RECLAMATION

Managing Water in the West

Liquefaction Triggering Assessment of Gravelly Soils: State-of-the-Art Review

Research and Development Office
Science and Technology Program
Final Report ST-2016-0712-01

Becker Penetration Test Rig on Clark Canyon Dam

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

September 2016

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

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.

REPORT DOCUMENTATION PAGE		*Form Approved* *OMB No. 0704-0188*
T1. REPORT DATE September 2016	**T2. REPORT TYPE** Research	**T3. DATES COVERED**
T4. TITLE AND SUBTITLE Liquefaction Triggering Assessment of Gravelly Soils: State-of-the-Art Review		**5a. CONTRACT NUMBER** 16XR0680A1-RY1541IS201610712
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER 1541 (S&T)
6. AUTHOR(S) Robert Rinehart, Ph.D., P.E. Amber Brusak Nicolas Potter, P.E.		**5d. PROJECT NUMBER** 0712
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER 86-68530
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Robert V. Rinehart, U.S. Bureau of Reclamation, Technical Service Center, Concrete, Geotechnical, and Structural Laboratory		**8. PERFORMING ORGANIZATION REPORT NUMBER**
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Research and Development Office U.S. Department of the Interior, Bureau of Reclamation, PO Box 25007, Denver CO 80225-0007		**10. SPONSOR/MONITOR'S ACRONYM(S)** R&D: Research & Development Office BOR/USBR: Bureau of Reclamation DOI: Department of the Interior
		11. SPONSOR/MONITOR'S REPORT NUMBER(S) ST-2016-0712-01

12. DISTRIBUTION / AVAILABILITY STATEMENT

Final report can be downloaded from Reclamation's website: https://www.usbr.gov/research/

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Liquefaction is recognized as a threat to much of Reclamation's infrastructure, and while liquefaction in sandy soils is relatively well understood there is a gap in the geotechnical engineering profession's knowledge base with regard to liquefaction of gravelly soils. A literature review was conducted to better understand the state-of-the-art of liquefaction triggering assessment of gravelly soils. Several tools are available to aid in the assessment of gravel liquefaction potential, but considerable uncertainty still exists. This report presents the finding of the literature review and makes recommendations for future research to advance the state-of-the-art.

15. SUBJECT TERMS Liquefaction, Gravel, Gravelly Soil

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Robert V Rinehart
a. REPORT U	**b. ABSTRACT** U	**c. THIS PAGE** U	**U**	19	**19b. TELEPHONE NUMBER** 303-445-2395

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

PEER REVIEW DOCUMENTATION

Project and Document Information

Project Name: Liquefaction Triggering Assessment of Gravelly Soils: State-of-the-Art Review

WOID: Z0712 Document: Final Report ST-2016-0712-01

Document Author(s): Robert Rinehart, Ph.D., P.E.; Amber Brusak; Nicolas Potter, P.E.

Document date: September 2016

Peer Reviewer: Evan Lindenbach, P.E., P.G.

Review Certification

Peer Reviewer: I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Reviewer EVAN LINDENBACH Digitally signed by EVAN LINDENBACH Date: 2016.09.23 07:53:23 -06'00' Date reviewed____________________
(Signature)

Executive Summary

Liquefaction is recognized as a threat to much of Reclamation's infrastructure, and while liquefaction in sandy soils is relatively well understood there is a gap in the geotechnical engineering knowledge base with regard to liquefaction of gravelly soils. When tasked with assessing the hazards and risks related to liquefaction of gravelly soils, the best engineers can do is attempt to apply their knowledge of sand liquefaction or perform correlations of field tests appropriate for gravels (e.g., Becker penetration test) to tests commonly used to investigate sands (e.g., standard penetration tests, cone penetration tests). These extrapolations and correlations are not precise, are not well developed, and result in high degrees of uncertainty with respect to the actual level of risk due to gravel liquefaction.

The first step in addressing this knowledge gap is to conduct a literature review to document the current state-of-the-art in order to understand the limitations of traditional methods, what emerging technologies exist or are under development, and to identify research needs. This report presents the results of a literature review and makes recommendations for future research. A very brief summary of the findings follows.

The Standard penetration test (SPT) and cone penetration test (CPT) are the preferred methods of assessment of liquefaction of sandy soils. Results have been proven to correlate to relative density (a key indicator of liquefaction potential) and are effective at identifying zones of loose, liquefiable material (i.e., material with low relative density). However, both of these techniques suffer due to the interference of large particles and their use is limited for gravelly soils. Several techniques have been proposed to "correct" SPT results to account for the influence of gravel, but there is little agreement on the best technique and any technique should be used with extreme caution. Given that other methods are available, use of SPT and CPT testing in gravelly soils is not recommended.

The Becker penetration test (BPT) and the newer instrumented Becker penetration test (iBPT) are well suited to gravelly soils due to their larger size. Unfortunately, there is no direct correlation between BPT/iBPT results and liquefaction potential – rather several layers of correlation are required, leading to significant uncertainty in the results. In addition, there is a lack of standardization, with respect to both equipment and data collection, and analysis techniques all of which tend to compound the uncertainty. The iBPT technique looks to hold promise to substantially reduce the uncertainty associated with data collection and analysis, and developments should be followed closely by Reclamation and potentially adopted as soon as commercially available products are offered. It should be recognized that even the BPT/iBPT suffers from the influence of larger cobble size particles. Reclamation should pursue research to aid in the development of a direct link between BPT/iBPT, relative density and gravel liquefaction potential.

The dynamic penetration test (DPT) is a penetration test where a solid, conical penetrometer is driven into the subsurface with a much heavier drop hammer than used for SPT testing. The heavier drop hammer and solid penetrometer configuration make the DPT particularly well suited for penetrating gravelly and cobble laden soils. The DPT is new and not well studied, but is a very simple, robust, and inexpensive test method that shows promise, and is therefore worthy of additional study. Reclamation should invest in research towards better understanding this new technology and should stay abreast of developments made by other researchers.

The shear wave velocity (SWV) of a soil is directly related to relative density and is therefore also related to liquefaction potential. Many different techniques exist to measure SWV in the field, each with advantages and limitations. It is critical to understand the various techniques and analysis methods in order to conduct an effective site investigation program. Liquefaction triggering curves for SWV are well developed for sandy soils and are conceptually similar to those for SPT and CPT. These triggering curves are believed to be less precise than those for CPT and SPT, and extension of these triggering curves to gravelly soils is less well understood. However, given that the SWV technique is applicable to any soil type it is desirable to keep advancing the state-of-the-art for SWV-based liquefaction assessment. Reclamation is well-suited to perform SWV research at gravelly liquefaction sites in combination with other techniques to provide comprehensive datasets.

The literature review resulted in several recommendations for further field and laboratory research. Opportunities for field-based research include leveraging existing Reclamation Safety of Dams projects to collect side-by-side data from multiple liquefaction assessment tools, allowing for advancement of the state-of-the-art by tightening: 1) the correlations between BPT or DPT and SPT, and 2) relationships between penetration resistance (i.e., blow counts) and relative density. Opportunities for lab-based research include conducting calibration chamber testing with the DPT to further develop: 1) relationships between penetration resistance and relative density, and 2) overburden correction factors. Additional lab research could utilize Reclamation’s vibration laboratory facility to conduct pre- and post-liquefaction testing on gravelly soils in a controlled lab environment to help establish: 1) relationships between penetration resistance and liquefaction potential, and 2) fundamental cyclic behavior of gravelly soil. Finally, a novel approach to liquefaction assessment in the form of machine learning was identified and appears to be worthy of additional study.

Contents

Background

Liquefaction refers to the complete or near complete loss of soil shear strength due to the buildup of excess pore water pressures (i.e., due to seismic loading). A soil's relative density is key indicator of liquefaction potential, and investigations typically aim at identifying zones of low relative density material located beneath the water table (i.e., loose, saturated zones). Occasionally, materials of interest are located near surface and are directly accessible by field personnel, but more often the materials of interest are located at depth and require rotary drilling or direct push probe methods in order to collect data or samples.

While there has been extensive work performed to understand and predict liquefaction behavior of sandy soils, liquefaction of gravelly soils is poorly understood and poses a risk to any Reclamation infrastructure founded on such soils (e.g, canals, levees, dams, power plants and other appurtenant structures). Testing gravelly soils is very challenging both in the lab and field, and this has contributed to the lack of knowledge. Example basic research questions related to liquefaction of gravelly soils include: 1) what is the pore pressure response of gravelly soils to seismic shaking, 2) what intensity and duration of shaking leads to liquefaction, and 3) what are the effects of gradation, plasticity, relative density, and permeability? Example applied research questions include: 1) can existing site investigation tools be used to determine liquefaction susceptibility of gravelly soils, and 2) what new and emerging technologies could be employed to determine susceptibility? The scoping study presented here included performing a literature review to: 1) gain a better understanding of the current state-of-the-art and studies performed in the past, 2) identifying if any of the research questions have already been addressed (fully or partially), and 3) detailing what additional research needs to be performed.

Proposal Development

In order to perform more cost effective (i.e., not necessarily overly conservative) designs and perform more accurate site evaluations for new infrastructure as well as risk assessments of existing infrastructure, Reclamation needs to gain a deeper understanding of liquefaction of gravelly soils. The specific infrastructure at risk include canals, levees, dams, power plants, and other appurtenant structures. With the constant (seemingly upward) revision of potential earthquake hazards, and the increase in human-induced seismicity (i.e., potentially due to hydraulic fracturing), Reclamation is poised to increasingly need and benefit from this research.

The research team recommends developing a research plan aimed at addressing the key basic and applied research needs identified in the report. Possible approaches that could be investigated include laboratory physical modeling, field testing, and numerical modeling; all of which should be undertaken in collaboration with universities or other government agencies working on the same topics. By involving several different parties, the research team envisions a proposal with a scope that both advances the state-of-the-art using existing Reclamation facilities (e.g., TSC's large-scale vibration laboratory, field investigation sites) and accurately addresses Reclamation's needs with respect to practical means to assess liquefaction potential of gravel-dominated soils without duplicating past or on-going efforts of others.

Literature Review

There are a variety of methods that have been used in an attempt to evaluate the potential for liquefaction of gravelly soils. Field methods include standard penetration testing, cone penetration testing, Becker penetration testing, large penetrometer testing, and shear wave velocity measurement. A limited amount of work has also been performed in the laboratory to characterize gravelly soil response to cyclic loading, primarily using large scale cyclic triaxial and resonant column testing. The following sections provide a brief overview of each method and describes the results of a literature review regarding their applicability in assessment of gravel liquefaction potential.

Standard Penetration Test (SPT) & Cone Penetration Test (CPT)

The standard penetration test (SPT) and cone penetration test (CPT) are fundamental geotechnical site investigation tools and are routinely used for assessing liquefaction resistance, as described in detail by Boulanger and Idriss (2014). The development of SPT-based and CPT-based liquefaction triggering procedures has progressed over the years and includes data from many site investigations of liquefaction sites, and continues to be updated as new data become available. Both techniques are standardized at the international voluntary consensus standards level. SPT testing has been further refined by mandatory incorporation of energy measurement (i.e., through pile driving analyzer [PDA]) when used for liquefaction analysis to quantify how much of the theoretical hammer energy is transferred to the drill string. However, for gravelly deposits these test methods are problematic. CPT testing can often not be performed in deposits containing gravel due to inability to penetrate the gravelly material and potential damage to the instrumented cones (Robertson and Cabal, 2014). While SPT (and potentially CPT) are preferred for sites containing minor amounts of gravel, SPT's performed in deposits containing appreciable amounts of fine gravel or any amount of coarse gravel or cobbles are often unreliable due to clogging, damage to the sampler, and the effects of increased particle size to sampler size ratio (Daniel et al., 2004).

Some research has indicated that even the presence of coarse sand erroneously increases SPT blow counts compared to fine sand at the same relative density (Farrar 1999). As further detailed by Daniel et al (2004), variations in particle size to sampler size ratio as the gradation changes and inconsistent degrees of sampler plugging lead to SPT blow counts in gravel being ambiguous. Available data do not consistently indicate whether blow counts will be higher, lower, or similar in gravel deposits as compared to sands (Daniel et al., 2004).

Even though SPTs have limited applicability for assessing gravel liquefaction directly, SPT data can still be useful in verifying Becker penetration test results (discussed in more detail below) through gravel correction procedures or short-interval sampling (Engemoen, 2007). Further, the typical liquefaction triggering charts for sands (e.g., Seed and Idriss, 1970, Boulanger and Idriss, 2014) have been shown to be applicable to gravelly sands, if reliable data can be obtained (Yan and Lum, 2003). This implies that when gravel particles are floating in a finer-grained matrix, the matrix appears to control the liquefaction characteristics, and this observation has been made by several researchers. Idriss and Boulanger (2008) stated that for silty sands with gravel contents of up to 15–20%, the liquefaction resistance is expected to depend primarily on the silty sand matrix.

If the SPT is used in gravelly material, current Reclamation guidance given by Engemoen (2007) suggests the careful use of techniques such as short-interval sampling (e.g., Yan and Lum, 2003) or gravel corrections based on examination of plots of penetration per blow (e.g., Vallee and Skryness, 1980, Harder, 1988, Andrus, 1994). If SPTs are used on gravelly soils, it has been suggested that the cutting shoe of the probe should be hardened. Seed et al. (2003) indicates that gravel correction procedures are best applied to materials with less than 50% gravel, and the authors also advise that it may be appropriate to use lower blow counts than the average values resulting from gravel correction procedures for a particular stratum due to the potential unknown influence of coarser particles. Application of these data collection/analysis techniques should always be accompanied by inspection of representative material samples to verify the presence and characteristics of gravel.

Becker Penetration Test (BPT)

The Becker penetration test (BPT) is a drilling method that can be used in coarse-grained material, and is likely the most common method for characterizing gravel deposits today. A diesel pile driving hammer is used to drive a large diameter casing (usually 5.5-inches or larger inside diameter) into the ground. Open-ended casing advancement is employed when sampling is desired, and plugged-end casing advancement is employed for penetration testing, which involves recording how many hammer blows are required to advance the casing one foot. This test can give continuous penetration data if sampling is not required. Unfortunately, there is not a direct correlation between BPT and liquefaction potential, so the BPT blow count is correlated to SPT blow count which is in turn correlated to liquefaction potential. This additional layer of correlation adds considerable uncertainty to BPT analyses (e.g., Farrar, 1999, Engemoen, 2007).

Harder and Seed (1986) proposed the first standardized method to interpret BPT blow counts. They developed procedures for indirectly measuring the energy transferred to the penetrometer using the bounce chamber pressure, then used energy normalized blow counts to obtain an experimental correlation for estimated equivalent SPT blow counts. There is significant uncertainty in the amount of energy transmitted to the drill string as well as the effect that casing friction can have on the results, leading to significant scatter in the data used to correlate SPT and BPT blow counts.

Sy (1993), Sy & Campanella (1994) and Sy et al. (1996) proposed a more rigorous method for estimating the energy transmitted to the penetrometer by measuring the accelerations and strains immediately below the hammer utilizing a pile driving analyzer (PDA). CAPWAP analysis is used to estimate the casing friction and calculate the energy delivered to the tip of the penetrometer. Despite the advances made by Sy's method in measuring the energy and understanding the factors affecting the BPT results, the technique is very expensive and therefore limited to high-budget projects, and there is still considerable uncertainty regarding the actual energy transmitted to the end of the BPT casing (Ghafgazi et al., 2014).

Farrar (1999) cautioned that BPT data for deposits with particles greater than three inches in size appears to have much more scatter, and that when particles sizes eclipse six inches, blow counts are likely overestimated. Engemoen (2007) echoes this concern and indicates that when cobble size particles are present (i.e., particles with greater than three-inches minimum dimension) that even BPT testing becomes problematic. Further, Reclamation Design Standard 13, Chapter 13 indicates that the BPT may give misleading results in soils containing boulders, cobbles, or even large amounts of gravel coarser than about 1½ inches. Daniel et al. (2004) indicates that for the SPT-based correlations of sand liquefaction potential to be valid for extrapolation to BPT-based gravel assessments, the soil particle size to sampler size ratio should be kept consistent – implying that BPT-based assessment of liquefaction potential might only be ideally suited for deposits containing fine gravel.

Attempted use of the BPT to assess liquefaction potential of gravelly soils is well documented in the literature. Harder and Seed (1986) performed a significant amount of BPT testing following the 1983 Borah Peak, Idaho earthquake where extensive liquefaction of shallow gravel deposits was observed. Some other examples from the literature include Keenleyside Dam investigated by Lum and Yan (1994), Mackay Dam investigated by Harder (1994), the Duncan damsite investigated by Lin et al. (2004), and Skookumchuck Dam investigated by Gorny and Liljegren (2006).

Reclamation also has experience utilizing the BPT to assess gravel liquefaction potential. Starting with testing at Bradbury Dam in the 1990's (Gillette, 1995), and continuing to more recent studies at Tieton Dam (Jensen, 2015, Galic, 2015), Clark Canyon Dam (Lee, 2014), and Granby Dam (Weidinger, 2014, Kuzniakowski, 2015). A summary of the Granby Dam investigation and analysis is presented later in this report.

Instrumented Becker Penetration Test (iBPT)

While it is still an emerging technology, the instrumented Becker penetration test (iBPT) shows considerable potential to be a significant improvement over standard BPT testing in terms of increased data reliability and decreased uncertainty. Compared to standard BPT testing, iBPT testing involves collecting data from instrumentation located near the tip of the penetrometer, allowing for more direct measurement of the energy delivered to the tip (Ghafgazi et al., 2014, 2016, DeJong et al., 2014, 2016). The friction developed along the side of the BPT drill string substantially influences the BPT blow counts and the iBPT negates this issue by measuring energy delivered at the tip of the penetrometer. The authors of these studies (who are also the developers of the new technology) claim that this approach results in less data scatter and improved stratigraphy delineation.

As described by Ghafgazi et al. (2014, 2016) and DeJong et al. (2014, 2016), development of correlations of energy normalized iBPT blow counts to SPT are underway. Data has been collected at four dam sites to date: Headworks West Reservoir includes testing of alluvial gravelly and cobbly deposits; the new alignment for North Haiwee Dam includes testing of silty sand and clean sand deposits with occasional gravel lenses; Stone Canyon Dam includes testing within a narrow canyon with deposits characterized by highly interlayered and intermixed low plasticity clays and sands with frequent gravel-sized, slate fragments; and Bouquet Canyon Dam which includes testing of both sandy and gravelly alluvium.

Limited details of the equipment, data collection procedures, analysis techniques, and correlations from the 4 test sites are briefly documented in the two 2014 papers, however, the two 2016 papers should provide more detailed documentation. Note that the 2016 papers are currently not available because they are under peer review by ASCE at the time of this publication (September 2016).

It is worth noting that even with the potential improvements represented by the iBPT, there is still no direct correlation of liquefaction resistance to iBPT N-values. Calculations must be made to convert the iBPT values into SPT values which in turn can be correlated to liquefaction resistance. The iBPT N-values are converted into SPT N-values by considering the residual energy transferred to the penetrometer tip, referenced to 30% hammer energy efficiency. Based on the work performed to date, this quantity appears linearly correlated to the SPT N-values by a factor of 1.5-1.8 (Ghafgazi et al., 2014; DeJong et al., 2014). According to DeJong et al. (2014), this correction factor may decrease due to an increase in fines content.

Large Penetration Tests (LPTs)

Several different types of large penetration tests (LPTs) are mentioned in the literature. In most cases, the tests involve using a hammer to drive a penetrometer into the soil. Technically speaking, the BPT/iBPT could be thought of as large penetrometer tests, but LPT is being used here to represent other, less common types of solid penetrometers.

Yoshida et al. (1988) describes an LPT. The penetrometer is described as a blunt probe approximately 2.9 inches in diameter, driven with a 220 pound hammer with a 59 inch drop height. Based on side-by-side testing in gravelly soils, they found a relationship between LPT and SPT blow counts that was thought to be $N_{LPT}=N_{SPT}/2$ for gravelly soils and $N_{LPT}=N_{SPT}/1.5$ for sandy soils. It was found that the effective overburden stress and N-values did not have a linear relationship. No other discussions of this particular LPT were found in the literature.

Lin et al. (2004) describes a different sort of LPT and provides some comparison between LPT results and shear wave velocity. Very few details about the LPT are given, but it is instrumented with strain gages and force transducers to allow for calculation of energy imparted to the penetrometer. It is possible that the LPT described here is similar to a BPT. Testing was performed on materials that liquefied during the 1999 Chi-Chi earthquake. The results showed that the LPT data agreed well with the shear wave velocity data in terms of liquefaction resistance.

Dynamic Penetration Test (DPT)

The dynamic penetration test (DPT), also called the Chinese dynamic penetration test and the dynamic cone penetration test (DCPT), is a specific type of LPT, as described by Cao et al. (2011). The test is run by dropping a 265 pound slide hammer onto an anvil, which is attached to a drill rod and the solid cone tip with a maximum diameter of 2.9 inches and a cone angle of 60 degrees. The process involves recording the number of drops it takes to advance the cone tip 30 centimeters. Advantages of using this technology include easy transportation, inexpensive, small time commitment, continuous data collection, and it can drive through gravel and even cobbles. The authors also discuss the ease with which energy measurements (e.g., through a PDA similar to that used on SPT hammer systems) can be incorporated into the system. As mentioned earlier, incorporation of energy measurement is recommended for any type penetration testing.

The DPT was used to evaluate liquefaction after an 8.0 magnitude earthquake in the Sichuan province of China in 2008. The corrected DPT resistance for blows per 30 centimeters is calculated by an equation that takes into consideration the effective overburden stress. From the collected data, a DPT liquefaction probability equation was created which takes into account the corrected DPT blow count and the cyclic stress ratio. Similar to other triggering curves (e.g., from SPT, CPT) the corrected DPT blow count was plotted against the cyclic stress ratio with curves to represent probability of liquefaction. The 50% probability of liquefaction shows 79% of sites with visible liquefaction plotting above the curve, and 82% of sites without liquefaction plotting below the curve.

Reclamation is highly interested in the advancement of DPT technology because of the potential for cost savings related to speed and simplicity of the test. Reclamation's Dam Safety Technology Development Program is funding a comparative evaluation of the liquefaction resistance estimated by the DPT and BPT at Millsite Dam, which has a gravel layer in in the foundation.

DPT testing was carried out by Reclamation personnel in January of 2015 using equipment owned by Brigham Young University and borrowed from Chinese researchers, and BPT testing was carried out by the Utah State Division of Water Resources. Additional data collection is planned for the fall/winter 2016. Data analysis and reporting are underway, with expected completion in the spring of 2017 (personal communication with Michael Talbot, 9/2016).

Shear Wave Velocity

Shear wave velocity (SWV) through soil is largely governed by a soil's density (among many other factors), and can therefore be correlated to liquefaction susceptibility. Methods for collecting SWV include spectral analysis of surface waves (SASW), multiple channel analysis of surface waves (MASW), crosshole surveys, downhole surveys, suspension logging, and seismic-CPT, all of which have various advantages and limitations. The wide variety of techniques available for measuring SWV in the field are documented in standard geophysical textbooks and literature. Engemoen (2007) presents summaries of many of the techniques commonly applied by Reclamation at the time of publication.

SWV is used as indicator for liquefaction potential through the use of triggering curves, analogous to those for SPT and CPT. Typically, SWV is plotted against liquefaction resistance and several curves are available representing a range of fines content (e.g., Youd and Idriss, 1997, Andrus and Stokoe, 2000, Andrus et al., 2004, Kayen et al., 2013). As with the SPT-based and CPT-based triggering curves, the SWV triggering curves seem to have been developed largely based on data from sandy sites. It remains unclear how appropriate it may or may not be to extend the sand-based triggering curves to gravelly soils.

Shear wave velocity measurement can be performed in a wide range of soils (virtually any soil), and it therefore follows that the SWV technique could be applied to liquefaction assessment of gravelly soils. Seed et al. (2003) indicated that while the SWV approach can be applied to the widest variety of soils, it gives the least well-defined correlation with liquefaction potential. This is likely due to a combination of factors including: a more limited number of test sites being available for incorporation into triggering curve development, less sensitivity to subtle changes in velocity and difficulty detecting thin layers, SWV measurement is a small strain measurement while other techniques and liquefaction itself are large strain phenomena, SWV velocity is strongly influenced by aging effects such as cementation, and uncertainty regarding how to normalize SWV for effective overburden (Youd et al., 1997, Seed et al., 2003).

Some work has been performed to address the limitations above. In general, a thorough understanding on the various SWV measurement techniques should allow for the selection of the most suitable technique for a given site. Andrus and Stokoe (2004) recommend that SWV be determined at intervals of one-quarter the thickness of the critical layer at a minimum. Further advances in geophysical interpretation and modeling are also addressing these limitations. Age correction factors are also being developed (Andrus and Stokoe, 2004).

Seed et al. (2003) cautioned that the SWV approach might be best suited for screening level applications. Current Reclamation practice does allow for the reliance on SWV velocity alone to determine liquefaction potential, but generally only in soils that are too coarse for any other method. It is always preferred to use a second method if at all possible (Engemoen, 2007).

There are several instances of use of the SWV technique being applied to the literature. The following presents some brief summaries.

For the 1983 Borah Peak 7.3 magnitude earthquake, Stokoe et al. (1988) used SASW to evaluate liquefaction potential. It was shown that SASW was suited to this site due to the difficulty associated with sampling the coarse gravelly material. The relationship between shear wave velocity and the maximum ground acceleration was determined in order to find the liquefaction resistance, and the researchers found that the triggering curves for sands applied well to the gravels at the site.

According to the results presented by Lum and Yan (1994), SWV gave liquefaction resistance results higher than SPT-based results during an assessment at Keenleyside Dam. The SASW, crosshole and downhole techniques were are employed. All the techniques agreed well for level ground, but SASW was less reliable for sloping ground.

Gorny and Liljegren (2006) performed a liquefaction analysis on gravelly alluvium that underlies the shells of Skookumchuck Dam. BPT testing proved erratic, but a combination of gravel corrected SPT N-values and downhole SWV measurements were used to assess the liquefaction potential at the site per the procedures in Youd et al (2001). SWV data was used in a supporting role.

MASW was used after the 8.0 magnitude earthquake in 2008 in Sichuan, China. A survey line 300 meters long was used to acquire 2D data 30 meters deep. The MASW measurements were used to predict liquefied sites and compare those to the field results for liquefaction. A 50% probability curve based on Chinese design codes was shown to correctly bound all but four data points for the 47 compiled SWV data (Cao et al., 2011).

Lewis et al. (2013) applied a different approach at a gravel liquefaction study site in British Columbia. SWV data was collected with the SASW technique. Field and laboratory tests were used to correlate SWV to void ratio and case histories were in turn used to correlate void ratio to liquefaction resistance. They showed good agreement between their approach and gravel-corrected SPT N-values.

Laboratory Testing

Physical Property Testing

It is now widely understood that gravelly soils are susceptible to liquefaction. In addition to in-place density, soil physical properties, including grain size distribution (gradation), plasticity, and grain shape have important effects on liquefaction resistance. There are no widely accepted rules or criteria governing the liquefaction behavior of gravelly soils, but the literature review resulted in the following observations.

It is widely held that when gravel particles are floating in a finer-grained matrix, the matrix appears to control the liquefaction characteristics (e.g., Yan and Lum 2003). Idriss and Boulanger (2008) stated that for silty sands with gravel contents of up to 15–20%, the liquefaction resistance is expected to depend primarily on the silty sand matrix.

Yan and Lum (2003) summarized ten case histories of liquefied gravelly soils, and the following conclusions can be made. There is ample evidence that loose to medium dense gravelly soils liquefy during earthquakes. SPT or equivalent BPT blow counts for liquefiable deposits are generally less than 15 blows/ft. Earthquake magnitude for nine of the ten sites summarized was greater than 6.8. The gravelly soils that did liquefy had either low permeability or drainage was impeded by an impervious layer.

Evans et al. (1995) tested gap-grade sand-gravel mixtures with 0-60% fine gravel. The authors found that maximum index density increased with gravel content to 60% gravel, past which it decreased. This could indicate that for gap-graded sandy soils containing only fine gravel, gravel particles could be floating in the sand matrix for gravel content approaching 60%. The authors also reported that liquefaction resistance increased with increasing gravel content up to 60%. For the 1983 Borah Peak Earthquake, Harder (1994) indicated that the liquefied material was primarily gap-graded silty, sandy gravels with gravel contents ranging from 36 to 74%.

Cao et al. (2011, 2013) presented the grain size distributions for liquefied sites in the Wenchuan, China Earthquake. These samples were primarily classified as well-graded gravels. Gravel content ranged from 30% to 75% for the four samples tested. The authors note that the distribution only account for material that could fit in the core barrel of approximately four inches inside diameter. This is an important consideration for all site investigations involving gravelly soil – sampling techniques must be selected to ensure that representative samples are collected.

Physical property testing showed that fill material that liquefied during the 1995 Hyogo-Ken Nanbu Earthquake in Japan was approximately 50% gravel with a maximum particle size of 4-inches (potentially larger due to sampling limitations). According to Japanese specifications at the time, this hydraulically placed fill would have been considered nonliquefiable. Maximum surface accelerations from the earthquake were approximately 0.35g, and the in-place fill had SPT N-values of 5-15. No details of the SPT testing or potential gravel corrections were presented. Hara et al. (2012) reported on the same soil, and indicated that the inclusion of nonplastic fines decreased liquefaction resistance but decreased post-liquefaction strengths.

Guoxing et al. (2015) reported on undrained cyclic triaxial tests conducted in gravelly soil with varying levels of plastic fines to observe the variation in the failure mechanisms. The study varied the fines content from 0% to 40% in 5% intervals. It was found that liquefaction failure occurs for plastic fines content (FC) < 30% and FC ≥ 30% results in axial strain failure (cyclic softening), defined as accumulated axial strain greater than 5%. Additionally, plastic fines content was noted to effect liquefaction resistance in three distinct ranges. The first was for FC ≤ 10% where liquefaction resistance decreased with increasing fines content. From 10% < FC < 30% liquefaction resistance increased with increasing fines content. For FC > 30%, liquefaction resistance remained unchanged with increasing fines content.

Cyclic Triaxial Testing

One goal of the cyclic triaxial test is to determine the relationship between liquefaction resistance and anticipated cyclic loading. In general, testing can be performed with varying density and gravel content, and these tests allow for insight into fundamental behavior of gravelly soils during cyclic (i.e., seismic) loading. Many such studies are reported in the literature. However, owing to the large and complex nature of the testing equipment needed for such tests on gravelly soils and the extremely wide array of materials and specimen reconstitution techniques possible, it is very difficult to draw conclusions from these works. Testing modified or partial gradations (i.e., to enable use of smaller, more standard equipment) further complicates the use of laboratory test results to study gravel liquefaction.

For gap-graded gravel-sand mixtures, Evans et al. (1995) found that increasing gravel content from 0-60% lead to an increase in liquefaction resistance. The maximum particle sized used in the study was 3/8-inch, meaning this study was limited to fine gravel.

For the Hanshin earthquake in 1995, the reliquefaction potential of samples was tested using repeated cyclic triaxial testing, as reported by Hatanaka et al. (1997). Results showed a negligibly small increase liquefaction resistance and an increase for the dry density after initial liquefaction.

Calibration Chamber Testing

A number of researchers have conducted penetration testing in the lab, utilizing a cylindrical steel container (i.e., steel drum) filled with soil. The steel drum is filled with soil, then saturated and loaded vertically. Holes located at the top of the container allow researchers to perform SPTs or LPTs; SWV measurements can also be made through the soil. Much of the early work regarding SPT and CPT correlations to relative density and corrections for overburden stresses were conducted in these types of apparatuses, usually referred to as calibration chambers (e.g., Gibbs and Merriman 1953, Marcuson and Bieganowsky 1977a, 1977b, Robertson and Campanella 1983, Baldi et al. 1986).

More recently, calibration chamber testing has been used to examine gravelly soils. Kokusho (1997) and Yoshida et al. (1998) found that the N-value at a specific confining pressure is linearly related to the void ratio on a logarithmic scale. Although this relationship was found, the void ratio can only be used to find an N-value for a specific gradation. An N-value can be the same for loose sand and loose gravel despite the different void ratios and grain sizes. Equations were formulated for the value for void ratio and N-value for a given uniformity coefficient, logarithmic relative density and confining pressure.

The calibration chamber approach can also used to test the SWV for samples. Kokusho et al. (1997) installed a seismic source and four sets of wave sensors on each side of their laboratory container. An equation for SWV was developed which takes into account the vertical stress, horizontal stress, and void ratio. The authors found that SWV is highly dependent on the gradation of a soil. It was shown that loose well-graded gravels can have similar SWV and N-values compared to loose poorly graded sand, despite a much smaller void ratio (related on a semi-logarithmic scale).

Recent Reclamation Case Study: Granby Dam

Description

Granby Dam is a zoned earth embankment dam that includes a wide central core of impervious material with a cutoff trench to bedrock, flanked by transition zones both upstream and downstream of the core. An outer rockfill shell comprises the downstream slope, riprap was placed on the upstream transition zone for erosion protection.

The dam rests directly on Quaternary alluvium (Qal) that is part of the current Colorado River channel and consists of a heterogeneous mixture of well graded gravel and poorly graded gravel with alternating layers of poorly graded sand and silty sand, with cobbles and boulders. During a 1991 drilling program, alluvium was found to be over 100 feet thick at the downstream toe.

Testing

SWV and SPT testing was completed in 1990 but was disregarded due to questionable drilling methods and potential disturbance of the foundation soils.

A field exploration conducted in 2012-2013 included Cross-Hole SWV testing, SPT, and BPT. All testing was performed in pre-drilled locations, which allowed the passage through the coarse Zone 5 materials into the underlying alluvium. Samples were collected during the sonic pre-drilling and physical properties were obtained, with care taken to remove material pulverized by the sonic drilling method.

The alluvial materials ranged from 67 to 74 feet in thickness, and gradations revealed a variety of interbedded granular soil types consisting of about 70 percent gravels and 30 percent sands. About 80 percent of the samples had cobbles. The fines content ranged from about 4 to 19% with an average of about 10. The majority of the samples (~80%) were non-plastic. The samples that were plastic had a Liquid Limit ranging from 19 to 29 and a Plasticity Index ranging from 2 to

14. The SPT samples were not included in this analysis due to concerns about them not being representative due to the very coarse nature of the Qal.

The upper 5 to 7 feet of Qal materials typically had non-normalized BPT blow counts ranging from 20 to 100 blows per foot. The shear wave velocities ranged from 1,350 to 1,550 feet per second (uncorrected for overburden pressures).

The lower portion of the Qal materials, below 5 to 7 feet, typically had non-normalized BPT blow counts ranging from 100 to greater than 700 blows per foot. The shear wave velocities ranged from 1,600 to over 2,000 feet per second (uncorrected for overburden pressures).

Analysis

Liquefaction triggering analyses were performed according to the Seed Simplified Procedure as outlined in the BOR Design Standards No. 13 Embankment Dams, Chapter 13: Seismic Design and Analysis (2001) and were augmented with, at the time, current state of the practice procedures as outlined by Idriss and Boulanger (2008).

Standard Penetration Tests

Based on evaluation of the gravel-corrected SPTs, there is only one potentially liquefiable layer located at about elevation 8040. It was indicated that this layer maybe liquefiable for 10,000 year loading and above. This analysis was only used in a supporting role.

Becker Penetration Tests

Using two methods, Sy & Campanella (1994) and Harder & Seed (1986), the BPT blow counts were converted to SPT-equivalent $N_{(1)60\text{-}cs}$. The analysis concluded that Sy & Campanella method was more applicable due to direct use of the side friction and energy imparted in the test casing in their conversions.

The Harder & Seed method was deemed to be the more conservative of the two methods, indicating liquefaction potential at the 10,000 year return period and below, for material above about elevation 8055. This finding was based on testing from all three BPT boreholes. The Sy & Campanella method indicated liquefaction potential for material above about elevation 8055 for earthquakes with return periods of 20,000-years for one test location, and only for the 50,000-year event for the other two test locations.

Shear Wave Velocity Measurement

The 2012 data did not indicate any layers where liquefaction triggering would be expected. It was noted that there was the possibility that the sonic drilling method would have densified the foundation soils as the hole was drilled, but the effect would be limited to a relatively small radius around the casing.

Conclusions

As presented by Weidinger (2014), based on the Seed Simplified liquefaction triggering assessment conducted at Granby Dam, there is a 10 to 25-foot thick layer of potentially liquefiable material between starting at elevations about 8050 or 8055, upward to the embankment/foundation contact. However, liquefaction will likely only occur under very strong earthquake loadings. This conclusion is not supported by the shear wave data, though the shear wave data do indicate that this same zone is not as dense as the remainder of the foundation.

Further, according to Kuzniakowski (2015), BPT data analyzed per the Sy and Campanella (1994) procedure indicate that the potential for liquefaction is possible at earthquake loadings with greater return periods than the 20,000 years. Liquefaction triggering analysis using the shear wave velocity data was performed using the method developed by Andrus & Stokoe, as presented in the Reclamation Design Standard Chapter 13 (2001); results showed no potential for liquefaction triggering for the 2013 data. The author also states that it is likely that the gravel soils are pervious enough that it could behave in a “drained” manner, even under the rapid earthquake loading, and thus not liquefy.

Recommendations for Further Research

The literature review resulted in deeper understanding regarding the state-of-the-art of liquefaction assessment of gravelly soils. It has also highlighted areas of need for additional research to thoroughly understand gravel liquefaction assessment tools. Key research needs that should be pursued by Reclamation are described below. Given the magnitude of several of these research efforts, pursuing collaboration with other entities and cost sharing partnerships will be of key importance. Each of the efforts described would benefit Reclamation and the geotechnical engineering community at large, and conducting level proposals should be developed.

iBPT

Reclamation does not currently have in-house capability to perform BPT/iBPT testing, but rather contracts for this service. It is recommended that Reclamation pursue contracting specifically for the iBPT technology for future projects. If Reclamation is able to acquire iBPT testing services, it is recommended that the data collected be published for use by the geotechnical engineering community in order to further the state-of-the-art. There is likely opportunity for collaboration with the iBPT developers to this end.

DPT

Given the simplicity of the DPT technology, it is recommended that Reclamation either purchase or construct a DPT device. Reclamation already owns energy measurement equipment routinely used for SPT testing, and this equipment could be made robust enough for use with the DPT. Having the DPT equipment on hand would allow for easy integration of this promising gravel liquefaction assessment tool into upcoming site investigation projects. Additional data collection at gravelly sites would provide important data sets that would allow for the technology to be further vetted and developed.

In addition, the DPT test methodology could benefit from numerical modeling studies. A method such as Discrete Element Modeling (DEM) could help define the relationship between penetration resistance and relative density, and the effects of variations in gradation. These relationships underpin the penetration resistance – liquefaction resistance triggering curves. Such studies are being performed for SPT testing (e.g., Daniel 2004), and similar studies for the DPT would be helpful. It is possible that the smaller scale Dynamic Cone Penetrometer (DCP) test, which is routinely used in the transportation industry, has been the subject of such studies and this should also be investigated.

Side-by-Side Comparison Studies

Reclamation is well-suited to pursue in-depth studies of several techniques through side-by-side testing during site investigation projects. Pairing data collection activities from methods such as SPT, iBPT, DPT, and SWV has the potential to provide extremely rich data sets that could rapidly advance the state-of-the-art. If a suitable site was identified that also allowed for the measurement in-situ relative density (i.e., through ring density testing of shallow deposits) this research could be even more beneficial. Reclamation is often involved in assessing liquefaction potential of gravelly soils through Safety of Dams investigations. If this project work can be leveraged to provide research data sets, in cooperation with other government agencies and universities, there is significant potential for very influential and productive research to take place.

Another option that could be pursued is performing the proposed side-by-side testing outside the scope of Reclamation Safety of Dams projects. For example, testing could be arranged at a gravel quarry where near-surface gravel deposits are present. Cost-sharing arrangements for this research could be pursued between the identified quarry, universities engaged in DPT and iBPT research (BYU and Cal-Davis, respectively) and Reclamation's R&D office.

Laboratory Testing

Three potential studies have been identified that could be conducted in Reclamation's Technical Service Center laboratories in Building 56. Several large-scale testing facilities are available that could be utilized for this potential research.

1. Reclamation's laboratory facilities could be used to perform calibration chamber type testing to allow for investigations of DPT penetration resistance versus relative density and overburden stress. Such studies were fundamental in the development of the SPT and CPT; repeating these studies using the DPT would be instructive. It would be beneficial to conduct these studies simultaneously with the numerical modeling studies mentioned above.

2. The TSC laboratories also have a vibration facility that could be utilized for testing. A large soil box (i.e., on the order of 10 ft square) could be constructed. Once filled with gravelly soil at known relative density, the soil could be saturated and subjected to

overburden stresses. Subsequently, a variety of liquefaction assessment tests could be performed including SPT, DPT, and SWV measurement. The vibration facility could then be used to perform cyclic loading of the soil box – essentially creating a large-scale strength test to allow investigation of liquefaction resistance vs cyclic loading relationships for gravelly soils. After the cyclic-loading portion of the experiment, post-liquefaction testing could also be performed with the same suite of techniques.

3. Further investigation could include repeating the Guoxing et al. (2015) tests investigating the influence of plastic fines with additional materials with various PIs, larger gravel, and across a range of confining pressure. This research could be pursued at Reclamation's laboratories but may also be a good candidate for partnering with universities.

Machine Learning

Assessment of gravel liquefaction could be a novel opportunity to apply machine learning technology. Non-physically based modeling using approaches like artificial neural networks, Bayesian networks, boosted regression trees, or random forests could be established and trained with data from existing sites. Data from SPT, CPT, BPT/iBPT, DPT, and SWV along with earthquake magnitude, soil properties such as gradation and plasticity, geologic environment, vertical stresses, normalized peak horizontal acceleration at ground surface could all be utilized. Developmental work along these lines has been performed by Goh (2002) and Samui (2016), and other precedents exist for application of machine learning within the dam engineering community (e.g., Salazar et al. 2015, 2016). These researchers recently gave a presentation to Reclamation personnel and were open to collaboration. Development of a machine learning method for liquefaction assessment of gravelly soil is an excellent opportunity for partnership with other university researchers.

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