Field monitoring of pore-water pressure profile in a slope subjected to heavy rainfalls

Surveillance sur place de la pression de l'eau interstitielle profil dans une pente soumis à de fortes pluies

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ABSTRACT

Fiber optic piezometers developed by the authors were installed in a single 60 m deep borehole where the profile of pore-water pressure can be monitored at 5m intervals. The test site was located in a section referred to as the Five Turn Point of Highway 18 that connects Chiayi to Alishan, in Taiwan. The highway makes five turns in order to increase the linear dimension and maintain a desirable slope for the vehicles. At least eight sectors within the Five Turn Point area have been identified with either previous slope failure or signs of continuous movement. Subsurface explorations have revealed that the subject area is covered by over 200 m of fractured rock or colluvial material accumulated from earlier landslides. The groundwater could rise more than 20 m as a result of heavy rainfall. The sudden and significant change in groundwater table is believed to be a major cause for the slope instability. The field pore-water pressure profile measurements showed that a heavy rainfall tends to create significant hydraulic gradient in the vertical direction. The distribution of groundwater pressure deviates significantly from hydro-static conditions. It would be difficult if not impossible to capture this phenomenon with the conventional groundwater monitoring technique where one or two piezometers were placed in a borehole. The results demonstrate the advantages of distributive pore-water pressure monitoring by deploying an array of piezometers in a single borehole.

RÉSUMÉ

Piézomètres à fibre optique développé par les auteurs ont été installés dans un seul trou de sondage de 60m de profondeur où le profil de la pression de l'eau interstitielle peut être contrôlé à intervalles 5m. Le site pour test était situé dans une section dénommée Five Turn Point 18 de l'autoroute qui relie Chiayi à Alishan, à Taïwan. L'autoroute fait cinq tours en vue d'accroître la dimension linéaire et de maintenir une pente souhaitable pour les véhicules. Au moins huit secteurs à l'intérieur de la zone de Five Turn Point ont été identifiés avec une pente de l'échec précédent ou des signes de mouvement continu. Les explorations sous-sol ont révélé que le domaine est couvert par plus de 200 m de roches fracturées ou colluvions matériel accumulé par de précédents glissements de terrain. Les eaux souterraines pourrait augmenter de plus de 20 m à la suite de fortes précipitations. La brusque et important changement dans le niveau de la nappe phréatique est considérée comme l'une des principales causes de l'instabilité des pentes. Les mesures de la pression de l'eau interstitielle sur place a montré que de fortes pluies ont tendance à créer un grand gradient hydraulique dans le sens vertical. La répartition de la pression des eaux souterraines s'écarte fortement des conditions hydro-statique. Il serait difficile, s'il n'est pas impossible de saisir ce phénomène avec la technique classique de surveillance de l'eau souterraine où un ou deux piézomètres ont été placés dans un trou de sondage. Les résultats démontrent les avantages de la distribution de surveillance de la pression de l'eau interstitielle pour déployer un réseau de piézomètres dans un seul puits. , en déployant un réseau de piézomètres dans un seul trou de sondage.

Keywords : piezometer, rainfall, pore-water pressure, fiber optic sensor

1 INTRODUCTION

The increase of pore water pressure is usually the main cause in rainfall incduced landslides. A three-dimensional numerical seepage analysis perofrmed by Ng et al. (2001) has indicated that the initial groundwater conditions and rainfall pattern can both affect the pore-water presure disributions in a slope. The effects of rainfall pattern on pore-water pressure distribution is the greatest when the initial groundwater table is deep and the rainfall is short and intense. In areas where infilration of surface water is taking place (i.e., near crest of slope), there is a signifcant increase of piezo-head towards the ground surface. This distribution of piezo-head near ground surface can be non-linear and trancient during a heavy rainfall.

Pore-water pressure is probably the most indicative of slope instability in its early stage, among the possible physical quantities that can be monitored in the field. The current practice in groundwater level or pore-water pressure monitoring generally involves the installation of one or two open end piezometers (i.e., standpipe), pneumatic or electronic pressure (i.e., diaphragm) transducers in a 100mm diameter borehole. These methods are either difficult to automate or lack of sufficient measurement points to reveal the highly non-linear and transient pore-water pressure profiles resulted from heavy rainfall. There are commercially available vibrating wire (VW) piezometers that allow multiple units to be sealed in a PVC pipe and then installed in a single borehole. The VW sensors are non-distributive; a separate signal cable is required for the individual VW piezometers. Thus, the number of VW piezometers allowed in a borehole is limited by the number of cables that can be placed in the PVC pipe. In addition, electronic sensors such as the VW piezometers can be affected by electromagnetic interference and/or short circuit when placed under water.

Fiber Bragg Grating (FBG) is a partially distributive optic fiber sensor where signal is transmitted via light. Multiple FBG sensors can be fitted to a single, 250 μm diameter optic fiber. The FBG optic signal can easily be transmitted over 10km in distance and is immune to electromagnetic interference. The stability of optic fiber is not affected by submergence under water. These unique features make FBG sensors ideally suited

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for the purpose of monitoring ground conditions where a profile-information is required. The paper describes the basic principles of an FBG piezometer developed by the authors and a case where an array of FBG piezometers was installed in a borehole to monitor the profile of pore-water pressure. The field monitoring took place at a highway slope of Alishan Mountain in Southern Taiwan. A time history of pore-water pressure profile recorded during a typhoon is presented and implications in future applications as part of a landslide warning system are discussed.

2 PARTIALLY DISTRIBUTIVE FBG PIEZOMETERS

A fiber Bragg grating (FBG) is made by periodic variation or modulation of the core refractive index on a 1 to 20 mm long segment of optic fiber (Meltz et al., 1989). When the FBG is illuminated by a wideband light source, a fraction of the light is reflected back upon interference by the FBG. The wavelength of the reflected light is linearly related to the longitudinal strains of the FBG. Thus, FBG has the same function as a strain gage. The returned signal from every FBG carries a unique range or domain of wavelength, making it possible to have multiple FBG elements on the same fiber. The multiplexing among various sensors on a single optic fiber can be accomplished by wavelength division addressing as conceptually described in Figure 1. There is a limited bandwidth of the light source and as the light passes an FBG there is a loss of its intensity, the number of FBG sensors that can be placed on a fiber is not more than 20 with the currently available FBG interrogation systems.

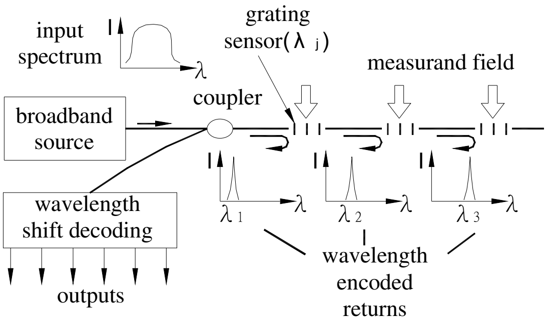

Figure 1. FBG sensor array (after Kersey, 1992).

Figure 2 shows the photograph of an FBG pressure transducer. The FBG was used to sense the deflection of a metallic diaphragm inside of the transducer due to changes in pressure against the atmosphere. A separate FBG was placed inside the transducer to monitor temperature fluctuations. A typical interrogation system is capable to detect shifting of FBG wavelength by 1pm (10^{-12} m). An FBG breaks when stretched by a strain equivalent to approximately 8000pm in wavelength variation. The range of pressure transducer was controlled by the stiffness of the diaphragm. Depending on the required safety margin, the maximum allowable pressure was designed to correspond to 1000 to 4000 pm of FBG wavelength variation.

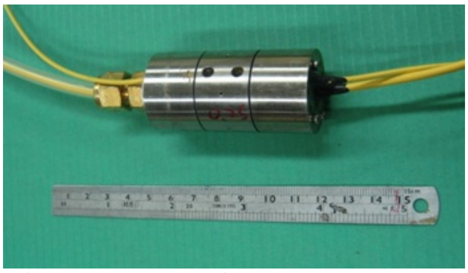

Figure 2. The FBG pressure transducer.

Figure 3 depicts the result of calibration of an FBG pressure transducer with a maximum allowable range of 300 kPa. The results are desirable in terms in linearity and repeatability. The pressure transducer is converted into a piezometer by inserting filter material in the pressure inlet.

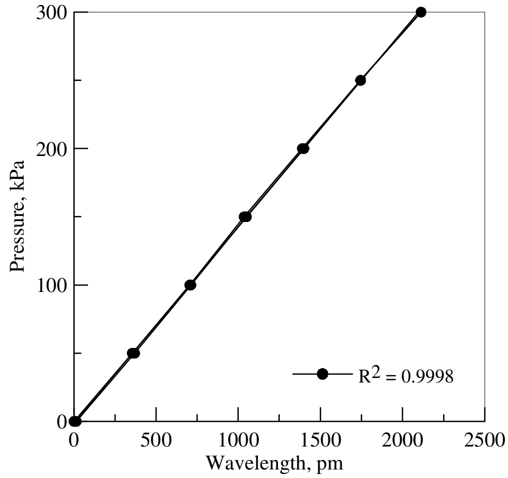

Figure 3. Calibration result of an FBG pressure transducer.

With a diameter of 25 mm, the FBG piezometer was fitted inside of a 28 mm ID and 32 mm OD PVC pipe. Small holes were drilled in the PVC pipe in areas surrounding the piezometer to allow passage of water. The piezometer was epoxied and sealed at both ends in the PVC pipe to prevent seepage between piezometers from within the PVC pipe. The PVC pipe serves as a spacer and housing for all the piezometers and optic fiber. All PVC pipe connectors were internal leaving a smooth exterior upon assembly in the field. The assembled PVC pipe/piezometers can be fully grouted in a borehole following the procedure reported by Contreras et al. (2008). Or, the piezometers can be surrounded by a sand pack. The space in between the sand pack is sealed with bentonite. A comparison between a string of nested FBG piezometers installed in a single borehole to the case of individual, separate installation of standpipes is depicted in Figure 4.

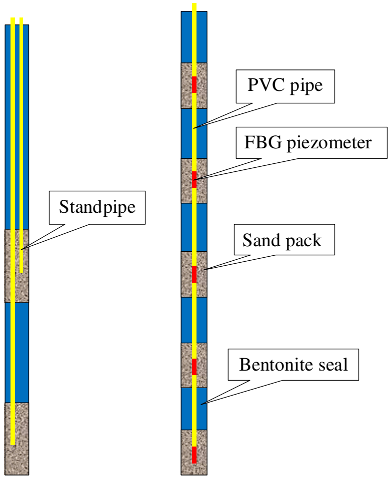

Figure 4. Comparison between the individual separate and nested piezometer installations.

3 FIELD INSTALLATION AT FIVE TURN POINT

A section of Highway 18 that connects Chiayi County to Alishan Mountain, refers to as the Five Turn Point has been selected as the most dangerous highway in Taiwan. The Five Turn Point is located in a slope area of approximately 1200 m by 1000 m where the ground surface elevation changed by as much as 300 m. Figure 5 shows a topographic map of the general area of Five Turn Point. The highway in this section originally had five turns in order to increase the linear dimension and maintain a desirable slope for the vehicles. The slope failures and rerouting of the highway created additional turns. At least eight sectors within the Five Turn Point area have been identified with either previous slope failure or signs of continuous movement. Figure 6 depicts section B-B indicating shear planes associated with earlier ground failures according to available investigations. Previous subsurface explorations have revealed that the subject area is covered by over 200 m of fractured rock or colluvial material accumulated from earlier landslides. The groundwater could rise from its low level by more than 20 m as a result of heavy rainfalls as shown in Figure 6 according to available monitoring data. It should be noted that due to normally low levels of groundwater table, open end piezometers or standpipes with the measuring tip at 50-60m below ground surface have been used to monitor the ground water table. Because of the number of sensors per borehole did not exceed two, the interpretation of all previous piezometer readings assumed hydrostatic groundwater conditions. The sudden and significant change in groundwater table is believed to be a major cause for the slope failures in this area. Alishan is a major mountain resort in Southern Taiwan that attracts large number of tourists in the summer which is also the typhoon season. The local highway department is often faced with a dilemma between highway safety and convenience for travelers during typhoon season. A real time field monitoring would be very helpful in providing the key information for the local authority to make timely decisions for highway shutdown in case of an imminent landslide.

A 60 m deep borehole marked as NCTU03 in Figure 5 was used to install the FBG piezometers. An FBG piezometer was housed and sealed on both ends in a section of 3m long PVC pipe in laboratory. Additional PVC pipe was connected in the field to space the FBG piezometers at 5m intervals. The segment of the PVC pipe that contained the FBG piezometer was wrapped with 1.5m wide non-woven geotextile as filter. Figure 7 shows a set of PVC pipes with FBG piezometers enclosed. Final assembly was made as the PVC pipe was being inserted into the borehole. The FBG piezometer was surrounded by 2 m thick sand pack. Sealing between the sand pack was provided by placing bentonite pellets. The deepest piezometer was located at 59 m below ground surface. The sensors were connected to an on-site computer using optic fiber cables for optic signal interrogation and data logging. The field computer was accessed via High Speed Downlink Packet Access, HSDPA) wireless internet system. The readings were updated hourly.

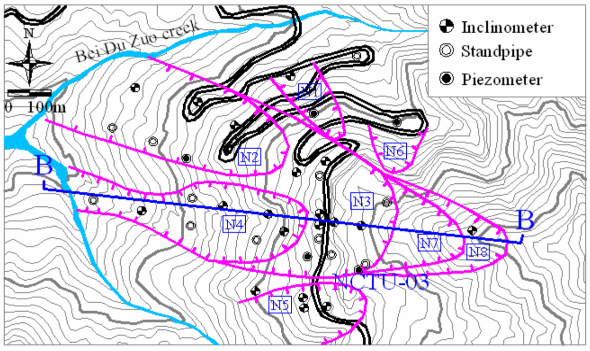

Figure 5. Topographic map of the Five Turn Point. (after Land Engineering Consultants, Co., Ltd., 2007).

4 FIELD MEASUREMENTS

The piezometer array installation was completed in mid-October, 2007. Figure 8 shows a set of representative readings taken between October 26, 2007 (beginning of automated data logging) and August 31, 2008. The piezometer at 59 m malfunctioned from the beginning and the one at 54 m lost signal two months after installation. The rest of the readings showed that initially the groundwater table was at 40 m below ground surface. There was a perched water table at 25 m. The water table remained low for the most part of the monitored period in Figure 8 except for those of 6/11 and 7/22 of 2008, when a mild rain storm occurred. By August 31, the water table lowered to approximately 33m below ground surface.

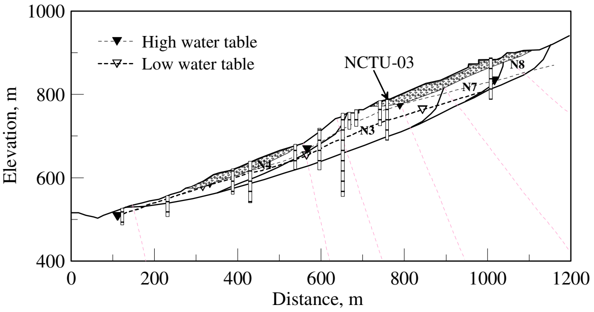

Figure 6. Section B-B of the Five Turn Point. (after Land Engineering Consultants, Co., Ltd., 2007).

Figure 7. PVC pipes with FBG piezometers enclosed.

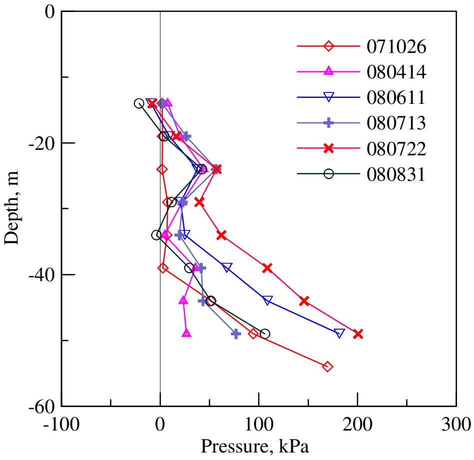

Figure 8. Piezometer record up to 8/31/2008.

Typhoon Synlaku landed in Southern Taiwan on September 14, 2008 and brought in rainfall that peaked at 660 mm/day. A histogram of daily precipitations during the period that includes Typhoon Synlaku is shown in Figure 9. Another typhoon arrived on September 29 and caused further groundwater fluctuation. To avoid confusion, no record from between September 29 and October 27 is shown. The piezometer readings were converted into piezo-heads (=elevation head + pressure head) for further demonstration. Ground surface was used as the datum where elevation = 0. Thus, depth equals to elevation. Figure 10 shows the change of piezo-heads from the beginning of Typhoon Synlaku to the time when piezo-heads reached the maximum values at their respective elevation. Significant increase of piezo-heads started at noon of September 14. In the following 26 hours, the piezo-heads from below the depth of 34 m increased more than 20 m. This increase is consistent with previous experiences according to standpipe measurements. The phreatic line (where piezo-head = elevation) is projected to peak at approximately 10m below ground surface according to Figure 10. This temporary rise of phreatic line was much higher than the high water level as shown in Figure 6. During this typhoon period, there was a noticeable gradient of piezometric heads in vertical direction as predicted by the numerical simulations by Ng et al. (2000). This gradient is associated with the significant but transient seepage in the vertical direction resulted from surface infiltration. The lowering of piezo-heads as shown in Figure 11 was a much slower process than rising. The rain diminished on September 25 according to Figure 9. On September 28, just prior to another typhoon, the piezometric heads were still as much as 10m above the pre-typhoon readings.

5 CONCLUDING REMARKS

Real-time and profile monitoring of pore-water pressure are desirable in many ways. The readings reflect groundwater conditions more realistically especially when they are transient and non-hydrostatic. Experience gained at Five Turn Point shows that the interpretation of the standpipe readings assuming hydrostatic conditions can underestimate the rise of phreatic surface during heavy rainfalls. The cost and efficiency of multiple FBG piezometer installation can be further enhanced if using the fully grouted method (Contreras et al., 2008). The pore-water pressure profile measurements taken near the slope crest such as at NCTU03 are useful as the boundary conditions in seepage and slope stability analysis schemes. The information is valuable in enhancing our understanding of the slope failure mechanisms.

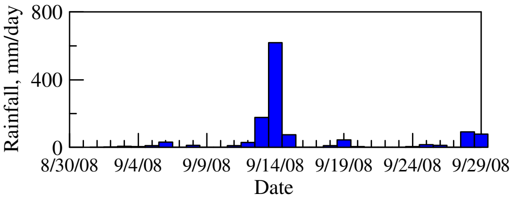

Figure 9 Daily precipitations at Five Turn Point.

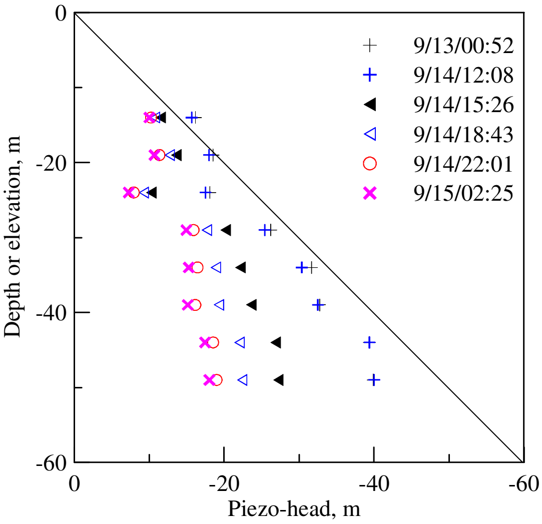

Figure 10. Rise of piezometric heads with time.

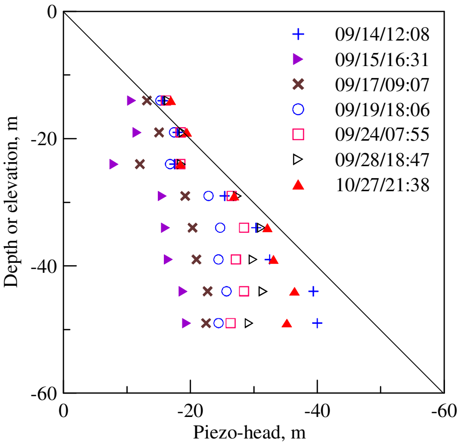

Figure 11. Lowering of piezometric heads after Typhoon Synlaku.

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