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Review of In Situ Measurements as Indications of Liquefaction Potential at Numerous Sites

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REVIEW OF *IN SITU* MEASUREMENTS AS INDICATIONS OF LIQUEFACTION POTENTIAL AT NUMEROUS SITES

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ABSTRACT

Current practice for assessing liquefaction potential of granular soils depends heavily on *in situ* indices of density, and sometimes direct measurements of density. Correlations have been developed to predict resistance to liquefaction as a function of standard penetration test (SPT) blow count, cone penetrometer (CPT) tip resistance, shear-wave velocity (V_S), or other index property. Recognizing that each correlation entails its own uncertainties, and that different indices of liquefaction potential may provide conflicting conclusions, the Bureau of Reclamation reviewed *in situ* test results from a large number of sites where multiple tests had been used. The goals were to 1) evaluate consistency among the various indices of liquefaction potential, 2) compare indirect indices of density, such as penetration resistance, against actual density measurements, and 3) survey current practice throughout the industry. This paper will provide a summary of the results.

INTRODUCTION AND PURPOSE

It has been more than 30 years since the near-failure of the Lower San Fernando Dam in California, an event that more than any other brought widespread attention to the potential for liquefaction-induced failure of embankment dams. Modern methods for predicting liquefaction susceptibility began with H. Bolton Seed and colleagues in the early 1970s. Further research has led to the variety of tools that the practitioner now has available for evaluating the potential for liquefaction or loss of strength from cyclic loading by an earthquake. That potential is governed primarily by the density of the soil, and indeed, liquefaction resistance can be correlated with relative density. (Seed and Idriss, 1971, Seed and Peacock, 1971) However, that requires either measurement of density in place in dewatered excavations, or on truly undisturbed samples, or estimation of the relative density using an *in situ* test such as the SPT.

Because of the difficulty of direct measurements in place or on undisturbed samples of loose sands, most of the methods in use today are empirical correlations combining field performance and *in situ* test data to indirectly indicate the density. The most widely used of these are the standard penetration test (SPT), the cone penetrometer test (CPT), the Becker hammer penetration test (BPT), and the shear-wave velocity (V_S). Only minimal description of the test methods is provided here. The report of 1996 NCEER Workshop on Evaluation of Liquefaction Resistance of Soils provides an excellent description of the test procedures and their use in liquefaction assessment. (Youd *et al*, 1997)

The study described herein was motivated by the recognition that there is considerable uncertainty in conclusions from any of the empirical methods in use today, and that different methods often give conflicting results at a site. (Reclamation, 2007) With the exception of the BPT, the correlations to predict liquefaction resistance take the form of boundaries between materials that were liquefied by the level of seismic loading that they experienced, and those that were not. The boundaries are considered approximate because the developers of a correlation do not have precise knowledge of the earthquake loading that occurred at each site, the material properties, and even exactly which strata were liquefied by the earthquake. In some cases, the *in situ* data had to be estimated rather than measured, and for almost all, the cyclic shear stresses were estimated by very simple means, or by response analysis using ground motions recorded nearby but with different foundation conditions.

APPROACH FOR THIS STUDY

Although the empirical methods used for assessing liquefaction potential were generally developed from large numbers of case-history data from major earthquakes, that fact does not prove that they are able to predict liquefaction potential well. Ideally, they would be tested by a large number of what T.W. Lambe termed "Class A" predictions, meaning those where the result is predicted prior to the earthquake. The next best thing would be post-earthquake blind studies, in which a skilled engineer who does not know the outcome would use the methods to predict whether liquefaction has occurred at a number of sites that were *not* used in the development of the correlation. Unfortunately, blind studies would be very time-consuming, and only one Class A prediction was located in the literature search for this project. This leaves comparisons of indices of relative density (e.g. CPT and SPT) to actual measured densities, and comparisons among indices for consistency. While density is not a direct indication of liquefaction potential, it is closely related. While consistency does not necessarily show that the measurements provide an accurate prediction of liquefaction potential, it would increase our confidence that the materials are being characterized correctly.

The writer and other Reclamation engineers gathered data from a large number of sites where multiple methods for liquefaction assessment had been applied by Reclamation, other government agencies, or consultants. The most desirable sites were those where two or more techniques had been used in very close proximity to each other, so the test data would be measured in the same materials. Side-by-side comparisons showed which indices agreed most consistently with in-place density measurements, and which were in general agreement on liquefaction potential. To the extent that they were developed independently, consensus among indices would allow greater confidence in a conclusion. Where possible, comparisons were made only between tests physically very close to each other so the actual properties of the materials should be similar. It is recognized that judging the quality of agreement among tests is subjective.

Although this paper was motivated by the need for liquefaction assessment, it does not address the procedures for doing so. Instead, it is focused on the various *in situ* tests that are most used in liquefaction assessments as indices of density (which is the primary factor in liquefaction potential). The only methods studied were related to the density of granular soils, excluding, for example, the use of Atterberg limits to assess liquefaction potential.

TEST METHODS EVALUATED

All of the test methods studied are described in detail in the 1997 National Center for Earthquake Engineering Research report (Youd *et al*, 1997), based on compilation of published research and extensive discussion among leading researchers and practitioners in earthquake geotechnical engineering. Only very brief descriptions are provided here.

Standard Penetration Test (SPT)

In the United States, the SPT has been the "workhorse" of test methods for estimating liquefaction resistance beginning in the 1970s, when it was found to be a practical basis for correlation. (Seed *et al*, 1975a) Liquefaction resistance appears to correlate at least as well with the SPT as it does with relative density, and it is much easier and less costly to obtain SPT data than it is to measure the relative density of a soil deposit, particularly one below the water table. The test consists of driving a standardized sampler in a drill hole, using a 140-lb drop hammer falling 30 inches. The sampler is driven 0.5 ft into the bottom of the hole to seat the tip below the most disturbed soil in the bottom of the hole, and then the blows are counted as it is driven the next 1.0 ft. The number blows is called "N," and is controlled primarily by the density of the material being tested. Empirical correlations are used to estimate the soil's resistance to liquefaction. (Seed and Idriss, 1971; Youd *et al*, 1997) However, "N" is not the whole story. For a given soil and relative density, the blow count varies with the confining stress and the amount of energy transmitted to the drill string by the hammer. Adjustments to standard conditions of 1 ton/ft^2 of effective overburden stress and 60 percent of the theoretical energy of the hammer are made by empirical factors. The result, called $(N_1)_{60}$, is then used as the independent variable in the correlation for liquefaction potential. Further adjustments are needed for energy transmission in very deep or very shallow tests, whether a liner is used in a sampler with space for one, and even the diameter of the drill hole. (Refer to the NCEER report for details, including the empirical adjustments.) Each adjustment in the process is needed because of some aspect of the test that affects the value of N that is measured for a given relative density (or given level of resistance to liquefaction), and each introduces some additional uncertainty in the estimate of cyclic resistance.

Cone Penetrometer Test (CPT)

The cone penetrometer apparatus consists of a conical tip, usually having a diameter of 3.6 cm and a projected area of 10 cm^2, and a cylindrical sleeve behind the tip. The tip and the sleeve are both equipped with load cells to measure the resistance to penetration. The penetrometer is pushed steadily into the ground, usually by hydraulic jacks, while the tip and sleeve load-cell readings are recorded electronically. Liquefaction resistance is then inferred from the tip resistance (adjusted for overburden pressure as is done for the SPT) which reflects the density, and the sleeve friction as an indicator of soil type. (Youd *et al*, 1997; Moss and Seed, 2004) Modern cones are usually equipped with pore-pressure transducers, which can highlight material that generates high excess pore-water pressure when sheared. The CPT allows a large amount of data to be gathered very quickly and at low cost compared to the SPT, and it lacks the SPT's issues with standardization and energy transmission through the rods by stress waves. When the soils are suitable (not containing too much gravel for valid readings and not including layers that are too dense or stiff for the cone to penetrate), the CPT is often the preferred method. The biggest drawback of the CPT relative to the SPT is that it does not retrieve a sample like the SPT does. Soil characteristics must be inferred indirectly from the tip and sleeve resistance and the pore-pressure response, or with sampling holes drilled next to selected CPT sites.

Becker Penetration Test (BPT)

In gravelly soils, both SPT and CPT can measure penetration resistance that is "too high," i.e., greater than what would be measured with the same relative density and liquefaction resistance, but without the gravel. The inside diameter of the SPT sampler is only 1 3/8 inches (35 mm), and the diameter of the cone penetrometer is approximately the same. Gravel as small as one third of those diameters, and possibly smaller, can interfere with the penetration. This causes blow counts or tip resistances that do not accurately reflect the density as it is inferred from correlations based on sand. Therefore, the BPT is often used to assess liquefaction potential in soils with too much gravel for SPT and CPT to be meaningful.

The BPT consists of driving 6.7-inch-diameter (170 mm) steel casing into the ground using a truck-mounted diesel pile hammer. This diameter is more than four times that of the cone penetrometer or the inside diameter of the SPT sampler. As with the SPT, the number of blows required to advance it each foot is recorded. The BPT is not used to predict liquefaction potential directly, as are the other tests described here. Instead, the BPT is used to estimate the equivalent SPT N_{60} value of gravelly soils, i.e., what the SPT would measure if not for the effects of gravel. Two different correlations are available, each of which includes a method for adjusting the blow count for the non-constant energy output of the diesel hammer. (Harder 1986, Sy and Campanella, 1994) The resulting estimate of N_{60} is then used with an SPT-based correlation for liquefaction resistance.

Much like the SPT, interpretation of the BPT is complicated by the need to estimate the energy transmitted to the tip.

SHEAR-WAVE VELOCITY (V_S)

The shear-wave velocity of a soil, V_S is governed primarily by the density of the soil. The measured V_S is therefore an indirect indication of the density, and of the soil's liquefaction resistance. (Youd *et al*, 1997; Andrus and Stokoe, 2000) There are empirical correlations between shear-wave velocity and liquefaction potential, analogous to those for SPT and CPT. These are often useful for soils that are difficult to test by penetration methods, or to provide redundancy. Often it is necessary to measure shear-wave velocity at a site for use in response analysis, and the same data can be used for assessing liquefaction resistance.

V_S can be measured between a wave source and a receiver in adjacent drill holes (cross hole), with a source on the surface and a receiver at depth (downhole), with the Oyo Corporation's suspension logger, which contains both source and receiver in one tool that is lowered into a drill hole, or by spectral analysis of surface waves (SASW). (Stokoe and Nazarian, 1985) Downhole tests can also be performed with a receiver contained in a cone penetrometer, which eliminates the need for drill holes measure V_s, allowing efficient and fairly inexpensive data collection. For details of the various measurement methods, one may refer to the NCEER workshop report. (Youd *et al* 1997)

Secondary influences on V_S come from particle cementation and aging, both of which tend to increase V_S, but don't necessarily cause a proportional increase in liquefaction resistance. Thus, concern has been raised that V_S could indicate higher resistance to liquefaction than there actually is. At a number of sites tested by Reclamation and by others, V_S has indicated higher liquefaction resistance than did penetration resistance, although there has been no test of performance under actual earthquake loading to resolve the difference.

OTHER *IN SITU* METHODS

For testing gravelly soils, there exist at least four different forms of larger-diameter penetration tests (LPT) that, unlike the BPT, yield a sample for visual examination and laboratory testing. (Daniel *et al,* 2003) These are similar to the SPT, in that they involve counting the blows from a drop hammer required to drive a sampler 1.0 foot into the bottom of a drill hole. Limited data suggest that they correlate fairly well with the SPT in soils fine enough for valid SPT measurements. This is to be expected because the tests are very similar.

EXAMPLE SITE: WICKIUP DAM, OREGON

Wickiup Dam includes a low wing dike over 10,000 feet long, founded on fluvio-lacustrine sediments that include interbedded layers of sand, gravel, volcanic ash, diatomaceous silt, dense silt and sand, and clay and silt. (Bliss, 2003) The site is potentially subject to earthquakes up to $M_W = 6.0$ from local sources, and extremely large-magnitude earthquakes (possibly as large as $M_W = 9.0$) from the Cascadia Subduction Zone. The diatomaceous silt beneath the dike was suspected of having low resistance to liquefaction; SPT and V_s were used to investigate its properties. It was not possible to measure actual densities in the loose saturated silt, but the results of the two methods (i.e., whether the material is potentially liquefiable under some loading) can be compared for consistency.

Shear-wave-velocity profiles were measured by the cross-hole method at three locations on the crest and one at the downstream toe. Each location had either one or two SPT holes located nearby. The diatomaceous silt layer was encountered in all of the holes. Both SPT and V_s testing indicated that this layer was prone to liquefaction under the assumed earthquake loading. The $(N_1)_{60}$ values were very low (always less than 10, and usually less than 5), and the normalized shear-wave velocities in the layer ranged from 460 to 590 ft/sec, both of which are quite low. (Measured V_s values must be normalized to account for the effect of confining stress, typically by the fourth root of the effective vertical stress. Refer to Youd *et al*, 1997.) Another layer of the diatomaceous silt had similar properties. The volcanic ash layer typically had $(N_1)_{60}$ values higher than 10, and normalized V_s values generally ranged from 400 to 600 ft/sec, although the normalized V_S was generally greater than 800 ft/sec in the cross-hole triplet at the downstream toe.

The SPT and V_s results compared favorably, showing similar trends with depth as well as both indicating liquefaction potential in the same critical layers. Out of 90 individual comparisons throughout the site, in only four did the two tests provide conflicting results. At 14 others, one of the tests indicated marginal potential for liquefaction when the other did not; these are not considered conflicting. Overall, the predictions of liquefaction potential from the SPT and from V_S were quite consistent with each other at this site, indicating potential for widespread liquefaction of the foundation. Because of that and the severe earthquake loading possible at the site, the foundation of Wickiup Dam was treated with jet grouting, which effectively replaced the worst of the loose silty material with soil-cement. (Bliss, 2003)

EXAMPLE SITE: BRADBURY DAM, CALIFORNIA

Reclamation's Bradbury Dam near Santa Barbara, California was modified because a number of different *in situ* tests (SPT, BPT, and shear wave velocity) all indicated the downstream alluvium had the potential to liquefy during a large earthquake. (Gillette, 1995) The maximum credible earthquake at the site was estimated to have a magnitude of 7.25, causing a peak horizontal acceleration of 0.7 g; the source is a nearby thrust fault. Consequently, the dam was modified by excavating through the alluvium to bedrock at the downstream toe, backfilling the excavation with compacted gravel and cobbles to create a "shear key," and constructing an earthfill berm over the key and embankment slope to buttress the slope and increase the confining stress in the key fill. (Because of embankment geometry, the upstream slope did not require treatment.) This site provided a unique opportunity to compare in-place relative density data to penetration resistance data, because materials previously tested by *in situ* index methods would be exposed during the excavation.

A total of 14 in-place density tests were done at 10 locations, all near SPT or BPT borings, using a 20-inch diameter sand cone. (Farrar, 1999) A number of different materials were tested, including a silt layer, silty sands, and poorly to well-graded gravels and sands. All but one of the materials tested were entirely smaller than 3 inches in diameter, but even 3-inch particles can make sand-cone tests more difficult. The results are shown in Table 1. In this table, the BPT N_{60} values were determined by the Sy and Campanella (1994) correlation. The relative densities from the SPT and BPT tests in the table were estimated using the Gibbs and Holtz method correlation. (Gibbs and Holtz, 1957) (A more recent correlation by Wu *et al* (2003) suggests relative densities generally 2 to 5 percentage points lower – a minor difference.) No measured relative density is reported for Sample 1A because it had too many fines for the minimum-density test to be applicable.

Table 1. – Predicted and Measured Relative Density, Bradbury Dam (Farrar, 1999)

Sample ID	Soil Classification	% Gravel	% Sand	% Fines	SPT N_{60}	BPT (Sy) N_{60}	SPT RD	BPT (Sy) RD	Measured RD
1A	SM	0	62	38	53	15	92	52	
1B	(SP)g	29	70	1	33	15	75	52	33
1C	SM	0	83	17	16	22	53	64	73
2	SM	4	82	14	6-14	22-31	<40	63-71	85
3	(SW)g	46	52	2	33-36	23-25	67-69	60-62	58
4	(GW)s	64	34	2	54	34-39	89	73-77	75
5	(GP)s	54	42	4	32-36	14-16	69-73	45-50	44
8A	SP	0	98	2	22-23		57-60		63
9	(GW)s	74	23	3		21-22		57-58	35
10A	(GW)sc	76	22	2		29		73	19
10B	(SP)g	26	71	3		31		76	74
10C	(GW)sc	61	36	3		35		80	33

At Bradbury Dam, the BPT proved to be the better predictor of RD. There was very close agreement between the BPT-predicted RD and the measured RD in tests 3, 4, 5, and 10B. In test 1C, the BPT-predicted RD was fairly low, which is in *qualitative* agreement with the measured RD, in that both indicate loose material. In general, the SPT tended to over-predict RD, probably because of gravel interference. Some of the worst matches occurred where there were cobbles or large gravel particles in the sample. This probably results from two phenomena: over-size particles interfering with penetration (tending to bias the results toward being "too high"), and the difficulty of measuring relative density in coarse gravel and cobbles. The latter, along with the depositional environment (coarse alluvium deposited as bed load in a rapidly moving river) makes any measured relative density below 40 highly suspect.

Some additional observations include:

• The gravelly soils were described as easily excavated by hand for the sand-cone density tests; hence, their relative density would not be expected to be very high.

• Four of the five tests in these gravels had measured relative densities less than 50%, much less in some cases.

• The two silty-sand samples for which relative density could be determined had some of the highest relative densities, which is somewhat surprising, although their absolute densities were lower than the coarser materials.

• Sand-gravel mixtures had measured relative densities intermediate between those of the silty sands and of the gravels.

• Corresponding SPT values at locations with gravel were higher, likely due to gravel influence, although an effort was made to eliminate those effects by plotting blow-by-blow penetration to look for gravel interference. Where there was an abrupt change in the slope of the plot, the portion corresponding to the lower blow count was projected to a full 1.0 foot.

• The SPT accurately predicted in-place relative density at only one location.

• Even the BPT with its 6.7-inch tip diameter is sensitive to the presence of large gravel and cobbles.

• Because the foundation at this site is alluvium from an intermittently fast-moving river, material properties varied from point to point on a much smaller scale than at Wickiup Dam, where the lacustrine diatomaceous silt showed continuity over large distances. This meant that some of the comparisons between methods at Bradbury Dam were not actually made in the same material.

• Shear-wave velocities were measured at Bradbury Dam, but not at locations that permitted direct point-by-point comparisons with the other measurements. The general implication of the V_S measurements was consistent with that of the SPT and BPT, i.e., that most of the alluvium was moderately dense, but there were layers of looser material, inferred to be liquefiable under severe loading.

A wide variety of different soils were sampled at this site, and the small number of data does not permit meaningful statistical analysis or definitive conclusions. Considering only this small sample, it is not obvious that strong correlations exist among the three different methods of estimating the relative density. However, it is likely that not all of the in-place measurements of relative density are fully accurate (particularly those that measured less than 40 percent), and that the presence of significant gravel and some cobbles make both the SPT and BPT subject to errors. The data do indicate that BPT and SPT tests tend to over-predict relative density when gravel is present. Wherever the BPT and relative density agreed, Farrar (1999) reported that the particles were less than 2 to 3 inches in diameter, which suggests that larger particles are more prone to cause problems in the liquefaction assessment, and perhaps in the relative-density measurements as well.

LOWER SAN FERNANDO DAM, CALIFORNIA

This most-studied of all liquefaction case histories included slope instability of a large dam embankment, very nearly causing a disastrous breach during the 1971 San Fernando Valley Earthquake. (Seed et al, 1975a; Seed et al, 1975b; Castro *et al, 1989)* Liquefaction occurred in hydraulic fill that made up a portion of the embankment. The material involved has been tested by a large number of methods, including SPT, CPT, and sand-cone density measurements in a 6-foot-diameter cased shaft 85 feet deep. (Seed *et al* 1975a and 1975b, Castro *et al* 1989, Seed *et al* 1989)

From the testing, the representative $(N_1)_{60}$ blow count for the materials that liquefied was judged to be about 11 to 13. Five in-place density tests gave the following results: 98.6, 96.7, 98.1, 95.8, and 100.7 lbs/ft^3. (No relative density tests were run, as the material was too fine-grained for relative density to be applicable.) The Proctor maximum density was approximately 116 lbs/ft^3. The five samples in this layer therefore ranged from 83 to 87 percent of the maximum. Thus, the low SPT blow counts agree well with the in-place density tests, as both indicate low density and cyclic resistance, consistent with what actually occurred during the earthquake.

OVERALL COMPARISONS AMONG INDICES OF DENSITY

Table 2 shows qualitative assessments of the level of agreement between measured relative densities and various indices of density from seven sites.

Table 2. General Level of Agreement Between Measured Relative Density and Various *In Situ* Indices of Density.

	Qualitative Comparison of Measured Relative Density With:		
Site	**SPT**	**BPT**	**V_S**
Avalanche Gravel (Kokusho *et al* 1995)			Good
Jackson Lake Dam (Farrar, 1999)	Good		
Bradbury Dam (Farrar, 1999)	Poor	Fair	
Mormon Island Dam (Hynes-Griffin *et al* 1988)		Good	Good
Lower San Fernando Dam (Castro *et al,* 1989)	*Good		
Pinopolis West Dam (GEI, Inc., 1985)	Good		
Keenleyside Dam (Lum and Yan, 1994)	Good	Good	Fair

* Comparison with Proctor maximum density only – material not suitable for relative density testing.

With the exception of Bradbury Dam, where gravel and cobbles are thought to have affected the penetration tests and possibly the relative density measurement as well, there is qualitatively “Good” agreement between measured relative densities and penetration resistance. At two out of three sites, there was also good agreement between D_R and V_s.

Table 3 summarizes the qualitative level of agreement among tests.

Table 3. Quality of "Agreement" Between Pairs of Test Methods

Site	SPT/CPT	SPT/BPT	SPT/V_s	CPT/V_s	BPT/V_s
Chinese industrial site (Wong 1986)	Good		Good	Good	
Calaveras Dam (Seed *et al* 2003)		Fair to Good			
East Dam and Dike (Paul C. Rizzo Assoc. data)	Fair to Good		Fair	Fair	
Skookumchuck Dam (Shannon and Wilson data)		Good	Fair		Fair
Steel Creek Dam (Keller *et al*, 1987)	Good		Good	Good	
Keenleyside Dam (Lum and Yan, 1994)			Fair		Fair
V_s-BPT Research (Rollins *et al*, *1998*)					Fair
Tacoma site (Womack *et al*, 1998)	Fair to Good		Fair to Good	Fair to Good	
Casitas Dam (Reclamation data)		Fair	Fair		Fair
Keechelus Dam (Reclamation data)			Fair to Good		
Salmon Lake Dam (Reclamation data)		Good	Fair		Fair
Wickiup Dam (Reclamation data)			Good		
Avalanche Gravel (Kokusho *et al*, 1995)					
Bradbury Dam Gravelly soils (Farrar, 1993)		Poor to Fair			
Mormon Island Dam (Hynes-Griffin *et al*, *1988)*					Good
Keenleyside Dam (Lum and Yan, 1994)		Good	Fair		Fair
Pineview Dam (Reclamation data)		Good	Fair		
Deer Creek Dam (Reclamation data)					
Carrefour Shopping Center (Martin *et al*, 2004)	Good		Good	Good	

CONCLUSIONS AND RECOMMENDATIONS

Different *in situ* methods for assessing the density of soils may not provide consistent results at a site, even in apparently similar materials at the same site. The mechanics of the methods differ, and each has its own complicating factors associated with the presence of gravel, heterogeneity, and possibly aging. The study described here was intended to provide the engineer with additional basis for interpreting test results.

In general, the closest agreement among *in situ* methods was among the various penetration-resistance tests, including the cone penetrometer and the standard penetration test. This is not surprising, since there is greater similarity among these tests than there is with V_s or measured relative density. For use in liquefaction assessment, the Becker hammer penetration test is used to predict the SPT blow count, or rather what it would be if there were no gravel present to interfere with penetration of the sampler. Hence, there should be reasonable agreement between the two in soils without gravel.

For critical structures, such as dams or bridges, it is appropriate to apply more than one *in situ* technique to evaluate liquefaction potential. In light of uncertainties with all methods, multiple techniques can add some confidence to the conclusions of liquefaction susceptibility, or at least highlight the uncertainties therein, which must be accounted for in analysis and decision making. In attempting to resolve inconsistencies among test results, one should consider the mechanics of each type of test, and how the soils at the site would affect the results. For example, in a layer with little gravel, one would generally favor CPT results over those from the BPT, unless the latter indicated high densities, in which case the picture would be less clear, and it would be necessary to look deeper for the cause of the unexpected result.

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