.96	5.87	1.34	27%	13.5	1.50	30%	0.18	two way drainage
	7.07	5.63	2.23	32%	27.0	2.26	32%	0.25	two way drainage
	11.12	5.35	4.18	38%	60.5	3.48	31%	0.36	two way drainage
10.95	4.98	8.72	1.31	26%	16.0	1.51	30%	0.21	two way drainage
	7.12	8.43	2.17	31%	33.0	2.39	34%	0.31	two way drainage
	11.27	8.09	4.03	36%	75.3	3.32	29%	0.45	two way drainage
3.65	5.01	3.23	1.29	26%	25.4	0.07	1%	0.34	one way drainage
	7.14	2.84	2.16	30%	46.8	0.07	1%	0.44	one way drainage
3.65	5.35	3.25	1.26	23%	26.6	0.16	3%	55.40	one way drainage & supernatant removal
	11.17	2.91	3.44	31%	86.9	0.15	1%	91.70	one way drainage & supernatant removal
3.65	5.26	3.20	1.32	25%	8.7	1.75	33%	42.87	two way drainage & supernatant removal
	10.82	2.82	3.78	35%	33.3	3.58	33%	74.80	two way drainage & supernatant removal
	14.82	2.71	5.77	39%	56.9	4.98	34%	91.40	two way drainage & supernatant removal

TABLE 7.8: WASTE PRODUCT: MANGANESE TAILINGS

Rate of placing	Height	Rate of rise	Settlement	Settlement as a percentage of height	Peak pore pressure	Position of peak from bottom	Peak position as percentage of height	Comments
Mpa	m	mpa	m	%	kPa	m	%	
1.83	12.46	1.69	1.338	11%	25.9	3.508	28%	two way drainage
	21.98	1.62	3.01	14%	101.0	5.57	25%	two way drainage
3.65	14.91	3.34	1.68	11%	58.0	3.65	24%	two way drainage
	22.11	3.27	2.88	13%	133.7	5.43	25%	two way drainage
	34.00	3.21	4.98	15%	294.5	7.45	22%	two way drainage
	50.60	3.17	8.01	16%	555.9	10.24	20%	two way drainage
7.30	12.55	6.79	1.24	10%	54.8	3.18	25%	two way drainage
	22.33	6.60	2.72	12%	168.7	5.46	24%	two way drainage
	36.75	6.48	5.04	14%	384.8	7.48	20%	two way drainage
	51.20	6.42	7.41	14%	625.6	9.34	18%	two way drainage
14.60	12.60	13.64	1.16	9%	76.3	3.55	28%	two way drainage
	22.50	13.32	2.52	11%	206.6	5.51	24%	two way drainage
3.65	14.35	3.37	1.45	10%	138.93	0.18	1%	one way drainage
	21.35	3.31	2.45	11%	270.80	0.18	1%	one way drainage
	36.97	3.24	4.83	13%	599.50	0.18	0%	one way drainage
1.83	12.35	1.74	1.25	10%	73.40	0.36	3%	one way drainage
	23.10	1.66	2.91X13%		240.50	0.35	2%	one way drainage
	31.67	1.63	4.32	14%	400.23	0.35	1%	one way drainage

Figure 7.1: Peak Pore Pressures for different rates of placing of Copper Tailings



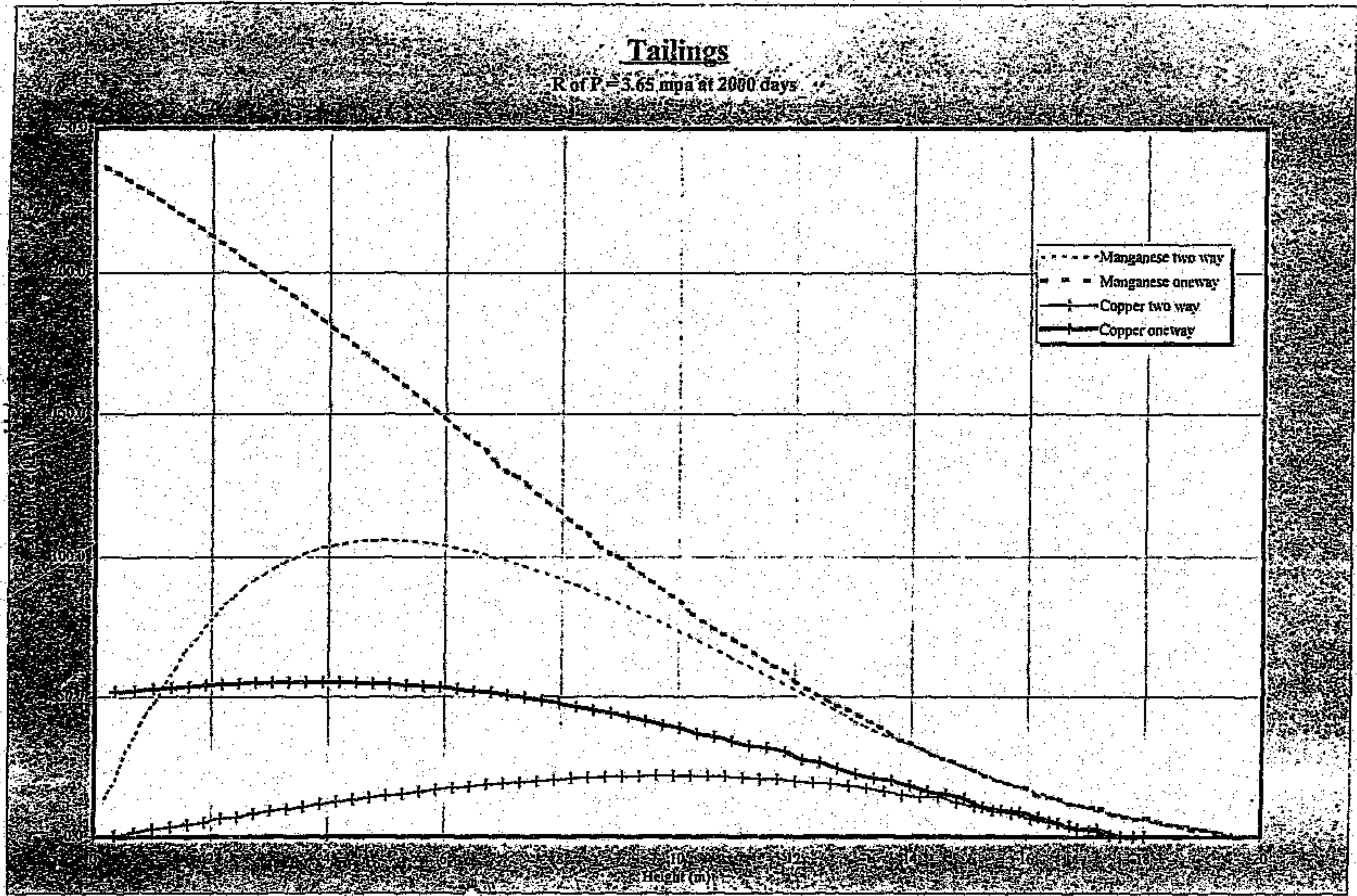
The above figure represents the case of two-way drainage of the tailings.

At the maximum rate of placing of 10,7mpa, and at a dam height of 70m, the peak pore pressure is 467kPa. In comparison, the total applied pressure to the tailings by way of deposited waste is 1145kPa. The position of the peak pore pressure zone in the tailings also varies as the height of the dam increases. For the one copper tailings sample the peak initially occurred at 50% of the height up from the bottom of the dam. As the dam rises, the peak zone drops downwards in the dam, to a point of 0,39H from the base of the dam; (H is the dam height). These ratios are material-sensitive, as the second copper tailings sample resulted in the peak pore pressure being at 31% of the height for low dams, and reducing to 22% of the height for high dams, at a rate of placing of 10,7mpa.

A similar result is observed in the one way drainage case, although much reduced in magnitude. The peak pore pressure does not only occur at the base, as a bulb of peak pore pressure develops. This bulb reduces in height, as the dam gets higher. The one sample of copper tailings that was used in the analysis, resulted in a bulb varying from 28% of the dam height, reducing to 9%. The second sample of copper tailings resulted in a thin bulb, starting at 9% and reducing to 1% of the dam height. This bulb of pressure is a zone where the pore pressure varies very little over the height of the tailings.

A comparison of the peak pore pressure for copper tailings at a rate of placement of 3,65mpa is given in **Figure 7.2**. At time = 2000 days, it can be seen that the peak pore pressure for a one-way drainage case is 2,5 times higher than for a two-way drainage case. Also, over the upper 20% of the dam, there is very little difference in the peak pore pressure for the two cases.

FIGURE 7.2: EXCESS PORE PRESSURE PROFILE FOR COPPER AND MANGANESE TAILINGS AT R of P = 3,65m.p.a.



- **Gold Tailings (Table 7.3)**

The tailings analysed in this section were from a hard rock mining operation. Hence the tailings consists of hard angular particles, and therefore drains quicker tha. the gold tailings that is discussed in the next section.

The settlement of these tailings is much less than that of, say, copper. The settlement ratio also increases as the dam height increases, varying from 10% of the height for low dams, to 14% for high dams.

The peak pore pressure location within the dam height also changes position as the dam height increases, varying from 49% of the height from the bottom for low dams, reducing to 32% for high dams. The tailings does not build up a high pore pressure, with the maximum pore pressure predicted being 119kPa for a 64m high dam built at a rate of placing of 6,5mpa (with base drainage). The trend of the increase in the peak pore pressure is exponential, with the increase in the dam heigh.

Similarly, the peak pore pressure at the base of a 67m high tailings dam built on impermeable ground at a rate of p ing of 6,5mpa, is 492kPa. This pressure drops to 388kPa for a 69m high dam built at 3,65mpa on impermeable ground. The tailings do not produce a dominant peak pore pressure bulb, due to its fairly quick drainage characteristic.

- **Gold Tailings from weathered rock (Table 7.4)**

The consolidation characteristics of this gold tailings is substantially different to that of the gold tailings above. The tailings is also placed at a high void ratio, resulting in large settlements. The settlements that have been predicted vary from 89% of the settled dam height for a dam of 7,4m high, to 134% for high dams. This indicates that the dam height reduces by more than half, relative to the initial height of placed tailings.

The rate of rise of the dam is similarly less than half the rate of placement of the tailings.

The position of the peak pore pressure of the tailings analysed starts at 45% of the dam height for low dams, and reduces to around 31% of the height for high dams.

The initial analysis of is tailings was carried out without allowing for the removal of seepage water. The large settlements that occur are indicative of the quantity of seepage water that is expelled from the consolidating tailings, i.e. a settlement of 28m is equal to a reduction of load in the tailings equal to 28m^3 of water, which is equal to a load of 280kPa. Hence, the predicted pore pressures allow for a load that does not exist, if the supernatant water is decanted from the surface of the dam. This will result in the incorrect calculation of pore pressure gradients, resulting in erroneous pore pressure predictions with time. In a case where the supernatant is not decanted, the analysis will be correct.

For illustrative purposes, one set of results will be discussed:

The peak pore pressure for a dam of 39,2m high is 666kPa. This occurs at a level of 12m from the base of the dam. This results in 28,7m of tailings above the peak pressure position. For this to balance, we need a tailings with an average density of 666/27,2 = 24,49kN/m^3 over the peak pressure zone in the dam. This assumes no free water at the surface. This is clearly incorrect.

The consolidation of the tailings has also been analysed, including the removal of supernatant liquid, for the case of no base drainage. These results indicate a peak pore pressure of 101,6kPa for a 20,84m high dam built at 3,65mpa. This analysis allows for the removal of 19,7m^3 of supernatant water, which is equivalent to 197kPa of load.

- **Coal Slurry (Table 7.5)**

The characteristics of coal slurry are similar to those of fresh rock source gold tailings. Settlement of the slurry ranges from 11% for low dams, to 18% for high dams. The position of the peak pore pressure zone also starts at 51% of the dam height, and moves downwards in the dam to 38% of the dam height for high dams.

The slurry is fairly quick draining, in that the peak pore pressure predicted is only 99,5kPa for a dam of 43,4m built at 10,4mpa, with base drainage.

For the case with no base drainage, the peak pore pressure is 95kPa at a dam height of 34,8m, with the rate of placement of 3,65mpa. This pressure drops to 22kPa, if base drainage exists.

The summary sheet also clearly shows that there is little difference in the results between the case of removing supernatant from the slurry, and not removing it. This is to be expected, as the slurry only settles by a small amount.

- **Bauxite Residue (Table 7.6)**

Bauxite residue is deposited with a high void ratio, and is usually placed behind an embankment. The residue is a very slow draining material, and hence the gain of strength is very slow. The analysis for this residue has been limited to low heights of the residue, primarily due to the data available covering only the low stress range. Also, high embankments to retain the residue would be uneconomical.

The residue settles substantially, varying from 54% at high deposition rates of 10,95mpa, to 149% of the settled height at a deposition rate of 3,65mpa. This indicates that supernatant removal must be included in any analyses, as the effect would be substantial. The analysis of this residue results in the largest settlement of all the scenarios analysed.

The position of the peak pore pressure zone exists at around 33% of the dam height, and moves downwards to 28% of the height, as the elevation of the dam increased three fold. At higher deposition rates, the peak tends to be lower down in the dam.

The peak pore pressure for a dam of 16,28m high, placed over a period of nearly 11 years, will be 58kPa. This is compared with an applied pressure from the residue of 272kPa. It is also noted that at more than double the rate of rise, the peak pore pressure increases by only 71%, for a dam of 12m high.

- **Acid Mine Drainage Sludge (Table 7.7)**

This is another waste that is placed at a high void ratio, in a slurry form. The analyses were run for both scenarios, i.e. with and without supernatant removal, at a rate of placement of 3,65mpa for both one way and two-way drainage.

The sludge settled between 25% and 40% of the dam height, over a range of dam heights of 4,9m to 14,8m high. The peak pore pressure zone location varied between 30% and 37% of the dam height, from the bottom of the sludge, for the two way drainage case. The one way drainage case had a peak pore pressure location at the base of the deposit.

The peak pore pressure magnitude however does not change substantially between the analysis with or without supernatant removal. For the case with no removal, the peak pore pressure is 37,3kPa for a 10,9m high dam, while for the case with supernatant removal, the peak pore pressure is 33,3kPa. The position of the peak pore pressure does however change from 37% of the height for no supernatant removal, to 33% for the case with removal of supernatant. For the case of one way drainage, a similar observation is made, with the difference being that a peak pore pressure bulb forms at the base of the deposit, for the case with supernatant removal.

At a rate of placement of 3,65mpa with supernatant removal, the peak pore pressure for one way drainage is 87kPa, compared to an applied load of 178.6kPa. For the two-way drainage case, these values are 33.3kPa and 108.1kPa, for a dam around 11m high.

- **Manganese Tailings (Table 7.8)**

This tailings has the lowest permeability of the materials analysed, and is deposited at a moderate void ratio. Hence the settlement of the tailings is small, with predicted values varying from 9% to 16% of the dam height. These settlements apply to dam heights from 12,5m to 51,2m high. The settlement also reduces as the rate of deposition increases, varying form 14% at 1,83mpa, to 11% at 14,6mpa for a dam height of 22m.

The tailings being of low permeability results in substantial pore pressures at different rates of placement, i.e. at a dam height of 50m, the peak pore pressure changes from 555,7kPa at a rate of placement of 3,65mpa, to 625,6kPa at 7,3mpa. Similarly, for the one way drainage case the peak pore pressure is 599,5kPa at a rate of placement of 3,65mpa for a dam height of 37m. This pressure drops to 400kPa at a rate of placement of 1.825mpa, for a dam of 31,7m high.

A comparison of the pore pressure profiles for the case of one and two-way drainage is given in **Figure 7.2**, for a rate of placement of 3,65mpa, at t = 2000 days. The peak pore pressure for the one-way case is 2,25 times higher than for the case of two-way drainage. The peak pore pressures occur at different levels in the profile.

The position of the peak pore pressure does not vary greatly, as the dam gets higher, varying from 28% to 18% of the dam height. A trend that is evident is that the peak pore pressure zone does appear to be higher up in the dam, the lower the deposition rate.

Figure 7.3: Peak Pore Pressure of Manganese Tailings with respect to RATE OF PLACEMENT, for two dam heights

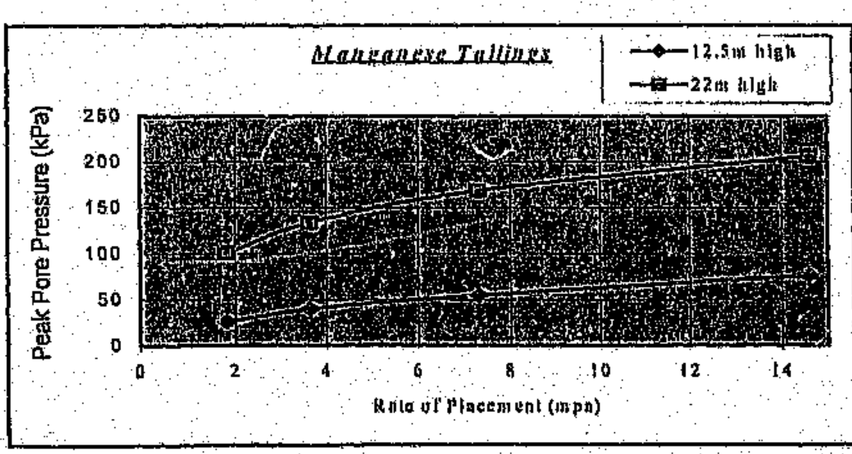


Figure 7.3 above presents the non-linear trend of the peak excess pore pressure in the manganese tailings, for different rates of placing for a dam at a height of

12,5m and 22m high. The trend indicates that at a rate of placement of less than 4mpa, the peak pore pressure increases substantially, as the rate of placement increases. However, at a rate of placement above 4mpa, the rate of the peak pore pressure increase flattens off. The rates at which the peak pore pressure increases for the two-dam heights are also different, with the higher dam's peak pore pressure increasing at a higher rate than the lower dam.

7.2 Discussion of Results

This section addresses the general trend of the results discussed in Section 7.1. For the purpose of discussion the following data was selected:

- Rate of placement of 3,65mpa
- Tailings/waste having been placed over a period of 2000 days
- Both one way and two drainage is to be assessed

Figure 7.4, shows the excess pore pressure for six of the materials analysed for two-way drainage. The seventh material, namely the gold tailings from fresh hard rock, falls on top of the curve of the coal slurry, and hence has been taken off the graph to avoid confusion. These results are to be viewed in the light that the deposition void ratios of the six materials vary greatly, from 2,38 to 1,06.

It can be seen that the manganese tailings produces the highest pore pressure and has the lowest settlement. The highest settlement occurs in the Bauxite residue. Another trend that is evident is the vastly different positions of the peak pore pressure for the different materials, varying from being close to the base, to the peak being above the middle of the dam height. The pore pressures vary from 18kPa to 107kPa for the materials analysed. This is a variation of nearly 72% either side of the average of the peak pore pressures of the seven materials, and a 500% variation with respect to the lowest pressure. The results also highlight the fact that the consolidation characteristics of one type of tailings can vary substantially, as shown by the two types of gold tailings.

The one way drainage case is represented in **Figure 7.5**. Here only four materials are represented, to show the relative trend of the results. It can be seen that manganese again has the highest peak pore pressure, with the other three materials being substantially lower, i.e. 235kPa compared to 25 to 50 kPa. The peak pressure point is generally close to the base of the deposit.

Another trend that can be observed is presented in **Figure 7.6**, which shows the effect of not including the removal of supernatant for the analysis. The Boddington gold tailings sample has been used to highlight the difference. The Boddington tailings is a slow draining tailings derived from weathered rock.

[redacted] PROFILE F OR SIX WASTE MATERIALS (TWO-WA DRAINAGE)

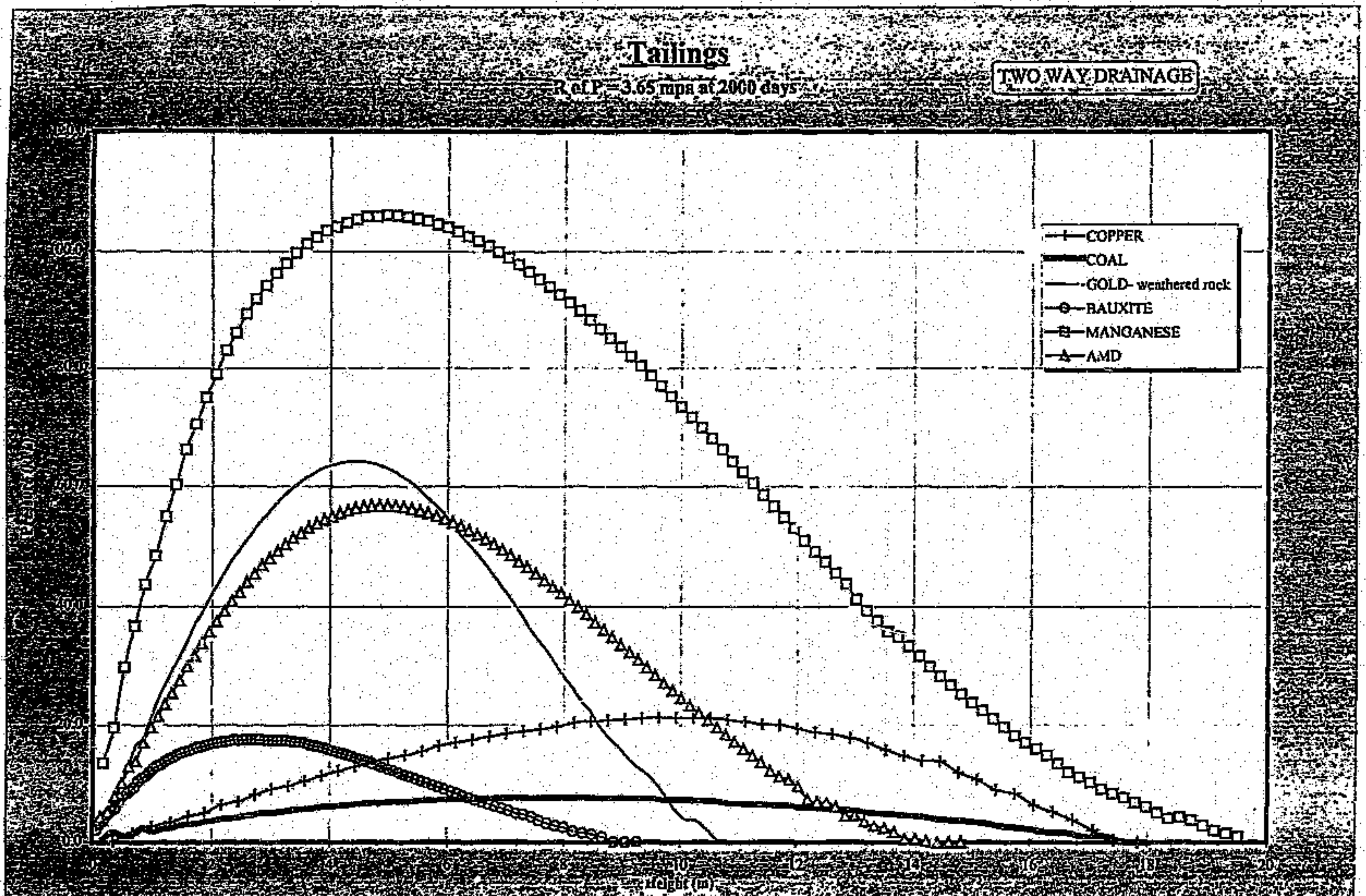


FIGURE 7.5: EXCESS PORE PRESSURE PROFILE FOR FOUR WASTE MATERIALS (ONE-WAY DRAINAGE)

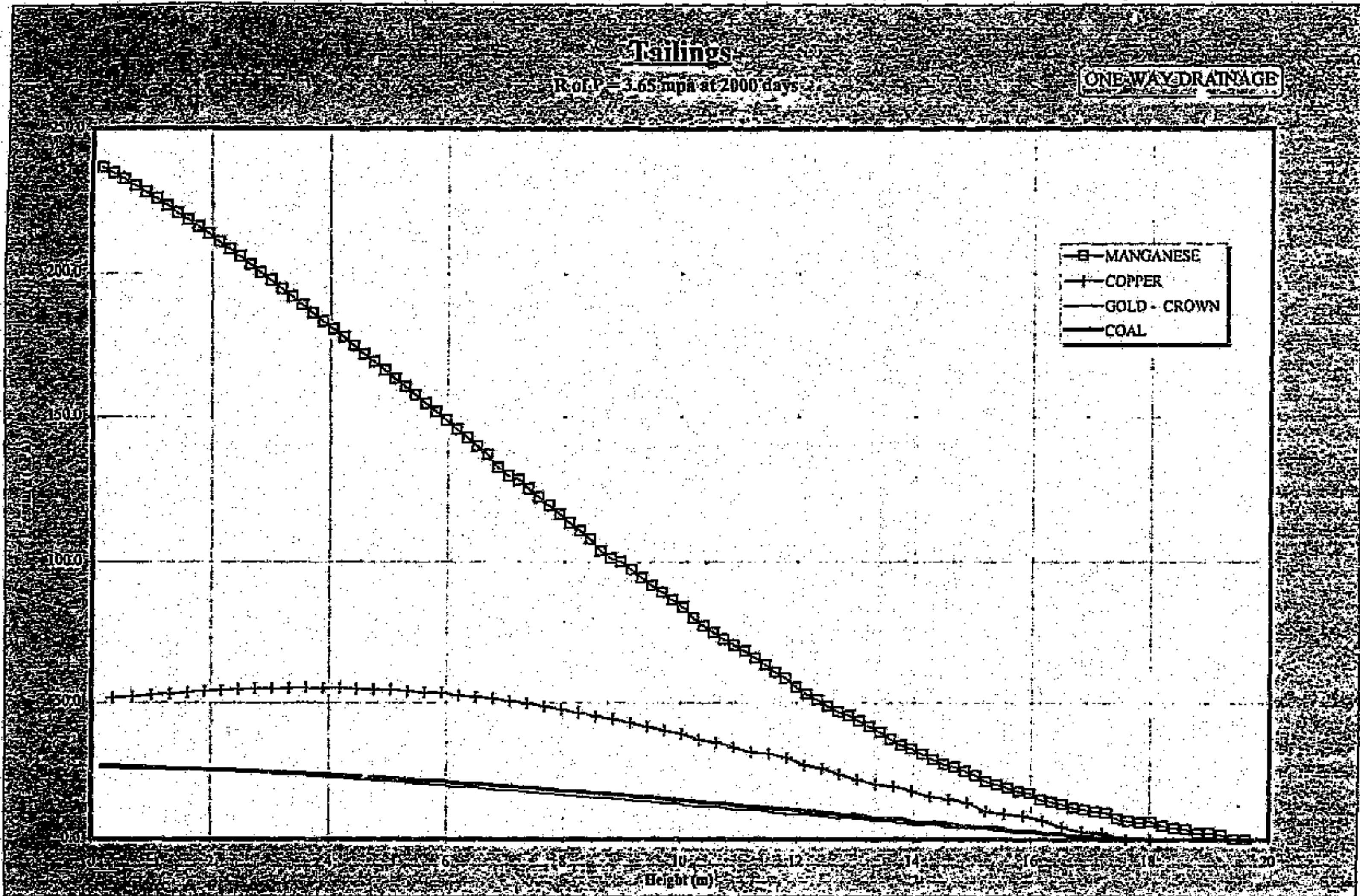


FIGURE 7.6: BODDINGTON GOLD TAILINGS, WITH AND WITHOUT SUPERNATANT REMOVAL, AT R of P = 3,65mpa

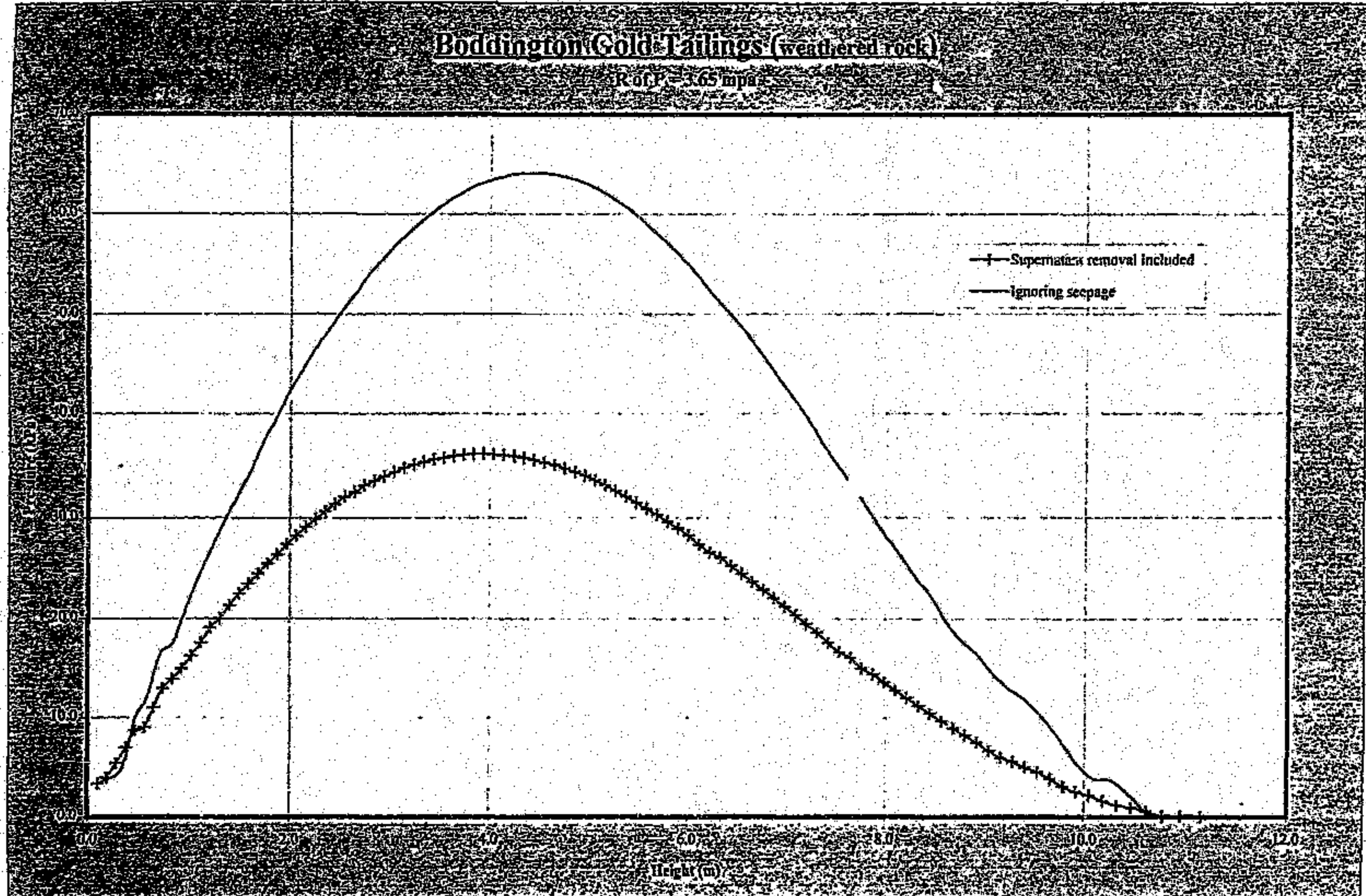


FIGURE 7.7: COAL SLURRY, WITH AND WITHOUT SUPERNATANT REMOVAL, AT R of P = 3,65mpa

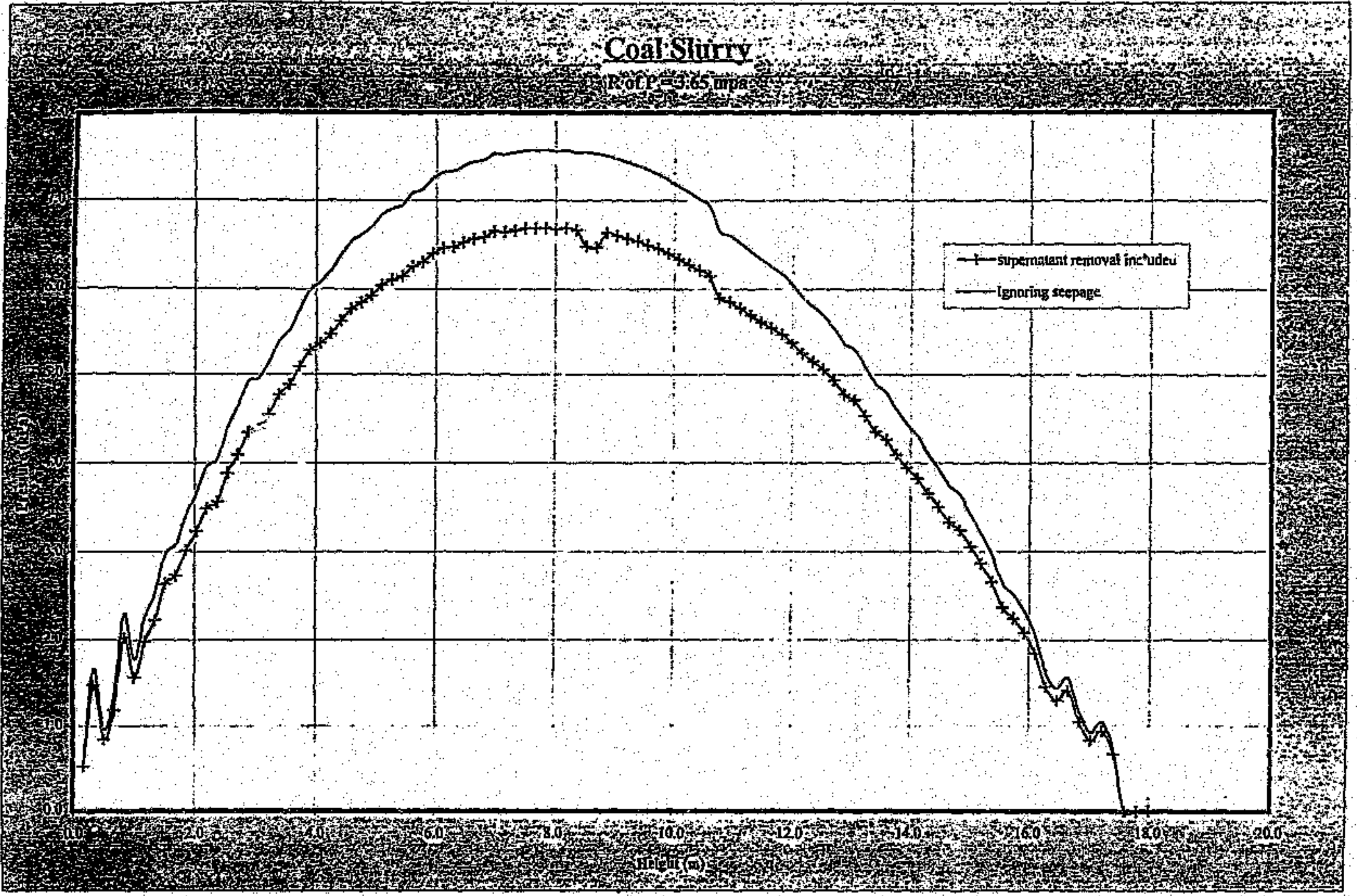
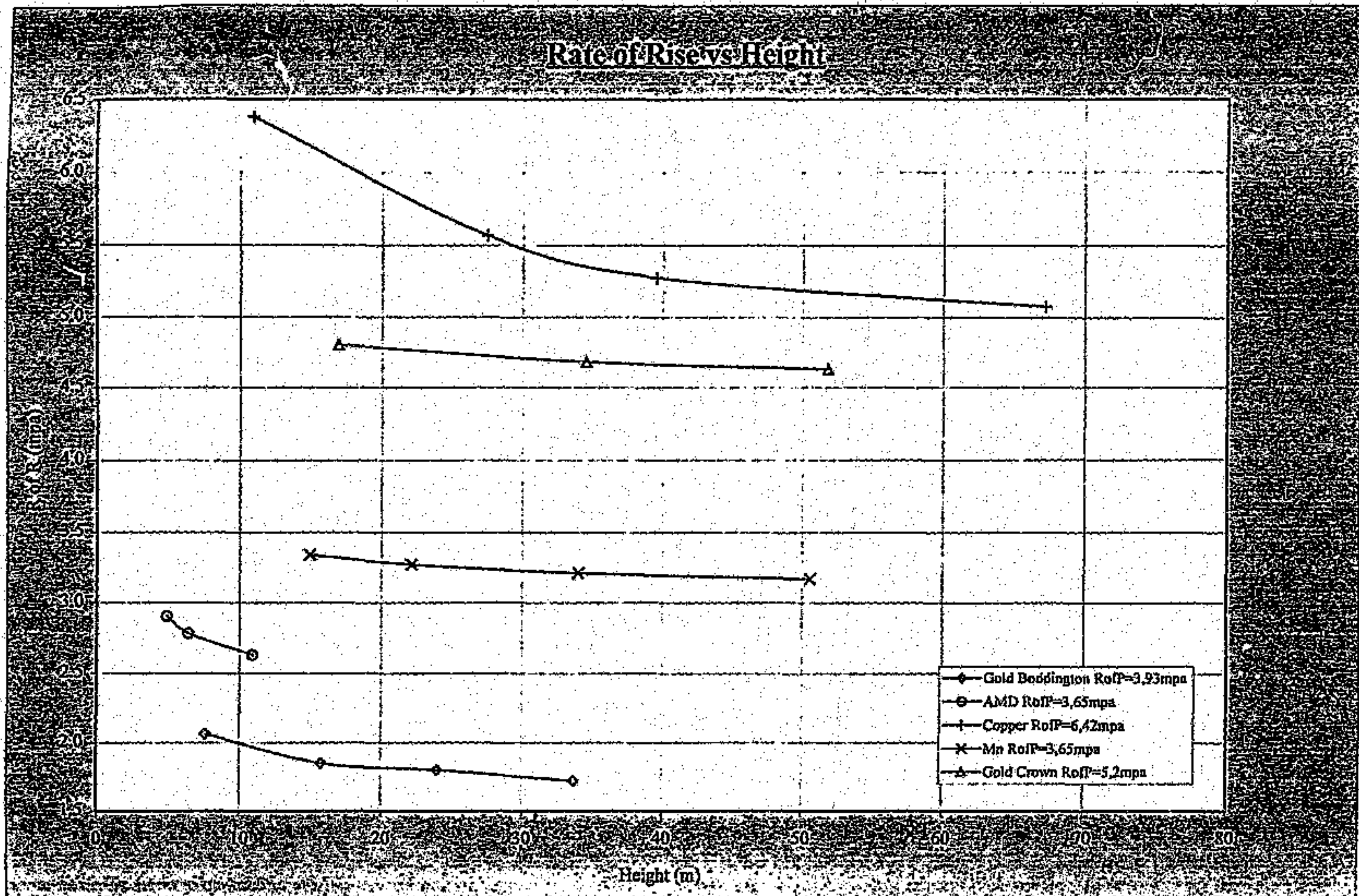


FIGURE 7.8: TREND OF RATE OF RISE OF FIVE TAILINGS, AS A FUNCTION OF THE DAM HEIGHT



It can be seen that the difference in the predicted pore pressure is large, as well as the location of the peak differing. The scenario of not including the removal of supernatant predicts a peak pore pressure of 64kPa, whereas including it predicts a peak pore pressure of 37kPa. This is an over-predicted pressure of 73%. The difference in position is less severe, in that the scenario of excluding supernatant removal predicts a peak pore pressure position 13% higher than the case including supernatant removal.

In contrast, **Figure 7.7** shows the same comparison for the coal slurry analysed. There is clearly a much smaller difference in the predicted peak pore pressure, being only 13%. The location of the peak pore pressure is virtually the same for both scenarios. It is therefore apparent that materials placed at a low void ratio, and analysed without taking cognisance of the change in load as a result of loss of interstitial water, results in relatively small errors. This is not unexpected, as the quantity of seepage from such a material will be small, and hence the change in load will be small.

There is a difference between the rate of rise and rate of placing of the tailings. **Table 7.9** below summarises the percentage difference in the rate of rise to the rate of placing for the scenarios and dam heights analysed in this study. The range of differences is shown, the higher percentage being applicable to low dams at high rates of placing, and the lower percentage applies to high dams with low rates of placing.

Table 7.9: Rate of Rise of dam as a percentage of the Rate of Placement.

Material	Percentage
Copper Tailings	72 to 99
Gold Tailings	88 to 94
Gold Tailings from weathered rock	43 to 58
Coal Slurry	86 to 94
Bauxite Residue	20 to 68
Acid Mine Drainage Sludge	72 to 89
Manganese Tailings	87 to 95

The trend of the rate rise of five tailings has been presented in **Figure 7.8** for a selected rate of placement, with respect to the actual dam height. The rate of rise has been calculated at a number of selected heights of the dam, using the calculated dam height of the dam, divided by the time elapsed to reach that height. Again, it is evident that the trends are material specific, and most of the tailings have a highly non-linear trend for the lower dams. The higher the dam, the more uniform the trend, tending towards a linear trend. This trend is in line with expectation, as the ratio of settlement relative to the dam height reduces as the dam height increases.

There is another result evident from the analysis, and that is the additional storage capacity of a tailings dam, due to the consolidation settlement of the deposited material. If the capacity of a facility is based on the rate of placement of the material, the capacity at a specified maximum height can be seriously under-estimated. This can have substantial impact on the capital expenditure for the owner of the facility. **Figures 7.9, 7.10 and 7.11** indicate the extra volume that can be stored on a dam, per square meter of surface area of the dam, as compared to the volume based on the rate of placement of the tailings. The extra volume is the space created by the settlement of the tailings in the dam. For example, for a copper tailings dam of 40m height, the extra volume that the dam has accommodated as a result of settlement, per hectare of r n area, is 150000m^3 for two way drainage, and 105 000m^3 for a dam with no base drainage (rate of placement = 9,4mpa).

It can also be seen that for certain tailings there is very little difference, if any, between the cases of one-way and two-way drainage. This may be suprising at first, but after careful assessment, it is correct. The reason for this is that the tailings consolidation at depth, and hence at high pressures or loads, is small, i.e. the change in void ratio at high pressures is small. This is specific to each material, as indicated in **Figure 7.9.** There is a marked storage difference between one-way and two-way drainage at a rate of placement of 9,4mpa for copper tailings, whereas there is no difference for hard rock gold tailings at a rate of placement of 6,5mpa.

Another property that appears to be material specific is the trend shown in **Figure 7.10.** For copper tailings at substantially different rates of placing, there is very little difference in the available storage space of the dam. Drainage is the dominant factor in determining the storage capacity of a copper tailings dam.

Figure 7.11 indicates the trend of manganese tailings, compared to gold (hard rock mining) tailings, for a two-way drainage case. It can be seen that for the gold tailings, there is little difference in the storage capacity of a dam, if the rate of placement is increased by 78%. However for the manganese tailings, the difference in storage capacity for a change in the rate of placement of 100%, varies from 14% at a dam height of 20m, to 68% at a dam height of 50m.

FIGURE 7.9: EXTRA STORAGE CAPACITY DUE TO CONSOLIDATION SETTLEMENT, FOR GOLD AND COPPER TAILINGS

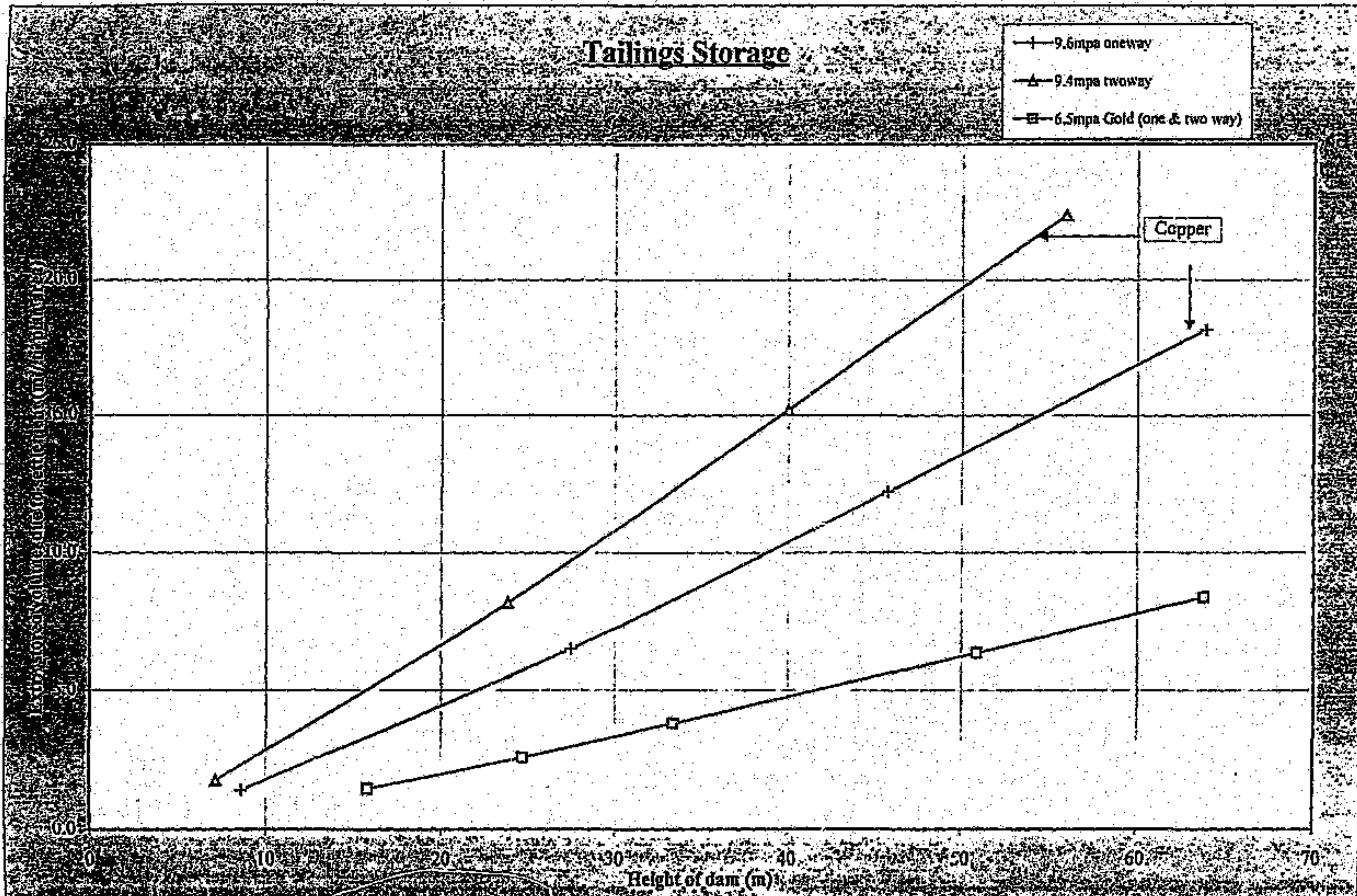


FIGURE 7.10: EXTRA STORAGE CAPACITY DUE TO CONSOLIDATION SETTLEMENT, FOR COPPER TAILINGS AT DIFFERENT RATES OF PLACEMENT AND DRAINAGE

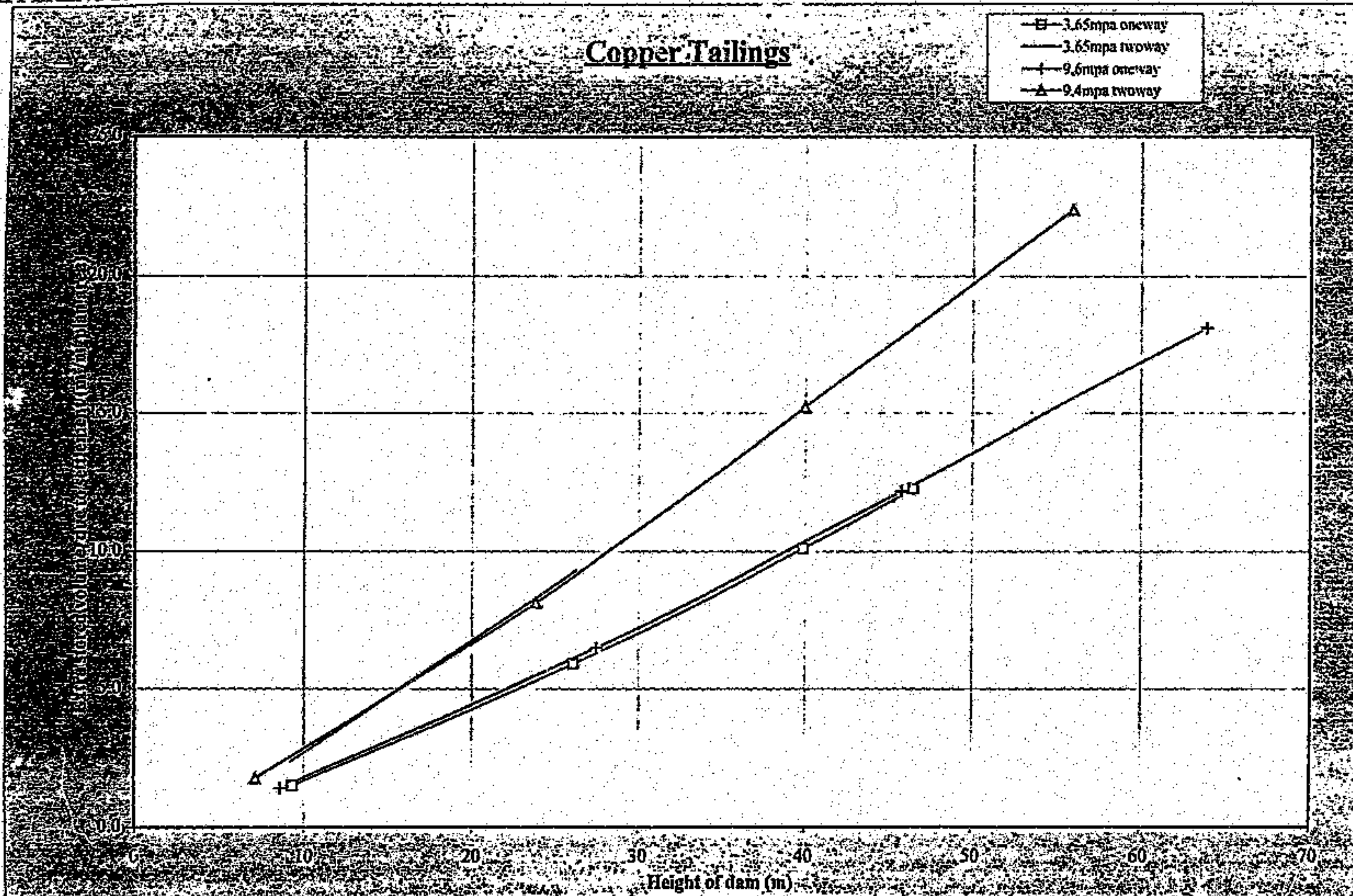
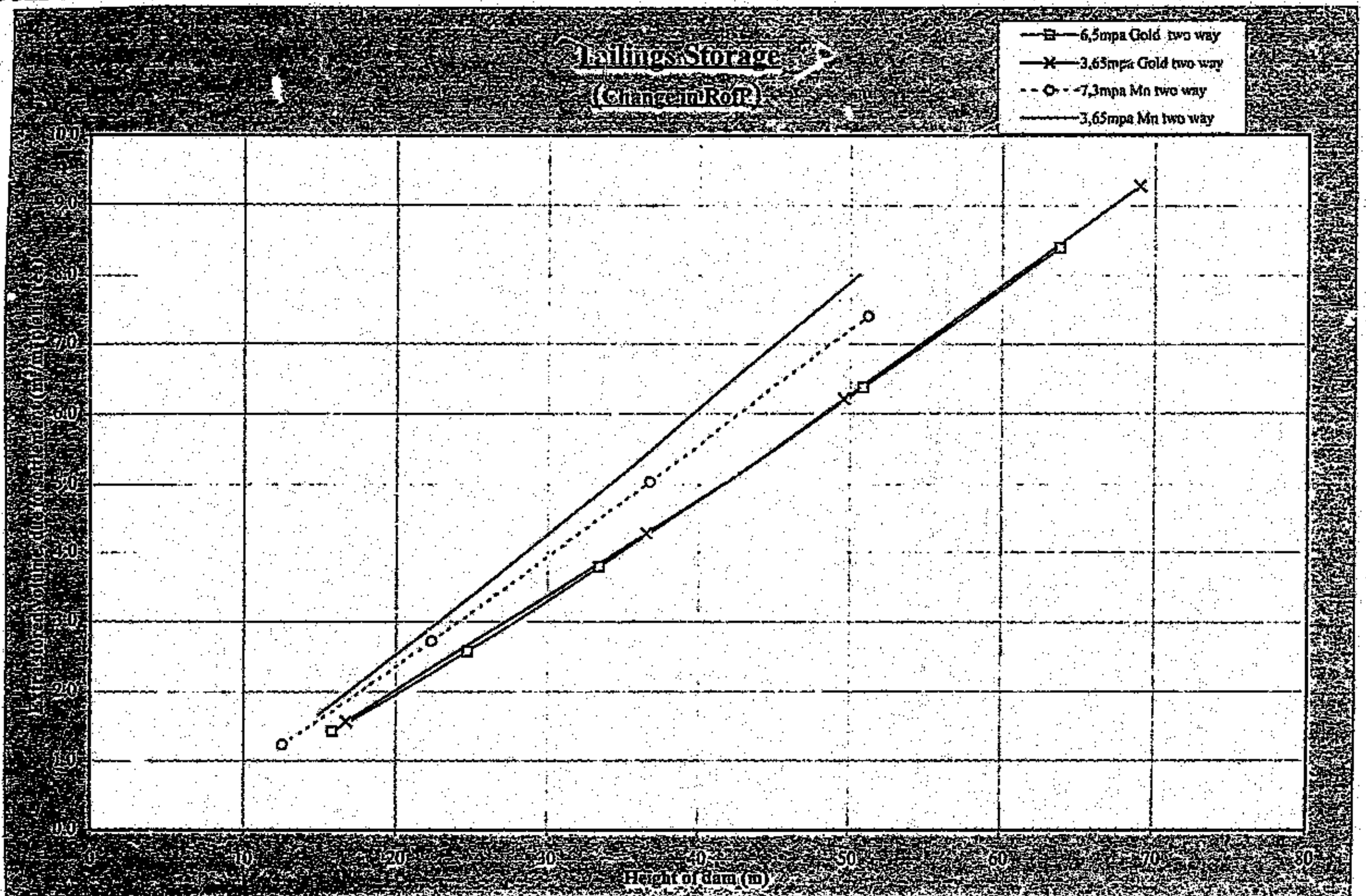


FIGURE 7.11: EXTRA STORAGE CAPACITY DUE TO CONSOLIDATION SETTLEMENT, FOR MANGANESE AND HARD ROCK GOLD TAILINGS, AT DIFFERENT RATES OF PLACEMENT



7.3 Stability Analysis Results

The results of the stability analyses have been summarised in the discussion below. Based on the assumptions of **Section 6.4**, the following trends have been observed:

Two-way drainage: These slopes did not show any dominant trend with circular failure planes, where the stability of the slope could be related to the level of pore pressures in the body of the dam. Allowing the program to search for the lowest factor of safety, resulted in failure surfaces outside the pore pressure zone, which indicates that the pore pressures predicted are too low to significantly affect the overall stability of the dam, or that the failure surface analysed is not representative of the worst situation. This was tested by analysing circular failure surfaces extending deep into the pore pressure zone of the dam. With this analysis, the factor of safety of the dam remained above 2, for the tailings such as coal and coarse gold.

The gold tailings (coarse) was then analysed using a dual wedge failure mode, for a rate of deposition varying from 3,9mpa to 6,54mpa, with the height of the dam changing from 30,5m to 63m. The variation of the factor of safety, varied from 1,113 to 1,096. The peak pore pressure over the range of scenarios varied from 22 kPa to 120 kPa; i.e. a change of peak pore pressure by a factor of nearly six, results in a 1,5% change in the factor of safety of the same failure surface. The failure surface analysed was specified as follows:

- The drain for the position of the zero pressure line is 30m from the toe.
- The junction point of the dual wedge failure line is 10m above the toe of the dam, and below the crest of the slope.
- The failure line exits at the base of the toe.

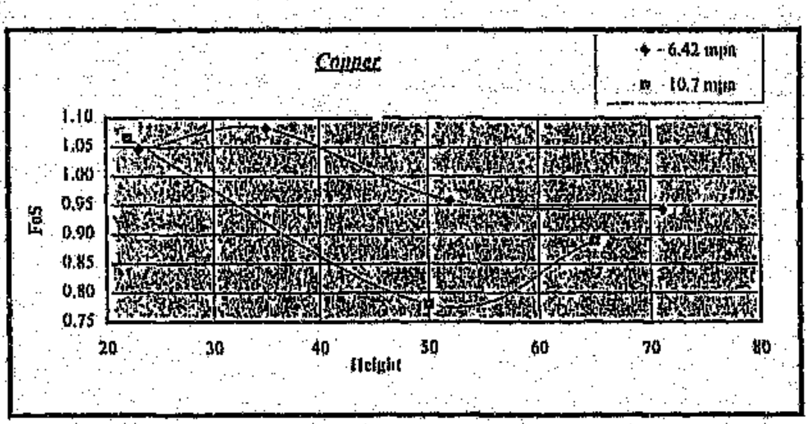
With a modification of the above specification where the junction point is at the peak pore pressure level in the dam, the factor of safety drops for a high dam of 63m from 1,096 to 0,961. For this scenario the variation in the factor of safety is 13,7%. The factor of safety for the low dam remains the same. Taking this variation further, the higher up in the dam elevation that the junction point is specified the lower the factor of safety. This trends indicates a sloughing failure, which can be expected. This is due to the fact that the shear strength ϕ for the tailings has been set at 33°, and the angle of the slope is 33,7°. No cohesion was included, which is true for wet gold tailings.

It can therefore be deduced that factors other than pore pressure control the overall factor of safety for these dams under the scenarios analysed. As an example, for the 30m high dam built at 3,9mpa, if the drainage point is changed from 30m from the toe, to 10m from the toe, the factor of safety drops from 1,113 to 0,791. This is in line with experience, where the most sensitive effect on slope stability is a change in the conditions near the toe of the slope.

The above also indicates that any failure will probably tend towards a linear wedge type failure, the junction point being controlled by the extent of partial saturation (resulting in pseudo cohesion) in the outer zone of the dam.

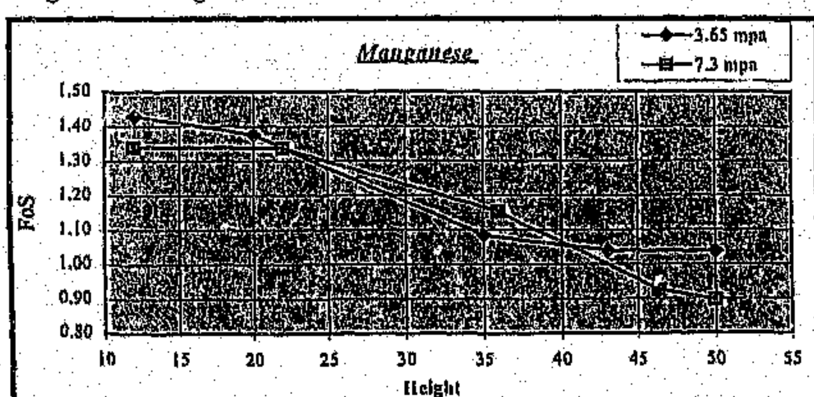
The above effect is different for the slower draining tailings, under two-way drainage. This is primarily due to the much higher peak pore pressure that is developed in the dam. The two tailings that were investigated are copper and manganese. Neither of the two tailings show a definite trend, using a circular failure surface analysis. This is shown in **Figure 7.12** below, which summarises the results of a number of stability analyses, using a circular failure surface, for two rates of placing.

Figure 7.12: Factor of Safety vs. height for circular failures for Copper Tailings



The trend is less scattered for manganese tailings, which is represented in **Figure 7.13** below.

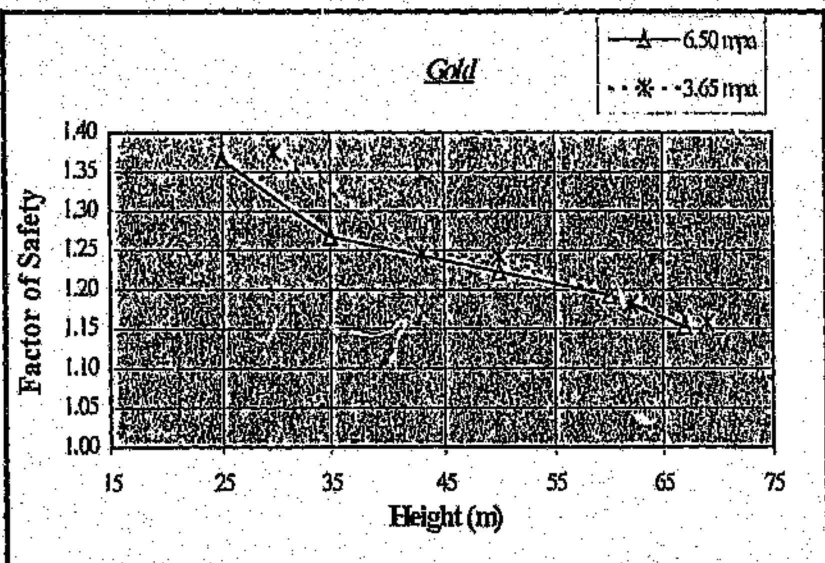
Figure 7.13: Factor of Safety vs. height for circular failures for Manganese Tailings



It can be seen that the general downward trend of the factor of safety with increase in height of the dam, is as expected. The difference, however, between the curves for the two rates of placement of manganese tailings is very small. The peak pore pressure of the dam at 50m height for the two rates of placement is 570 kPa and 620 kPa respectively. For a dam at 20m height the two peak pore pressures are 110kPa and 175kPa respectively. The difference in pore pressures for the two placement rates results in a small difference in factor of safety for the two scenarios.

The scatter of the graphs also tends to indicate that factors other than the pore pressure are dominating the factor of safety of the slope. The relative position of the drain with respect to the height of the dam tends to have a dominant influence on the overall stability of the dam. This however is a study all on its own, and outside the scope of this investigation.

Figure 7.14: Factor of Safety vs. height of Gold Tailings Dams with no base drainage.



One way drainage: The results of the analysis of the one way drainage case shows a more clear trend that reflects the influence of the peak pore pressure in the dam. This is predominantly due to higher pore pressures being developed near the bottom section of the dam. The failure surface is limited to a dual wedge failure through a pre-determined zone in the dam. For this analysis three tailings have been selected for the analysis, namely copper, manganese and gold (coarse). The factor of safety reduces with respect to the height of the dam but there is a difference in the trend with respect to the different rates of placement. **Figure 7.14** shows the difference for the gold tailings, which is not as dominant as the difference shown in **Figures 7.15** for copper tailings and **Figure 7.16** and manganese tailings. The higher the rate of placement, the greater the reduction in the factor of safety of the slope with respect to the height.

The difference in the factor of safety for the copper tailings dam increases as the dam height increases. At approximately 50m height, the difference in the factor of safety at a rate of placing of 3,65mpa compared to 9,4mpa is a 22% reduction, whereas at a height of 25m the difference is only 8%. The peak pore pressure for the 50m high dam changes from 270kPa at 3,65mpa to a peak pore pressure of 590kPa at 9,4mpa, i.e. more than double.

At a dam height of around 25m, a difference in the factor of safety exists only between the low rate of deposition of 3,65mpa, and 6,42mpa. There is no difference between the factor of safety for a dam built at 6,42mpa and 9,4mpa. Again, this appears to be as a result of the drainage position controlling the stability of the dam. Once the pore pressure is above a certain value, the change in shear resistance of the tailings due to pore pressure is negligibly small, and no longer contributes significantly to any variation in the factor of safety of the slope. This occurs when the tailings is effectively a heavy liquid, with little shear strength.

The trend is also established for manganese tailings, where two rates of deposition are analysed at different slope heights. The differentiated downward trend of the factor of safety as the dam height increased also exists, with a reduction of 9,7% at a slope height of 25m, placed at 3,65mpa compared to 1.825mpa. This is compared to an increased peak pore pressure from 280kPa to 380kPa.

At a slope height of 30m, the reduction in factor of safety is 11,5%, compared with an increase of peak pore pressure from 400kPa to 460kPa, for the same change in rate of placement referred to above.

Hence, it can be seen that a small difference in the peak pore pressure does not imply a small change in the factor of safety of the slope. Every situation will have to be analysed for the conditions in the field. No quantitative relationship appears to exist between the factor of safety and the peak pore pressure of a slope, given a pore pressure profile over the dam height.

FIGURE 7.15: FACOR OF SAFERY OF COPPER TAILINGS SLOPES AT DIFFERENT RATES OF PLACEMENT

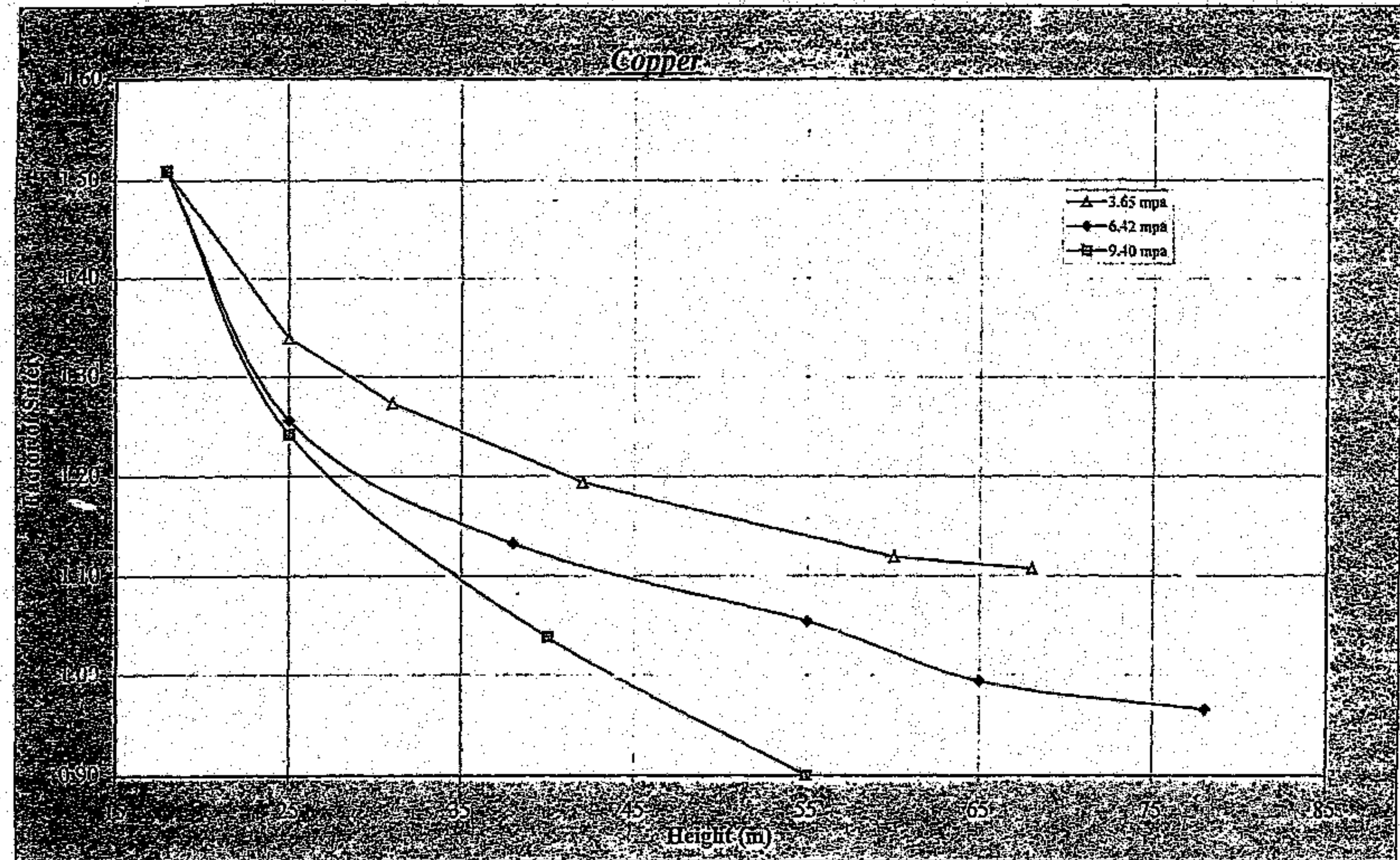
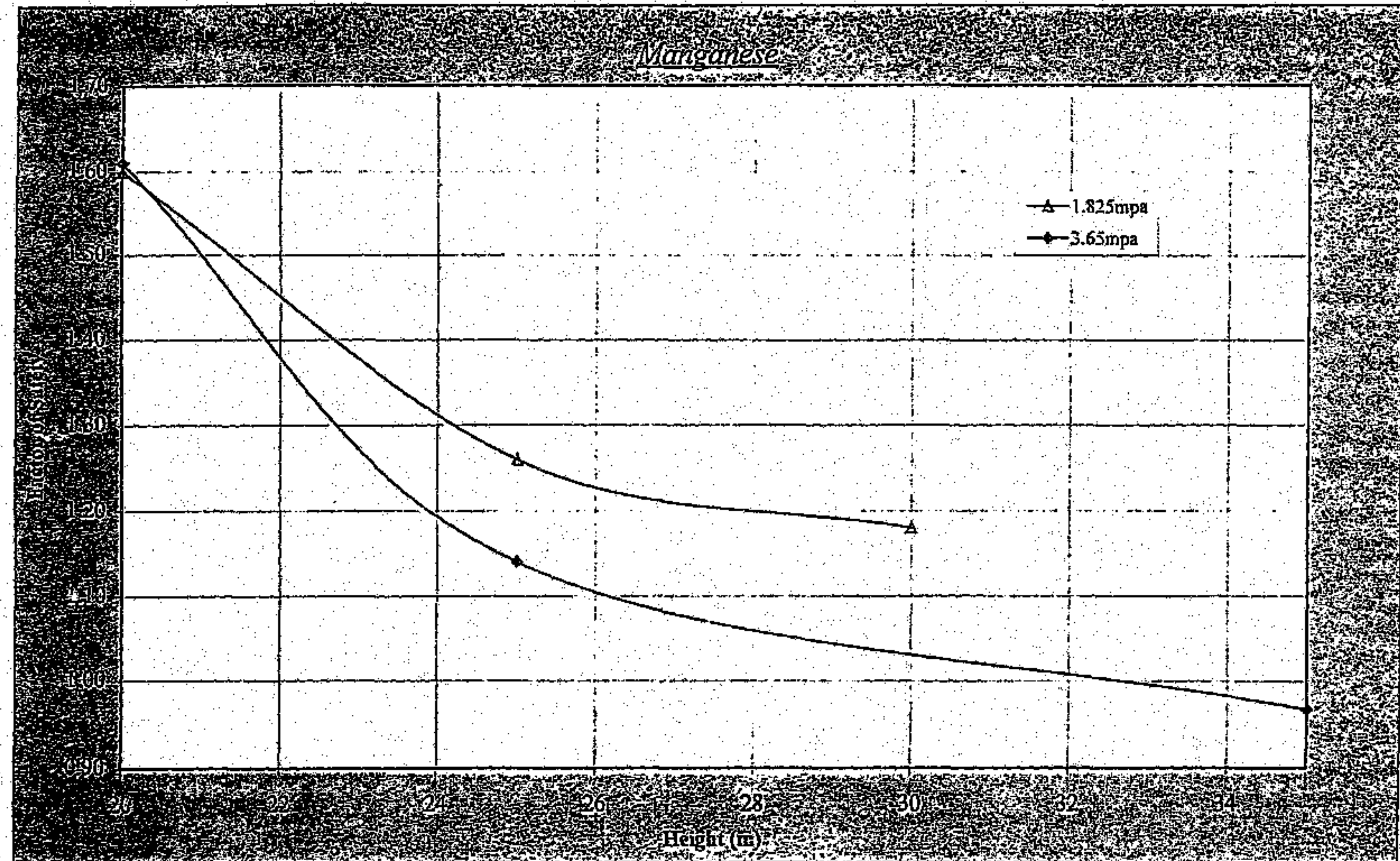


FIGURE 7.16: FACOR OF SAFERY OF MANGANESE TAILINGS SLOPES AT DIFFERENT RATES OF PLACEMENT



CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions

The following conclusions can be made from this study:

1. Tailings are similar to soils, where each tailings has its own unique characteristics of drainage and compressibility. This is strongly influenced by the void ratio, and by implication the moisture content, at which the tailings is placed.

2. Tailings placed at high void ratios have strongly non-linear relationships of permeability and compressibility with respect to the effective stress, which represents the consolidation process. Failure to recognise this can result in substantial differences between the predicted and field performance of a tailings dam.

3. The analysis of the consolidation process must take the changing boundary conditions into account, particularly in the case of tailings placed at high void ratios.

4. Application of Terzaghi's[24] theory of consolidation is not suitable for tailings dams, as most of the assumptions of his theory are violated during the consolidation process of tailings.

5. The non-linear finite strain theory can be applied to tailings dams, by including changing load conditions and moving boundary conditions, with respect to time.

6. The empirical values for maximum acceptable rate of rise for tailings dams should be abolished, as they are only applicable to certain tailings under certain conditions, and can result in unnecessary expenditure of capital costs for other tailings.

7. For tailings dams where two way drainage exists, the overall stability of the dam slope is probably not controlled by the rate of placement of the tailings. Fine, slow draining tailings at high rates of placement can lead to high peak pore pressures, which could contribute to initiating sloughing failures. This however needs to be addressed with further work, to evaluate two-dimensional effects near the outer slope of the dam.

8. For dams with no drainage at the base, overall slope instability does occur at high rates of placement of tailings. The stability is strongly influenced by the location of the toe drain, which is in line with accepted knowledge in the industry. The higher the rate of placement, the greater the rate of reduction in the factor of safety of the slope.

9. Large changes in peak pore pressure do not necessarily result in the same percentage change in factor of safety.

10. The position of peak pore pressure varies significantly between different tailings, varying from near the base of the deposit, to a point above the halfway level for two-way draining dams. For one way drainage, the peak is generally at the bottom, but conditions exist where the peak extends upwards into the dam up to the one-third height level.

11. There is a significant difference between the case of no base drainage and the case with drainage at the base of the dam. Hence, field conditions must be assessed critically, to ensure that the correct situation is modelled.

12. Modelling tailings dams using non-linear finite strain theory can lead to savings in the capital expenditure of the pre-deposition works, due to the more accurate prediction of the storage capacity of the facility.

    There are a number of additional benefits from this analysis. A possible higher acceptable rate of rise results in less land being required to accommodate a fixed deposition rate of the tailings. Being able to more accurately predict the pore pressure in the tailings allows the stability of the slope to be predicted with a higher level of confidence, and hence can be included in the risk assessment of a tailings dam.

    Predicting the true height of the dam also results in savings in the capital expenditure of slurry pumps, as smaller pumps can be used due to the lower static head to the top of the dam.

13. The water balance of a tailings dam can be predicted more accurately, using the non-linear finite strain theory of consolidation.

8.2 Recommendations for Further Work

The following recommendations are made for possible further studies, to expand on the work done to date, and to allow the industry to further benefit from the knowledge presented in this report.

The program that has been written for this study has been written in a form that allows it to be expanded to analyse complex problems. The following improvements can be considered:

- Inclusion of two-dimensional effects into the consolidation process, to model the edge effect of tailing dam slopes.

- Include the effect of evaporation from the surface of the tailings, and a variable rate of removing supernatant.

- Include the effect of sedimentation into the tailings relationships. This can be done by adding a second set of relationships for the tailings into the program

- Model the anisotropy of tailings.

The program has been written to allow modelling of a new dam placed on old tailings. This can be adapted to allow the modelling of two different types of tailings on the same dam.

APPENDIX A

Laboratory Test Results & Curve Fitting:

Gold - fine (Boddington Mine)
Gold - coarse (Crown Mine)
Bauxite Residue
Coal Slurry
Manganese Waste
AMD sludge

LABORATORY DATA INPUT

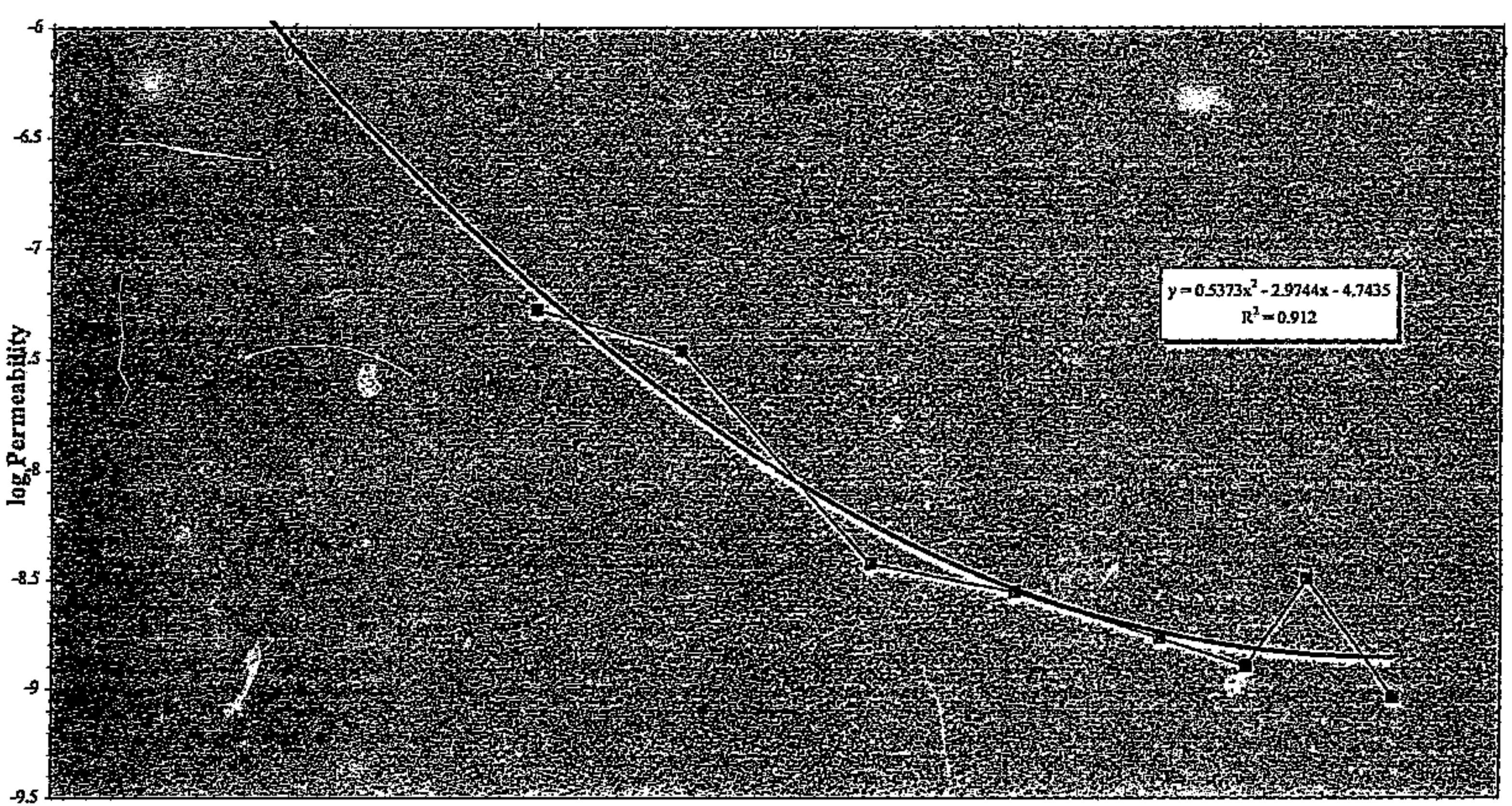
BODDINGTON GOLD MINE - WESTERN AUSTRALIA

Specific Gravity (SG)=	2.65						
surface void ratio=	2.35	@ 0kPa				calculated density=	[illegible]1492
void ratio =	1	@depth	22	m		calculated density=	[illegible]1825

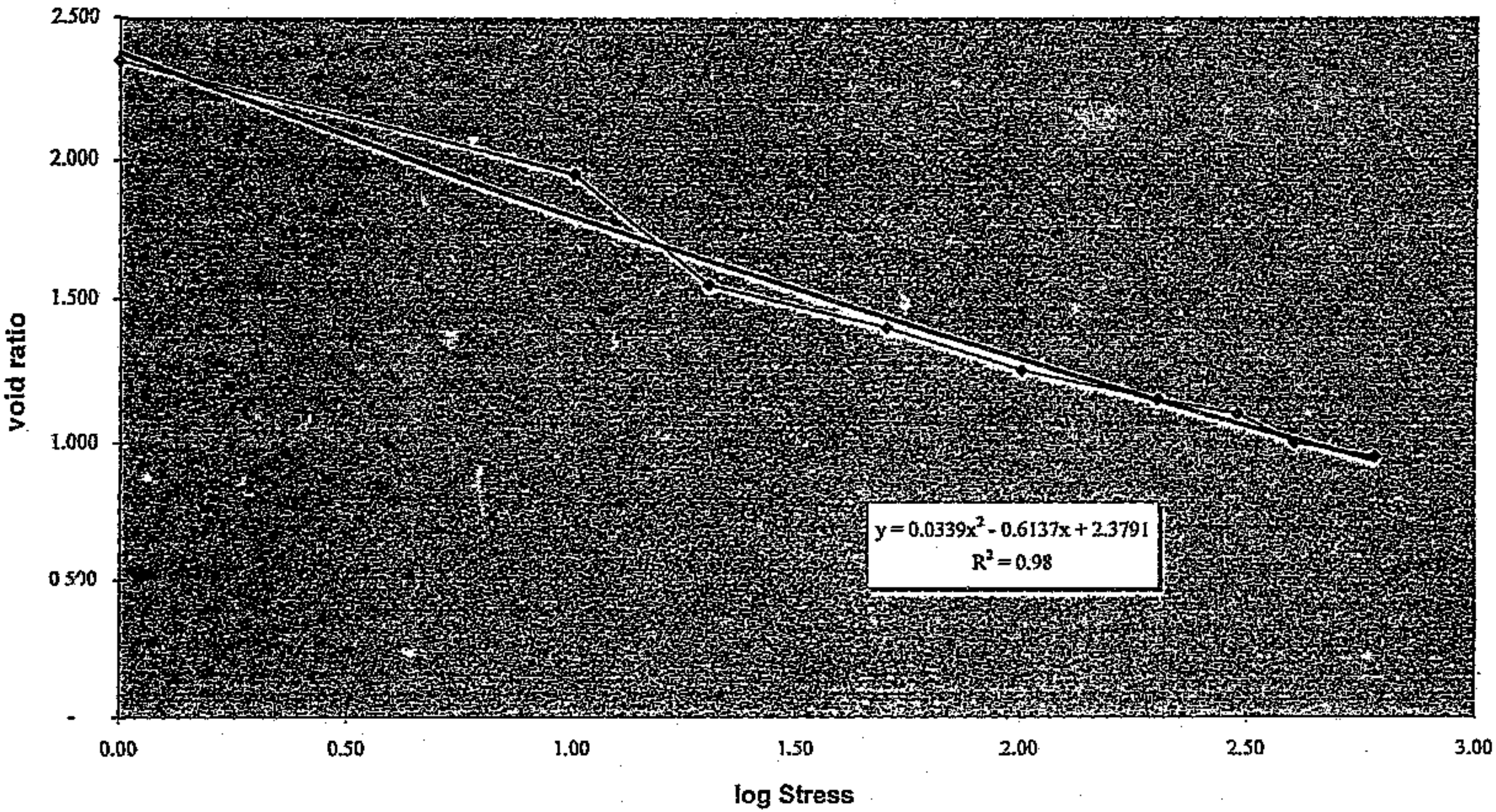
INPUT | ***CALCULATED***

stress *kPa*	*void ratio*	*Cv* m^2/yr	log stress	Permeability	log Permeability		
5	2.350	7				-	2.350
10	1.950	7	1.0000	5.301E-08	-7.2757	1.0000	1.950
20	1.550	8	1.3010	3.440E-08	-7.4635	1.3010	1.550
50	1.400	6	1.6990	3.751E-09	-8.4282	1.6990	1.400
100	1.250	7	2.0000	2.775E-09	-8.5568	2.0000	1.250
200	1.150	12	2.3010	1.691E-09	-8.7718	2.3010	1.150
300	1.100	17	2.4771	1.254E-09	-8.9018	2.4771	1.100
400	1.000	21	2.6021	2.171E-09	-8.4988	2.6021	1.000
600	0.950	23	2.7782	9.117E-10	-9.0402	2.7782	0.950

Permeability plot



Stress plot



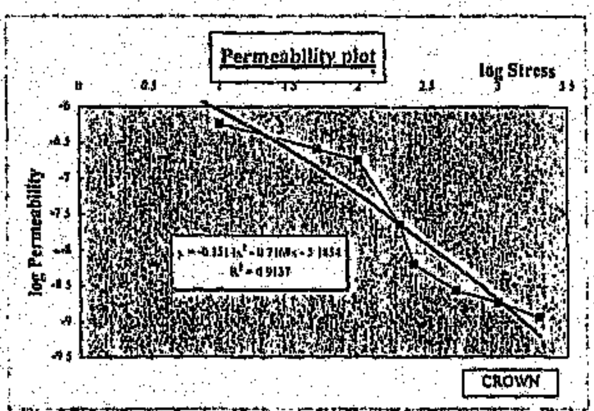
Bod

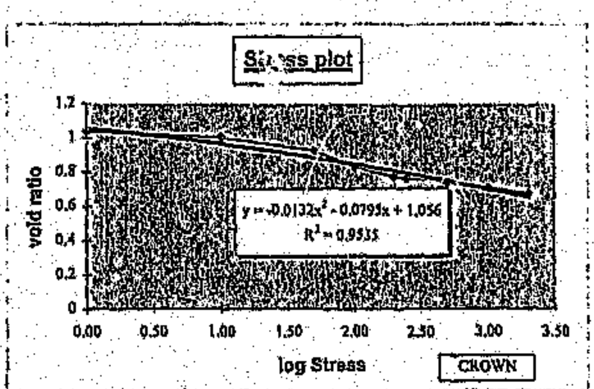
LABORATORY DATA INPUT

CONSOLIDATED CROWN SLIME

Specific Gravity (SG)=	2.65				
surface void ratio=	1.037	@ 0kPa		calculated density=	18.10
void ratio =	0.827	@depth	6 m	calculated density=	19.03

INPUT			***CALCULATED***				
stress kPa	*void ratio*	*Cv* m^2/yr	log stress	Permeability	log Permeability		
1	1.037	1200				-	1.037
10	1.000	900	1.0000	5.760E-07	-6.2396	1.0000	1.000
50	0.923	847	1.6990	2.585E-07	-6.5875	1.6990	0.923
100	0.827	566	2.0000	1.792E-07	-6.7467	2.0000	0.827
200	0.769	224	2.3010	2.255E-08	-7.6469	2.3010	0.769
250	0.759	180	2.3979	6.453E-09	-8.1902	2.3979	0.759
500	0.738	180	2.6990	2.726E-09	-8.5645	2.6990	0.738
1000	0.709	175	3.0000	1.852E-09	-8.7324	3.0000	0.709
2000	0.672	164	3.3010	1.126E-09	-8.9485	3.3010	0.672





Permeability constants:

log (permeability)=e*(log stress)^2+f*(log stress)+h

e=	-0.15140
f=	-0.71690
h=	-5.18540

Void ratio constants:

Void Ratio=b*(log stress)^2+c*(log stress)+d

b=	-0.01320
c=	-0.07950
d=	1.05600

RELATIONSHIP BETWEEN STRESS AND SOIL PROPERTIES FOR INITIAL LAYER

Bauxite Residue
Western Australia

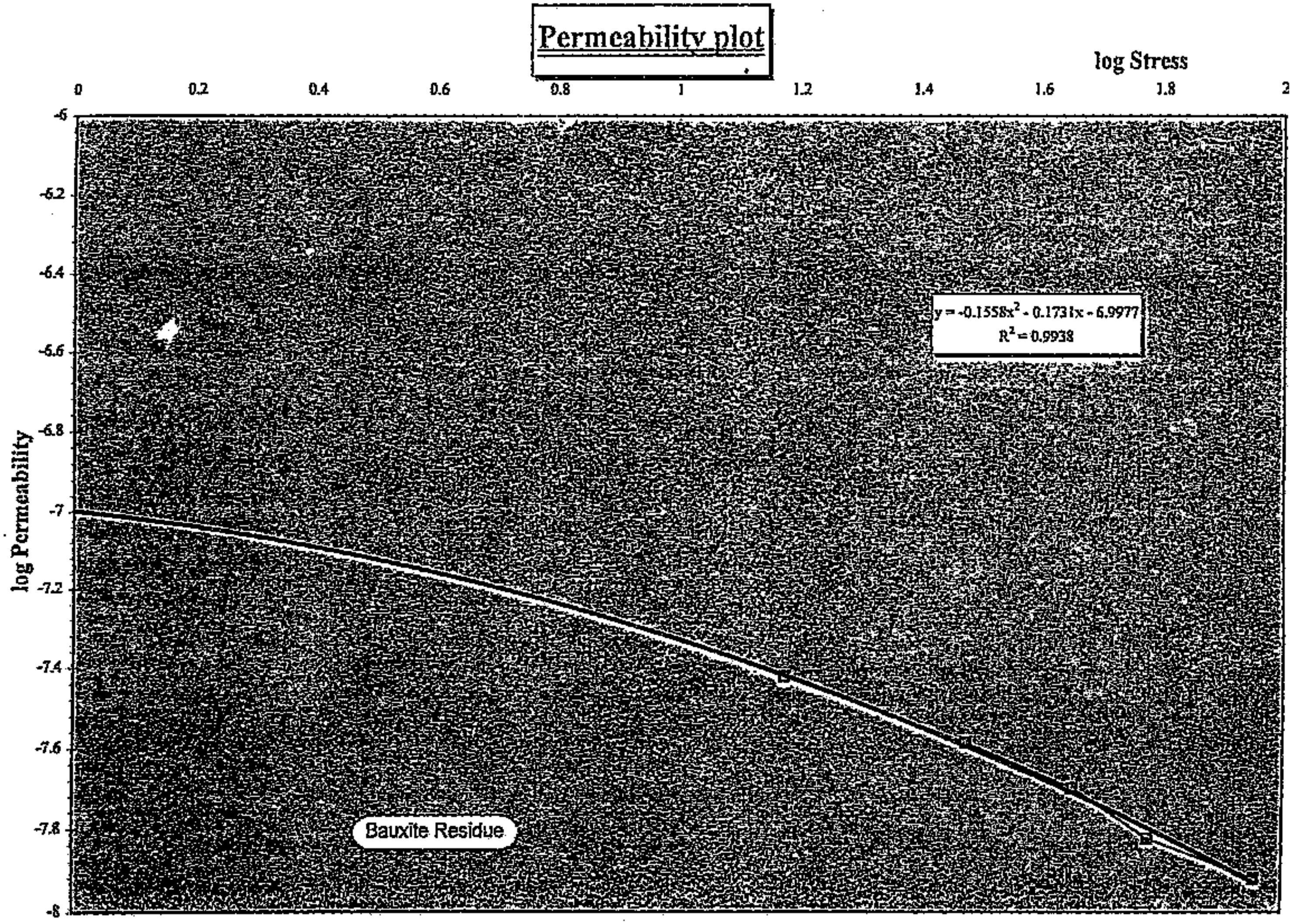
S.G.= 3.15

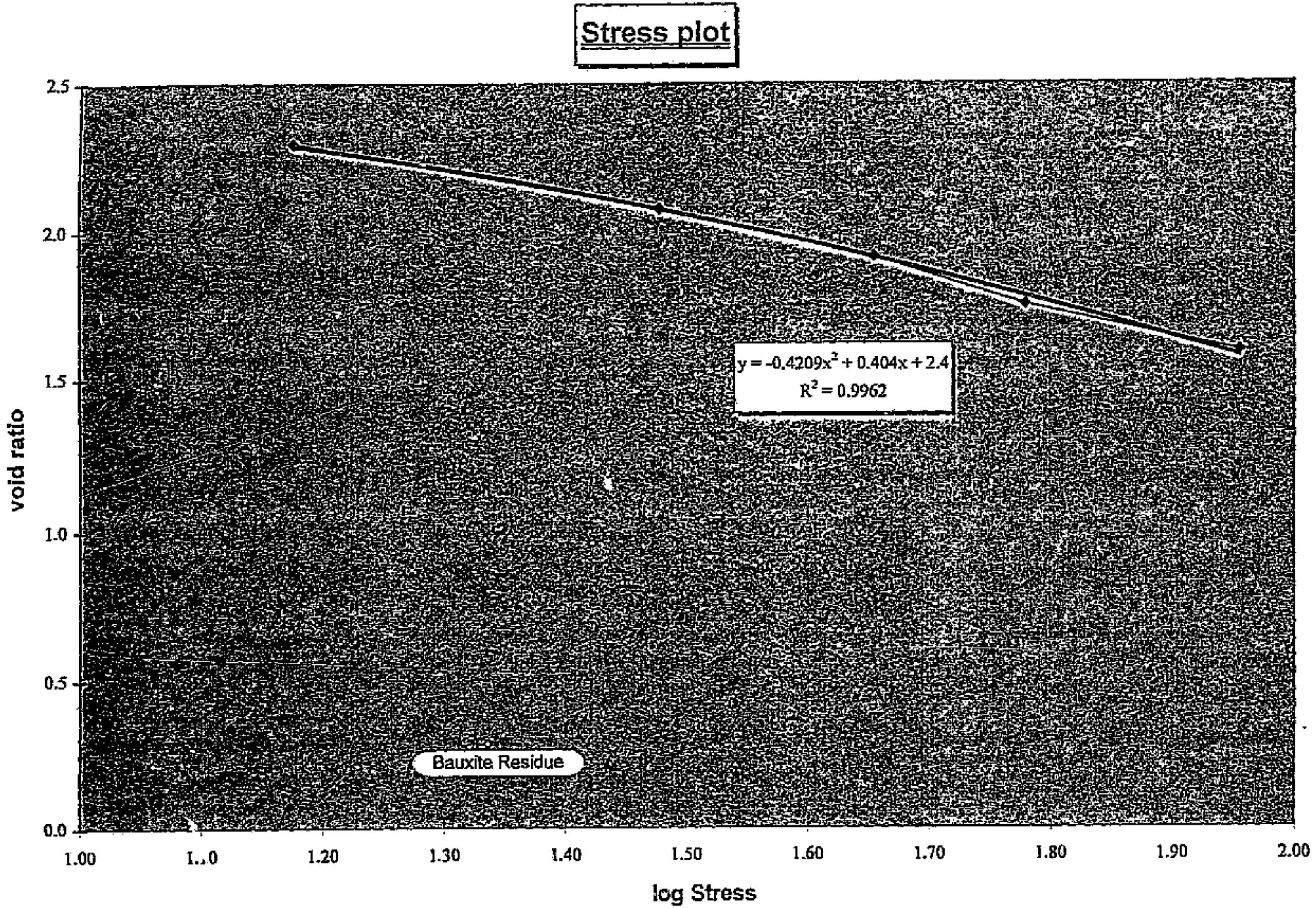
DEPTH	soil effective stress	e	permeability	g(e)
m	kN/m²		log (m/s)	m²/day
-	0	2.3400	-6.9977	0.0643112
0.150	2.47	2.3300	-7.0895	0.0520613
0.300	4.93	2.3200	-7.1925	0.0411938
0.450	7.40	2.3100	-7.2658	0.0348986
0.600	9.86	2.3000	-7.3237	0.0306359
0.750	12.33	2.2900	-7.3719	0.0274976
0.900	14.79	2.2800	-7.4135	0.0250622
1.050	17.26	2.2700	-7.4502	0.0231020
1.200	19.72	2.2600	-7.4831	0.0214815
1.350	22.19	2.2500	-7.5131	0.0201138
1.500	24.66	2.2400	-7.5405	0.0189406
1.650	27.12	2.2300	-7.5659	0.0179205
1.800	29.59	2.2200	-7.5895	0.0170238
1.950	32.05	2.2100	-7.6117	0.0162281
2.100	34.52	2.2000	-7.6325	0.0155163
2.250	36.98	2.1900	-7.6522	0.0148751
2.400	39.45	2.1800	-7.6708	0.0142940
2.550	41.91	2.1700	-7.6886	0.0137646
2.700	44.38	2.1600	-7.7056	0.0132799
2.850	46.85	2.1500	-7.7218	0.0128342
3.000	49.31	2.1400	-7.7373	0.0124228

Assumes linear void ratio relationship!

Void ratio at surface	2.34
Void ratio at base	2.30
Depth	0.60

Permeability relationship is same as Sheet 3 !


Permeability plot
log Stress
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
log Permeability
-6
-6.2
-6.4
-6.6
-6.8
-7
-7.2
-7.4
-7.6
-7.8
-8
y = -0.1558x² - 0.1731x - 6.9977
R² = 0.9938
Bauxite Residue


Stress plot
y = -0.4209x² + 0.404x + 2.4
R² = 0.9962
Bauxite Residue
void ratio
log Stress
2.5
2.0
1.5
1.0
0.5
0.0
1.00
1.20
1.30
1.40
1.50
1.60
1.70
1.80
1.90
2.00

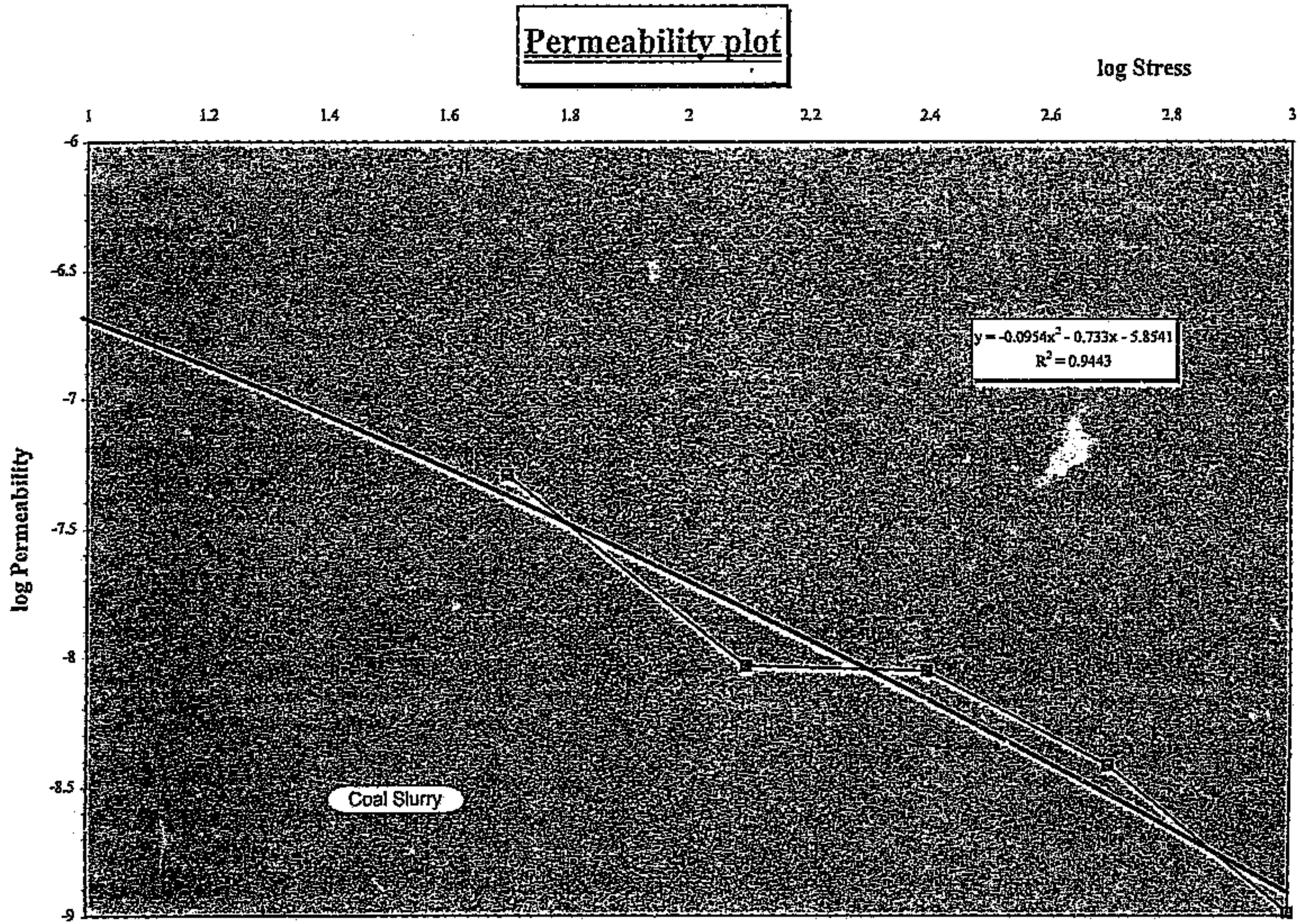
LABORATORY DATA INPUT

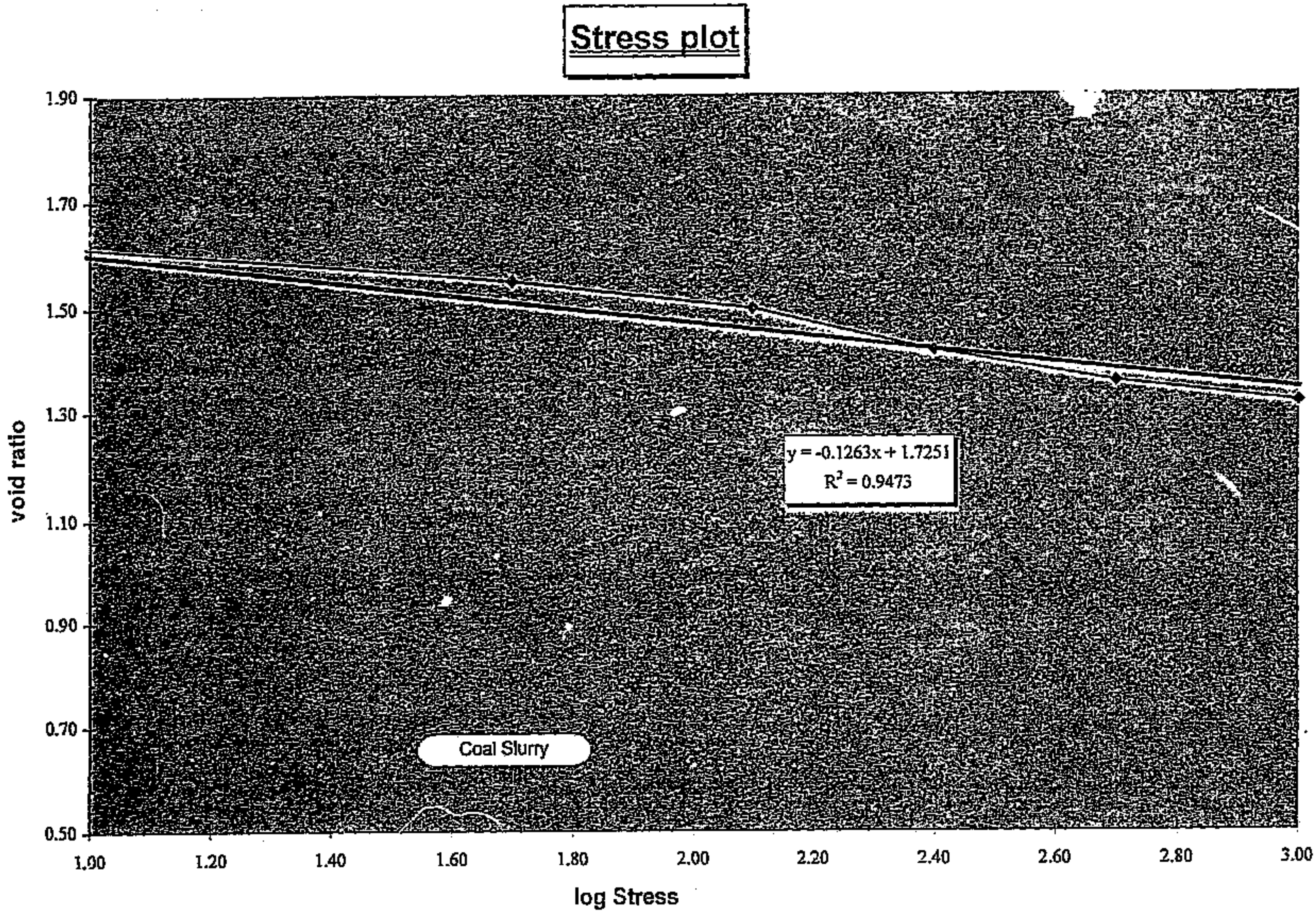
Coal Slurry
Witbank

Specific Gravity (SG)= 2.17
surface void ratio= 1.699
void ratio at base of initial layer, and
thickness of initial layer = 1.67 thickness= 0.60 m

calculated density= [illegible]

INPUT			*CALCULATED*				
stress *kPa*	*void ratio*	*Cv* m^2/yr	*log Stress*	*Permeability* m/s	*log Permeability*		
0	1.699	140				-	1.699
50	1.550	136	1.6990	5.040E-08	-7.2976	1.6990	1.550
125	1.500	110	2.0969	9.302E-09	-8.0[illegible]4	2.0969	1.500
250	1.420	106	2.3979	8.889E-09	-8.0511	2.3979	1.420
500	1.360	[illegible]	2.6990	3.837E-09	-8.4160	2.6990	1.360
1000	1.320	94	3.0000	1.028E-09	-8.9881	3.0000	1.320
2000	1.30[illegible]	60					


Permeability plot
log Stress
1
1.2
1.4
1.6
1.8
2
2.2
2.4
2.6
2.8
3
-6
-6.5
-7
-7.5
-8
-8.5
-9
log Permeability
y = -0.0954x² - 0.733x - 5.8541
R² = 0.9443
Coal Slurry


Stress plot
void ratio
1.90
1.70
1.50
1.30
1.10
0.90
0.70
0.50
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
2.60
2.80
3.00
log Stress
y = -0.1263x + 1.7251
R2 = 0.9473
Coal Slurry

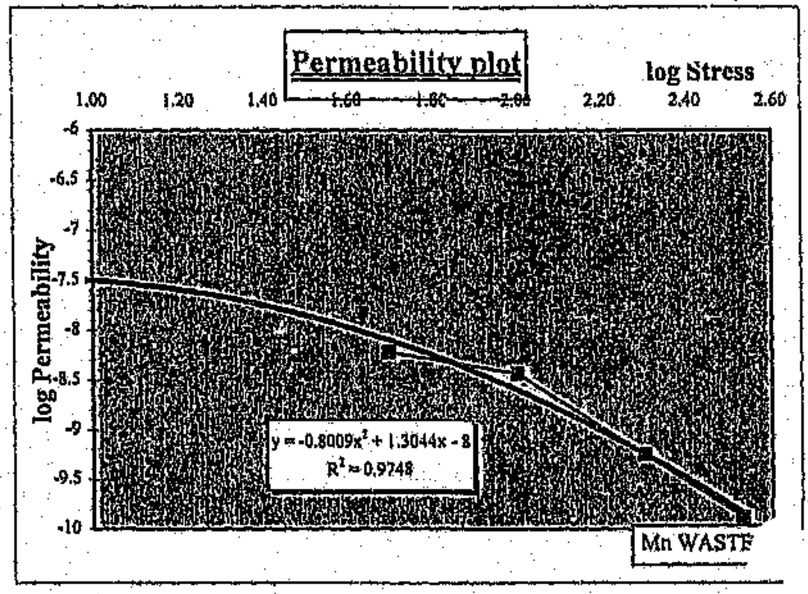
LABORATORY DATA INPUT

PAPPAS QUARRY

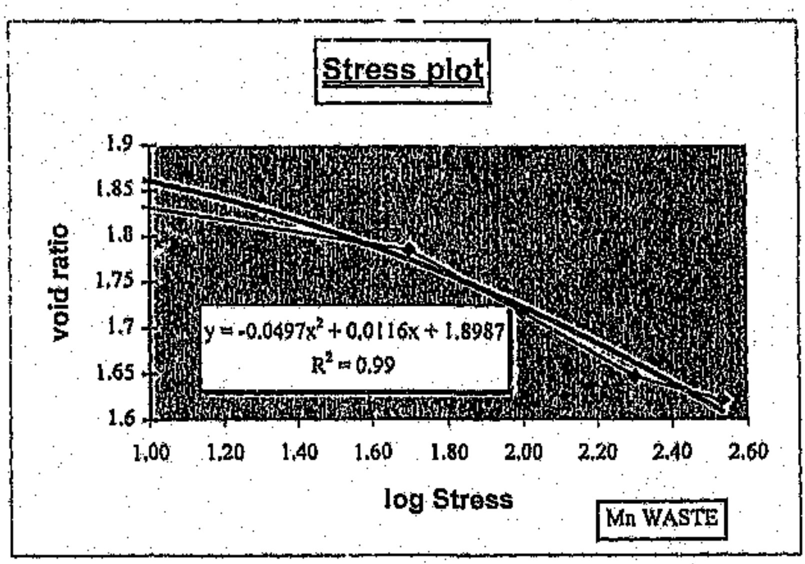
Specific Gravity (SG)=	3.65				calculated density=	[redacted]
surface void ratio=	1.898	@ 0kPa			calculated density=	[redacted]
void ratio =	1.621	@depth	17.6	m		

INPUT [redacted] ***CALCULATED***

stress *kPa*	*void ratio*	*Cv* *m²/yr*	[redacted]		
1	1.898	50	[redacted]	-	1.898
50	1.785	24	[redacted]	1.6990	1.785
100	1.717	24	[redacted]	2.0000	1.717
200	1.647	7	[redacted]	2.3010	1.647
340	1.621	6	[redacted]	2.5315	1.621



Permeability plot
log Stress
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
2.60
-6
-6.5
-7
-7.5
-8
-8.5
-9
-9.5
-10
log Permeability
y = -0.8009x² + 1.3044x - 8
R² = 0.9748
Mn WASTE



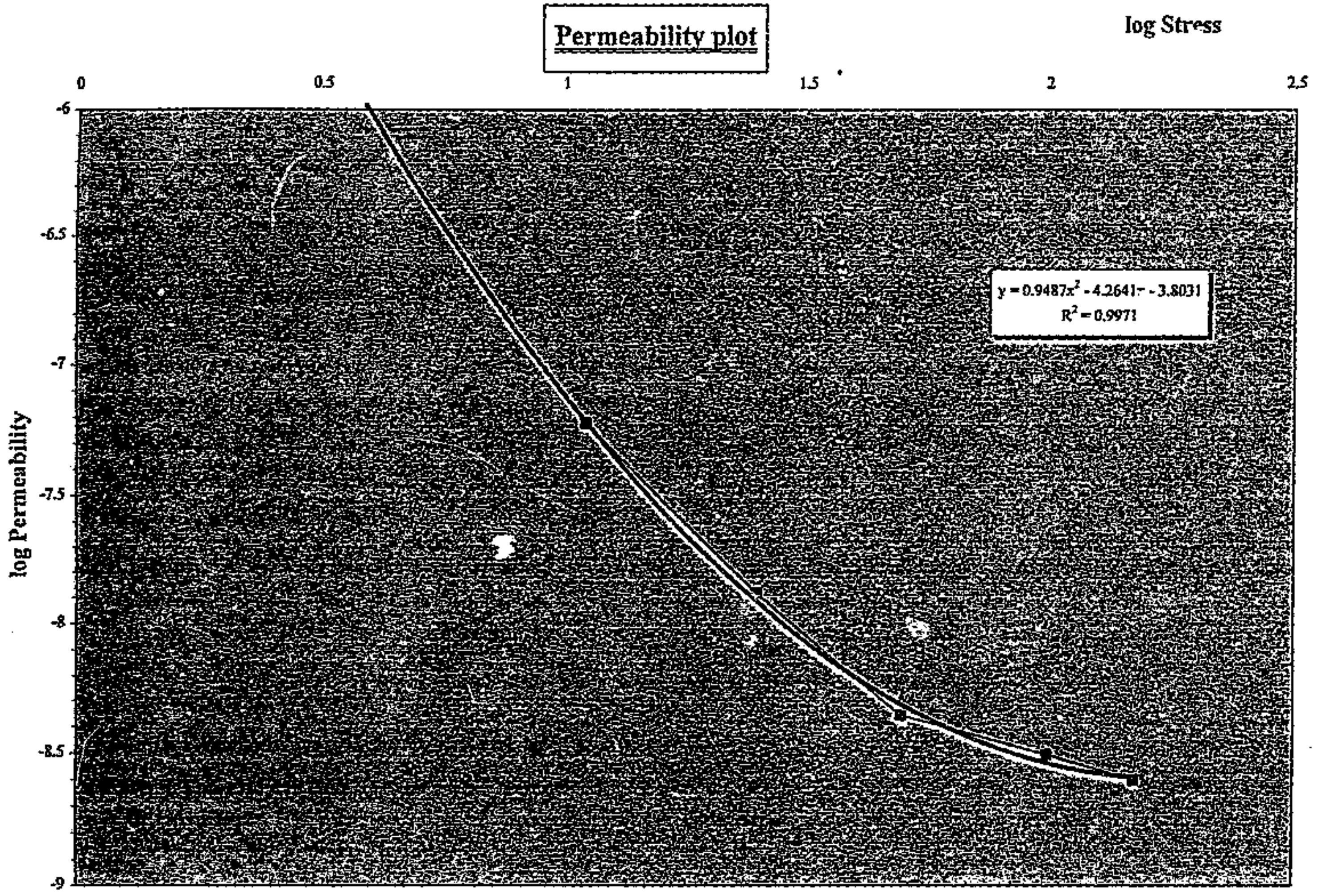
Stress plot
1.9
1.85
1.8
1.75
1.7
1.65
1.6
void ratio
y = -0.0497x² + 0.0116x + 1.8987
R² = 0.99
1.00
1.20
1.40
1.60
1.80
2.00
2.20
2.40
2.60
log Stress
Mn WASTE

LABORATORY DATA INPUT

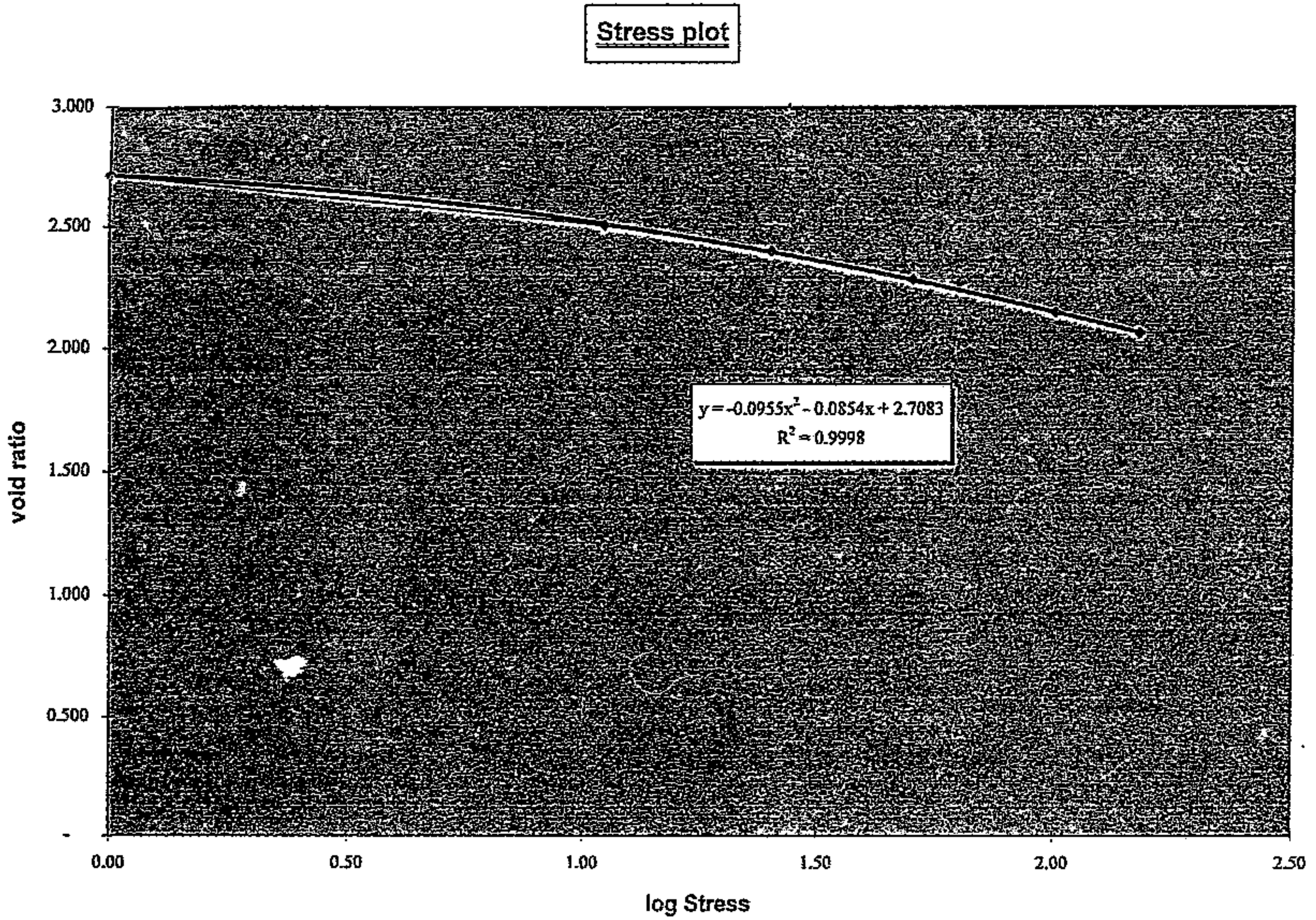
AMD sludge

Specific Gravity (SG)=	2.76					
surface void ratio=	2.709	@ 0kPa			calculated density=	[illegible]
void ratio =	2.155	@depth=	6.84	m	calculated density=	[illegible]

INPUT			*CALCULATED*				
stress	*void ratio*	*Cv*	*log stress*	*permeability*	*log permeability*		
kPa		*m²/yr*		[illegible]			
0	2.709					-	2.709
11	2.511	39	1.0414	[illegible]	[illegible]	1.0414	2.511
25	2.406	19.4	1.3979	[illegible]	[illegible]	1.3979	2.406
50	2.290	10.3	1.6990	[illegible]	[illegible]	1.6990	2.290
100	2.155	12	2.0000	[illegible]	[illegible]	2.0000	2.155
150	2.069	14.5	2.1761	[illegible]	[illegible]	2.1761	2.069
999							
1999							



Permeability plot
log Stress
0
0.5
1
1.5
2
2.5
-6
-6.5
-7
-7.5
-8
-8.5
-9
log Permeability
y = 0.9487x² - 4.2641x - 3.8031
R² = 0.9971


Stress plot
3.000
2.500
2.000
1.500
1.000
0.500
void ratio
0.00
0.50
1.00
1.50
2.00
2.50
log Stress
y = -0.0955x² - 0.0854x + 2.7083
R² = 0.9998

APPENDIX B

Program Listing of:

"Module1 Cont.loading - 2 way" - which excludes supernatant removal

"With supernatant removal" - which includes supernatant removal

(both programs listings are 17 pages)

```
Option Base 1
Option Explicit

Public b As Single
Public c As Single
Public d As Single
Public e As Single
Public f As Single
Public h As Single
Sub settlement_continuous()
Dim increments As Integer
Dim first_increments As Integer
Dim load_timesteps As Integer
Dim pressure As Single
Dim i As Integer
Dim j As Integer
Dim k As Integer
Dim p As Integer
Dim n As Integer
Dim m As Single
Dim old_effect_stress(300) As Single
Dim old_void(300) As Single
Dim Ge(300) As Double
Dim old_T As Double
Dim new_T As Double
Dim new_effect_stress(300) As Single
Dim drainage_l_bot As Single
Dim drainage_l_top As Single
Dim new_void(300) As Single
Dim pwp_change_tot(300) As Single
Dim pwp_changed As Double
Dim pwp_change(290) As Double
Dim time_step As Integer
Dim time_loop As Integer
Dim settlement_of_layer As Single
Dim settlement_of_layer_ini As Single
Dim full_settlement As Single
Dim settlement(300) As Double
Dim last_time As Integer
Dim new_time As Integer
Dim applied_thickness As Single
Dim tot_applied_thickness As Single
Dim del_void As Single
Dim display As Integer
Dim load_step As Integer
Dim loads As Integer
Dim active_loads As Integer
Dim t_unit As Single
Dim display_test As Single
Dim d_added(300) As Single
Dim d_ini(125) As Single
Dim thickness As Single
Dim H_ini As Single
Dim top_l As Integer
Dim ini_layer_thickness As Single
Dim posn As Single
Dim pwp(300, 300) As Single
Dim pwp_sum(300) As Single
Dim old_pwp As Single
Dim new_pwp As Single
Dim paths As Integer
Dim peak_pressure_point As Integer
Dim layers As Integer
Dim start As Integer
Dim bot_peak As Integer
Dim top_peak As Integer
Dim d_time As Single
Dim incr As Single
Dim load_layers As Integer
Dim peak_pressure_point_1 As Integer
```

```
Dim peak_pressure_point_2 As Integer
Dim pwp_sum_peak As Single
Dim e_min As Single
Dim e_max As Single
Dim sg As Single
Dim depth As Single
'
'  Set initial soil density value
'
   e_min = Worksheets("sheet2").[e5].Value
   sg = Worksheets("sheet2").[c4].Value
   Worksheets("sheet2").[i5].Value = 10 * (sg + e_min) / (1 + e_min)
'
'  Get input data from speadsheet into program variables
'
load_step = Worksheets("sheet1_continuous").[d5].Value
loads = Worksheets("sheet1_continuous").[i4].Value
load_timesteps = loads * load_step
time_step = Worksheets("sheet1_continuous").[d6].Value
H_ini = Worksheets("sheet1_continuous").[d7].Value
applied_thickness = Worksheets("sheet1_continuous").[i5].Value
pressure = Worksheets("sheet1_continuous").[d4].Value
display = Worksheets("sheet1_continuous").[d3].Value
paths = Worksheets("sheet1_continuous").[h3].Value
drainage_1_top = H_ini / paths + applied_thickness / paths
first_increments = Worksheets("sheet1_continuous").[i6].Value

   If paths = 2 Then
      drainage_1_bot = drainage_1_top
   Else
      drainage_1_bot = 0
   End If

   b = Worksheets("sheet3").[l28].Value
   c = Worksheets("sheet3").[l29].Value
   d = Worksheets("sheet3").[l30].Value
   e = Worksheets("sheet3").[l7].Value
   f = Worksheets("sheet3").[l8].Value
   h = Worksheets("sheet3").[l9].Value
   ini_layer_thickness = 0
   settlement_of_layer_ini = 0
   settlement_of_layer = 0
   increments = first_increments + 1

Worksheets("Sheet1_continuous").Select
   Range("E8:Gh500").Select
   Selection.ClearContents
   Selection.Borders(xlLeft).LineStyle = xlNone
   Selection.Borders(xlRight).LineStyle = xlNone
   Selection.Borders(xlTop).LineStyle = xlNone
   Selection.Borders(xlBottom).LineStyle = xlNone
   Selection.BorderAround LineStyle:=xlNone
   Selection.Interior.ColorIndex = xlNone

'
'  set the initial soil parameters wrt depth
'

For i = 1 To first_increments
   n = (first_increments - i) + 1
   old_effect_stress(i) = Worksheets("sheet4").[c8].Cells(n, 1).Value
   old_void(i) = Worksheets("sheet4").[c8].Cells(n, 2).Value
   Ge(i) = Worksheets("sheet4").[f8].Cells(n, 1).Value
Next i

   new_effect_stress(increments) = Worksheets("sheet4").[c8].Value
   old_void(increments) = Worksheets("sheet4").[d8].Value
   new_void(increments) = old_void(increments)
   Ge(increments) = Worksheets("sheet4").[f8].Value
   d_added(increments) = applied_thickness
```

```
If paths = 2 Then
   peak_pressure_point = Fix(first_increments / paths)
Else
   peak_pressure_point = 1
End If

'
' determine pwp distribution for initial load on layers
'

For i = 1 To first_increments

   new_T = T(Ge(i), old_void(i), drainage_1_top, time_step)
   posn = i / (increments / paths)
   pwp(i, 1) = ui(pressure, posn, new_T)
   pwp_change(i) = pressure - pwp(i, 1)
   new_effect_stress(i) = old_effect_stress(i) + pwp_change(i)
   new_void(i) = void(new_effect_stress(i))

   If new_effect_stress(i) > 1 Then
      Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))
   Else
      Ge(i) = Ge(i)
   End If

   del_void = old_void(i) - new_void(i)
   settlement(i) = H_ini / first_increments * del_void * (1 - 1 / (1 + old_void(i)))
   d_ini(i) = H_ini / first_increments - settlement(i)
   ini_layer_thickness = ini_layer_thickness + d_ini(i)
   settlement_of_layer_ini = settlement_of_layer_ini + settlement(i)

Next i

   pwp(increments, 1) = 0
   drainage_1_top = drainage_1_top - settlement_of_layer_ini / paths

   If paths = 2 Then
      drainage_1_bot = drainage_1_top
   Else
      drainage_1_bot = 0
   End If

k = 2
load_layers = 1

For time_loop = (2 * time_step) To load_timesteps Step time_step

If remain(time_loop, load_step) = 0 Then

   drainage_1_top = drainage_1_top + applied_thickness
   increments = increments + 1
   old_effect_stress(increments) = Worksheets("sheet4").[c8].Value
   old_void(increments) = Worksheets("sheet4").[d8].Value
   Ge(increments) = Worksheets("sheet4").[f8].Value
   new_effect_stress(increments) = Worksheets("sheet4").[c8].Value
   new_void(increments) = old_void(increments)
   d_added(increments) = applied_thickness
   load_layers = increments - first_increments

      For i = 1 To increments - 1

         pwp(i, load_layers) = pressure

      Next i

   Else
End If

'
```

```
' ANALYSIS OF INITIAL LAYER THICKNESS
'
' Drainage of upper layers upwards
'
' If peak pressure point is in added layers, all drainage will be
' downwards, and this next section will be jumped over.
'
d_time = remain(time_loop, load_step) * load_step

If peak_pressure_point >= first_increments Then

  GoTo 100

  Else

For i = peak_pressure_point To first_increments

If old_void(i) <> new_void(i) Then

  Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))

Else

  Ge(i) = Ge(i)

End If

pwp_sum(i) = 0
pwp_change_tot(i) = 0

' position ratio of upward draining section of ini layers.
' relative to peak pressure point.
' Only applies if peak is in initial layers
'

posn = (increments - i) / (increments - peak_pressure_point)

'
' calculate the pwp for each increment, for each load application
'

For p = 1 To load_layers

     last_time = (load_layers - p) * load_step + d_time

       If last_time < 0 Then
       Exit For
       Else
       End If

     new_time = last_time + time_step
     old_T = T(Ge(i), new_void(i), drainage_1_top, last_time)
     new_T = T(Ge(i), new_void(i), drainage_1_top, new_time)

'    determine change in pwp between last time and this time, and subtract
'    from the last pwp, for each increment, for each load.
'
If new_T >= 1 And pwp(i, p) <> 0 Then

     pwp_changed = pwp(i, p)
     pwp(i, p) = 0

ElseIf new_T >= 1 And pwp(i, p) = 0 Then

     pwp_changed = 0
     pwp(i, p) = 0
Else
     old_pwp = ui(pressure, posn, old_T)
     new_pwp = ui(pressure, posn, new_T)
```

```
    pwp_changed = old_pwp - new_pwp

    If pwp_changed > pwp(i, p) Then

     pwp(i, p) = 0
     pwp_changed = pwp(i, p)

    ElseIf pwp_changed > 0 Then

     pwp(i, p) = pwp(i, p) - pwp_changed

    Else

     pwp(i, p) = pwp(i, p)
     pwp_changed = 0

    End If

End If

'
'   sum the pwp pressures at each increment, to determine the total
'   pressure of the increment
'
    pwp_sum(i) = pwp_sum(i) + pwp(i, p)

'
'   record total change in pressure as an input for the changed soil
'   parameters, due to changed pwp
'
    pwp_change_tot(i) = pwp_change_tot(i) + pwp_changed

Next p

'
' changed soil stresses and calc. of settlement of ini layers
'
If pwp_change_tot(i) > 0 Then

  old_effect_stress(i) = new_effect_stress(i)
  new_effect_stress(i) = new_effect_stress(i) + pwp_change_tot(i)
  old_void(i) = new_void(i)
  new_void(i) = void(new_effect_stress(i))
  del_void = old_void(i) - new_void(i)
  settlement(i) = del_void * d_ini(i) * (1 - 1 / (1 + old_void(i)))
  d_ini(i) = d_ini(i) - settlement(i)

Else

  settlement(i) = 0

End If

Next i

End If
'
' Analysis of bottom draining layers of ini layers
'
100 If peak_pressure_point >= first_increments Then

     layers = first_increments
     Else
     layers = peak_pressure_point
     End If

If paths = 2 Then

For j = 1 To layers
```

```
If old_void(i) <> new_void(i) Then

   Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))

Else

   Ge(i) = Ge(i)

End If

pwp_sum(i) = 0
pwp_change_tot(i) = 0

' position ratio in ini layers for bottom draining, relative to peak
' pressure point

posn = i / peak_pressure_point

'
' calculate the pwp for each increment, for each load applica.ion
'

For p = 1 To load_layers

     last_time = (load_layers - p) * load_step + d_time

       If last_time < 0 Then
       Exit For
       Else
       End If

     new_time = last_time + time_step
     old_T = T(Ge(i), new_void(i), drainage_1_bot, last_time)
     new_T = T(Ge(i), new_void(i), drainage_1_bot, new_time)

'
'    determine change in pwp between last time and this time, and subtract
'    from the last pwp, for each increment, for each load.
'
If new_T >= 1 And pwp(i, p) <> 0 Then

     pwp_changed = pwp(i, p)
     pwp(i, p) = 0

ElseIf new_T >= 1 And pwp(i, p) = 0 Then

     pwp_changed = 0
     pwp(i, p) = 0
Else
     old_pwp = ui(pressure, posn, old_T)
     new_pwp = ui(pressure, posn, new_T)

     pwp_changed = old_pwp - new_pwp

     If pwp_changed > pwp(i, p) Then

      pwp(i, p) = 0
      pwp_changed = pwp(i, p)

     ElseIf pwp_changed > 0 Then

      pwp(i, p) = pwp(i, p) - pwp_changed

     Else

      pwp(i, p) = pwp(i, p)
      pwp_changed = 0

     End If
```

```
End If

'
'    sum the pwp pressures at each increment, to determine the total
'    pressure of the increment
'
     pwp_sum(i) = pwp_sum(i) + pwp(i, p)

'
'    record total change in pressure as an input for the changed soil
'    parameters, due to changed pwp
'
     pwp_change_tot(i) = pwp_change_tot(i) + pwp_changed

Next p

'
' changed soil stresses and calc. of settlement of ini layers
'
If pwp_change_tot(i) > 0 Then

   old_effect_stress(i) = new_effect_stress(i)
   new_effect_stress(i) = new_effect_stress(i) + pwp_change_tot(i)
   old_void(i) = new_void(i)
   new_void(i) = void(new_effect_stress(i))
   del_void = old_void(i) - new_void(i)
   settlement(i) = del_void * d_ini(i) * (1 - 1 / (1 + old_void(i)))
   d_ini(i) = d_ini(i) - settlement(i)

Else

   settlement(i) = 0

End If

Next i

Else          ' end of "if" structure for one way drainage case
End If

For i = 1 To first_increments

   settlement_of_layer_ini = settlement_of_layer_ini + settlement(i)

Next i

'
' changed thickness of layer
'

ini_layer_thickness = ini_layer_thickness - settlement_of_layer_ini

'
' ANALYSIS OF ADDED LAYERS
'
'    1. Pressure calculation for upward drainage
'
'    Determine the start point of the drainage direction in added layers
'

If peak_pressure_point > first_increments Then

     start = peak_pressure_point
     Else
     start = first_increments
     End If

For i = start + 1 To increments - 1

   If old_void(i) <> new_void(i) Then
```

```
    Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))
  Else
    Ge(i) = Ge(i)
  End If

pwp_change_tot(i) = 0
pwp_sum(i) = 0

'  position ratio of upward draining section of added layers
'  which is a ratio relative to the peak pressure point
'

posn = (increments - i) / (increments - peak_pressure_point)

'
'  calculate the pwp for each ADDED increment, for each load application
'

  For p = i - first_increments To load_layers

     last_time = (load_layers - p) * load_step + d_time

       If last_time < 0 Then
          Exit For
       Else
       End If

     new_time = last_time + time_step
     old_T = T(Ge(i), new_void(i), drainage_1_top, last_time)
     new_T = T(Ge(i), new_void(i), drainage_1_top, new_time)

'
'    determine change in pwp between last time and this time, and subtract
'    from the last pwp, for each increment, for each load.
'
If new_T >= 1 And pwp(i, p) <> 0 Then

     pwp_changed = pwp(i, p)
     pwp(i, p) = 0

ElseIf new_T >= 1 And pwp(i, p) = 0 Then

     pwp_changed = 0
     pwp(i, p) = 0

Else
     old_pwp = ui(pressure, posn, old_T)
     new_pwp = ui(pressure, posn, new_T)

     pwp_changed = old_pwp - new_pwp

     If pwp_changed > pwp(i, p) Then

       pwp(i, p) = 0
       pwp_changed = pwp(i, p)

     ElseIf pwp_changed > 0 Then

       pwp(i, p) = pwp(i, p) - pwp_changed

     Else

       pwp(i, p) = pwp(i, p)
       pwp_changed = 0

     End If
```

```
End If

'
'    sum the pwp pressures at each increment, to determine the total
'    pressure of the increment
'

     pwp_sum(i) = pwp_sum(i) + pwp(i, p)

'
'    record total change in pressure as an input for the changed soil
'    parameters, due to changed pwp
'
     pwp_change_tot(i) = pwp_change_tot(i) + pwp_changed

Next p
'
'  changed soil stresses and calc. of settlement of added layers
'
If pwp_change_tot(i) > 0 Then

   old_effect_stress(i) = new_effect_stress(i)
   new_effect_stress(i) = new_effect_stress(i) + pwp_change_tot(i)
   old_void(i) = new_void(i)
   new_void(i) = void(new_effect_stress(i))
     del_void = old_void(i) - new_void(i)
   settlement(i) = del_void * d_added(i) * (1 - 1 / (1 + old_void(i)))
   d_added(i) = d_added(i) - settlement(i)

Else

   settlement(i) = 0

End If

Next i

pwp(increments, load_layers) = 0
pwp_sum(increments) = 0
pwp_change_tot(increments) = 0
settlement(increments) = 0

'
'  2. Pressure calculation for downward drainage of added layers
'
If paths = 2 Then
If peak_pressure_point > first_increments Then

   For i = first_increments + 1 To peak_pressure_point

If old_void(i) <> new_void(i) Then

   Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))

Else

   Ge(i) = Ge(i)

End If

pwp_sum(i) = 0
pwp_change_tot(i) = 0

'
'  position ratio of downward draining section of added layers
'  applies only if peak is in added layers section of overall layer
'  This is controlled by the programme flow
'
```

```
posn = i / peak_pressure_point

'
' calculate the pwp for each increment, for each load application
'

For p = i - first_increments To load_layers

    last_time = (load_layers - p) * load_step + d_time

      If last_time < 0 Then
      Exit For
      Else
      End If

    new_time = last_time + time_step
    old_T = T(Ge(i), new_void(i), drainage_l_bot, last_time)
    new_T = T(Ge(i), new_void(i), drainage_l_bot, new_time)

'
'   determine change in pwp between last time and this time, and subtract
'   from the last pwp, for each increment, for each load.
'
If new_T >= 1 And pwp(i, p) <> 0 Then

    pwp_changed = pwp(i, p)
    pwp(i, p) = 0

ElseIf new_T >= 1 And pwp(i, p) = 0 Then

    pwp_changed = 0
    pwp(i, p) = 0

Else
    old_pwp = ui(pressure, posn, old_T)
    new_pwp = ui(pressure, posn, new_T)

    pwp_changed = old_pwp - new_pwp

    If pwp_changed > pwp(i, p) Then

     pwp(i, p) = 0
     pwp_changed = pwp(i, p)

    ElseIf pwp_changed > 0 Then

     pwp(i, p) = pwp(i, p) - pwp_changed

    Else

     pwp(i, p) = pwp(i, p)
     pwp_changed = 0

    End If

End If

'
'   sum the pwp pressures at each increment, to determine the total
'   pressure of the incremen
'
    pwp_sum(i) = pwp_sum(i) + pwp(i, p)

'
'   record total chang  in pressure as an input for the changed soil
'   parameters, due to changed pwp
'
    pwp_change_tot(i) = pwp_change_tot(i) + pwp_changed

Next p
```

```
'
' changed soil stresses and calc. of settlement of added layers
'
If pwp_change_tot(i) > 0 Then

   old_effect_stress(i) = new_effect_stress(i)
   new_effect_stress(i) = new_effect_stress(i) + pwp_change_tot(i)
   old_void(i) = new_void(i)
   new_void(i) = void(new_effect_stress(i))
    del_void = old_void(i) - new_void(i)
   settlement(i) = del_void * d_added(i) * (1 - 1 / (1 + old_void(i)))
   d_added(i) = d_added(i) - settlement(i)

Else

   settlement(i) = 0

End If

Next i

Else          ' end of "if" structure for case where no downward drainage in added layers
End If

Else          ' end of "if" structure for one way drainage
End If

For i = first_increments + 1 To increments

   settlement_of_layer = settlement_of_layer + settlement(i)

Next i

'
' settlement of both initial and added layers
'

   full_settlement = settlement_of_layer + settlement_of_layer_ini

'
' revised total layer thickness for next round of calculations
'
ini_layer_thickness = 0

   For i = 1 To first_increments

      ini_layer_thickness = d_ini(i) + ini_layer_thickness

   Next i

thickness = ini_layer_thickness

   For i = first_increments + 1 To increments

      thickness = thickness + d_added(i)

   Next i

 drainage_l_top = thickness / paths

   If paths = 2 Then
         drainage_l_bot = thickness - drainage_l_top
         peak_pressure_point = Fix(increments / paths)
   Else
         drainage_l_bot = 0
         peak_pressure_point = 1
   End If

'
```

```
' CONTROL FOR DISPLAY OF RESULTS
'

display_test = remain(time_loop, display)

If display_test = 0 Then

   Worksheets("sheet1_continuous").Select

   For i = 1 To increments

     ActiveSheet.[f15].Cells(i, 2 * k - 3).Select
        With ActiveCell
           .Value = Application.Round(pwp_sum(i), 3)
           .NumberFormat = "#0.000"
           .ColumnWidth = 12
           .Font.Size = 10
           .Font.Name = "Times New Roman"
           .Borders(xlRight).LineStyle = xlNone

             With .Borders(xlRight)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
             End With

           .Borders(xlTop).LineStyle = xlNone
           .Borders(xlBottom).LineStyle = xlNone
           .BorderAround LineStyle:=xlNone

        End With

   Next i

   thickness = 0

   For i = 1 To first_increments

   thickness = thickness + d_ini(i)

   ActiveSheet.[e15].Cells(i, 2 * k - 3).Select
      With ActiveCell
         .Value = thickness
         .NumberFormat = "#0.000"
         .ColumnWidth = 12
         .Font.Size = 10
         .Font.Name = "Times New Roman"
      End With

   Next i

   For i = first_increments + 1 To increments

   thickness = thickness + d_added(i)

   ActiveSheet.[e15].Cells(i, 2 * k - 3).Select
      With ActiveCell
         .Value = thickness
         .NumberFormat = "#0.000"
         .ColumnWidth = 12
         .Font.Size = 10
         .Font.Name = "Times New Roman"
      End With

   Next i

  tot_applied_thickness = applied_thickness * (Int(time_loop / load_step) + 1)

   ActiveSheet.[a8].Cells(1, 2 * k + 1).Select

      With ActiveCell
```

```
        .Value = time_loop
        .NumberFormat = "#0"
        .HorizontalAlignment = xlCenter
        .Borders(xlTop).LineStyle = xlNone

            With .Borders(xlTop)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlRight).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With

ActiveSheet.[b8].Cells(1, 2 * k + 1).Select

    With ActiveCell
        .Value = "days"
        .Borders(xlRight).LineStyle = xlNone

            With .Borders(xlRight)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlTop).LineStyle = xlNone

            With .Borders(xlTop)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With

ActiveSheet.[a9].Cells(1, 2 * k + 1).Select

    With ActiveCell
        .Value = full_settlement
        .NumberFormat = "#0.000"
        .HorizontalAlignment = xlCenter

    End With

ActiveSheet.[b9].Cells(1, 2 * k + 1).Select

    With ActiveCell
        .Value = "m"
        .Borders(xlRight).LineStyle = xlNone

            With .Borders(xlRight)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With
ActiveSheet.[a10].Cells(1, 2 * k + 1).Select
    With ActiveCell
        .Value = (Int(time_loop / load_step) + 1) * pressure
```

```
        .NumberFormat = "#0.00"
        .HorizontalAlignment = xlCenter
    End With

ActiveSheet.[b10].Cells(1, 2 * k + 1).Select

    With Ac..'eCell
        .Valu. = "kPa"
        .Borders(xlRight).LineStyle = xlNone

            With .Borders(xlRight)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With

ActiveSheet.[a11].Cells(1, 2 * k + 1).Select
    With ActiveCell
        'alue = tot_applied_thickness
        umberFormat = "#0.000"
        lorizontalAlignment = xlCenter
    .. With

ActiveSheet.[b11].Cells(1, 2 * k + 1).Select

    With ActiveCell
        .Value = "m"
        .Borders(xlRight).LineStyle = xlNone

            With .Borders(xlRight)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With

ActiveSheet.[a12].Cells(1, 2 * k + 1).Select
    With ActiveCell
        .Value = thickness
        .NumberFormat = "#0.000"
        .HorizontalAlignment = xlCenter
    End With

ActiveSheet.[b12].Cells(1, 2 * k + 1).Select

    With ActiveCell
        .Value = "m"
        .Borders(xlRight).LineStyle = xlNone

            With .Borders(xlRight)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlBottom).L . eStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone
```

```
        End With

    ActiveSheet.[e13].Cells(1, 2 * k - 3).Select
      With ActiveCell
        .Value = "Depth from base up"
        .Font.Name = "Times New Roman"
        .Font.Size = 10
        .ColumnWidth = 10
        .Interior.ColorIndex = 19
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlCenter
        .WrapText = True
        .Orientation = xlHorizontal
        .Borders(xlLeft).LineStyle = xlNone

            With .Borders(xlLeft)
              .Weight = xlMedium
              .ColorIndex = xlAutomatic
            End With

        .Borders(xlTop).LineStyle = xlNone

            With .Borders(xlTop)
              .Weight = xlMedium
              .ColorIndex = xlAutomatic
            End With

        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlRight).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

      End With

    ActiveSheet.[e14].Cells(1, 2 * k - 3).Select
      With ActiveCell
        .Value = "m"
        .Font.Name = "Times New Roman"
        .Font.Size = 10
        .Interior.ColorIndex = 19
        .ColumnWidth = 10
        .HorizontalAlignment = xlCenter
        .VerticalAlignment = xlBottom
        .WrapText = False
        .Orientation = xlHorizontal
        .Borders(xlLeft).LineStyle = xlNone

            With .Borders(xlLeft)
              .Weight = xlMedium
              .ColorIndex = xlAutomatic
            End With

        .Borders(xlBottom).LineStyle = xlNone

            With .Borders(xlBottom)
              .Weight = xlMedium
              .ColorIndex = xlAutomatic
            End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlRight).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone
      End With

    ActiveSheet.[f13].Cells(1, 2 * k - 3).Select
      With ActiveCell
        .Value = "u"
        .Font.Bold = True
        .Font.Italic = True
        .Font.Name = "Times New Roman"
        .Font.Size = 14
```

```
    .Interior.ColorIndex = 19
    .ColumnWidth = 12
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .WrapText = False
    .Orientation = xlHorizontal
    .Borders(xlRight).LineStyle = xlNone

        With .Borders(xlRight)
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With

    .Borders(xlTop).LineStyle = xlNone

        With .Borders(xlTop)
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With

    .Borders(xlBottom).LineStyle = xlNone
    .Borders(xlLeft).LineStyle = xlNone
    .BorderAround LineStyle:=xlNone
   End With

  ActiveSheet.[f14].Cells(1, 2 * k - 3).Select
   With ActiveCell
    .Value = "kPa"
    .Font.Name = "Times New Roman"
    .Font.Size = 10
    .Interior.ColorIndex = 19
    .ColumnWidth = 10
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlBottom
    .WrapText = False
    .Orientation = xlHorizontal
    .Borders(xlRight).LineStyle = xlNone

        With .Borders(xlRight)
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With

    .Borders(xlBottom).LineStyle = xlNone

        With .Borders(xlBottom)
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
        End With

    .Borders(xlTop).LineStyle = xlNone
    .Borders(xlLeft).LineStyle = xlNone
    .BorderAround LineStyle:=xlNone

   End With

  k = k + 1

  Else

End If

Next time_loop

End Sub

Function ul(pressure, posn, T)
Dim ul_incr As Single
Dim m As Single
Dim k As Integer
```

```
k = 0: ui = 0

  Do

      m = 0.5 * (22 / 7) * (2 * k + 1)
      ui_incr = 2 * pressure / m * Sin(m * posn) * Exp(-(m ^ 2 * T))
      ui = ui + ui_incr
      k = k + 1

      If k >= 200 Then
      Exit Do
      Else
      End If

  Loop Until Abs(ui_incr) <= pressure / 1000 And remain(k, 10) = 0

End Function

Function void(new_stress)

Dim a As Double

If new_stress <= 1 Then
    void = Worksheets("sheet4").[d8].Value

Else
   a = 0.43429448 * Log(new_stress)
   void = b * a ^ 2 + c * a + d
End If

End Function

Function G(new_stress, old_stress, old_void, new_void)

Dim a As Double
Dim Mv_i As Double
Dim perm As Double

   a = 0.43429448 * Log(new_stress)
   perm = 10 ^ (e * a ^ 2 + f * a + h)
   Mv_i = ((new_stress - old_stress) / (old_void - new_void))
   G = perm * Mv_i / 9.81 / (1 + old_void) * 3600 * 24

End Function

Function T(G, void_ratio, drainage_l, time)

   T = G * (1 + void_ratio) ^ 2 * time / drainage_l ^ 2

End Function

Function remain(number, division)

Dim a_number As Single
Dim b_number As Single

   a_number = number / division
   b_number = Int(number / division)
   remain = a_number - b_number

End Function
```

```
Option Base 1
Option Explicit

Public b As Single
Public c As Single
Public d As Single
Public e As Single
Public f As Single
Public h As Single
Sub settlement_continuous()
Dim increments As Integer
Dim first_increments As Integer
Dim load_timesteps As Integer
Dim pressure(300) As Single
Dim i As Integer
Dim j As Integer
Dim k As Integer
Dim p As Integer
Dim n As Integer
Dim m As Single
Dim old_effect_stress(300) As Single
Dim old_void(300) As Single
Dim Ge(300) As Double
Dim old_T As Double
Dim new_T As Double
Dim new_effect_stress(300) As Single
Dim drainage_l_bot As Single
Dim drainage_l_top As Single
Dim new_void(300) As Single
Dim pwp_change_tot(300) As Single
Dim pwp_changed As Double
Dim pwp_change(290) As Double
Dim time_step As Integer
Dim time_loop As Integer
Dim settlement_of_layer As Single
Dim settlement_of_layer_ini As Single
Dim full_settlement As Single
Dim settlement(300) As Double
Dim last_time As Integer
Dim new_time As Integer
Dim applied_thickness As Single
Dim tot_applied_thickness As Single
Dim del_void As Single
Dim display As Integer
Dim load_step As Integer
Dim loads As Integer
Dim active_loads As Integer
Dim t_unit As Single
Dim display_test As Single
Dim d_added(300) As Single
Dim d_ini(125) As Single
Dim thickness As Single
Dim H_ini As Single
Dim top_l As Integer
Dim ini_layer_thickness As Single
Dim posn As Single
Dim pwp(300, 300) As Single
Dim pwp_sum(300) As Single
Dim old_pwp As Single
Dim new_pwp As Single
Dim paths As Integer
Dim peak_pressure_point As Integer
Dim layers As Integer
Dim start As Integer
Dim bot_peak As Integer
Dim top_peak As Integer
Dim d_time As Single
Dim incr As Single
Dim load_layers As Integer
Dim pwp_sum_peak As Single
Dim e_min As Single
Dim e_max As Single
Dim sg As Single
```

```
Dim depth A : Single
Dim water_mass As Single
Dim incr_settlement  As Single
'
' Set initial soil density value
'
   e_min = Worksheets("sheet2").[c5].Value
   sg = Worksheets("sheet2").[c4].Value
   Worksheets("sheet2").[i5].Value = 10 * (sg + e_min) / (1 + e_min)
'
' Get input data from speadsheet into program variables
'
load_step = Worksheets("sheet1_continuous").[d5].Value
loads = Worksheets("sheet1_continuous").[i4].Value
load_timesteps = loads * load_step
time_step = Worksheets("sheet1_continuous").[d6].Value
H_ini = Worksheets("sheet1_continuous").[d7].Value
applied_thickness = Worksheets("sheet1_c  nuous").[i5].Value
pressure(1) = Worksheets("sheet1_continuous").[d4].Value
display = Worksheets("sheet1_continuous").[d3].Value
paths = Worksheets("sheet1_continuous").[h3].Value
drainage_l_top = H_ini / paths + applied_thickness / paths
first_increments = Worksheets("sheet1_continuous").[i6].Value

   If paths = 2 Then
     drainage_l_bot = drainage_l_top
   Else
     drainage_l_bot = 0
   End If

   b = Worksheets("sheet3").[l28].Value
   c = Worksheets("sheet3").[l29].Value
   d = Worksheets("sheet3").[l30].Value
   e = Worksheets("sheet3").[l7] Value
   f = Worksheets("sheet3").[l6  ]alue
   h = Worksheets("sheet3").[l9].Value
   Ini_layer_thickness = 0
   settlement_of_layer_Ini = 0
   settlement_of_layer = 0
   increments = first_increments + 1

Worksheets("Sheet1_continuous").Select
   Range("E8:Gh500").Select
   Selection.ClearContents
   Selection.Borders(xlLeft).LineStyle = xlNone
   Selection.Borders(xlRight).LineStyle = xlNone
   Selection.Borders(xlTop).LineStyle = xlNone
   Selection.Borders(xlBottom).LineStyle = xlNone
   Selection.BorderAround LineStyle:=xlNone
   Selection.Interior.ColorIndex = xlNone

'
' set the initial soil parameters wrt depth
'

For i = 1 To first_increments
   n = (first_increments - i) + 1
   old_effect_stress(i) = Worksheets("sheet4").[c8].Cells(n, 1).Value
   old_void(i) = Worksheets("sheet4").[c8].Cells(n, 2).Value
   Ge(i) = Worksheets("sheet4").[f8].Cells(n, 1).Value
Next i

   new_effect_stress(increments) = Worksheets("sheet4").[c8].Value
   old_void(increments) = Worksheets("sheet4").[d8].Value
   new_void(increments) = old_void(increments)
   Ge(incr  nents) = Worksheets("sheet4").[f8].Value
   d_add_d(increments) = applied_thickness

   If paths = 2 Then
      peak_pressure_point = Fix(first_increments / paths)
   Else
      peak_pressure_point = 1
   End If
```

```
'
' determine pwp distribution for initial load on layers
'

For i = 1 To first_increments

   new_T = T(Ge(i), old_void(i), drainage_l_top, time_step)
   posn = i / (increments / paths)
   pwp(i, 1) = ui(pressure(1), posn, new_T)
   pwp_change(i) = pressure(1) - pwp(i, 1)
   new_effect_stress(i) = old_effect_stress(i) + pwp_change(i)
   new_void(i) = void(new_effect_stress(i))

   If new_effect_stress(i) > 1 Then
      Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))
   Else
      Ge(i) = Ge(i)
   End If

   del_void = old_void(i) - new_void(i)
   settlement(i) = H_ini / first_increments * del_void * (1 - 1 / (1 + old_void(i)))
   d_ini(i) = H_ini / first_increments - settlement(i)
   ini_layer_thickness = ini_layer_thickness + d_ini(i)
   settlement_of_layer_ini = settlement_of_layer_ini + settlement(i)

Next i

   pwp(increments, 1) = 0
   drainage_l_top = drainage_l_top - settlement_of_layer_ini / paths

   If paths = 2 Then
      drainage_l_bot = drainage_l_top
   Else
      drainage_l_bot = 0
   End If

k = 2
load_layers = 1

For time_loop = (2 * time_step) To load_timesteps Step time_step

If remain(time_loop, load_step) = 0 Then

   drainage_l_top = drainage_l_top + applied_thickness
   increments = increments + 1
   old_effect_stress(increments) = Worksheets("sheet4").[c8].Value
   old_void(increments) = Worksheets("sheet4").[d8].Value
   Ge(increments) = Worksheets("sheet4").[f8].Value
   new_effect_stress(increments) = Worksheets("sheet4").[c8].Value
   new_void(increments) = old_void(increments)
   d_added(increments) = applied_thickness
   load_layers = increments - first_increments
   water_mass = incr_settlement * 9.81
   incr_settlement = 0

   ' reduction in load due to water loss from consolidated mass
   pressure(load_layers) = pressure(1) - water_mass

      For i = 1 To increments - 1

         pwp(i, load_layers) = pressure(load_layers)

      Next i

   Else
End If
'
' ANALYSIS OF INITIAL LAYER THICKNESS
'
' Drainage of upper layers upwards
'
' If peak pressure point is in added layers, all drainage will be
```

```
' downwards, and this next section will be jumped over.
'
d_time = remain(time_loop, load_step) * load_step

If peak_pressure_point >= first_increments Then

  GoTo 100

  Else

For i = peak_pressure_point To first_increments

If old_void(i) <> new_void(i) Then

  Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))

Else

  Ge(i) = Ge(i)

End If

pwp_sum(i) = 0
pwp_change_tot(i) = 0

' position ratio of upward draining section of ini layers
' relative to peak pressure point.
' Only applies if peak is in initial layers
'

posn = (increments - i) / (increments - peak_pressure_point)

'
' calculate the pwp for each increment, for each load application
'

For p = 1 To load_layers

    last_time = (load_layers - p) * load_step + d_time

      If last_time < 0 Then
      Exit For
      Else
      End If

    new_time = last_time + time_step
    old_T = T(Ge(i), new_void(i), drainage_1_top, last_time)
    new_T = T(Ge(i), new_void(i), drainage_1_top, new_time)

'   determine change in pwp between last time and this time, and subtract
'   from the last pwp, for each increment, for each load.
'
If new_T >= 1 And pwp(i, p) <> 0 Then

    pwp_changed = pwp(i, p)
    pwp(i, p) = 0

ElseIf new_T >= 1 And pwp(i, p) = 0 Then

    pwp_changed = 0
    pwp(i, p) = 0
Else
    old_pwp = ui(pressure(p), posn, old_T)
    new_pwp = ui(pressure(p), posn, new_T)

    pwp_changed = old_pwp - new_pwp

    If pwp_changed > pwp(i, p) Then

     pwp(i, p) = 0
     pwp_changed = pwp(i, p)

    ElseIf pwp_changed > 0 Then
```

```
    pwp(i, p) = pwp(i, p) - pwp_changed

   Else

    pwp(i, p) = pwp(i, p)
    pwp_changed = 0

   End If

End If
'
'   sum the pwp pressures at each increment, to determine the total
'   pressure of the increment
'
    pwp_sum(i) = pwp_sum(i) + pwp(i, p)

'
'   record total change in pressure as an input for the changed soil
'   parameters, due to changed pwp
'
    pwp_change_tot(i) = pwp_change_tot(i) + pwp_changed

Next p

'
' changed soil stresses and calc. of settlement of ini layers
'
If pwp_change_tot(i) > 0 Then

  old_effect_stress(i) = new_effect_stress(i)
  new_effect_stress(i) = new_effect_stress(i) + pwp_change_tot(i)
  old_void(i) = new_void(i)
  new_void(i) = void(new_effect_stress(i))
  del_void = old_void(i) - new_void(i)
  settlement(i) = del_void * d_ini(i) * (1 - 1 / (1 + old_void(i)))
  d_ini(i) = d_ini(i) - settlement(i)

Else

  settlement(i) = 0

End If

  incr_settlement = incr_settlement + settlement(i)

Next i

End If
'
' Analysis of bottom draining layers of ini layers
'
100 If peak_pressure_point >= first_increments Then

     layers = first_increments
     Else
     layers = peak_pressure_point
     End If

If paths = 2 Then

For i = 1 To layers

If old_void(i) <> new_void(i) Then

  Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))

Else

  Ge(i) = Ge(i)

End If
```

```
pwp_sum(i) = 0
pwp_change_tot(i) = 0

' position ratio in ini layers for bottom draining, relative to peak
' pressure point

posn = i / peak_pressure_point

'
' calculate the pwp for each increment, for each load application
'

For p = 1 To load_layers

     last_time = (load_layers - p) * load_step + d_time

        If last_time < 0 Then
        Exit For
        Else
        End If

     new_time = last_time + time_step
     old_T = T(Ge(i), new_void(i), drainage_I_bot, last_time)
     new_T = T(Ge(i), new_void(i), drainage_I_bot, new_time)

'
'    determine change in pwp between last time and this time, and subtract
'    from the last pwp, for each increment, for each load.
'
If new_T >= 1 And pwp(i, p) <> 0 Then

     pwp_changed = pwp(i, p)
     pwp(i, p) = 0

ElseIf new_T >= 1 And pwp(i, p) = 0 Then

     pwp_changed = 0
     pwp(i, p) = 0
Else
     old_pwp = ui(pressure(p), posn, old_T)
     new_pwp = ui(pressure(p), posn, new_T)

     pwp_changed = old_pwp - new_pwp

     If pwp_changed > pwp(i, p) Then

      pwp(i, p) = 0
      pwp_changed = pwp(i, p)

     ElseIf pwp_changed > 0 Then

      pwp(i, p) = pwp(i, p) - pwp_changed

     Else

      pwp(i, p) = pwp(i, p)
      pwp_changed = 0

     End If

End If

'
'    sum the pwp pressures at each increment, to determine the total
'    pressure of the increment
'
     pwp_sum(i) = pwp_sum(i) + pwp(i, p)

'
'    record total change in pressure as an input for the changed soil
'    parameters, due to changed pwp
'
```

```
    pwp_change_tot(i) = pwp_change_tot(i) + pwp_changed

Next p

'
' changed soil stresses and calc. of settlement of ini layers
'
If pwp_change_tot(i) > 0 Then

  old_effect_stress(i) = new_effect_stress(i)
  new_effect_stress(i) = new_effect_stress(i) + pwp_change_tot(i)
  old_void(i) = new_void(i)
  new_void(i) = void(new_effect_stress(i))
  del_void = old_void(i) - new_void(i)
  settlement(i) = del_void * d_ini(i) * (1 - 1 / (1 + old_void(i)))
  d_ini(i) = d_ini(i) - settlement(i)

Else

  settlement(i) = 0

End If

  incr_settlement = incr_settlement + settlement(i)

Next i

Else            ' end of "If" structure for one way drainage case
End If

For i = 1 To first_increments

  settlement_of_layer_ini = settlement_of_layer_ini + settlement(i)

Next i

'
' changed thickness of layer
'

ini_layer_thickness = ini_layer_thickness - settlement_of_layer_ini

'
' ANALYSIS OF ADDED LAYERS
'
'   1. Pressure calculation for upward drainage
'
'   Determine the start point of the drainage direction in added layers
'

If peak_pressure_point > first_increments Then

    start = peak_pressure_point
    Else
    start = first_increments
    End If

For i = start + 1 To increments - 1

  If old_void(i) <> new_void(i) Then

    Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))

  Else

    Ge(i) = Ge(i)

  End If

 pwp_change_tot(i) = 0
 pwp_sum(i) = 0

' position ratio of upward draining section of added layers
```

```
' which is a ratio relative to the peak pressure point

posn = (increments - i) / (increments - peak_pressure_point)

'
' calculate the pwp for each ADDED increment, for each load application
'

  For p = i - first_increments To load_layers

    last_time = (load_layers - p) * load_step + d_time

      If last_time < 0 Then
         Exit For
      Else
      End If

    new_time = last_time + time_step
    old_T = T(Ge(i), new_void(i), drainage_l_top, last_time)
    new_T = T(Ge(i), new_void(i), drainage_l_top, new_time)

'
'   determine change in pwp between last time and this time, and subtract
'   from the last pwp, for each increment, for each load.
'
If new_T >= 1 And pwp(i, p) <> 0 Then

    pwp_changed = pwp(i, p)
    pwp(i, p) = 0

ElseIf new_T >= 1 And pwp(i, p) = 0 Then

    pwp_changed = 0
    pwp(i, p) = 0

Else
    old_pwp = ui(pressure(p), posn, old_T)
    new_pwp = ui(pressure(p), posn, new_T)

    pwp_changed = old_pwp - new_pwp

    If pwp_changed > pwp(i, p) Then

     pwp(i, p) = 0
     pwp_changed = pwp(i, p)

    ElseIf pwp_changed > 0 Then

     pwp(i, p) = pwp(i, p) - pwp_changed

    Else

     pwp(i, p) = pwp(i, p)
     pwp_changed = 0

    End If

End If

'
'    sum the pwp pressures at each increment, to determine the total
'    pressure of the increment
'

    pwp_sum(i) = pwp_sum(i) + pwp(i, p)

'
'    record total change in pressure as an input for the changed soil
'    parameters, due to changed pwp
'

    pwp_change_tot(i) = pwp_change_tot(i) + pwp_changed
```

```
Next p
'
'  changed soil stresses and calc. of settlement of added layers
'
If pwp_change_tot(i) > 0 Then

   old_effect_stress(i) = new_effect_stress(i)
   new_effect_stress(i) = new_effect_stress(i) + pwp_change_tot(i)
   old_void(i) = new_void(i)
   new_void(i) = void(new_effect_stress(i))
    del_void = old_void(i) - new_void(i)
   settlement(i) = del_void * d_added(i) * (1 - 1 / (1 + old_void(i)))
   d_added(i) = d_added(i) - settlement(i)

Else

   settlement(i) = 0

End If

    incr_settlement = incr_settlement + settlement(i)

Next i

pv      crements, load_layers) = 0
pwp_sum(increments) = 0
pwp_change_tot(increments) = 0
settlement(increments) = 0

'
'  2. Pressure calculation for downward drainage of added layers
'
If paths = 2 Then
If peak_pressure_point > first_increments Then

   For i = first_increments + 1 To peak_pressure_point

If old_void(i) <> new_void(i) Then

   Ge(i) = G(new_effect_stress(i), old_effect_stress(i), old_void(i), new_void(i))

Else

   Ge(i) = Ge(i)

End If

pwp_sum(i) = 0
pwp_change_tot(i) = 0

'
'  position ratio of downward draining section of added layers
'  applies only if peak is in added layers section of overall layer
'  This is controlled by the programme flow
'

posn = i / peak_pressure_point

'
'  calculate the pwp for each increment, for each load application
'

For p = i - first_increments To load_layers

      last_time = (load_layers - p) * load_step + d_time

         If last_time < 0 Then
         Exit For
         Else
         End If

      new_time = last_time + time_step
      old_T = T(Ge(i), new_void(i), drainage_l_bot, last_time)
```

```
    new_T = T(Ge(i), new_void(i), drainage_1_bot, new_time)

'
'   determine change in pwp between last time and this time, and subtract
'   from the last pwp, for each increment, for each load
'
If new_T >= 1 And pwp(i, p) <> 0 Then

    pwp_changed = pwp(i, p)
    pwp(i, p) = 0

ElseIf new_T >= 1 And pwp(i, p) = 0 Then

    pwp_changed = 0
    pwp(i, p) = 0

Else
    old_pwp = ui(pressure(p), posn, old_T)
    new_pwp = ui(pressure(p), posn, new_T)

    pwp_changed = old_pwp - new_pwp

    If pwp_changed > pwp(i, p) Then

     pwp(i, p) = 0
     pwp_changed = pwp(i, p)

    ElseIf pwp_changed > 0 Then

     pwp(i, p) = pwp(i, p) - pwp_changed

    Else

     pwp(i, p) = pwp(i, p)
     pwp_changed = 0

    End If

End If

'
'   sum the pwp pressures at each increment, to determine the total
'   pressure of the increment
'
    pwp_sum(i) = pwp_sum(i) + pwp(i, p)

'
'   record total change in pressure as an input for the changed soil
'   parameters, due to changed pwp
'
    pwp_change_tot(i) = pwp_change_tot(i) + pwp_changed

Next p

'
' changed soil stresses and calc. of settlement of added layers
'
If pwp_change_tot(i) > 0 Then

   old_effect_stress(i) = new_effect_stress(i)
   new_effect_stress(i) = new_effect_stress(i) + pwp_change_tot(i)
   old_void(i) = new_void(i)
   new_void(i) = void(new_effect_stress(i))
    del_void = old_void(i) - new_void(i)
   settlement(i) = del_void * d_added(i) * (1 - 1 / (1 + old_void(i)))
   d_added(i) = d_added(i) - settlement(i)

Else

   settlement(i) = 0

End If
```

```
  incr_settlement = incr_settlement + settlement(i)

Next i

Else        ' end of "if" structure for case where no downward drainage in added layers
End If

Else        ' end of "if" structure for one way drainage
End If

For i = first_increments + 1 To increments

  settlement_of_layer = settlement_of_layer + settlement(i)

Next i

'
' settlement of both initial and added layers
'

  full_settlement = settlement_of_layer + settlement_of_layer_ini

'
' revised total layer thickness for next round of calculations
'
ini_layer_thickness = 0

  For i = 1 To first_increments

    ini_layer_thickness = d_ini(i) + ini_layer_thickness

  Next i

thickness = ini_layer_thickness

  For i = first_increments + 1 To increments

    thickness = thickness + d_added(i)

  Next i

drainage_l_top = thickness / paths

  If paths = 2 Then
       drainage_l_bot = thickness - drainage_l_top
       peak_pressure_point = Fix(increments / paths)
  Else
       drainage_l_bot = 0
       peak_pressure_point = 1
  End If

'
' CONTROL FOR DISPLAY OF RESULTS
'

display_test = remain(time_loop, display)

If display_test = 0 Then

  Worksheets("sheet1_continuous").Select

  For i = 1 To increments

    ActiveSheet.[f15].Cells(i, 2 * k - 3).Select
      With ActiveCell
        .Value = Application.Round(pwp_sum(i), 3)
        .NumberFormat = "#0.000"
        .ColumnWidth = 12
        .Font.Size = 10
        .Font.Name = "Times New Roman"
        .Borders(xlRight).LineStyle = xlNone

          With .Borders(xlRight)
```

```
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
          End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlBottom).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

      End With

  Next i

  thickness = 0

  For i = 1 To first_increments

  thickness = thickness + d_ini(i)

  ActiveSheet.[e15].Cells(i, 2 * k - 3).Select
    With ActiveCell
      .Value = thickness
      .NumberFormat = "#0.000"
      .ColumnWidth = 12
      .Font.Size = 10
      .Font.Name = "Times New Roman"
    End With

  Next i

  For i = first_increments + 1 To increments

  thickness = thickness + d_added(i)

  ActiveSheet.[e15].Cells(i, 2 * k - 3).Select
    With ActiveCell
      .Value = thickness
      .NumberFormat = "#0.000"
      .ColumnWidth = 12
      .Font.Size = 10
      .Font.Name = "Times New Roman"
    End With

  Next i

 tot_applied_thickness = applied_thickness * (Int(time_loop / load_step) + 1)

  ActiveSheet.[a8].Cells(1, 2 * k + 1).Select

      With ActiveCell
        .Value = time_loop
        .NumberFormat = "#0"
        .HorizontalAlignment = xlCenter
        .Borders(xlTop).LineStyle = xlNone

          With .Borders(xlTop)
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
          End With

        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlRight).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

      End With

  ActiveSheet.[b8].Cells(1, 2 * k + 1).Select

      With ActiveCell
        .Value = "days"
        .Borders(xlRight).LineStyle = xlNone

          With .Borders(xlRight)
```

```
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
          End With

        .Borders(xlTop).LineStyle = xlNone

          With .Borders(xlTop)
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
          End With

        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With

ActiveSheet.[a9].Cells(1, 2 * k + 1).Select

    With ActiveCell
        .Value = full_settlement
        .NumberFormat = "#0.000"
        .HorizontalAlignment = xlCenter

    End With

ActiveSheet.[b9].Cells(1, 2 * k + 1).Select

    With ActiveCell
        .Value = "m"
        .Borders(xlRight).LineStyle = xlNone

          With .Borders(xlRight)
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
          End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With
ActiveSheet.[a10].Cells(1, 2 * k + 1).Select
    With ActiveCell
        .Value = (Int(time_loop / load_step) + 1) * pressure(1)
        .NumberFormat = "#0.00"
        .HorizontalAlignment = xlCenter
    End With

ActiveSheet.[b10].Cells(1, 2 * k + 1).Select

    With ActiveCell
        .Value = "kPa"
        .Borders(xlRight).LineStyle = xlNone

          With .Borders(xlRight)
            .Weight = xlMedium
            .ColorIndex = xlAutomatic
          End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlBottom).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With

ActiveSheet.[a11].Cells(1, 2 * k + 1).Select
    With ActiveCell
        .Value = tot_applied_thickness
        .NumberFormat = "#0.000"
        .HorizontalAlignment = xlCenter
```

```
    End With

ActiveSheet.[b11].Cells(1, 2 * k + 1).Select

    With ActiveCell
      .Value = "m"
      .Borders(xlRight).LineStyle = xlNone

        With .Borders(xlRight)
          .Weight = xlMedium
          .ColorIndex = xlAutomatic
        End With

      .Borders(xlTop).LineStyle = xlNone
      .Borders(xlBottom).LineStyle = xlNone
      .Borders(xlLeft).LineStyle = xlNone
      .BorderAround LineStyle:=xlNone

    End With

ActiveSheet.[a12].Cells(1, 2 * k + 1).Select
    With ActiveCell
      .Value = thickness
      .NumberFormat = "#0.000"
      .HorizontalAlignment = xlCenter
    End With

ActiveSheet.[b12].Cells(1, 2 * k + 1).Select

    With ActiveCell
      .Value = "m"
      .Borders(xlRight).LineStyle = xlNone

        With .Borders(xlRight)
          .Weight = xlMedium
          .ColorIndex = xlAutomatic
        End With

      .Borders(xlTop).LineStyle = xlNone
      .Borders(xlBottom).LineStyle = xlNone
      .Borders(xlLeft).LineStyle = xlNone
      .BorderAround LineStyle:=xlNone

    End With

ActiveSheet.[e13].Cells(1, 2 * k - 3).Select
  With ActiveCell
      .Value = "Depth from base up"
      .Font.Name = "Times New Roman"
      .Font.Size = 10
      .ColumnWidth = 10
      .Interior.ColorIndex = 19
      .HorizontalAlignment = xlCenter
      .VerticalAlignment = xlCenter
      .WrapText = True
      .Orientation = xlHorizontal
      .Borders(xlLeft).LineStyle = xlNone

        With .Borders(xlLeft)
          .Weight = xlMedium
          .ColorIndex = xlAutomatic
        End With

      .Borders(xlTop).LineStyle = xlNone

        With .Borders(xlTop)
          .Weight = xlMedium
          .ColorIndex = xlAutomatic
        End With

      .Borders(xlBottom).LineStyle = xlNone
      .Borders(xlRight).LineStyle = xlNone
      .BorderAround LineStyle:=xlNone
```

```
  End With

ActiveSheet.[e14].Cells(1, 2 * k - 3).Select
  With ActiveCell
    .Value = "m"
    .Font.Name = "Times New Roman"
    .Font.Size = 10
    .Interior.ColorIndex = 19
    .ColumnWidth = 10
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlBottom
    .WrapText = False
    .Orientation = xlHorizontal
    .Borders(xlLeft).LineStyle = xlNone

        With .Borders(xlLeft)
          .Weight = xlMedium
          .ColorInde  = xlAutomatic
        End With

    .Borders(xlBottom).LineStyle = xlNone

        With .Borders(xlBottom)
          .Weight = xlMedium
          .ColorIndex = xlAutomatic
        End With

    .Borders(xlTop).LineStyle = xlNone
    .Borders(xlRight).LineStyle = xlNone
    .BorderAround LineStyle:=xlNone
  End With

 ActiveSheet.[f13].Cells(1, 2 * k - 3).Select
  With ActiveCell
    .Value = "u"
    .Font.Bold = True
    .Font.Italic = True
    .Font.Name = "Times New Roman"
    .Font.Size = 14
    .Interior.ColorIndex = 19
    .ColumnWidth = 12
    .HorizontalAlignment = xlCenter
    .VerticalAlignment = xlCenter
    .WrapText = False
    .Orientation = xlHorizontal
    .Borders(xlRight).LineStyle = xlNone

        With .Borders(xlRight)
          .Weight = xlMedium
          .ColorIndex = xlAutomatic
        End With

    .Borders(xlTop).LineStyle = xlNone

        With .Borders(xlTop)
          .Weight = xlMedium
          .ColorIndex = xlAutomatic
        End With

    .Borders(xlBottom).LineStyle = xlNone
    .Borders(xlLeft).LineStyle = xlNone
    .BorderAround LineStyle:=xlNone
  End With

 ActiveSheet.[f14].Cells(1, 2 * k - 3).Select
  With ActiveCell
    .Value = "kPa"
    .Font.Name = "Times New Roman"
    .Font.Size = 10
    .Interior.ColorIndex = 19
    .ColumnWidth = 10
    .HorizontalAlignment = xlCenter
```

```
        .VerticalAlignment = xlBottom
        .WrapText = False
        .Orientation = xlHorizontal
        .Borders(xlRight).LineStyle = xlNone

            With .Borders(xlRight)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlBottom).LineStyle = xlNone

            With .Borders(xlBottom)
                .Weight = xlMedium
                .ColorIndex = xlAutomatic
            End With

        .Borders(xlTop).LineStyle = xlNone
        .Borders(xlLeft).LineStyle = xlNone
        .BorderAround LineStyle:=xlNone

    End With

  k = k + 1

  Else

End If

Next time_loop

End Sub

Function ui(pressure, posn, T)
Dim ui_incr As Single
Dim m As Single
Dim k As Integer

k = 0: ui = 0

  Do

    m = 0.5 * (22 / 7) * (2 * k + 1)
    ui_incr = 2 * pressure / m * Sin(m * posn) * Exp(-(m ^ 2 * T))
    ui = ui + ui_incr
    k = k + 1

    If k >= 200 Then
    Exit Do
    Else
    End If

  Loop Until Abs(ui_incr) <= pressure / 1000 And remain(k, 10) = 0

End Function

Function void(new_stress)

Dim a As Double

If new_stress <= 1 Then
    void = Worksheets("sheet4").[d8].Value

Else
   a = 0.43429448 * Log(new_stress)
   void = b * a ^ 2 + c * a + d
End If

End Function

Function G(new_stress, old_stress, old_void, new_void)

Dim a As Double
```

```
Dim Mv_i As Double
Dim perm As Double

    a = 0.43429448 * Log(new_stress)
    perm = 10 ^ (c * a ^ 2 + f * a + h)
    Mv_i = ((new_stress - old_stress) / (old_void - new_void))
    G = perm * Mv_i / 9.81 / (1 + old_void) * 3600 * 24

End Function

Function T(G, void_ratio, drainage_l, time)

    T = G * (1 + void_ratio) ^ 2 * time / drainage_l ^ 2

End Function

Function remain(number, division)

Dim a_number As Single
Dim b_number As Single

    a_number = number / division
    b_number = Int(number / division)
    remain = a_number - b_number

End Function
```

APPENDIX C

Curve Fitting Procedure:

Procedure to Create Charts With Curve Fitting to Data

In Excel, a function exists to create charts by way of a number of shortcut key strokes. This is done by the use of the "Chart Wizard" button on the default menu of Excel.

Using the "Property Graphs" sheet, carry out the following actions:

1) Click on the Chart wizard button, and holding the left mouse button down, create a window on the sheet where the chart is to be placed.

2) A dialogue box appears asking for the data range. With the mouse pointer, go to the "lab input" sheet (click) and go to the first cell of the X-range, click left button of mouse and keeping it down go to the bottom of the X-range. Then depress the Ctrl key and go to the top of the Y range with the mouse pointer, click left button and keeping it down go to the bottom of the Y-range. Then click on the NEXT button of the dialogue box.

3) Next dialogue box, click on XY (Scatter) box, and then NEXT button.

4) Next dialogue box, click on the No 2 box, and then NEXT button.

5) Next dialogue box, click on the upper arrow of "Use First Column(s) for X Data", to change the counter in the box to one. The second box is relevant if the X-range and Y-range selected includes titles for the data. This can be displayed on the graph. Click on NEXT button.

6) The next dialogue box is self explanatory, the purpose of which is to give titles to the axes and chart. Click on FINISH button.

   The chart is now complete.

The next step is to get Excel to do a linear regression analysis on the graph. These steps are:

1) Double click the mouse left button with pointer inside the plot area.

2) Click with <u>right</u> button of mouse with pointer on the data line of the graph. A menu appears, and one needs to select "Insert Trendline"; click once on left mouse button.

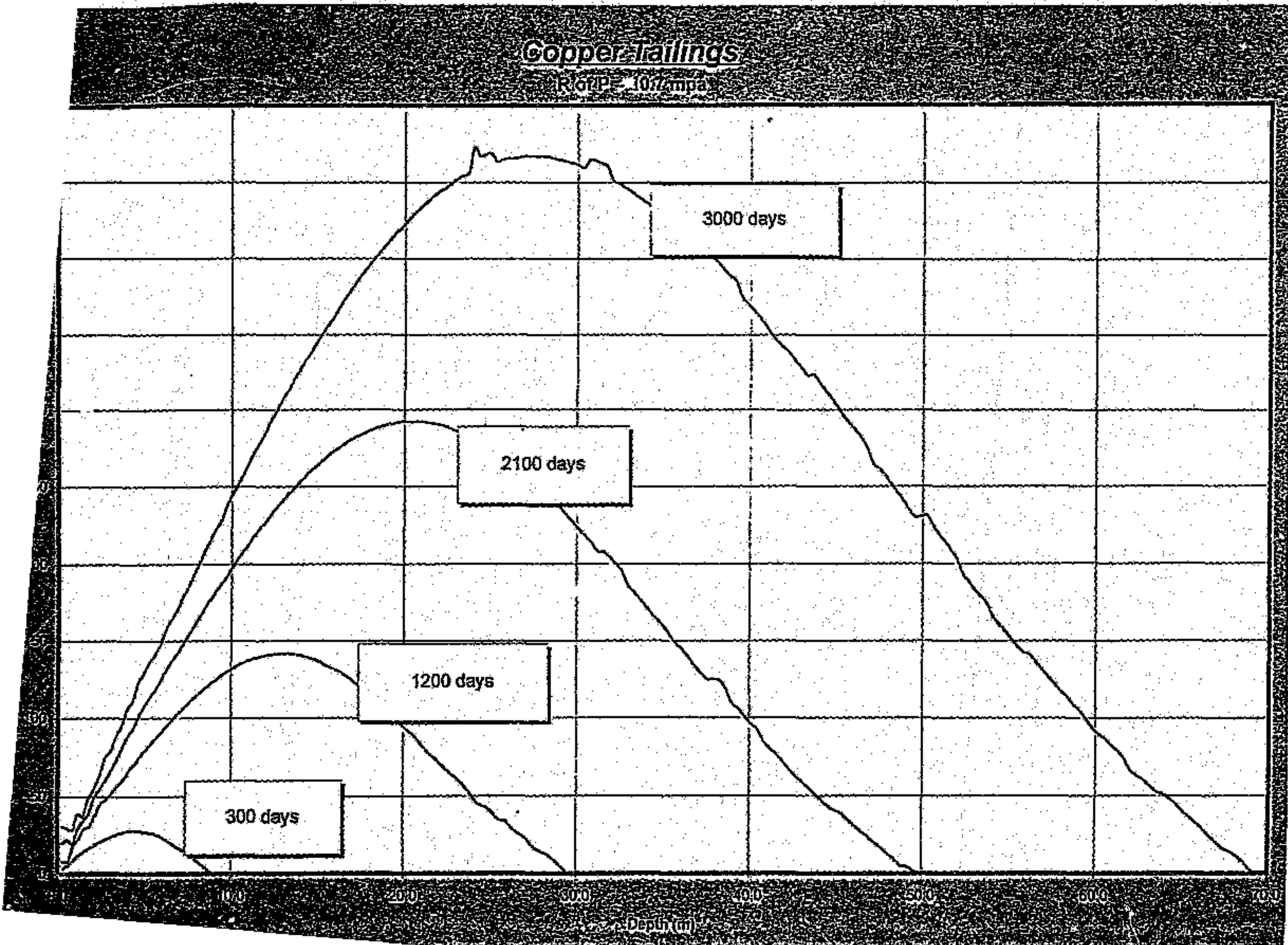
3) A dialogue box comes up, where one can select the type of trendline to be fitted to the data (usually polynomial of order 2 works well). Click on "Options" label of dialogue box, and click on the lowest two boxes, to activate "Display Equations on Chart" and "Display R-squared Valve on Chart", Click on OK button.

The regression equation is displayed on the graph, with its correlation. This equation now needs to be manually copied to the relevant cells in the "Soil Properties" sheet of the spreadsheet. If the correlation coefficient is low, steps 2 and 3 can be repeated with a different type of trendline until the correlation is acceptable.

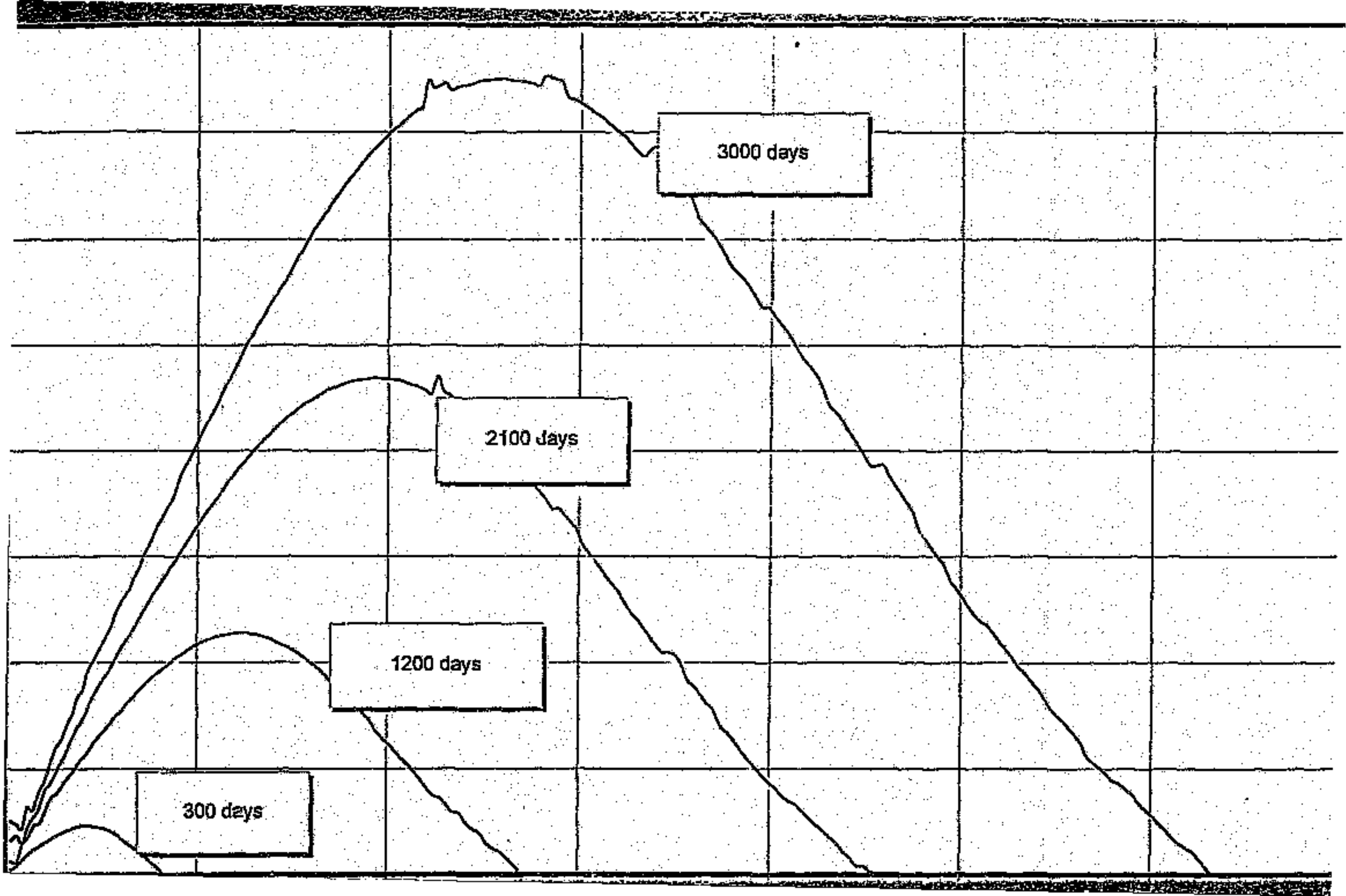
APPENDIX D

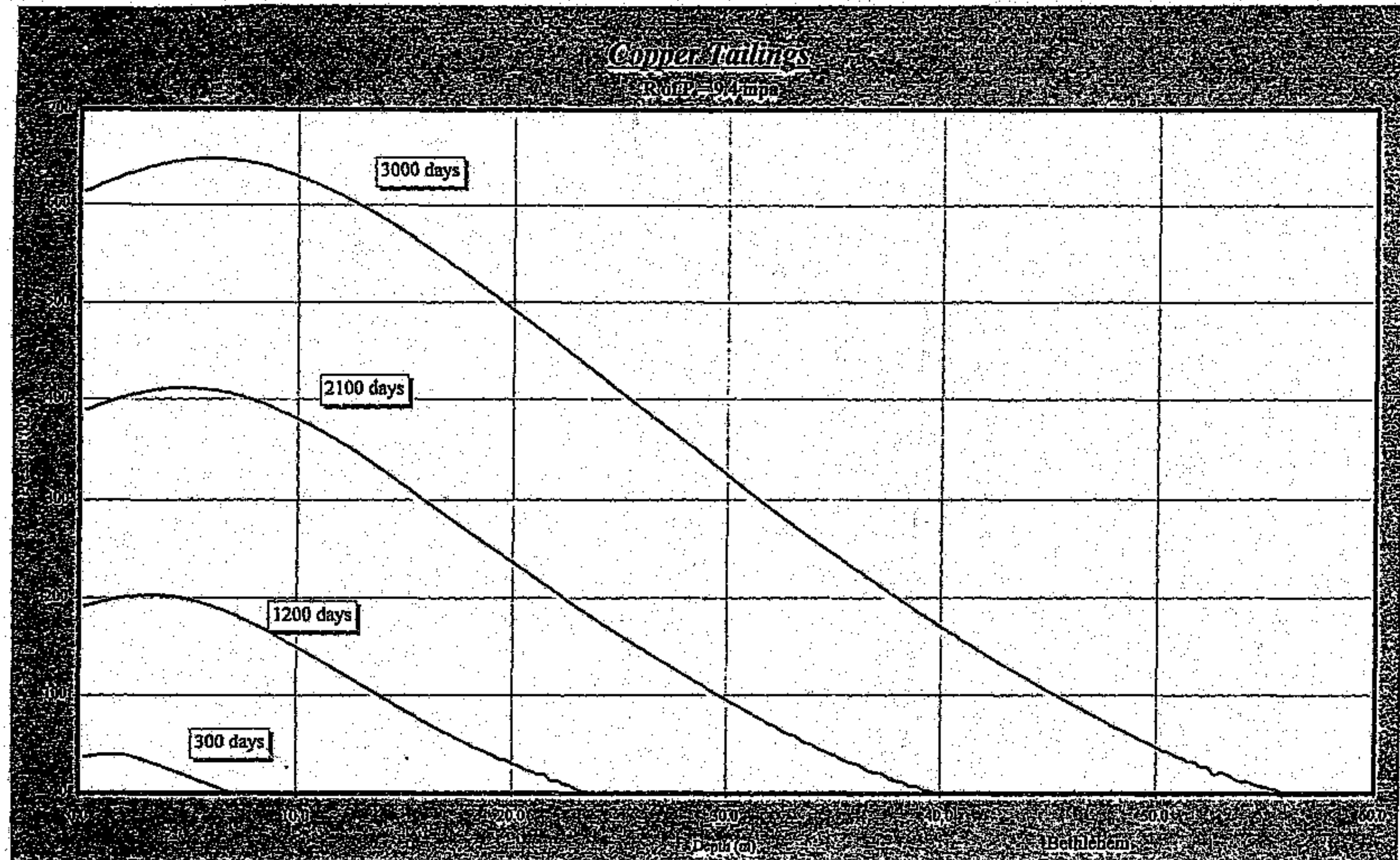
Pore Pressure Profiles for:

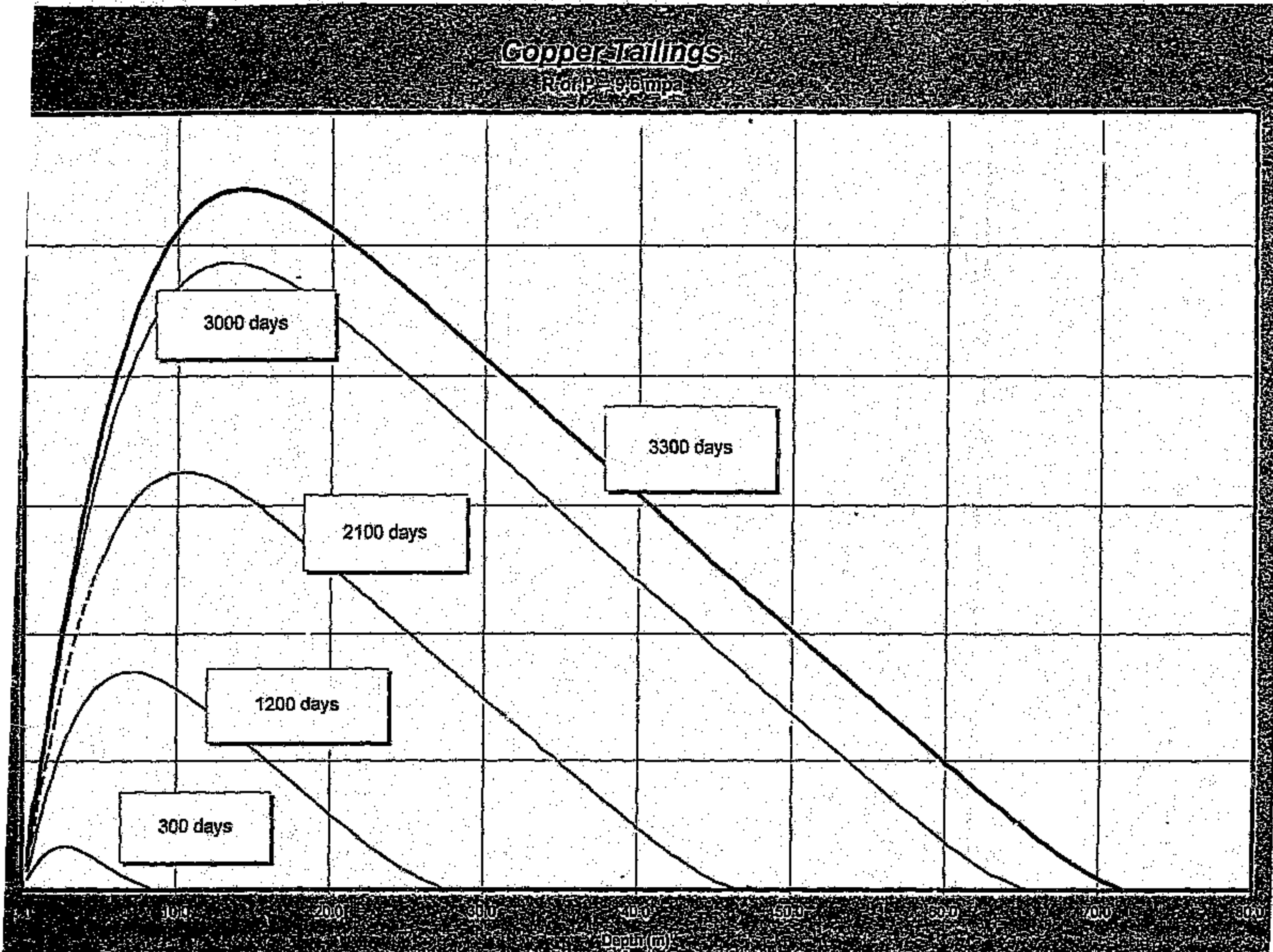
Copper	11 pages
Gold - fine	5 pages
Gold - coarse	6 pages
Bauxite	7 pages
Coal	5 pages
Manganese	6 pages
Acid Mine Drainage Sludge	6 pages

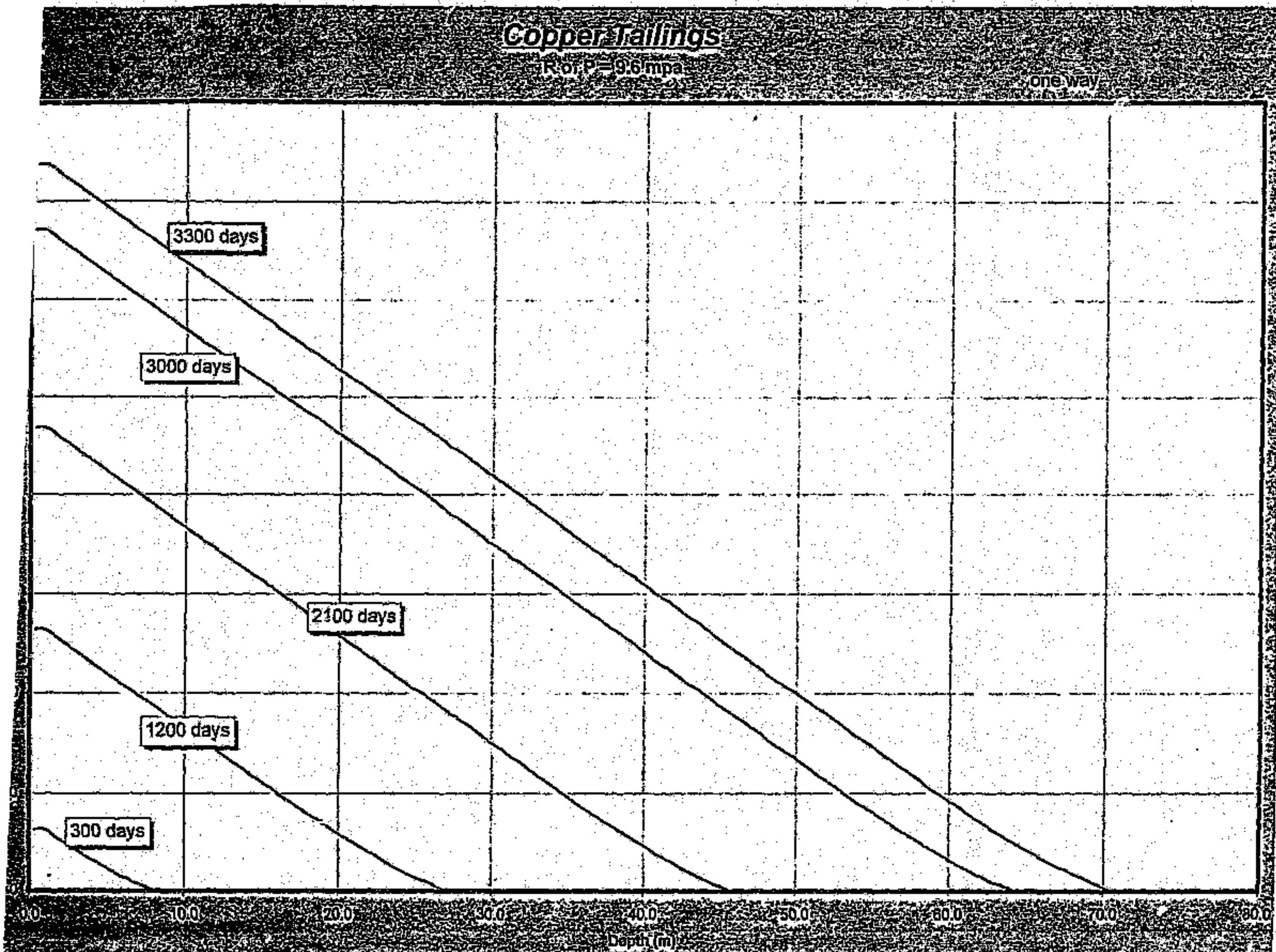


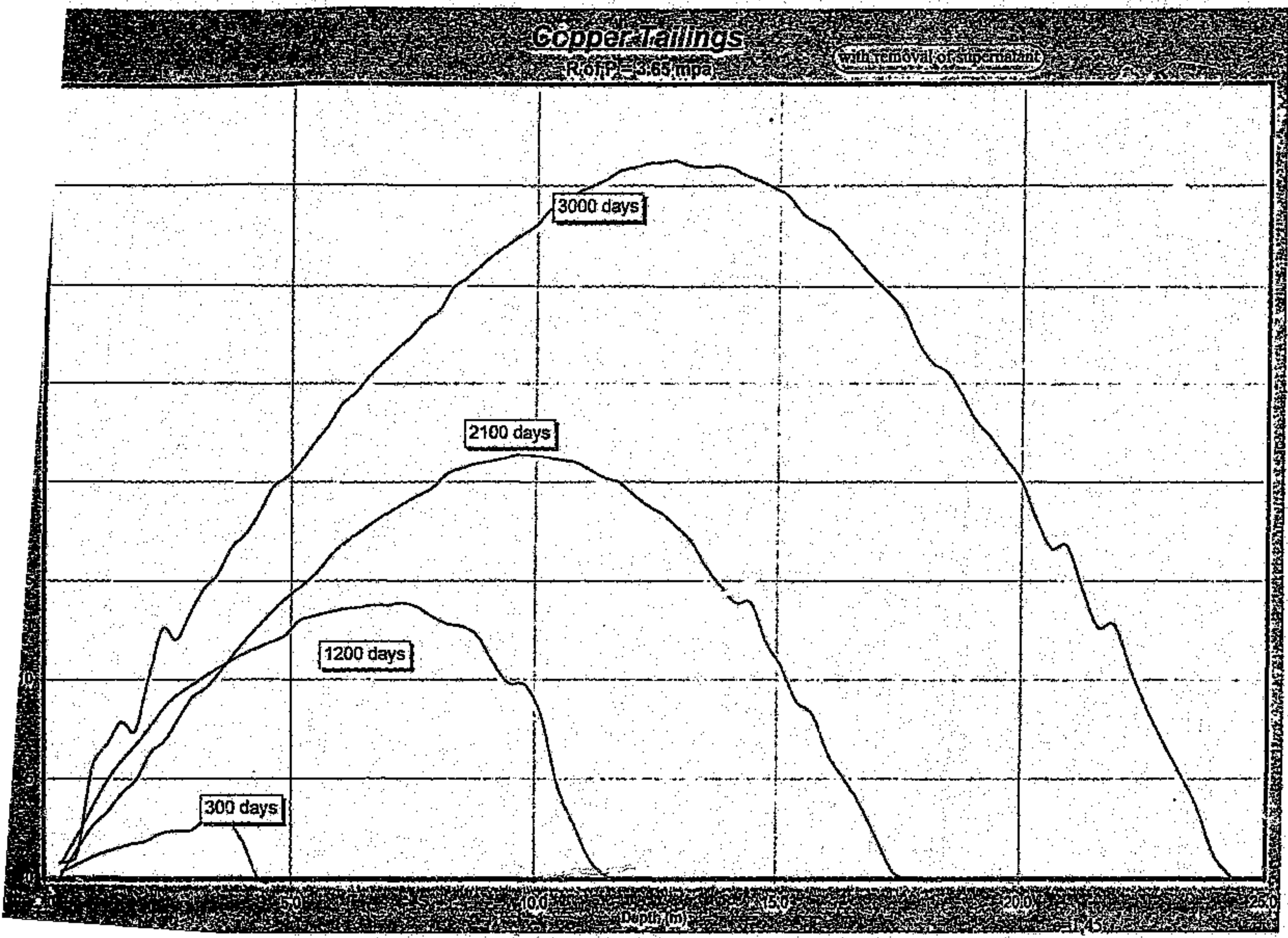
Copper Tailings
3000 days
2100 days
1200 days
300 days
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Depth (m)


3000 days
2100 Jays
1200 days
300 days

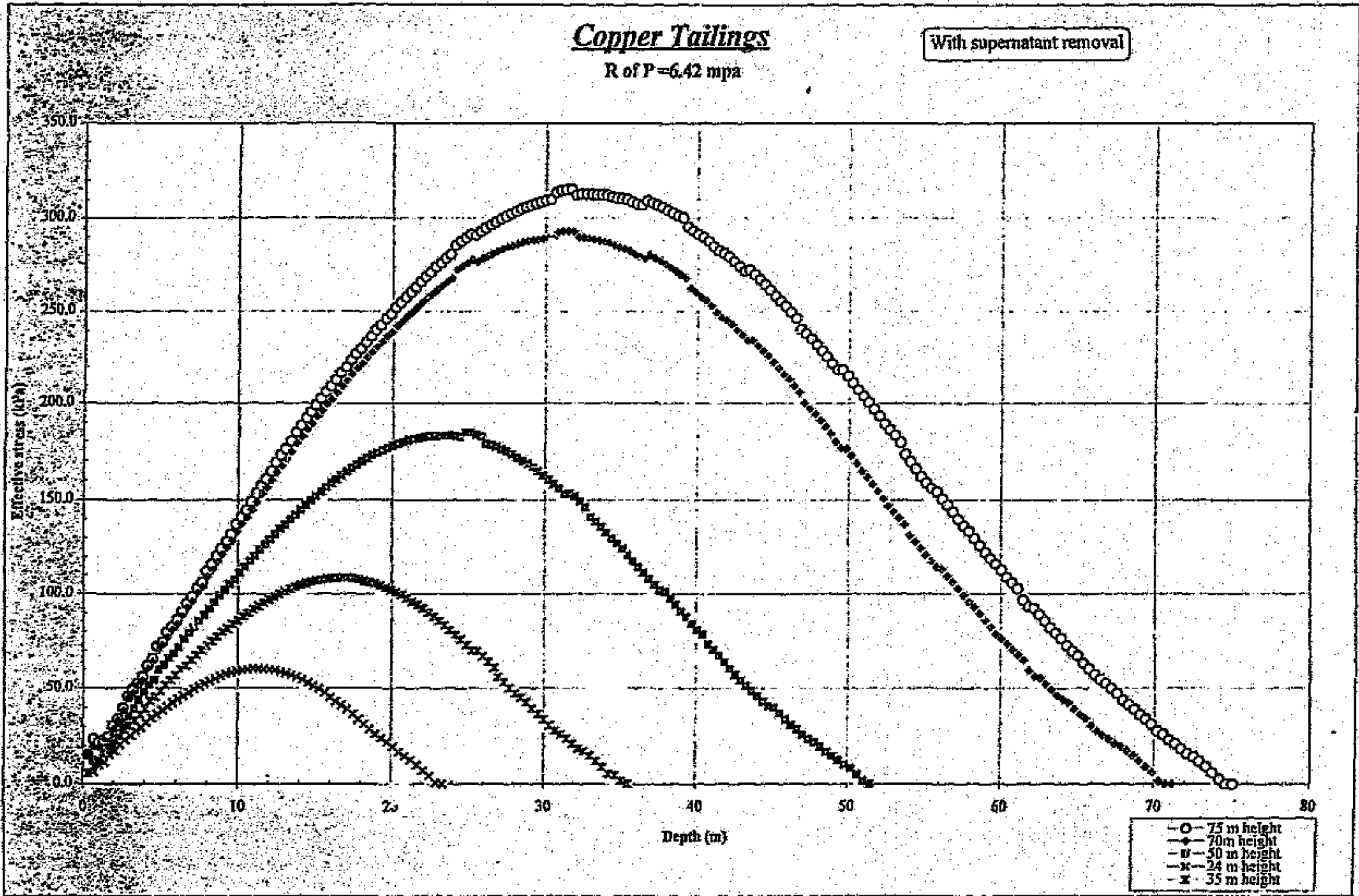

Copper Tailings
3000 days
2100 days
1200 days
300 days
10.0
20.0
30.0
40.0
50.0
60.0
Depth (m)
Bethlehem

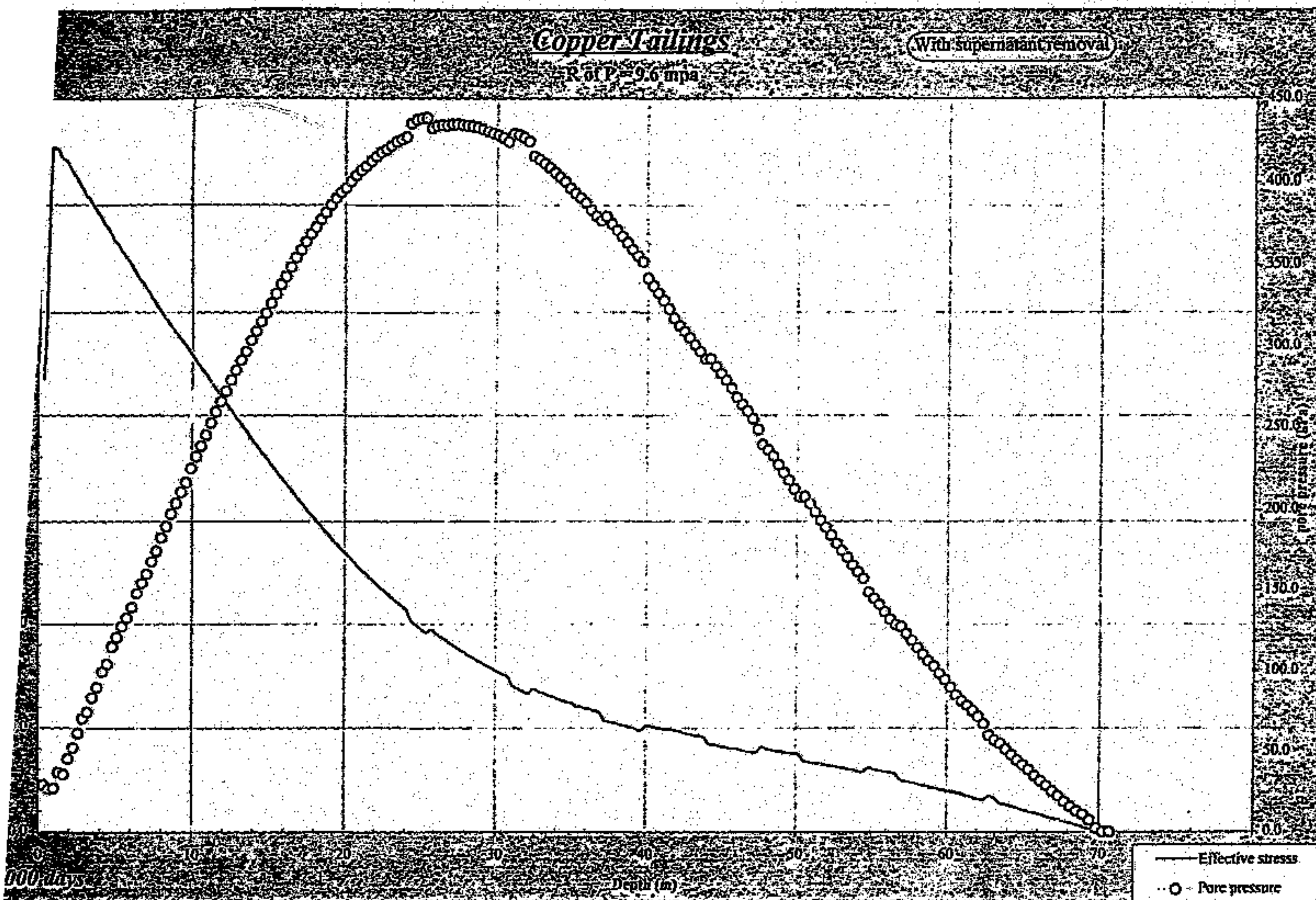

Copper Tailings
R of P = 9.6 mpa
3000 days
3300 days
2100 days
1200 days
300 days
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Depth (m)

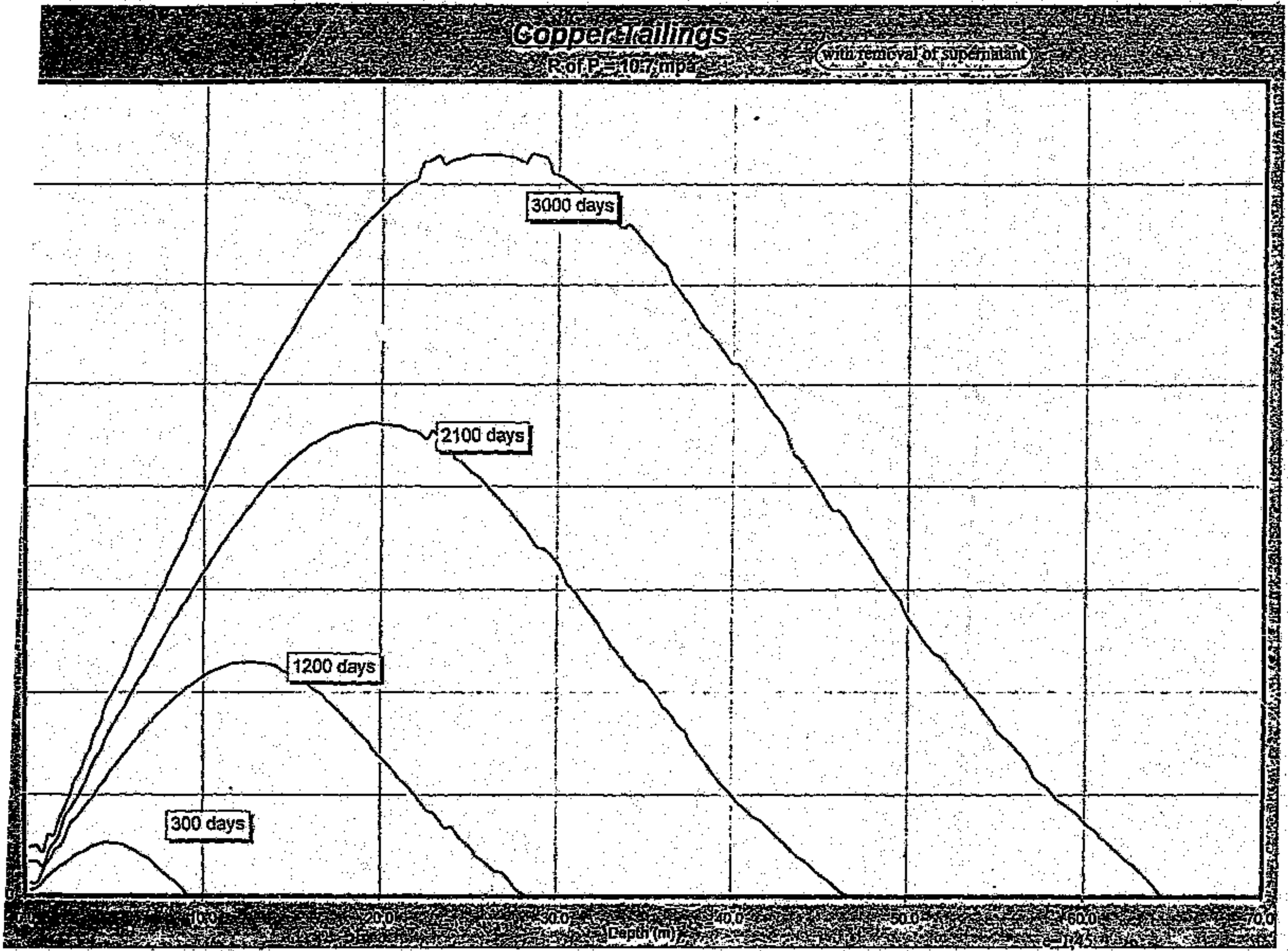

Copper Tailings
R or P = 9.6 mpa
one way
3300 days
3000 days
2100 days
1200 days
300 days
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Depth (m)

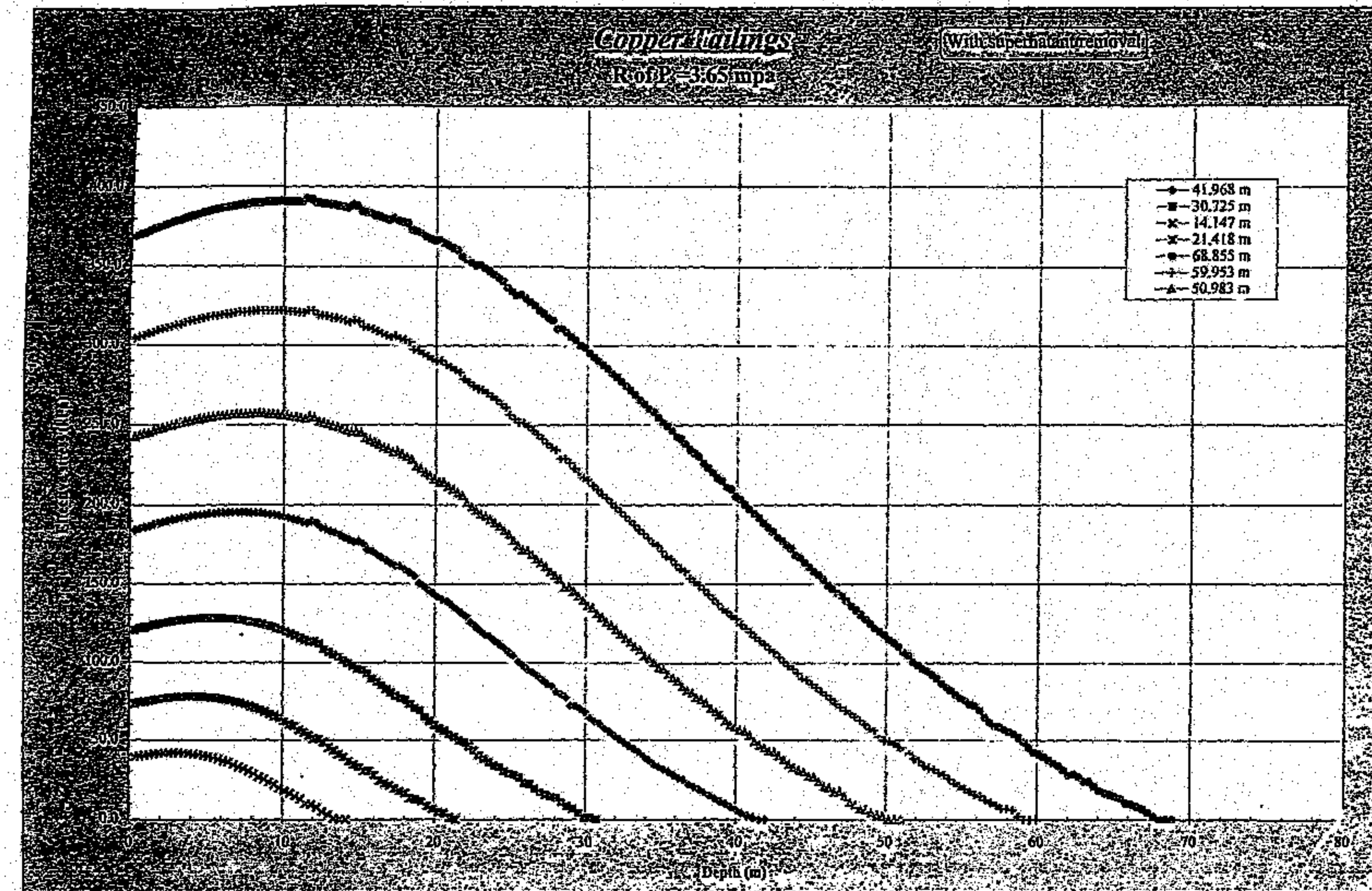


Copper Tailings
R of P = 3.65 mpa
with removal of supernatant
3000 days
2100 days
1200 days
300 days
5.0
10.0
15.0
20.0
25.0
Depth (m)

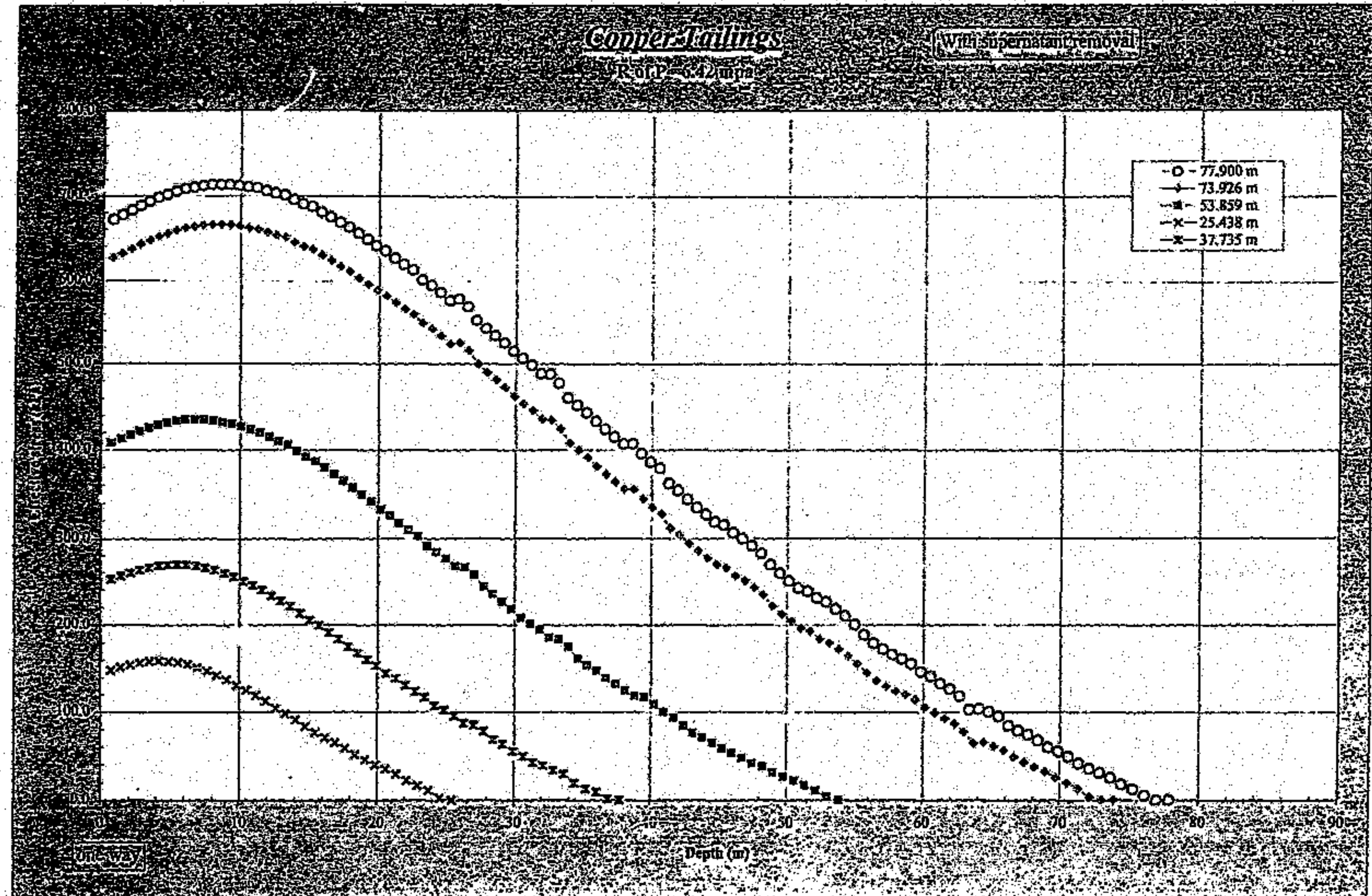

Copper Tailings
R of P =6.42 mpa
With supernatant removal
Effective stress (kPa)
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0
10
20
30
40
50
60
70
80
Depth (m)
75 m height
70m height
50 m height
24 m height
35 m height


Copper Tailings
With supernatant removal
R of P = 9.6 mpa
450.0
400.0
350.0
300.0
250.0
200.0
150.0
100.0
50.0
0.0
0
10
20
30
40
50
60
70
Depth (m)
000 days
Effective stresss
Pore pressure

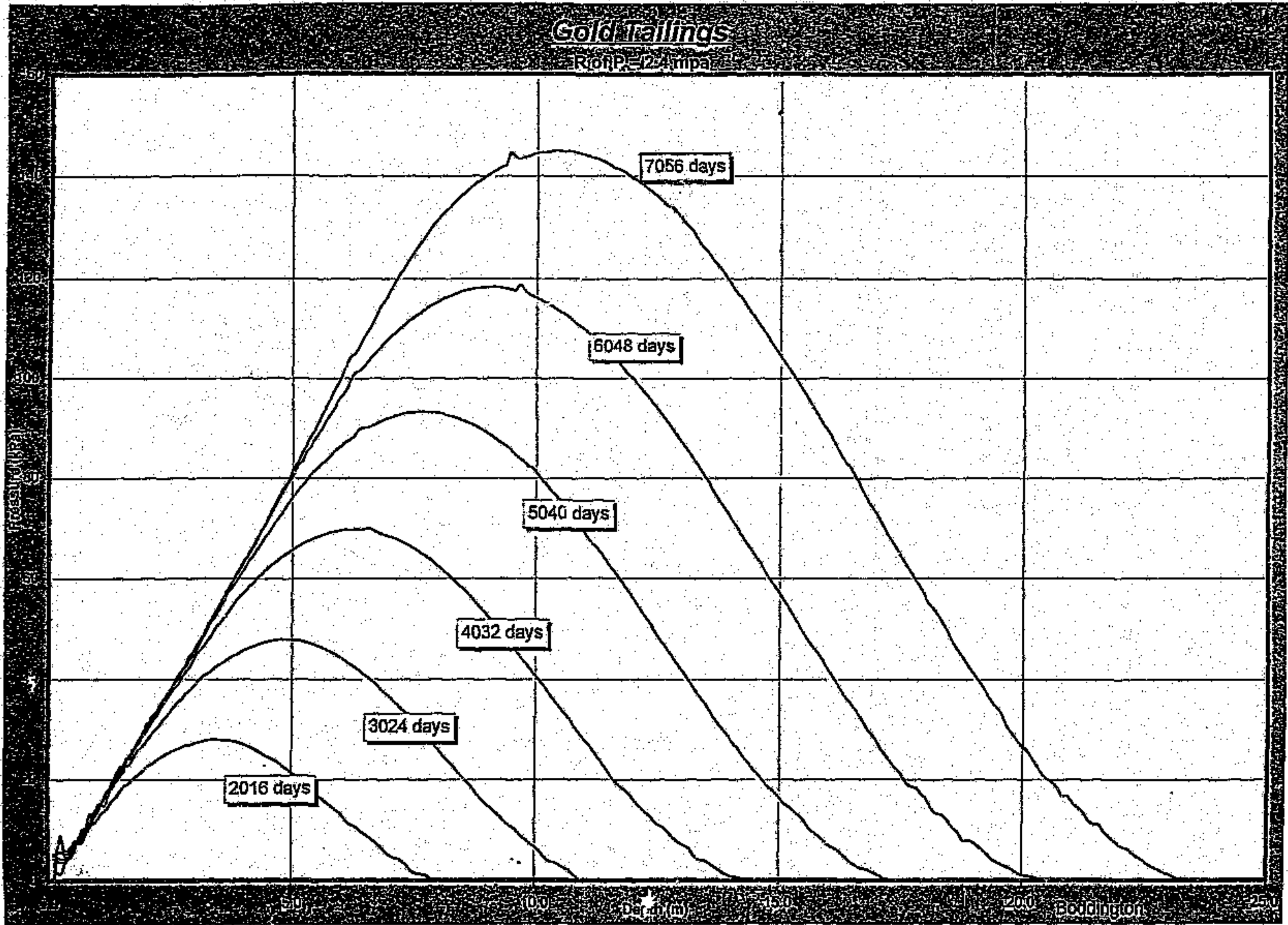

Copper Tailings
R of P = 10.7 mpa
with removal of supernatant
3000 days
2100 days
1200 days
300 days
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Depth (m)



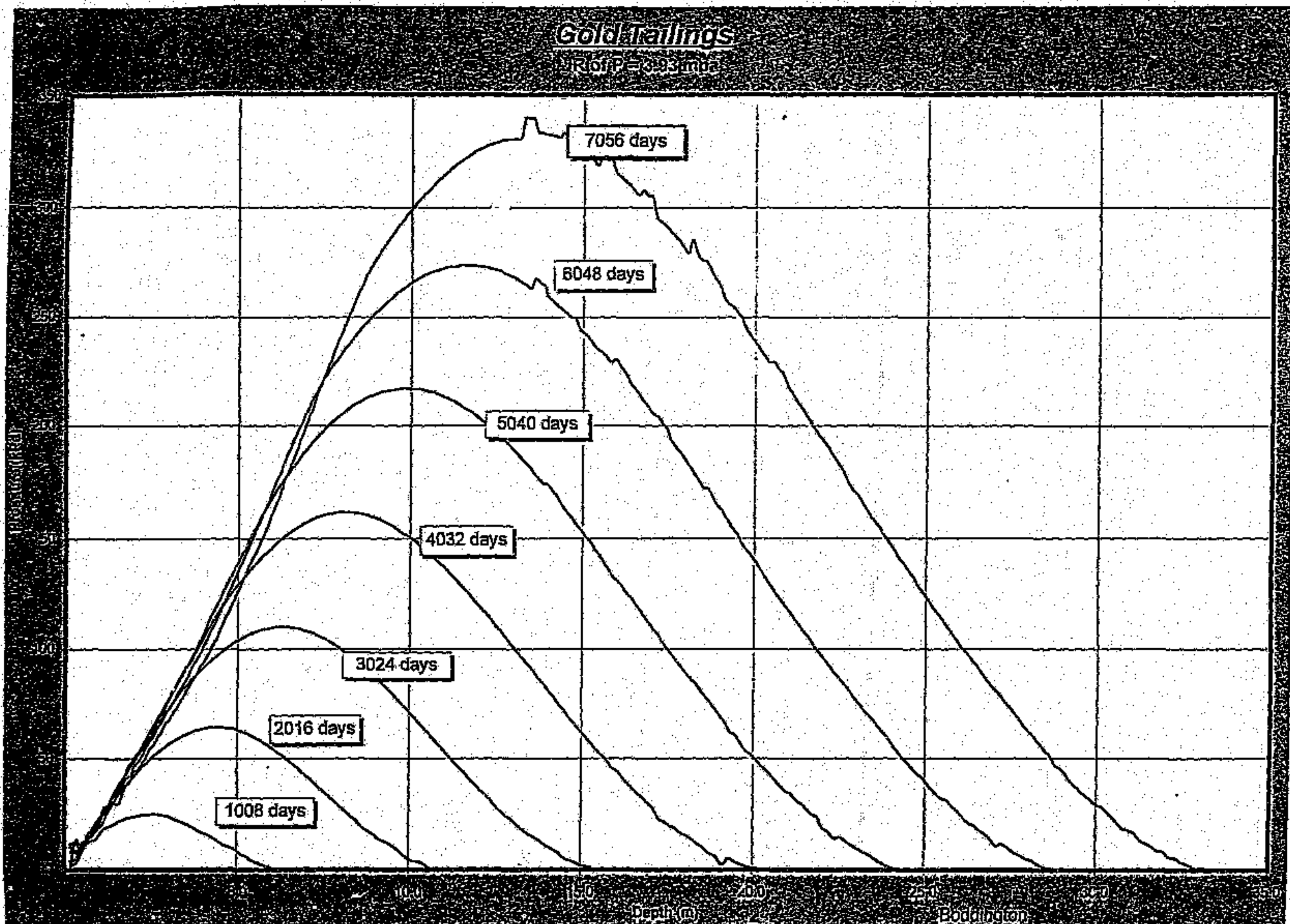
Copper Tailings
R of P = 3.65 mpa
41.968 m
30.725 m
14.147 m
21.418 m
68.855 m
59.953 m
50.983 m
0
10
20
30
40
50
60
70
80
Depth (m)

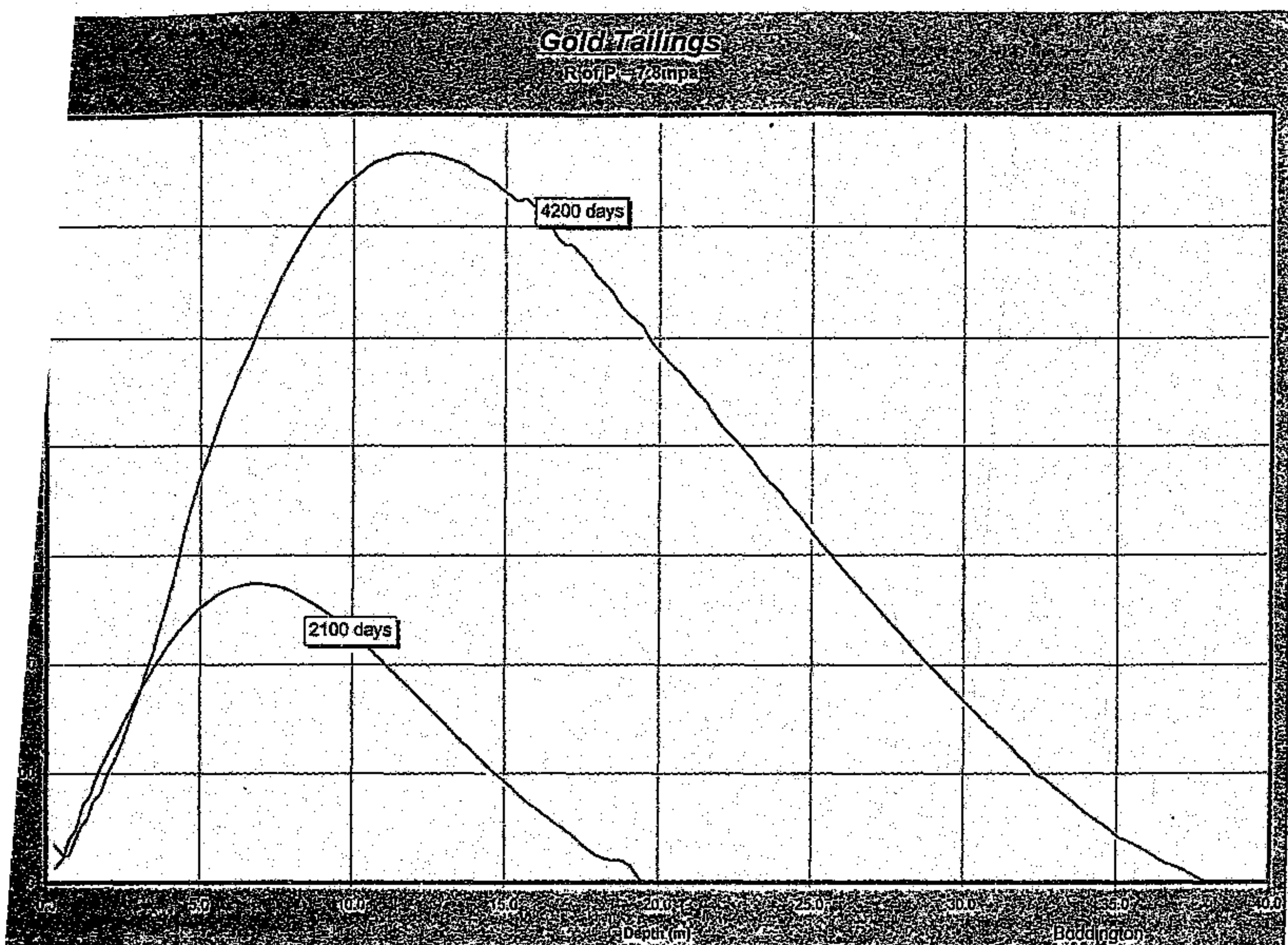


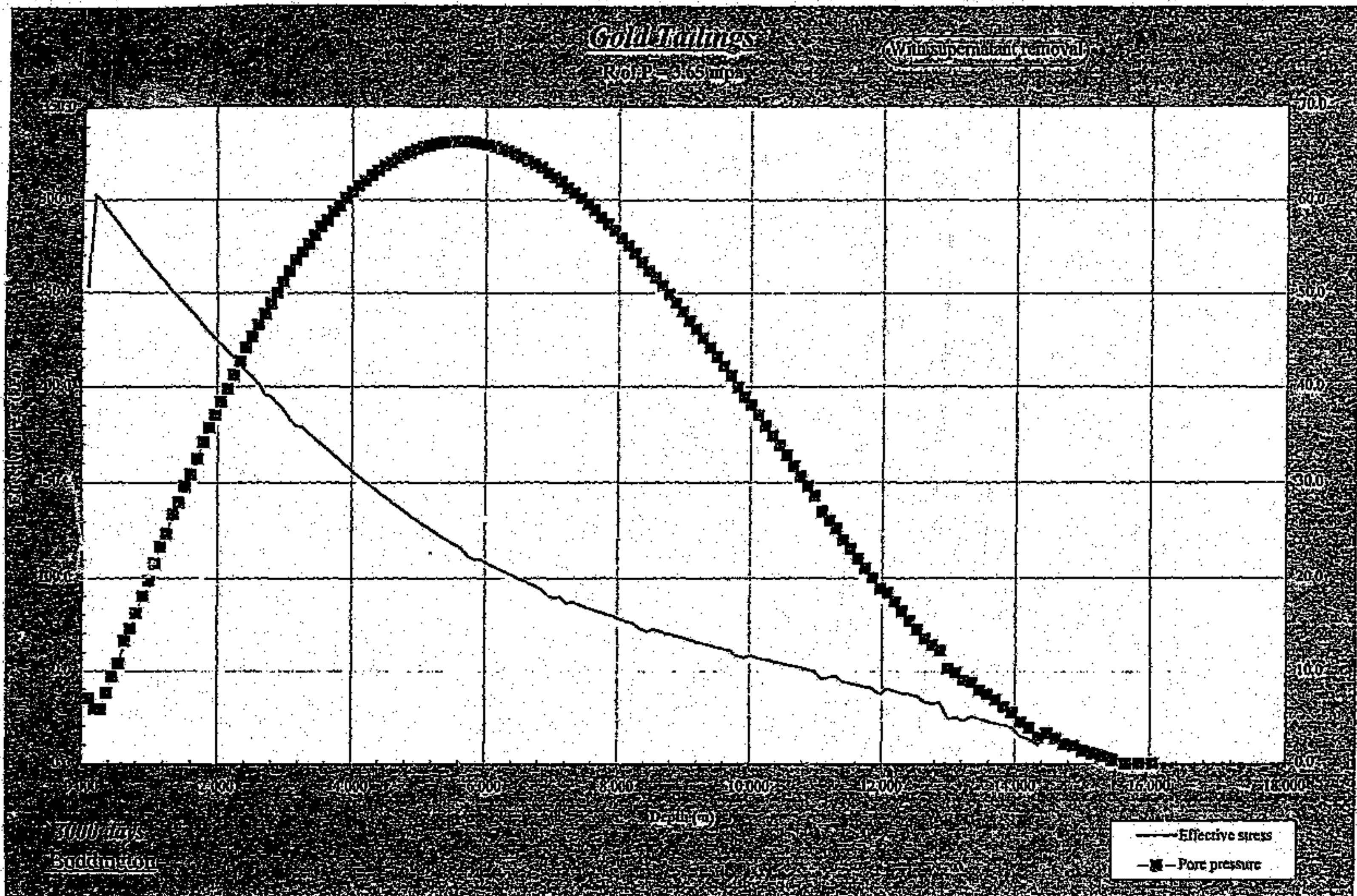
Copper Tailings
With supernatant removal
R of P = 6.42 mpa
77.900 m
73.926 m
53.859 m
25.438 m
37.735 m
Depth (m)
one way

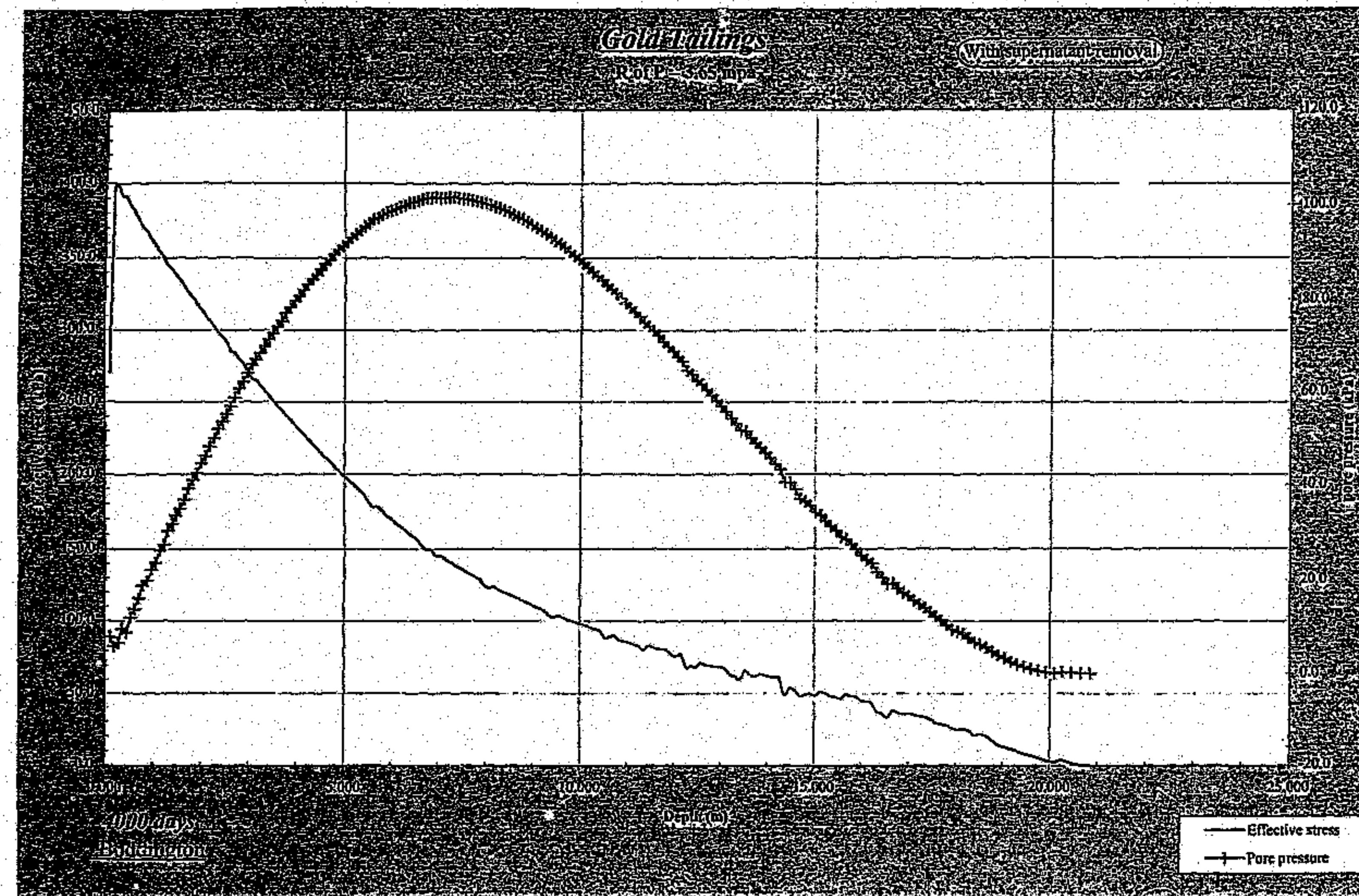


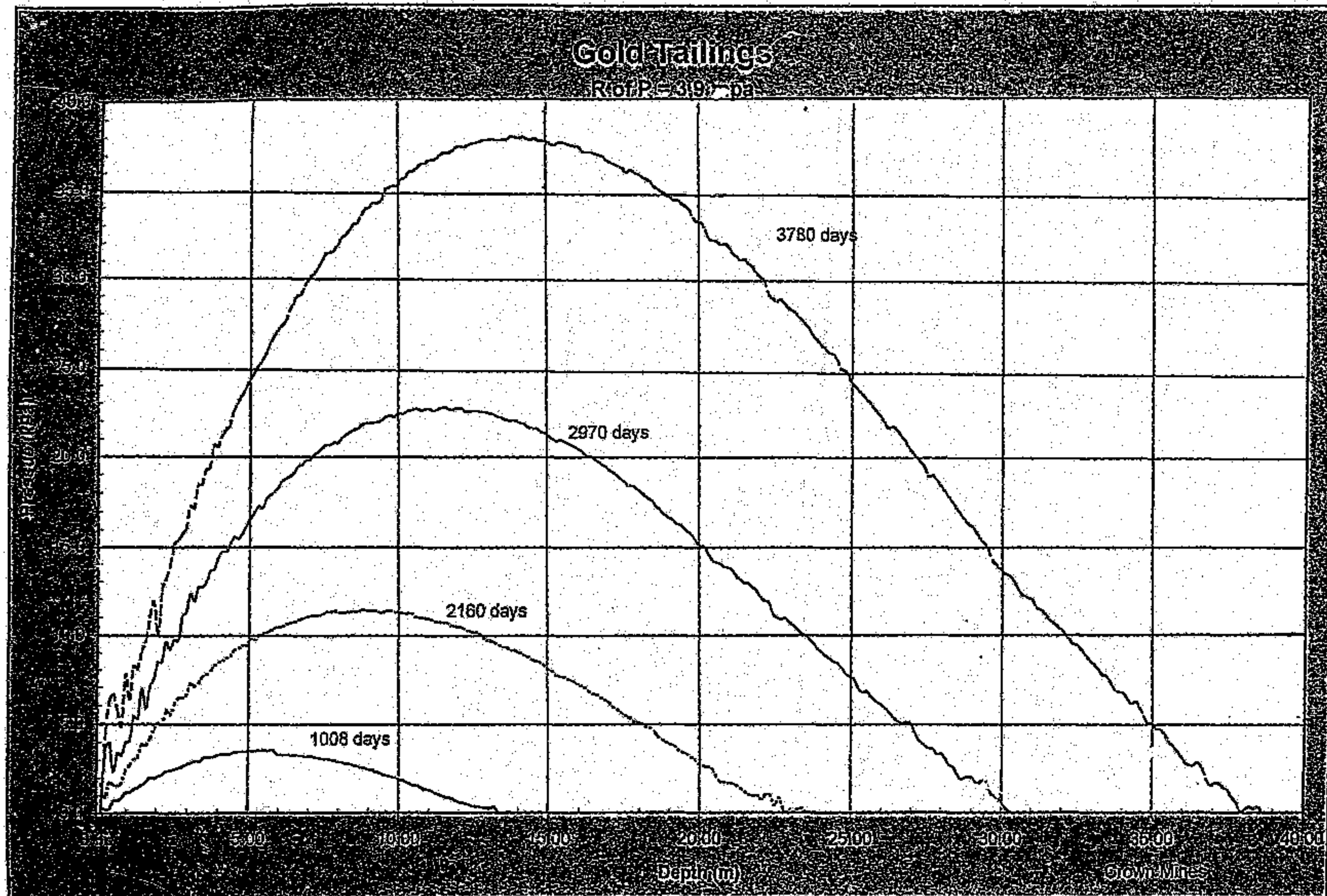
Gold Tailings
RofP = 2.4 mpa
7056 days
6048 days
5040 days
4032 days
3024 days
2016 days
Depth (m)
Boddington


Gold Tailings
7056 days
6048 days
5040 days
4032 days
3024 days
2016 days
1008 days
Depth (m)
Boddington

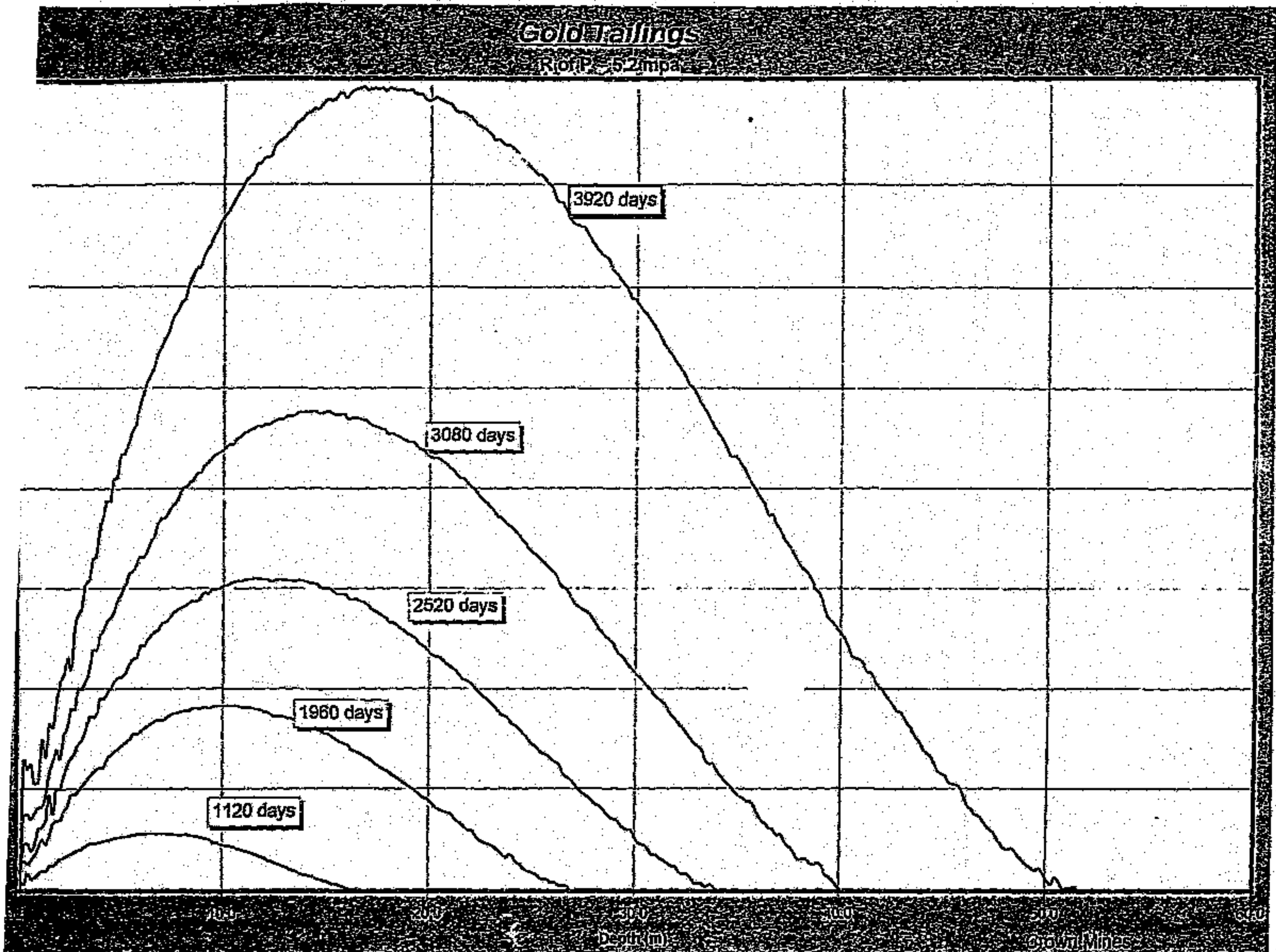

Gold Tailings
4200 days
2100 days
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Depth (m)
Boddington

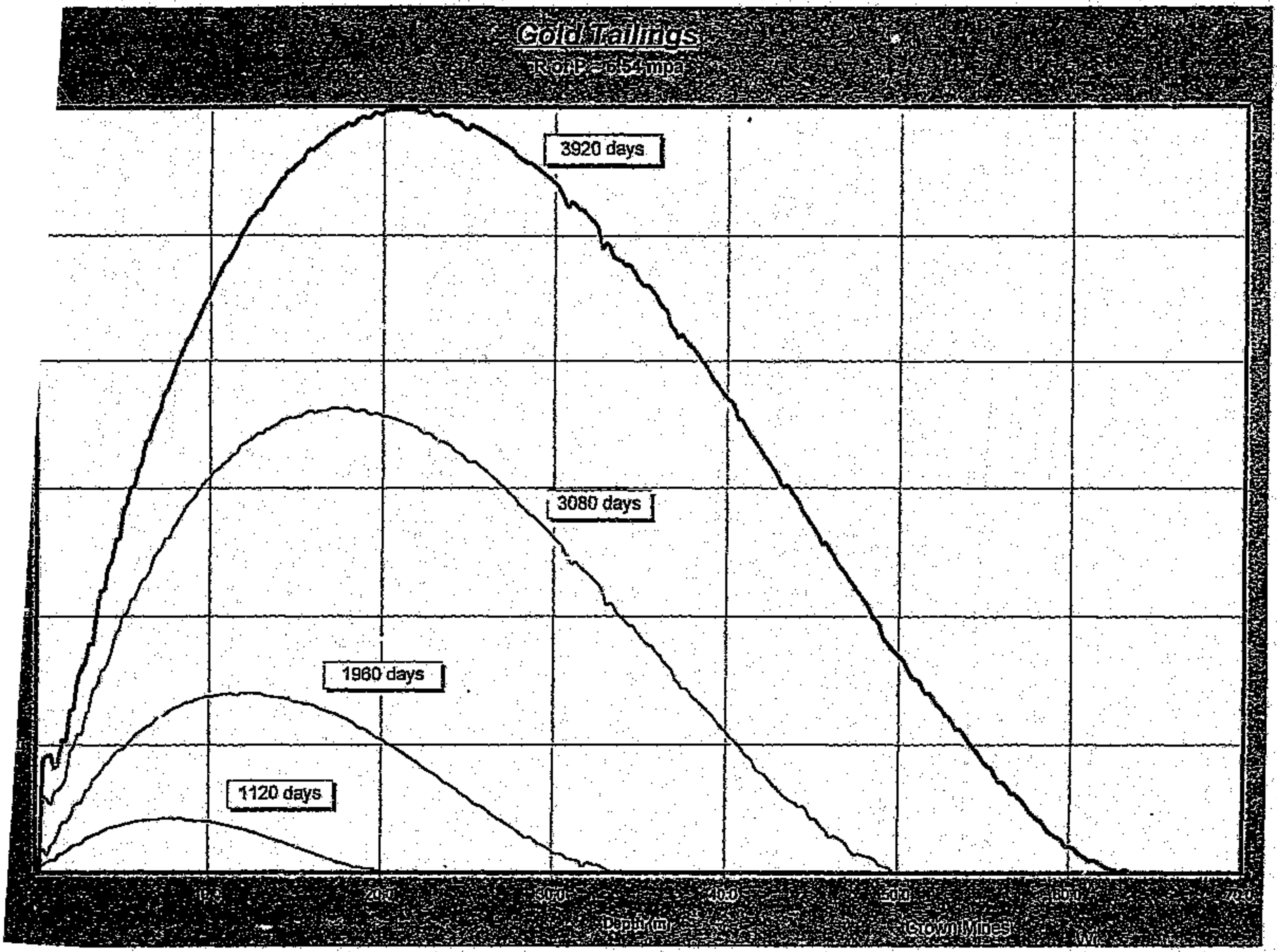

Gold Tailings
With supernatant removal
R of P = 3.65 mpa
3000 days
Buddington
Depth (m)
0.000
2.000
4.000
6.000
8.000
10.000
12.000
14.000
16.000
18.000
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
Effective stress
Pore pressure

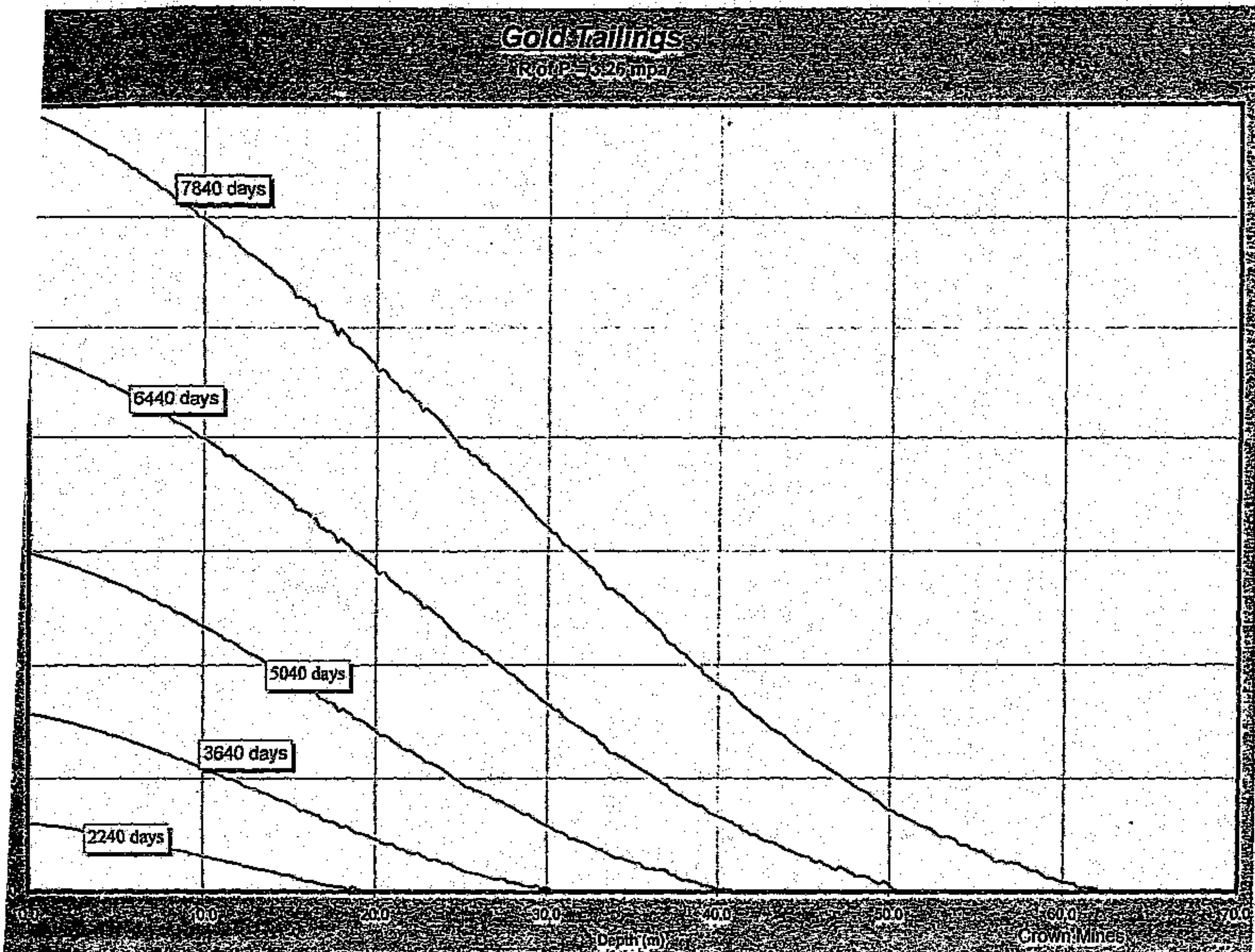

Gold Tailings
120.0
100.0
80.0
60.0
40.0
20.0
0.0
-20.0
5.000
10.000
15.000
20.000
25.000
Depth (m)
Effective stress
Pore pressure

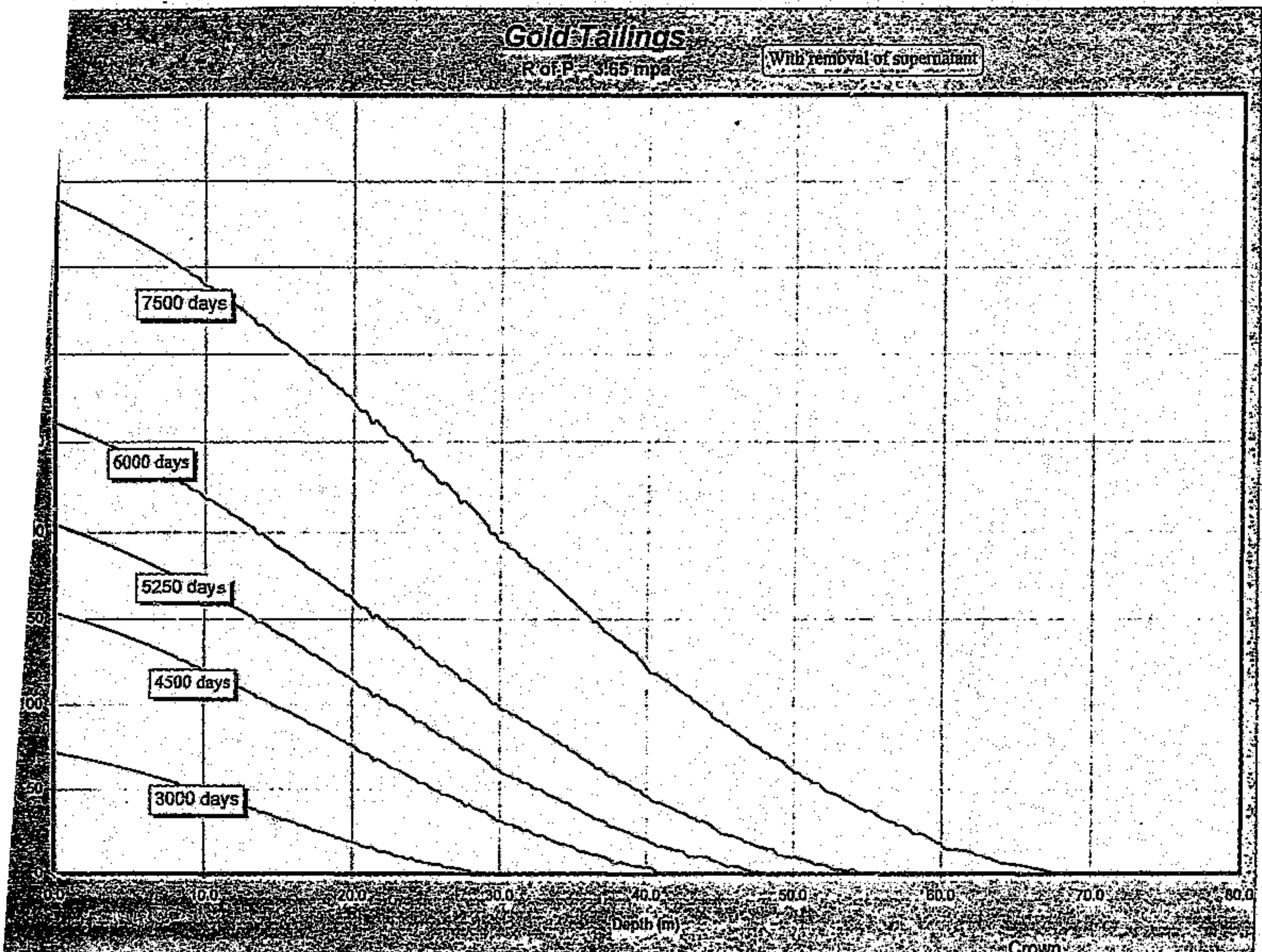


Gold Tailings
3780 days
2970 days
2160 days
1008 days
5.00
10.00
15.00
20.00
25.00
30.00
35.00
40.00
Depth (m)
Crown Mines

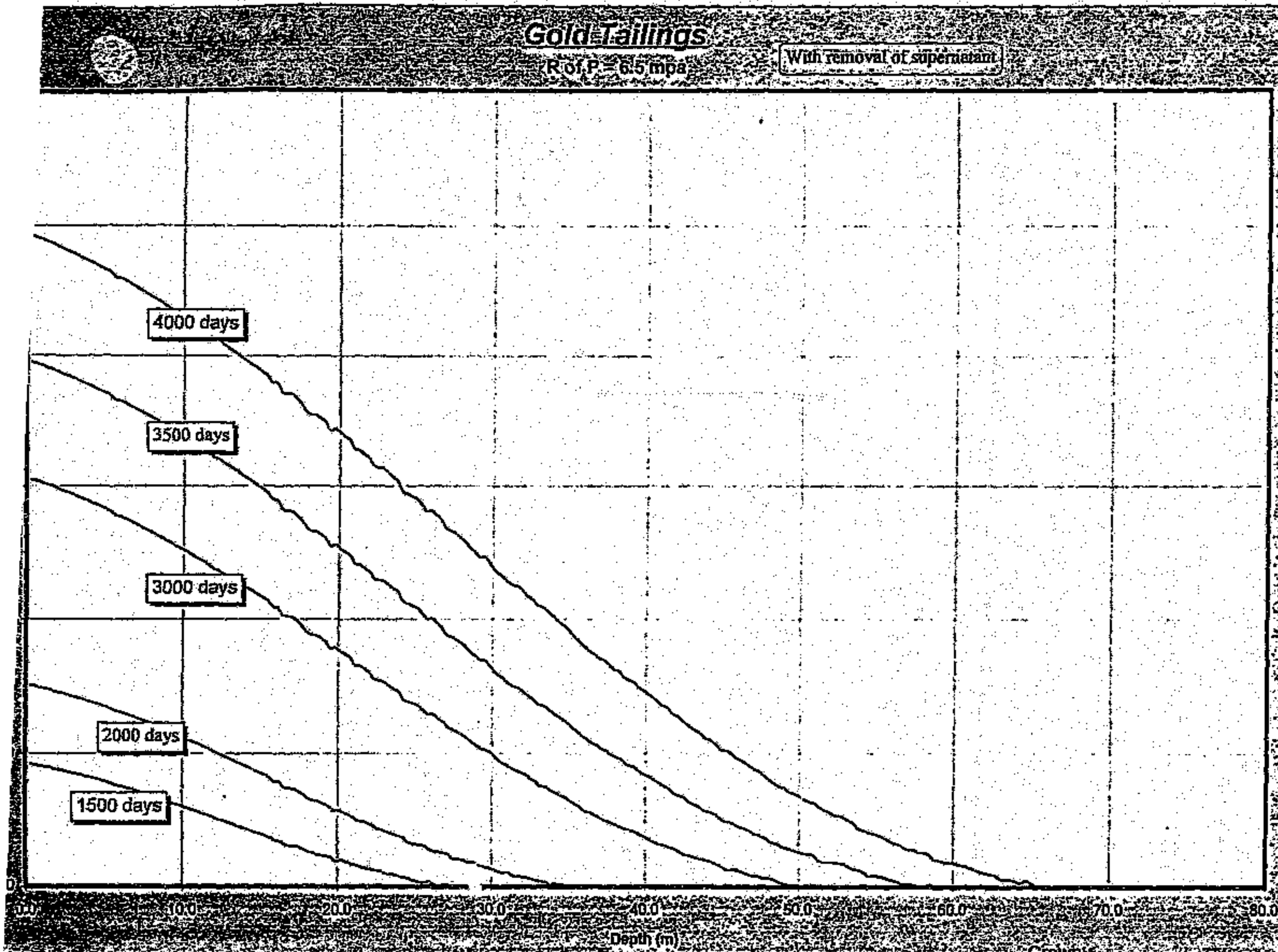

Gold Tailings
R of P = 5.2mpa
3920 days
3080 days
2520 days
1960 days
1120 days
10.0
20.0
30.0
40.0
50.0
60.0
Depth (m)
Crown Mines

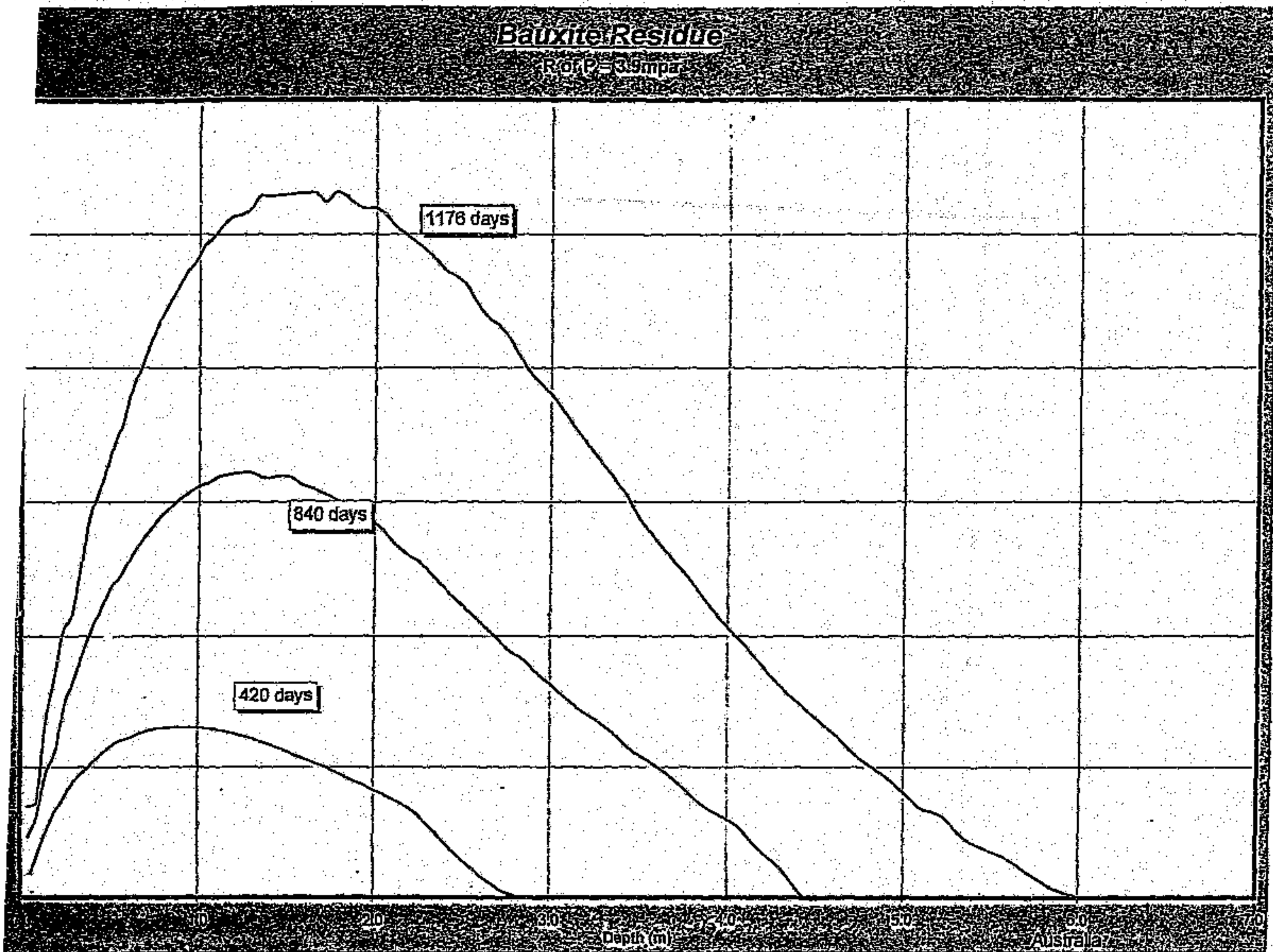

Gold Tailings
3920 days
3080 days
1960 days
1120 days
Depth (m)
Crown Mines

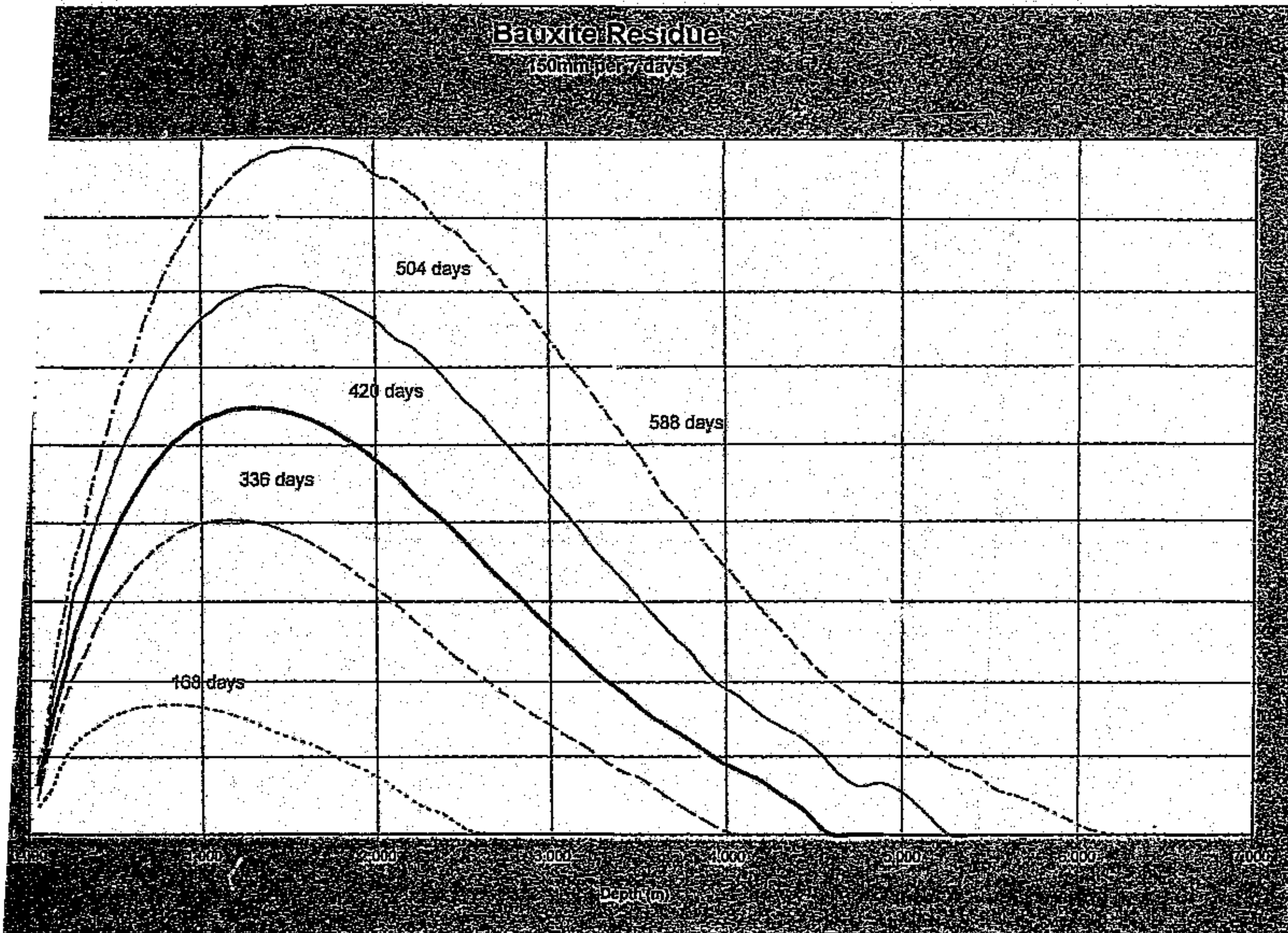

Gold Tailings
R of P = 3.26 mpa
7840 days
6440 days
5040 days
3640 days
2240 days
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
Depth (m)
Crown Mines



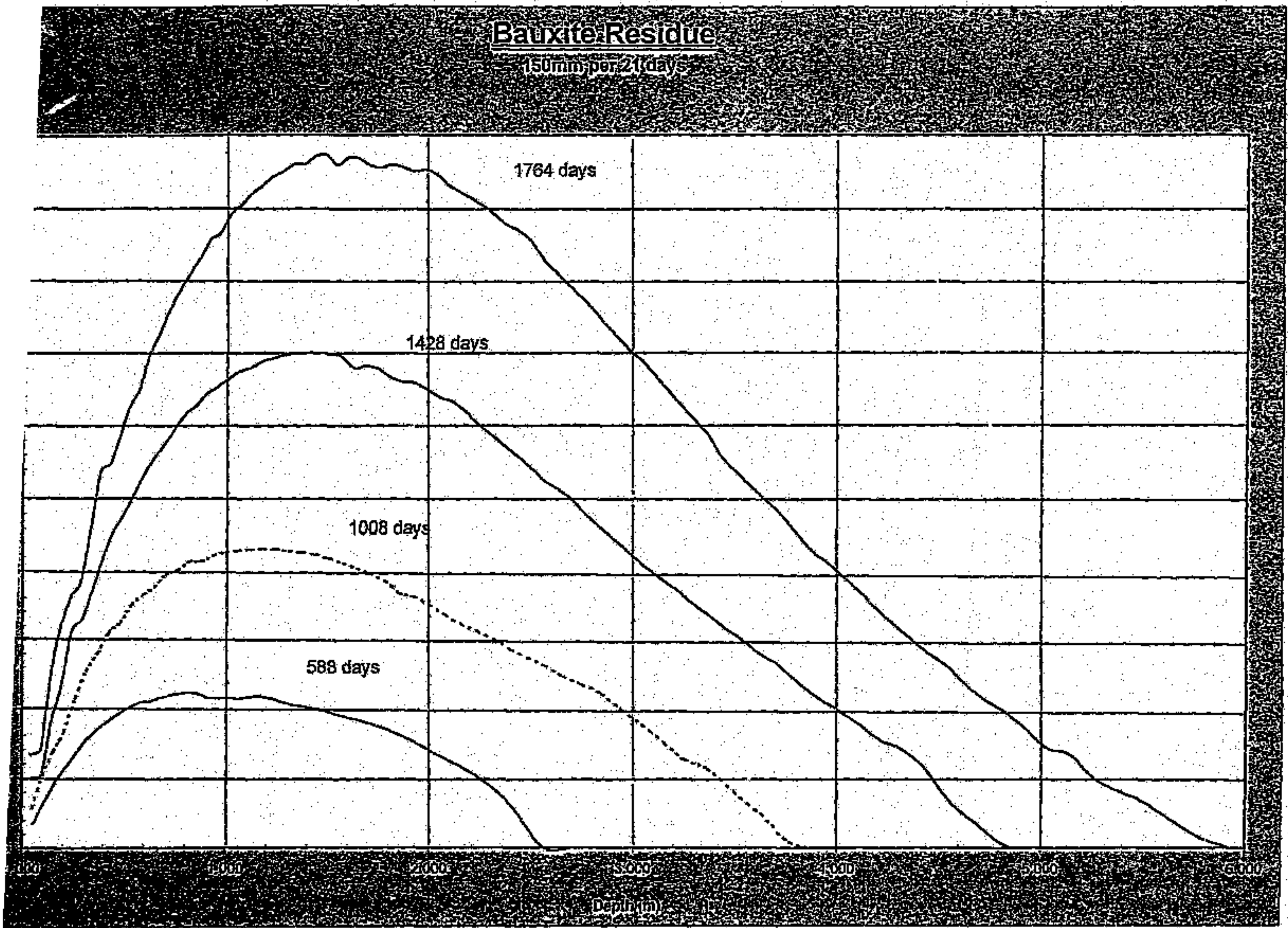
Gold Tailings
R of P – 3.65 mpa
With removal of supernatant
7500 days
6000 days
5250 days
4500 days
3000 days
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Depth (m)
Crown

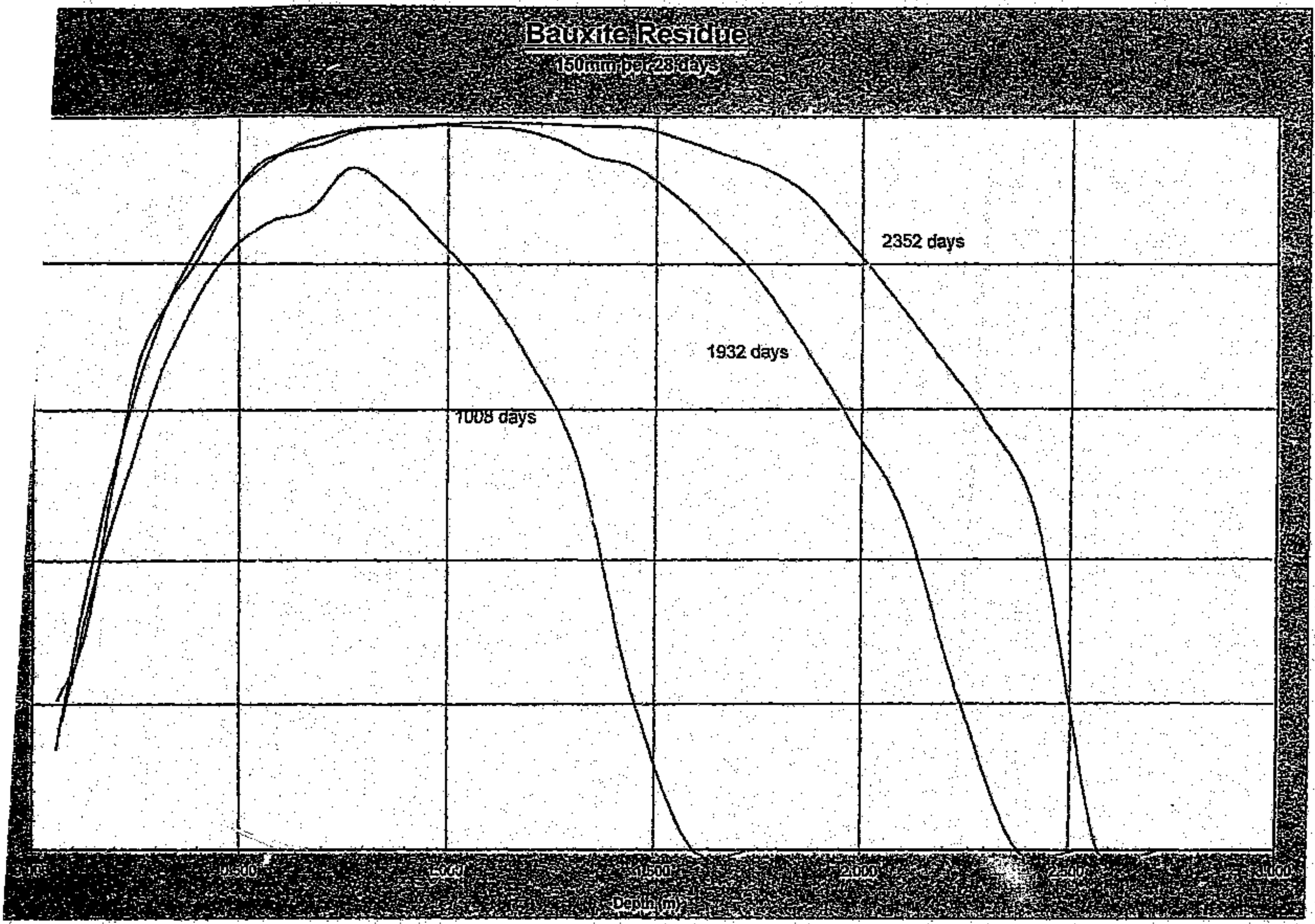

Gold Tailings
R of P = 6.5 mpa
With removal of supernatant
4000 days
3500 days
3000 days
2000 days
1500 days
0.0
10.0
20.0
30.0
40.0
50.0
60.0
70.0
80.0
Depth (m)
Crown


Bauxite Residue
R or P = 3.9mpa
1176 days
840 days
420 days
1.0
2.0
3.0
4.0
5.0
6.0
7.0
Depth (m)
Australia

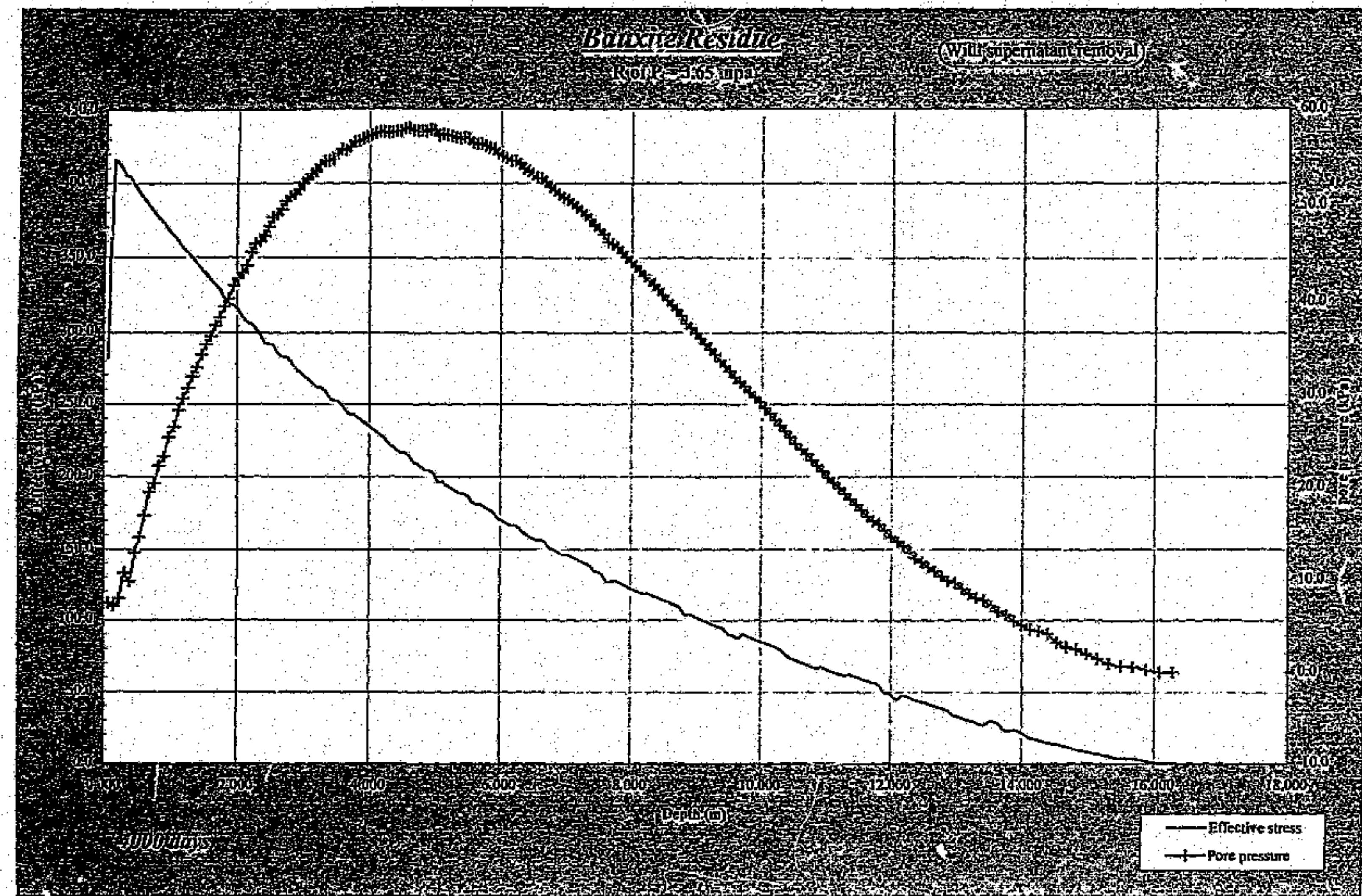


Bauxite Residue
150mm per 7 days
504 days
420 days
588 days
336 days
168 days
1,000
2,000
3,000
4,000
5,000
6,000
7,000
Depth (m)

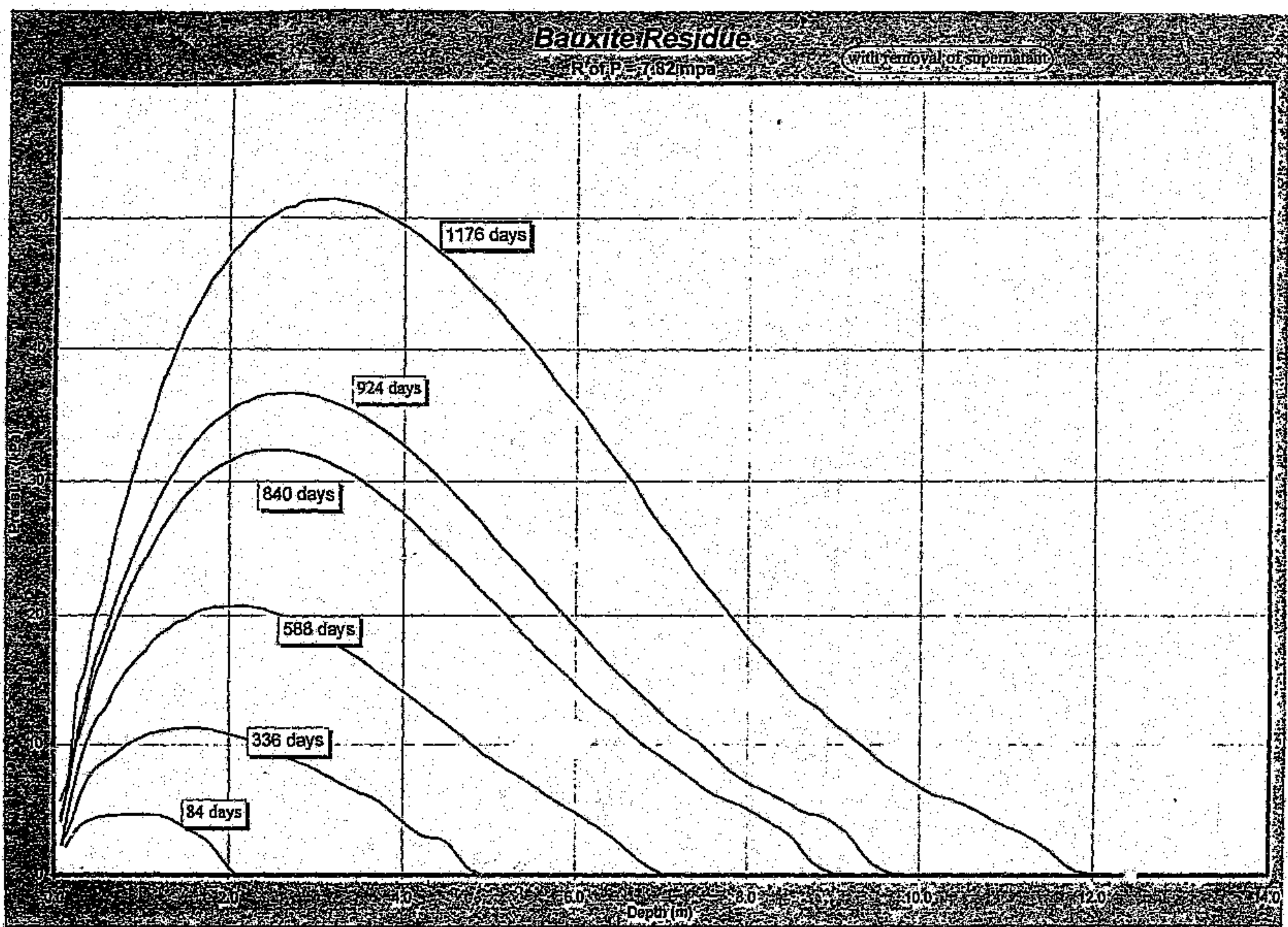

Bauxite Residue
150mm per 21 days
1764 days
1428 days
1008 days
588 days
Depth (m)



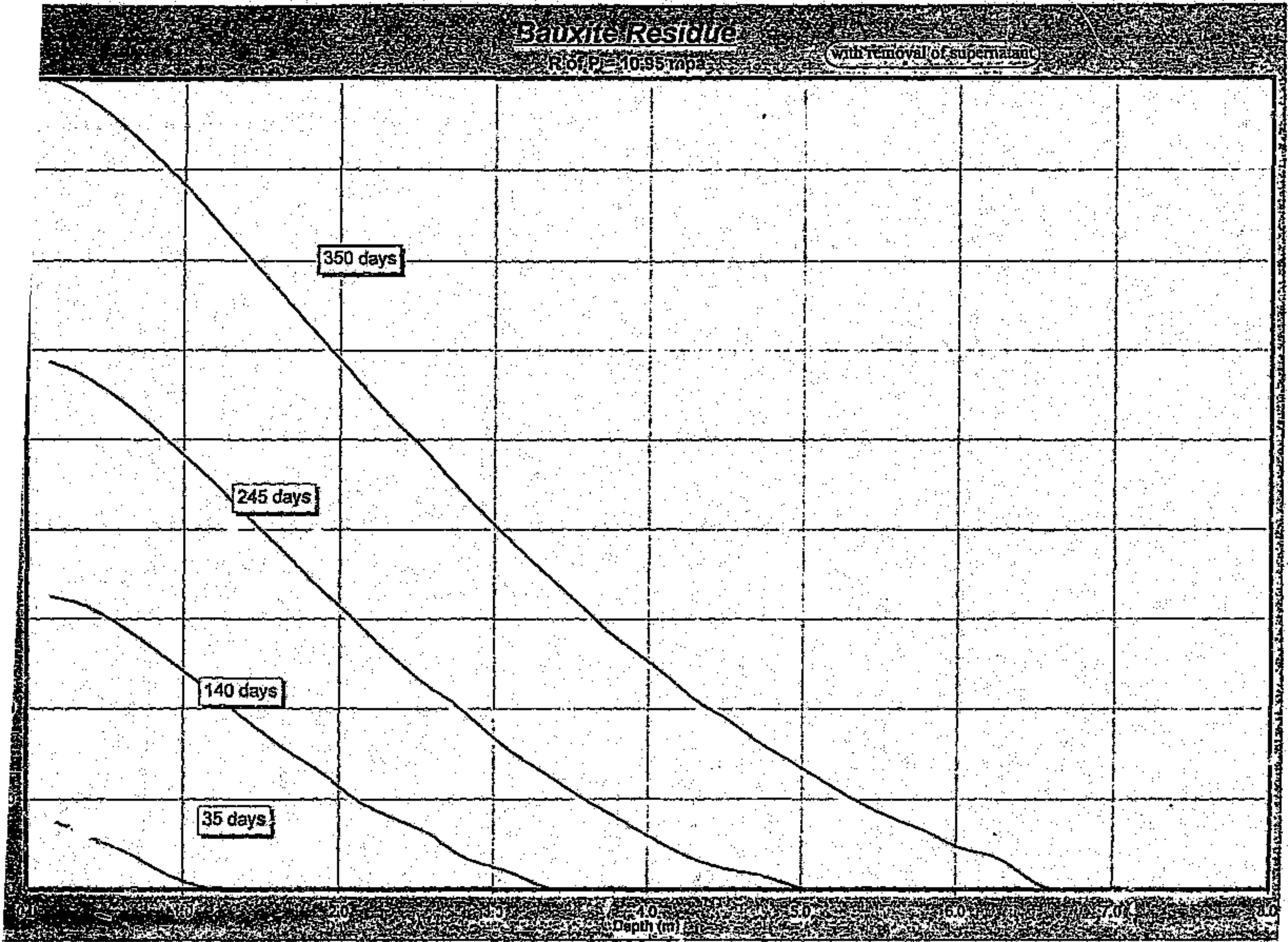
Bauxite Residue
150mm per 28 days
2352 days
1932 days
1008 days
0.500
1.000
1.500
2.000
2.500
3.000
Depth (m)



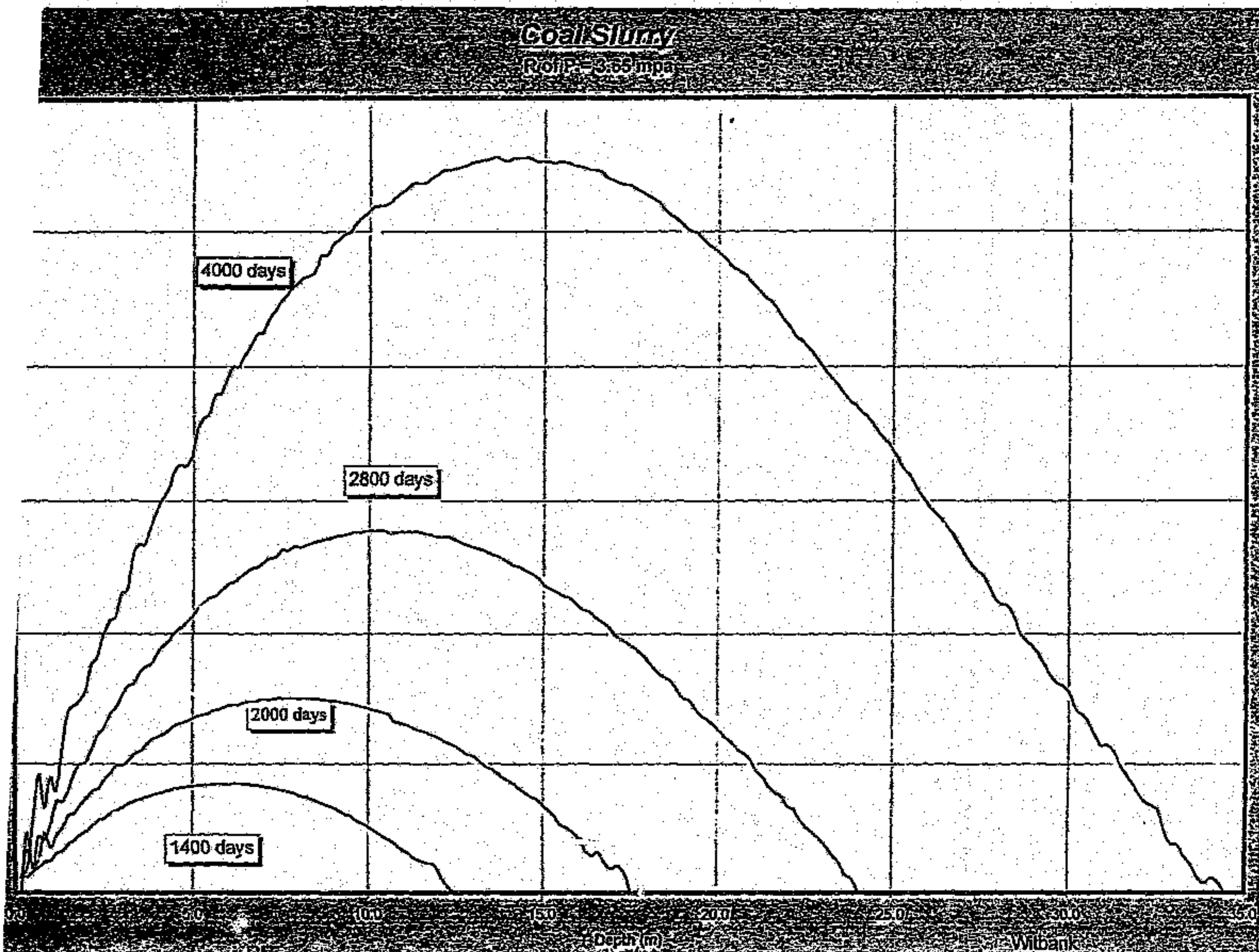
Bauxite Residue
R of P = 3.65 mpa
With supernatant removal
60.0
50.0
40.0
30.0
20.0
10.0
0.0
-10.0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
Depth (m)
1000 days
Effective stress
Pore pressure

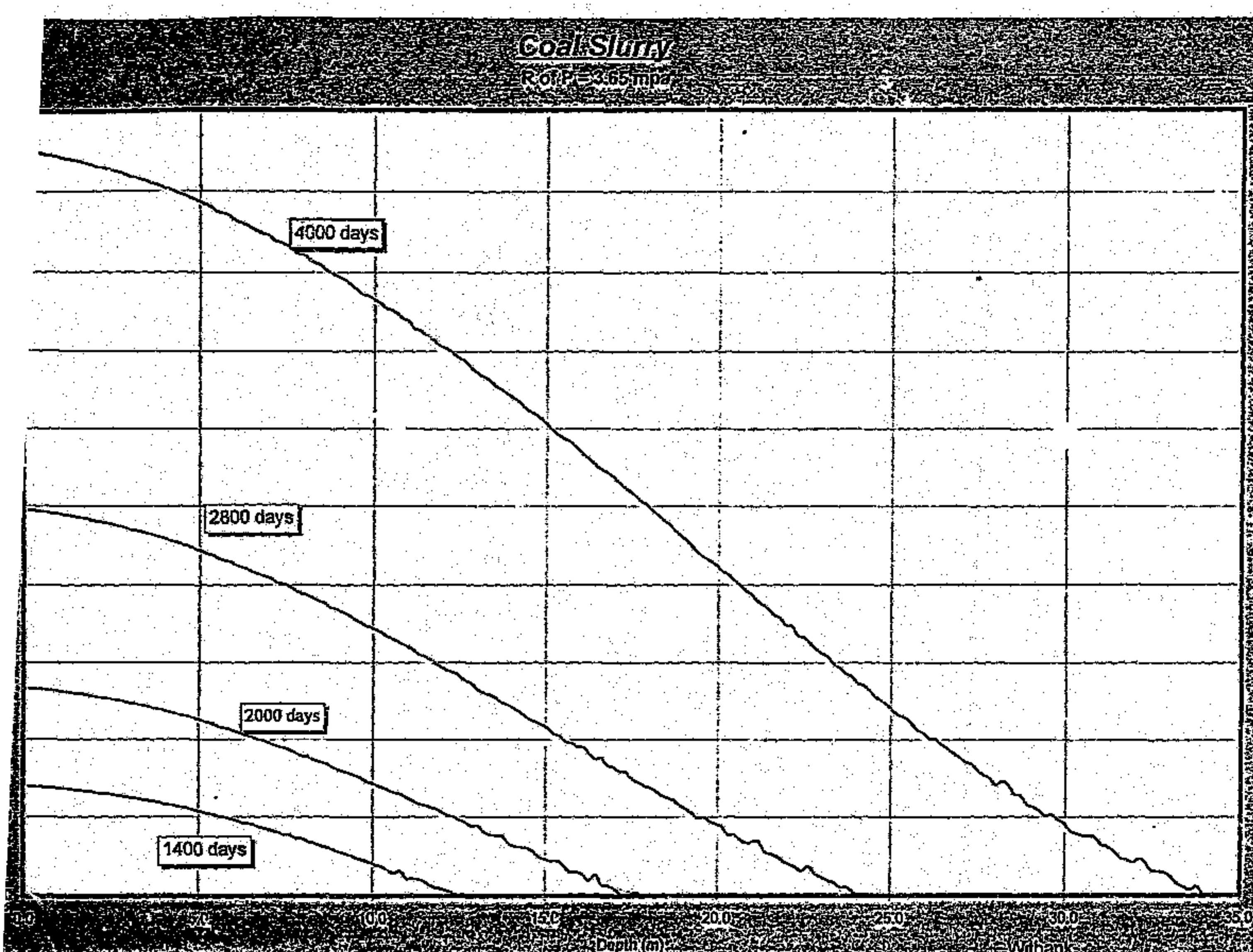


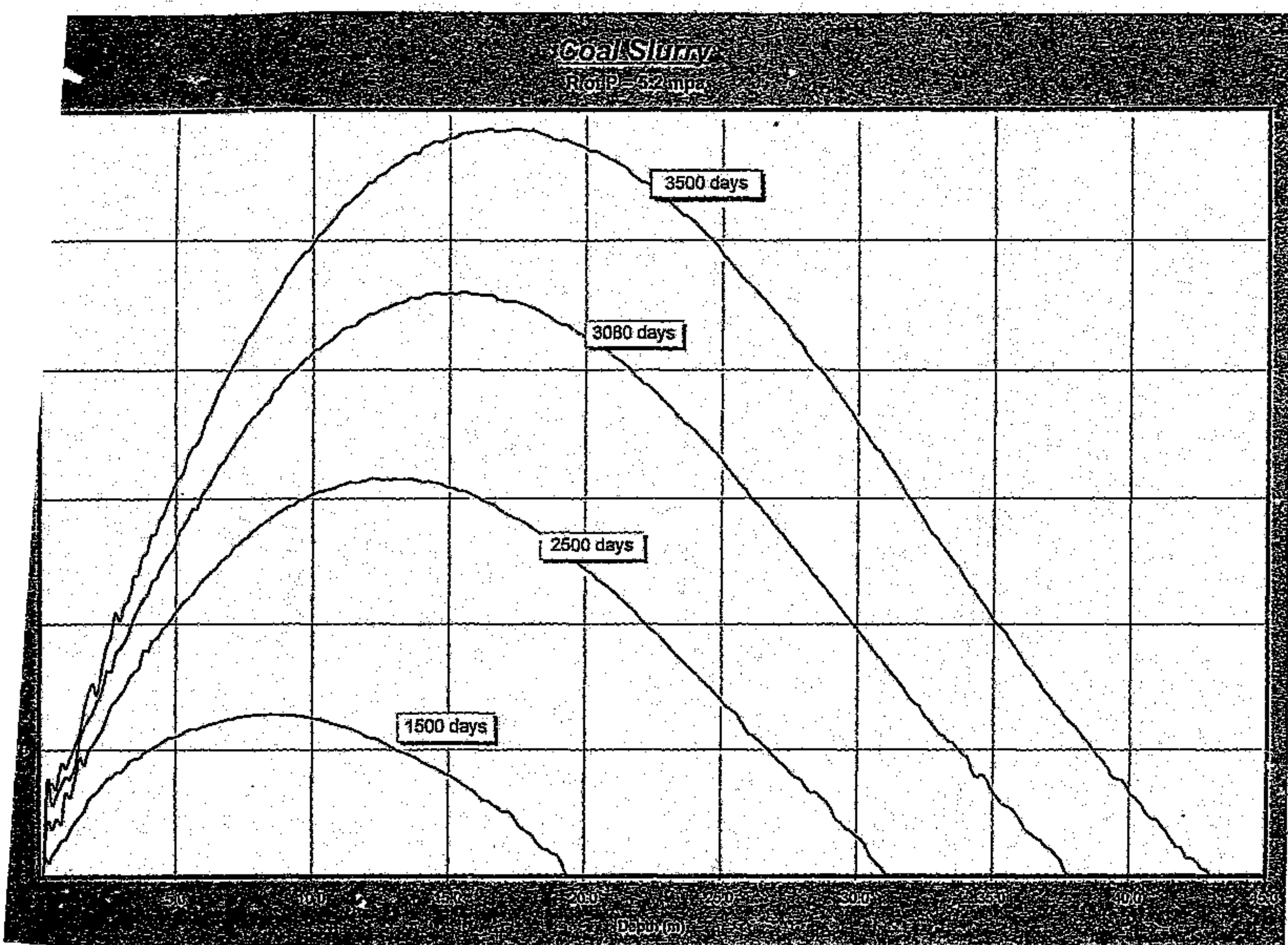
Bauxite Residue
R of P = 7.82 mpa
with removal of supernatant
1176 days
924 days
840 days
588 days
336 days
84 days
Depth (m)
2.0
4.0
6.0
8.0
10.0
12.0
14.0
10
20
30

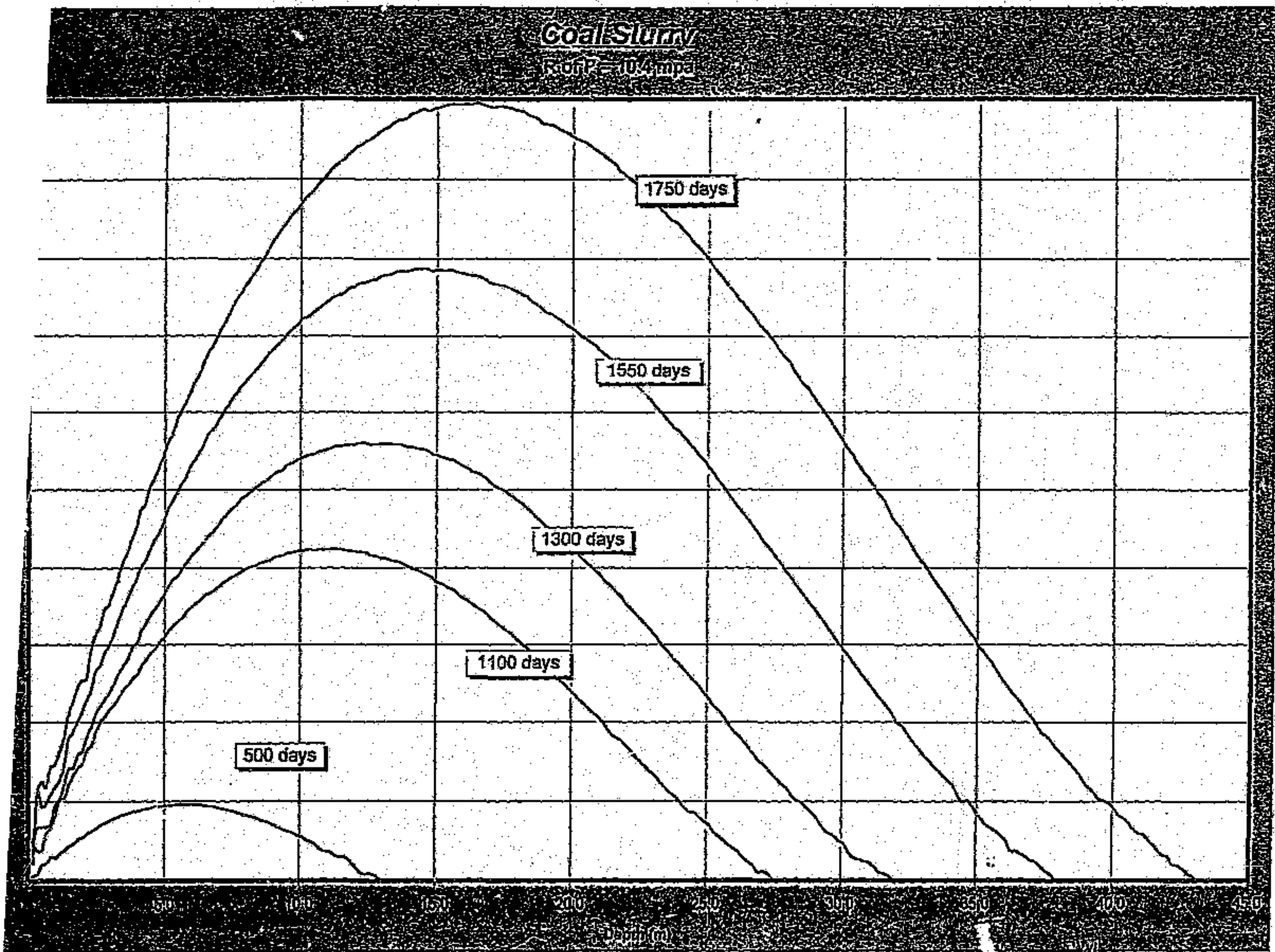


Bauxite Residue
R of P = 10.95 mpa
with removal of supernatant
350 days
245 days
140 days
35 days
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Depth (m)

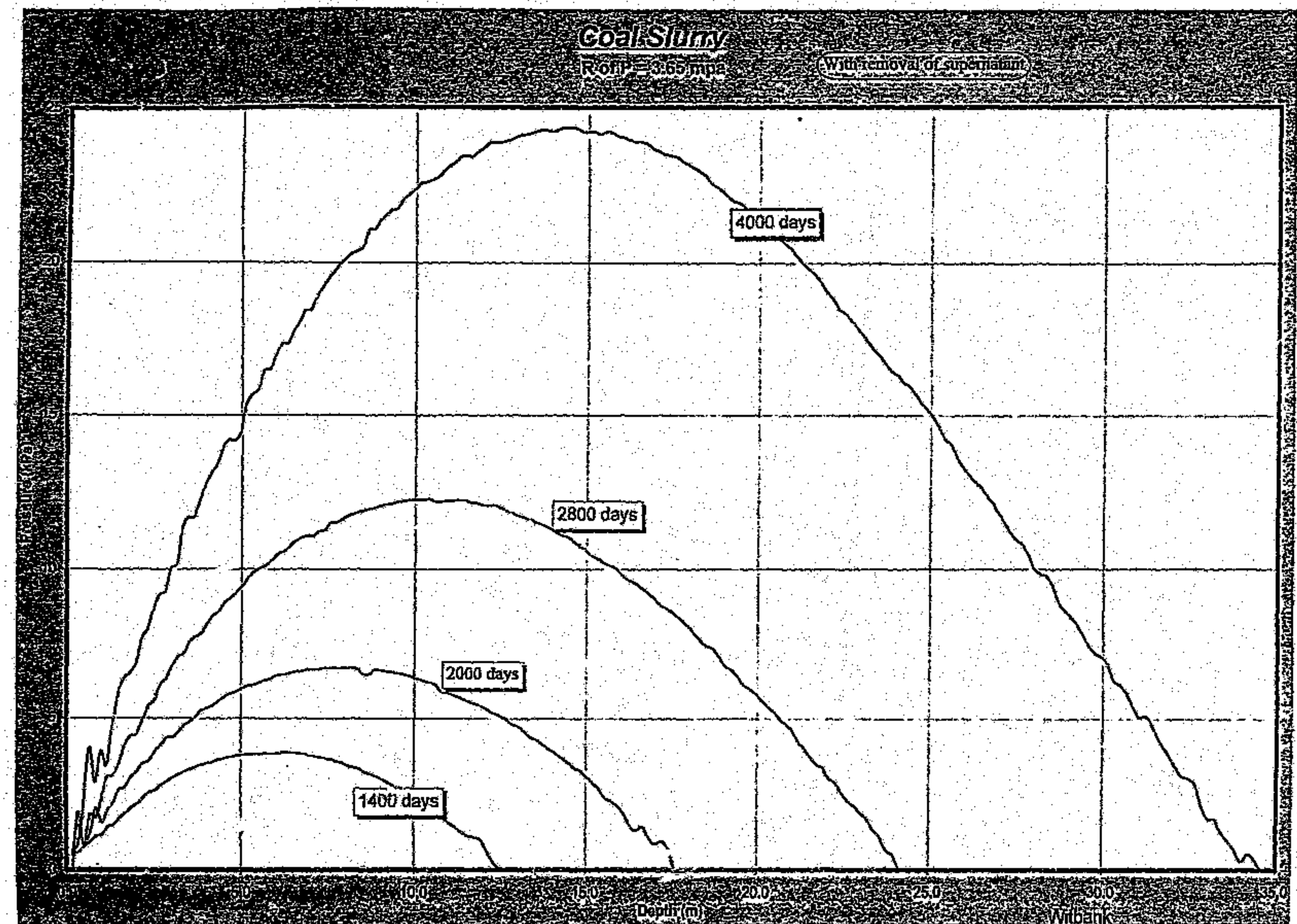

Coal Slurry
R of P = 3.55 mpa
4000 days
2800 days
2000 days
1400 days
0.0
10.0
15.0
20.0
25.0
30.0
Depth (m)
Witbank


Coal Slurry
R of P = 3.65 mpa
4000 days
2800 days
2000 days
1400 days
10.0
15.0
20.0
25.0
30.0
35.0
Depth (m)
Wilbank

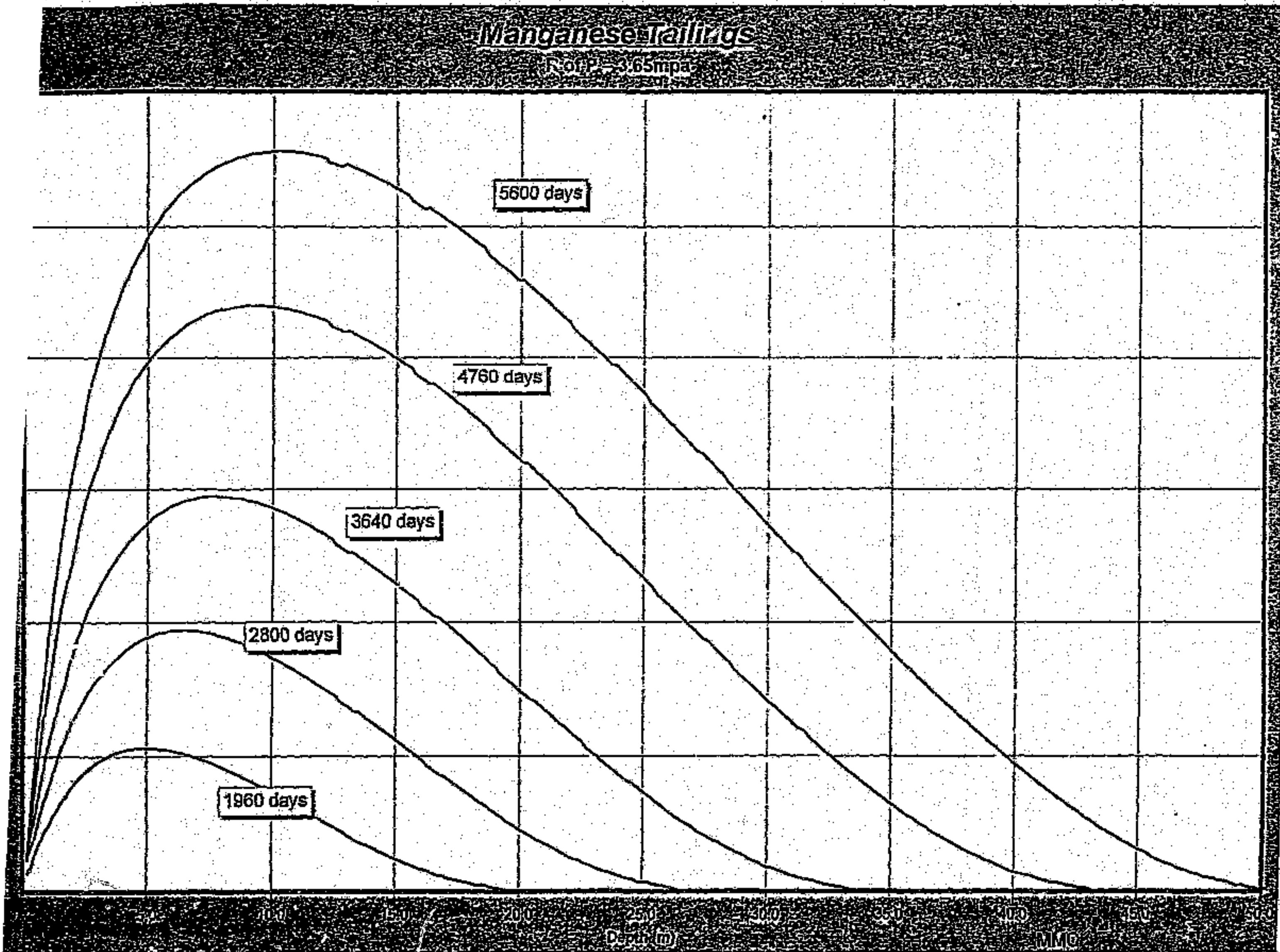

Coal Slurry
R of P = 5.2 mpa
3500 days
3080 days
2500 days
1500 days
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Depth (m)

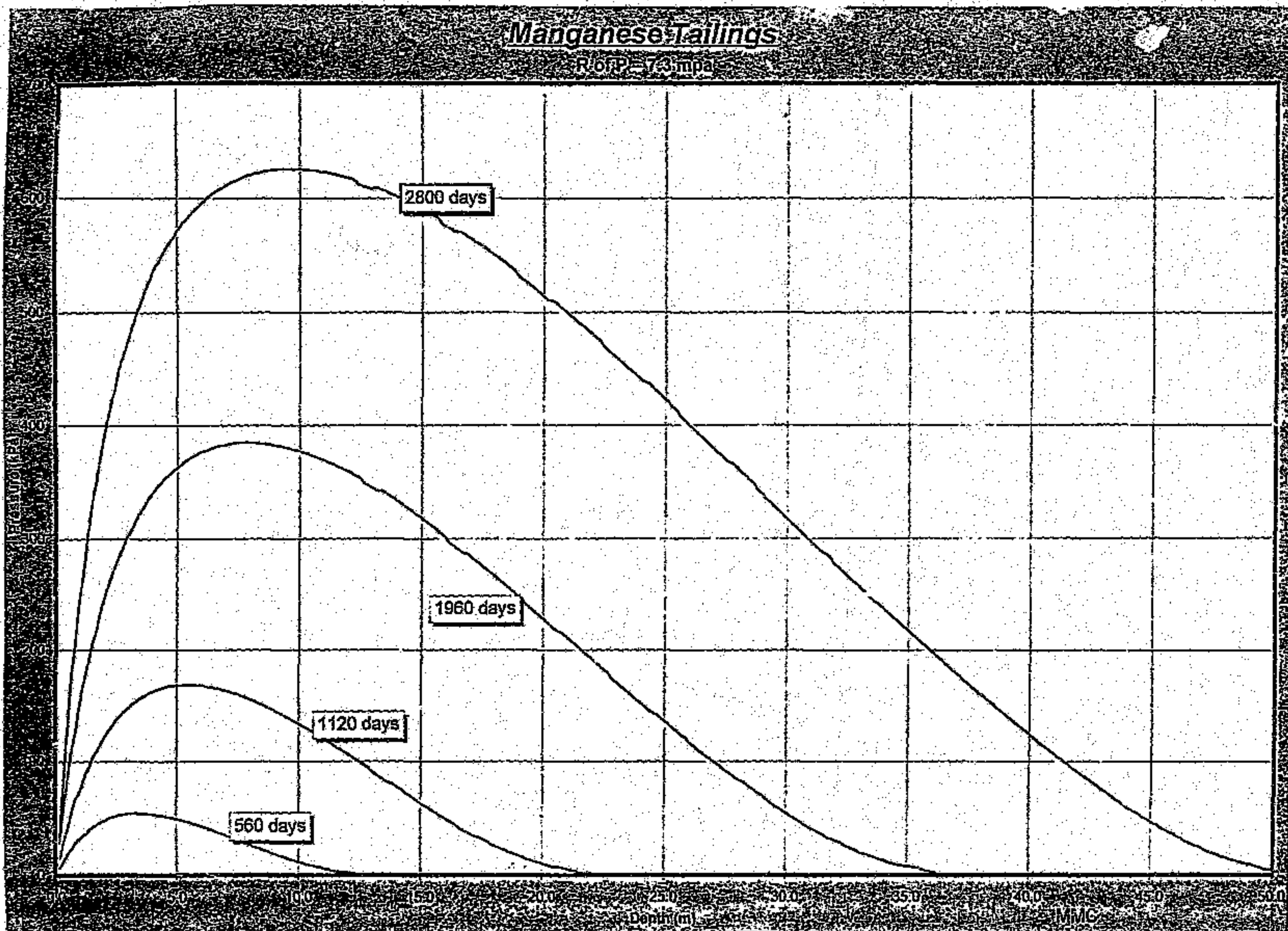


Coal Slurry
R of P = 10.4 mpa
1750 days
1550 days
1300 days
1100 days
500 days
50
100
150
200
250
300
350
400
450
Depth (m)

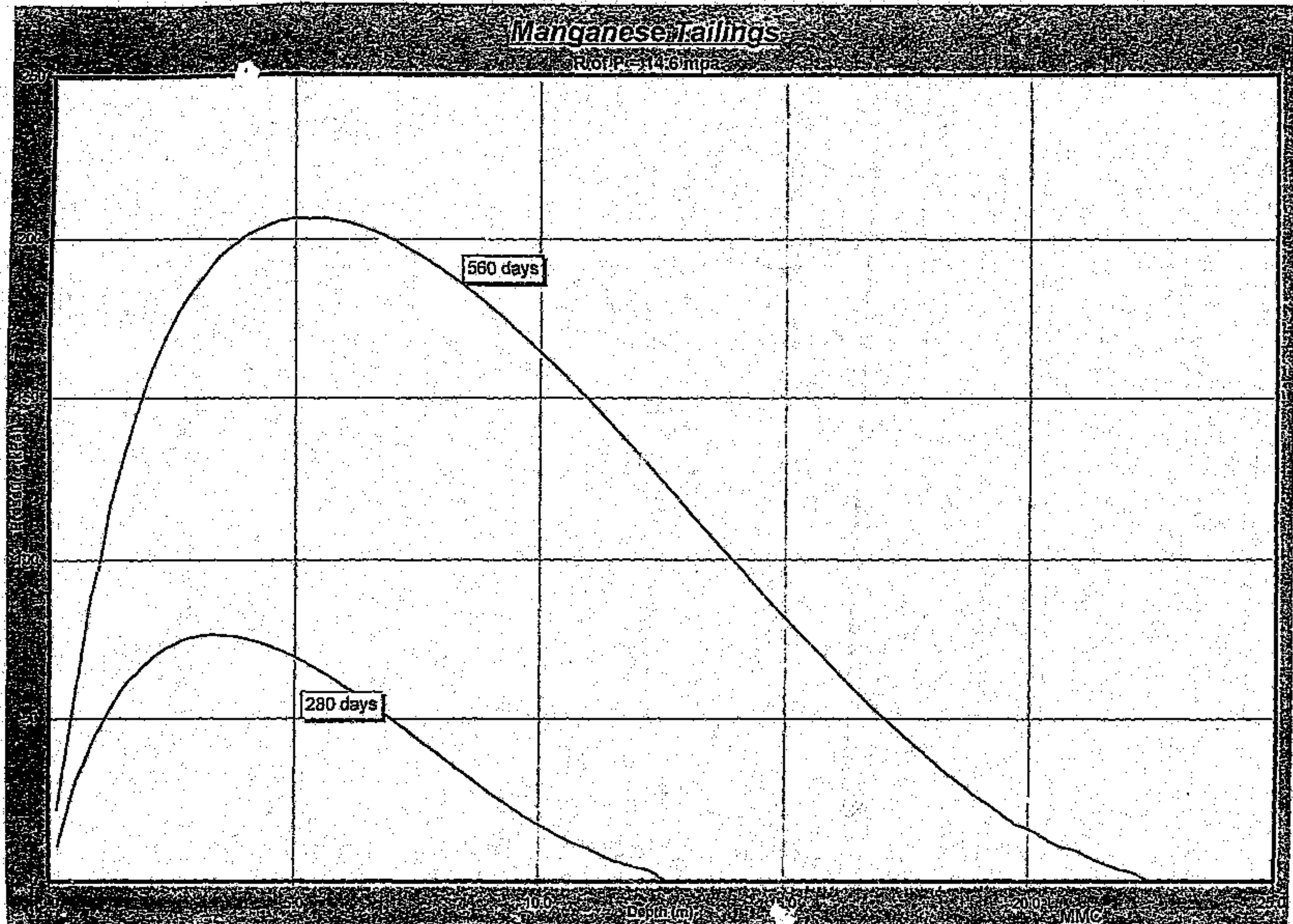


Coal Slurry
With removal of supernatant
4000 days
2800 days
2000 days
1400 days
10.0
15.0
20.0
25.0
30.0
35.0
Depth (m)
Witbank

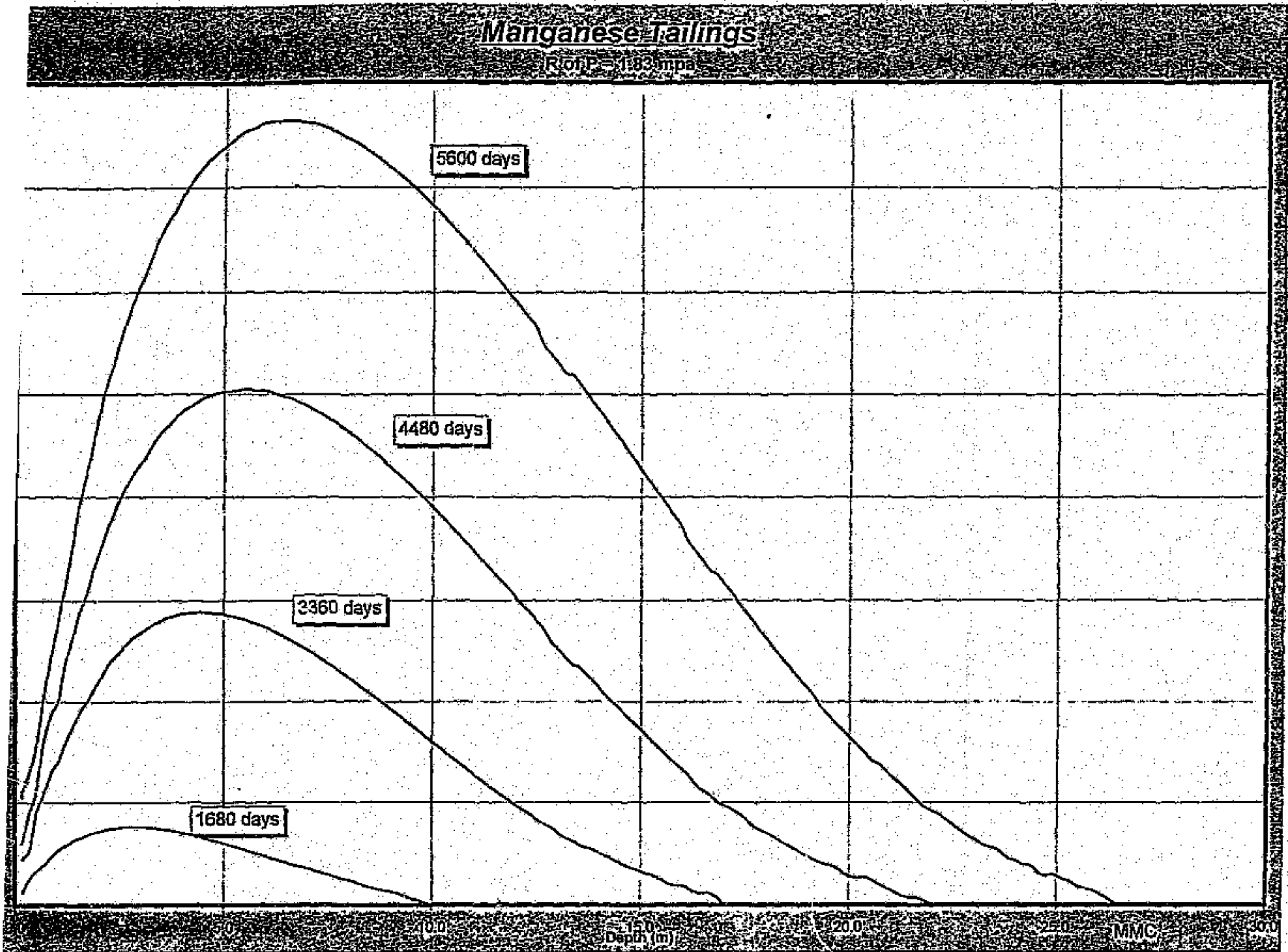

Manganese Tailings
5600 days
4760 days
3640 days
2800 days
1960 days
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Depth (m)
MMC

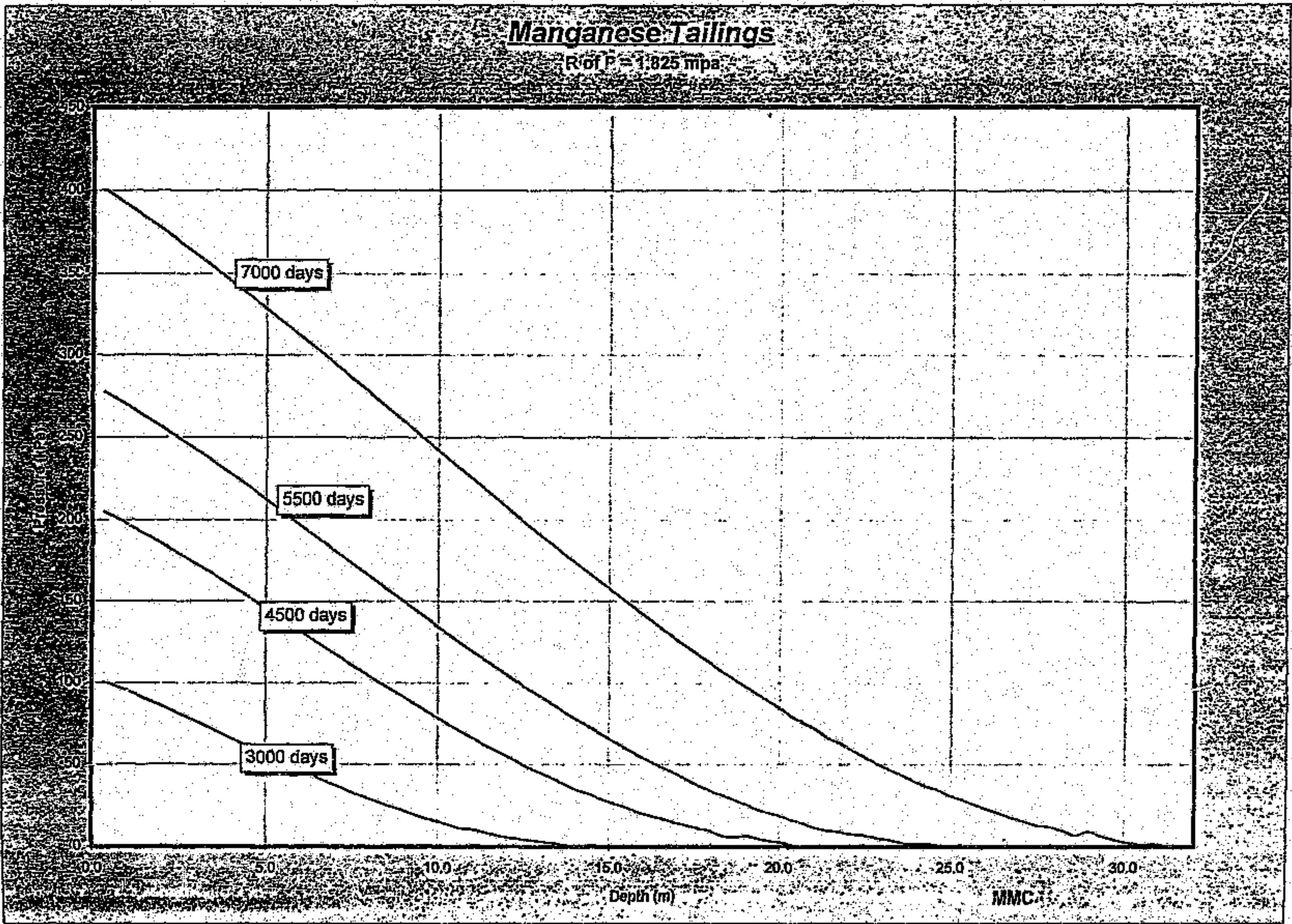


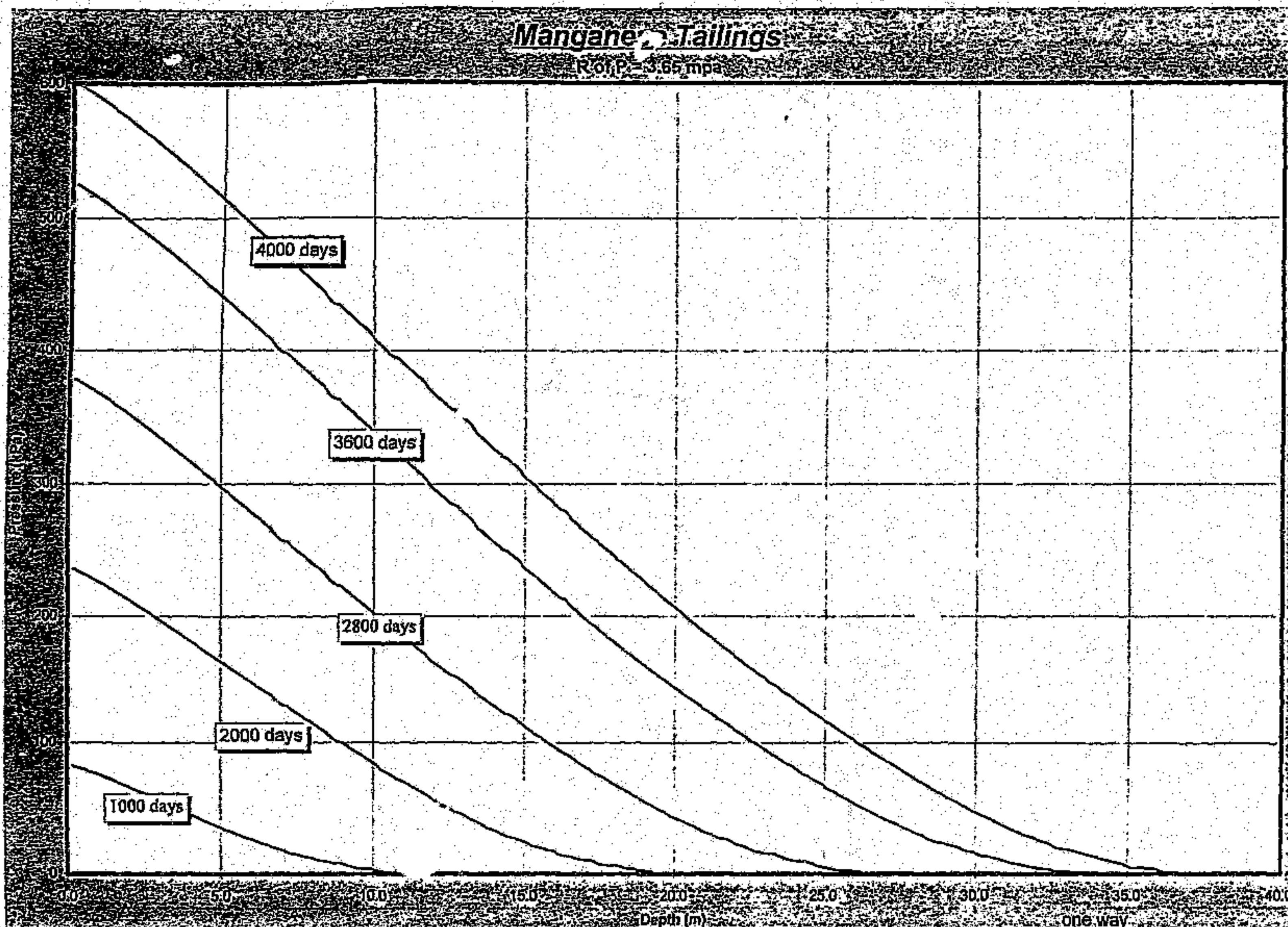
Manganese Tailings
R of P = 7.3 mpa
2800 days
1960 days
1120 days
560 days
600
400
200
0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
Depth (m)
MMC



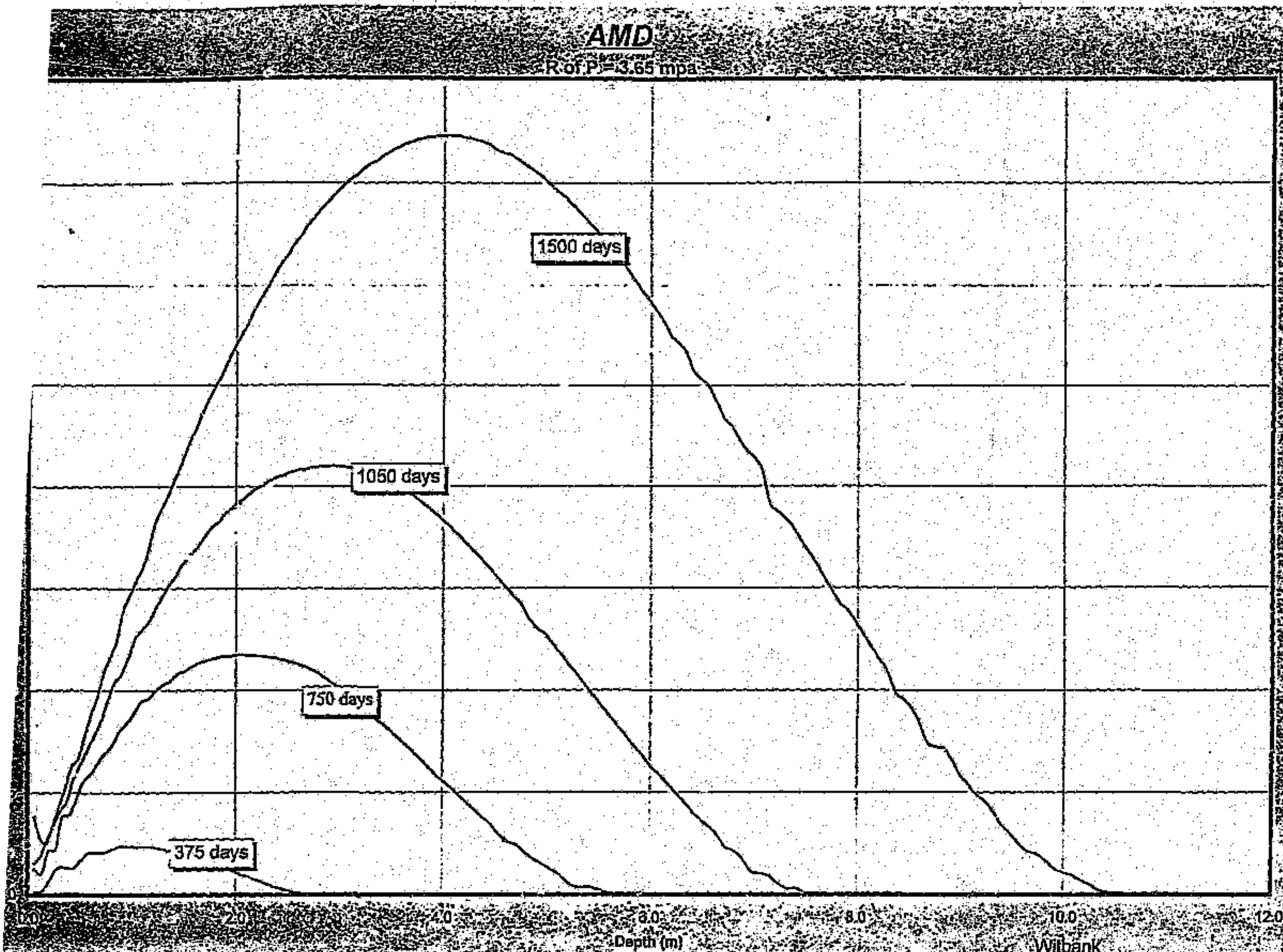
Manganese Tailings
560 days
280 days
5.0
10.0
20.0
Depth (m)
MMC

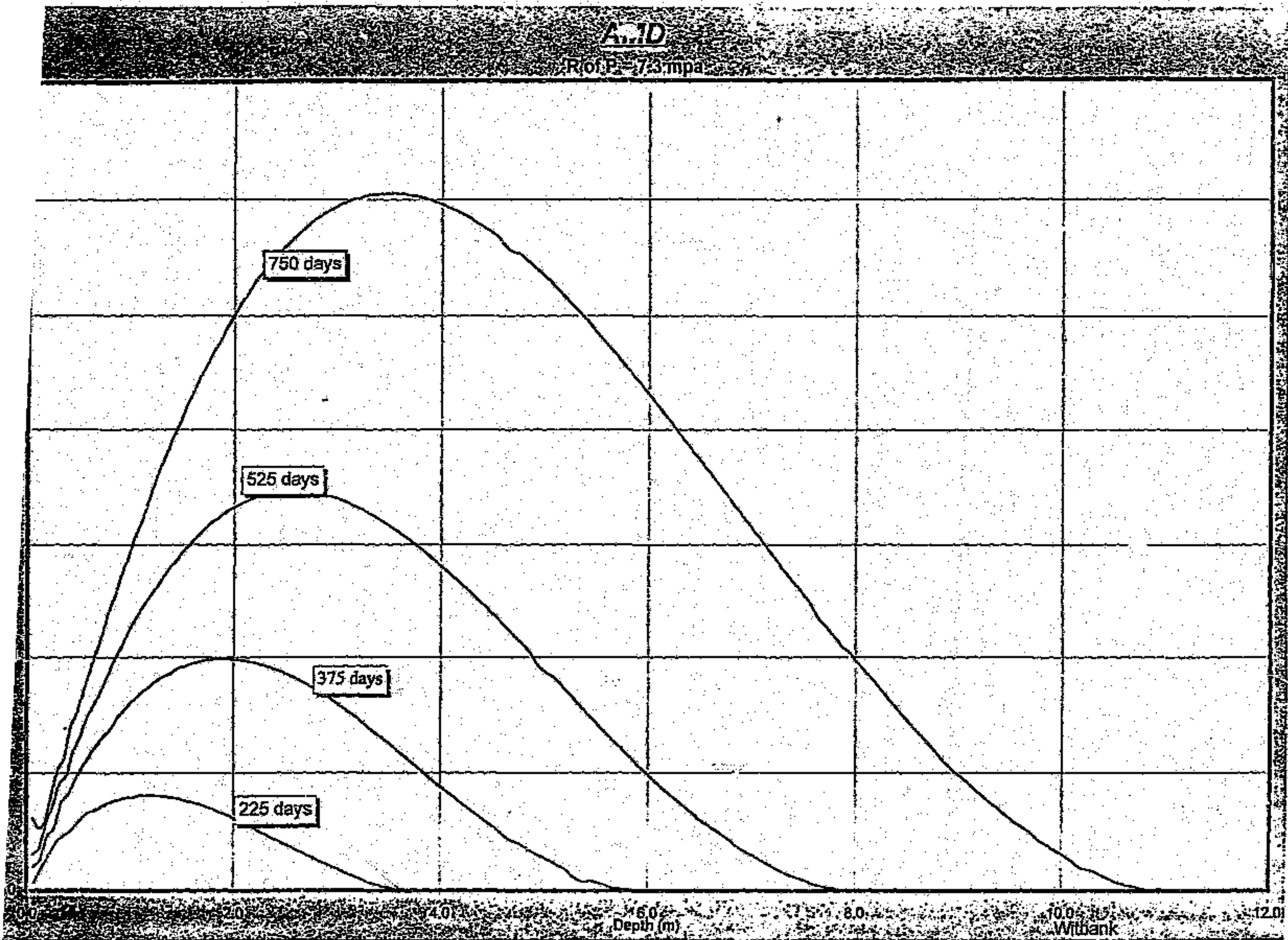

Manganese Tailings
R of P = 1.83 mpa
5600 days
4480 days
3360 days
1680 days
0
5.0
10.0
15.0
20.0
25.0
30.0
Depth (m)
MMC


Manganese Tailings
R of F = 1.825 mpa
7000 days
5500 days
4500 days
3000 days
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Depth (m)
MMC

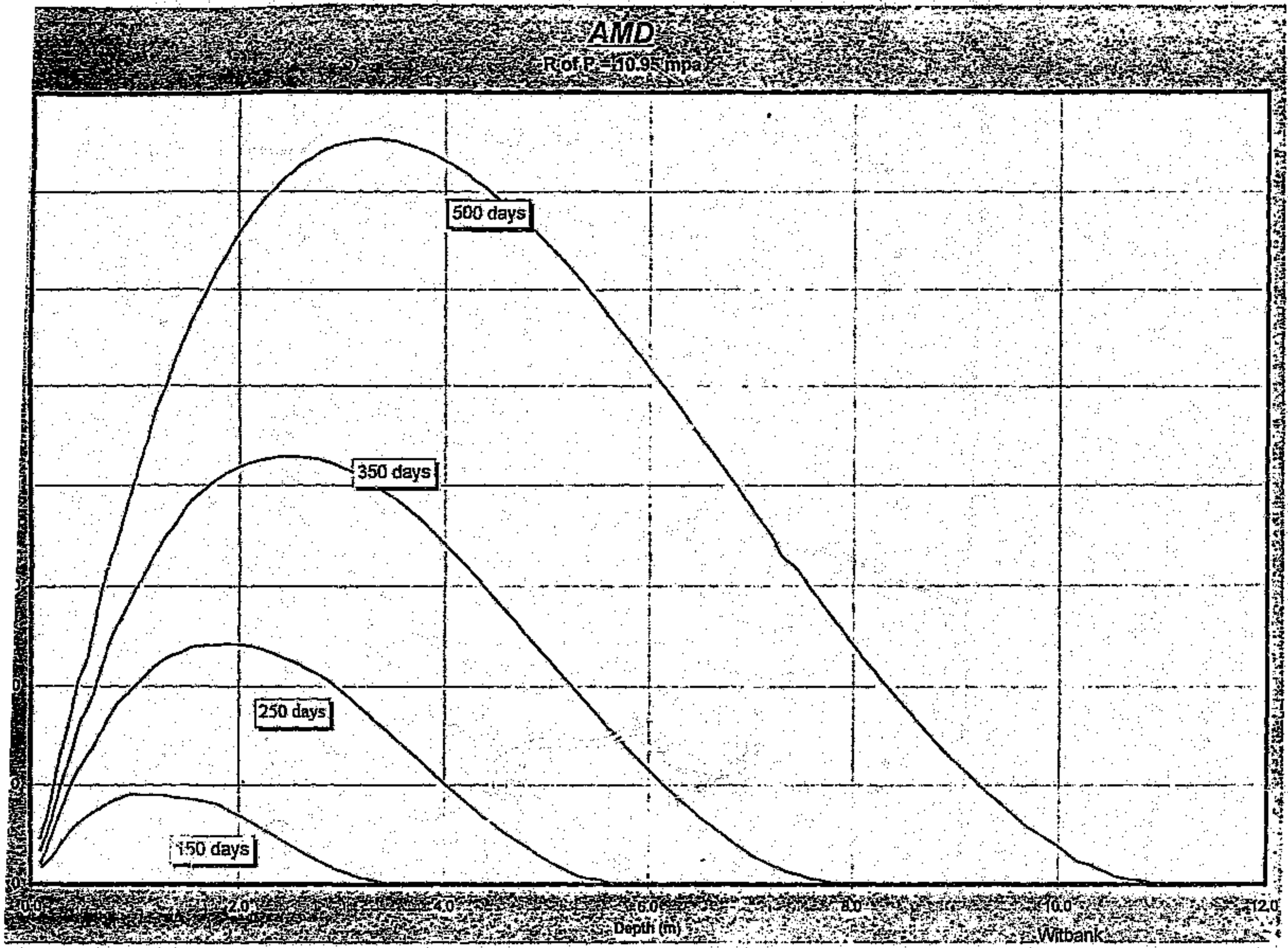


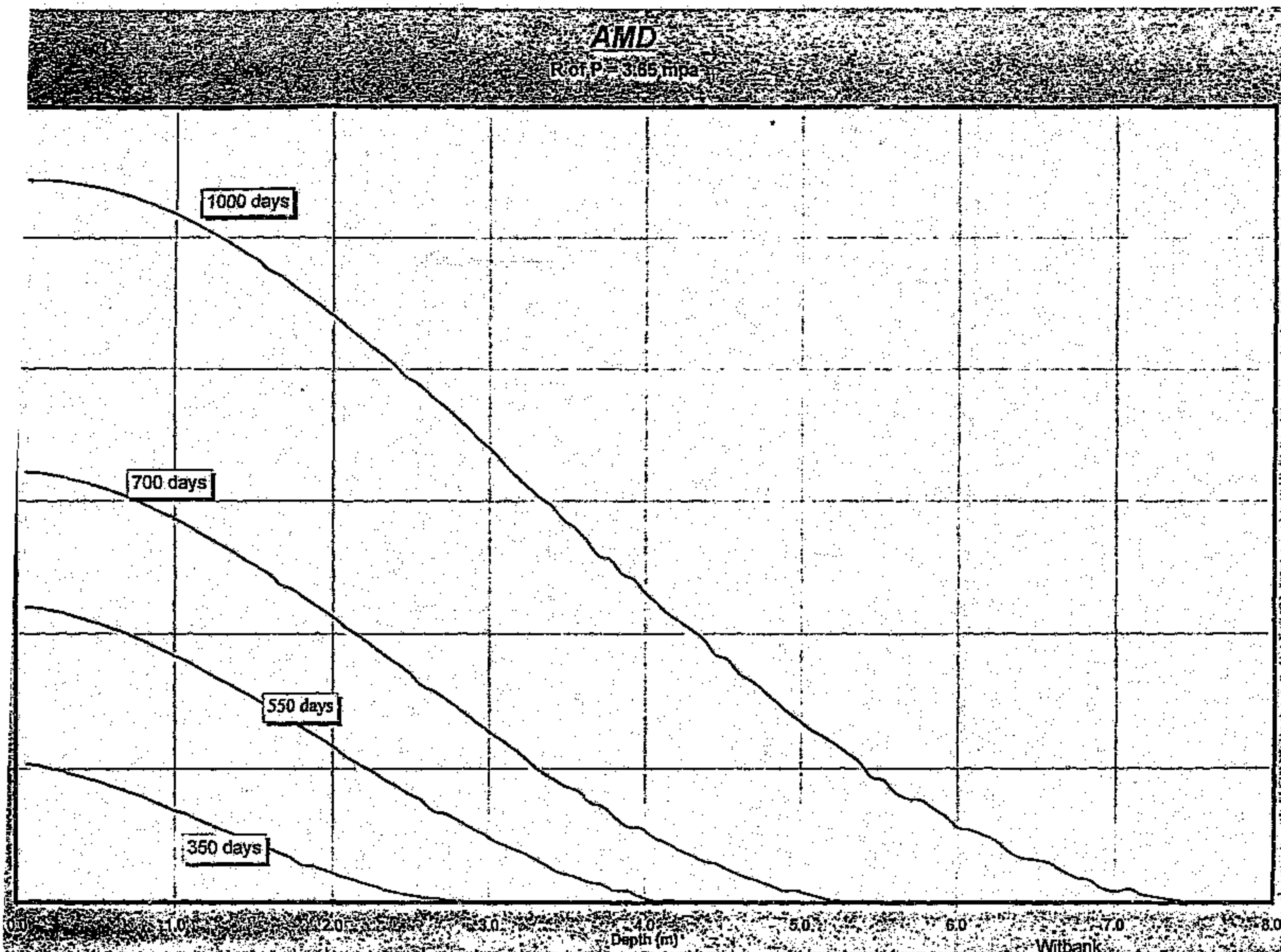
Mangane Tailings
R of P = 3.65 mpa
4000 days
3600 days
2800 days
2000 days
1000 days
Pressure (kPa)
0
100
200
300
400
500
600
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
Depth (m)
one way


AMD
R of P = 3.65 mpa
1500 days
1050 days
750 days
375 days
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Depth (m)
WilbanK

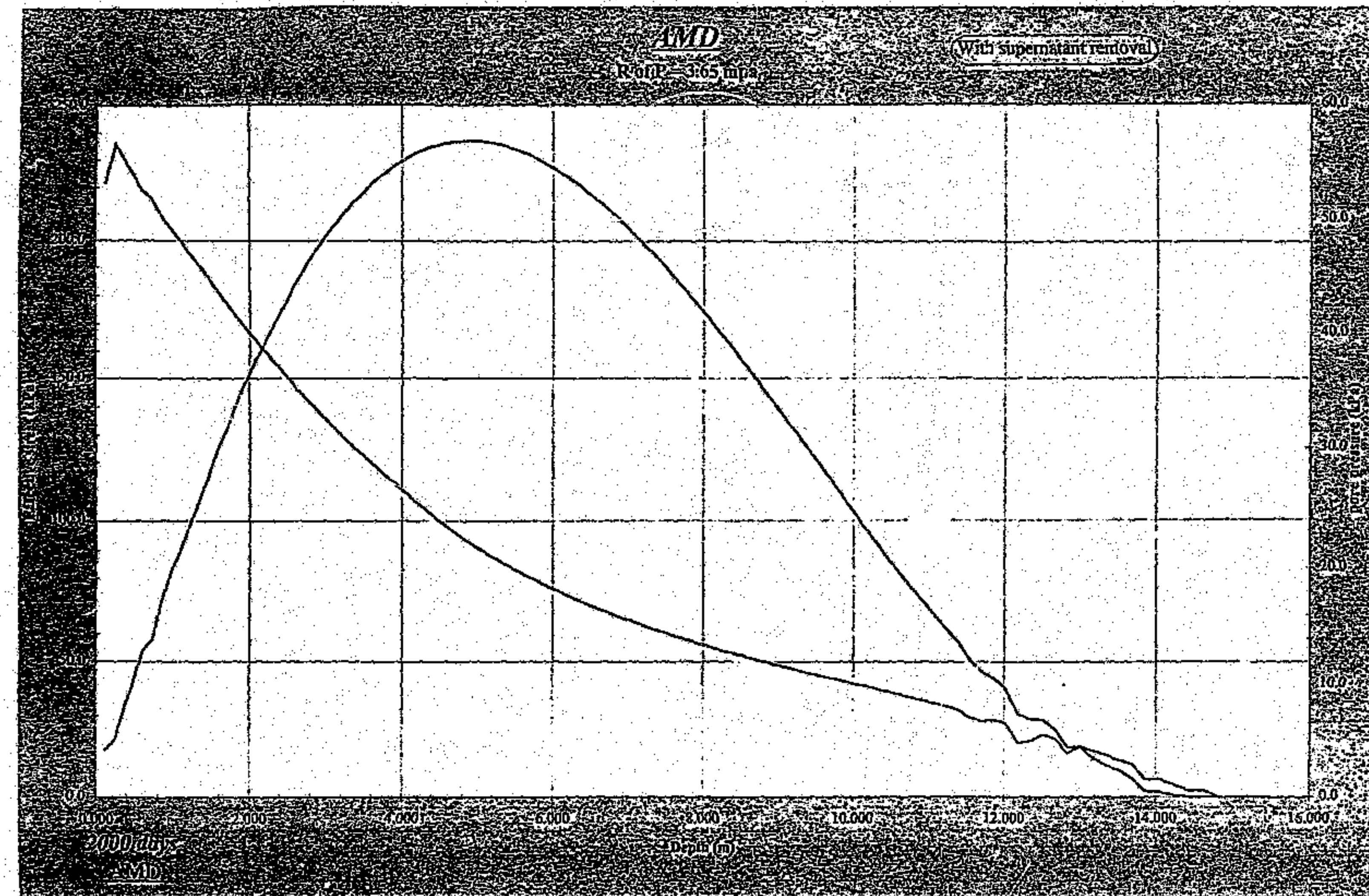


750 days
525 days
375 days
225 days
2.0
4.0
6.0
8.0
10.0
12.0
Depth (m)
Witbank

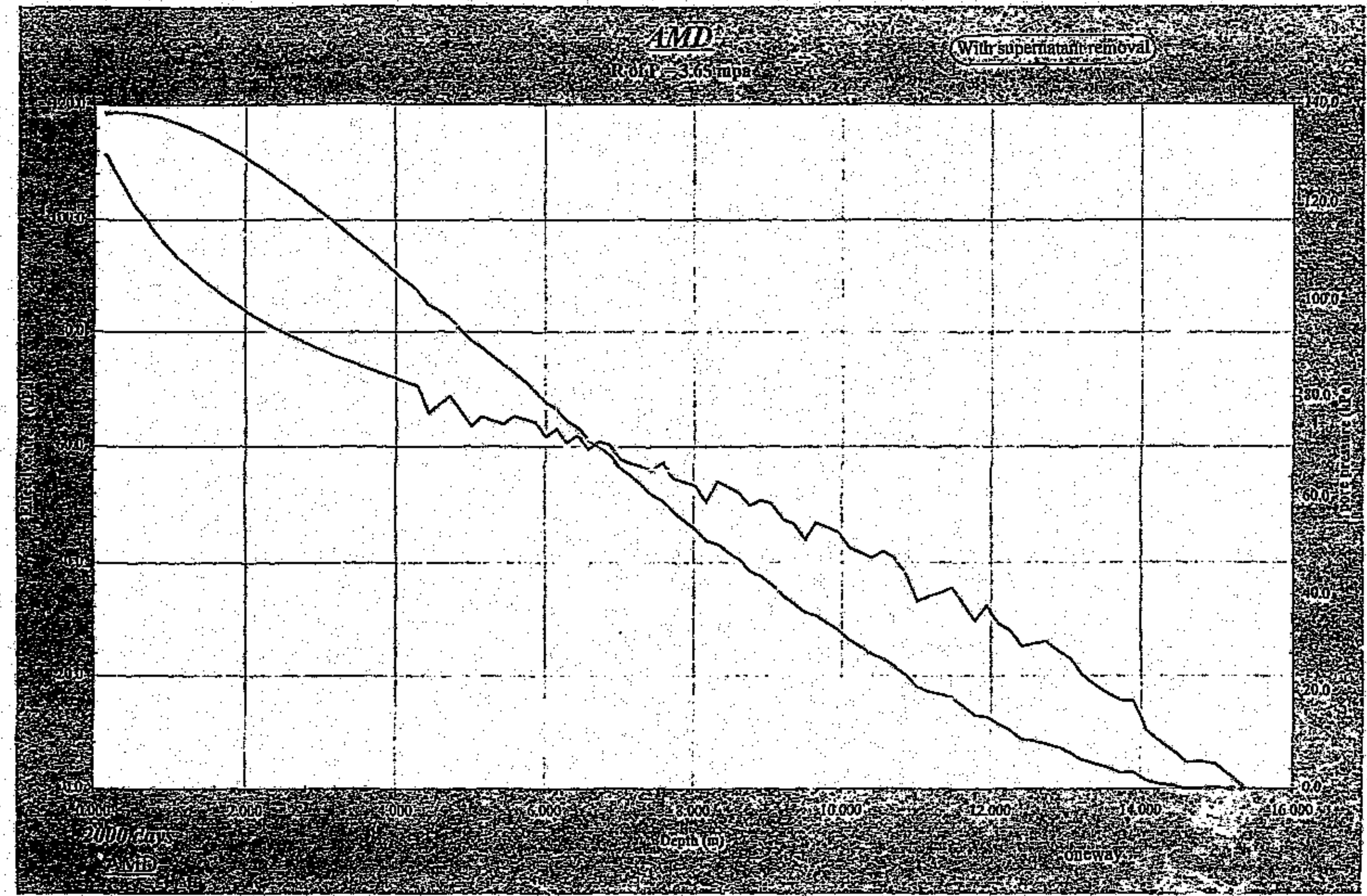

AMD
R of P = 10.95 mpa
500 days
350 days
250 days
150 days
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Depth (m)
Witbank



AMD
R of P = 3.65 mpa
1000 days
700 days
550 days
350 days
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Depth (m)
Witbank



AMD
R of P = 3.65 mpa
With supernatant removal
0.0
10.0
20.0
30.0
40.0
50.0
60.0
Pore Pressure (kPa)
0.000
2.000
4.000
6.000
8.000
10.000
12.000
14.000
16.000
Depth (m)
2000 day
AMD



AMD
With supernatant removal
R of P = 3.65 mpa
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
2.000
4.000
6.000
8.000
10.000
12.000
14.000
16.000
Depth (m)
2000 days
oneway

APPENDIX E

Sample printout from Program

RESULTS OF PORE PRESSURE ANALYSIS FOR CONTINUOUS LOADING

WITH REMOVAL OF SUPERNATANT

Copper

Time increment for display of results=	[illegible]	Days
Load applied at each stage=	7.53?	kPa
Time step of loading (every days)	[illegible]	Days
Time interval for analysis=	[illegible]	unit=days
Initial layer thickness =	1.76?	m

Number of drainage paths	[illegible]	
Total number of loads applied=	[illegible]	No.
Thickness of applied load=	0.44?	m
Initial increments in start layer=	4	(must be an even number !)

	300 days	600 days	900 days
Time increment: (day No.) =	300 days	600 days	900 days
Total settlement =	1.441 m	3.177 m	5.052 m
Total load to date (kPa)=	158.69 kPa	309.53 kPa	460.95 kPa
Total applied thickness to date (m) =	9.240 m	18.040 m	26.840 m
Settled thickness=	9.546 m	16.610 m	23.535 m

RELATIVE LEVELS	Depth from base up (m)	u (kPa)	Depth from base up (m)	u (kPa)	Effective Stress (kPa)	Depth from base up (m)	u (kPa)	Effective Stress (kPa)	Depth from base up (m)	u (kPa)
25%	0.440	0.00	0.387	3.326	164.721	0.375	2.627	299.416	0.369	6.173
50%	0.880	0.00	0.764	5.946	152.703	0.740	7.093	285.453	0.726	9.537
75%	1.320	0.00	1.129	9.645	141.879	1.093	12.012	273.643	1.072	14.255
100%	1.760	0.00	1.483	12.774	132.658	1.434	17.082	262.481	1.406	17.123
125%	2.200	0.00	1.839	15.445	121.278	1.776	20.319	250.544	1.742	23.799
150%	2.640	0.00	2.196	17.680	112.443	2.120	22.817	241.445	2.078	27.742
175%	3.080	0.00	2.556	20.242	102.695	2.464	27.373	229.703	2.414	32.374
200%	3.520	0.00	2.917	22.233	93.760	2.809	31.856	218.273	2.751	37.679
225%	3.960	0.00	3.280	23.921	5.230?	3.155	34.306	208.986	3.089	41.000
250%	4.400	0.00	3.645	25.713	76.053	3.502	36.486	198.895	3.427	45.231
275%	4.840	0.00	4.013	26.904	67.917	3.849	40.191	188.631	3.766	48.758
300%	5.280	0.00	4.383	27.705	60.541	4.198	42.953	179.080	4.105	52.842
325%	5.720	0.00	4.756	27.816	53.414	4.548	45.107	169.658	4.445	56.623
350%	6.160	0.00	5.132	27.059	47.409	4.899	47.532	160.693	4.786	59.724
375%	6.600	0.00	5.510	26.074	41.449	5.251	50.229	151.079	5.127	61.739
400%	7.040	0.00	5.891	24.812	36.166	5.604	52.338	142.537	5.469	66.916
425%	7.480	0.00	6.276	22.717	31.581	5.958	54.188	133.006	5.812	70.237
450%	7.920	0.00	6.661	20.012	27.337	6.314	55.588	121.569	6.156	73.280
475%	8.360	0.00	7.056	17.565	23.007	6.670	56.782	117.696	6.500	76.234
500%	8.800	0.00	7.453	15.023	18.640	7.028	57.811	109.755	6.845	78.991
525%	9.240	0.00	7.855	11.904	15.162	7.388	58.177	102.663	7.190	81.812
550%	9.680	0.00	8.262	7.935	12.342	7.749	58.007	96.122	7.537	84.182
			8.677	4.503	9.018	8.111	57.566	89.777	7.884	86.445
			9.106	1.356	5.193	8.474	57.059	83.338	8.233	88.550
			9.546	0.000	0.000	8.839	55.912	77.717	8.582	90.303
						9.206	53.892	73.291	8.932	91.442
						9.573	52.031	68.407	9.282	93.515
						9.943	50.280	63.262	9.634	93.616
						10.312	47.990	58.714	9.987	94.202
						10.685	41.393	55.854	10.340	93.871
						11.059	41.564	51.908	10.695	93.787
						11.435	39.935	46.870	11.050	93.642
						11.812	36.742	43.149	11.407	93.117
						12.191	32.494	40.965	11.764	91.465
						12.571	29.307	37.376	12.122	90.001
						12.955	26.629	33.324	12.481	88.408
						13.340	23.551	29.754	12.841	86.371
						13.729	20.343	26.274	13.202	84.125
						14.121	17.417	22.582	13.564	81.662
						14.518	14.168	19.079	13.927	79.270
						14.919	11.145	15.196	14.291	76.436
						15.337	7.947	12.006	14.655	73.277
						15.744	4.628	8.547	15.021	70.474
						16.170	0.723	5.943	15.388	67.272
						16.610	0.000	0.000	15.755	63.768
									16.124	59.727
									16.493	56.339
									16.864	53.415
									17.236	50.245
									17.609	46.491
									17.983	42.644
									18.359	39.097
									18.736	35.622
									19.115	32.239
									19.496	29.280
									19.880	26.427
									20.266	23.323
									20.654	19.648
									21.047	17.039
									21.444	14.396
									21.846	10.987
									22.253	7.453
									22.668	4.174
									23.095	0.690
									23.535	0.000

Copper 9 3mps with stress & supernatant

First relationship

	1200 days			1500 days			1800 days			2100 days		
	6.984 m			9.003 m			11.032 m			13.104 m		
	612.08 kPa			763.21 kPa			914.34 kPa			1065.47 kPa		
	35.640 m			44.410 m			53.240 m			62.040 m		
	30.402 m			37.183 m			43.951 m			50.682 m		
Effective Stress	Depth from base up	u	Effective Stress	Depth from base up	u	Effective Stress	Depth from base up	u	Effective Stress	Depth from base up	u	Effective Stress
kPa	m	kPa	kPa	m	kPa	kPa	m	kPa	kPa	m	kPa	kPa
428.525	0.365	7.933	552.328	0.362	11.717	613.482	0.360	14.805	708.862	0.358	19.550	775.719
415.752	0.717	8.214	548.915	0.711	13.173	673.273	0.706	15.446	804.136	0.702	20.200	930.158
404.151	1.059	17.460	533.097	1.048	19.051	662.878	1.041	17.457	795.379	1.035	18.696	924.842
395.384	1.388	21.077	523.331	1.375	24.630	651.134	1.365	27.114	779.833	1.356	27.530	910.227
379.819	1.719	27.715	508.069	1.702	31.039	636.103	1.689	33.259	765.061	1.678	33.158	895.977
369.251	2.050	29.897	499.265	2.029	33.472	628.040	2.013	33.355	758.295	2.000	36.961	885.496
357.251	2.381	36.373	485.609	2.357	40.263	613.085	2.338	43.300	741.215	2.322	47.293	868.036
345.208	2.713	41.553	471.500	2.685	46.848	599.555	2.663	50.140	727.432	2.645	52.192	856.197
335.050	3.045	46.231	461.963	3.013	51.414	588.125	2.988	54.264	716.449	2.968	57.653	843.867
323.242	3.378	51.020	449.602	3.342	55.715	576.261	3.314	59.141	704.003	3.291	63.826	830.119
312.767	3.711	55.578	438.100	3.671	60.669	564.331	3.640	66.087	690.101	3.614	70.447	816.548
301.868	4.045	59.741	427.091	4.000	66.536	551.603	3.966	72.904	676.424	3.938	77.666	802.468
291.127	4.379	65.013	414.845	4.330	72.498	538.726	4.292	78.613	663.777	4.262	81.355	788.836
281.171	4.713	69.022	404.005	4.660	76.588	527.786	4.619	83.418	652.121	4.586	89.290	777.056
270.216	5.048	73.913	392.161	4.991	82.158	515.200	4.946	90.375	638.212	4.910	96.253	763.643
260.627	5.384	78.063	381.609	5.322	87.197	503.811	5.274	94.844	627.132	5.235	102.163	750.817
250.155	5.720	82.098	370.789	5.653	91.761	492.411	5.601	100.111	615.231	5.560	107.867	738.376
240.511	6.056	86.122	359.797	5.985	96.218	481.029	5.929	104.470	603.949	5.885	112.716	726.505
230.860	6.393	90.260	348.950	6.317	101.131	469.412	6.258	110.540	591.162	6.210	119.263	713.236
221.202	6.731	93.787	338.308	6.649	105.659	457.959	6.586	116.212	578.560	6.536	125.231	700.345
211.613	7.069	98.150	327.378	6.982	110.805	446.047	6.915	121.636	566.571	6.862	131.618	687.202
202.540	7.407	101.432	317.410	7.315	115.117	435.035	7.245	126.403	554.342	7.188	136.518	675.619
193.477	7.746	105.171	306.831	7.649	119.911	423.428	7.575	132.279	542.218	7.515	143.636	662.661
184.552	8.086	108.631	296.534	7.983	124.062	412.451	7.905	137.217	530.430	7.841	148.438	650.022
175.895	8.427	112.022	286.281	8.318	128.331	401.281	8.235	142.160	518.609	8.169	154.118	637.431
168.276	8.768	114.811	277.021	8.653	132.455	390.712	8.566	146.989	507.337	8.496	159.721	625.408
160.412	9.109	117.903	267.086	8.988	136.603	379.630	8.897	152.294	495.170	8.824	165.407	612.557
152.481	9.451	120.495	257.700	9.325	140.129	369.379	9.229	156.706	483.914	9.152	170.702	600.740
145.057	9.794	123.431	247.933	9.661	144.275	358.275	9.560	161.743	472.075	9.480	176.405	588.207
138.972	10.138	125.203	239.690	9.998	147.575	348.638	9.893	165.372	461.974	9.809	180.725	577.418
132.397	10.482	127.319	230.872	10.335	151.074	338.416	10.225	170.105	450.541	10.158	186.485	564.935
125.559	10.827	129.384	222.115	10.673	154.415	328.363	10.559	174.631	439.298	10.468	191.779	552.945
119.347	11.172	130.951	213.520	11.012	157.758	318.034	10.892	179.105	427.832	10.797	197.096	540.635
114.606	11.518	131.893	206.315	11.351	160.319	309.199	11.226	182.700	417.949	11.127	201.445	529.968
109.348	11.865	132.900	198.507	11.690	163.180	299.542	11.560	186.866	407.005	11.458	206.665	517.996
104.129	12.213	133.780	190.856	12.031	165.765	290.173	11.895	190.698	396.395	11.789	211.419	506.468
99.471	12.561	134.220	183.057	12.371	167.917	281.312	12.230	194.188	386.187	12.120	215.735	495.419
95.052	12.910	134.393	176.861	12.712	169.936	272.624	12.566	197.479	376.232	12.451	220.130	484.369
90.983	13.260	134.296	170.387	13.054	171.771	264.206	12.902	200.895	366.211	12.783	224.642	473.250
86.579	13.610	134.241	163.658	13.397	173.518	255.664	13.239	203.915	355.403	13.115	228.610	462.489
82.558	13.961	133.588	157.477	13.740	175.007	247.386	13.576	207.011	346.316	13.448	232.872	451.436
79.312	14.313	132.440	152.266	14.083	175.770	240.257	13.913	209.091	338.043	13.781	236.083	441.863
75.327	14.666	131.307	146.324	14.427	176.821	232.311	14.251	211.912	328.361	14.114	240.341	430.730
71.865	15.019	130.173	141.035	14.772	177.535	224.962	14.590	214.252	319.421	14.448	243.817	420.639
68.579	15.373	128.416	136.050	15.117	177.887	217.878	14.929	216.264	310.623	14.782	247.276	410.396
66.251	15.728	125.884	132.152	15.462	177.471	211.066	15.268	217.551	302.914	15.117	249.803	401.467
62.806	16.083	124.173	127.026	15.809	177.646	204.836	15.608	219.421	294.243	15.452	253.065	391.354
59.292	16.439	122.200	122.609	16.156	177.683	198.418	15.949	221.053	286.168	15.788	255.968	382.057
55.461	16.796	119.941	117.853	16.503	177.396	191.722	16.289	222.432	277.830	16.124	258.823	372.206
52.875	17.153	116.973	114.445	16.851	176.304	186.427	16.631	223.024	270.851	16.459	260.759	363.901
50.036	17.511	113.991	110.714	17.200	175.309	180.679	16.973	223.899	263.209	16.797	263.176	354.722
46.912	17.869	111.025	107.085	17.549	174.131	175.257	17.315	224.410	256.507	17.134	265.169	346.140
43.545	18.229	107.902	103.416	17.899	172.657	169.976	17.658	224.714	249.048	17.471	266.889	337.656
40.563	18.589	104.090	100.818	18.249	170.289	165.925	18.001	224.012	243.319	17.809	267.995	330.129
36.823	18.949	100.837	97.372	18.600	168.522	160.975	18.345	224.120	236.508	18.147	269.540	321.857
33.061	19.310	97.814	93.766	18.951	166.805	156.048	18.689	224.190	229.761	18.486	271.021	313.723
29.484	19.672	94.444	90.753	19.303	164.414	151.775	19.034	223.547	223.776	18.826	271.957	306.129
26.692	20.035	90.032	88.423	19.656	161.629	148.126	19.379	222.464	218.422	19.165	272.435	299.235
22.321	20.398	86.790	84.657	20.009	159.397	143.317	19.725	221.863	212.005	19.505	273.441	291.224
18.286	20.762	83.588	81.188	20.362	157.026	139.040	20.071	221.101	206.104	19.846	274.053	283.943
15.451	21.127	79.489	79.059	20.716	153.973	135.818	20.418	219.558	201.381	20.187	274.043	277.673
12.330	21.492	74.661	77.179	21.071	149.905	133.261	20.765	217.315	196.982	20.528	273.513	271.563
8.872	21.858	70.811	74.342	21.425	146.621	129.825	21.112	215.539	192.083	20.870	273.296	265.084
5.892	22.225	67.742	70.790	21.781	144.204	125.640	21.460	214.177	186.791	21.213	273.387	258.337
0.000	22.593	64.123	67.701	22.137	140.623	122.543	21.808	212.026	182.268	21.554	272.774	252.257

Copper 9 3mps with stress & supernatant

22.961	60.260	65.258	23.493	136.901	119.944	22.157	209.477	178.523	21.897	271.669	247.123
23.331	57.140	61.616	23.850	133.777	116.273	22.507	207.346	173.826	22.241	270.995	240.961
23.702	53.396	56.863	23.209	130.189	113.361	22.857	204.625	170.061	22.585	269.821	235.641
24.074	49.488	50.027	23.566	126.359	110.451	23.207	201.960	165.979	22.929	268.613	230.114
24.447	44.518	54.353	23.921	122.080	108.114	23.557	198.557	162.780	23.273	266.677	225.453
24.820	40.579	51.776	24.283	118.201	105.478	23.908	195.410	159.402	23.618	264.890	220.695
25.196	39.297	46.423	24.642	114.736	102.256	24.260	192.903	155.247	23.961	263.587	215.349
25.573	35.488	43.754	25.002	110.201	100.289	24.611	189.128	152.571	24.310	261.272	211.210
25.952	31.570	41.039	25.363	106.177	97.747	24.963	185.583	149.407	24.656	258.825	207.010
26.338	30.646	28.779	25.720	105.911	84.836	25.318	187.024	134.915	25.003	262.073	190.636
26.728	27.171	25.320	26.090	102.153	81.678	25.672	183.725	131.265	25.352	260.077	185.688
27.121	23.837	21.899	26.455	98.261	78.832	26.028	179.982	128.288	25.700	257.355	181.773
27.518	20.461	18.719	26.821	93.702	76.805	26.383	175.681	125.983	26.049	253.977	178.444
27.910	16.477	22.930	27.184	85.903	84.761	26.738	167.497	134.388	26.397	245.690	186.976
28.307	13.772	18.903	27.548	82.395	81.560	27.092	164.060	131.029	26.746	243.155	182.710
28.709	11.175	14.975	27.913	78.329	79.173	27.447	160.025	128.609	27.095	239.884	179.522
29.118	8.026	11.583	28.278	74.428	76.473	27.803	155.728	126.326	27.444	236.298	176.531
29.535	4.754	8.185	28.644	71.419	72.845	28.159	152.282	123.167	27.793	233.339	172.683
29.963	0.669	5.863	29.012	67.689	70.013	28.515	148.435	120.410	28.143	230.338	169.300
30.402	0.000	0.000	29.380	63.300	67.849	28.872	144.010	118.273	28.493	226.358	166.705
			29.748	59.674	64.916	29.229	140.066	115.8[illegible]	28.844	222.809	163.734
			30.118	56.230	61.763	29.586	136.048	113.087	29.195	219.218	160.731
			30.489	51.812	59.759	29.944	131.557	111.198	29.546	215.101	158.260
			30.860	48.153	56.701	30.303	127.239	108.753	29.897	211.245	155.520
			31.233	45.041	53.241	30.661	123.086	106.334	30.249	207.057	153.134
			31.607	41.536	50.297	31.020	118.602	104.308	30.601	203.010	150.779
			31.983	38.182	47.075	31.380	114.873	101.519	30.953	199.269	147.919
			32.360	34.693	44.134	31.740	110.614	99.340	31.306	195.128	145.602
			32.739	31.627	40.675	32.100	105.092	98.318	31.659	190.053	144.130
			33.135	29.987	29.179	32.464	104.283	86.050	32.013	189.745	131.323
			33.515	26.742	25.723	32.828	101.307	82.358	32.369	186.503	127.954
			33.907	23.011	23.670	33.192	97.282	79.574	32.724	182.493	125.157
			34.304	19.653	19.231	33.558	93.161	76.875	33.081	178.242	123.573
			34.696	16.702	23.107	33.921	85.719	84.315	33.435	169.673	131.136
			35.093	13.387	19.012	34.285	81.916	81.598	33.790	165.538	128.763
			35.491	[illegible]	15.775	34.650	78.301	78.613	34.146	161.384	126.335
			35.901	[illegible]	12.079	35.016	74.441	76.006	34.501	157.021	134.219
			36.317	4.052	8.839	35.382	69.895	74.090	34.857	152.387	122.573
			36.742	0.650	5.848	35.748	66.236	71.279	35.214	148.071	120.199
			37.183	0.000	0.000	36.116	63.290	67.678	35.570	144.380	117.503
						36.484	57.619	67.008	35.927	138.833	116.579
						36.852	53.421	64.440	36.285	134.490	114.129
						37.224	51.089	60.393	36.643	130.770	111.516
						37.595	47.873	56.916	37.001	120.418	109.143
						37.968	43.889	51.563	37.360	121.753	107.474
						38.341	40.015	51.740	37.719	117.517	104.974
						38.717	37.879	47.352	38.078	113.860	102.160
						39.099	36.333	35.836	38.440	113.363	89.618
						39.482	32.201	33.410	38.803	108.718	87.703
						39.868	29.108	29.880	39.166	104.118	85.671
						40.256	25.631	26.790	39.530	99.668	83.519
						40.649	23.493	22.337	39.894	96.481	80.133
						41.045	20.308	18.908	40.260	92.221	77.690
						41.446	16.507	13.935	40.625	87.923	75.296
						41.853	13.045	13.775	40.992	84.645	71.976
						42.255	10.797	15.035	41.357	77.661	78.957
						42.664	7.606	11.536	41.723	73.833	76.124
						43.082	4.907	8.052	42.089	70.278	73.403
						43.514	1.697	4.812	42.456	66.138	71.167
						43.954	0.000	0.000	42.823	61.553	69.209
									43.191	57.441	66.828
									43.561	54.311	63.569
									43.931	50.692	60.577
									44.302	47.370	57.417
									44.675	44.315	53.973
									45.049	40.284	51.382
									45.424	37.632	47.530
									45.806	36.014	36.265
									46.189	32.839	32.863
									46.575	29.423	29.622
									46.964	25.748	26.635
									47.356	22.832	22.893
									47.751	19.050	20.106
									48.151	15.876	16.658
									48.558	12.996	12.745
									48.971	9.647	9.517
									49.393	5.442	7.237
									49.810	4.630	8.361
									50.243	1.878	4.772
									50.682	0.000	0.000

2400	days		2700	days		3000	days		3300	days	
15.216	m		17.333	m		19.480	m		21.657	m	
1216.60	kPa		1367.73	kPa		1518.86	kPa		1669.99	kPa	
70.840	m		79.640	m		88.440	m		97.240	m	
57.370	m		64.054	m		70.706	m		77.330	m	
Depth from base up	*u*	*Effective Stress*	Depth from base up	*u*	Effective Stress	*Depth from base up*	*u*	*Effective Stress*	Depth from base up	*u*	Effective Stress
m	kPa	kPa	m	kPa	kPa	m	kPa	kPa	m	kPa	kPa
0.357	24.701	822.589	0.357	28.307	857.881	0.356	29.015	870.177	0.356	28.474	870.719
0.699	21.536	1057.027	0.697	28.255	1180.520	0.695	26.448	1309.400	0.694	37.809	1427.877
1.020	20.690	1053.250	1.026	25.137	1178.556	1.022	28.770	1306.937	1.020	32.033	1431.446
1.349	29.084	1038.978	1.343	32.104	1160.230	1.339	36.712	1291.630	1.335	37.211	1420.938
1.669	34.360	1024.990	1.661	34.918	1154.912	1.655	35.435	1284.244	1.650	40.518	1408.969
1.989	40.581	1012.290	1.980	44.603	1138.545	1.972	45.306	1267.856	1.965	47.461	1395.514
2.309	49.990	995.738	2.298	51.448	1124.576	2.289	51.933	1251.107	2.281	55.203	1380.647
2.630	54.608	981.193	2.617	57.969	1111.109	2.606	61.323	1237.770	2.597	61.417	1365.465
2.951	62.084	969.853	2.936	67.523	1094.690	2.924	70.560	1221.668	2.913	73.705	1348.335
3.272	67.762	956.601	3.255	71.456	1083.183	3.241	74.506	1210.139	3.229	78.697	1335.753
3.593	75.674	931.712	3.575	79.598	1068.085	3.559	81.536	1194.161	3.546	86.654	1320.856
3.914	82.352	928.199	3.894	86.343	1054.482	3.877	89.662	1181.180	3.862	93.795	1306.858
4.236	89.525	914.086	4.214	94.205	1039.680	4.195	99.495	1164.405	4.179	102.699	1291.013
4.558	94.489	902.373	4.534	99.331	1027.712	4.514	104.178	1152.880	4.496	108.381	1278.485
4.880	103.000	886.742	4.854	109.061	1010.994	4.832	114.902	1135.195	4.813	120.719	1259.189
5.202	108.926	874.406	5.175	114.563	999.101	5.151	120.562	1123.119	5.130	124.815	1248.656
5.525	114.781	861.775	5.495	120.988	983.841	5.470	127.211	1109.635	5.447	131.352	1233.305
5.848	119.291	850.340	5.816	126.179	973.720	5.789	132.540	1097.376	5.765	137.976	1221.747
6.171	126.105	836.811	6.137	132.900	960.204	6.108	139.286	1083.914	6.082	145.020	1207.988
6.494	133.301	822.687	6.458	140.704	945.561	6.427	148.174	1068.108	6.400	153.476	1192.615
6.817	139.903	809.323	6.780	147.308	931.994	6.747	154.810	1054.703	6.718	161.590	1177.732
7.141	145.251	797.299	7.101	153.216	919.603	7.067	160.736	1042.092	7.036	167.774	1164.861
7.465	152.069	783.639	7.423	161.149	904.834	7.387	168.598	1027.396	7.355	176.100	1149.699
7.789	157.602	771.207	7.745	166.411	892.701	7.707	174.878	1014.227	7.673	182.171	1136.785
8.114	164.408	757.567	8.067	174.156	878.090	8.027	183.161	999.090	7.992	191.342	1120.714
8.439	170.619	744.913	8.390	180.823	864.974	8.348	189.982	985.827	8.311	198.286	1107.333
8.764	177.219	731.448	8.713	187.771	851.166	8.668	197.622	971.324	8.630	204.281	1092.473
9.089	182.680	719.170	9.036	193.849	838.305	8.989	204.074	958.063	8.949	213.398	1078.547
9.414	189.251	705.772	9.359	200.578	824.715	9.311	210.714	944.588	9.269	220.417	1064.690
9.740	194.105	694.442	9.683	208.454	812.303	9.632	216.559	932.268	9.588	226.895	1051.739
10.066	200.623	681.226	10.006	213.392	798.723	9.954	224.977	917.150	9.908	235.919	1035.983
10.393	206.718	668.415	10.330	219.984	785.117	10.276	232.168	903.240	10.228	243.104	1022.109
10.720	212.437	655.704	10.654	225.993	772.413	10.598	238.995	889.822	10.548	250.048	1008.173
11.046	217.420	644.430	10.978	231.982	760.139	10.920	245.294	876.839	10.869	257.193	994.741
11.374	223.761	631.304	11.303	238.985	746.339	11.242	252.513	862.826	11.189	264.142	981.000
11.701	229.115	619.160	11.628	245.058	733.483	11.565	259.330	849.219	11.510	272.227	966.128
12.029	234.338	607.324	11.953	250.509	721.255	11.888	265.530	836.276	11.831	278.590	953.043
12.357	239.361	595.551	12.279	256.577	708.005	12.211	271.740	823.447	12.153	285.613	939.381
12.686	244.817	583.466	12.605	262.557	695.997	12.535	278.495	810.063	12.474	293.096	925.271
13.015	249.289	572.211	12.931	268.016	683.752	12.859	284.575	797.194	12.796	299.807	911.710
13.344	254.428	560.281	13.257	273.792	671.474	13.183	290.988	783.989	13.118	306.368	898.407
13.674	258.798	549.547	13.584	278.761	659.812	13.507	296.547	772.082	13.440	312.892	885.524
14.003	264.261	537.216	13.911	285.263	646.476	13.831	303.891	757.855	13.762	320.655	870.895
14.334	268.359	526.293	14.238	290.322	634.793	14.156	309.658	745.400	14.085	326.958	857.965
14.664	273.141	514.931	14.565	295.714	622.624	14.481	315.849	732.502	14.408	333.820	844.335
14.995	276.742	504.912	14.893	300.056	611.865	14.806	320.931	720.993	14.731	339.690	832.042
15.326	281.052	493.762	15.221	305.400	599.670	15.132	326.938	708.132	15.054	346.296	818.596
15.658	285.099	483.324	15.550	310.301	588.382	15.458	332.567	696.118	15.378	352.309	806.176
15.990	289.131	472.309	15.878	315.233	576.406	15.784	338.055	683.652	15.702	358.650	792.850
16.322	292.090	462.967	16.208	319.256	566.067	16.110	343.508	672.795	16.025	363.993	781.146
16.655	295.856	452.451	16.537	323.999	554.373	16.437	348.067	660.512	16.350	370.180	768.200
16.988	298.968	442.738	16.867	328.205	543.763	16.764	353.739	648.232	16.675	376.549	755.229
17.321	301.917	433.022	17.197	332.108	533.090	17.091	358.286	636.920	16.999	381.854	743.155
17.655	304.390	424.126	17.527	335.858	522.912	17.418	363.334	625.448	17.324	387.718	730.872
17.989	307.435	414.368	17.857	339.779	512.276	17.746	368.162	613.903	17.650	393.397	718.476
18.323	309.930	405.220	18.188	343.154	502.263	18.074	372.401	603.022	17.975	398.338	706.887
18.658	312.364	396.137	18.520	347.053	491.706	18.402	376.961	591.796	18.301	403.791	694.774
18.993	314.186	387.881	18.851	349.888	482.437	18.731	381.125	581.210	18.627	408.676	683.461
19.329	316.510	378.565	19.183	353.526	471.805	19.060	385.796	569.536	18.954	414.309	670.827
19.665	318.467	369.923	19.516	356.593	462.052	19.389	389.851	558.794	19.280	419.146	659.305
20.001	319.858	362.250	19.848	359.223	453.144	19.719	393.518	548.852	19.607	423.916	648.360
20.338	320.732	354.736	20.181	361.276	444.461	20.049	396.343	539.410	19.934	427.536	637.972
20.675	322.002	346.776	20.515	363.916	435.132	20.379	400.290	528.758	20.263	432.654	626.197
21.013	323.585	338.541	20.848	366.346	425.831	20.709	403.892	518.494	20.590	437.019	615.166
21.350	324.176	331.216	21.182	368.443	417.237	21.040	406.939	508.754	20.918	441.059	604.424

Copper 9 3mm with stress & supernatant

21.689	325.401	324.777	21.516	369.92	409.514	21.371	409.527	499.914	21.246	444.613	594.608
22.027	325.191	317.168	21.851	371.7	400.866	21.702	412.538	490.032	21.574	448.558	583.858
22.366	325.454	310.445	22.186	373.432	392.086	22.034	415.390	480.737	21.903	452.284	573.641
22.706	325.695	303.407	22.521	375.031	384.340	22.366	417.990	471.379	22.232	455.970	563.198
23.045	325.043	297.481	22.857	375.565	377.211	22.698	419.589	463.182	22.562	458.611	553.970
23.385	324.597	291.373	23.193	376.546	369.685	23.031	421.964	454.263	22.891	462.239	543.783
23.726	324.626	284.702	23.529	377.786	361.800	23.363	424.312	445.272	23.221	465.518	533.867
24.067	323.668	279.208	23.866	378.195	354.930	23.697	425.868	437.264	23.551	468.202	524.739
24.408	322.595	273.627	24.203	378.396	348.099	24.030	427.212	429.280	23.882	470.411	515.882
24.750	327.913	255.185	24.541	385.274	328.076	24.365	435.659	407.692	24.213	480.308	492.841
25.093	327.327	248.830	24.880	386.045	320.382	24.700	437.723	398.707	24.545	483.436	482.793
25.437	325.699	243.724	25.219	385.717	313.969	25.035	438.560	391.124	24.877	485.353	474.131
25.780	323.660	239.157	25.558	384.990	308.085	25.370	439.038	384.048	25.209	487.051	465.833
26.123	315.943	247.098	25.897	378.009	315.287	25.705	432.916	390.376	25.541	481.836	471.257
26.467	314.713	241.533	26.236	378.057	308.436	26.041	434.288	382.213	25.874	484.082	462.220
26.810	312.593	237.202	26.575	377.171	302.988	26.377	434.527	375.537	26.206	485.456	454.412
27.154	310.193	233.051	26.915	375.945	297.561	26.713	434.489	369.017	26.539	486.643	446.669
27.499	308.453	228.170	27.255	375.349	291.526	27.049	434.946	361.929	26.872	488.147	438.523
27.843	306.305	223.730	27.595	374.445	285.863	27.386	435.211	355.089	27.206	489.590	430.510
28.189	303.296	220.166	27.936	372.662	281.062	27.723	434.774	348.952	27.540	490.225	423.305
28.534	300.560	216.382	28.277	371.101	276.084	28.060	434.326	342.855	27.874	490.858	416.118
28.880	298.004	212.314	28.619	369.703	270.869	28.398	433.921	336.657	28.208	491.589	405.777
29.226	294.956	209.007	28.960	367.860	266.365	28.736	433.164	331.052	28.543	491.920	402.096
29.572	291.833	205.330	29.302	365.757	261.666	29.074	432.195	325.230	28.878	492.118	395.109
29.918	288.471	202.166	29.644	363.365	257.498	29.412	430.870	319.992	29.213	491.814	388.851
30.265	285.035	199.150	29.987	361.007	253.451	29.751	429.664	314.797	29.548	491.654	382.606
30.612	281.895	195.684	30.330	358.818	248.983	30.090	428.591	309.252	29.884	491.701	375.941
30.960	278.351	192.781	30.673	356.240	245.160	30.429	427.021	304.377	30.220	491.129	370.072
31.308	273.725	190.844	31.016	352.572	243.252	30.769	424.723	300.078	30.556	487.929	364.672
31.657	275.170	176.356	31.361	355.657	226.122	31.110	429.367	282.398	30.893	496.415	345.140
32.007	272.687	172.170	31.706	354.151	220.907	31.451	428.815	276.305	31.231	496.814	338.104
32.357	269.070	168.974	32.051	351.397	216.924	31.792	427.138	271.190	31.569	496.164	331.969
32.707	265.013	166.197	32.397	348.058	213.425	32.134	424.800	266.608	31.907	495.042	326.254
33.056	255.927	175.306	32.742	338.913	222.578	32.475	415.863	275.612	32.245	486.425	334.883
33.406	252.181	172.533	33.087	335.887	219.082	32.817	413.825	271.152	32.583	485.323	329.457
33.755	248.262	169.876	33.431	332.515	215.876	33.158	411.410	266.928	32.921	481.970	324.232
34.105	243.916	167.722	33.778	328.829	213.072	33.500	408.858	263.051	33.260	482.286	319.424
34.456	239.358	165.805	34.124	324.936	210.485	33.842	405.771	259.660	33.598	480.238	314.993
34.806	235.489	163.198	34.470	321.505	207.413	34.184	402.989	255.941	33.937	478.534	310.208
35.157	231.674	160.506	34.816	318.050	204.340	34.527	400.272	252.112	34.277	476.638	305.549
35.508	236.240	159.576	35.163	313.400	202.096	34.870	396.362	249.747	34.616	473.610	302.290
35.859	231.728	157.287	35.510	309.523	199.749	35.213	393.252	246.023	34.956	471.453	297.633
36.211	217.932	154.761	35.857	305.943	197.013	35.556	390.373	242.582	35.296	469.417	293.330
36.563	213.579	152.418	36.204	301.982	194.271	35.900	387.300	238.941	35.636	467.217	288.819
36.915	208.466	151.170	36.552	297.069	192.832	36.244	382.917	236.936	35.977	463.638	286.054
37.267	203.960	148.960	36.899	292.957	190.227	36.587	379.279	233.809	36.317	460.903	282.077
37.619	200.327	146.097	37.247	289.568	187.113	36.932	376.483	230.211	36.658	458.972	277.519
37.974	200.254	133.120	37.597	290.538	173.093	37.277	378.870	214.767	37.000	462.877	260.564
38.328	195.207	131.596	37.946	285.708	171.356	37.621	374.480	212.588	37.342	459.167	257.704
38.683	190.771	129.476	38.296	281.303	169.161	37.969	370.516	209.955	37.683	455.977	254.208
39.039	186.087	127.479	38.647	276.919	166.910	38.315	366.681	207.148	38.028	452.821	250.800
39.395	181.939	125.085	38.997	272.608	164.678	38.662	362.927	204.355	38.371	449.671	247.414
39.751	177.089	123.210	39.348	267.740	162.838	39.008	358.614	201.968	38.714	445.983	244.396
40.107	172.724	128.900	39.699	263.528	160.346	39.355	354.655	199.231	39.058	442.737	240.948
40.461	169.168	117.864	40.050	259.949	157.336	39.703	351.260	196.043	39.402	439.812	237.296
40.819	160.834	126.183	40.400	250.893	166.388	40.049	341.604	205.692	39.745	429.977	247.118
41.175	156.547	123.802	40.751	246.285	164.323	40.395	337.281	203.339	40.088	426.083	244.329
41.531	152.171	121.915	41.101	241.584	162.758	40.742	332.751	201.601	40.431	422.064	242.101
41.888	147.587	130.081	41.452	237.136	160.808	41.089	328.631	199.323	40.775	418.537	239.220
42.244	142.483	118.662	41.803	231.897	159.521	41.436	323.659	197.771	41.119	413.915	237.325
42.601	137.041	117.606	42.154	226.241	158.674	41.783	318.012	196.915	41.462	408.510	236.222
42.958	132.631	115.553	42.506	221.562	156.801	42.130	313.352	195.309	41.806	404.303	233.959
43.316	129.260	112.372	42.857	217.691	154.204	42.478	309.659	192.248	42.151	401.397	230.309
43.674	125.162	109.994	43.209	213.757	151.067	42.826	305.805	189.620	42.495	397.873	227.357
44.033	121.138	107.519	43.561	209.271	149.665	43.174	301.303	187.642	42.840	393.468	225.282
44.392	117.119	104.925	43.914	204.454	147.835	43.522	296.720	185.537	43.184	389.208	222.902
44.751	112.926	102.610	44.266	199.944	145.839	43.870	392.236	183.539	43.529	384.870	220.718
45.113	112.112	90.558	44.621	199.489	133.456	44.220	292.333	170.619	43.876	385.947	206.808
45.476	107.739	88.320	44.976	194.881	131.448	44.570	287.489	168.845	44.232	381.418	204.716
45.839	103.458	85.967	45.331	190.368	129.334	44.920	282.965	166.736	44.569	377.164	202.346
46.203	99.893	82.891	45.686	186.281	126.772	45.271	278.710	54.357	44.916	373.065	199.811
46.567	95.727	80.369	46.042	181.632	124.719	45.621	273.736	162.629	45.263	368.161	197.997
46.932	90.780	78.750	46.398	176.202	123.597	45.972	268.069	161.746	45.610	362.403	197.158
47.298	87.224	75.677	46.754	172.104	121.563	46.323	263.621	159.554	45.958	358.120	194.849
47.665	84.276	71.860	47.111	168.437	117.949	46.675	259.891	156.504	46.303	354.620	191.573
48.033	80.562	69.014	47.468	163.747	116.078	47.027	255.105	154.731	46.653	349.989	189.646
48.400	74.560	68.492	47.826	157.191	116.137	47.378	248.736	154.585	47.001	343.607	189.523
48.766	67.582	75.646	48.181	149.201	124.281	47.729	239.479	164.014	47.348	333.922	199.382
49.133	65.628	71.170	48.538	146.112	120.906	48.080	236.390	160.676	47.695	330.584	196.241
49.501	62.390	68.000	48.894	142.738	117.871	48.431	232.504	158.116	48.042	326.583	193.836
49.869	58.200	65.767	49.252	138.000	116.211	48.782	227.310	157.016	48.390	321.351	192.684
50.239	54.229	63.236	49.609	133.712	114.019	49.134	222.422	155.314	48.738	316.592	190.948
50.609	50.917	60.115	49.967	129.076	112.230	49.485	217.857	153.444	49.086	311.797	189.307
50.981	47.024	57.466	50.325	124.067	110.686	49.837	212.556	152.188	49.434	306.299	188.248

Copper 9 3mpa with stress & supernatant

51.353	42.452	55.483	50.683	120.185	108.032	50.189	207.983	150.247	49.782	301.512	180.512
51.730	40.949	44.097	51.044	119.721	95.544	50.543	207.966	137.314	50.135	303.931	173.149
52.110	39.789	38.730	51.406	116.395	92.348	50.897	203.809	134.912	50.481	297.578	170.972
52.492	36.130	35.761	51.768	111.622	90.502	51.252	198.643	133.487	50.832	292.239	169.700
52.875	31.804	33.562	52.130	107.009	88.607	51.606	193.674	131.959	51.181	287.181	168.255
53.260	28.692	30.103	52.493	103.175	85.852	51.961	189.315	129.706	51.531	282.578	166.249
53.649	26.009	26.243	52.857	99.131	87.347	52.317	184.475	127.091	51.881	277.377	164.898
54.041	22.285	23.403	53.221	94.151	81.779	52.672	179.491	126.430	52.232	272.305	163.422
54.436	18.896	20.240	53.586	89.813	79.573	53.028	175.064	124.320	52.583	267.427	161.768
54.836	16.506	16.125	53.951	86.481	76.385	53.384	170.738	122.133	52.934	262.025	160.048
55.243	13.059	12.841	54.318	81.822	74.340	53.741	165.794	120.355	53.285	257.996	157.940
55.657	9.973	9.332	54.685	78.508	71.068	54.097	161.606	117.982	53.637	253.518	155.835
56.080	6.100	6.851	55.053	75.190	67.883	54.455	157.344	113.744	53.988	248.873	154.014
56.498	4.809	8.143	55.419	67.868	75.120	54.811	149.158	123.809	54.339	239.878	162.888
56.930	1.657	4.703	55.785	64.462	72.195	55.167	145.093	121.546	54.690	234.968	161.478
57.370	0.000	0.000	56.153	61.343	68.876	55.523	141.313	118.904	55.041	230.585	159.428
			56.521	57.523	66.314	55.880	136.630	117.158	55.392	225.592	158.023
			56.891	54.420	62.957	56.238	133.260	115.094	55.743	221.110	156.052
			57.261	51.145	59.819	56.595	128.774	112.187	56.095	217.167	153.580
			57.636	49.095	48.670	56.955	127.644	100.107	56.449	216.202	141.338
			58.013	45.599	45.640	57.316	123.242	97.975	56.802	211.403	139.614
			58.390	41.518	43.092	57.677	118.959	95.648	57.156	206.864	137.541
			58.770	38.349	39.917	58.038	114.665	93.616	57.510	201.930	136.141
			59.131	35.058	36.675	58.400	110.564	91.157	57.864	197.011	134.495
			59.534	31.641	[illegible]	58.763	106.387	88.226	58.219	192.694	132.219
			59.923	30.681	27.946	[illegible]	103.204	85.424	58.574	188.083	129.409
			60.311	26.858	25.246	59.490	98.375	83.710	58.929	183.589	128.292
			60.705	23.650	21.920	59.854	94.643	80.943	59.285	178.976	126.411
			61.101	20.046	18.966	60.219	89.926	79.064	59.641	173.820	124.967
			61.501	15.955	16.457	60.584	84.883	77.517	59.997	168.764	123.439
			61.907	12.463	13.177	60.950	81.413	74.160	60.353	165.160	120.258
			62.320	9.231	9.850	61.318	78.439	70.628	60.710	161.356	117.671
			62.742	5.716	6.961	61.686	75.233	67.446	61.067	157.127	115.330
			63.174	1.643	4.870	62.055	71.810	64.349	61.425	153.414	113.536
			63.614	0.000	0.000	62.425	67.155	62.514	61.783	148.871	110.590
			64.055	0.000	0.000	62.792	60.169	69.610	62.140	139.921	119.636
						63.160	57.170	66.286	62.497	135.641	117.607
						63.533	55.178	55.137	62.856	134.916	105.202
						63.906	54.000	52.536	63.215	130.544	103.384
						64.281	48.026	49.544	63.575	126.206	101.156
						64.657	44.925	46.119	63.935	121.443	99.323
						65.035	41.960	42.506	64.296	117.596	96.656
						65.415	39.089	38.973	64.657	114.441	93.396
						65.796	35.140	35.404	65.019	109.214	92.107
						66.180	31.984	33.086	65.381	105.418	89.377
						66.566	29.090	29.477	65.744	101.739	86.630
						66.954	25.576	26.498	66.108	96.900	84.947
						67.346	22.589	22.967	66.472	92.860	82.477
						67.741	18.945	20.121	66.836	88.677	80.156
						68.141	17.813	16.736	67.201	85.528	76.767
						68.547	13.026	13.072	67.568	82.205	73.607
						68.962	10.784	8.813	67.935	78.980	70.391
						69.390	7.199	5.818	68.303	75.159	67.655
						69.826	2.364	4.139	68.672	70.175	66.094
						70.266	0.000	0.000	69.041	66.493	62.944
						70.706	0.000	0.000	69.412	63.548	59.415
									69.784	59.678	56.845
									70.157	56.314	53.663
									70.531	52.606	50.913
									70.906	47.877	49.103
									71.282	45.647	45.153
									71.660	41.539	42.768
									72.040	38.508	39.243
									72.422	35.100	36.129
									72.805	31.535	33.221
									73.191	28.798	29.473
									73.581	25.777	26.011
									73.973	22.837	22.437
									74.369	19.403	19.348
									74.771	17.025	15.288
									75.179	13.651	12.249
									75.594	10.499	8.915
									76.017	5.894	6.721
									76.450	1.597	4.825
									76.890	0.000	0.000
									77.330	0.000	0.000

REFERENCES

REFERENCES

1. Blight, G.E., (1969), "Shear Strength of Dumps and Dams of Gold Mining Waste", The Civil Engineer in South Africa, Vol. 11, No 3, March 1969, pp. 49 – 54.

2. Chamber of Mines, 1979, "Handbook of Guidelines for Environmental Protection", Vol. 1/1979, pp. 80 – 81.

3. Taylor, D.W., 1948, "Fundamentals of Soil Mechanics", John Wiley & Sons, New York, pp. 226 – 237.

4. Duncan, J.M., (1993), "Limitations of Conventional Analysis of Consolidation Settlement", Twenty Seventh Karl Terzaghi Lecture, Journal of Geotechnical Engineering, ASCE, Vol. 199, No. 9, September 1993, pp. 1333 – 1359.

5. Fahey, M. and Fujiyasu, Y., "Consolidation Behaviour of Saline Gold Tailings", First International Congress on Environmental Geotechnics, Edmonton Alberta Canada, 10-15 July 1994, pp. 417 – 428.

6. Fahey, M. and Fujiyasu, Y., "The Influence of Evaporation on the Consolidation Behaviour of Gold Tailings", First International Congress on Environmental Geotechnics, Edmonton Alberta Canada, 10-15 July 1994, pp. 481 – 486.

7. Gibson, R.E., (1958), "The Progress of Consolidation in a Clay Layer Increasing in Thickness with time", 1958, Geotechnique, 8, pp. 171 – 182.

8. Gibson, R.E., Schiffman, R.L., Cargill, K.W., (1981), "The Theory of One-Dimensional Consolidation of Saturated Clays, II Finite non-linear Consolidation of Thick Homogeneous Layers", Canadian Geotechnical Journal, 18, pp. 280 – 293.

9. Gibson, R.E., England, G.L., Hussey J.L., (1967), "The Theory of One-Dimensional Consolidation of Saturated Clays, I Finite non-linear Consolidation of Thin Homogeneous Layers", Geotechnique, 17, pp. 261 – 273.

10. Glenister, D., Press M., "Engineering Characteristics of Bauxite Residue", Workshop Notes, Mine Tailings Disposal, University of Queensland, Australia. 28 – 29 August 1986, Section 5.

11. Lambe and Whitman, "Soil Mechanics", 1979, John Wiley & Sons, Chapter 27, pp. 406 – 422.

12. Lui, J., Znidarcic, D., "Modelling One-Dimensional Compression Characteristics of Soils", Journal of Geotechnical Engineering, Vol. 117, No. 1, January 1991, pp. 162 – 16[illegible]

13. McVay, M.C., Townsend, F.C., Bloomquist D.G. "One-Dimensional Lagrangian Consolidation", Journal of Geotechnical Engineering, Vol. 115, No. 6, June 1989, pp. 893 – 898.

14. Mitsunari, T, "Self-weight Consolidation Settlement of Red Mud Layer," Compression and Consolidation of Clayey Soils, Hiroshima Japan 10-12 May 1995, Vol. 1, pp. 715 – 718.

15. Robertson, A., Mac, G. "The Influence of Depositional Methods on the Engineering Properties of Tailings Deposits", Mining and Industrial Waste Management, (SAICE), International Conference, Johannesburg, 1987.

16. Schiffmann, R.L., Vick, S.G., Gibson, R.E., "Behaviour and Properties of Hydraulic Fills", 1988, Hydraulic Fill Structures, American Society of Civil Engineers, Colorado State University, pp. 166 – 202.

17. Schiffman, R.L., Pane, V., Gibson, R.E., "The Theory of One-Dimensional Consolidation of Saturated Clays, IV An Overview of non-linear Finite Strain Sedimentation and Consolidation", 1984 Sedimentation/Consolidation Models, ASCE, pp. 1 – 29.

18. Seneviratne, H.N., Newson, T.A., Fahey, M., Fujiyasu, Y. "Some Factors Influencing the Consolidation Behaviour of Mine Tailings", Compression and Consolidation of Clayey Soils, Hiroshima Japan 10-12 May 1995, Vol. 1, pp. 459 – 472.

19. Stauffer, P.A., Obermeyer, J.R., "Pore Water Pressure Conditions in Tailings Dams", Hydraulic Fill Structures, American Society of Civil Engineers, Colorado State University, pp.166 – 202.

20. Stone, K.J.L., Randolph, M.F., Toh, S., Sales A.A., "Evaluation of Consolidation Behaviour of Mine Tailings", Journal of Geotechnical Engineering, Vol. 120, No. 3, March 1994, pp. 473 – 489.

21. Swarbrick, G.E., Fell, R., "Modelling Desiccating Behaviour Mine Tailings", Journal of Geotechnical Engineering, Vol. 118, No. 4, April 1992, pp. 540 – 557.

22. Tan, T., Inoue, T., Lee, S.L., "Hyperbolic Method for Consolidation Analysis", Journal of Geotechnical Engineering, Vol. 117, No. 11, November 1991, pp. 1723 – 1737.

23. Wates, J.A., "The effect of Stope Backfilling on the Construction and Operation of Slimes Dams in the Gold Mining Industry", Journal of the South African Institute of Mining and Metallurgy, Vol. 88, No 2, February 1988, pp. 41 – 48.

24. Terzaghi, K., "Theoretical Soil Mechanics", 1943, John Wiley & Sons, Chapter 13, pp. 265 – 296.

25. Prokon, Software Consultants, Geotechnical Analysis Programs, Programs GSI, Generalised slope analysis, Version 1, 11, and GGI, Generalised non-circular slip analysis, Version 1, 01.