Numerical Simulation of Observed Pore-Pressure Changes in an Aquitard due to Changes of Total Soil Moisture

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ABSTRACT
In situ pore-pressure changes in an aquitard due to mechanical loading resulting from changes of total soil moisture have been distilled from observed pore-pressures with the aid of numerical modelling. A finite element model of coupled load-induced pore-pressure and transient groundwater flow due to water table fluctuations was used for the simulations. The modelled pore-pressures showed good agreement with observed pore-pressures over a 9-year period.

RÉSUMÉ
Les changements de pressions interstitielles in situ dans un aquitard dû au chargement mécanique résultant des changements de l'humidité totale du sol ont été distillés à partir des pressions interstitielles observées à l'aide de la modélisation numérique. Un modèle éléments finis, couplant la pression interstitielle induite par le chargement avec l'écoulement transitoire d'eaux souterraines dû aux fluctuations de la nappe phréatique, a été employé pour les simulations. Les pressions interstitielles calculées étaient en bon accord avec les pressions interstitielles observées au cours d'une période de neuf ans.

1 INTRODUCTION

Mechanical surface loading will generate an instantaneous change in pore water pressure at depths within a saturated soil profile (Terzaghi and Frohlich 1936; Jacob 1940; Skempton 1954). Van der Kamp and Maathuis (1991) demonstrated the potential application of this principle to monitoring mechanical loading generated by changes in total soil moisture by observing in situ pore-pressure (hydraulic head) fluctuations in deep confined aquifers. Subsequently, similar monitoring of soil water balance using pore pressure observations have been made in aquitards (van der Kamp and Schmidt 1997; Barr et al. 2000; and van der Kamp et al. 2003) and in aquifers (Bardsley and Campbell 2006; Sophocleous et al. 2007).

In-situ pore-pressure measurements made with piezometers of high sensitivity have been used to monitor changes in the weight of water added or removed from the top zone of a soil profile at four sites in Canada for several years (van der Kamp et al. 2003). The pore-pressure response at these sites was interpreted assuming that the entire geological formation responds as a large scale weighing lysimeter (van der Kamp and Schmidt 1997). Verification of this interpretation was obtained by measuring the pore-pressure response at the piezometer tip using a 39-tonne gravel-loaded truck as a surface "point" load (Figure 1).

The ideal geological setting for this "lysimeter" approach would be a thick, elastically compressible, low-permeability saturated formation (aquitard) in which there was insignificant drainage and which did not undergo changes in pore-pressure as a result of changing groundwater flow conditions (van der Kamp and Schmidt 1997). This ideal condition is not common, consequently, the effect of transient flow due to dissipation of induced pore-pressures as well as changing groundwater flow must be considered in the interpretation of the measured pore water pressure (Barr et al. 2000). Transient flow created by changes in total head within surficial, high permeability units in particular complicated the "lysimeter" interpretation of pore-pressure response (Barr et al. 2000).

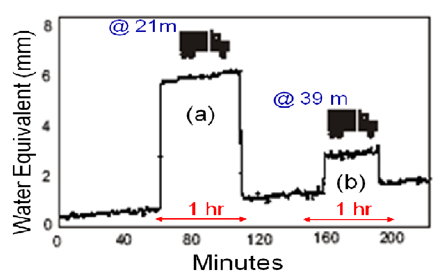

Figure 1. Observed piezometric response to 39-tonne truck at: (a) 21m and (b) 39m distances (after van der Kamp and Schmidt (1997). Copyright 1997 by the American Geophysical Union. Modified by permission of American Geophysical Union)

This paper describes a method of superimposing numerical analyses of the overlapping causes of pore-pressure transients so as to allow the pore-pressure changes due to surface loading alone to be isolated. Transient pore-pressures arising from variations in the water table within a surface aquifer can then be removed from measured pore-pressure in an underlying aquitard to isolate the observed response to changes of total soil moisture. The details will be provided in the subsequent journal publication.

2 THEORY

The governing one-dimensional partial differential equation describing transient changes in pore-pressure arising from loading and drainage was presented by van der Kamp and Gale (1983) and Domenico and Schwartz (1998):

$$\frac{\partial u}{\partial t}=\bar{B}\frac{\partial \sigma}{\partial t}+D\frac{\partial^2 u}{\partial z^2} \qquad [1]$$

where u is the changing pore-pressure at any elevation, z, with time, t; $\bar{B}\,\partial\sigma/\partial t$ is the undrained pore-pressure response to the changes in surface mechanical loading; $\bar{B}$ is the (constrained) elastic pore pressure coefficient; σ is mechanical load; $D\,\partial^2 u/\partial z^2$, represents vertical transient groundwater flow; and D is the hydraulic diffusivity. $\bar{B}$ is often referred to as the Skempton's B-bar coefficient (Skempton 1954) and is also known as loading efficiency or tidal efficiency defined as the ratio of the pore-pressure response to the applied load (Skempton 1954; Jacob 1940; van der Kamp and Gale 1983). D is the ratio of vertical hydraulic conductivity, K_v, to specific storage, S_s, (K_v/S_s) and is equivalent to Terzaghi's coefficient of consolidation, C_v.

2.1 Method of Superposition

The governing equation is a linear (second order) partial differential equation and as such the primary variable, u, can be decomposed and its components can also be superimposed. Therefore, the change of pore-pressure, u, can be broken into the components of change of pore-pressure contributed from load changes, u_L and from water table fluctuations, u_w:

$$u = u_L + u_w \qquad [2]$$

The general governing equation is then re-written as:

$$\frac{\partial (u_L+u_w)}{\partial t}=\bar{B}\frac{\partial \sigma}{\partial t}+D\frac{\partial^2 (u_L+u_w)}{\partial z^2} \qquad [3]$$

The governing equation for the case of change of pore-pressure, u_L, produced by only mechanical surface loading due to total soil moisture changes and its attendant dissipation can be written as follows:

$$\frac{\partial u_L}{\partial t}=\bar{B}\frac{\partial \sigma}{\partial t}+D\frac{\partial^2 u_L}{\partial z^2} \qquad [4]$$

The loading corresponds to the total stress applied at surface arising from the changes in weight of water associated with changes of total moisture, $\partial\sigma/\partial t$, [$ML^{-1}T^{-3}$] (van der Kamp and Schmidt 1997; Barr et al. 2000):

$$\frac{\partial \sigma}{\partial t}=\rho_w g(P-AET-R) \qquad [5]$$

where ρ_w is the density of water [ML^{-3}]; g is acceleration due to gravity [LT^{-2}]; P is precipitation; AET is the evapotranspiration and R is the net runoff. The latter term is considered to be negligible for the site considered in this paper due to its flat topography. P, AET and R are expressed as height of water accumulated over a given period [LT^{-1}].

The boundary conditions for Eq. 4 include hydraulic head (or pressure) or flux, and stress (force) or deflection along with initial conditions of pore-pressure throughout the domain. A constant hydraulic head was used for the upper boundary in this paper. This may appear to be somewhat contradictory since the purpose of the decomposition is to address the effect of water table fluctuations on pore-pressure response. Deformation and drainage associated with surface mechanical loading of the aquitard would lead to discharge or absorption of water to or from an overlying unconfined aquifer, thereby, contributing to the overall water table fluctuation (adding to the fluctuation due to seasonal recharge/discharge). However, for a very stiff aquitard, the changes in water volume stored within the aquitard as a result of pressure changes associated with the surface mechanical loading from changes in soil moisture are very small and are unlikely to make significant changes to the weight (density) of the aquitard or the volume of water released or absorbed from the overlying aquifer. It is conservatively estimated that this change in water table elevation would be less than 1% of the water pressure head equivalent of an applied surface load due to changes in moisture storage. Since this change in water table (in millimetre scale) due to mechanical loading is small compared to annual fluctuation (in metre scale), therefore, water table elevation can be assumed constant in the simulation of loading alone (Eq. 4). The zero-stress change and the same constant hydraulic head apply throughout the domain as initial conditions.

Fluctuations in the water table elevation within a surface aquifer overlying the aquitard will result in the propagation of pore-pressure. The governing equation describing this pore-pressure transient is similar to that form proposed by Terzaghi (1925) for consolidation:

$$\frac{\partial u_w}{\partial t}=D\frac{\partial^2 u_w}{\partial z^2} \qquad [6]$$

The hydraulic head (or head of change of pore-pressure) of the temporal water table fluctuation can be applied as a hydraulic boundary at the top of the aquitard at zero stress change. The change of pore pressure within the aquitard will lead to small changes of total water mass within the (elastic) domain and, consequently, to small changes of total stress. However, if the soil is very stiff these changes of water mass are so small compared to the stress changes due to surface loading (moisture changes) that they can be neglected. Constant hydraulic head and the same zero stress change apply throughout the domain as initial conditions.

Given that the principle of superposition is admissible in this problem (from Eq. 2), it then follows that the components of the change of pore-pressure, u_L and u_w, can be separately solved for and superimposed. That is, combining the solutions to both Equations 4 and 6 should result in the same solution as that of Equation 3, such that the combination of the two equations as well as their initial and boundary conditions also satisfy those of Eq. 3. Similarly, a fully field-calibrated simulation for pore-pressure variations arising from water table fluctuations (Equation 6) could be subtracted from observed pore-pressures changes to obtain a set of observations of pore-pressure variations arising as a result of changes in surface loading.

The methodology followed in this paper included three sets of analyses. First, coupled seepage and stress analyses were undertaken to verify that for a given set of typical conditions the simulations of Equations 4 and 6 provided the same result as a simulation of Equation 3. Next, a simulation of Equation 3 was created using a set of field observations of surface water balance measurements and pore-pressure measurements (for water table fluctuation) in an overlying surficial aquifer and calibrated by trial and error to "best fit" a set of pore-pressure measurements in a deep aquitard. The pore pressures were first corrected for earth tides and barometric response. Finally, the material properties from the calibrated model were then used to isolate the pore-pressure variations due to water table fluctuations. These were then subtracted from the observed aquitard pore-pressures to evaluate whether the remaining pore-pressure variations would provide a reasonable estimate of the net water balance for the site as measured by meteorological instrumentation.

The first step is not presented in this paper; however it did demonstrate that superposition of the results from simulations of Equations 4 and 6 alone did agree with the results obtained from simulation of Equation 3.

2.2 Key Elastic Parameters

The elastic parameters required to solve the differential equation are linked to the Skempton's $\bar{B}$ (pore-pressure) coefficient, and were determined from barometric response. The relationship between the constrained elastic pore pressure coefficient (Skempton's $\bar{B}$) and the constrained elastic modulus of soil structure, K_c, presented by van der Kamp and Gale (1983) is as follows:

$$\bar{B} = \frac{1/K_c}{1/K_c + n/K_w} \qquad [7]$$

where n is the porosity of the formation; $1/K_c$ is the compressibility of the soil structure, m_v; and K_w is the elastic modulus of water, such that $1/K_w$ is the compressibility of water. The porosity was assumed to be 0.26 in this study based on a range of reported n values for similar tills of 0.26 – 0.36 in Saskatchewan (Keller et al. 1986, 1988). The constrained elastic modulus of the till formation at the depth of the deep piezometer is easily derived from Eq. 7.

Elastic storage (specific storage) of laterally constrained soil, S_s, is reliably obtained from barometric response (van der Kamp 2001). Once K_c is determined, and with an n value, S_s is obtained. Specific storage was presented by Jacob (1940):

$$S_s = \rho_w g \left(\frac{1}{K_c} + \frac{n}{K_w}\right) \qquad [8]$$

The elastic Young's modulus, E, used as input in the numerical model was obtained from the relationship with Poisson's ratio, v, (assumed to be 1/3) and K_c (Poulos and Davis 1974; van der Kamp and Gale 1983).

3 STUDY SITE

The measured pore-pressure responses were from a "lysimeter" installation near the Old Aspen flux tower site of Boreal Ecosystem Research and Monitoring Sites (BERMS) area, in the southern part of Prince Albert National Park, Saskatchewan, Canada, geographically located at (53.7°N, 106.2°W) (Barr et al. 2000).

3.1 Geology and Hydrogeology

The geologic profile at this site is composed of a 20m-thick surface layer of sand and gravel with some silt layers, overlying a clayey till extending to a depth of at least 42m. Drilling was met with refusal around this depth on what might have been a boulder. The glacial till in the site is estimated to be up to 100m thick and comprises a Saskatoon group till overlying a Sutherland group till (Christiansen 1992). The entire sequence overlies Cretaceous shale (Millard 1994; Christiansen 1973).

Glacial till in Saskatchewan generally has a low hydraulic conductivity of about 10^{-11} to 10^{-8} m/s (Keller et al. 1986, 1988, 1989; Shaw and Hendry 1998). Oxidized zones and fractures may be present in these tills and this increases the hydraulic conductivity by up to two or more orders of magnitude over that of the unfractured matrix (Grisak and Cherry 1975; Keller et al. 1986, 1989; Shaw and Hendry 1998).

3.2 Field Instrumentation and Operation

Two sensitive and stable non-vented, 50psi, Geokon 4500H vibrating wire piezometric transducers were installed as piezometers for this study. The piezometric transducers have a resolution of better than 1 mm-water. The deep piezometer was buried at a depth of 34.6m. The second installation was buried at 6.26m to monitor water table fluctuations (Barr et al. 2000). Figure 2 shows the site profile and installations. The depth to the water table in the upper sand and gravel averages 3m to 4m below ground level (Barr et al. 2000). The water table fluctuated by as much as 2.3m over a nine-year period.

A major attraction for selecting the study area was the presence of a flux tower and climate station 1.3km away (Barr et al. 2000). Independently measured hydrological data (P, AET) from this station provided the data used for the site water balance which was used for comparison to the lysimeter. P was measured using accumulation gauge for year round measurement and a tipping bucket rain gauge while AET was measured using an eddy covariance tower. Barometric pressure was also measured and was used to evaluate barometric response within the deep piezometer (Jacob 1940; van der Kamp, 2001) and for correcting the barometric effects in the piezometric data. The specifications of the climate station instrumentation are provided by Barr et al. (2000).

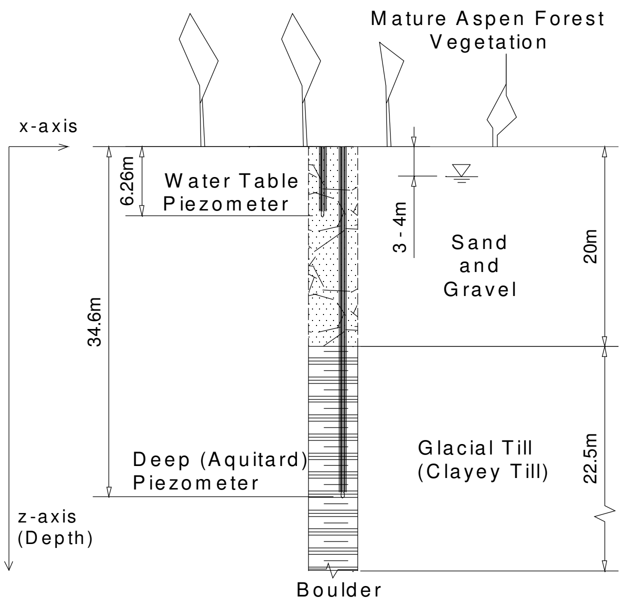

Figure 2. Profile of geology and hydrogeology in the Old Aspen Forest Site up to depth where drilling met refusal on a boulder showing the two piezometric installations

Measurements from each of the instruments at the site were logged continuously at high frequency (every 30 minutes). Data was accumulated to a daily time scale for 9 years (1998-2006) for this study.

4 SOLUTION APPROACH AND KEY ASSUMPTIONS

The stress and transient flow were simulated using the coupled load deformation and seepage finite element numerical models SIGMA/W and SEEP/W (GEO-SLOPE 2008).

The model domain was defined as a one dimensional soil column from the top of the aquitard (base on the upper sand and gravel aquifer) extending to depth (Figure 3). The surficial unconfined aquifer was excluded from the domain in order to avoid complications with non-linearity arising from changes in saturation within the aquifer during rise and fall of the water table. This allows only the response of the saturated aquitard to be modelled.

The aquitard was assumed to behave as a linearly elastic isotropic material. This is consistent with the linear elastic constitutive model implied in the governing equation (van der Kamp and Gale 1983) and as assumed by Terzaghi (1925) and Biot (1941). It is also consistent with the overconsolidated state of the till (Klohn 1965; Sauer et al. 1993).

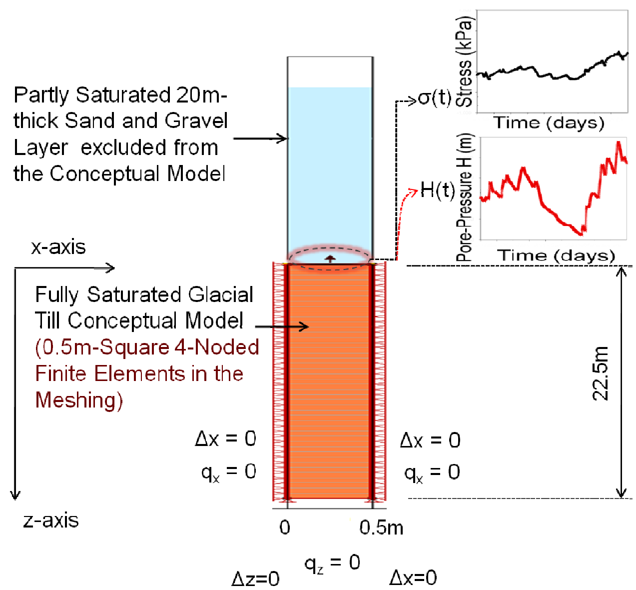

Figure 3. Conceptual model of fully saturated glacial till showing all the stress, σ(t), (or displacement, Δx or Δz) and hydraulic boundary conditions, H(t) or q_x or q_z

Since the full depth of the till aquitard was not confirmed by drilling, a sensitivity study was undertaken to evaluate the significance of both aquitard thickness and varying aquitard properties (e.g. elastic modulus) with depth. The final model adopted was that of an “equivalent” single layer extending to the refusal depth. This assumes that the boulder marks the transition to till of another formation with significantly lower hydraulic conductivity.

The boundary conditions for the one-dimensional domain included zero deflection and zero flux boundary conditions along the sides and base of the domain. The upper boundary has specified total head and stress boundary conditions.

Different combinations of stress and hydraulic boundary conditions were applied at the upper boundary for the three simulation cases. In the simulation of Equation 3 for calibration of the model against all available monitoring data, the stress increment obtained from the monitored water balance, $\rho_w g$(P-AET), was applied as the top stress boundary condition along with the measured total head from the water table fluctuation. In the simulation of the pore-pressure transients due to water table fluctuations alone a zero stress boundary condition was utilized along with the measured hydraulic head from the water table fluctuations. The daily 9-year (1998 – 2006) data set for cumulative (P-AET) and water table elevation used to generate the upper boundary conditions are shown in Figure 4.

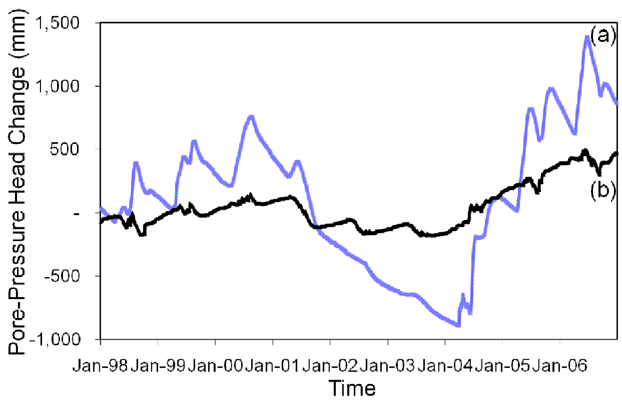

Figure 4. (a) Water table fluctuation; and (b) Cumulative (vertical) water balance (P-AET) for generating model input hydraulic and stress top boundary conditions for Old Aspen Site (1998 – 2006)

4.1 Elastic Response and Site Input Data Processing

The raw pore pressure-time data from the deep piezometer also includes responses to earth tide dilation of the earth-crust and barometric pressure (Jacob 1940; van der Kamp and Gale 1983). Skempton's $\bar{B}$ elastic pore-pressure coefficient was determined through the correction for barometric loading (Barr et al. 2000). Figure 5 illustrates the barometric correction on the data set. The specific storage coefficient S_s of the till formation at the depth of the deep piezometer was obtained from Skempton's $\bar{B}$ coefficient through the use of Equations 7 and 8.

5 MODEL CALIBRATION TO DEFINE THE SITE GEOLOGY AND HYDROGEOLOGY

5.1 The Model Calibration Process

Various sensitivity tests were carried out to evaluate the influence of till thickness and varying till stiffness with depth (single- and multilayer- profiles). In each case the best fit K_v values were obtained by trial and error.

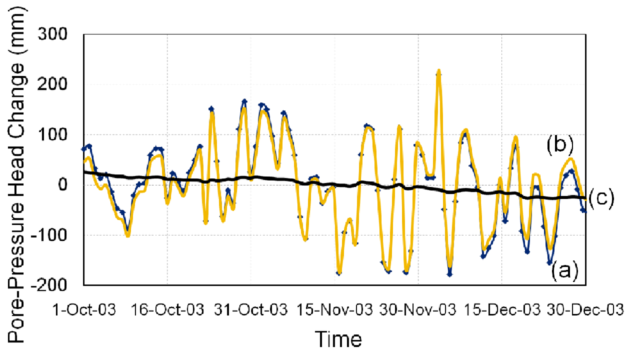

Figure 5. Barometric effect and its correction on pore-pressure head changes from which Skempton's $\bar{B}$ (B-bar) of 0.91 was determined (at the depth of 34.6m for Old Aspen Site): (a) Observed pore-pressure head changes corrected only for earth tide; (b) Observed barometric pressure head change x 0.91; and (c) Pore-pressure head changes corrected for earth tide minus observed barometric pressure head change x 0.91 [i.e. (a) – (b)]

Given the large potential range in the value of K_v (Keller et al. 1986; Keller et al. 1988; Shaw and Hendry 1998) it was decided to allow it to vary while assuming a constant value for the elastic (specific) storage, Ss, as derived from Skempton's $\bar{B}$ and porosity. Elastic properties (E or Ss) likely vary by less than a factor of 2 across the till thickness and were assumed uniform throughout the domain. Their effect on pore pressure response did not appear as significant as that arising from variations in K_v.

Transient residual (excess) pore pressure profile (Stein and Schiffman 1970) due to historic water table fluctuation or loading disturbance prior to the simulation period would typically exist in the pore-pressure profile (Keller et al. 1989). In order to avoid difficulties with some "residual" pore-pressure transient appearing in the data set due to forcing that occurred prior to the onset of monitoring it was decided, based on preliminary numerical modelling of the time for 99% dissipation of a daily surface load, that the results for the first 3 years were excluded from the calibration.

5.2 Outcome of Calibration (S_s and K_v)

The results of the final model calibration are shown in Figure 6. The large fitting error in 2006 (a wet year like 2005) was possibly due to errors in under-catchment by the precipitation gauge (Barr et al. 2000) or the result of increased total moisture arising as result of lateral flow within the aquifer rather than infiltration vertically. The large fitting error in spring 2005 may be due to run-off.

The calibration resulted in a diffusivity, D, (coefficient of consolidation) of 1.52 m^2/day (1.8 x 10^{-5} m^2/s). The vertical hydraulic conductivity, K_v, was estimated at 2.1 x 10^{-5} m/day (2.4 x 10^{-10} m/s) with specific storage, S_s, of 1.36 x 10^{-5} m^{-1} (confined compressibility, m_v, of 1.26 x 10^{-6} kPa^{-1}). The calibrated K_v of the model agrees with the range reported for glacial till in Saskatchewan (Keller et al.

1986; Keller et al. 1988; Keller et al. 1989; Shaw and Hendry 1998). Other input elastic properties of the glacial till include the measured Skempton's $\bar{B}$ coefficient of 0.91, the assumed porosity of 0.26 and Young's modulus of 528MPa assuming a Poisson's ratio of 1/3.

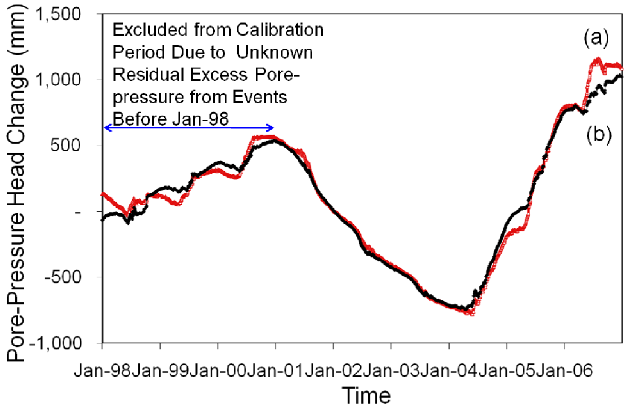

Figure 6. Calibration "best fit" of (a) Observed; and (b) Modelled pore pressure responses for Old Aspen Site (considering 2001 – 2006)

6 OBSERVED PORE-PRESSURE RESPONSE TO TOTAL SOIL MOISTURE CHANGES

The response of the aquitard formation to the water table fluctuation was modelled separately using the best fit values of S_s and K_v from the previous model calibration. Pore-pressure response to the water table fluctuation was then subtracted from the observed pore pressure response to give the long term pore pressure response due to changes in soil moisture alone and the associated consolidation drainage (Figure 7).

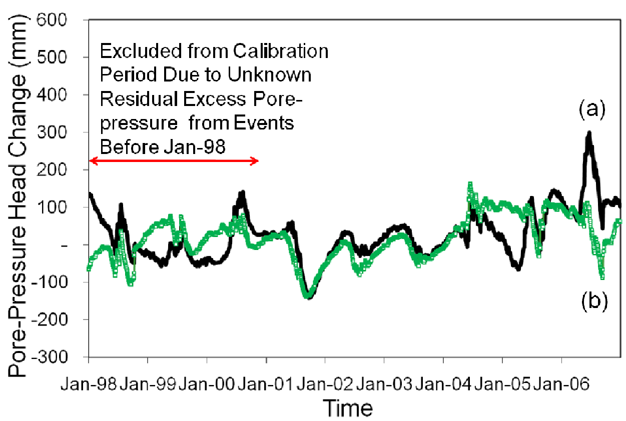

Figure 7. (a) Observed pore-pressure responses to changes of soil moisture as obtained using method of superposition (measured pore-pressure changes minus pore-pressure responses to water table fluctuation alone); and (b) Modelled pore-pressure responses to vertical water balance from meteorological monitoring (using climate station data as input in the coupled model) for Old Aspen Site (considering 2001 – 2006)

The lysimeter based water balance and the water balance obtained from the meteorological monitoring (both in terms of pore-pressure responses) are in relatively good agreement in trends except for short periods of 2005 and 2006, which were particularly "wet" years. In those exceptional years, the effect of net lateral flow or runoff may have been responsible for the disparity.

7 SUMMARY AND CONCLUSION

Measured pore pressure responses to coupled water table fluctuations and variations in total stress arising from changes in total soil moisture was successfully simulated using coupled finite element models of load deformation and seepage. The calibration of the model to field monitoring data was used to establish "equivalent" formation properties of K_v of 2.1 x 10^{-5} m/day (2.4 x 10^{-10} m/s) and S_s of 1.36 x 10^{-5} m^{-1}, using Skempton's $\bar{B}$ of 0.91 and porosity of 0.26.

There is a general agreement between the observed lysimeter-pore-pressure response to daily total soil moisture changes (extracted with the aid of numerical modelling) and the modelled lysimeter-pore-pressure response to daily cumulative vertical water balance from the climate station for years. The only exceptions in the long term (9-year) observation are the highly "wet" years. Potentially highly reliable estimate of lysimeter response to specific hydrological (large precipitation) events, averaged over 30-minute intervals, is anticipated.

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