PORE PRESSURE CHARACTERIZATION OF GEOTECHNICAL EXPERIMENTATION SITE USING MULTILEVEL VIBRATING WIRE PIEZOMETERS

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ABSTRACT
A pore water pressure monitoring study using vibrating wire piezometers was implemented at the National Geotechnical Experimentation Site (NGES) located at the University of Massachusetts Amherst campus. The purpose of the study is to characterize the hydrogeologic behaviour of the NGES soil deposit and to test a recently developed multiple level piezometer (MLP) design. An array of seven MLP's was installed fully grouted in a single borehole. Three conventional reference piezometers were installed in order to evaluate MLP performance. Additionally, a single conventional piezometer was installed fully grouted without a sand pack. Results indicate nearly identical response times to precipitation events, with highest attenuation near the ground surface. Modelling of a precipitation-evapotransporation event was performed using the Carslaw and Jaeger equation as outlined by Ostendorf et al. (2004). The MLP's exhibit a more sensitive response to pore water pressure changes than the conventional piezometers at shallower depths. Interestingly, the performance of the fully grouted conventional piezometer was shown to be nearly identical to that of the sand packed instrument.

RÉSUMÉ
Une pression d'eau interstitielle surveillant l'étude à l'aide des piezometers vibrants de fil a été mise en application à l'emplacement géotechnique national d'expérimentation (NGES) situé à l'université du campus du Massachusetts Amherst.Le but de l'étude est caractériser le comportement hydrogéologique du dépôt de sol de NGES et d'examiner une conception de niveau multiple récemment développée du piezometer (MLP).Une rangée de sept MLP a été installée entièrement scellée au ciment dans un forage simple.Trois piezometers conventionnels de référence ont été installés afin d'évaluer l'exécution de MLP.En plus, un piezometer conventionnel simple a été installé entièrement scellé au ciment sans paquet de sable.Les résultats indiquent des temps de réponse presque identiques aux événements de précipitation, avec l'atténuation la plus élevée près de la surface au sol.Modeler d'un événement de précipitation-evapotransporation a été exécuté en utilisant l'équation de Carslaw et de Jaeger comme décrit par Ostendorf et autres. (2004).L'objet exposé du MLP que une réponse plus sensible à la pression d'eau interstitielle change que les piezometers conventionnels à des profondeurs plus faibles.Intéressant, l'exécution du piezometer conventionnel entièrement scellé au ciment s'est avérée presque identique à celle de l'instrument emballé par sable.

1. INTRODUCTION

This paper describes the installation and preliminary results of a pore water pressure monitoring program conducted at the National Geotechnical Engineering Experimentation Site (NGES) located at the University of Massachusetts Amherst. A series of vibrating wire pressure transducers manufactured by Geokon, Inc. were installed within the lightly over-consolidated varved clay deposit and underlying glacial till of the test site. The piezometers are read on a bi-hourly basis to develop a pore water pressure profile versus depth and time. A fundamental goal of the study is to observe the fluctuations of pore water pressure resulting from storm events and seasonal variation in groundwater flow whereby the long-term pore water pressure behavior of the experimentation site could thus be better understood.

An additional goal of the study is to evaluate Geokon Inc.'s new multi-level piezometer (MLP) design. The design of the MLP allows for the installation of an array of sensors distributed within a single borehole and therefore presents a potential design improvement and cost savings over the conventional piezometer design. A series of seven MLP's were installed in a single borehole adjacent to three separate boreholes, each containing a conventional vibrating wire piezometer, as a reference. The installed piezometers will be monitored long term and the data obtained analyzed to verify the operation of the new MLP design.

2. LITERATURE REVIEW

The measurement of pore water pressure is an important practice in geotechnical engineering. Engineers use piezometers to monitor the pore water pressure of an area of interest. Piezometers are used in two primary applications: to monitor the pattern of water flow, and to provide an index of soil or rock mass strength (Dunnicliff 1988). The long standing method of monitoring pore water pressure is the use of open standpipe piezometers. While open standpipe piezometers are a reliable pore water pressure measurement system, their accuracy is limited due to a slow response to changes in piezometric head. This slow response, referred to as hydrodynamic time lag, is due to the significant volume of water that must flow into the soil or rock mass to register a change of head.

Hydrodynamic time lag is significantly reduced through the use of diaphragm piezometers. When diaphragm piezometers are utilized to measure piezometric head, displacement of an infinitesimally small volume of water is required to deform the sensor diaphragm and generate a measurement (Mikkelson and Green 2003). This allows the instrument to respond to changes in pore pressure more rapidly. Diaphragm piezometers are available in pneumatic and vibrating wire designs, the latter utilized for this study.

Vibrating wire piezometers operate on the principle that the vibrational frequency of a magnetically plucked wire is proportional to the square root of its tension. As pore water presses against the diaphragm, wire tension is reduced and changes in pore water pressure can be calculated. Details on vibrating wire instrumentation are available at Geokon, Inc. (2004).

3. SITE DESCRIPTION

A vibrating wire piezometer study was implemented at the National Geotechnical Engineering Experimentation Site (NGES) located at the University of Massachusetts Amherst. The site is bounded by Mullins Way to the north, the Town of Amherst Wastewater Treatment Plant to the south and east, and an empty lot to the west. A schematic of the experimentation site's soil stratigraphy with typical engineering properties is shown in Figure 1.

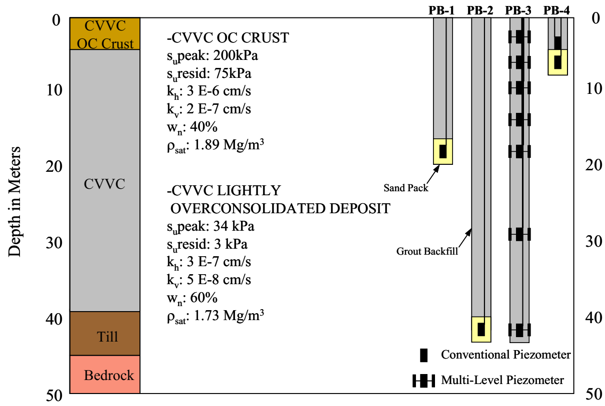

Figure 1. Schematic of NGES soil profile with typical soil properties.

3.1 Soil Conditions

The site is located over a varved clay deposit locally known as Connecticut Valley Varved Clay (CVVC). This soft clay was deposited in a lacustrine environment by glacial Lake Hitchcock, and is approximately 40 meters thick at the site. The upper approximately 5 meters of the deposit is an over-consolidated crust, which formed as a result of a number of processes including overburden removal from erosion, groundwater table fluctuations, freeze-thaw, desiccation, and other physical and chemical weathering processes (Lutenegger, 2000).

Beneath the crust is the lightly over-consolidated portion of the CVVC deposit, which extends to a depth of about 40 m. The vertical hydraulic conductivity of the CVVC ranges from approximately 4 X 10^{-8} cm/s to 2 X 10^{-7} cm/s, whereas the horizontal hydraulic conductivity varies from about 2 X 10^{-7} cm/s to 2 X 10^{-6} cm/s, as determined from laboratory flexible wall tests (DeGroot and Lutenegger 2003). Field permeability tests generally provide values one to two orders of magnitude greater than laboratory tests. The anisotropy ratio ranges between 2 to 14 and averages approximately 7. The coefficient of consolidation is approximately equal to 1 to 2 X 10^{-3} cm^2/s, based on laboratory CRS tests on Sherbrooke Block samples (DeGroot and Lutenegger 2003).

The CVVC is underlain by a relatively thin layer of well graded glacial till, which overlies the local bedrock. The hydraulic conductivity of the glacial till ranges from 1.4 X 10^{-6} cm/s to 6.0 X 10^{-4} cm/s determined from in situ slug tests (Melvin, et al. 1992).

A unique local stratigraphic condition exists at the geotechnical experimentation site. The CVVC deposit is located in a valley rimmed with glacial till, resulting in the glacial till beneath the CVVC deposit being connected to the exposed till on the valley slopes. The relatively coarse-grained till is capable of transferring groundwater more quickly than the fine-grained CVVC. It is thought that during periods of increased groundwater flow, such as storm events or wet seasons, the movement of groundwater from higher gradients can penetrate into the base of the CVVC, creating an artesian condition. Data from open standpipe piezometers indicates a relatively uniform 0.87 kPa/m increase in pore pressure with depth above hydrostatic conditions (DeGroot and Lutenegger 2003). An interesting aside of the piezometer study is to observe what affect, if any, this artesian movement of groundwater will have on the pore pressure profile observed at the experimentation site.

Piezometer	Transducer Capacity (kPa)	Depth (m)	Borehole
R-1	70	6.1	PB-4
R-2	170	18.0	PB-1
R-3	700	39.6	PB-3
R-4	70	5.8	PB-4
MLP-1	70	3.0	PB-2
MLP-2	70	6.1	PB-2
MLP-3	170	9.1	PB-2
MLP-4	170	12.2	PB-2
MLP-5	170	18.3	PB-2
MLP-6	350	27.4	PB-2
MLP-7	700	39.6	PB-2
B-1	70	0.0	Barometer

Table 1. Summary of Installed Piezometer Arrays.

4. INSTRUMENTATION

This study utilized a series of Model 4500 vibrating wire pressure transducers manufactured by Geokon, Inc. to monitor the in-situ pore water pressure gradient within the NGES soil profile with depth. Table 1 contains a summary of the installed piezometer arrangement.

4.1 Multi-Level Piezometers

Of particular interest in this study was the use of the multi-level piezometer (MLP) design. The MLP is designed to allow several piezometers to be installed in a single borehole without the need for the placement of conventional sand zones around each piezometer. The installation is made by simply filling the borehole with a bentonite cement pumped into the bottom of the hole through a tremie pipe. The installation is thus simpler, less time consuming and more economic. Each MLP is lowered to the designated depth, whereupon a spring-loaded mechanism is actuated, which forces the piezometer filter stone out against the walls of the borehole. This ensures good hydraulic contact between the piezometer diaphragm and the pore water, and eliminates any time lag there might have been if the filter stone had been surrounded entirely by bentonite. The elimination of the sand zones also makes it easier to ensure that there are no leakage paths from one piezometer to the next, along the borehole. To highlight these instrumentation differences, Figure 2 contains a schematic of an installation detail for an MLP and conventional piezometer.

An array of seven MLP's were installed within borehole PB-3 at depths of 3.0, 6.1, 9.1, 12.2, 18.3, 27.4, and 39.6 m below ground surface. The upper six MLP's were installed within the CVVC deposit, while the bottom MLP was placed within the underlying glacial till.

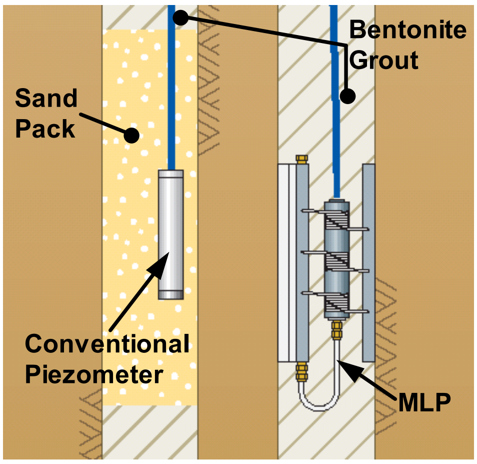

Figure 2. Schematic of installation detail for conventional and multi-level piezometers (after Geokon, Inc. 2004).

4.2 Conventional Piezometers

Three conventional-design reference piezometers (Figure 2) were installed at 6.1, 18.3, and 39.6 m below the ground surface to compare the data obtained from the MLP's at corresponding depths. An additional conventional piezometer was installed without any sand pack at 5.8 meters below ground surface to evaluate the performance of a fully grouted conventional piezometer. A single vibrating wire piezometer was installed at the ground surface to monitor air temperature and barometric pressure. Data obtained from the subsurface piezometers was corrected for barometric pressure to account for their sealed design.

4.3 Installation

The vibrating wire pressure transducers were installed between 18 November 2003 and 01 December 2003. Boreholes were advanced by the rotary wash method using an 11.4-centimeter roller bit and water as the drilling fluid. The upper 1.5 to 3 meters of each borehole was cased using 12.7-centimeter outer diameter flush-mount steel casing to advance through the sand seams and miscellaneous debris present in the upper crust of the deposit. Boreholes were advanced to the target depth and then flushed with clean water until water exiting at the casing ran clear. Once the hole was flushed clean and drill rods removed, the depth was verified manually.

Piezometer filters were saturated in clean water, and the instruments were zeroed at the ground surface immediately prior to installation. Piezometers were installed at their respective target depths and the holes tremie-filled with bentonite grout.

Conventional piezometers were placed in a burlap bag filled with saturated clean sand and installed in the boreholes with approximately 15 cm of clean sand beneath and 30 cm of clean sand above the piezometer diaphragm.

The MLP's were installed using the perforated grout pipe method. Using this method, the MLP's are fastened to predrilled locations in the PVC tremie pipe using nylon zip ties. Once all MLP's have been lowered to their respective target depths, a cutting slug is dropped down the tremie pipe. This releases the spring loaded mechanism, engaging the MLP filter in direct contact with the CVVC against the wall of the borehole. The tremie pipe is removed as the borehole is grouted, resulting in a continuous grout column with only instrumentation cables coming to the surface. All holes were grouted using a pre-manufactured bentonite grout mix, prepared at approximately 20% solids. Mud weights were checked using a mud balance before and during pumping.

The piezometers are wired to a Campbell Scientific CR-10 datalogger programmed to collect data from the entire array of pressure transducers every two hours. Data acquisition was initiated on December 17, 2003.

5. WEATHER DATA

To evaluate the hydrogeologic behavior of the local soil deposit and determine the performance of the array of piezometers, weather data is required. Precipitation events are recorded on a daily basis at a National Weather Service weather station located on the grounds of the Town of Amherst Wastewater Treatment Plant (WWTP), which borders the NGES. The data provided by the WWTP provides a total precipitation volume and an approximation of the time precipitation had occurred. Precipitation data is automatically recorded on a 15 minute interval at the WWTP weather station and sent to the National Weather Service database.

6. MLP MONITORING RESULTS

A plot of precipitation events and barometric pressure as well as the pore pressures observed at each of the MLP's between 1 March and 1 June 2004 are presented in Figure 3. Dash vertical lines through all plots indicate the beginning of select precipitation events. Relevant observations can be made regarding the magnitude of response and the time lag of a given precipitation event with depth. The magnitude of the pore pressure responses at the shallower depths are more pronounced, with increased attenuation with depth. For example, during the 14 April precipitation event, MLP-1 experienced a change in pressure of 2.75 kPa, whereas MLP-5 through MLP-7 registered a change in pressure of about 1.0 kPa. Similar trends are evident through other precipitation events.

By observing the change in pore water pressures resulting from the three precipitation events summarized in Table 2, an interesting trend is observed in the MLP responses at greater depths. Again the change in pore pressures is largest at the shallow piezometer depths. However, a minimum change is generally detected near the mid-depth of the CVVC deposit, in the vicinity of MLP-5. Below the mid-depth of the CVVC, the change in pressure again increases slightly throughout the deposit. In the glacial till (MLP-7) the changes in pore pressure observed reduces relative to MLP-6 for both April precipitation events, but continues to increase during the May event.

Although the magnitude of the pore pressure response differs with depth, the data indicate that the time at which precipitation events are detected is virtually identical for all MLP's, regardless of depth. This again can be most clearly observed for the precipitation event of 14 April. As addressed in the subsequent section, some time lag in response may be anticipated although through effective stress principles one may at first expect an immediate response.

7. PRECIPITATION EVENT MODELING

A methodology for interpretation of hydraulic head measurements for estimation of landform hydraulics and formation hydraulic properties presented Ostendorf et al. (2004) was implemented herein to provide an initial evaluation of the subsurface hydraulic behaviour of the CVVC. This methodology uses data collected on annual, monthly, and/or daily timescales. Longer timescales are used to estimate landform hydraulic properties while shorter timescales are for estimation of soil deposit properties, the latter being of interest in this particular study. The analysis uses the following complementary error function solution:

$$H = \mathrm{erfc}\left(-z\sqrt{\frac{1}{4Dt}}\right)\left[H_o - \frac{E}{n}\left(t + \frac{z^2}{2D}\right)\right] - \frac{Ez}{n}\sqrt{\frac{t}{\pi D}}\exp\left(-\frac{z^2}{4Dt}\right) \quad (z<0) \qquad [1]$$

where H = instantaneous hydraulic head fluctuation (m), z = depth below datum (m), D = hydraulic diffusivity (m^2/s), t = time (s), H_o = initial groundwater mound amplitude (m), E = instantaneous evaporation rate (m/s), and n = macropore porosity of CVVC (-). The depth below datum z is determined from:

$$z = d + z_o \qquad [2]$$

where d = installation depth (m) and z_o = distance from groundwater to ground surface (m). The depth d is taken as negative downward, while the distance from groundwater to ground surface is positive. The hydraulic diffusivity is a soil-dependent parameter defined as:

$$D = \frac{k}{\rho \beta \nu} \qquad [3]$$

where k = permeability (m^2), ρ = water density (kg/m^3), β = soil compressibility (Pa^{-1}), and ν = water kinematic viscosity (m^2/s).

The value of initial groundwater amplitude H_o and the E/n ratio are initially estimated from examination of the pore pressure response observed at MLP-1. H_o, E/n, D, and z_o are variable parameters which are optimized until the

Table 2. Summary of Changes in Pore Pressure for Select Precipitation Events.

Piezometer	Depth (m)	4/1 Precipitation Event			4/14 Precipitation Event			5/26 Precipitation Event		
		u_o (kPa)	u_f (kPa)	Δu	u_o (kPa)	u_f (kPa)	Δu	u_o (kPa)	u_f (kPa)	Δu
MLP-1	3.0	23.80	25.08	1.28	22.02	24.78	2.76	17.95	21.95	4.00
MLP-2	6.1	50.41	51.38	0.98	49.98	51.98	2.01	47.02	49.53	2.51
MLP-3	9.1	78.96	79.98	1.02	78.50	80.77	2.28	78.17	80.24	2.07
MLP-4	12.2	111.17	111.99	0.82	110.37	112.35	1.98	110.82	111.20	0.38
MLP-5	18.3	177.13	177.66	0.53	176.59	177.64	1.06	-	-	-
MLP-6	27.4	270.78	271.80	1.02	270.71	272.13	1.41	271.35	271.38	0.03
MLP-7	39.6	389.44	390.40	0.96	389.27	390.28	1.01	389.62	389.91	0.30

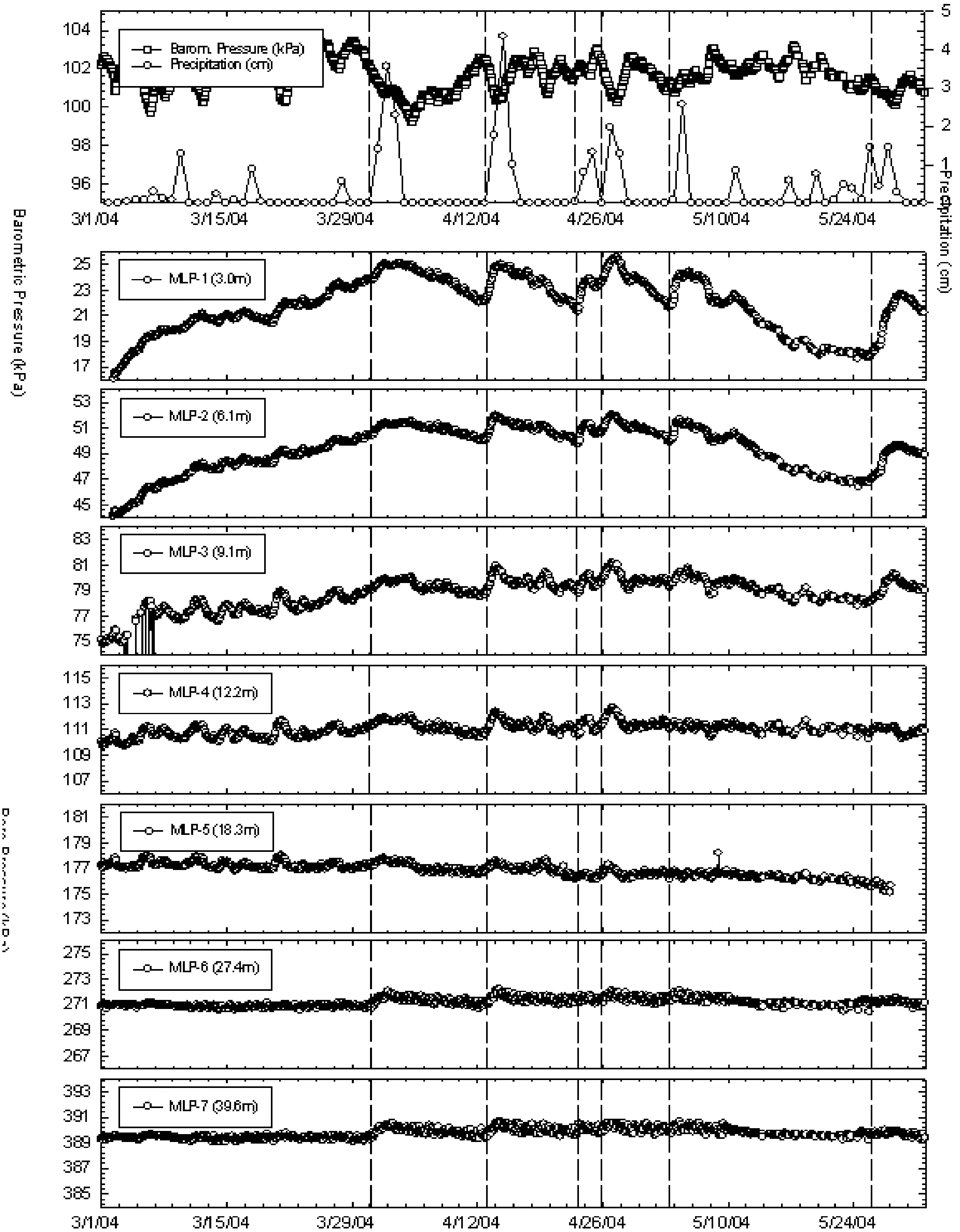

Figure 3. Barometric Pressure and Precipitation from Weather Station and Measured Response of Each MLP from 1 March to 1 June 2004.

model curve approaches the actual pore pressure response observed at MLP's 1 through 6. Diffusivity, D, is related to the coefficient of consolidation (c_v) although D applied to small strain behaviour at in situ stress conditions whereas c_v is most often determined after the soil has undergone relatively large strains and has been loaded beyond the yield stress. Consequently the value of D may be one or more orders of magnitude larger than the c_v value conventionally reported in literature for geotechnical applications. Once optimized, the above parameters are held constant and the value of d changed to the installation depth of the piezometer.

Data collected during the 14 April 2004 precipitation event was used for the event modelling portion of this paper. The values of the calibrated parameters were as follows: H_o=0.3 m , E/n = 4.0 X 10^{-7} m/s, D = 5.0 X 10^{-4} m^2/s , and z_o = 0.5 m. Results from the event modelling analysis for this study are presented in Figure 4. For a given precipitation event, the piezometer response is normalized by its initial pore pressure reading and plotted. As evident, there is reasonable agreement between the MLP data and the model at the shallower depths while at greater depths the model deviates from the MLP data. The MLP-5 and MLP-6 data may be influenced by the simultaneous recharge of the underlying glacial till during a precipitation event, a phenomena not captured in the model presented.

8. PIEZOMETER DESIGN EVALUATION

Comparison of the data obtained from the MLP's and conventional-design vibrating wire piezometers indicates generally good agreement (Figure 5). The observed pore pressures at the reference depths often differ only in magnitude. This discrepancy is primarily attributed to slight differences in the mean sea level elevation. The MLP design appears to be more sensitive, capable of detecting slight variations in the pore water pressure. This trend appears to be more pronounced at shallower depths, and becomes less significant as depth increases. This increased sensitivity is reasonable as the MLP's filter is in direct contact with the soil whereas the conventional piezometer may have some bentonite grout between the piezometer filter and the in situ soil.

The MLP-2 response exhibits higher sensitivity to precipitation events relative to the conventional piezometer (R-1) installed at approximately the same depth (Figure 5) (R-4, the grouted conventional piezometer is analyzed later). The data from MLP-2 tracks the precipitation event plot, detecting each separate event, whereas the pore pressure response recorded by R-1 show a more gradual or no detection of precipitation events, followed by a comparatively slower attenuation. This effect is also observed, albeit to a lesser extent, when comparing data obtained at 18.3 meters below ground surface from R-2 and MLP-5. Here the pore pressure response observed at MLP-5 appears only slightly more sensitive than that of R-2. The pore pressure response to precipitation events is still more pronounced in the MLP data however. Observation of data from R-3 and MLP-7 shows that the pore pressure responses observed at the two piezometers are virtually identical. Both data plots show corresponding responses and attenuations of the same nature.

The pore pressure profile of the fully grouted piezometer R-4 is virtually identical to that of piezometer R-1, installed within a sand pack. Both sets of data indicate similar attenuation and sensitivity to precipitation events. Similar behaviour between fully grouted and sand-packed piezometers has also been observed with the use of pneumatic diaphragm piezometers (McKenna 1995). The similarity of the data between R-1 and R-4 indicates that the sand pack may be an unnecessary step in the installation of diaphragm piezometers (Mikkelsen and Green 2003). Elimination of the sand pack would allow for multiple conventional piezometers to be installed in the same borehole, reducing the materials, time consumption, and cost of installation. However, a fully grouted piezometer would suffer from a lower sensitivity relative to the MLP design.

9. CONCLUSIONS

The installation, monitoring, and performance of an array of new multiple level piezometers (MLP) as well as conventional piezometers installed with sand pack and fully encased in grout has been presented. From the MLP array the hydrogeologic conditions of the site have been preliminarily evaluated and modelled. In addition, the MLP design was shown to have higher sensitivity, successfully detecting every precipitation event over a three month period.

10. ACKNOWLEDGEMENTS

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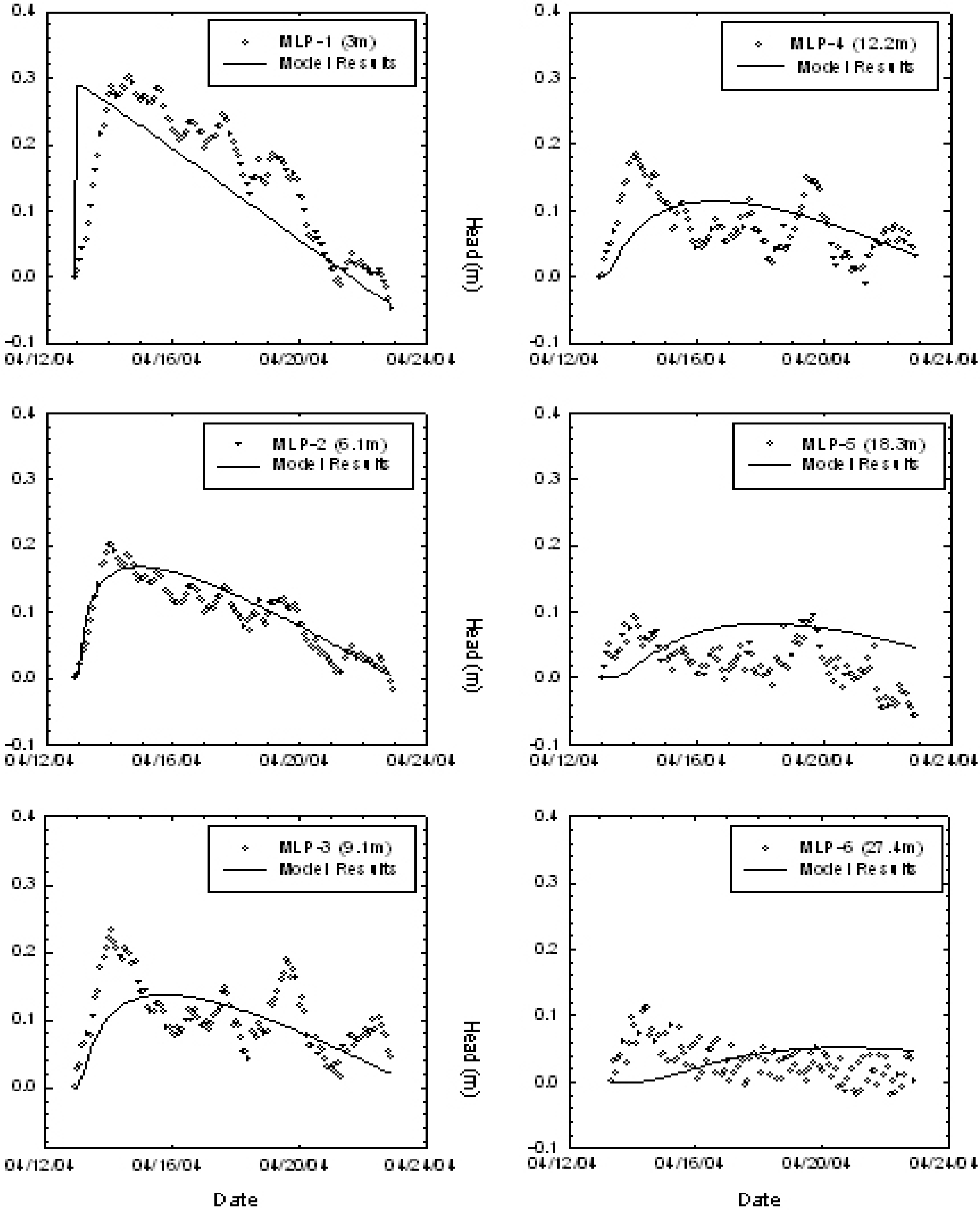

Figure 4. Piezometer Data and Analytical Calibrated Model Results for April 14 Precipitation Event.

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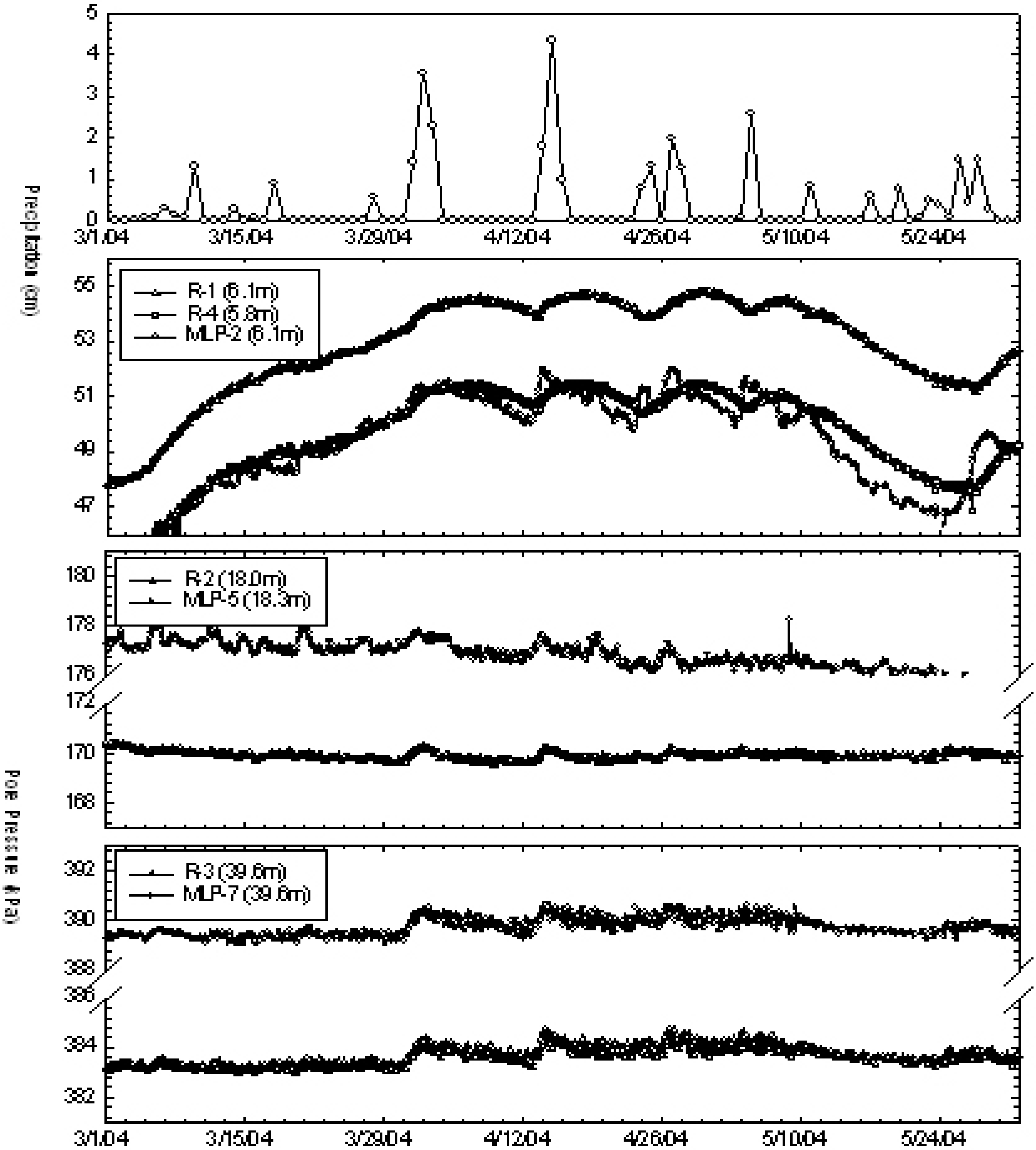

Figure 5. MLP and Conventional Piezometer Results from 1 March to 1 April 2004.