

# RECLAMATION

*Managing Water in the West*

## Dynamic Cone Penetration Tests for Liquefaction Evaluation of Gravelly Soils

Research and Development Office  
Science and Technology Program  
(Final Report) ST-2017-7102



U.S. Department of the Interior  
Bureau of Reclamation  
Research and Development Office

November 2017

## **Mission Statements**

The mission of the Department of the Interior is to protect and manage the Nation's natural resources and cultural heritage; provide scientific and other information about those resources; and honor its trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public

### **Disclaimer:**

This document has been reviewed under the Research and Development Office Discretionary peer review process [https://www.usbr.gov/research/peer\\_review.pdf](https://www.usbr.gov/research/peer_review.pdf) consistent with Reclamation's Peer Review Policy CMP P14. It does not represent and should not be construed to represent Reclamation's determination, concurrence, or policy.

<b>REPORT DOCUMENTATION PAGE</b>		<i>Form Approved</i> <i>OMB No. 0704-0188</i>
<b>T1. REPORT DATE:</b> SEPTEMBER 2017	<b>T2. REPORT TYPE:</b> RESEARCH	<b>T3. DATES COVERED</b> Oct 2016-Oct 2017
<b>T4. Dynamic Cone Penetration Tests for Liquefaction Evaluation of Gravelly Soils</b>		<b>5a. CONTRACT NUMBER</b>
		<b>5b. GRANT NUMBER</b>
		<b>5c. PROGRAM ELEMENT NUMBER</b> 1541 (S&T)
<b>6. Mike Talbot, <a href="mailto:mtalbot@usbr.gov">mtalbot@usbr.gov</a>, 801-379-1286</b>		<b>5d. PROJECT NUMBER</b> ST-2017-7102-IS
		<b>5e. TASK NUMBER</b>
		<b>5f. WORK UNIT NUMBER</b> PRO-703
<b>7. Mike Talbot, Provo Area Office, Bureau of Reclamation</b>		<b>8. PERFORMING ORGANIZATION REPORT NUMBER</b>
<b>9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)</b> Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007		<b>10. SPONSOR/MONITOR'S ACRONYM(S)</b> <b>R&amp;D:</b> Research and Development Office <b>BOR/USBR:</b> Bureau of Reclamation <b>DOI:</b> Department of the Interior
		<b>11. SPONSOR/MONITOR'S REPORT NUMBER(S)</b> ST-2017-7102-IS
<b>12. DISTRIBUTION / AVAILABILITY STATEMENT</b> Final report can be downloaded from Reclamation's website: <a href="https://www.usbr.gov/research/">https://www.usbr.gov/research/</a>		
<b>13. SUPPLEMENTARY NOTES</b>		
<b>14. ABSTRACT</b>  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 Mw7.9 Wenchuan earthquake. The DPT consists of a 74 mm diameter cone tip driven by a 120 kg hammer with a free fall height of 100 cm. To expand the data base, DPT soundings were performed at the Pence Ranch and Larter Ranch sites where gravelly soil liquefied during the 1983 Mw6.9 Borah Peak earthquake. DPT testing was performed using an automatic hammer with the energy specified in the Chinese standard and with an SPT hammer. Comparisons suggest that standard energy corrections developed for the SPT can be used for the DPT. In general, the DPT correctly predicted liquefaction and non-liquefaction at these two test sites. Liquefaction resistance from the DPT also correlated reasonably well with that from Becker penetration testing (BPT).		

<b>15. SUBJECT</b> Liquefaction, Dynamic Cone Penetration, DPT					
<b>16. SECURITY CLASSIFICATION OF:</b>			<b>17. LIMITATION OF ABSTRACT</b> U	<b>18. NUMBER OF PAGES</b>	<b>19a. NAME OF RESPONSIBLE PERSON:</b> Mike Talbot
<b>a. REPORT</b> U	<b>b. ABSTRACT</b> U	<b>c. THIS PAGE</b> U			<b>19b. TELEPHONE NUMBER</b> 801-379-1286

S Standard Form 298 (Rev. 8/98)  
P Prescribed by ANSI Std. 239-18


# **BUREAU OF RECLAMATION**


**Research and Development Office  
Science and Technology Program**

**UC Region, Provo Area Office**

**Final Report ST-2017-1702**

## **Dynamic Cone Penetration Tests for Liquefaction Evaluation of Gravelly Soils**

  
Prepared by: Mike Talbot  
Resident Engineer, UC Region, Provo Area Office

  
Peer Review: Kyle M. Rollins, Ph.D.  
Graduate Advisor, Brigham Young University

**For Reclamation disseminated reports, a disclaimer is required for final reports and other research products, this language can be found in the peer review policy:**

*This document has been reviewed under the Research and Development Office Discretionary peer review process [https://www.usbr.gov/research/peer\\_review.pdf](https://www.usbr.gov/research/peer_review.pdf) consistent with Reclamation's Peer Review Policy CMP P14. It does not represent and should not be construed to represent Reclamation's determination, concurrence, or policy.*

# Acknowledgements

Funding for this study was provided by the US Bureau of Reclamation Science and Technology Program, Research and Development Office, and is gratefully acknowledged. In cooperation with Brigham Young University, additional funding was provided by a grant from the US Geological Survey Earthquake Hazard Reduction Program.

# Acronyms and Abbreviations

BPT    Becker Hammer Penetration Test

CPT    Cone Penetration Test

DPT    Dynamic Cone Penetration Test

SPT    Standard Penetration Test

# Executive Summary

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 in a significant number of earthquakes. As a result of these case histories, engineers and geologists are frequently called upon to assess the potential for liquefaction in gravels. Therefore, innovative methods for characterizing and assessing liquefaction hazards in gravels are an important objective in geotechnical engineering.

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 Mw7.9 Wenchuan earthquake. The DPT consists of a 74 mm diameter cone tip driven by a 120 kg hammer with a free fall height of 100 cm. To expand the data base, DPT soundings were performed at the Larter Ranch site where gravelly soil liquefied during the 1983 Mw6.9 Borah Peak earthquake. DPT testing was performed using an automatic hammer with the energy specified in the Chinese standard and with an SPT hammer. Comparisons suggest that standard energy corrections developed for the SPT can be used for the DPT. In general, the DPT correctly predicted liquefaction and non-liquefaction at this test site. Liquefaction resistance from the DPT also correlated reasonably well with that from Becker penetration testing (BPT).

Based on investigations conducted using the Chinese Dynamic Cone Penetrometer (DPT) test at the Larter Ranch liquefaction site the following conclusions have been developed:

1. The Chinese dynamic cone penetrometer can generally be driven through gravelly profiles using only the conventional SPT hammer energy with modern truck-mounted equipment.
2. Typical hammer energy correction factors provide a reasonable means for adjusting the blow count from the SPT hammer to give blow counts that would be obtained with the conventional

Chinese DPT hammer energy. However, where possible the original hammer energy should be used to minimize uncertainty from scatter in the correlation between SPT and DPT energy.

3. CSR- $N'_{120}$  data pairs for all holes at the Larter Ranch and Pence Ranch sites plotted above the 50% probability of liquefaction curve consistent with the observed field performance.

4. The results in this paper suggest that the DPT can economically provide reasonable liquefaction hazard evaluations using direct correlations with field performance. However, data points are still relatively limited and additional data points for sites that did and did not liquefy are needed to verify and refine the probabilistic DPT-based triggering curves.

Recommended next steps are:

Continue to bolster data with more investigations and correlations. The results contained in this paper suggest that the DPT can economically provide reasonable liquefaction hazard evaluations using direct correlations with field performance. However, data points are still relatively limited and additional data points for sites that did and did not liquefy are needed to verify and refine the probabilistic DPT-based triggering curves.



# Contents

Executive Summary .....	vii
Introduction.....	1
LIMITATIONS OF CURRENT METHODS FOR CHARACTERIZING GRAVEL ...	2
DEVELOPMENT OF DYNAMIC CONE PENETRATION TEST (DPT) FOR GRAVELS	
.....	3
LIQUEFACTION RESISTANCE CURVE BASED ON DPT PENETRATION	
RESISTANCE .....	4
LIQUEFACTION RESISTANCE CURVE BASED ON BECKER PENETRATION	
RESISTANCE .....	6
LIQUEFACTION AND SITE CHARACTERIZATION AT LARTER RANCH IN IDAHO	
.....	7
DPT TESTING AT LARTER RANCH .....	9
Conclusions.....	14
References.....	15

# Tables

Table 1. Case histories involving liquefaction of gravelly soil .....	1
---	---

# Figures

<b>Figure 1.</b> Correlation between corrected BPT and SPT blowcounts from Harder and Seed (1986) supplemented with data from additional test sites (Harder, 1997). ....	2
<b>Figure 2.</b> Component sketch of tripod and drop hammer setup for dynamic penetration tests (DPT) along with DPT cone tip. (After Cao, Youd, and Yuan, 2011). ....	4
<b>Figure 3.</b> CRR vs. DPT $N'_{120}$ triggering curves for various probabilities of liquefaction in gravelly soils developed by Cao et al (2013) adjusted for $M_w7.5$ earthquakes. Liquefaction/no liquefaction data points from sites on the Chengdu plain are also shown after adjustment to $M_w7.5$ . ....	6
<b>Figure 4.</b> Correlation between cyclic resistance ratio and corrected SPT blowcount based on liquefaction case histories for $M_w7.5$ earthquakes (Youd et al. 2001). ....	7

<b>Figure 5.</b> Regional Map of the Big Lost River and Thousand Springs Valleys showing geographic features, approximate trace of fault rupture, and locations of liquefaction sites (Andrus 1994).....	8
<b>Figure 6.</b> Cross-section through alluvial fan perpendicular to the Thousand Springs Creek showing soil stratigraphy, locations of BPT and DPT holes, and lateral spread features, (Modified from Andrus, 1994). ....	8
<b>Figure 7.</b> Photograph showing large fissures produced by liquefaction-induced lateral spread displacement towards the Thousand Springs Creek to the left.....	9
<b>Figure 8.</b> Plots of DPT $N'_{120}$ versus depth for (a) light hammer and (b) heavy hammer after energy ratio correction in comparison with BPT test BPc-1. ....	10
<b>Figure 9.</b> Plots of DPT $N'_{120}$ versus depth for (a) light hammer and (b) heavy hammer after energy ratio correction in comparison with BPT test BPc-2. ....	11
<b>Figure 10.</b> Plots of DPT $N'_{120}$ versus depth for (a) light hammer and (b) heavy hammer after energy ratio correction in comparison with BPT test BPc-3. ....	11
<b>Figure 11.</b> Plots of DPT $N'_{120}$ versus depth for (a) light hammer and (b) heavy hammer after energy ratio correction in comparison with BPT test BPc-4. ....	12
<b>Figure 12.</b> CRR vs. DPT $N'_{120}$ curves for various probabilities of liquefaction in gravelly soils developed by Cao et al (2013) along with liquefaction/no liquefaction data points from Chengdu plain. Points from DPT tests at Pence Ranch and Larter Ranch are also shown.....	13
<b>Figure 13.</b> 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 (Cao et al. 2013) for $M_w 7.5$ earthquakes. ....	13

# 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 indicated 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. Therefore, innovative methods for characterizing and assessing liquefaction hazards in gravels are certainly an important objective in geotechnical engineering.

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 objective of this paper is to provide comparative evaluations of the liquefaction resistance estimated by the DPT and the BPT for a site where gravelly soils liquefied during a major earthquake. In addition, comparisons will be provided between DPT resistance obtained with the Chinese hammer energy and the energy delivered by an SPT hammer after appropriate energy corrections.

**Table 1. Case histories involving liquefaction of gravelly soil**

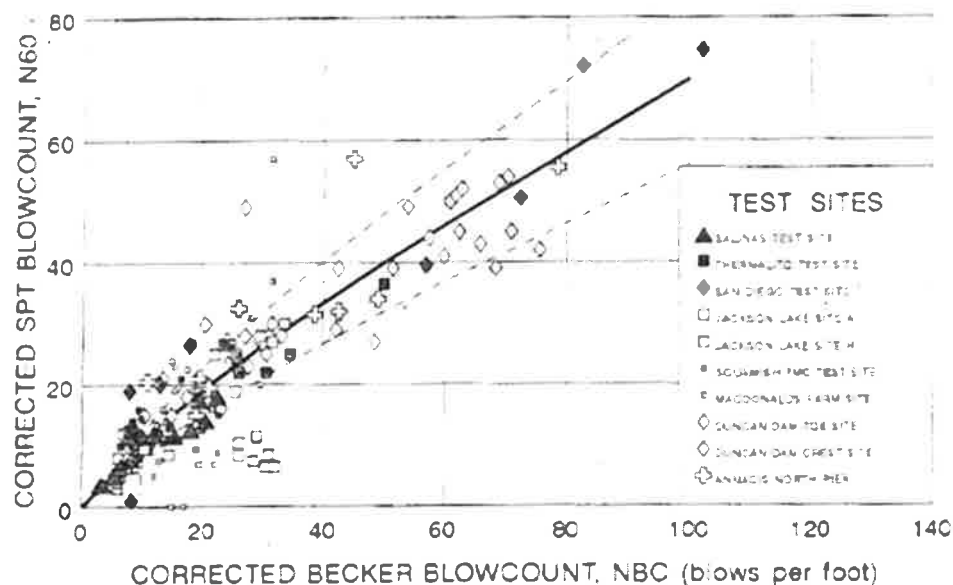
Year	Earthquake	$M_w$	Reference
1891	Mino-Owari, Japan	7.9	Tokiatsu & Yoshimi (1983)
1948	Fukui, Japan	7.1	Ishihara (1985)
1964	Seward, Alaska	9.2	Coulter & Migliaccio (1966)
1975	Haicheng, China	7.3	Wang (1984)
1976	Tangshan, China	7.8	Wang (1984)
1976	Friuli, Italy	6.2	Sirovich (1996)
1978	Miyagiken-Oki, Japan	7.4	Tokimatsu & Yoshimi (1983)
1983	Borah Peak, Idaho	6.9	Youd et al(1985)
1988	Armenia	6.8	Yegian et al (1994)
1992	Roermond, Netherlands	5.8	Maurenbrecher et al (1995)
1993	Hokkaido, Japan	7.8	Kokusho et al (1995)
1995	Kobe, Japan	7.2	Kokusho & Yoshida (1997)
1999	Chi-Chi, Taiwan	7.6	Chu et al (2000)
2008	Wenchuan, China	7.9	Cao et al (2013)
2014	Cephalonia Is., Greece	6.1	Nikolaou et al (2014)
2016	Kaikora, New Zealand	7.8	Cubrinovsky et al (2017)

# LIMITATIONS OF CURRENT METHODS FOR CHARACTERIZING GRAVEL

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 (Harder and Seed 1986, Harder 1997) as shown in Figure 1. Despite the scatter, the correlation appears to be reasonably good.



**Figure 1. Correlation between corrected BPT and SPT blowcounts from Harder and Seed (1986) supplemented with data from additional test sites (Harder, 1997).**

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. Sy and Campanella (1994) 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. Sy (1997) 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. (2014) 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 (DeJong et al. 2017). This correlation, while representing a major improvement on the Harder (1997) correlation, 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  $q_{cIN}$ , for example.

## **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 (Chinese Specifications 1999, Chinese Design Code 2001). Because of widespread gravelly deposits beneath the Chengdu plain, the DPT is widely used in that region, particularly for the evaluation of liquefaction potential (Cao et al. 2011).

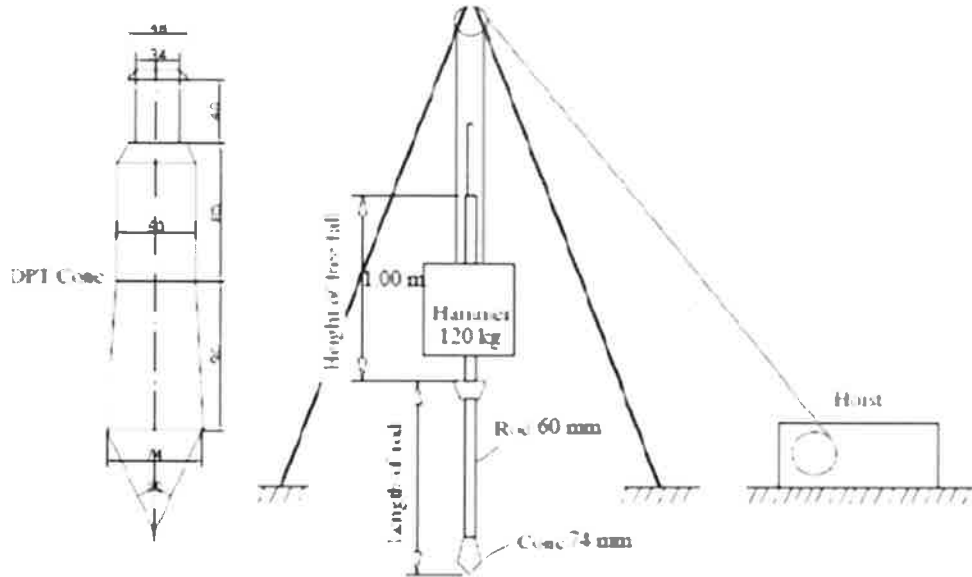
DPT equipment is relatively simple, consisting of a 120-kg (264 lb) hammer, raised to a free fall height of 100 cm (39 in), then dropped onto an anvil attached to 60-mm diameter drill rods which in turn are attached to a solid steel cone tip with a diameter of 74 mm and a cone angle of 60° as shown in Figure 2. The smaller diameter rod helps to reduce shaft friction on the rods behind the cone tip.

Prior to testing, the drill rods are marked at 10 cm intervals and the number of blows required to penetrate each 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 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

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

where  $N'_{120}$  is the corrected DPT resistance in blows per 30 cm,  $N_{120}$  is the measured DPT resistance in blows per 30 cm, 100 is atmospheric pressure in  $\text{kN/m}^2$ , and  $\sigma'_v$  is the vertical effective stress in  $\text{kN/m}^2$  (Cao et al, 2013).



**Figure 2. Component sketch of tripod and drop hammer setup for dynamic penetration tests (DPT) along with DPT cone tip. (After Cao, Youd, and Yuan, 2011).**

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 (Cao et al. 2013). These measurements indicate that on average 89% of the theoretical hammer energy was transferred to the drill rods with this system.

## 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 2 to 4 m of clayey soils, which, in turn, were underlain by gravel beds up to 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 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 DPT sites without liquefaction effects. Thus, low DPT resistance became a reliable identifier of liquefiable layers (Cao et al. 2011).

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

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

where  $a_{max}$  is the peak ground acceleration,  $\sigma_{vo}$  is the initial vertical total vertical stress,  $\sigma'_{vo}$  is the initial vertical effective stress, and  $r_d$  is a depth reduction factor as defined by Youd et al (2001).

Using DPT data, Cao et al. (2013) plotted the cyclic stress ratio causing liquefaction against DPT  $N'_{120}$  for the  $M_w 7.9$  Wenchuan earthquake. Points where liquefaction occurred were shown as solid red dots, while sites without liquefaction were shown with open circles. Cao et al. (2013) also defined curves indicating 15, 30, 50, 70 and 85% probability of liquefaction based on logistical regression. Most other liquefaction triggering curves are calibrated for  $M_w 7.5$  earthquakes. To facilitate comparison with data points from other earthquakes, we have shifted the Cao et al. data points and triggering curves upward to represent performance during a  $M_w 7.5$  earthquake using the equation

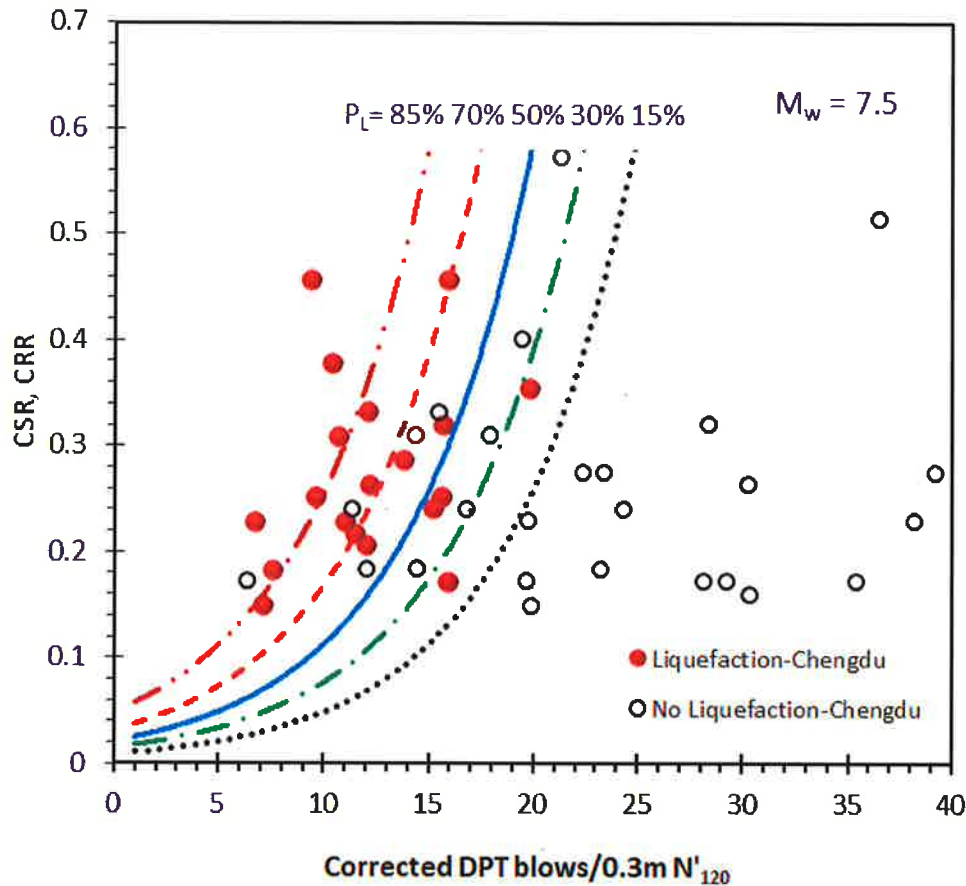
$$CSR_{M_w 7.5} = \frac{CSR}{MSF} \quad (3)$$

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

$$MSF = \frac{10^{2.24}}{M_w^{2.56}} \quad (4)$$

proposed by Youd et al. 2001. 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 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 Cao et al (2013) to predict accurately liquefaction in gravelly soil. For the Idaho case histories, the geology, earthquake magnitude, and gravel layers are significantly different from those in the Chengdu plain of China and will provide a good test of the method.



**Figure 3. CRR vs. DPT  $N'_{120}$  triggering curves for various probabilities of liquefaction in gravelly soils developed by Cao et al (2013) adjusted for  $M_w 7.5$  earthquakes. Liquefaction/no liquefaction data points from sites on the Chengdu plain are also shown after adjustment to  $M_w 7.5$ .**

## LIQUEFACTION RESISTANCE CURVE BASED ON BECKER PENETRATION RESISTANCE

Using the correlation between the corrected BPT penetration resistance, NBC, and the SPT penetration resistance corrected for hammer energy,  $N_{60}$ , shown in Figure 1, liquefaction resistance curves for sand shown in Figure 4 can be used to evaluate liquefaction in gravelly soil. This approach assumes that the Becker hammer is relatively unaffected by the particle size of the gravel.

As shown in Figure 4, the liquefaction boundary curves are essentially vertical at cyclic stress ratios greater than 0.5. For example, with a fines content less than 5%, the CRR is undefined for SPT  $(N_1)_{60}$  values greater than 29, although the liquefaction resistance is clearly higher than a value of 0.50. In contrast, the CRR vs  $N'_{120}$  curves have a somewhat positive slope at their upper limits likely because of the lack of adequate field performance data.



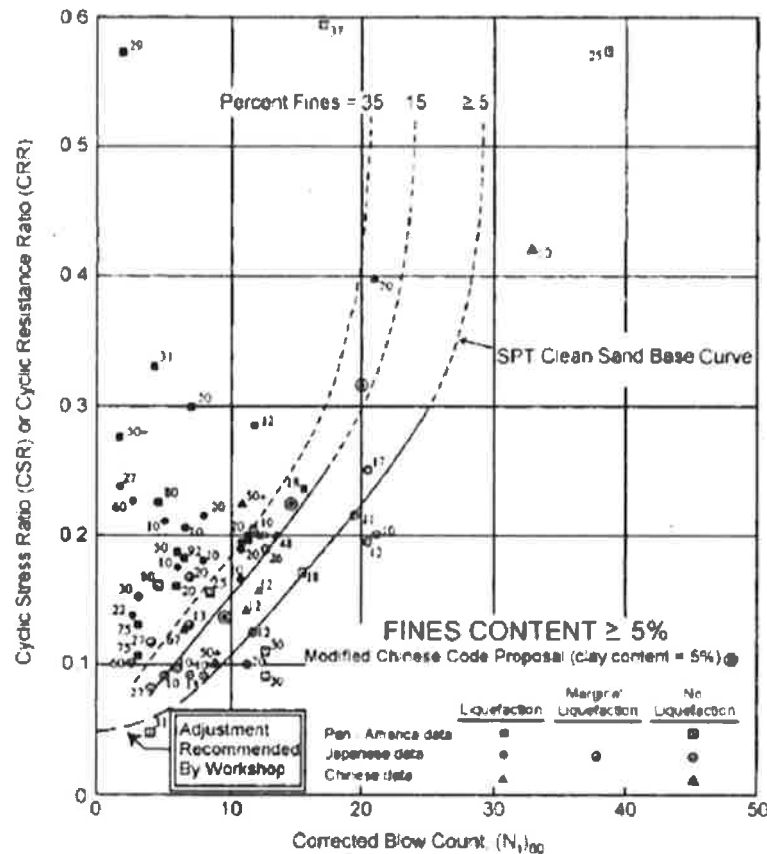


Figure 4. Correlation between cyclic resistance ratio and corrected SPT blowcount based on liquefaction case histories for Mw7.5 earthquakes (Youd et al. 2001).

## 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 (Andrus, 1994; Youd et al. 1985). The Larter Ranch is located about 16 miles northwest of Mackay, Idaho near Thousand Springs Creek in central Idaho (latitude: 44.073452°, longitude: -113.842211°). As illustrated in Figure 6, liquefaction of the gravelly soils at the distal end of an alluvial fan caused lateral spread displacements of about one meter (Andrus, 1994).

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 (Andrus, 1994). 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.

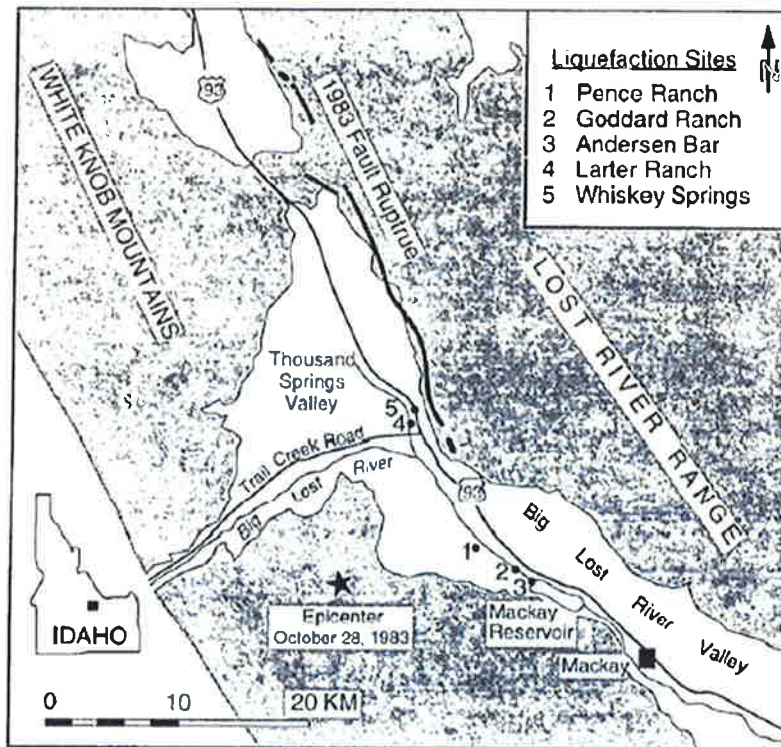


Figure 5. Regional Map of the Big Lost River and Thousand Springs Valleys showing geographic features, approximate trace of fault rupture, and locations of liquefaction sites (Andrus 1994).

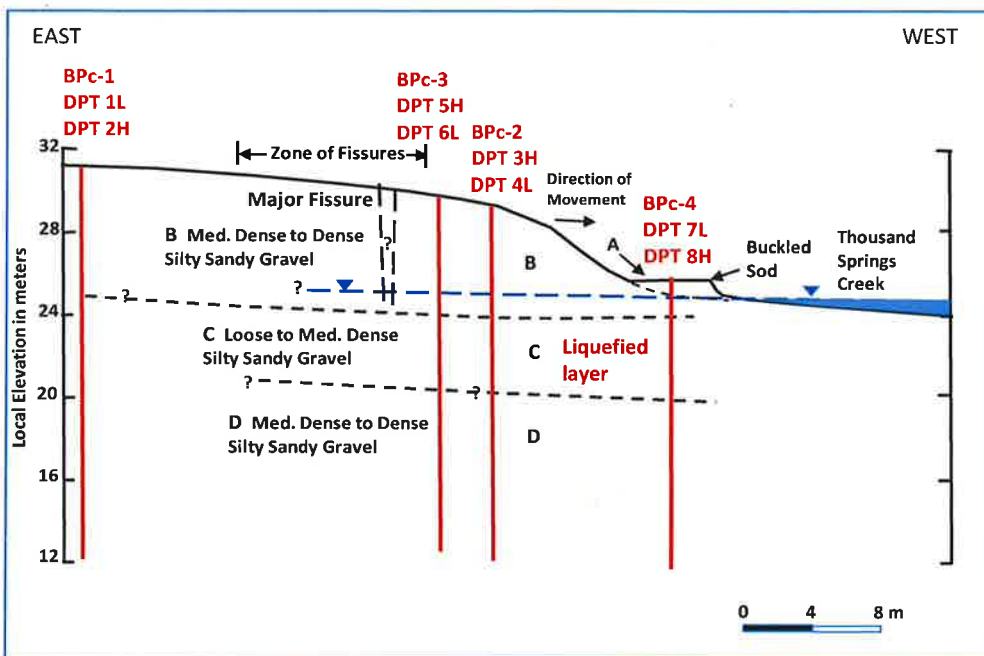


Figure 6. . Cross-section through alluvial fan perpendicular to the Thousand Springs Creek showing soil stratigraphy, locations of BPT and DPT holes, and lateral spread features, (Modified from Andrus, 1994).



**Figure 7. . 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 (Harder and Seed, 1986). In addition, cone penetration tests (CPT), Standard Penetration tests (SPT) and shear wave velocity testing was performed. Based on these field investigations, Andrus (1994) 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%.

## **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. In one sounding, the DPT cone was advanced using a conventional automatic

SPT hammer with a weight of 63.6 kg (140 lbs) dropped from a height of 0.76 m (30 in). The second sounding was performed using a 154.4 kg (340 lb) automatic hammer with a drop height of 0.76 m (30 in). The DPT was able to penetrate to over 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 about 91% and 90% of the theoretical free-fall energy, respectively. 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

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

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 8-11 in comparison with the BPT NBC. For both hammer energies, the energy corrected DPT  $N_{120}$  value is fairly consistent with the trend defined by the BPT NBC value with depth. However, at shallower depths, both DPT soundings appear to identify a denser layer from 1 to 3 m of the profile than observed in the BPT testing. This could be a result of aging in the 34 years since the time of the earthquake although the exact reason is unknown.

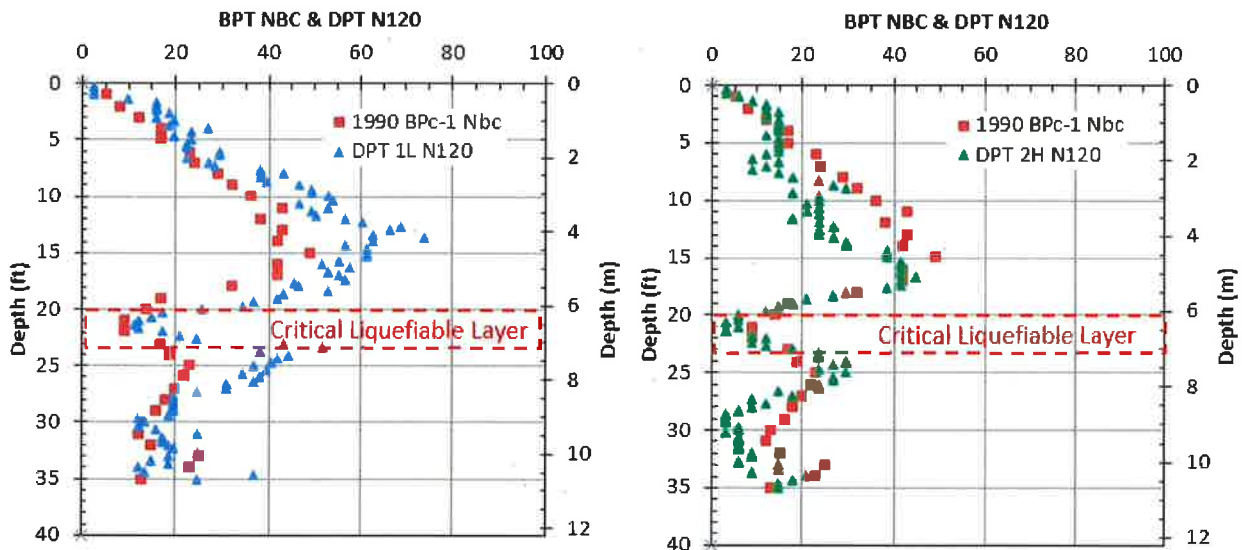
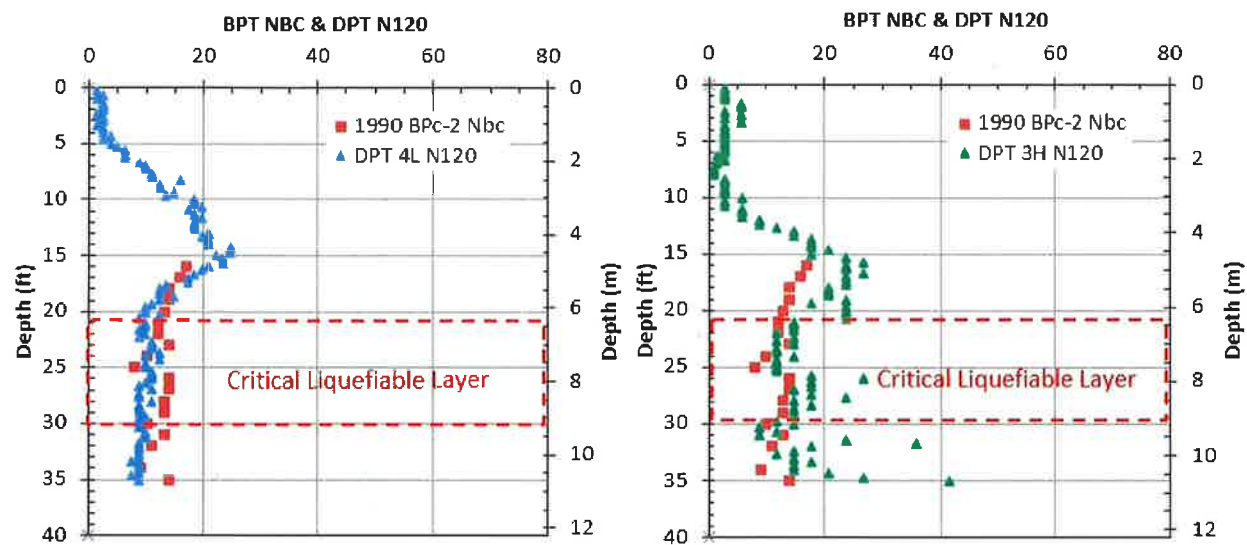
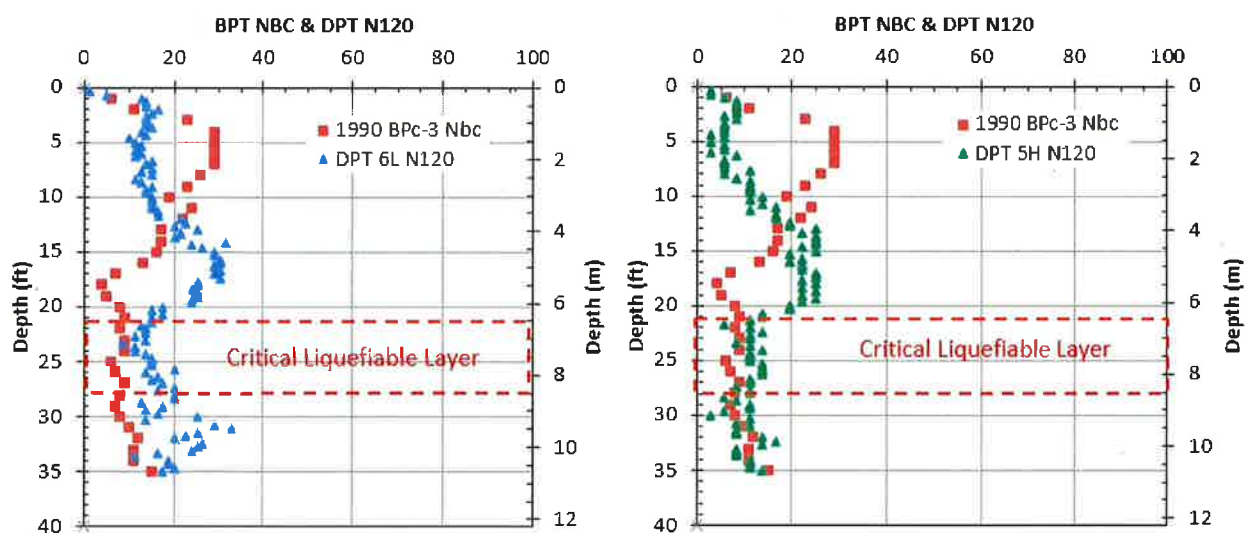


Figure 8. Plots of DPT  $N_{120}$  versus depth for (a) light hammer and (b) heavy hammer after energy ration correction in comparison with BPT test BPC-1.

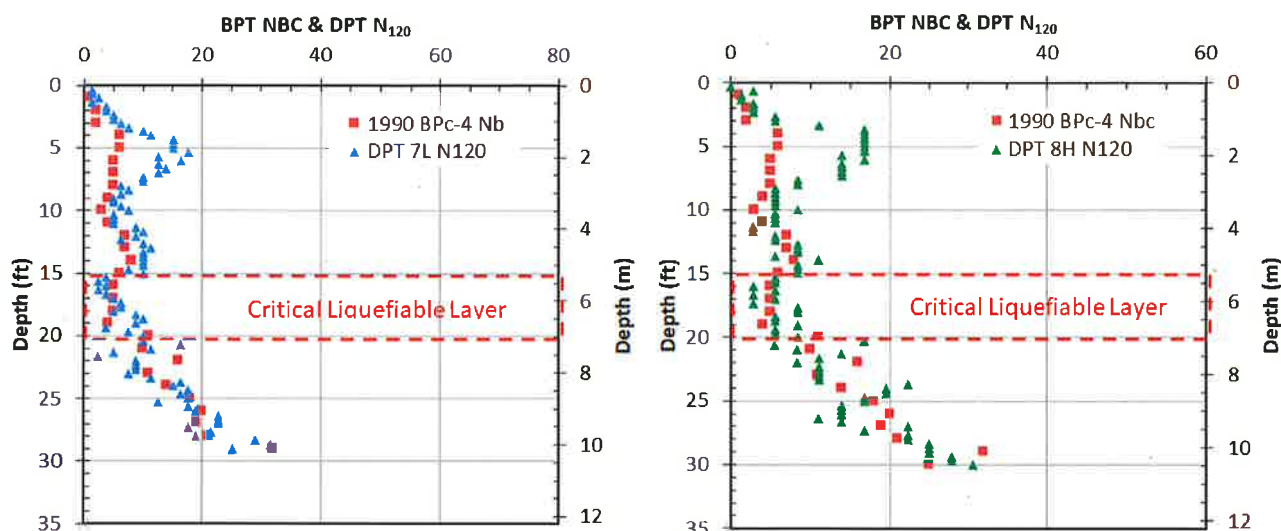




**Figure 9. Plots of DPT N'120 versus depth for (a) light hammer and (b) heavy hammer after energy ration correction in comparison with BPT test BPC-2.**



**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-3.**



**Figure 11. 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.**

The eight DPT test profiles provide an excellent opportunity to evaluate the ability of the DPT-based liquefaction triggering curves developed by Cao et al (2013) to predict accurately liquefaction in gravelly soil. For each DPT sounding, we estimated the critical layer for liquefaction as illustrated in Figures 8-11. 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. In addition, similar CSR- $N'_{120}$  data pairs for 8 DPT soundings obtained from the Pence Ranch site (Rollins et al 2017) located 10 km North of the Larter Ranch (see Figure 6) were also plotted. The data pairs for each hole at the Pence Ranch and Larter Ranch are plotted in Figure 12 in comparison with the Cao et al (2013) liquefaction triggering curves 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 13 provides a comparison of the induced cyclic stress ratios (CSR) for 8 boreholes at Larter Ranch and 8 boreholes at Pence 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 based on the 30% probability of liquefaction curve developed by Cao et al (2013) adjusted for  $M_w 7.5$  with the magnitude scaling factor defined by Equation 4. The  $(N_1)_{60}$ -based triggering curve is that proposed for clean sand by Youd et al. (2001). A comparison of the data in Figures 13a and 13b 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 (2013) appears to provide reasonable agreement with the deterministic curve developed by Youd et al (2001). This finding is consistent with previous investigations (Rollins et al. 2016).

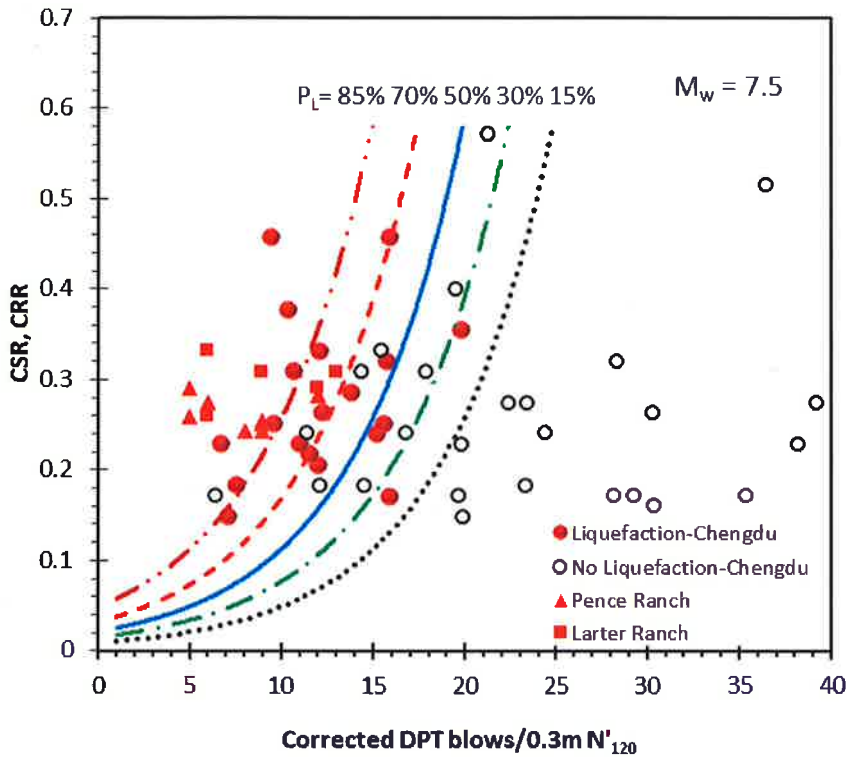


Figure 12. CRR vs. DPT  $N'_{120}$  curves for various probabilities of liquefaction in gravelly soils developed by Cao et al (2013) along with liquefaction/no liquefaction data points from Chengdu plain. Points from DPT tests at Pence Ranch and Larter Ranch are also shown.

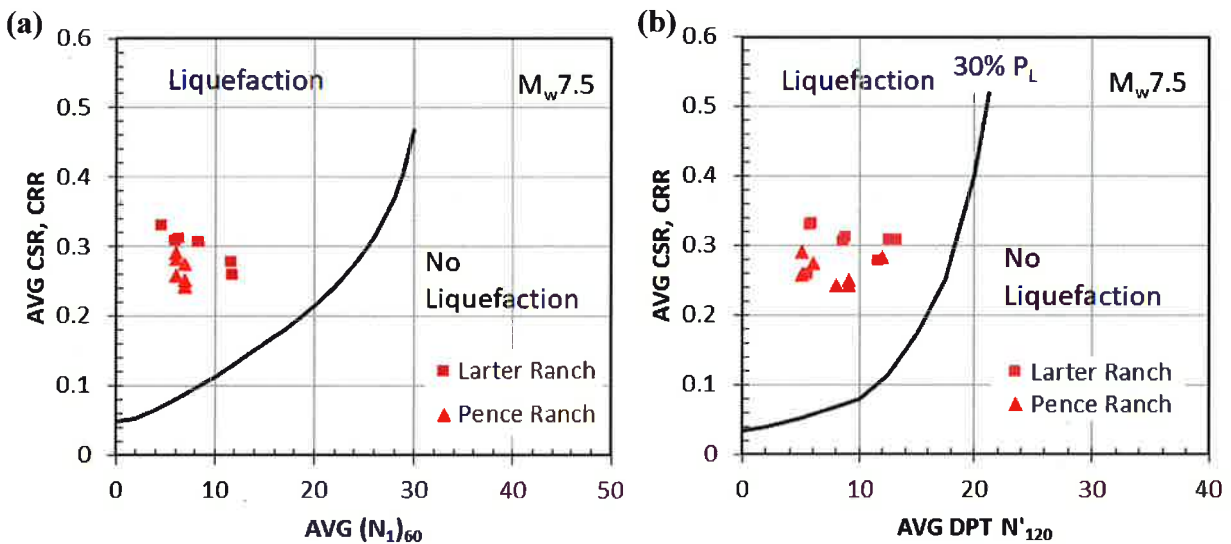


Figure 13. Comparison of (a) CSR vs. BPT-based  $(N_1)_{60}$  data points for Larter Ranch and Pence Ranch in comparison with triggering curve with (b) CSR vs. DPT  $N'_{120}$  data points for Larter Ranch and Pence Ranch in comparison with triggering curve for 30% probability of liquefaction (Cao et al. 2013) for  $M_w 7.5$  earthquakes.

# Conclusions

Based on investigations conducted using the Chinese Dynamic Cone Penetrometer (DPT) test at the Pence Ranch and Larter Ranch liquefaction sites the following conclusions have been developed:

1. The Chinese dynamic cone penetrometer can generally be driven through gravelly profiles using only the conventional SPT hammer energy with modern truck-mounted equipment.
2. Typical hammer energy correction factors provide a reasonable means for adjusting the blow count from the SPT hammer to give blow counts that would be obtained with the conventional Chinese DPT hammer energy. However, where possible the original hammer energy should be used to minimize uncertainty from scatter in the correlation between SPT and DPT energy.
3. CSR- $N'_{120}$  data pairs for all holes at the Larter Ranch and Pence Ranch sites plotted above the 50% probability of liquefaction curve consistent with the observed field performance.
4. The factors of safety for the 8 boreholes at the Larter Ranch and the 8 boreholes at the Pence Ranch Sites for the Borah Peak earthquake using the DPT-based 30% probability of liquefaction triggering curve are approximately the same as that obtained with the BPT-based liquefaction triggering curve.
5. The results in this paper suggest that the DPT can economically provide reasonable liquefaction hazard evaluations using direct correlations with field performance. However, data points are still relatively limited and additional data points for sites that did and did not liquefy are needed to verify and refine the probabilistic DPT-based triggering curves.



# References

- Andrus, R.D. (1994). "In situ characterization of gravelly soils that liquefied in the 1983 Borah Peak earthquake." Ph.D. Dissertation, Civil Engineering Dept., University of Texas at Austin, 579 p.
- Cao, Z., Yuan, X., Youd, T.L., and Rollins, K.M. (2012). "Chinese Dynamic Penetration tests (DPT) at liquefaction sites following 2008 Wenchuan Earthquake." *Proc. 4th Intl. Conf. on Site Characterization*, Pernambuco, Brazil.
- Cao, Z., Youd, T.L., Yuan, X., (2011). Gravelly soils that liquefied during 2008 Wenchuan, China Earthquake, Ms=8.0. *Soil Dynamics and Earthquake Engineering*, Elsevier, v. 31 (1132-1143).
- Cao, Z., Youd, T., and Yuan, X. (2013). Chinese Dynamic Penetration Test for liquefaction evaluation in gravelly soils. *J. Geotech. Geoenviron. Eng.*, ASCE 139(8): 1320–1333.
- Chinese Design Code (2001). *Design code for building foundation of Chengdu region*, Administration of Quality and Technology supervision of Sichuan Province PRC. (in Chinese), DB51/T5026-2001.
- Chinese Specifications (1999). *Specification of soil test*, Ministry of Water Resources of the People's Republic of China. (in Chinese), SL237-1999.
- Chu, B.L., Hsu, S.C., Lai, S.E., Chang, M.J. (2000). *Soil Liquefaction Potential Assessment of the Wufeng Area after the 921 Chi-Chi Earthquake*. Report of National Science Council. 2000. (in Chinese)
- Coulter, H.W. and Migliaccio (1966). "Effect of the Earthquake of March 22, 1964 at Valdez. Alaska." *U.S. Geological Survey Professional Paper 542-C*
- Cubrinovski, M., Bray, J., de la Torre, C., Olsen, 497 M., Bradley, B., Chiaro, G., Stocks, E., Wotherspoon, L. (2017). "Liquefaction effects and associated damages observed at the Wellington CentrePort from the 2016 Kaikoura earthquake." *Bulletin of the New Zealand Society for Earthquake Engineering*, 50(2), 152-173.
- Ghafghazi, M., DeJong, J.T., Sturm, AP., Temple, C.E. (2017). "Instrumented Becker Penetration Test. II:iBPT-SPT Correlation for Characterization and Liquefaction Assessment of Gravelly Soils." *J. Geotech. Geoenviron. Eng.* 143(9): 04017063
- Harder, L.F. (1997). "Application of the Becker Penetration Test for evaluating the liquefaction potential of gravelly soils." *NCEER Workshop on Evaluation of Liquefaction Resistance*, held in Salt Lake City, Utah.
- Harder, L. F., Jr., and Seed, H. B. (1986). "Determination of penetration resistance for coarse-grained soils using the Becker hammer drill." Report UCB/EERC-86/06, Earthquake Engrg. Res. Ctr., University of California-Berkeley
- Ishihara, K. (1985). "Stability of natural deposits during earthquakes." *Proc. 11th Int. Conf. on Soil Mech. and Found. Eng.*, San Fransico, Calif., Vol. 1, 321-376
- Kokusho, T., Tanaka, Y., Kudo, K., and Kawai, T., (1995). "Liquefaction case study of volcanic gravel layer during 1993 Hokkaido-Nansei-Oki earthquake." *Proc. 3rd Int. Conf. on Recent Advances in Geotech. Earthquake Eng. and Soil Dyn.*, St. Louis, Missouri, 235-242
- Kokushu, T. and Yoshida, Y., (1997). SPT N-value and S-wave velocity for gravelly soils with different grain size distribution, *Soils & Foundations*, 37(4): 105-113

- Maurenbrecher P.M., Den Outer A. and Luger, H.J. (1995). "Review of geotechnical investigations resulting from the Roermond April 13, 1992 earthquake." *Proc. 3<sup>rd</sup> Int. Conf. on Recent Advances in Geotech. Earthquake Eng. and Soil Dyn.*, St. Louis, Missouri, 645-652.
- Nikolaou, S., Zekkos, D., Assimaki, D., and Gilsanz, R. (2014). GEER/EERI/ATC Earthquake Reconnaissance January 26<sup>th</sup>/February 2<sup>nd</sup> 2014 Cephalonia, Greece Events, Version 1. ([http://www.geerassociation.org/index.php/component/geer\\_reports/?view=geerreports&id=32](http://www.geerassociation.org/index.php/component/geer_reports/?view=geerreports&id=32))
- Rollins, K., Youd, T.L. and Talbot, M. (2016). "Liquefaction Resistance of Gravelly Soil from Becker Penetrometer (BPT) and Chinese Dynamic Cone Penetrometer (DPT)." *Procs., 5<sup>th</sup> Intl. Conf. on Site Characterization*, Australian Geomechanics Society, Sydney, Vol. 1, p. 645-650.
- Rollins, K.M., Youd, T.L. and Talbot, M. (2017). "Liquefaction evaluation at a gravel site using the dynamic penetration test and the Becker penetration test." *Procs. Performance Based Design III*, Vancouver, Canada, 8 p.
- Sirovich, L., (1996). "In-situ testing of repeatedly liquefied gravels and liquefied overconsolidated sands." *Soils and Foundations*, (36)4: 35-44.
- Sy, A. (1997). "Twentieth Canadian Geotechnical Colloquium: Recent developments in the Becker penetration test: 1986-1996." *Canadian Geotech. J.* Vol. 34, 952-973
- Tokimatsu, K. and Yoshimi, Y., (1983). "Empirical correlation of soil liquefaction based on SPT N-value and fines content." *Soils and Foundations*, 23(4): 56-74
- Wang, W.S. (1984). "Earthquake damages to earth dams and levees in relation to soil liquefaction and weakness in soft clays." *Procs. Intl. Conf. on Case Histories in Geotech. Eng.*, St. Louis, Missouri, Vol. 1, 511-521
- Yegian, M.K., Ghahraman, V.G., and Harutiunyan, R.N., (1994). "Liquefaction and embankment failure case histories." 1988 Armenia earthquake. *J. of Geotech. Eng.*, ASCE, 120(3): 581-596
- Youd, T.L., Idriss, I.M., Andrus, R.D., Arango, I., Castro, G., Christian, J.T., Dory, R., Finn, W.D.L., Harder, L.F., Hynes, M.E., Ishihara, K., Koester, J.P., Liao, S.S.C., Marcuson, W.F., Martin, G.R., Mitchell, J.K., Moriwaki, Y., Power, M.S., Robertson, P.K., Seed, R.B., and Stokoe, K.H. (2001). "Liquefaction resistance of soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on evaluation of liquefaction resistance of soils." *J Geotech. Geoenviron. Eng.*, ASCE, 127(10): 817-833.
- Youd, T.L., Harp, E.L., Keefer, D.K. and Wilson, R.C., (1985). "The Borah Peak, Idaho Earthquake of October 29, 1983—Liquefaction," *Earthquake Spectra*, v. 2, p. 71-90



