Piezocone testing applications for safety analyses of dams on stratified deposits

Valerie Michaud & Pierre-Alain Konrad
Groupe Qualitas Inc., Jonquière, Québec, Canada
Marc Smith & Eric Péloquin
Hydro-Québec, Montreal, Québec, Canada

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Des défis du Nord au Sud

ABSTRACT
Piezocone testing is largely used for dam foundation investigations. This sounding technique has shown satisfactory result in stratified deposit. For dam safety analysis, the main challenge remains the understanding of the groundwater conditions within the stratified deposits. The latter is assessed from dissipation test achieved within the sounding. This article presents two cases studies where piezocone testing (including dissipation tests) were performed in order to determine an accurate stratigraphy not only based on soil behavior but also on units having similar total head pressure.

RÉSUMÉ
Le piézocône comme outil d'investigation géotechnique est largement répandu pour les ouvrages de retenue. Cette technique s'est avérée utile pour l'investigation de dépôts fortement stratifiés. Dans ces cas, le défi demeure l'élaboration d'un modèle simplifié et représentatif du dépôt qui tient compte des conditions de l'eau souterraine. L'article présente deux cas où le piézocône (et les essais de dissipation) ont été réalisés afin de produire ces modèles.

1 INTRODUCTION

Since dams were built, new technologies are available as well as new safety standards. Thus, dams of a certain age require that their safety assessment be performed. In geotechnical practice, these analyses mainly concern slope stability which takes into account soil mechanics and groundwater conditions.

Hydro-Québec owns more than 650 dams located on Québec's province territory. A large amount of those structures were erected in the 60's and 70's. Considering new safety standard and historic data available (or the lack of), more accurate and specific data are required to assess those older dam safety. Since a significant part of dams have their foundations on soil deposits, modern geotechnical investigation tools such as piezocone penetration test (CPTu) has proven to be very effective.

CPTu sounding allows semi-continuous recording (each 2 to 5 cm) of three parameters (cone tip resistance, q_c, porewater pressure generated by the soil displacement, u, and friction along the probe's sleeve, f_s). Porewater pressure dissipation tests can also be performed when the cone penetration is stopped while sounding. Porewater pressure in excess is monitored along with the time required until the stabilized porewater pressure is reached in the soil deposit at a certain depth. Knowing this data, total head (H) corresponding to water pressure at a certain datum can be computed.

It is then useful, in highly stratified deposits, to regroup soil layers into units based on their mechanical properties but also with the same total head. Tributary groundwater conditions are thus highlighted with that method which otherwise difficult with boring exploration.

2 SITE # 1 – DAM - 2, BERSIMIS-2 HYDROELECTRIC COMPLEX

2.1 Site description and geology

Bersimis-2 hydroelectric development of the Bersimis complex, located approximately 70 km north of Forestville, Qc (figure 1), was built between 1956 and 1959. It includes three major retaining structures: Dam – 1, concrete Main Dam and Dam – 2 (figure 2).

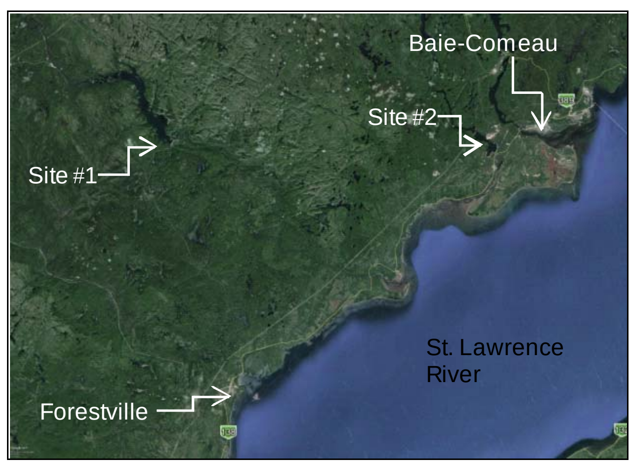

Figure 1. Site #1 and #2 locations

Dam – 2 is located on the right bank of the Betsiamites River. It is 1190 m long and its maximum height reaches 15.42 m.

The major part of the earthfill dam lies on a clay deposit overlying a sand deposit of high permeability.

Boreholes from 1980 indicate that the bedrock could be present at approximately 70 m depth.

As shown in figure 2, interesting features are present at the toe of the dam: lakes A and B and «Mille 45» creek.

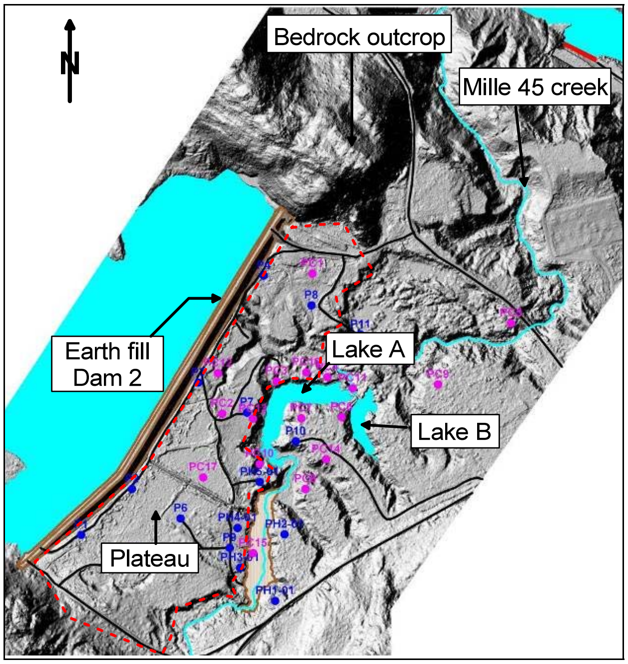

Figure 2. Dam 2 main features

As seen in figure 2, a plateau is present at elevation 126 m at the dam's toe. Bedrock outcrops on the dam left bank.

2.2 Problematic

Seepage exits have been observed at the toe of the dam for many years since operation debut. Water outlet appeared particularly along the Mille 45 creek upstream bank, in the erosion gullies and along the lake A bank's as well as from its bottom. Geophysics survey of groundwater flow paths showed evidence of horizontal flow underneath lake A along a north-south axis. These horizontal flows are related to the upstream reservoir.

In 2007, mitigation works consisting of a blanket of granular soil were done along the Mille 45 creek and in the upstream part of lake A in order to act as a filter for the seepage exits observed in these zones. Following these works, some seepage was still present in the vicinity of lake A and a new seepage exit was noted on the Mille 45 creek south bank. Moreover, a second phase of mitigation works was planned in order to lower the uplift porewater pressure in the underlying sand deposit using relief wells.

Geotechnical data available on the site was obtained from boreholes using «jetting» technique realized prior to the dam construction. In that case, soil description is based on soil cuttings. Therefore, those samples are remolded and distinction between homogenous and stratified deposit is hardly possible. Also, monitoring wells installed at this moment were installed prior to the filling of the dam reservoir, therefore prior increased porewater pressure. Since stratigraphy was not detailed enough back then and also because the purpose of this study was to select the installation depth of the relief wells, groundwater levels can hardly be related to particular soil strata.

2.3 Investigation program

Following Geophysics survey carried out in 2007, a geotechnical investigation program was developed in order to characterize soil deposits and groundwater conditions in the vicinity of lakes A and B and the two landslides.

Main objectives of the geotechnical investigation program were: prepare a detailed stratigraphy of soil deposits, measure pressure head varying with depth within the high permeability sand deposit underlying low permeability clay deposit, define more precisely the contact depths between these deposits and their thickness.

Geotechnical investigation results would also be used to design relief wells in order to reduce pressure head observed following the construction of the drainage blanket in 2007.

Considering these objectives, 17 CPTu soundings of depths from 17 to 48 m were completed in 2008. Following CPTu results, monitoring wells were installed in 7 boreholes to measure hydraulic head in the high permeability sand deposit. A total of 9 additional CPTu soundings were done in 2009, while 14 drive point piezometers were also installed. Porewater dissipation tests were then performed within sand layers while driving the piezocone. Figure 3 presents CPTu sounding for locations of interest.

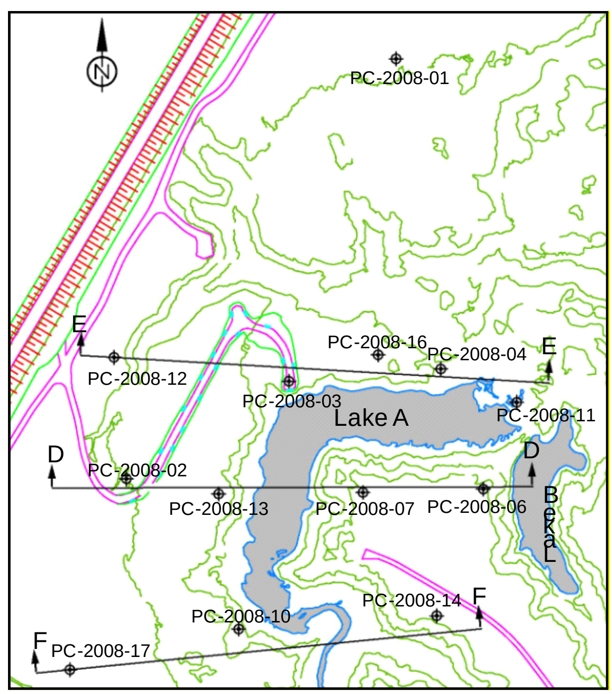

Figure 3. CPTu for locations of interest

2.4 Results interpretation

Following first CPTu sounding results (including more than 200 dissipation test results), stratigraphy and groundwater conditions were proven to be more complex than expected by the previous model (clay overlying sand deposit). For instance, figure 4 shows a typical CPTu log obtained in the dam foundation. As shown on this figure, the q_t line tends to show fewer resistance in cohesive soils (blue strata) while it shows sudden increase and then slight decrease in stratified deposit (green strata). In addition, the pore pressure line, u, (in pink) shows sudden increase in cohesive soil while it tends to show no increase in stratified deposit.

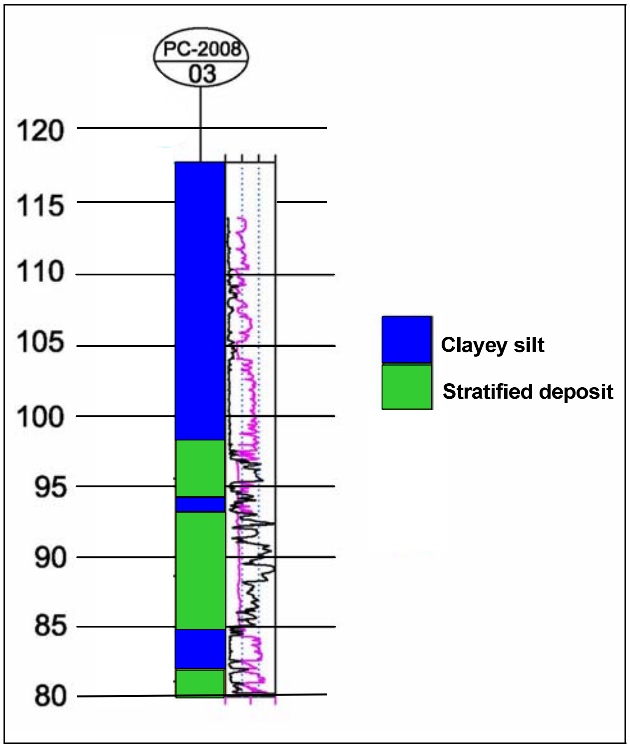

Figure 4. PC-2008-03 corrected tip resistance (q_t – black line) and porewater pressure (u – pink line) profiles and simplified stratigraphy

Stratigraphy varies both in horizontal and vertical directions. Pressure head values show the same variability. In that particular case, these values were calculated using dissipation curve shown in figure 5.

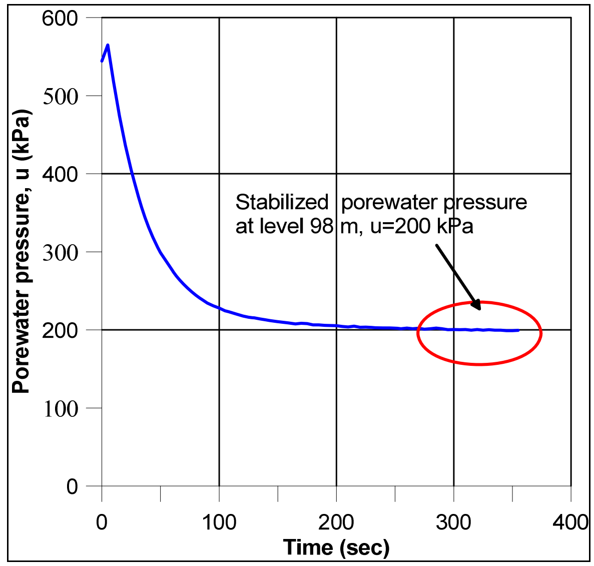

Figure 5. Porewater pressure dissipation curve at level 98 m in CPTu PC-2008-03

In the case of dissipation test presented in figure 5, porewater pressure at the beginning of the test was 570 kPa. After approximately 300 seconds (or 5 minutes), the porewater pressure decay was near 0 and its stabilized value was 200 kPa.

Stabilized porewater pressure shown in figure 5 is then expressed in terms of pressure head (h_p) as presented in table 1.

Table 1. Total head calculated from porewater dissipation test

Surface elevation (m)	Dissipa-tion test elevation (m)	Stabilized porewater pressure (kPa)	Pressure head, h_p (m)	Correspon-ding total head, H (m)
118.04	98	200	20	98+20 = 118

As shown in table 1, the corresponding total head in PC-2008-03 at 98 m in elevation is 118 m. For all CPTu soundings, pressure head values corresponding to stabilized porewater pressure have been calculated and then plotted. Figure 5 presents all the computed values for PC-2008-03.

For a specific soil layer, it appeared that the pressure heads were presenting a certain alignment. Then, these values were gathered into simplified units (clayey silt, stratified deposit or sand deposit) and a single pressure head value, expressed in term of total head (in reference to groundwater level) was assigned to each specific layer. As presented in figure 6, 3 different total head values were defined for PC-2008-03. Surface groundwater level and lake A bottom are also represented.

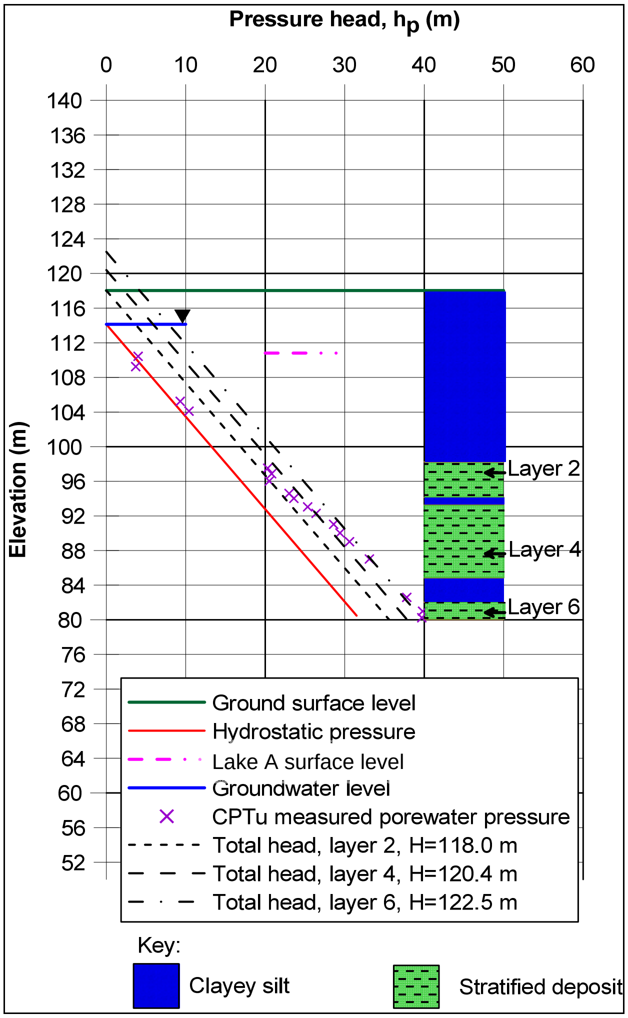

Figure 6. Pressure head values calculated for PC-2008-03 and simplified stratigraphy

From figure 6, it appears that total head values beneath the surface clayey silt deposit are located above the ground surface of 118.0 m and well above the bottom of the lake A.

Globally, deposits are not as homogenous as initially proposed. Thin layers of sand and silt are interbedded within the clay deposit and thin layers of clay are present in the sand deposit. Four main soil types are found: a clay deposit, a transition zone composed of alternating from silt to silty clayey sand to fine sand, a sand deposit and finally a till deposit. Moreover, total head values calculated for layers 2, 4 and 6 are higher than the hydrostatic pressure. Thus, upward hydraulic gradients ranging from 0.20 to 0.25 were measured in these layers.

Geotechnical investigation also shows that the clay deposit thickness is from 15 to 25 m and is found near the surface. It also appears to be thicker in CPTus located north of lake A while underlying granular layers (transition zone and sand deposit) top contact is shallower in the vicinity of the drainage blanket.

Moreover, pressure head values are higher in the latter than east from lake A.

Despite the complexity of the stratigraphy, the simplified model allowed to locate high permeability layers with total head above ground surface level. The model demonstrates that total head values were generally higher within deeper permeable layers. They tend to decrease from the dam toe towards the western side of lakes A and B and Mille 45 creek.

As previously mentioned, seepage exits were observed at the lake A bottom's and west bank and the west bank of Mille 45 creek. In these zones, porewater pressure generated by the reservoir within the sand layers created upward hydraulic gradients. As discussed by Smith (2012), the hydraulic pressure are acting in sand layers and may exceed downward pressure due to overlying clay in zones of minimal thickness. These zones are located in the vicinity of lake A and Mille 45 creek.

Thus, it was suggested to install relief wells into sand layers present in these zones as well. A total of 18 relief wells were built in 2009 along with vibrating wire piezometers next to them. The efficiency of relief wells was proven using monitoring data showed in figure 7. The piezometric levels in the sand layers decreased of more than 2.5 m (Smith, 2012).

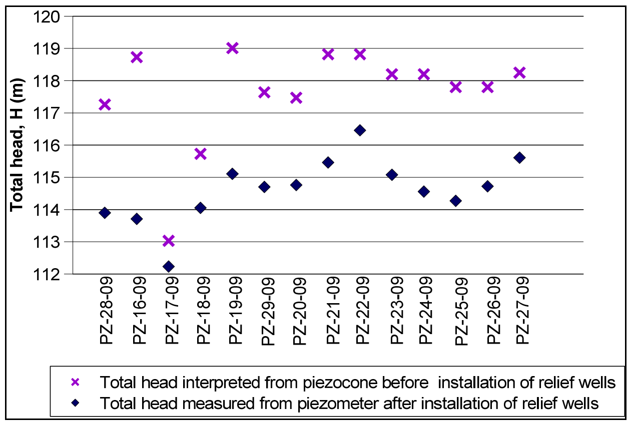

Figure 7. Relief wells monitoring data

3 SITE # 2 – EAST DAM, OUTARDES-2 HYDROELECTRIC COMPLEX

3.1 Site description and geology

Outardes-2 hydroelectric development on the Outardes complex is located on Outardes River, approximately 20 km south west of Baie-Comeau (figure 1). It was built in 1978 and includes three major retaining structures: West Dam, Main Dam and East Dam (figure 8).

East Dam impervious core consists of a compacted mix of sand and clay. Upstream and downstream slopes, of an inclination of respectively 2H:1V and 10H:1V, are made of sand and gravel fill. Maximum height of the dam is 30 m with of 3766 m in lenght.

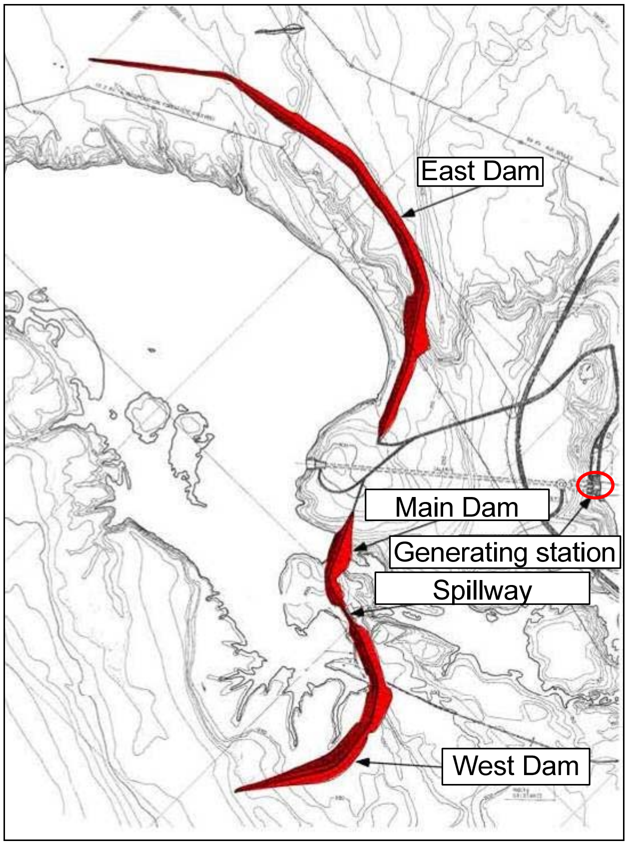

Figure 8. Outardes-2 hydroelectric development main features

According to historic data available, East Dam generally lies on a 40 m thick stiff and sensitive marine clay. Gneissic bedrock underlies the dam's clay foundation. In fact, since the dam is quite long, its foundation is more complex since it lies directly on bedrock on the east abutment, the central part lies on clay or silty sand deposit and the left abutment lies on a peatland. Figure 9 shows detailed view of East Dam foundation.

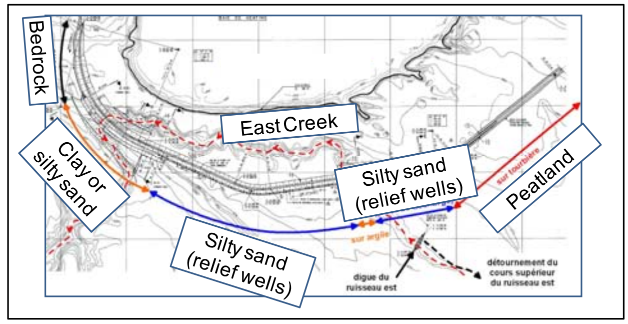

Figure 9. East Dam main features

As shown in figure 9, relief wells were installed in 1978 in sections of silty sand foundation in order to reduce porewater pressure at the toe of the dam.

3.2 Problematic

In the course of a dam safety analysis, Hydro-Québec wanted to outline the nature and geotechnical properties (both static and dynamic) of the dam foundation overlying the silty sand deposit. The specific zone consists of a 1000 m long and 75 to 125 m wide quadrangle located at the dam's toe.

Geotechnical investigation was also intended to specify groundwater conditions for the concerned area.

3.3 Investigation program

Geotechnical investigation program consisted of completing 12 CPTu sounding from 9 to 53 m in depth (amongst 8 of them, shear wave velocity measurements were performed - sCPTu) and two geotechnical boreholes of 25 and 49 m depth (including SPT-N values in granular soils and vane testing in cohesive soils). CPTus and boreholes were located along two longitudinal sections located at 75 and 125 m offset downstream from the dam's center line. Multilevel piezometers were installed in both boreholes. Figure 10 shows CPTu testing and borehole locations.

3.4 Results interpretation

Geotechnical investigation results revealed a more complex stratigraphy and groundwater conditions than anticipated. As found in Bersimis D-2 dam, highly stratified deposit is present in the investigation zone and variability is observed in both horizontal and vertical directions.

The same methodology was therefore used in order to identify four main soil types: a coarse sand to gravelly sand deposit, a stratified deposit alternating thin beds of sandy clayey silt and silty sand, a second stratified deposit alternating low plasticity clay and clayey sandy silt. Figure 11 shows simplified stratigraphy on the 2 longitudinal sections located 75 and 125 m offset downstream from the dam's center line within the investigation zone.

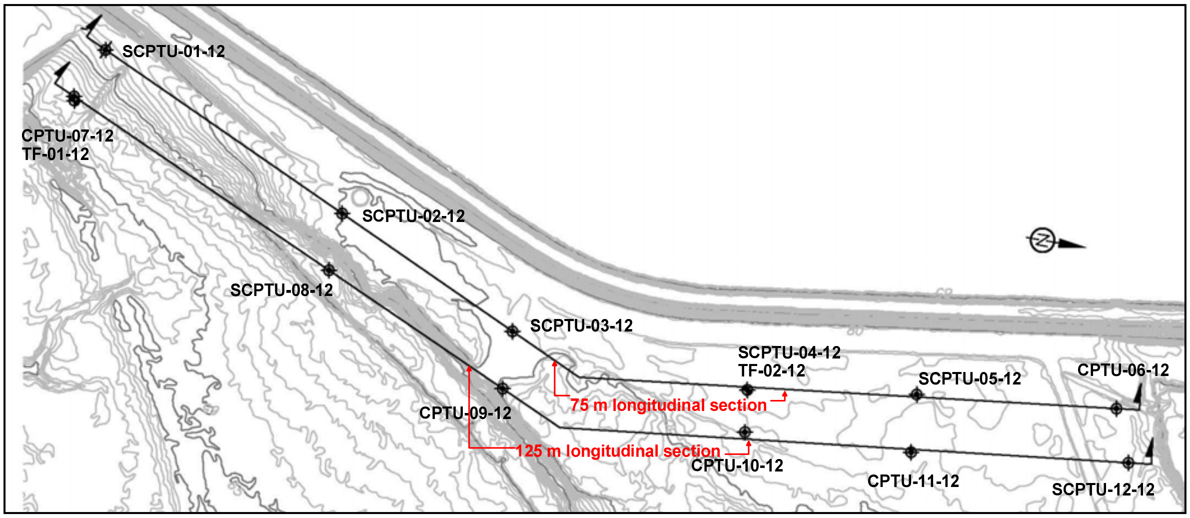

Figure 10. CPTu, borehole and longitudinal section locations in Outardes-2 East Dam

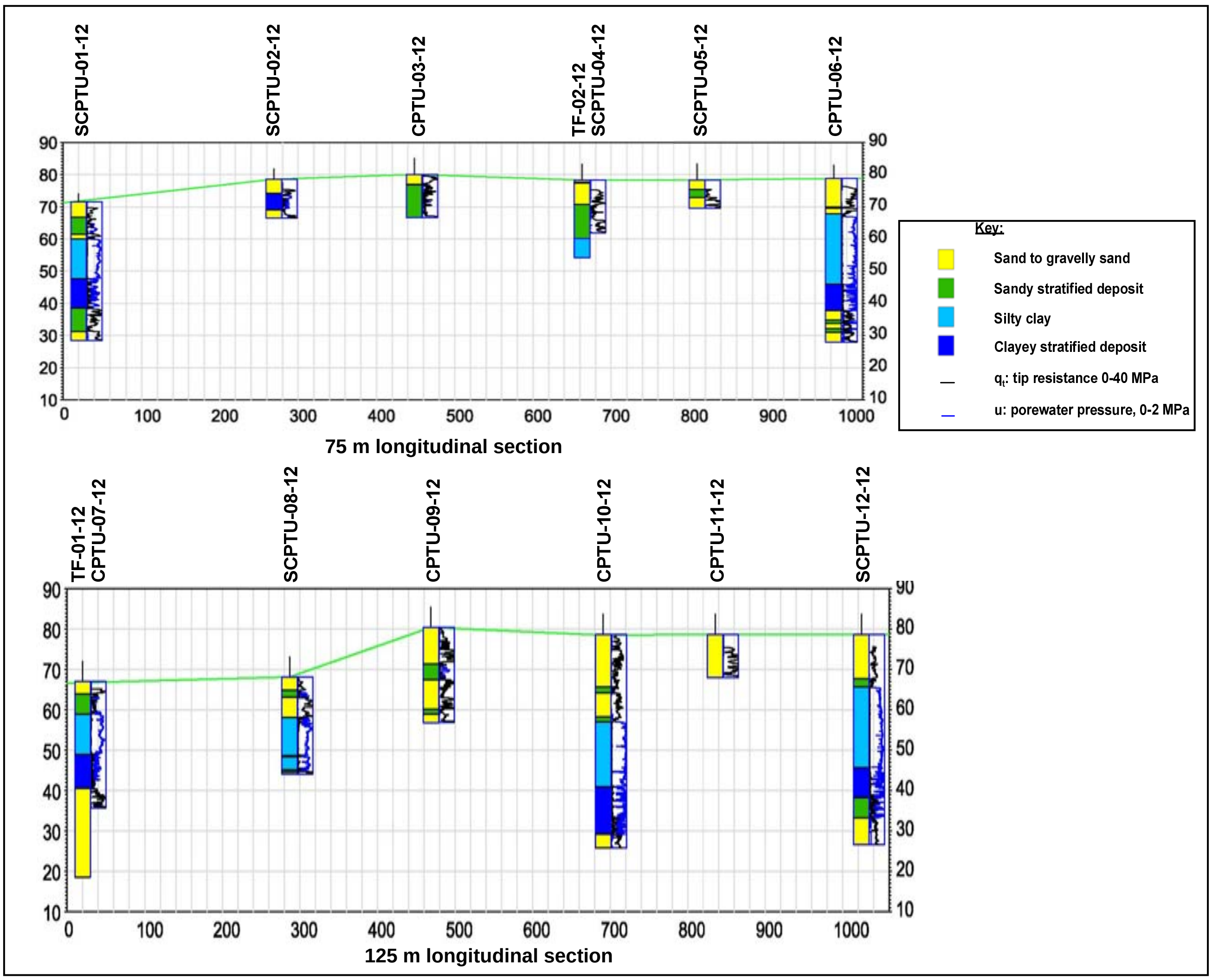

Figure 11. Geotechnical investigation results

The presence of the 4 deposits varies significantly from one CPTu to another as shown in figure 11. Generally, coarse sand to gravelly sand deposit is found near the surface overlying the sandy to silty stratified deposit. Cohesive soils (including both stratified clayey and clayey sandy silt deposits) are present in most of the CPTUs between 60 and 40 m in elevation. Then, additional granular deposits are found upon penetration refusal. Moreover, CPTu refusals tend to be shallower in the center part of the investigation zone than for those located near the south and the north boundaries.

Then, pressure head values measured with porewater dissipation tests allowed to compute total head within permeable layers. The same method as previously presented in table 1 was used. Figure 12 presents total head values plotted versus elevation for Outardes-2 East Dam.

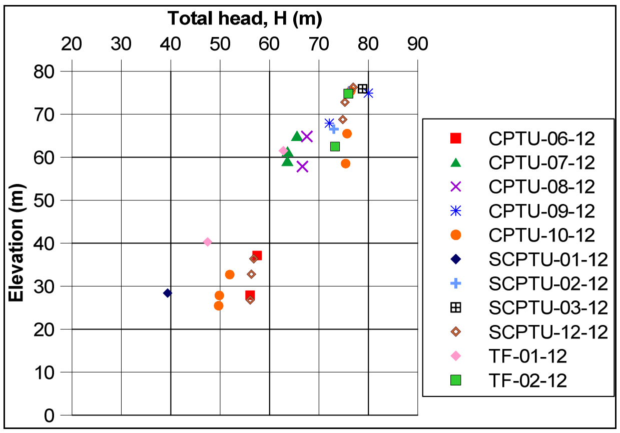

Figure 12. Geotechnical investigation results

The gap between elevations 60 to 40 m corresponds to the cohesive soils deposits (silty caly and/or clayey stratified deposit). Values measured in the sandy layers located at 65 m of elevation tend to show an average pressure head of 10 m (total head value of 75 m) while values measured at 30 m of elevation show an average pressure head of 20 m (total head value of 50 m). From these results, it appears that a downward hydraulic gradient is present within the investigation zone. This hydraulic gradient is about 0.5 m/m. It is then assumed that the decrease of hydraulic pressure is made in the cohesive soil layers present between elevations 60 to 40 m.

4 CONCLUSION

The cases studies of Bersimis-2 D-2 Dam and Outardes-2 East Dam show that the use of piezocone sounding allowed more accurate ground investigations. In both cases, the investigations were successful at showing tributary groundwater conditions in highly stratified deposits. The relevant groundwater conditions were obtained from dissipation test carried out while sounding in permeable layers. In order to dress a realistic soil model, it is recommended to run many dissipation tests within the same sounding in order to merge highly stratified deposits into same total head units. In Bersimis-2, the groundwater conditions were used to select the appropriate depth to install relief wells while in Outardes-2, the better understanding of the seepage conditions under East Dam will greatly improve the adequacy of the seismic stability assessment of its foundation.

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