Using CPT to refine subsurface characterization for a subway project

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ABSTRACT: The San Francisco Bay Area Rapid Transit (BART) Warm Springs Extension (WSX) includes a segment of project referred to as the Fremont Central Park Subway Project, which involves an approximately 2.3-km-long alignment of cut-and-cover structure. Following the preliminary subsurface geotechnical investigation mainly using auger borings, three phases of CPT investigations comprising 50 CPTs with depths ranging from 9.8 to 29.6 m (32 to 97 feet) were performed between 2002 and 2007. Downhole seismic shear wave velocity measurements were also performed in 4 CPTs and dissipation tests were conducted in 8 CPTs. This paper describes how the CPT investigations have significantly refined the subsurface characterization, supplemented the boring data, been used to evaluate the extent of the potentially liquefiable soils, and for geotechnical design and construction considerations. Selected CPT results are also presented and discussed.

1 INTRODUCTION

The BART WSX will extend BART service south along an 8.7-km-long corridor from the Fremont Station to just north of Mission Boulevard in the city of Fremont, California. This extension will include a proposed Irvington Station and a Warm Springs Station. The segment of BART WSX project referred to as the Fremont Central Park Subway project involves an approximately 2.3-km-long alignment which cuts through South Tule Pond and Fremont Central Park (Figure 1). The project begins just south of Walnut Avenue, crosses through South Tule Pond and under the Fremont Central Park, and ends north of Paseo Padre Parkway. The alignment will consist of fill embankments over South Tule Pond and a subway box with transition structures at the north and south subway portals.

Following the preliminary subsurface geotechnical investigations mainly using auger borings until 2002, three phases of CPT investigations with a total of 50 CPTs were performed between 2002 and 2007. The CPTs have significantly supplemented the boring data and refined the subsurface characterization as described in this paper. In addition, the CPT data was used for evaluation of the lateral extents of potentially liquefiable soil layers. Selected CPT results are also presented and discussed.

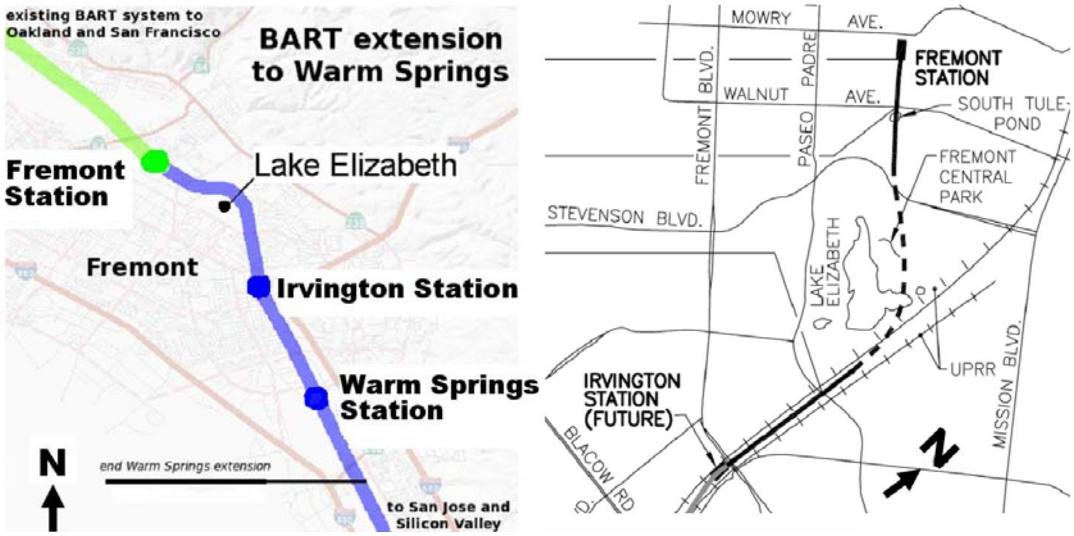

Figure 1. Project location and alignment

2. LOCAL GEOLOGICAL CONDITIONS

The WSX alignment is located on the San Francisco Bay plain, which is composed primarily of alluvial deposits ranging 150 to 300 m in thickness. The subway alignment is underlain by Holocene age alluvial fan and basin deposits. In general, four soil units have been indentified for the subsurface along the subway alignment; i.e., Fill (mainly consisting of silty clay), Young Alluvium (consisting primarily of clays, with medium dense silty sand and sandy silts), Basin Deposits (consisting of soft to firm clays, organic clay and loose to medium dense silts) and Older Alluvium (consisting primarily of dense sand and gravels). The Basin Deposits only exist near Lake Elizabeth. The depth to water table along the subway route has ranged from 4.6 to 10 m (15 to 33 feet) in recent years.

3. FIELD EXPLORATION PROGRAMS

Several boring exploration programs and three phases of CPT investigations were conducted along the subway project alignment, as summarized in Table 1. The boring investigations were conducted between 1989 and 2002 and included a total of 28 rotary-wash, hollow or solid stem auger borings. This information was used to establish preliminary subsurface conditions for the project.

Table 1. Summary of Boring and CPT investigations

Item		No. of Holes	No. of Seismic Tests	No. of CPTs with Pore Pressure Dissipation Tests	Year Performed	Approx. Depth (ft)	
						From	To
Boring		28	-	-	1989 - 2002	16	102
CPT	Phase 1*	24	4	-	2002	32	97
	Phase 2**	11	-	6	April 2007	47	56
	Phase 3***	15	-	2	July 2007	49	53

* CPT-1 to CPT-18 and CPT-W1 to CPT-W6. ** CPT-19 to -27, -29 and -30 (CPT-28 was not advanced due to existing utility conflict). *** CPT-31 to -32 and -34 to -46 (CPT-33 was not attempted due to time constraint). Note: 1 m = 3.28 feet.

A total of 24 CPTs were conducted for the project in 2002. Continuous readings of cone tip resistance, sleeve friction, and pore pressure were digitally recorded. Downhole seismic shear wave velocity measurements were performed in 4 CPTs (CPT-15 through CPT-18). The seismic CPT system includes the basic thrust system, a seismic cone assembly, a seismic wave source, and a digital recording seismograph. Seismic data were acquired to as great a depth as practical or until refusal was reached. The seismic CPT depths ranged between 10.4 and 22.6 m (34 and 74 feet).

In April 2007, a phase 2 CPT investigation comprising 11 CPTs were completed. All locations except CPT-22 were hand-augered to a depth of 1.5 m to ensure clearance of shallow underground utilities before penetration of the CPT probe. The CPT soundings provided depths to the contact between the Young and Older Alluvium along the proposed alignment.

In July 2007, a phase 3 CPT investigation comprising 15 additional CPTs were conducted to further define the Young/Older Alluvium interface in the vacant unlandscaped area immediately north of Lake Elizabeth. The penetration depths of these CPTs extended a few feet into the Older Alluvium.

Dissipation tests were conducted in 8 of 26 CPTs of phases 2 and 3 investigations at depths between 6.1 and 16.2 m (20 and 53 feet), as summarized in Table 2. The duration of dissipation tests ranged from five minutes in sandy material to two hours in fine-grained material. Results of the dissipation tests are discussed in Section 5.

Table 2. Summary of CPT dissipation tests

CPT No.	Total Depth (ft)	Test Depth (ft)	Estimated GWT Depth (ft)	Soil Type	Test Duration (minute)
CPT-20	50.2	40.0	23.1	Silty Sand	10
		45.0	---	Sand	15
CPT-22	50.2	40.0	21.0	Sand	10
CPT-23	48.6	47.0	21.8	Sandy Silt	40
CPT-26	53.2	47.0	21.5	Silt	22
		50.0	21.5	Sand	9
CPT-29	56.1	22.0	2.5	Silty Clay	120
		37.0	8.0	Clayey Silt	120
CPT-30	55.8	20.0	5.0	Silt	30
		55.8	24.2	Silty Sand	4
CPT-40	49.2	49.2	20.4	Sand	5
CPT-45	53.2	53.2	20.9	Sand	5

Note: 1 m = 3.28 feet.

4. REFINEMENT OF SUBSURFACE PROFILE BASED ON CPT RESULTS

Based on the results of the boring explorations and the Phase 1 CPT investigation, a preliminary subsurface profile was developed for the project alignment. The area near the north of Lake Elizabeth has the most complex subsurface conditions, as presented in Figure 2, which comprises a layer of basin deposits within the Young Alluvium. The profile also indicates that the contact between the Young and Older Alluvium generally drops towards the Lake.

The results of Phase 2 CPT data were reviewed with respect to the preliminary geologic profile. Plotting of Phase 2 CPT data on the geologic profile reduced the spacing between CPTs/borings and resulted in some significant changes to the contact between Young and Older Alluvium, particularly in the area between well WSX-

B8-M and Lake Elizabeth. Thus, additional CPT (i.e. the Phase 3 CPT) were performed in July 2007 between WSX-B8-M and Lake Elizabeth to ensure that the geologic contact between Young and Older Alluvium was well defined in this transition area where the contact depth is increasing towards the lake. Figure 3 shows the geologic profile after incorporating the Phase 2 and Phase 3 CPT results, which have refined the geologic contact between the Young and Older Alluvium north of the lake.

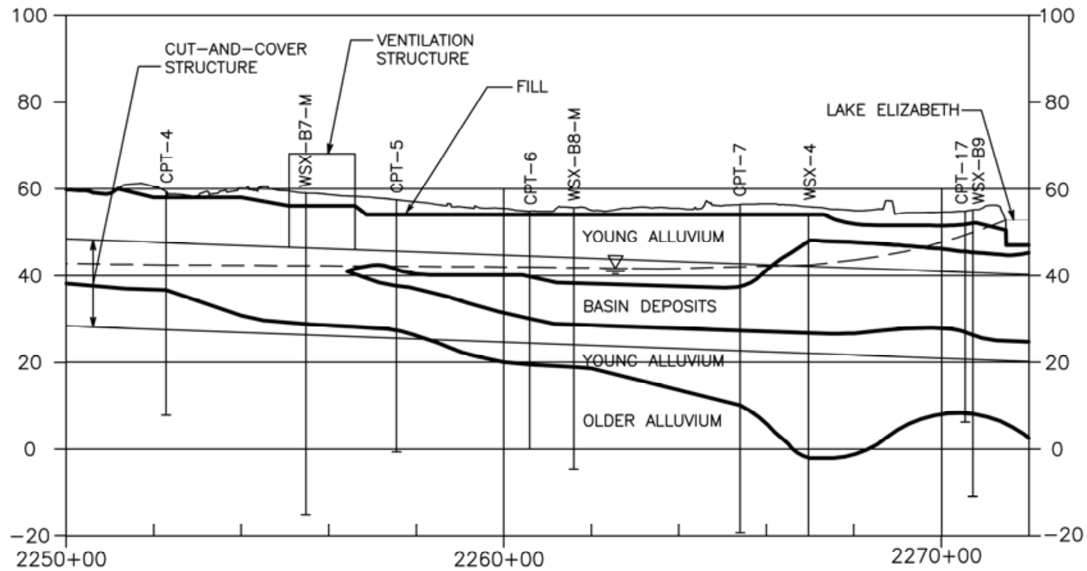

Figure 2. Inferred geologic profile near north of the lake based on borings and Phase 1 CPT investigation. (Note: vertical axis is elevation in feet and horizontal axis is station number in feet)

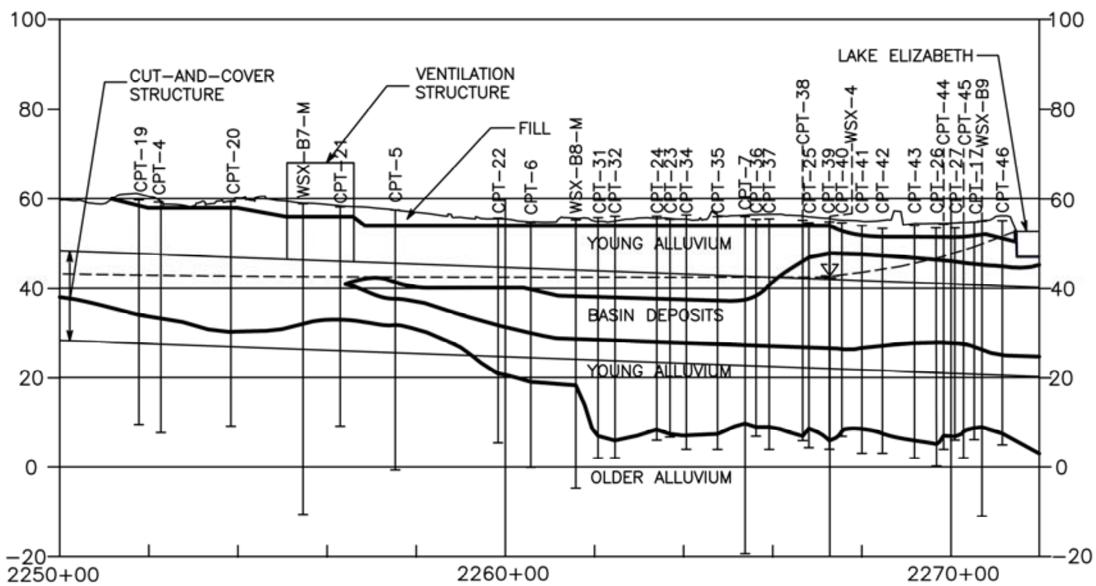

Figure 3. Inferred geologic profile near north of the lake updated with Phases 2 and 3 CPT investigations. (Note: vertical axis is elevation in feet and horizontal axis is station number in feet)

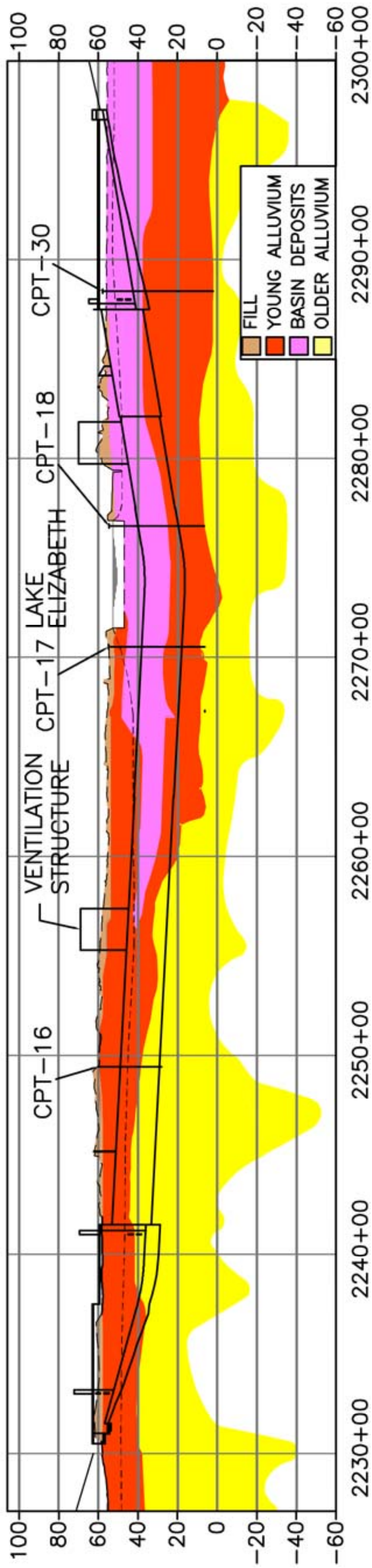

Figure 4. Inferred geologic profile for the subway alignment. (Note: vertical axis is elevation in feet and horizontal axis is station number in feet)

The final geologic profile for the entire subway alignment is depicted in Figure 4, which incorporates the portion of the profile shown in Figure 3. As indicated in Figure 4, the contact between Young and Older Alluvium are relatively shallow from the beginning of the subway alignment to the ventilation structure, and becomes relatively deep from the ventilation structure to the end of the subway alignment. The Basin Deposits were only encountered from near the ventilation structure to end of the subway alignment. The Basin Deposits, with a maximum thickness of about 9.1 m (30 feet), are sandwiched by the Young Alluvium at north side of the lake, but are only underlain by the Young Alluvium at south side of the lake.

5. SELECTED CPT RESULTS AND DISCUSSIONS

The CPT results have mainly been used for the interpretation of the subsurface conditions and development of the geologic profile. Details of some of the CPT results are presented and discussed in this section.

5.1 Selected CPT results

Results of representative CPTs (CPT-16, -17 and -30) are presented in Figure 5. CPT-16 is located about 91.5 m (300 feet) north of the ventilation structure; CPT-17 is located near Lake Elizabeth; and CPT-30 is located at the south portal (Figure 4). Results of CPT-16 clearly indicate the distinction between the Young Alluvium and the Older Alluvium at the depth of about 6.7 m (22 feet). The tip resistance (qt) ranges from 0 to 80 tons per square foot (tsf) and from 100 to larger than 400 tsf in the Young Alluvium and the Older Alluvium, respectively. The skin resistance (fs) ranges from 0 to 4.5 tsf and from 0.6 to 4.0 tsf in the Young Alluvium and the Older Alluvium, respectively. Results of CPT-17 suggest the thickness of the Fill is about 1 m as indicated by the qt and fs values that are significantly higher than the immediately underlying soil. The distinction between the Young Alluvium and the Older Alluvium is also evident, as can be seen from the dramatic increase in qt and fs at the depth of about 14.0 m (46 feet). CPT-30 also clearly distinguishes the Young Alluvium from the Older Alluvium at the depth of about 15.2 m (50 feet). However, both CPT-17 and CPT-30 could not definitely determine the contacts between the Young Alluvium and the Basin Deposits; the contacts were based more on the nearby borings.

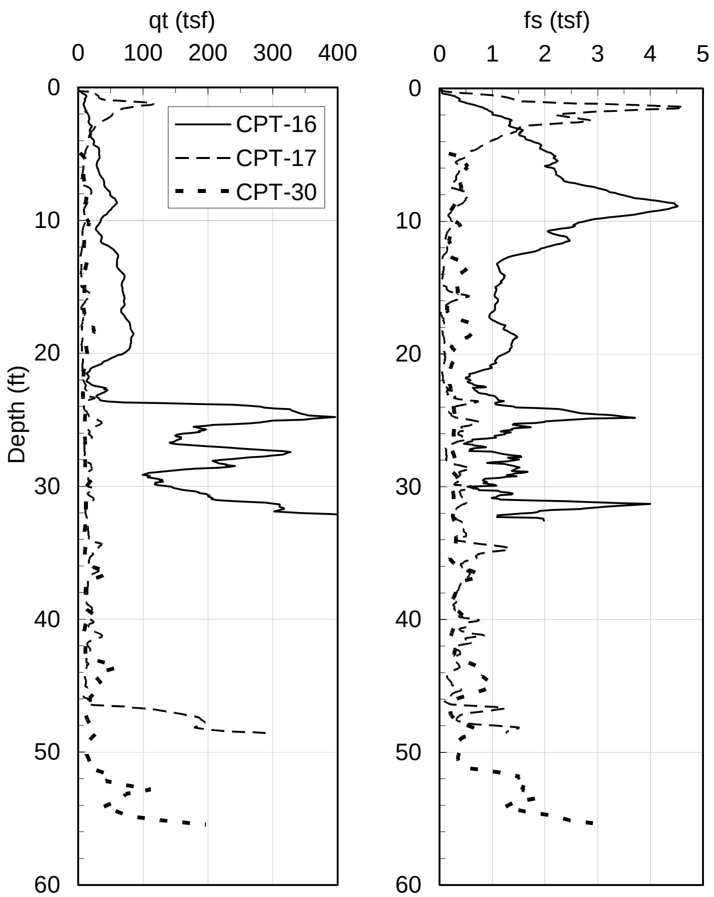

Figure 5. Logs of selected CPT soundings

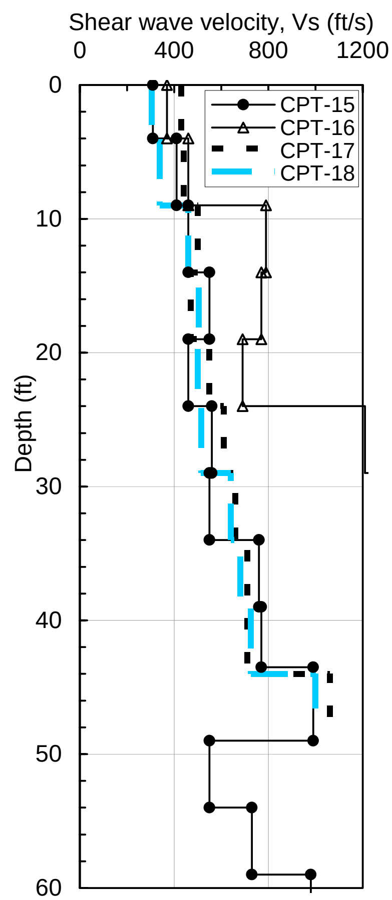

Figure 6. Vs profiles

5.2 Seismic shear wave velocity

The profiles of the shear wave velocity (Vs) performed in 4 CPTs are presented in Figure 6. These profiles are consistent with the corresponding CPT profiles (Figure 5) and the interpreted geologic profile (Figures 3 and 4). The Vs profiles clearly indicate the depth of the contact between the Young and Older Alluvium. The depths of the contact and the ranges of Vs as interpreted for the Vs profiles are summarized in Table 3. However, similar to the qt and fs profiles of CPTs, the Vs profiles for the Basin Deposits and Young Alluvium as encountered in CPT-17 and CPT-18 are not distinctive.

Table 3. Summary of interpretation of shear wave velocity results

CPT No.	Approx. Depth to Top of Older Alluvium	Vs in Young Alluvium/ Basin Deposit (ft)	Vs in Older Alluvium (ft)
CPT-15	44	320 - 780	550 - 1,320
CPT-16	22	360 - 790	680 - 1,600
CPT-17	44	440 - 760	>760
CPT-18	44	320 - 720	>720

5.3 Selected CPT dissipation test results

CPT dissipation tests provided estimated depths to groundwater as reported in Table 2. In general, the tests indicated depths to groundwater ranging from about 6.4 to 7.3 m (21 to 24 feet). However, the testing at CPT-29 and CPT-30 indicate possible perched groundwater. A total of four dissipation tests were performed at CPT-29 and CPT-30, as reported in Table 2. Three of the tests were performed in Young Alluvium at depths ranging from about 6.1 to 11.3 m (20 to 37 feet), and the fourth test was performed in Older Alluvium at the depth of 17.0 m (55.8 feet). The tests in the Young Alluvium indicated groundwater depths as shallow as about 0.8 to 2.4 m (2.5 to 8 feet), whereas the test performed in the Older Alluvium indicated groundwater at the depth of 7.4 m (24.2 feet). The shallow groundwater levels measured in the Young Alluvium may have been influenced by rain that had occurred prior to the testing, as well as being influenced by the surface water elevation in Lake Elizabeth.

Pore pressure versus time for selected dissipation tests are presented in Figure 7. It can be seen that it takes much longer time for the pore pressure to dissipate (or to reach equilibrium) in fine-grained soil (as the two tests at CPT-29) than in coarse-grained soil (such as the two tests at CPT-26), as expected. The time to achieve 50 percent dissipation was correlated with soil permeability using the recommendations by Robertson et al. (1992). However, the dissipation tests can provide a rough estimate of permeability in fine-grained material, but are not considered reliable for permeability estimates in coarse-grained material. Therefore, permeability values for tests run in coarse-grained sediments of the Older Alluvium were not estimated. The correlation indicates that the permeability of the Young Alluvium at locations CPT-29 and CPT-30 is between about 10^{-9} and 10^{-6} cm/s.

6. FURTHER APPLICATIONS OF THE CPT RESULTS

Liquefaction analyses based on the CPT data were performed using the method as recommended in the 1996 NCEER and 1998 NCEER/NSF Workshops (Youd et al. 2001). A design ground motion resulting from a magnitude 7.1 earthquake with a peak ground acceleration of 0.75g was assumed. The results of liquefaction evaluations indicate potentially liquefiable layers were encountered in the northern half of the subway alignment. However, these potentially liquefiable layers are deep below ground surface and are confined and localized in nature. They are expected not to impact the below-grade structures. The southern half of the subway alignment generally has a low to very low liquefaction potential.

Due to the presence of an aquifer used by the local municipal water agency for storage and recharge, it was BART's intent to minimize the impact on the aquifer by not dewatering during construction of the subway box. Water-tight walls with a bottom jet-grout plug were specified to limit the amount of groundwater entering the excavation. Two types of walls were selected, cement deep soil mix (CDSM) and conventional sheet piling. Conventional sheet piles were selected where the soils are generally cohesive while CDSM was selected in areas where the soils are gravelly. Information collected from the Phase 2 and 3 CPT investigations allowed the interface between the CDSM and sheet piling to be shifted north to Station 2264+00. In addition, the CPT data provides valuable information to the jet grouting subcontractor on the location of the Young Alluvium (cohesive) to Older Alluvium (non-cohesive soils) interface.

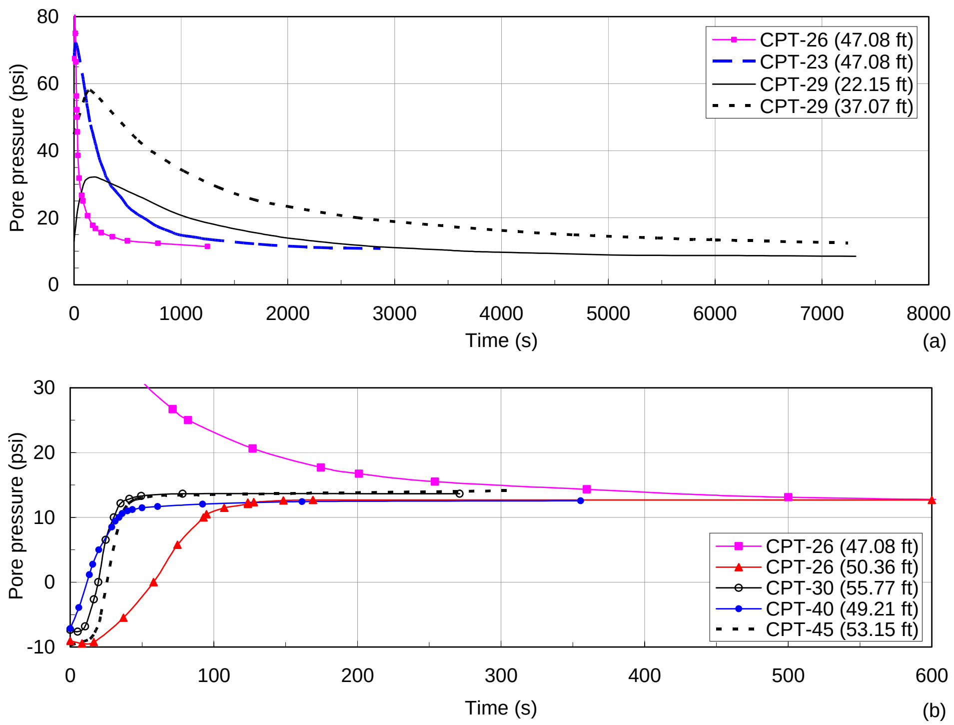

Figure 7. Pore pressures versus times for selected dissipation tests. (Note: result of CPT-26 at 47.08 ft is plotted in both Figures 7(a) and 7(b) for comparison. 1 psi = 6.89 kPa.)

7. SUMMARY AND CONCLUSIONS

Three phases of CPTs were performed on the subway project alignment and the results considerably refined the subsurface characterization. The CPT data was also used for liquefaction potential evaluations and geotechnical designs and construction consideration.

8. ACKNOWLEDGEMENTS

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9. REFERENCES

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