Geofísica Internacional (1996), Vol. 35, Num. 2, pp. 135-145

Analytical and numerical evaluation of one-dimensional transient stress release at Wellenberg, Switzerland

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Received: April 7, 1995; accepted: October 13, 1995.

RESUMEN

Se observaron deficiencias de presión en pozos exploratorios en Wellenberg, Alpes Centrales, en el curso de estudios para un depósito de desechos radioactivos. En la Formación Valanginiana existen presiones de agua de hasta 600 m (6 MPa) por debajo de la hidrostática. De entre diversas hipótesis, ni el flujo regional ni los efectos químicos logran explicar este fenómeno, el que atribuimos a factores geomecánicos relacionados con la retirada de los glaciares. Las zonas de presión anómalas se reproducen bastante bien con el modelo, y las escalas de tiempo inferidas por la liberación de esfuerzos concuerdan con la ecuación de difusividad en una dimensión. Actualmente se disiparon 75-84% de los efectos de la perturbación y podrían pasar otros 20,000 - 30,000 años para que la presión se ajuste en 95-97% a las nuevas condiciones permanentes. Se concluye que el sitio de Wellenberg se encuentra bajo condiciones de desequilibrio hidrogeológico por causa de los cambios en la glaciación que continúan influenciando el sistema. Un análisis más avanzado en 2 y 3 dimensiones se ha efectuado con un modelo local y regional que incluye efectos transitorios (Rivera y Senger, 1993).

PALABRAS CLAVE: Wellenberg, deficiencias de presión, hidromecánica, esfuerzos transitorios, modelos 1-D.

ABSTRACT

In the exploration of the Wellenberg site, central Alps, where a repository for low- and intermediate-level radioactive waste is proposed, water pressure measurements from boreholes showed significant *underpressures*. Pore water pressures *below* hydrostatic, in the order of 600 m (6 MPa), occurred within the Valanginian Marl formation. Several studies evaluated different scenarios that would explain this anomalous trend. Because neither regional groundwater flow nor chemical effects could explain this phenomenon, it is attributed to *geomechanical* factors due to glacial retreat. A one-dimensional vertical model, considering hydromechanical processes and time scales associated with the dissipation of the pressure disturbances, is proposed. The results show that the rebound hypothesis due to glacial retreat is plausible. The abnormal pressure zones are reproduced reasonably well. The time scales associated with the stress release due to the perturbation are in accordance with the one-dimensional diffusivity equation. Today about 75-84% of the effect of the perturbation has dissipated, but it may take another 20,000 to 30,000 years for 95% to 97% of the pressure to adjust to the new steady-state conditions. The implications for the Wellenberg site are that the local groundwater system is under non-equilibrium conditions due to the geological changes (i.e., glaciations), that are still influencing the behaviour of the system. This work was used as the basis for more advanced, two- and three-dimensional analysis with a local or regional model which includes the transient effects (Rivera and Senger, 1993).

KEYWORDS: Wellenberg, underpressure, hydromechanic, transient stress, 1D model.

INTRODUCTION

Considerable data has been gathered from a proposed consolidated, deformed Valanginian Marl of early Cretaceous age, as a host rock for the disposal of short-lived radioactive waste at Wellenberg, central Alps in Switzerland (Figure 1). During the drilling of the first three Wellenberg boreholes (SB1, SB3, and SB4), "anomalous" fluid pressures (see next section for definition) were observed at some depth intervals within the Valanginian Marl. Based on preliminary data from *in situ* observations, no consistent lithologic, structural, gas, or hydrogeological changes appeared to be associated with the variations in the static pressure profile. The only significant difference came from conductivity values from fluid logging data which were up to three orders of magnitude lower in the intervals where the pressure is less than hydrostatic.

These observations prompted investigations to study different scenarios that would explain this apparently anomalous trend. Based on the assumption that the anomalous trend accurately reflects the physical system at the Wellenberg site, several conceptual site-scale models were proposed. These models were evaluated by preliminary "scoping" studies intended to test their validity by using relevant in-situ data. The conclusions from these studies are limited to qualitative and semi-quantitative results, which test the reasonableness of the models.

In the most probable model to explain the preliminary static pressure profiles observed at Wellenberg, called the stress-release model, the flow system is assumed to be in a transient state and undergoing mechanical rebound as a result of a release of stress. A simplified analytical calculation in one dimension performed at borehole SB4 provided a fairly good match of the pressure profile from this borehole. Vinard *et al.* (1993) presented a complete description of a step-by-step procedure in which alternative hypotheses were proposed and evaluated until a currently preferred (restricted) set was defined. The same authors also presented preliminary results for two-dimensional models.

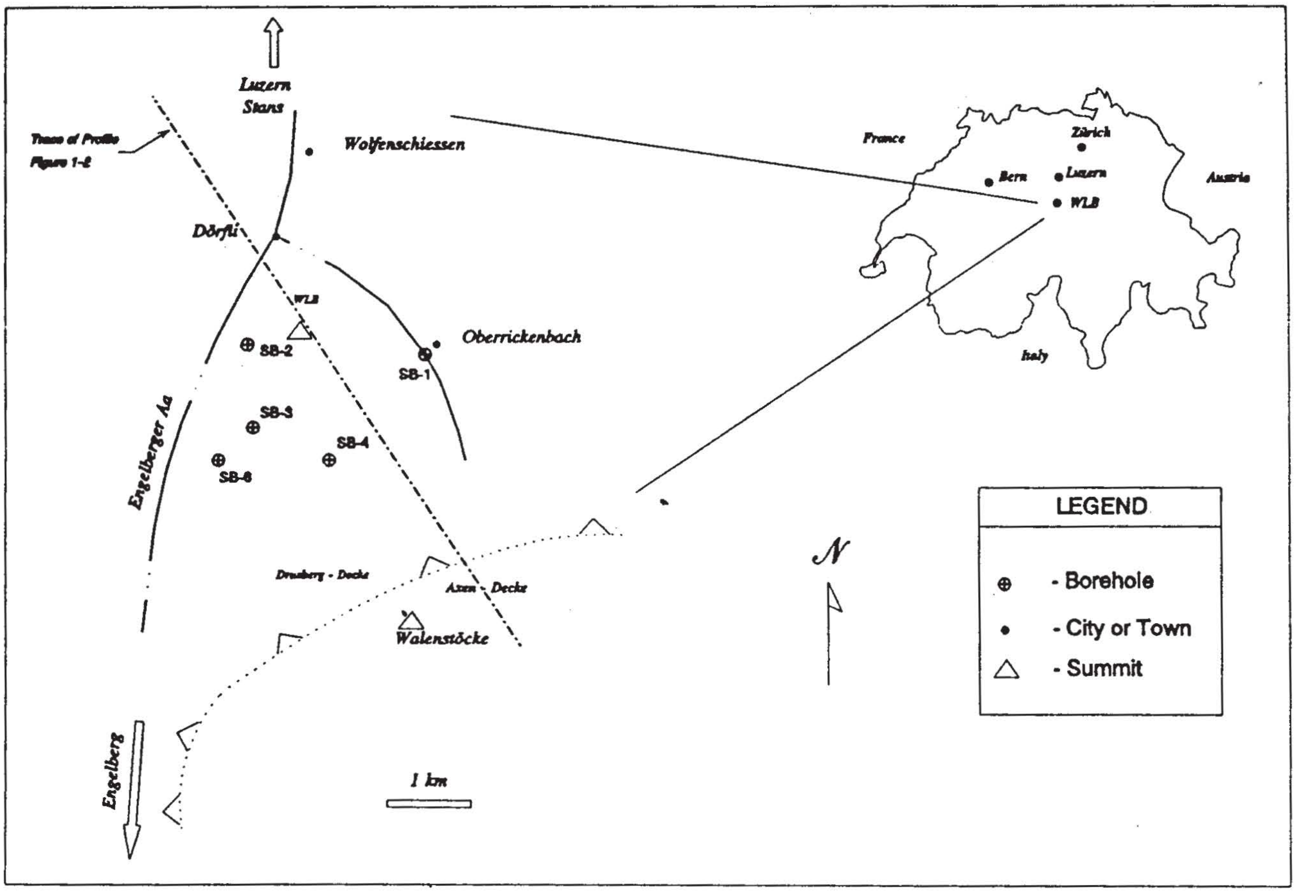


Fig. 1. Location of the Wellenberg site showing borehole positions.

In the present work, the same conceptual model is used in an attempt to explain the anomalous trend. This model considers the hypothesis that the underpressuring was caused principally by hydromechanical processes. This hypothesis is tested in more detail by using borehole pressure data in simple analytical and numerical models to investigate the degree to which field data can be reproduced with reasonable initial and boundary conditions and parameter values. Finally, we quantify the time scales associated with the dissipation of the pressure disturbances.

We present a complete set of analytical calculations for the three boreholes SB1, SB3, and SB4, and a numerical calculation for one borehole (SB4). An abnormal pressure zone is defined; the main hypothesis adopted for Wellenberg is presented; the complete one-dimensional elastic consolidation/rebound model after Terzaghi is given. The quantitative analyses include the estimation of heave (or rebound) and the time needed to complete the transient stress release for each borehole.

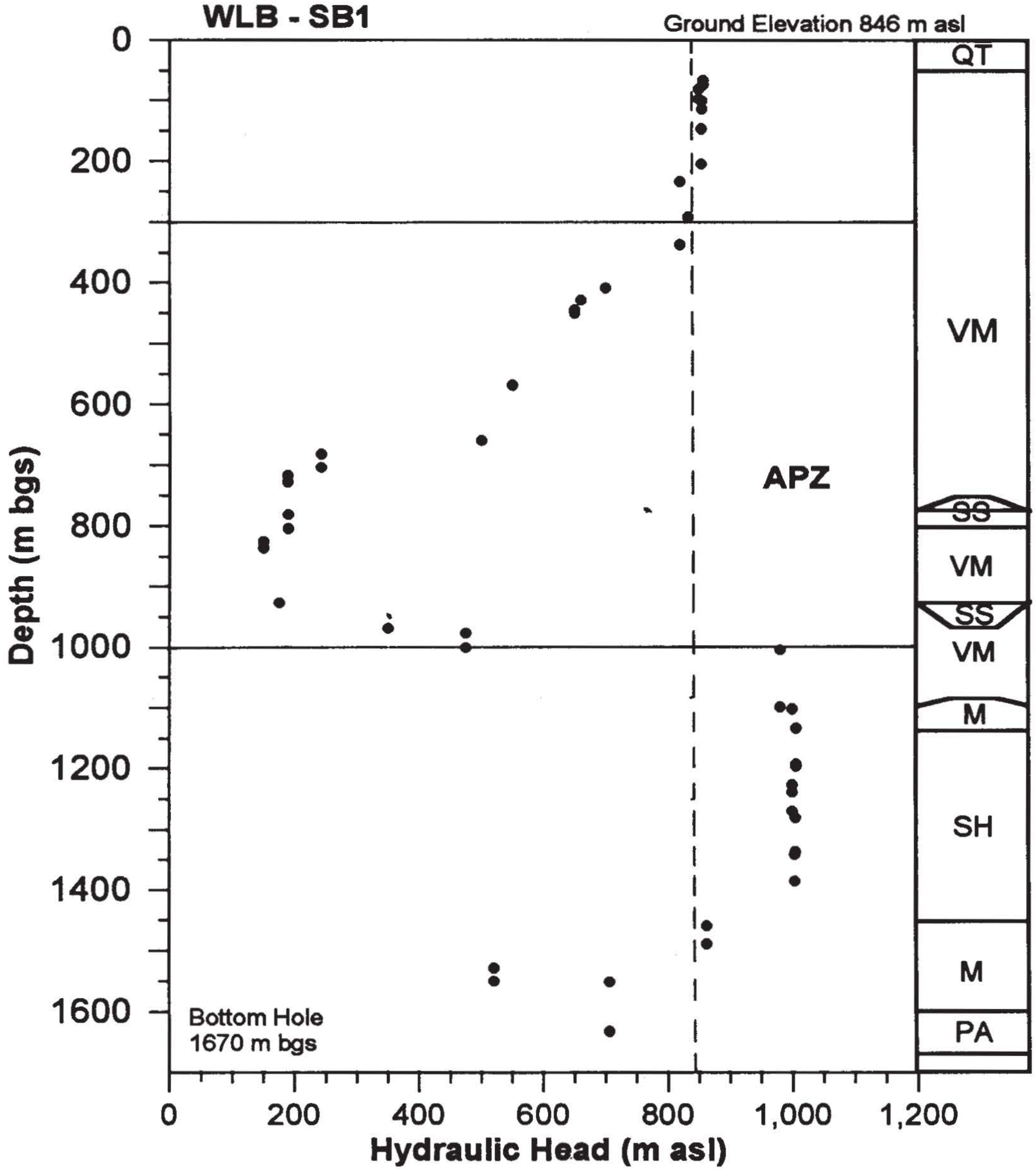
This work is expected to identify significant processes and parameters/variables, and to validate or eliminate the currently preferred hypothesis which is part of the overall hydrogeological conceptual model of the Wellenberg site (Vinard *et al.*, 1993).

Abnormal pressure zones in Wellenberg

Formation fluid pressures are defined as "anomalous" or "abnormal" if they differ from the hydrostatic for the depth considered.

Measurements on the Wellenberg (WLB) boreholes SB1, SB3, and SB4, including borehole history, lithologic interpretation, results from packer tests and hydrotests, freshwater heads interpretation, and estimated transmissivity (or hydraulic conductivity) values, were made during the previous years by several investigators; the essential results are incorporated and presented in graphs and tables in this paper.

The hydraulic head profiles estimated from hydrotests conducted in each borehole are shown in Figures 2, 3 and 4. For each borehole, we defined an "Abnormal Pressure Zone" (APZ) where the interpreted heads are smaller than a reference level, RL, equal to the elevation of the top of each borehole. From this value we calculated the underpressure head defined as the reference level minus the estimated equivalent freshwater head. Vertical one-dimensional analytical and numerical models were then applied for each borehole to try to reproduce each APZ, using parameters measured *in situ* or in the laboratory and using the initial and boundary conditions as described in the following sections.



GEOLOGY

QT: Quaternary
VM: Valanginian Marl
(Palfris-Formation and Vitznau-Marl)
SS: Schimberg Schiefer

SE: Subhelvetische Elemente
(Aequivalente der Wissberg-Scholle)
M: Mélange
PA-Parautochthon

Fig. 2. Hydraulic head profile of the SB1 borehole.

PROPOSED CONCEPTUAL MODEL TO EXPLAIN THE APZ

The one-dimensional elastic consolidation/rebound process as given by Terzaghi is proposed as the conceptual model to explain the abnormal pressure zones at the Wellenberg boreholes. The principal hypothesis is that the heave or rebound process is due to glacial retreat. A transient effect occurs in the Valanginian Marl (considered as an aquitard), due to its smaller diffusivity ratio as compared to the overlying and underlying rocks.

Consider the vertical deformation of a bed stressed instantaneously under constant load. The time-dependent effective applied stress ($\bar{\sigma}=\bar{\sigma}(t)$) can be computed analytically with the one-dimensional consolidation theory of Terzaghi. Consider a homogeneous clay layer of thickness 2H enclosed between two permeable sandy layers (Figure 5). At time t=0, an excess pressure p_o occurs instantaneously over the whole thickness of the layer; at the boundaries this overpressure is zero due to the contact with the permeable sandy layers. The equation characterizing the vertical flow in the clay is

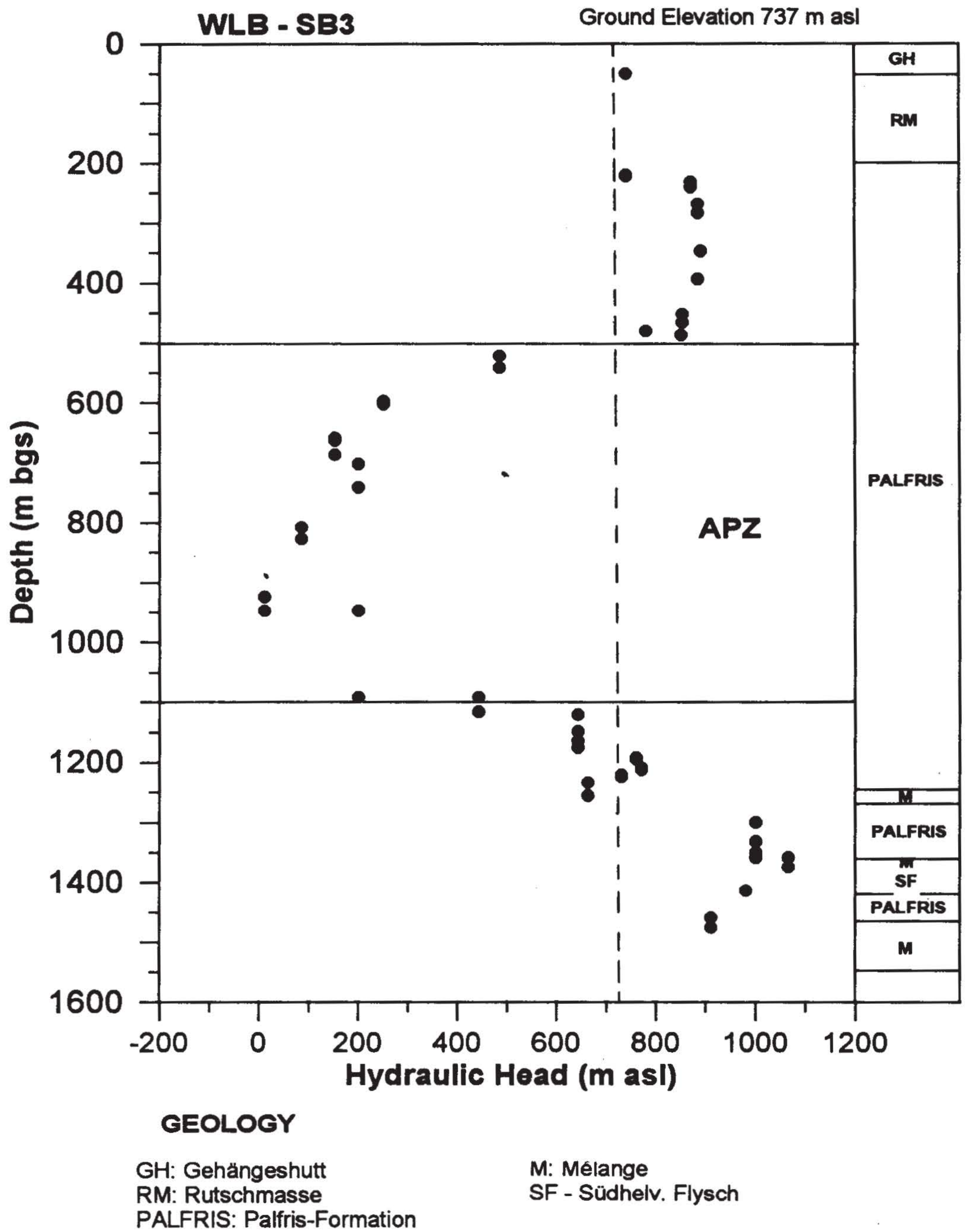


Fig. 3. Hydraulic head profile of the SB3 borehole.

$$\frac{\partial p}{\partial t} = \frac{K(1+e)\partial^2 p}{a_v \rho g \partial z^2} \qquad (1)$$

where p is the pore pressure, K is the hydraulic conductivity, e is the void ratio, a_v is the compressibility coefficient, ρ is fluid density, g is the acceleration due to gravity, and z is the vertical axis. In equation (1) the coefficient of consolidation C_v is defined as

$$C_v = \frac{K(1+e)}{a_v \rho g} \simeq \frac{K}{S_s} = \kappa \qquad (2)$$

where S_s is the specific storage coefficient neglecting fluid compressibility, and κ is the diffusivity ratio.

The initial and boundary conditions for the present case are

$$\begin{aligned} & z=0,\ p(z=0) = 0,\ t \geq 0 \\ & p(z) = P_o,\ t=0 \\ & z=2H,\ p(z=2H) = 0,\ t \geq 0 \\ & 0 < z < 2H \end{aligned} \qquad (3)$$

The analytical solution for this problem was given by Terzaghi and Fröhlich (1939). In this solution, equation (1) was integrated assuming that the isochrones were parabolas:

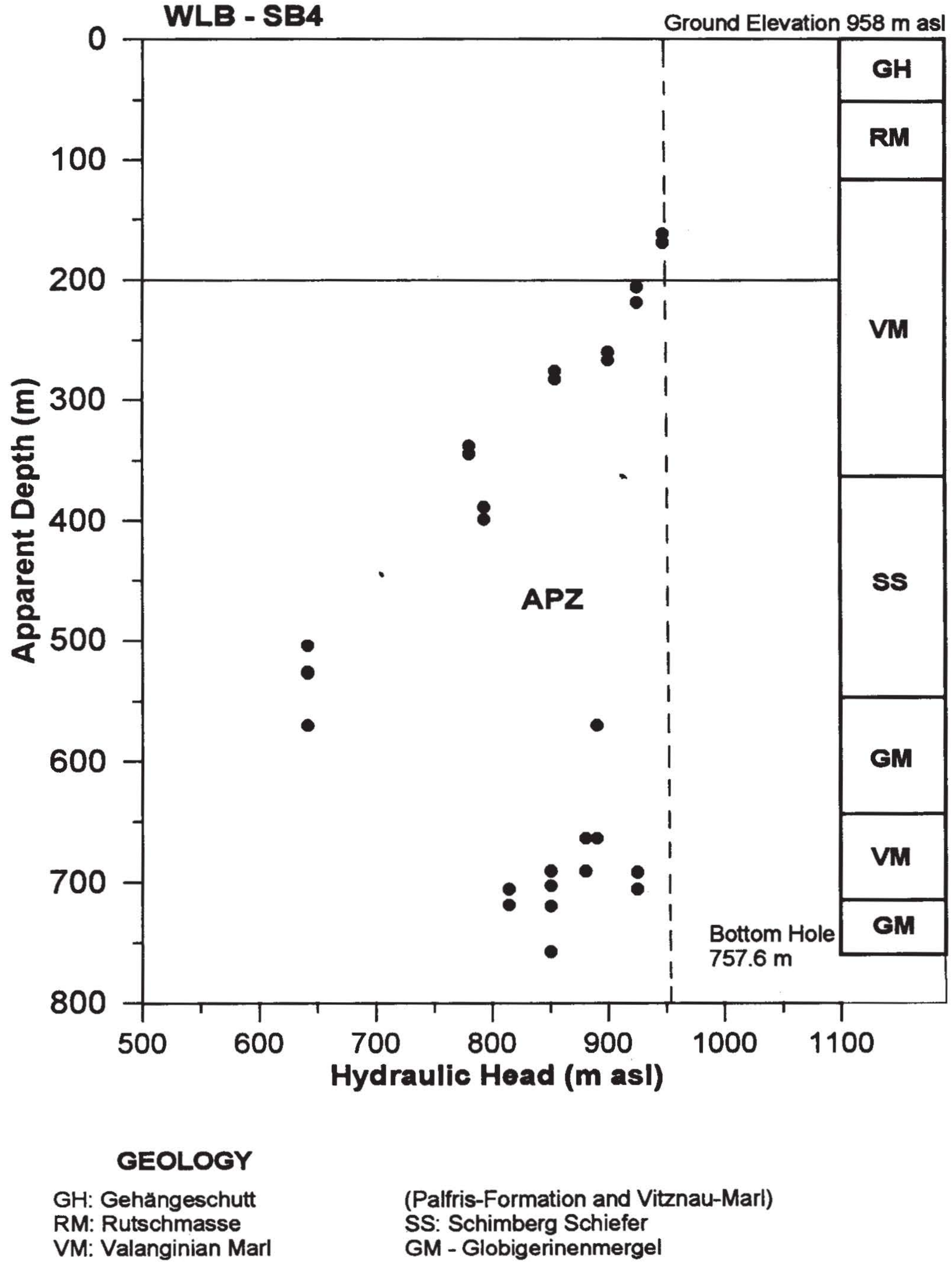


Fig. 4. Hydraulic head profile of the SB4 borehole.

$$\Delta p(z,t)=\frac{4}{\pi}\left[\sum_{m=0}^{\infty}\frac{p_o}{2m+1}\sin\left(\frac{(2m+1)\pi z}{2H}\right)\cdot \exp\left(\frac{-(2m+1)^2\pi^2T_v}{4}\right)\right] \quad (4)$$

where

$$T_v=\frac{t\kappa}{H^2} \quad (5)$$

and T_v is a dimensionless time factor.

HYDROMECHANICAL PROCESSES AT WELLENBERG

The stresses acting in the compaction or rebound of an aquifer system are the total (geostatic) pressure, σ due to the weight of overlying deposits; the effective stress, $\overline{\sigma}$; and the fluid pressure P due to the weight of pore water. At the interface between a highly permeable layer (aquifer) and a less permeable layer (aquitard), the total geostatic pressure equals the sum of the pore pressure P and the effective pressure $\overline{\sigma}$.

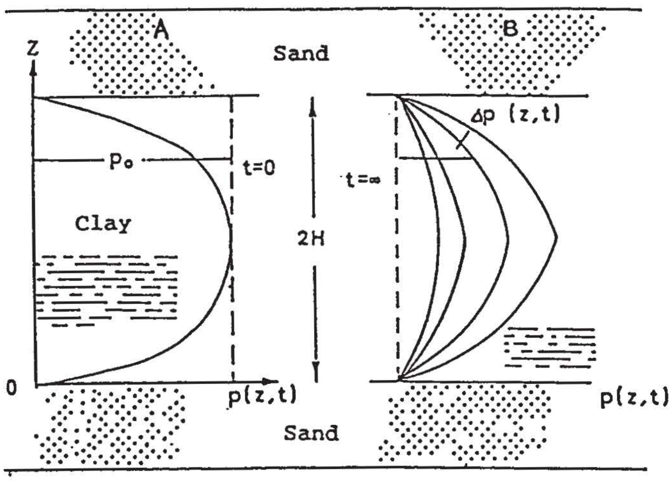


Fig. 5.Clay layer of thickness 2H enclosed between two sandy layers forming drains.

After Terzaghi, the effective stress is defined as the difference between total and pore pressure,

$$\bar{\sigma} = \sigma - p \quad (6)$$

It follows that $\bar{\sigma}$ increases when σ increases (i.e., as a result of construction problems), or when P decreases (i.e., as a result of water withdrawal).

Prior to the end of the Würm glaciation, approximately 20,000 years b.p., the maximum ice thickness in the vicinity of Wellenberg was about 1500 m. If the total pressure σ=1500 m remained constant for a long period of time, the effective stress should have increased whereas the fluid pressure should have decreased. The underlying Valanginian Marl was probably preconsolidated.

At the end of the Würm glaciation the ice cap retreated, causing a decrease of the effective stress and an increase of pore pressure. We assume that the more permeable material above (and probably below) the Valanginian Marl was reset to a new hydrostatic pressure profile (Figure 6). The retreat of the ice cap caused the Valanginian Marl to heave and generated a transient, much slower, stress release.

For a density of ice of ρ=1000 kg/m^3 and a total thickness of 1500 m, as suggested by some authors, the total pressure exerted by the glacier was p= ρgz = $1.5 \cdot 10^7$ Pa. This pressure is equivalent to a column of water of about 1500 m.

Thus, in order to simulate the APZ at each borehole in Wellenberg, the initial condition is,

$$p = p_o = 0, t = 0, \quad for\ 0<z<2H \quad (7)$$

where H is the half-thickness of the APZ; and the boundary condition is,

$$p_o = -1500\ m, t \geq 0, \quad for\ z=0 \quad (8)$$

where z=0 is the top of the APZ.

These initial and boundary conditions apply to all three boreholes; but the hydromechanical parameters and the depths of each APZ are different.

HYDRAULIC CONDUCTIVITY AND SPECIFIC STORATIVITY FOR THE VALANGINIAN MARL

From hydrotests and fluid logging there exist sufficient data for determining the hydraulic conductivity of the Valanginian Marl. However, the largest uncertainty in the diffusion equation is the specific storage, because only a few values were obtained from core investigations.

The mean hydraulic conductivity in the APZ was evaluated from hydrotests and fluid logging results. The intervals tested were divided into horizontal layers and the harmonic mean for each APZ was calculated as

$$K_v = \frac{\sum e_i}{\sum \frac{e_i}{K_i}} \quad (9)$$

where K is the hydraulic conductivity and e_i is the thickness of the ith layer. The computed harmonic mean values of hydraulic conductivity in the APZ for the three boreholes are summarized in Table 1.

Table 1

Computed values of K in the APZ for the three boreholes

Borehole	APZ from - to (m bg)	Harmonic mean K (m/s)
SB1	300 - 1000	3.2E-12
SB3	500 - 1100	2.6E-12
SB4	200 - 800	2.4E-14

The specific-storage coefficient was estimated from uniaxial compression tests performed in the laboratory for samples from boreholes SB1, SB3, and SB4. Unfortunately, compression tests for Wellenberg are not abundant. For borehole SB1 only ten samples were tested over a depth interval of 80 m, from 226 to 306 m. While all samples come from the Valanginian Marl, only the two deepest come from the defined APZ at SB1 (see APZ depth intervals in Table 1).

Eleven samples were tested over a depth interval of 211 m (from 302 to 513 m) in SB3. As in SB1 only the two deepest samples come from the uppermost section of the APZ for this borehole. For SB4, eight samples were tested over a depth interval of 11 m (from 350 to 361 m); in this

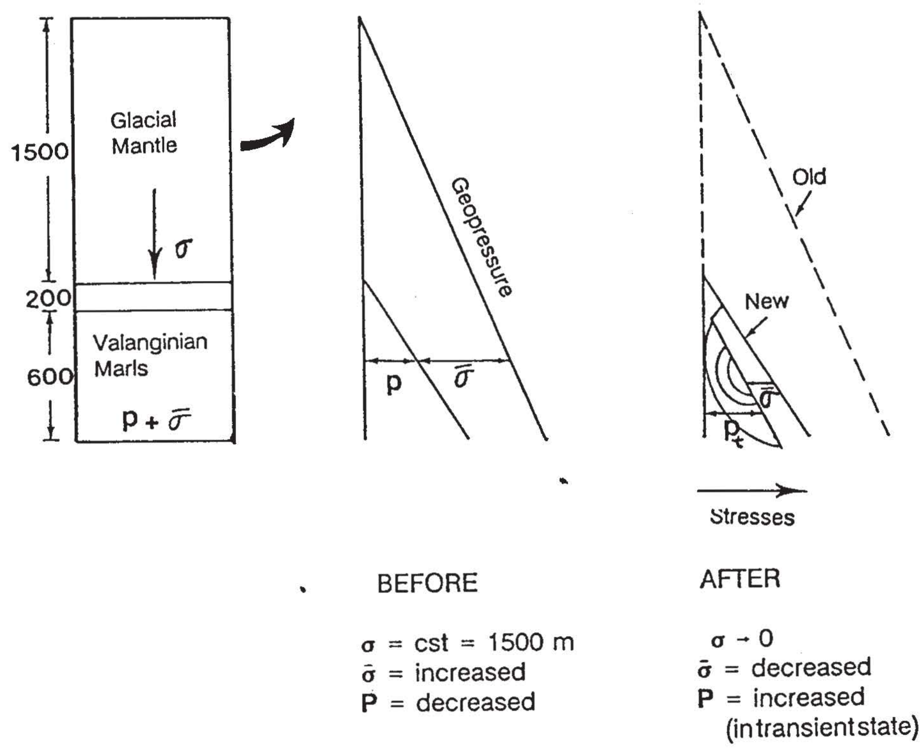


Fig. 6. Schematic evolution of pressure profiles at Wellenberg.

borehole, all the samples come from the defined APZ (see Table 1). Table 2 summarizes the specific-storage values estimated from these laboratory compression tests.

RESULTS

The application of Terzaghi's model with the one-dimensional analytical solution (equation 4) and the initial (7) and boundary conditions (8) as described in section 4, is presented for each borehole.

Table 2

Estimation of compressibility and specific-storage coefficients from laboratory compression tests

Borehole	Depth Interval (m bg)	Interval length (m)	α (Pa^{-1}) range	S_s (m^{-1})
SB1	226-306	80	4.7E-11 to 1.5E-10	5E-7 to 1.5E-6
SB3	302-513	211	8.3E-11 to 2.8E-10	8.5E-7 to 2.7E-6
SB4	350-361	11	3.2E-11 to 4.6E-10	3.9E-7 to 4.7E-6

Borehole SB1

The APZ for SB1 was defined as the depth interval from 300 to 1000 m below surface (Figure 2). The reference level is RL=846 m a.s.l., corresponding to the top of the borehole. The underpressure head values are the mean values measured from packer tests minus the RL, so all of the values within the APZ are negative.

The half-thickness of the APZ is 350 m. The distribution of pressure in meters of water was calculated for a time t=20,000 years. Several diffusivity ratios were tried until a reasonable match with the measured values could be established. The best match is shown in Figure 7. The final calibrated diffusivity ratio is $\kappa = 9.4 \cdot 10^{-8}$ m²/s, corresponding to $K=1.6 \cdot 10^{-12}$ m/s and $S_s=1.7 \cdot 10^{-5}$ m^{-1}.

Given the uncertainty in the storage coefficient, calibration was accomplished by keeping the hydraulic conductivity constant and varying S_s during the calculations. The storativity value is about an order of magnitude higher than the maximum value evaluated from core investigations (Table 2). The final value of hydraulic conductivity is practically the same as the harmonic mean value. On Figure 7 we show also the calculations for times t=40,000 years and t=50,000 years; the latter is the time needed for 95 % of excess pressure to dissipate.

We now compute the evolution of the effective stress, $\bar{\sigma}$, based on (6), and we determine the component of the glacial rebound. This is derived from

$$\frac{\Delta V}{V} = \frac{\Delta l}{l} = \alpha \Delta \bar{\sigma} \qquad (10)$$

being the volume change of a rock element; l is the thickness of the layer (2H in our case) if the rebound occurs only in the vertical direction. The stress decrement is

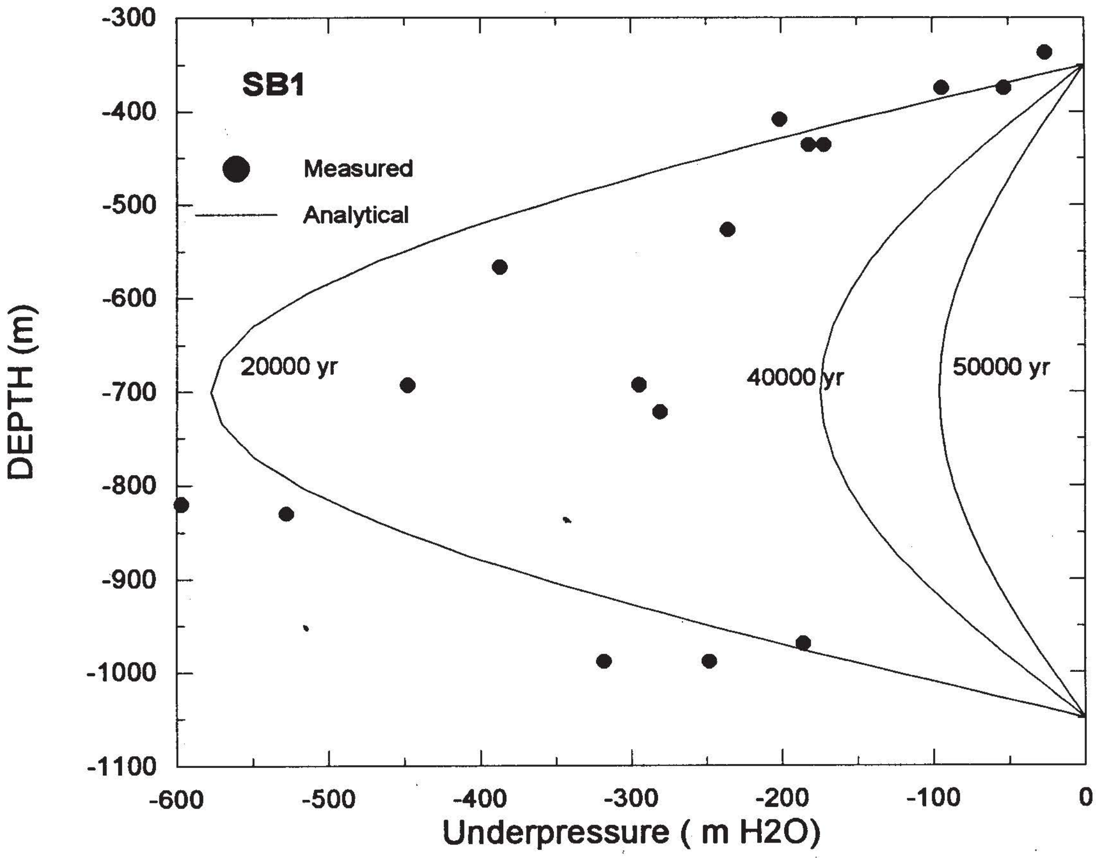


Fig. 7. Comparison of measured and calculated underpressures for SB1.

$$\Delta\bar{\sigma} = \Delta p \;\rightarrow\; \Delta p = -1500\,\text{m H}_2\text{O}$$
$$\Delta\bar{\sigma} = -1{,}5 \cdot 10^7\,\text{Pa}$$
$$\Delta l = -\alpha \cdot \Delta\bar{\sigma} \cdot l$$

Thus, with l=2H= 700 m, and the values of compressibility from table 2, α(SB1) = $3.5 \cdot 10^{-11}$ Pa^{-1} to $2.8 \cdot 10^{-10}$ Pa^{-1}, the rebound is Δl = 0.37 m to 2.94 m.

An alternative way to calculate heave from one-dimensional consolidation theory is

$$\eta\uparrow = \frac{\Sigma H_o}{1+e_o}\Delta e, \qquad with\ e = \frac{n}{1-n} \tag{11}$$

where ΣH_o = 2H = 700 m; or, in terms of porosity n,

$$\eta\uparrow = l(1-n) \cdot \frac{\Delta n}{1-n} \tag{12}$$

The porosity variation from axial tests for SB1 is n=2‰ - 0.82 ‰ = 1.18 ‰. The rebound is $\eta\uparrow$ = 0.82 m.

Similar values were obtained for SB3 and SB4. The results show that the rebound due to the expansion of the Marl is negligible compared to its thickness.

Borehole SB3

The APZ for SB3 was defined as the depth interval from 500 to 1100 m below surface (Figure 3). The reference level is RL=738 m a.s.l., corresponding to the top of the borehole. The underpressure head values are the mean values measured from packer tests minus the RL; thus all of the values within the APZ are negative.

The half-thickness of the APZ is 300 m. The distribution of pressure was calculated for a time t=20,000 years, starting with K and S_s values from Tables 1 and 2. The best match with the measured values is shown in Figure 8; the final calibrated diffusivity ratio is $\kappa = 8.3 \cdot 10^{-8}$ m^2/s, corresponding to K=$2.5 \cdot 10^{-12}$ m/s and $S_s = 3 \cdot 10^{-5}$ m^{-1}.

As in SB1, the hydraulic conductivity was kept constant; calibration was accomplished by varying S_s during the calculations. The storativity value is more than an order of magnitude higher than the maximum value evaluated from core investigations (Table 2). The final value of hydraulic conductivity is practically the same as the harmonic mean value. On Figure 8 we show also the calculations for t=30,000 years and t=50,000 years; the latter is the time needed for 95 % of excess pressure to dissipate following the change in heads due to the glacial retreat.

Borehole SB4

The total depth of SB4 is 758 m; however, for calculation purposes the APZ was defined as the depth interval from 200 to 800 m below surface (Figure 4). The reference level is RL=939 m a.s.l. corresponding to the top of the

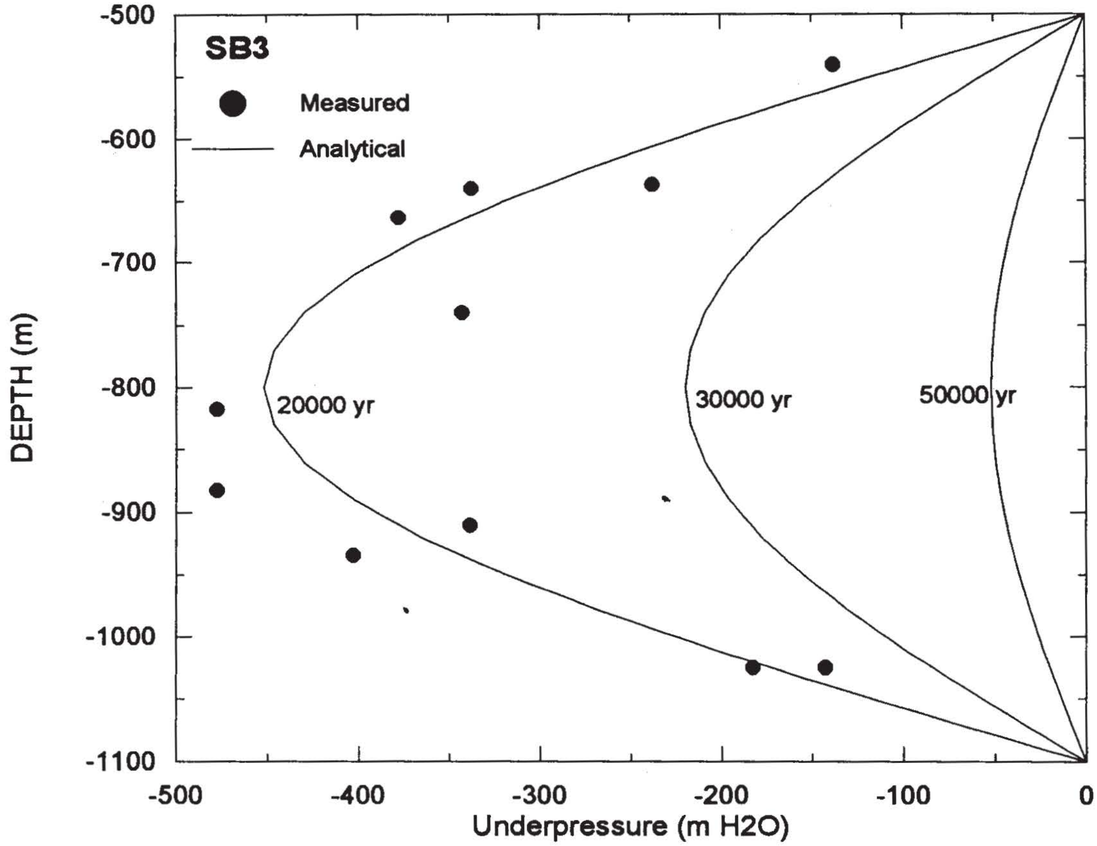


Fig. 8. Comparison of measured and calculated underpressures for SB3.

borehole. The underpressure head values are the mean values measured from packer tests minus the RL, so all of the values within the APZ are negative. The half-thickness of the APZ is 300 m. The distribution of pressure was calculated for t=20,000 years, starting with K and S_s values presented in Tables 1 and 2. The best match with the measured values is shown in Figure 9; the final calibrated diffusivity ratio is $\kappa = 9.6 \cdot 10^{-8}$ m²/s, corresponding to $K=2.4 \cdot 10^{-14}$ m/s and $S_s=2.5 \cdot 10^{-7}$ m^{-1}. As in the other boreholes, the hydraulic conductivity was kept constant and S_s varied during the calibration calculations. The storativity value is slightly smaller than the minimum value evaluated from core investigations (Table 2). The final value of hydraulic conductivity is the same as the harmonic mean value.

On Figure 9 we also show the calculation for t=40,000 years; this is the time needed for 97 % of excess pressure to dissipate following the change in heads due to the glacial retreat. The transient stress release for SB4 was also calculated numerically. For symmetry reasons, only the APZ half-thickness was evaluated. The code NAMMU (Hartley and Jackson, 1993) was used for this numerical analysis by discretizing a one-dimensional string of nodes, 300-m long, with a prescribed-head boundary condition of -1500 m at one end, and a no-flux boundary condition at the other. The initial condition was h=0 at all z's. The numerical results for t = 20,000 yr are also presented in Figure 9.

The final results for all three boreholes are summarized in Table 3. In this table, U represents the degree of recovery, or the percentage of the pressure dissipation 20,000 years after the change in heads due to the glacial retreat. Figure 10 shows a plot of U against time. Because the diffusivity ratios in the three boreholes are very similar, this graphic can be applied to the three cases. Figure 10 indicates that 20,000 years after the glacial retreat the pressures in the APZ have re-equilibrated to about 80% of the new pressure profile. About 20,000 to 30,000 years are still needed for 95% of the pressure in the APZ to equilibrate to the new steady state.

A check can be made on the time needed for a hydraulic system to reach piezometric equilibrium after a perturbation has been propagated through it in one direction. It can be shown (Marsily, 1986) that equilibrium is approximately reached when

$$\frac{Kt}{S_s x^2} > 1 \qquad (13)$$

where t is the time elapsed since the start of the perturbation, and x is the size of the dimension in which the perturbation propagates. A simple calculation was made with (13), using the calibrated values of K and S_s for t=20,000 yr and x equal to the half-thickness of the APZ, H=300 m. The result is $Kt/S_s x^2=0.7$, which is consistent with calculations of U (Table 3).

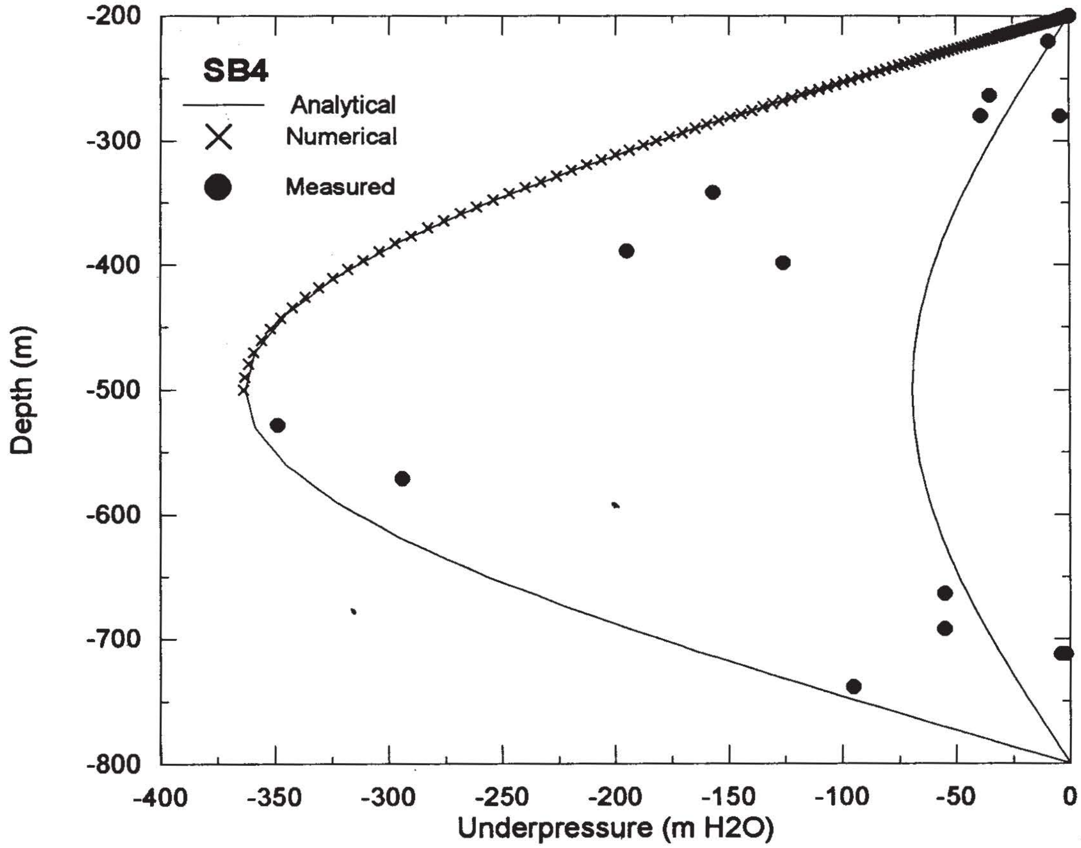


Fig. 9. Comparison of measured and calculated underpressures for SB4.

Table 3

Calibrated K and S_s values in the APZ

Borehole	K (m/s)	S_s (m^{-1})	κ (m^2/s)	U t=20000 yr
SB1	1.6E-12	1.7E-5	9.4E-8	0.75
SB3	2.5E-12	3E-5	8.3E-8	0.81
SB4	2.4E-14	2.5E-7	9.6E-8	0.84

U is the degree of recover;

DISCUSSION AND CONCLUSIONS

The analysis shows that the rebound hypothesis is plausible. By using borehole pressure data in simple 1D analytical and numerical models with parameter values derived from *in-situ* or laboratory tests, the abnormal pressure zones may be reproduced reasonably well.

In the mathematical analysis, the geologic history is approximated by simulating the ice retreat (believed to have occurred 20,000 yr b.p.) as a sudden instantaneous perturbation of the groundwater conditions at Wellenberg.

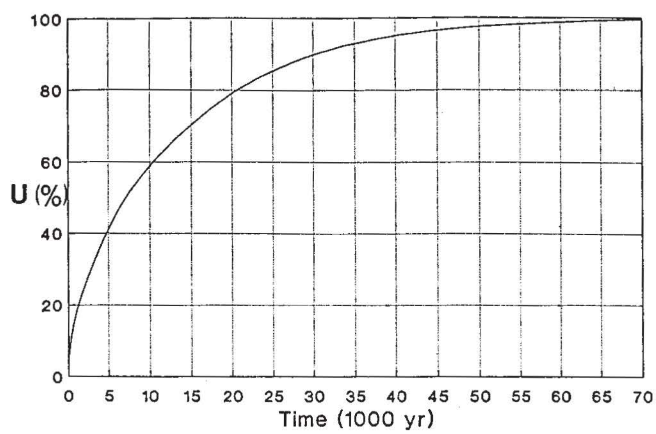


Fig. 10. Degree of recovery for SB3.

The time scales associated with the stress release due to the perturbation agree with the one-dimensional diffusivity equation. About 75-84% of the effect of the perturbation has already dissipated, but it may take another 20,000 to 30,000 years for 95% to 97% of the pressure in the APZ to settle to a new steady-state condition.

A diffusivity ratio of around 10^{-7} m^2/s for the three boreholes was found the most likely value corresponding to the hydraulic diffusivity of Valanginian Marl. The component of rebound due to expansion of the marl was found to be negligible compared to its thickness; therefore, it is not necessary to evaluate this component in future studies.

This work supports the currently preferred hypothesis concerning the origin of the underpressure in the Valanginian Marl at Wellenberg. The hypothesis states that hydromechanical processes are responsible for the underpressured zones.

Based on this analysis, we believe that the groundwater system at Wellenberg is under non-equilibrium conditions due to the glaciations to which this site has been subjected and that are still influencing the behaviour of the system. These calculations can be refined with 2D or 3D models, and/or by modifying the proposed initial and boundary conditions; in any event, the very long transient response of the system must not be ignored.

This work has been used as the basis for more advanced two- and three-dimensional analysis in which all boreholes were included and evaluated under a single local or regional model where the transient effects were included. Vinard *et al.* (1993) presented results of two 2-dimensional models: a glacial-retreat model, and a model which includes two-phase flow conditions. Rivera and Senger (1993) have used the results of the present work to build a three-dimensional model with the available data from all existing boreholes.

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