Evaluation and Optimization of Dynamic Cone Penetration test (DPT) for Assessment of Liquefaction in Gravelly Soils

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Abstract-- The dynamic cone penetration test (DPT) developed in China has been correlated with liquefaction resistance in gravelly soils based on field performance data from the M_w7.9 Wenchuan, China earthquake. The DPT consists of a 74 mm diameter cone tip driven by a 120 kg hammer with a free fall height of 1 m. To expand the data base, DPT soundings were performed at the Pence Ranch and Larter Ranch sites where gravelly soil liquefied during the 1983 M_w6.9 Borah Peak earthquake. DPT testing was performed using an automatic hammer with the energy specified in the Chinese standard and with an SPT hammer. In general, comparisons suggest that standard energy corrections developed for the SPT can be used for the DPT. The DPT correctly predicted liquefaction and non-liquefaction at these two test sites. Liquefaction resistance from the DPT (30% probability) also correlated reasonably well with that from Becker penetration testing (BPT).

I. Introduction

Characterizing gravelly soils in a reliable, cost-effective manner for routine engineering projects is a major challenge in geotechnical engineering. Even for large projects, such as dams, ports, and power projects, characterization is still expensive and problematic. This difficulty is particularly important for cases where liquefaction may occur. Liquefaction is known to have occurred in gravelly soils at multiple sites during at least 16 earthquakes over the past 130 years as summarized in Table 1. As a result of these case histories, engineers and geologists are frequently called upon to assess the potential for liquefaction in gravels. In a number of cases, older dams were constructed on gravelly soil foundations before the potential for liquefaction in gravels was recognized by the profession. For these projects, assessing the potential for liquefaction and determining appropriate remedial measured are often multi-million dollar decisions. Therefore, innovative methods for characterizing and assessing liquefaction hazards in gravels are certainly an important objective in geotechnical engineering.

Because of the difficulty of obtaining meaningful results from Standard Penetration tests (SPT) and Cone Penetration tests (CPT) in gravelly soils, the large diameter Becker Penetration test (BPT) has been developed. Although the BPT-based approach has provided a reasonable method for liquefaction assessment of gravels, the method is expensive and involves empirical correlations which increase uncertainty. Over the past 60 years, Chinese engineers have developed a Dynamic cone Penetration Test (DPT) which is effective in penetrating coarse or even cobbly gravels and provides penetration data useful for liquefaction assessment (Chinese Design Code, 2001). This test provides an important new procedure for characterization of gravels that fills a void in present geotechnical practice.

The objectives of this on-going research are:

1. to provide comparative evaluations of the liquefaction resistance estimated by the DPT and the BPT for sites where gravelly soils have liquefied during a major earthquake
2. to provide comparisons between DPT resistance obtained with the Chinese hammer energy and the energy delivered by an SPT hammer after appropriate energy corrections in an effort to optimize the method for US practice.
3. to provide additional data points defining the liquefaction resistance as a function of DPT blowcount at sites throughout the world where gravels have liquefied in past earthquakes.
4. to use the additional data points from these investigations to improve the probabilistic liquefaction triggering curves for the DPT for future evaluation of liquefaction hazard in gravelly soils.

To accomplish these objectives DPT tests were first performed at two sites in Idaho where BPT tests were previously performed. This paper describes the tests procedures, the results that were obtained, and compares the liquefaction resistance obtained from the BPT with that obtained from the DPT.

Financial support for this study was provided by a grant G16AP00108 from the USGS Earthquake Hazard Reduction Program, External Research Program and grant CMMI-1663288 from the National Science Foundation. However, the conclusions and opinions are those of the authors.

Table 1 Case histories involving liquefaction of gravelly soil

Earthquake	Year	M_w	Reference
Mino-Owari, Japan	1891	7.9	[1]
Fukui, Japan	1948	7.3	[2]
Alaska	1964	9.2	[3]
Haicheng, China	1975	7.3	[4]
Tangshan, China	1976	7.8	[4]
Friuli, Italy	1976	6.4	[5]
Miyagiken-Oki, Japan	1978	7.4	[1]
Borah Peak, Idaho	1985	6.9	[6]
Armenia	1988	6.8	[8]
Roermond, Netherlands	1992	5.8	[9]
Hokkaido, Japan	1993	7.8	[10]
Kobe, Japan	1995	7.2	[11]
Chi-Chi, Taiwan	1999	7.8	[12]
Wenchuan, China	2008	7.9	[13]
Cephalonia Is., Greece	2012	6.1	[14]
Pedernales, Ecuador	2016	7.8	[15]

II. LIMITATIONS OF CURRENT METHODS FOR CHARACTERIZING GRAVELS

Because of the difficulty of extracting undisturbed samples from gravelly soils, laboratory tests on undisturbed samples have not proven effective or reliable for measurement of shear strength or liquefaction resistance. Freezing of a gravel layer before sampling improves sample quality, but the cost is prohibitive for routine projects. Even when undisturbed samples can be extracted, changes in stress conditions between the field and laboratory can limit the usefulness of laboratory test results.

For sands and fine-grained soils, standard penetration tests (SPT) and cone penetration tests (CPT) are widely used to measure penetration resistance for applications in engineering design and for assessing liquefaction resistance. However, SPT and CPT are not generally useful in gravelly soils because of interference from large particles. Because of the large particles, the penetration resistance increases and may even reach refusal in cases when the soil is not particularly dense. This limitation often makes it very difficult to obtain a consistent and reliable correlation between SPT or CPT penetration resistance and basic gravelly soil properties.

In North American practice, the Becker Penetration Test (BPT) has become the primary field test used to measure penetration resistance of gravelly soils. The BPT was developed in the late 1950s and consists of a 168-mm diameter, 3-m-long double-walled casing, whose resistance is defined as the number of blows required to drive the casing through a depth interval of 30 cm. For liquefaction resistance evaluations, closed-end casing is specified. To facilitate use of the BPT for liquefaction resistance calculations, Harder and Seed developed correlations between BPT and SPT blow counts in sand after correction for Becker bounce chamber pressure and atmospheric pressure at the elevation of testing [16], [17] as shown in Figure 1. Although the correlation in Figure 1 appears to be reasonably good, the scatter in the data about the mean curve adds an additional level of uncertainty into the estimation of the liquefaction resistance. Once the blowcount has been converted to an equivalent SPT N_{BC} value, energy and overburden corrections can be made to obtain the corrected equivalent SPT $(N_1)_{60}$ value. In this study, the cyclic resistance ratio (CRR) for a given SPT $(N_1)_{60}$ value was then obtained using procedures recommended by [18] to facilitate more direct comparisons of liquefaction resistance as discussed subsequently.

Although more recent liquefaction triggering methods could potentially be used (e.g. [19]), these newer methods use iterative procedures for correction factors based on relative density which is poorly defined for gravelly soils. In addition, the overburden pressure correction factor, C_n, in the newer procedures differs from that proposed by [13] which makes direct comparisons more difficult.

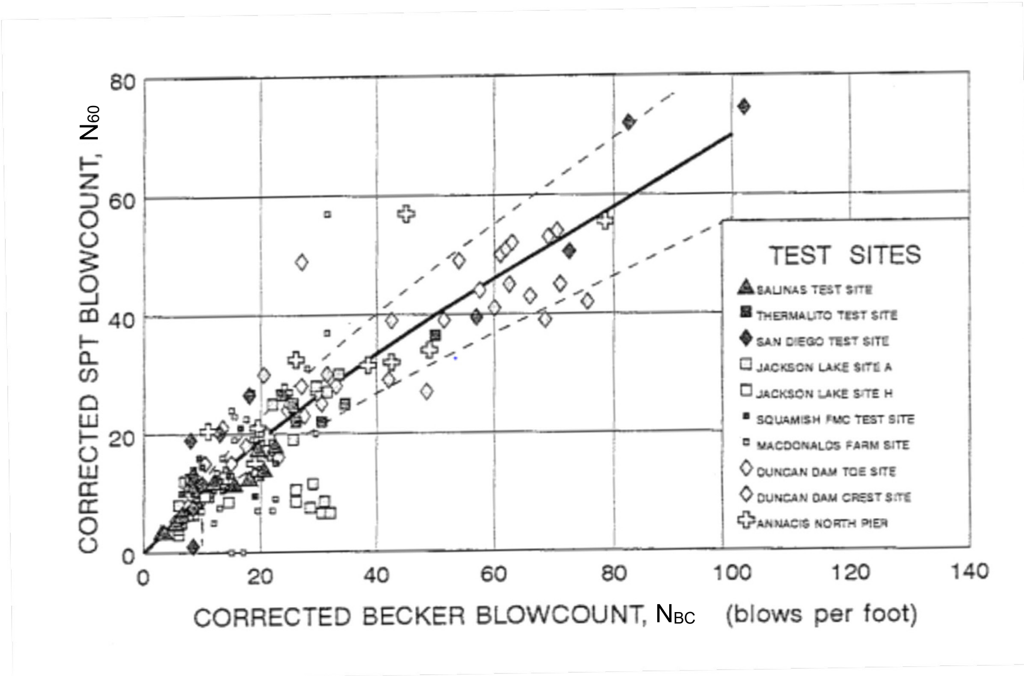


Figure 1. Correlation between corrected Becker (N_{BC}) and SPT (N_{60}) blowcounts from [16] supplemented with data from additional test sites [17].

Disadvantages in applying the BPT for liquefaction hazard investigations include the high cost of mobilization, uncertainty in measuring BPT resistances, uncertainties in correlations between SPT and BPT blow counts, and friction resistance between the soil and the driven BPT casing. Reference [20] found that friction on the Becker penetrometer affects the measured penetration resistance. They developed a procedure for correcting BPT measurements for friction resistance by using strain and acceleration measurements to perform a CAPWAP analysis to quantify the effect of casing friction on BPT resistance. Reference [21] has also used mud slurry injection at the base of the Becker to reduce casing friction, with some success, but both the CAPWAP and the mud injection approaches add to the overall complexity of the test procedure. More recently, Ghafghazi et al. [22] have developed more sophisticated instrumentation for determining the energy delivered to the base of the BPT which greatly reduces the uncertainty associated with skin friction. The BPT blowcounts adjusted with this procedure have subsequently been correlated with SPT blowcounts at several sites [22]. This correlation, while representing a major improvement on the Harder correlation [16], still leads to increased uncertainty in the liquefaction assessment approach in contrast to a direct correlation with an in-situ test parameter such as the SPT $(N_1)_{60}$ or CPT q_{c1N}. For example, the coefficient of variation for the correlation in reference [22] curve is 0.40.

III. Development of Dynamic Cone Penetration Test (DPT) for Gravels

A dynamic cone penetration test (DPT) was developed in China in the early 1950s to measure penetration resistance of gravel for application in bearing capacity analyses. Based on their experience, standard test procedures and code provisions have been formulated ([23], [24]). Because of widespread gravelly deposits beneath the Chengdu plain, the DPT is widely used in that region, particularly for the evaluation of liquefaction potential [25].

DPT equipment is relatively simple, consisting of a 264 lb (120-kg) hammer, raised to a free fall height of 39 in (100 cm) (39 in), then dropped onto an anvil attached to 60-mm diameter drill rods which in turn are attached to a solid steel cone tip with a diameter of 3 inches (74 mm) and a cone angle of 60º as shown in Figure 2. The larger cone diameter is designed to make the penetrometer less susceptible to gravel size particles than conational CPT and SPT testing. The smaller diameter rod helps to reduce shaft friction on the rods behind the cone tip. The cone is driven continuously into the ground

Prior to testing, the drill rods are marked at 10 cm intervals and the number of blows required to penetrate each 4 in (10 cm) is recorded. The raw DPT blow count is defined as the number of hammer drops required to advance the cone tip 10 cm. A second penetration resistance measure, called N_{120}, is specified in Chinese code applications where N_{120} is the number of blows required to drive the cone tip one foot or 30 cm; however, N_{120} is calculated simply by multiplying raw blow counts by a factor of three which preserves the detail of the raw blow count record.

As with the standard penetration test, a correction for overburden stress on the DPT blow count was applied using the equation

$$N'_{120} = N_{120}\left(\frac{100}{\sigma'_v}\right)^{0.5} \qquad (1)$$

where N'_{120} is the corrected DPT resistance in blows per foot (30 cm), N_{120} is the measured DPT resistance in blows per 30 cm, 100 is atmospheric pressure in kN/m^2, and σ'_v is the vertical effective stress in kN/m^2 [13]. This is identical to the overburden correction factor applied in [18] which facilitates comparisons. Energy transfer measurements were made for about 1200 hammer drops with the DPT in China using the conventional pulley tripod and free-fall drop weight system [13]. These measurements indicate that on average 89% of the theoretical hammer energy was transferred to the drill rods with this system but the standard deviation of the energy transfer was about 9%.

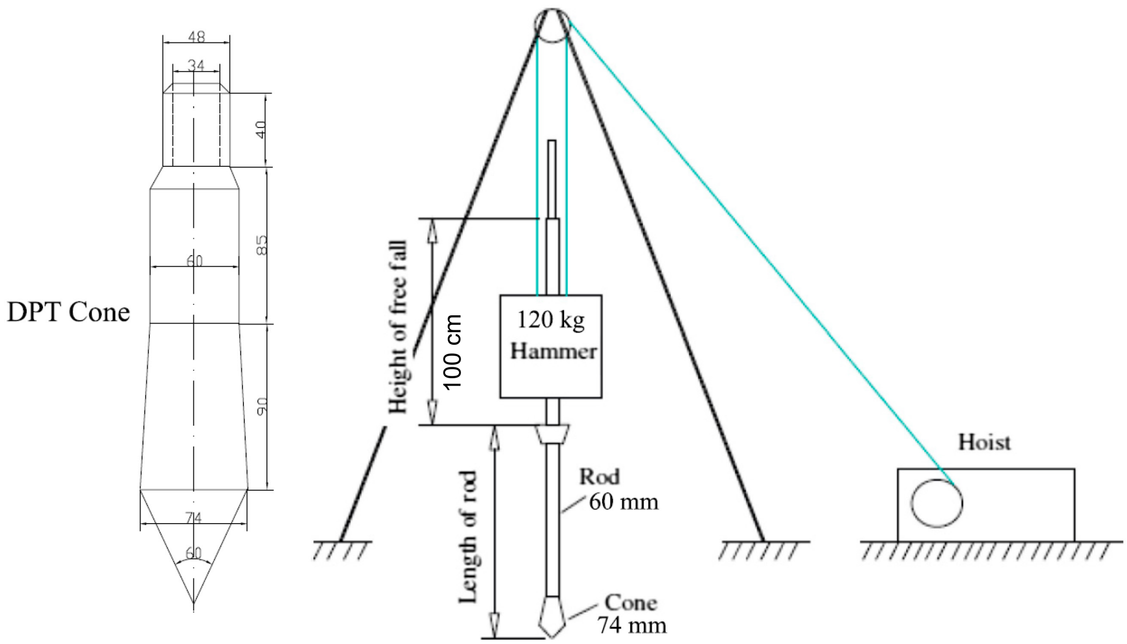


Figure 1. Component sketch of tripod and drop hammer setup for dynamic penetration tests (DPT) along with DPT cone tip. (After [13]).

IV. Liquefaction Resistance Curve Based on DPT Penetration Resistance

Following the 2008 M_w 7.9 Wenchuan earthquake in China, 47 DPT soundings were made at 19 sites with observed liquefaction effects and 28 nearby sites without liquefaction effects. Each of these sites consisted of 6.5 to 13 ft (2 to 4 m) of clayey soils, which, in turn, were underlain by gravel beds up to 1600 (500 m) thick. Looser upper layers within the gravel beds are the materials that liquefied during the Wenchuan earthquake. Because samples are not obtained with DPT, boreholes were drilled about 2 m away from most DPT soundings with nearly continuous samples retrieved using 3.5 to 4 inch (90 to 100 mm) diameter core barrels.

Layers with the lowest DPT resistance in gravelly profiles were identified as the most liquefiable or critical liquefaction zones. At sites with surface effects of liquefaction these penetration resistances were generally lower than those at nearby sites without liquefaction effects. Thus, low DPT resistance became a reliable identifier of liquefiable layers [25].

At the center of each layer, the cyclic stress ratio (CSR) induced by the earthquake was computed using the simplified equation

$$\mathrm{CSR} = 0.65\left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) r_d \qquad (2)$$

where a_{max} is the peak ground acceleration, σ_{vo} is the initial vertical total vertical stress, σ'_{vo} is the initial vertical effective stress, and r_d is a depth reduction factor as defined by [18].

Using DPT data, Cao et al. [13] plotted the cyclic stress ratio causing liquefaction against DPT N'_{120} for the M_w7.9 Wenchuan earthquake. Points where liquefaction occurred were shown as solid red dots, while sites without liquefaction were shown with open circles. Cao et al. [13] also define curves indicating 15, 30, 50, 70 and 85% probability of liquefaction based on logistical regression. Most other liquefaction triggering curves are calibrated for M_w7.5 earthquakes. To facilitate comparison with data points from other earthquakes, we have shifted the Cao et al. data points and triggering curves in [13] upward to represent performance during a M_w7.5 earthquake using the equation

$$\mathrm{CSR}_{M_w7.5} = \frac{\mathrm{CSR}}{\mathrm{MSF}} \tag{3}$$

where the Magnitude Scaling Factor (MSF) is given by the equation

$$\mathrm{MSF} = \frac{10^{2.24}}{M_w{}^{2.56}} \tag{4}$$

proposed by [18]. More recent magnitude scaling factor equations have been developed but they typically require an assessment of relative density or include SPT or CPT based parameters which makes their applicability questionable or problematic for gravel sites. For large magnitude earthquake events the differences in scaling factors are generally small. The data points and probabilistic triggering curves corrected for a M_w7.5 earthquake are shown in Figure 3. The spread in the DPT-based probabilistic triggering curves is greater than that for SPT-based curves [19]. This results from the fact that there are much fewer DPT data points and fines contents are not considered. Additional data points and potential adjustments for fines content should help refine the DPT-based triggering curves in the future.

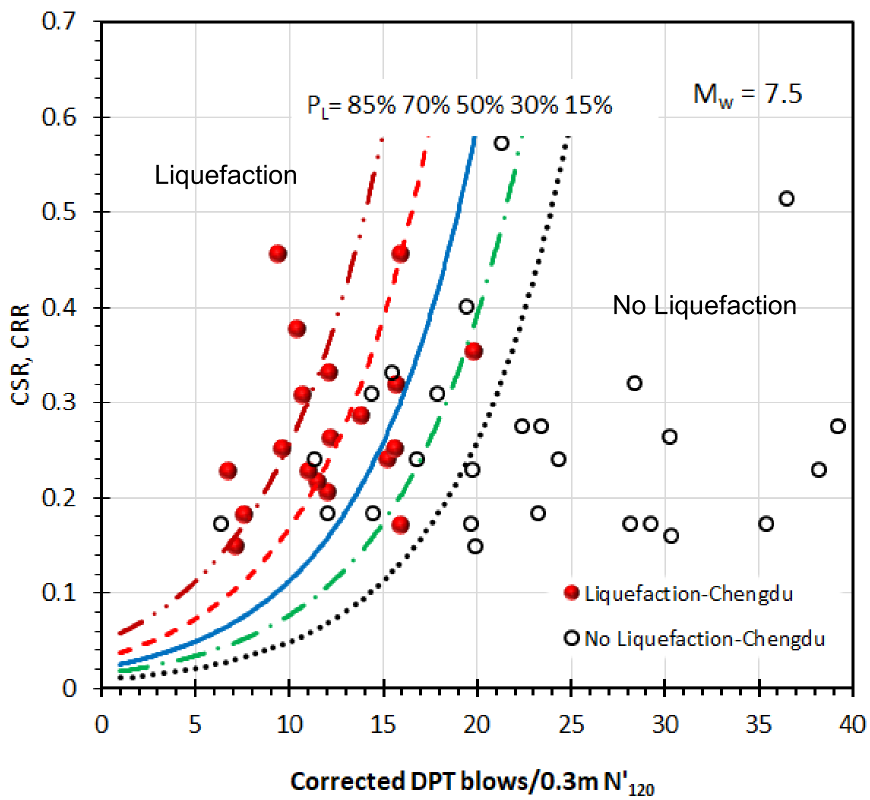


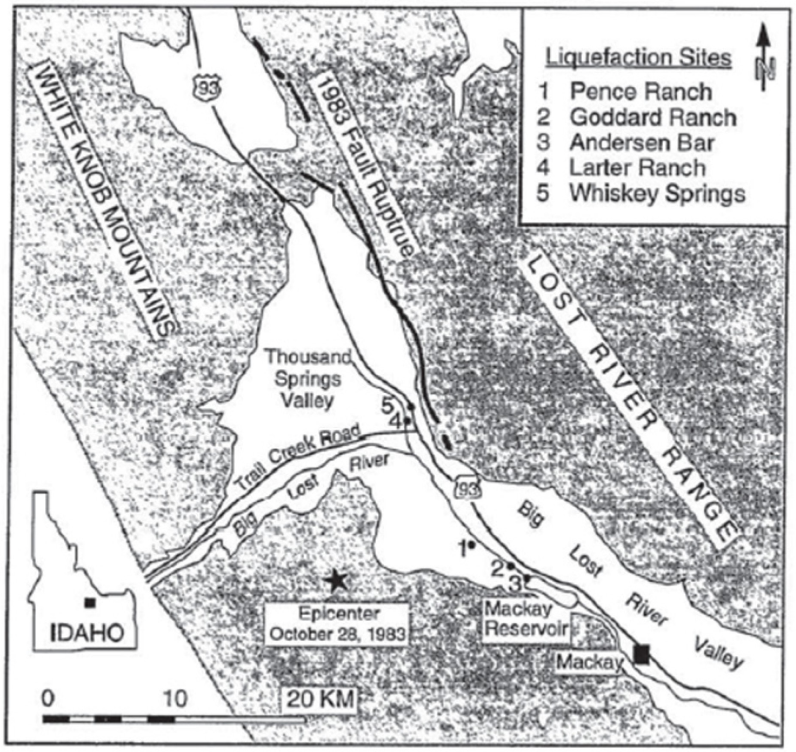
Figure 2. CRR vs. DPT N'_{120} triggering curves for various probabilities of liquefaction in gravelly soils developed by [13] adjusted for M_w7.5 earthquakes. Liquefaction/no liquefaction data points from sites on the Chengdu plain are also shown after adjustment to M_w7.5.

The case histories in Idaho with DPT test results provide an excellent opportunity to evaluate the ability of the DPT-based liquefaction triggering curves developed by [13] Cao et al (2013) to predict accurately liquefaction in gravelly soil. For the Idaho case histories, the geology, earthquake magnitude, and stratigraphy are significantly different from those in the Chengdu plain of China and will provide a good test of the method.

V. Liquefaction and Site Characterization at Larter Ranch in Idaho

Liquefaction of gravelly soil occurred at the Larter Ranch shown in Figure 5 following the M_w 6.9 Borah Peak earthquake in 1983 [6], [7]. The Larter Ranch is located about 16 miles northwest of Mackay, Idaho near Thousand Springs Creek in central Idaho (latitude: 44.073452º, longitude: -113.842211º).

Figure 3. Regional map of the Big Lost River and Thousand Springs Valleys showing geographic features, approximate trace of fault rupture, and locations of liquefaction sites [6].



A. Liquefaction Features and Previous Investigations

As illustrated in Figure 6, liquefaction of the gravelly soils at the distal end of an alluvial fan caused lateral spread displacements of about 3 feet (one meter) [6]. As the denser, non-liquefied alluvium moved towards the creek, sliding over the underlying liquefied layer, large fissures opened up at the ground surface. Eye-witness accounts describe water spouts nearly a meter-high erupting from the fissures carrying sand ejecta [6]. These fissures run roughly parallel to the creek for a distance of over 500 meters. Figure 7 presents a photo taken at the time of the DPT field tests in February 2017 showing two large fissures still visible 34 years after the earthquake. The sliding caused the sod near the toe of the slope to buckle as shown in Figure 6.

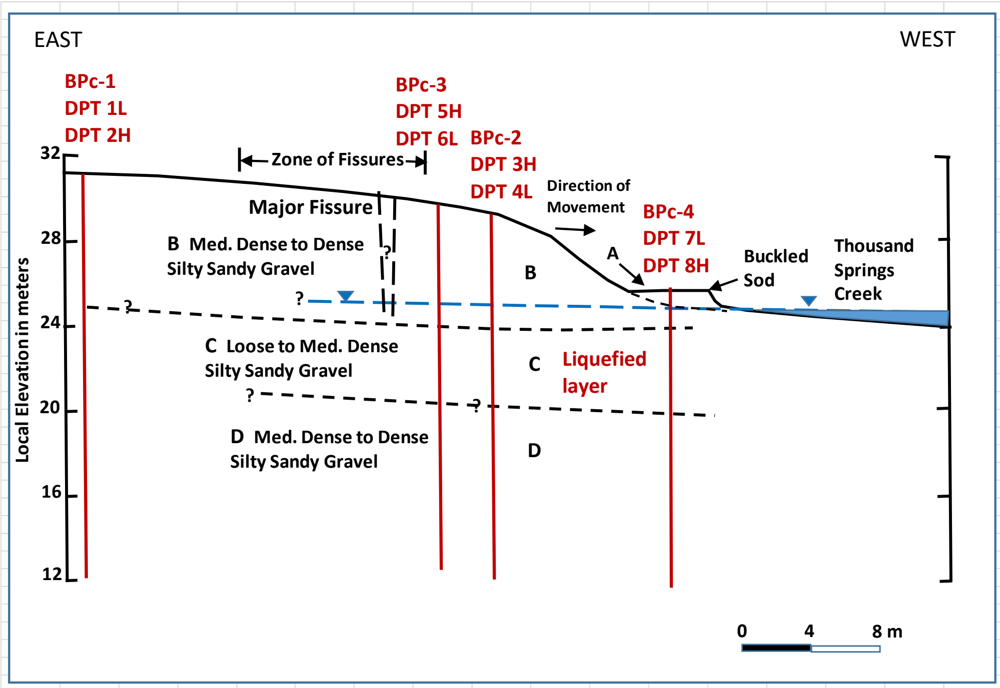


Figure 6. Cross-section through alluvial fan perpendicular to the Thousand Springs Creek showing soil stratigraphy, locations of BPT and DPT holes, and lateral spread features [6].

Figure 4. Photograph showing large fissures produced by liquefaction-induced lateral spread displacement towards the Thousand Springs Creek to the left.

To characterize the subsurface soils, four Becker penetration tests (BPT) were performed at locations shown on the cross-section in Figure 6 in August 1990 [16]. In addition, cone penetration tests (CPT), Standard Penetration tests (SPT) and shear wave velocity testing was performed. Based on these field investigations, Andrus [6] identified four basic units as noted in Figure 6. Unit A consists of an organic rich silty sand (SM) and is less than a meter thick. Unit B is a medium dense to dense silty sandy gravel (GM-GW) that likely didn't liquefy because of its density and the deep location of the groundwater table. Average fines content was 7% and the fines were non-plastic while gravel content ranged from 40 to 60%. Unit C is a loose to medium dense silty sand gravel (GM-GW to GM) and was expected to liquefy because of the low BPT blow counts and shear wave velocities. Gravel contents ranged from 45 to 65% while fines were typically non-plastic and ranged from 7 to

17%. The silty sandy gravel (GM) in Unit D increases substantially in density with a fines content of 18%.

B. DPT Testing at Larter Ranch

As part of this study, two DPT soundings were performed within about a meter of the previous four BPT soundings using a CME 85 drill rig with the capability of using two different hammer energies. DPT test hole locations relative to the BPT holes are shown in Figure 6. In one sounding, the DPT cone was advanced using a conventional automatic SPT hammer with a weight of 140 lbs (63.6 kg) dropped from a height of 0.76 m (30 in). The second sounding was performed using a 340 lbg (154.4 kg) automatic hammer with a drop height of 30 inches (0.76). The DPT was able to penetrate to over 33 ft (10 m) using even the lighter hammer. Hammer energy measurements were made using an instrumented rod section and a PDA device. These measurements indicate that the SPT hammer and the 154.4 kg hammer delivered averages of about 90% and 91% of the theoretical free-fall energy, respectively as shown by the histograms in Figure 8. In contrast with PDA results for DPT testing in China where the standard deviation on energy transfer was between 6.9 and 8.6%, standard deviations with the automatic hammers used for DPT testing in the US were typically less than 1.5% as shown in Figure 8.

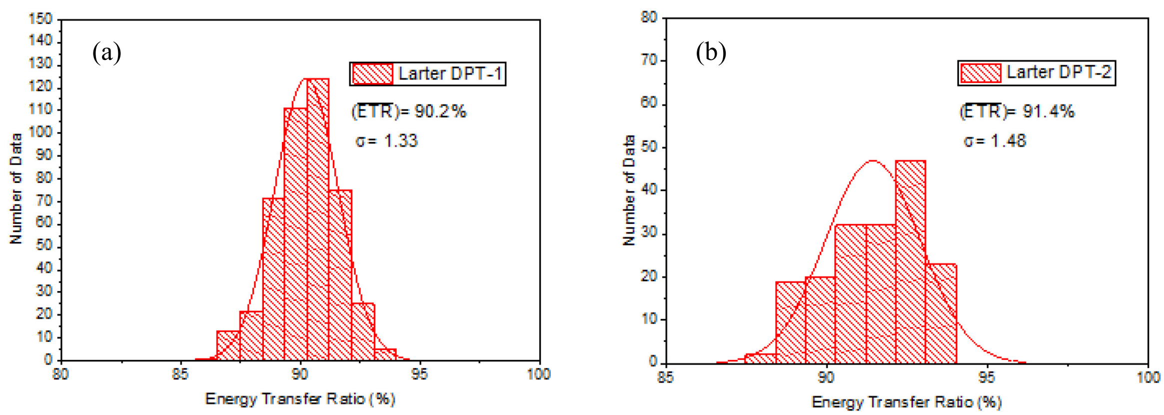


Figure 8. Histograms of theoretical energy transfer for (a) 63.6 kg (140 lb SPT) hammer and (b) 154.4 kg (340 lb) hammer along with average energy transfer (ETR) and standard deviation, σ.

Because the delivered energies are less than the energy typically supplied by a Chinese DPT hammer, it was necessary to correct the measured blow count downward using the equation

$$N_{120} = N_{Measured}\left(\frac{E_{Delivered}}{E_{\text{Chinese DPT}}}\right) \qquad (5)$$

The ratio of energy actually delivered divided by the energy delivered by the Chinese DPT hammer was 0.99 and 0.41 for the 154.4 and 63.6 kg hammers, respectively. Plots of the energy corrected DPT N_{120} versus depth for the light 'L' (63.6 kg) and heavy 'H' (154.4 kg) hammers are provided in Figures 9 and 10 in comparison with the BPT N_{BC}. For both hammer energies, the energy corrected DPT N_{120} value is fairly consistent with the trend defined by the BPT N_{BC} value with depth. In addition, at the BPc-4 site, both DPT soundings appear to identify a denser layer from 1 to 3 m below the ground surface than that observed in the BPT testing. This could be a result of energy reflection for the short rods reducing the energy transfer and inflating the blowcounts or some local variation; however, the exact reason is unknown.

Figure 11 provides comparison plots of DPT N_{120} values obtained from heavy (154.4 kg) and light (63.6) hammers for BPT holes (a) BPc-1 and (b) BPc-4 at the Larter Ranch site. For site BPc-1, the DPT 2L sounding became inclined beyond 5º from vertical when impacting gravel particles which led to artificially high blowcounts relative to the DPT sounding with the heavy hammer. For an inclined rod, increased friction on the rod reduces the energy delivered to the cone tip and artificially increases the blowcount. In contrast, for site BPTc-4 the DPTs remained vertical for both soundings and the blowcounts are relatively consistent after correction for hammer energy. These results highlight the importance of maintaining a vertical rod particularly when it is necessary to make corrections for hammer energy.

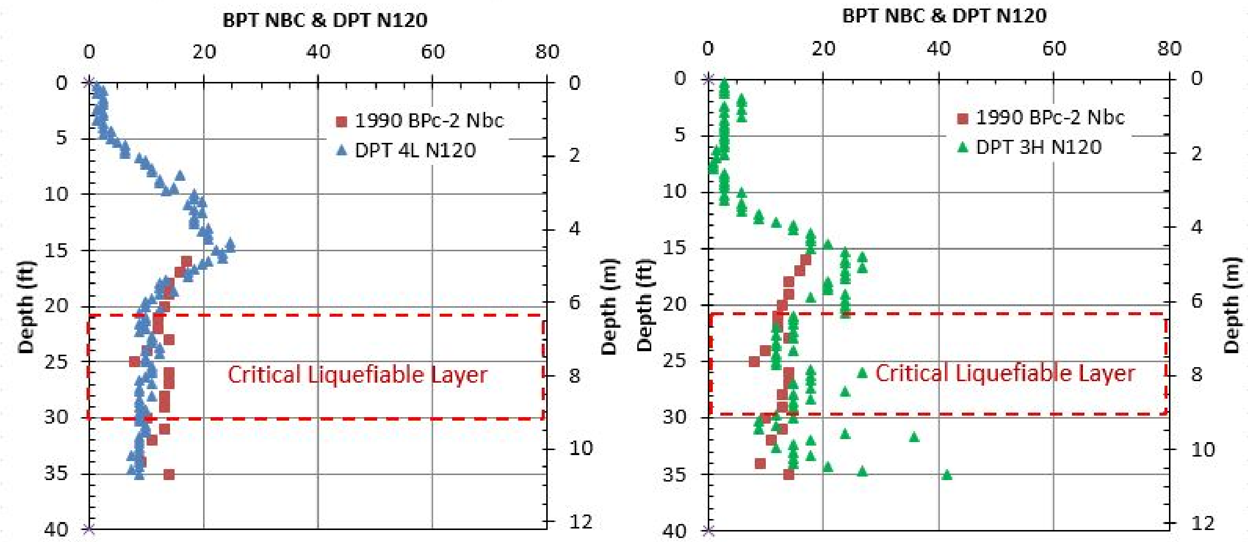


Figure 9. Plots of DPT N_{120} versus depth for (a) light hammer and (b) heavy hammer after energy ration correction in comparison with BPT test BPc-2.

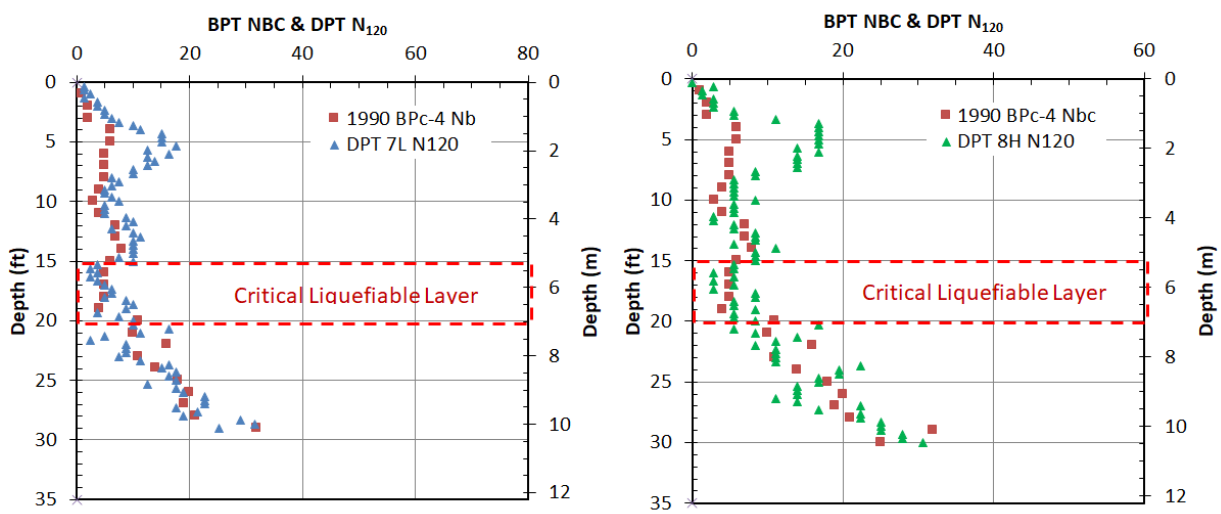


Figure 10. Plots of DPT N_{120} versus depth for (a) light hammer and (b) heavy hammer after energy ration correction in comparison with BPT test BPc-4.

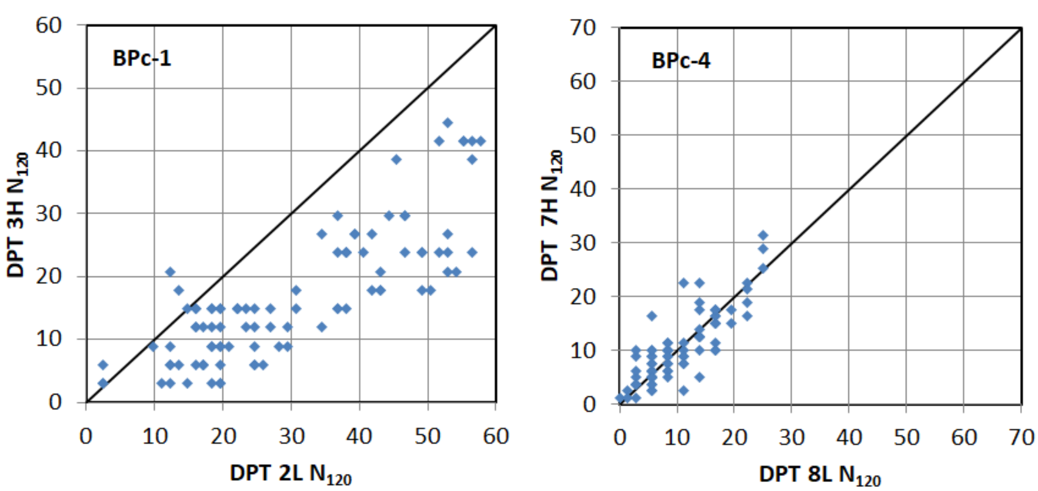


Figure 11. Plots of DPT N_{120} obtained from heavy (154.4 kg) and light (63.6) hammers for BPT holes (a) BPc-1 and (b) BPc-4 at the Larter Ranch site.

C. Liquefaction Evaluations at Larter Ranch

The eight DPT test profiles provide an excellent opportunity to evaluate the ability of the DPT-based liquefaction triggering curves developed by [13] to predict accurately liquefaction in gravelly soil. For each DPT sounding, we estimated the critical layer for liquefaction as illustrated in Figures 9 and 10. This zone was generally the loosest average layer below the water table and closest to the surface. The average DPT N'_{120} for each critical layer was plotted against the average CSR in the layer using a PGA of 0.5g and adjusted to a moment magnitude M_w of 7.5 using equation 4. The data pairs for each hole at the Larter Ranch are plotted in Figure 14 in comparison with the liquefaction triggering curves in [13] after magnitude scaling adjustments which shifted the measured CSR values downward. In all cases the data pairs plot above the 50% probability of liquefaction curve which is consistent with the observed liquefaction at both sites.

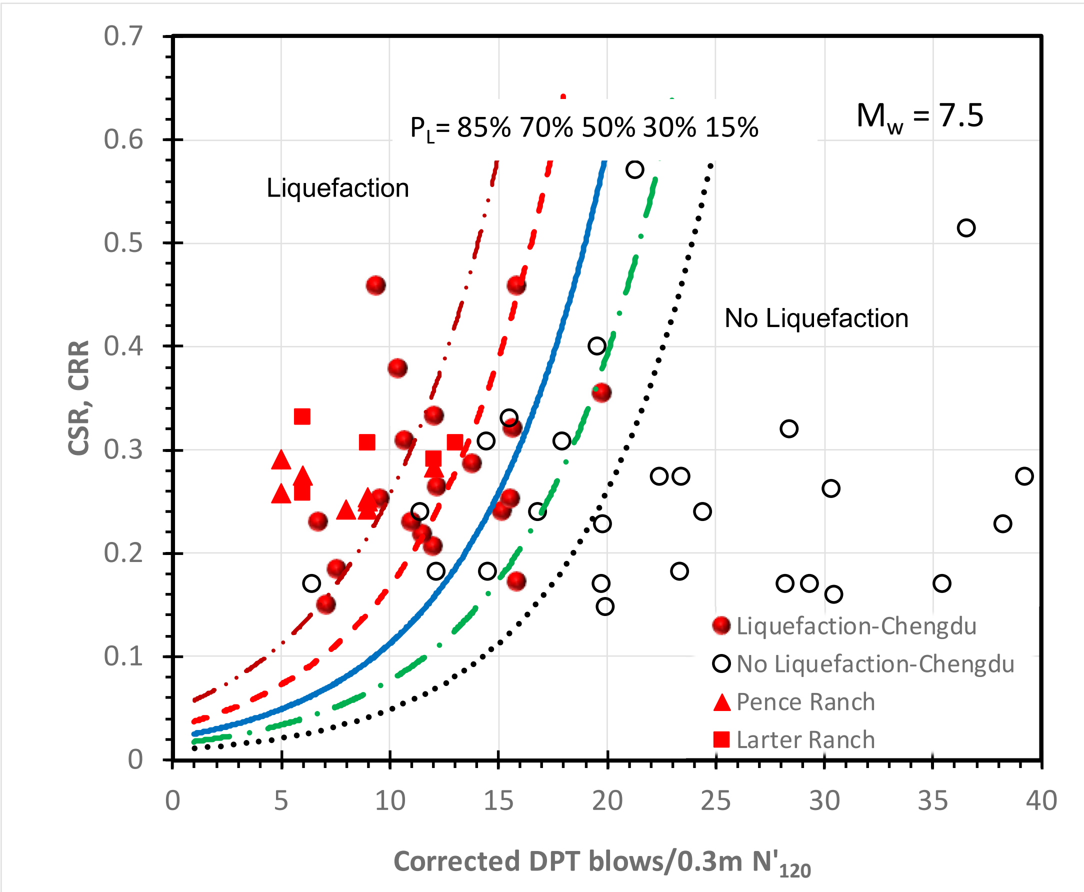


Figure 12. CRR vs. DPT N'_{120} curves for various probabilities of liquefac0tion in gravelly soils developed by Cao et al in {13] along with liquefaction/no liquefaction data points from Chengdu plain. Eight points from DPT tests at Larter Ranch and eight points from Pence Ranch are also shown.

Figure 13 provides a comparison of the induced cyclic stress ratios (CSR) for 8 boreholes at Larter Ranch relative to liquefaction triggering curve based on (a) BPT-based $(N_1)_{60}$ values and (b) DPT-based N'_{120} values. Each data point represents the average blow count and average CSR value for the critical liquefiable layer for the borehole. The DPT-based triggering curves are tied to the 30% probability of liquefaction curve developed by Cao et al. [13] adjusted for M_w7.5 with the magnitude scaling factor defined by Equation 4. The $(N_1)_{60}$-based triggering curve is that proposed for clean sand by [18] Youd et al. (2001). A comparison of the data in Figures 13 (a) and 13 (b) show that the factors of safety for the two sets of data are approximately the same using either the BPT based $(N_1)_{60}$ triggering curve or the DPT based N'_{120} triggering curve. The 30% probability of liquefaction curve developed by Cao et al. [13] appears to provide reasonable agreement with the deterministic curve developed by Youd et al. [18].

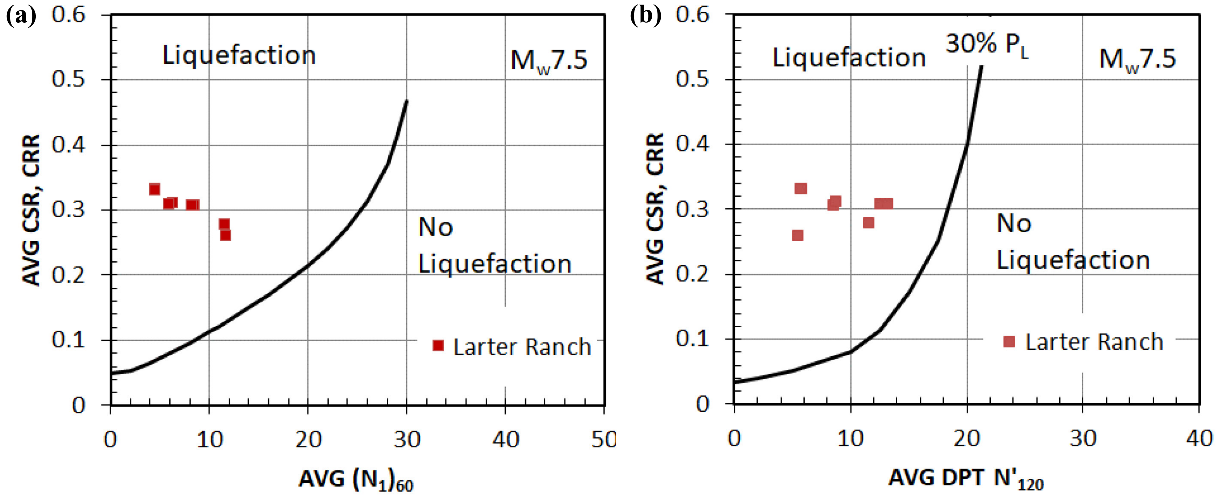


Figure 13. Comparison of (a) CSR vs. BPT-based $(N_1)_{60}$ data points for Larter Ranch and Pence Ranch in comparison with triggering curve with (b) CSR vs. DPT N'_{120} data points for Larter Ranch and Pence Ranch in comparison with triggering curve for 30% probability of liquefaction [13] for M_w7.5 earthquakes.

VI. Liquefaction and Site Characterization at Pence Ranch in Idaho

Liquefaction of gravelly soil was observed at the Pence Ranch during the M_w6.9 Borah Peak earthquake in 1983 [6], [7]. The Pence Ranch is located about 10 miles north of Mackay near the Big Lost River in central Idaho (latitude: 43.993860º, longitude: -113.77300º) at shown in Figure 5. Peak ground acceleration was estimated to be about 0.39g at the ranch [6].

A. Liquefaction Features and Previous Investigations

A number of boils were observed at the surface consisting of sand and gravel. In addition, gravelly sand ejecta erupted from a fissure formed as a result of lateral spreading near the hay yard as shown in Figure 14. After the earthquake, site investigations were reported by [6] near the surface fissure. The locations of closed-end BPT holes are shown in Figure 15 and the interpreted soil profile is shown in Figure 16.

Figure 14. Photograph showing a fissure in the ground at Pence Ranch produced by lateral spreading during the M_w6.9 Borah Peak Earthquake in 1983.

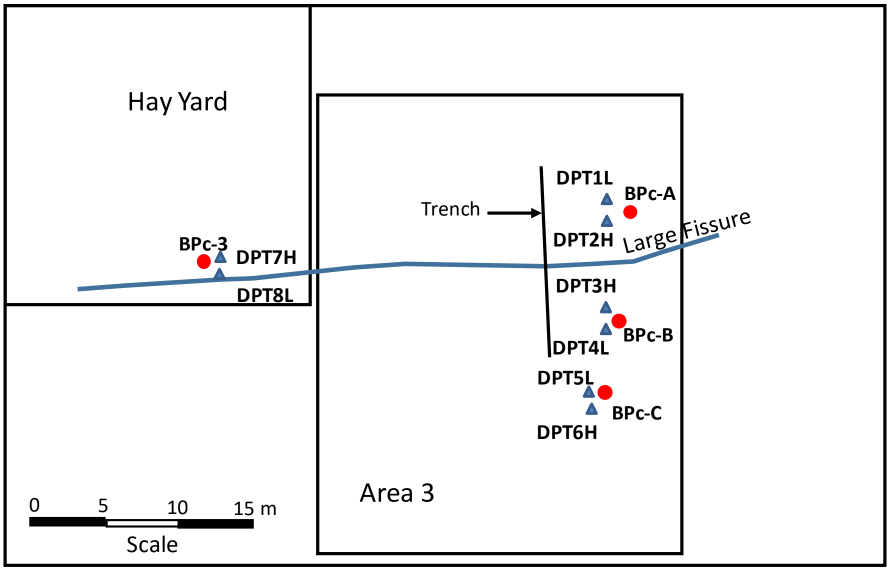


Figure 15. Plan view drawing showing location of closed-end Becker Penetration tests (BPc-A, BPc-B, BPc-C, and BPc-3) relative to the DPT test sounding in relation to the hay yard and a large fissure that formed owing to lateral spreading (Simplified from [6])

The idealized soil profile in Figure 16 consists of a surface layer which classifies as silty sand with gravel that is underlain by a layer ranging from gravelly sand to sandy gravel with cobbles. The water table was estimated to be at a depth of 1.5 m during the earthquake but was at a depth of about 4.5 m at the time of the DPT testing in November 2016. A plot showing the corrected Becker penetration resistance, N_{BC}, as a function of depth is provided in Figure 10 for BPT hole BPc-B. The BPT sounding suggests that the critical zone for liquefaction was a layer of sandy gravel located between about 1.5 and 4.0 m below the ground surface (Unit C). Trenching also showed that the ejecta originated from this layer [6]. The BPT blow count increases to between 15 and 20 between 4 and 6.5 m (Unit D), then jumps above 25 at about 7.5 m (Unit E) and increases linearly to about 60 at a depth of 11 m. The soils at the site are generally Holocene alluvial deposits [6].

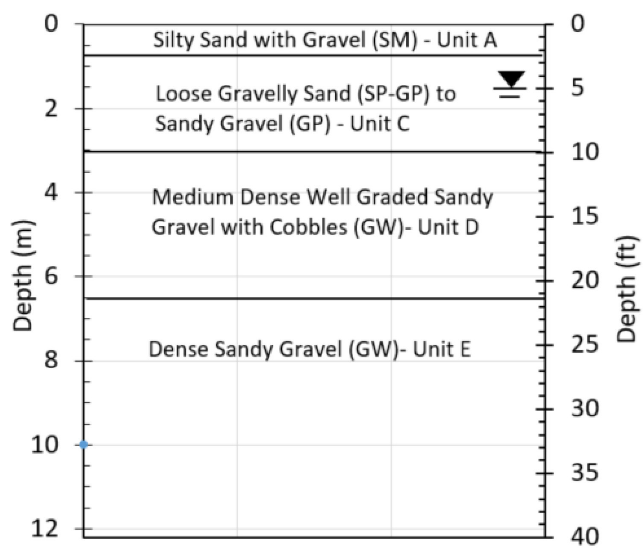


Figure 16. Interpreted soil profile at Hay Yard at Pence Ranch based on soil property descriptions provided by [6].

B. DPT Testing at Pence Ranch

As part of this study, two DPT soundings were performed within about a meter of the previous BPT soundings using a CME 85 drill rig with the capability of using two different hammer energies. In one sounding the DPT cone was advanced using a conventional automatic SPT hammer with a weight of 140 lb (63.6 kg) dropped from a height of 30 inches (0.76 m). The second sounding was performed using a 340 lb (154.4 kg) automatic hammer with a drop height of 30 inches (0.76 m). Hammer energy measurements were made using an instrumented rod section and a PDA device. These measurements indicate that the SPT hammer and the 154.4 kg hammer delivered 93% and 85% of the theoretical free-fall energy, respectively. In contrast to the Chinese hammer system, which had a standard deviation in energy transfer of 6.9 to 7.6%, the standard deviation for tests with the automatic hammer were less than about 1.5%. Because the delivered energies are less than the energy typically supplied by a Chinese DPT hammer, it was necessary to correct the measured blow count downward using equation 5. The ratio of energy actually delivered divided by the energy delivered by the Chinese DPT hammer was 0.93 and 0.42 for the 154.4 and 63.6 kg hammers, respectively. Plots of the energy corrected DPT N_{120} versus depth for the 63.6 and 154.4 kg hammers are provided at BPc-B in Figure 17(a) and (b), respectively, in comparison with the BPT N_{BC}. Similar plots are provided for BPc-A in Figure 18.

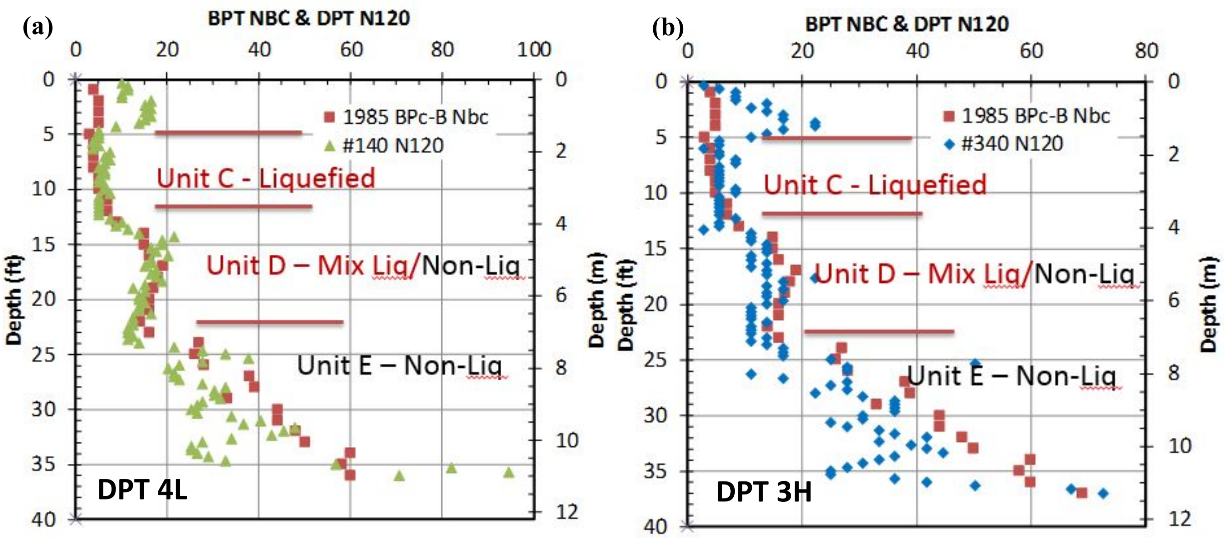


Figure 17. Plots of BPT NBC and DPT N_{120} versus depth using (a) a 63.6 kg (140 lb) SPT automatic hammer and (b) a 154.4 kg (340 lb) automatic hammer to drive the DPT at BPc-B. DPT N_{120} values are energy corrected to account for hammer energy.

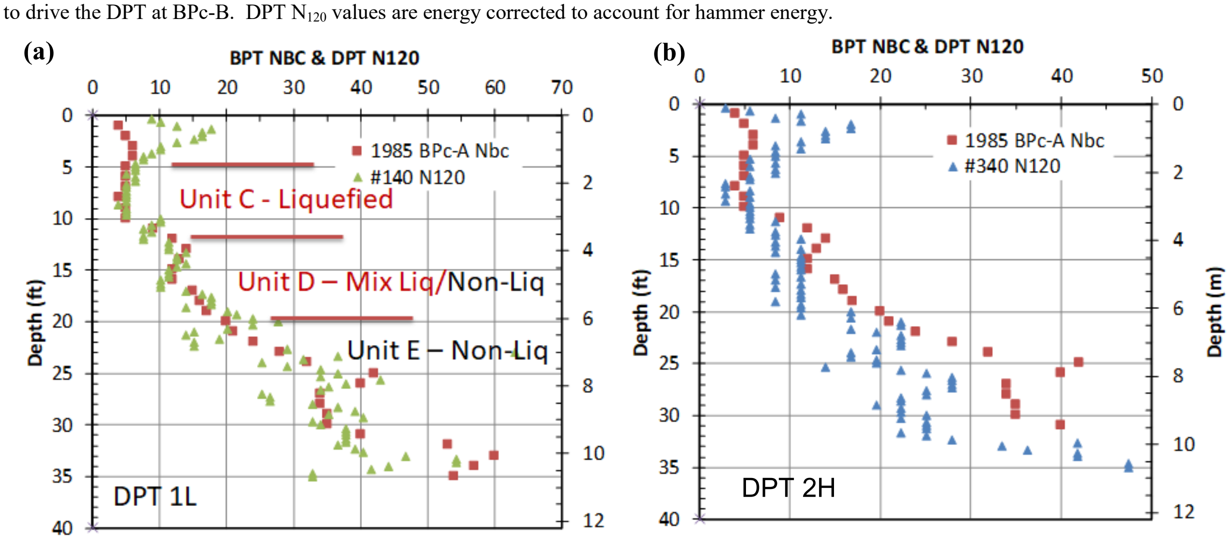


Figure 18. Plots of BPT NBC and DPT N_{120} versus depth using (a) a 63.6 kg (140 lb) SPT automatic hammer and (b) a 154.4 kg (340 lb) automatic hammer to drive the DPT at BPc-A. DPT N_{120} values are energy corrected to account for hammer energy.

For both hammer energies, the energy corrected DPT N_{120} value is fairly consistent with the trend defined by the BPT N_{BC} value with depth. The agreement is best within the depth range from 1.5 to 7.5 m. At shallower depths, both DPT soundings appear to identify a denser layer within the top 1.5 m of the profile than observed in the BPT testing. Likewise, at depths greater than 7.5 m, where the BPT blow count began to increase significantly, the DPT N_{120} was typically less than the BPT N_{BC} for both hammer energies. This result suggests that the cone tip is somewhat more efficient in penetrating the denser gravels than the Becker hammer. However, in terms of liquefaction assessment the difference may not be too significant as the blowcounts in these cases are relatively high and liquefaction would not be predicted with either in-situ test. It should also be noted that the triggering curve for the DPT curves upward at lower blowcounts than for SPT based method so differences at higher blowcounts must be expected.

A comparison of the N_{120} blow counts obtained from the two different hammer energies after energy correction with Equation 2 is provided in Figure 19 for two Becker locations. The data points generally fall within a reasonable range of the 1:1 line. Results from additional testing will be necessary to define the error bands and to determine if adjustments in the energy correction factor may be necessary for depth or gravel particle size.

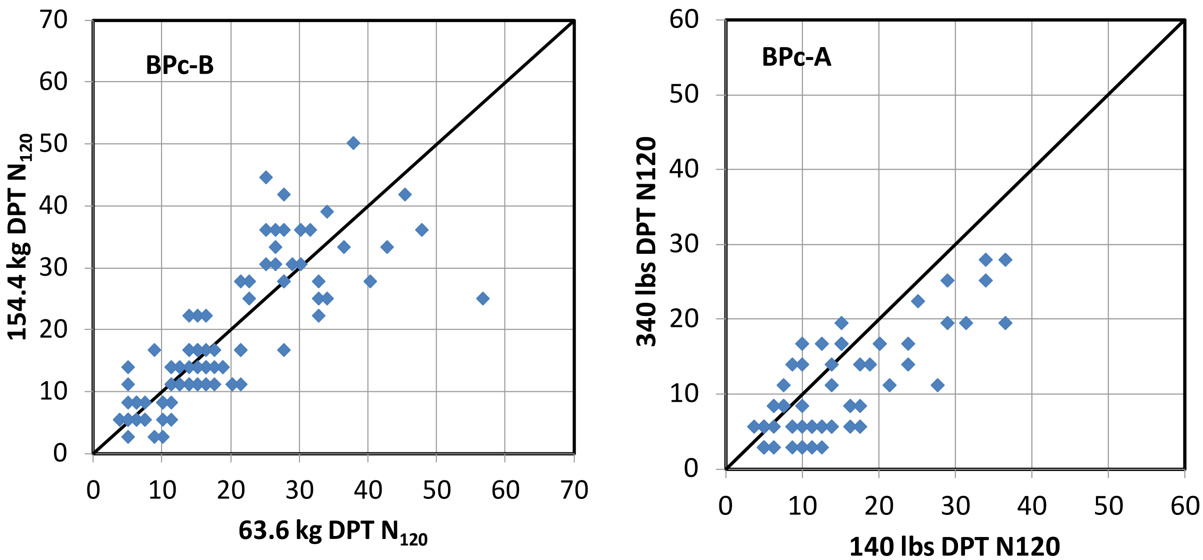


Figure 19. Comparison of DPT N_{120} obtained using the 140 lb (63.6 kg) and the 340 lb (154.4 kg) hammers after energy correction with equation 5 at two locations Becker Test l locations at Pence Ranch.

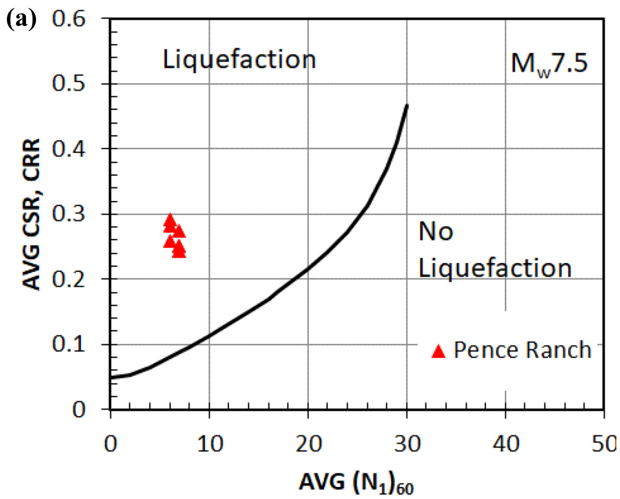
C. Liquefaction Evaluations at Pence Ranch

Liquefaction potential was evaluated using both the DPT and BPT methods of analysis. In the case of the BPT, the NBC value was converted to the equivalent sand SPT N_{60} using the Harder correlation approach [16]. The SPT N_{60} value was then corrected for overburden pressure effects using the same equation proposed by [18] Youd et al (2001). The cyclic stress ratio or CSR was computed using equation 2 which was originally developed by Seed and Idriss [26] where a_{max} is the peak ground acceleration of 0.39g. The CSR was adjusted for the M_w6.9 Borah Peak earthquake using the magnitude scaling factor in equation 3.

The cyclic stress ratio (CSR) at the Pence Ranch site is plotted as a function of BPT-based $(N_1)_{60}$ for the Unit C layers for all four Becker holes and 4 m below the ground surface in Figure 20(a). The triggering curve for M_w7.5 is also plotted in Figure 20 for comparison. All the CSR values are sufficiently high to produce liquefaction for the range of blow counts within this layer. $(N_1)_{60}$ values in the layer range from 6 to 16 and liquefaction factors-of-safety range from 0.28 to 0.54.

In the case of the DPT, the N_{120} value was first converted to N'_{120} using Equation 1. Then the CSR obtained from Equations 2 and 3 was plotted as function of N'_{120} using average values within the zone of liquefaction (Unit C) for each of the 8 DPT holes in Figure 20(b). The liquefaction triggering curve was based on the 30% probability curve developed by Cao et al [13] as was done previously for the data at Larter Ranch. However, the triggering curve in Figure 22(b) was adjusted to be consistent with a standard M_w7.5 event using the magnitude scaling factor relative to the M_w7.9 China earthquake used to develop the DPT triggering curves.

As in the previous case with the BPT-based analysis, all the CSR values are high enough to produce liquefaction for the range of N'_{120} values within the susceptible layer. N'_{120} values in the layer range from 3 to 15, but are more typically between 6 and 10. Liquefaction factors-of-safety range from 0.18 to 0.45. The CSR-DPT N'_{120} data pairs for each hole at the Pence Ranch are plotted in Figure 12 in comparison with the probabilistic liquefaction triggering curves [13] after magnitude scaling adjustments which shifted the measured CSR values downward. In all cases the data pairs plot above the 50% probability of liquefaction curve which is consistent with the observed liquefaction at both sites.



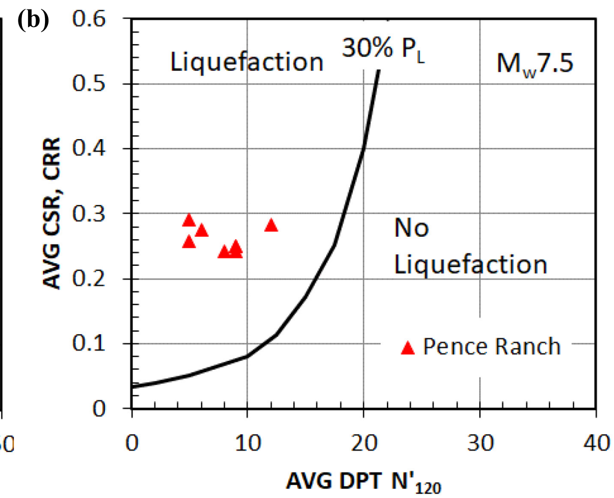


Figure 20. Comparison of (a) CSR vs. BPT-based $(N_1)_{60}$ data for Pence Ranch in comparison with triggering curve with (b) CSR vs. DPT N'_{120} data points for Pence Ranch in comparison with triggering curve for 30% probability of liquefaction [13] for M_w7.5 earthquakes.

VII. Conclusions

Based on the results of the field investigations conducted during this study, the following conclusions have been developed:

1. The Chinese dynamic cone penetrometer could generally be driven through profiles of sandy gravel alluvium with 40 to 60% gravel content using only the conventional SPT hammer energy despite the larger particle sizes.
2. Typical hammer energy correction factors provide a reasonable means for adjusting the blowcount from the SPT hammer to give blowcounts that would be obtained with the conventional Chinese DPT hammer energy. However, use of this procedure will lead to additional uncertainty in the blowcount because of observed scatter in the correlation. Ideally, the heavier hammer should be used for liquefaction evaluation whenever possible.
3. When the DPT rods are more than about 5º from vertical, the side friction can increase, reducing the energy that is actually transferred to the cone tip, and producing artificially high N'_{120} values which are unreliable. If this condition develops, the DPT cone should be withdrawn and the test repeated.
4. Liquefaction triggering correlations based on the DPT N'_{120}, correctly identified sites where liquefaction features were observed at both the Pence Ranch and Larter Ranch site.
5. The field case histories investigated during this study indicate that DPT N'_{120} correlations can provide liquefaction triggering evaluations quickly, reliably and more economically than the Becker Penetration test at depths less than about 15 m or 50 ft.

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Kyle Rollins received his BS degree from Brigham Young University and his Ph.D. from the University of California at Berkeley. After working as a geotechnical consultant, he joined the Civil Engineering faculty at BYU in 1987 following after his father who was previously a geotechnical professor. His research has involved geotechnical earthquake engineering, liquefaction, deep foundation behavior, bridge abutment behavior, collapsible soils and soil improvement techniques. ASCE has recognized his work with the Huber research award, the Wellington prize, and the Wallace Hayward Baker award. In 2009, he was the Cross-Canada Geotechnical lecturer for the Canadian Geotechnical Society. He received the Jorj Osterberg Award from the Deep Foundations Institute in 2014.