High response rate piezometer and its application at a high-speed railway site

Piézomètre de réponse rapid et son application à un emplacement ferroviaire à grande vitesse

E.S. Aw
Exponent Failure Analysis Associate, USA

J. T. Germaine
Massachusetts Institute of Technology, USA

A. J. Whittle
Massachusetts Institute of Technology, USA

ABSTRACT

This paper describes the development of a low cost, miniature, high-response piezometer and its application at a high-speed train site in the United States. The piezometer requires fast response measurement time (i.e. time taken for the piezometer to equilibrate with external applied pore pressure) in order to capture the transient pore pressure development in the subgrade caused by 150 mph Acela high-speed trains (an eight-carriage train takes less than 3 seconds to pass the piezometer). The fast response time of the piezometer is achieved by increasing the stiffness of the measuring system via minimizing the internal fluid chamber, using stiffer encasing, and ensuring good saturation of the measurement fluid (using vigorous fluid saturation techniques) In addition, the piezometer utilizes a slender needle-tip measurement shaft to minimize the effects of soil arching during train loading. A three-dimensional finite element is also performed to estimate and compare the theoretical and field-measured development of the wheel-induced pore pressures within the subgrade. The piezometer is able to capture the train-induced pore pressure signatures and, to a lesser extent, the wheel-induced pore pressures. The latter is a result of low in-situ soil permeability which reduces the overall system's response time.

RÉSUMÉ

Cet article décrivent le développement d'un coût bas, de la miniature, du piézomètre de haut-réponse et de son application à un emplacement de train à grande vitesse aux Etats-Unis. Le piézomètre a besoin de le temps rapide de mesure de réponse (c.-à-d. temps pris pour que le piézomètre équilibre avec de la pression de pore appliquée d'external) afin de capturer le développement passager de pression de pore dans le sous-grade provoqué par 150 trains à grande vitesse de M/H Acela (un train de huit-chariot prend moins de 2 secondes pour passer le piézomètre). Le temps de réponse rapide du piézomètre est réalisé en augmentant la rigidité du système de mesure par l'intermédiaire de réduire au minimum la chambre liquide interne, utilisant un emballage plus raide, et assurant la bonne saturation du fluide de mesure (utilisant des techniques liquides vigoureuses de saturation) en outre, le piézomètre utilise un axe à bec mince de mesure pour minize les effets du sol arquant pendant le chargement de train. Un élément fini de three-dimentional est également exécuté pour estimer et comparer le développement théorique et champ-mesuré des pressions de pore roue-induites dans le sous-grade. Le piézomètre peut capturer les signatures former-induites de pression de pore et, à un moindre degré, les pressions de pore roue-induites. Ce dernier est un résultat de la basse perméabilité in-situ à sol qui réduit le temps de la réaction du système global.

Keywords : high response, piezometer, water pressure sensor, subgrade, high speed train, pore pressures, mud pumping

1 INTRODUCTION

A miniature, high-response piezometer has been designed for measuring transient train-induced pore pressures beneath a high-speed railway track. This development was part of a research project to investigate the mechanism of mud pumping (migration of subgrade soils up and through the ballast) in a section of track traversed by Amtrak ('Acela Express') trains running at 240 kph. The term "high response" refers to the capability of the piezometer in measuring rapid development of pore pressures caused by the passage of a single train. This paper describes the principles and challenges in designing a high-response piezometer and illustrates its application at the field site.

2 PRINCIPLE OF PIEZOMETER MEASUREMENT

Piezometers are sensors that are capable of measuring the fluid pressure in the ground independently from the pressure exerted by the soil skeleton. A typical electronic piezometer consists of a pressure transducer, an inner chamber (houses the pressure transducer and internal fluid), and the porous filter. The pore water pressure is decoupled from the total pressure through a porous filter that allows passage of pore water (to act upon the internal fluid and pressure transducer), while effective stresses are carried by the filter material itself. The response capability of a piezometer (i.e. how fast a piezometer can measure changes in pore water pressure) depends on both the measuring stiffness of the device and the permeability of the surrounding soil.

2.1 *Measuring stiffness of the piezometer*

In order to measure an increase in pore pressure, the water in the soil needs to enter the piezometer via the porous filter and deflect the diaphragm of the pressure transducer (most pressure transducers are strain-gage based and measure pressure as a function of the diaphragm deflection). The greater the amount of water that needs to enter the porous filter, the slower is the response of the piezometer. Kutter *et al.* (1990) succinctly captured this behavior using the following equation:

$$\Delta p = K \frac{\Delta V}{V} \quad (1)$$

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1869

where

Δp = external pressure change
K = bulk modulus of the internal fluid in the chamber
ΔV = change in the internal fluid volume of piezometer
V = total internal volume of the piezometer

It is clear that devices with smaller volume can achieve faster response rates for a given influx of external pore fluid.

Henderson (1992) developed a more rigorous approach in predicting the theoretical response of a piezometer probe:

$$\frac{p_o}{p_a} = \left(1 - e^{-bt}\right) \tag{2}$$

where $b = \dfrac{kA}{\gamma_{fluid} l M}$ and $M = \dfrac{\Delta V(t)}{\Delta P(t)}$

p_o is the probe output pressure, p_a is the atmospheric pressure, k is the hydraulic conductivity of the porous filter, γ_f is the unit weight of the internal fluid, l is the length of the filter, M is the probe system compliance and t is the time. Δp and ΔV are the probe system pressure and volume respectively.

Equation 2 shows that the response rate (p_o/p_a) is a function of the probe system compliance (M) and the hydraulic conductivity of the porous filter (k). The elastic expansion/ contraction of the piezometer housing, porous filter and internal fluid can all have a significant effect on the compliance of the system. A more flexible pressure transducer diaphragm increases the system compliance and response time; unsaturated internal fluid contains compressible air bubbles which will also increase response time (Rad & Tumay, 1985, showed that the piezometer will still measure the pressure accurately, albeit at a slower response time.). Using a high hydraulic conductivity porous filter (governed by the size and connectivity of the pores) will decrease response time due to faster entry of the water into the porous filter. There is a limitation on the size of the pores (i.e. the hydraulic conductivity) if the piezometer is to be used in partially saturated media; the piezometer will be drained when the soil matrix suction exceeds the tension capillary strength of the internal fluid within the porous filter. The current design uses a porous steel filter with 40mm pore diameter in order to ensure an air entry pressure of approximately 200 kPa (with silicon oil as the internal fluid).

2.2 *Permeability of the soil*

If the piezometer is embedded in soil, the response time is often governed by the properties of the soil. Water will have to flow out of the soil before entering the porous filter. Therefore, the response of the piezometer will be faster in porous media such as sands than it is in low permeability soils such as clay.

3 DESIGN OF THE PIEZOMETER

The following section describes the design of a high response piezometer. Components of the piezometer include: a) a measurement unit consisting of a pressure transducer, a porous steel filter attached to a small diameter steel tubing, silicone oil internal fluid, and a waterproof plastic enclosure which protects the piezometer.

3.1 *Pressure Transducer*

An Omega PX139 differential pressure transducer with ±200 kPa capacity is selected because of its: a) good long term off-set stability (i.e. minimal drifting in the transducer), b) high voltage output (less susceptible to environmental noises), c) fast response rate (i.e. small and stiff diaphragm), and d) low cost. The miniature needle steel tip is attached to the port of the pressure transducer via a Swagelok™ reducing union (3/16" to 1/8"). The use of a differential pressure transducer eliminates the need to correct for atmospheric pressure.

3.2 *Miniature Needle Steel Tip and Porous Steel Filter*

The miniature steel shaft is a slender tube with an outer diameter of 3.2 mm and length of 17 cm. At the end of the steel shaft resides the porous steel filter element of 1.76 mm diameter and has small pore size of 40 microns. The porous steel filter has permeability of 0.002 mm/s (measured with falling head laboratory experiments). The connection between the miniature steel shaft and the plastic port of the transducer is made by clamping the Swagelok nut to the port using a bronze ferrule and back ferrule. Kutter *et al.* (1990) found that arching dramatically reduces the measurement capability of the piezometer, an effect that would be profound at the event of high frequency dynamic loading. The use of a slender, miniature steel shaft reduces the arching effect during train loading.

3.3 *Silicone Oil*

De-aired water is frequently used in commercial piezometers and tensiometers. However, difficulties with maintaining saturation and freezing (during winter, if piezometers are located near the ground surface) have led to favorable considerations of using silicone oil which has very low freezing point and requires easier saturation procedures. A low kinematic viscosity silicone oil of 20 cst was selected. Silicone oil was successfully used for pore pressure measurement under freezing conditions (e.g. Da Re, 2000). However, the use of silicone oil does introduce a small error in measurements due to differences in the interface between the silicone oil and water.

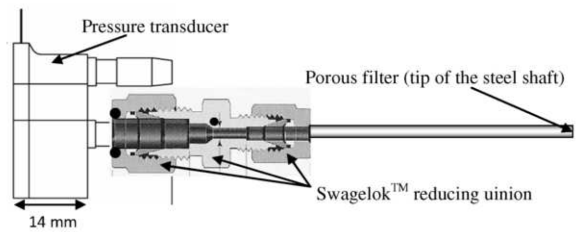

Figure 1. Components of the high response piezometer. All measurements (length and diameter) of the components are in millimeters.

3.4 *Saturation of the piezometer*

The sophistication of a saturation procedure greatly determines the response time performance of piezometer in the saturated state; high-end saturation requires saturation techniques are often too elaborate for practical use. The current research follows a less elaborate but still rigorous saturation procedure originally proposed by Take and Bolton (2003):

- Place the steel tubing containing the porous filter into a silicone bath and apply ultrasound for 30 minutes. Connect all components in a silicone oil bath and saturate the pressure transducer with a very thin hypodermic needle.
- The piezometer is then placed in a vacuum. The piezometer is currently not submerged under the silicone oil. A

vacuum of -100 kPa is applied to draw bubbles out of the system for 10 minutes.

- The vacuum chamber is then turned 90 degrees so that the piezometer tip is submerged under the silicone oil and the oil is able to flow into the piezometer through the action of gravity. The setup is then left for another 10 minutes.
- The vacuum pump is then released and the piezometer is allowed to further undergo saturation under atmospheric pressure for another 20 minutes.

3.5 *Response of the piezometer*

The theoretical response time of the piezometer (based on Equation 2) in silicone oil is 0.01 seconds. The laboratory measured time response (apply a unit pressure and measure the time taken for the piezometer to reach that applied pressure) is 0.04 seconds (close to the predicted response time). For tests in soils, an instanteneuos load (100 kPa for the clay and 50 kPa for the sand) was applied onto the soil sample (double drainage setup; a head of 1 kPa was introduced at the base of the sample to ensure positive pore pressure) containing an embedded piezometer (see Figure 2). The response time of the piezometer increases to 0.2 seconds for the high permeability sand (Figure 2) and 30 seconds for the low permeability clay (Figure 3).

Tests in silicone oil yield the ideal and fastest possible response time: unlimited supply of oil is available to enter the porous filter and there is an instanteneous of transfer of applied stress onto the oil. Under these conditions, the response time is fully governed by the measuring stiffness of the piezometer and the permeability of the porous filter. When tested in clay, water has to come out of the low permeability clay and enter the porous filter, thus delaying the response time. In sand, the response time is faster than clay, but is still slower than silicone oil; the instantaneous application of pressure does not translate into an instanteneuos increase in pore pressure (sand grains are reorganized, contributing to the system compliance). In addition, the measured excess pore pressure is smaller than the applied pressure. Sand, unlike clay, does not fully transmit the applied stress into an increase in pore pressure (the sand skeleton adsorbs some of the applied stress) and the excess pore pressures dissipated very quickly due to the high permeability of the sand.

The subgrade soil is classified as silty-sand (SM) using the Unified Soil Classification system. The permeability is estimated as 4 x 10^{-6} cm/s (using Hazen's empirical permeability formula), thus giving theoretical response time of 1 second for the piezometer.

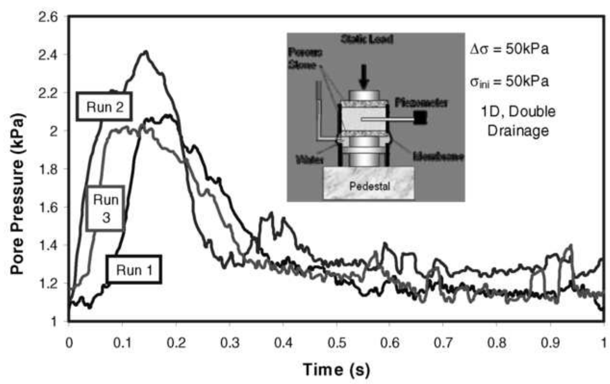

Figure 2. Response of the piezometer in high permeability sand.

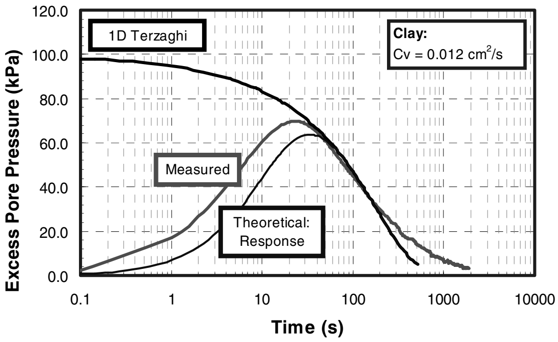

Figure 3. Response of the piezometer in low permeability clay.

4 INSTALLATION

Two piezometers were installed in between ties at the depth of 0.3 m below the top of the ballast. The ground water table was located approximately 2 m below the top of the ballast. Based on prior experience, the sensors should not be installed in the ballast (due to high loading stresses and damage from large ballast particles) and a minimum of 5 cm subgrade cover is sufficient to protect the sensors. The two piezometers were pushed into the natural subgrade (needle end first) to ensure good contact between the porous filter and the subgrade.

5 FIELD MEASUREMENTS

Figures 4a-c show the typical response measured at the top of the subgrade during the passage of a high speed Amtrak train. Figures 4a and 4b show the ground acceleration response (the accelerometer is installed next to the piezometer) and dynamic pore pressure responses sampled at 10 kHz respectively. The pore pressure data contain spikes of high frequency noises which are readily removed using a low-pass 300 Hz frequency filter as shown in Figure 4b. It should be noted that the pore pressures are negative indicating that the soil is under matrix suction and the ground water is below the piezometer.

At the onset of train loading, the piezometer registered a positive "pulse" in the pore pressure (≈ 2 cm) from t = 0.6 to 0.8 secs. Subsequent wheel loadings produced pore pressure pulses that dissipated after the wheels had passed. A negative water pressure "pulse" was measured from t = 3.8 to 4.0 secs after the train left the instrumented area.

The train passage is cyclic in nature; involving a series of successive wheel loadings which produce a rotation of principal stress directions. The pore pressures can be considered the sum of components due to changes in the mean total stress and cyclic shear-induced stresses. As the train approaches the instrumented area, the piezometer registered an increase in average pore pressure (result of increased in average total stress due to the train load) starting from time 0.6. However, the excess average pore pressure was immediately dissipated due to the relatively high permeability of the silty-sand subgrade (time 0.7 to 0.8 seconds). Subsequent individual wheel loads produced shear-induced pore pressures. As the train left the instrumented area, the subgrade experienced stress relief and this was manifested by a negative pore pressure pulse, which is also quickly equilibrated.

The close up of the positive "pulse" and the development of excess pore pressure due to wheel loading are shown in Figure 5. The rapid build-up in the pore pressures due to incoming train were immediately dissipated even as the individual wheel-induced cyclic pore pressures were generated.

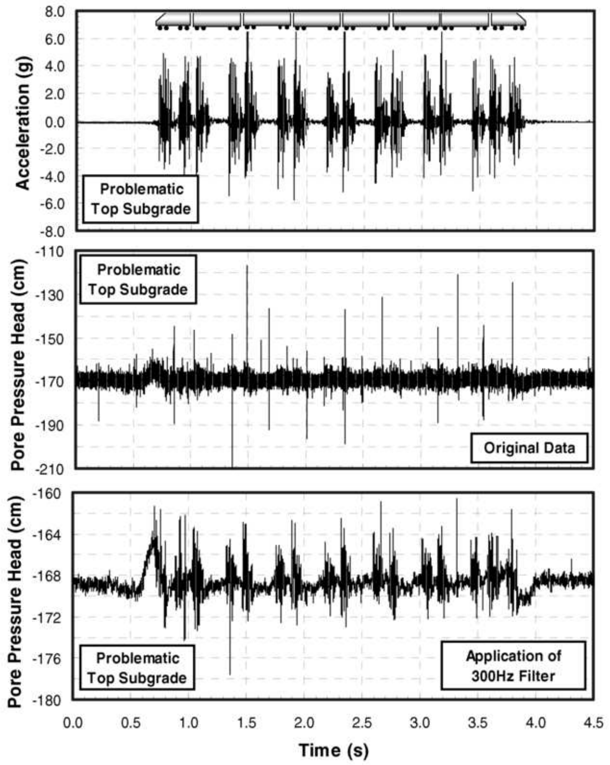

Figure 4. Typical acceleration (a: top) and pore pressure (b: middle and c: bottom) responses due to the train at the top subgrade.

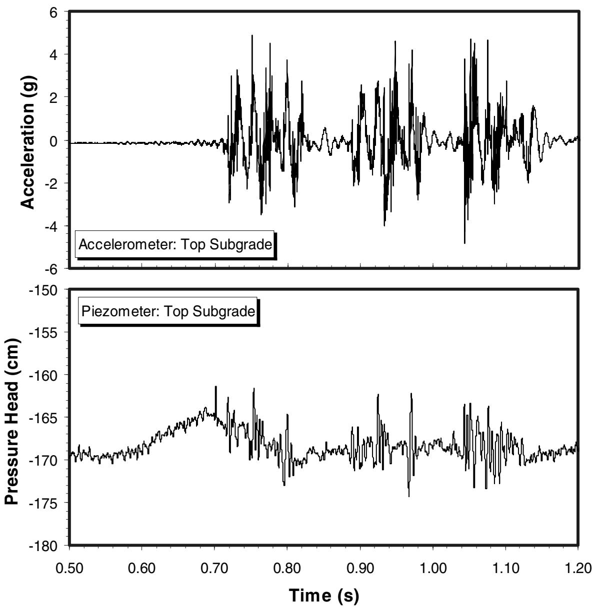

Figure 5. Close up of the train-induced pore pressures

6 FINITE ELEMENT ANALYSIS

In order to verify and estimate how much excess pore pressures were generated in the subgrade, a 3-D elastic finite element analysis (FEA) was performed using 3-D Plaxis program for a single wheel loading. An undrained condition was modeled (i.e. response under fully saturated conditions with no drainage) and the pore pressure pulse was controlled by the increments in octahedral stresses $(\Delta\sigma_1+\Delta\sigma_2+\Delta\sigma_3)/3$.

The finite element model estimated pore pressure pulses of 20kPa (200 cm head) for the top subgrade. The piezometer in the top subgrade measured up to 1 kPa (10 cm) of pore pressure. The deviation in the measurements can be attributed to: a) the FEA analysis assumed fully saturated condition while the real subgrade was mostly unsaturated. Under these conditions, the generated pore pressures in the subgrade will be much lower than the predicted ones, and b) the theoretical response time of the piezometer in this subgrade soil was 1 second. The limitation in the response time meant that the piezometer could accurately measure the three-second train-induced average pore pressures but not the faster dynamic wheel-induced cyclic pore pressures. Fortunately, this is sufficient for most analyses since the effective stress of the subgrade is governed by the average pore pressure and, to a lesser extent, the shear-induced pore pressure.

7 CONCLUSIONS

This paper presents the development of a high response piezometer. The response rate of the piezometer in silicone oil is 0.04 seconds (response rate fully governed by the measuring stiffness of the piezometer and the permeability of the porous filter). However, when the piezometer is embedded in soil, the response time is now dependent on the permeability of the soil: approximately 0.1 seconds for sand and up to 30 seconds for low permeability clay. The theoretical performance of the piezometer in the site subgrade soil is 1 second.

The piezometers were installed at a high speed railway site. The measured pore pressure indicated no evidence of cumulative excess mean pore pressures (due to the relatively high soil permeability), suggesting that water plays a minor role in the subgrade and ballast fouling may be attributed to other mechanisms (such as perched water at the fouled ballast / subgrade interface).

ACKNOWLEDGEMENT

The authors are especially grateful to Mike Trosino, Mike Tomas and Ray Samuels from Amtrak for providing track support.

REFERENCES

Cauble D.F. 1997, "*An Experimental Investigation of the Behavior of a Model Suction Caisson in a Cohesive Soil"*, PhD Thesis, Massachusetts Institute of Technology

Da Re G. 2000, "*Physical mechanisms controlling the pre-failure stress-strain behavior of frozen sand*", PhD Thesis, Massachusetts Institute of Technology

Henderson, E. 1994, "*Evaluation of the Time Response of Pore Pressure Measurements*", S.M Thesis, Department of Civil Engineering, Massachusetts Institute of Technology

Kutter, B. L., Sathialingam, N., Herrmann L.R. 1990, "*Effects of Arching on Response Time of Miniature Pore Pressure Transducer in Clay*", American Society for Testing and Materials, pp164-178

Rad, N.S. & Tumay, M.T. (1985), "*Pore-Pressure Response of the Piezocone Penetrometer"*, Geotechnical Testing Journal, , Vol 8, Sept, No 3, p125 – 131

Take, W.A., & Bolton, M.D. 2003, "*Tensiometer saturation and the Reliable Measurement of Soil Suction", Geotechnique* 3, No 2, pp159-172