#133

ASCE National Convention, San Diego, California
Session on Dynamic Properties of Gravelly Soils, Oct. 24, 1995

BPT-SPT CORRELATIONS FOR EVALUATION OF LIQUEFACTION RESISTANCE IN GRAVELLY SOILS

Alex Sy[1], M.ASCE, R.G. Campanella[2], M.ASCE
and Raymond A. Stewart[3]

ABSTRACT

Seismic liquefaction of gravelly soils is receiving increased attention in recent years, particularly after well-documented evidences from the 1983 Borah Peak earthquake and the 1988 Armenian earthquake became available. The Becker penetration test (BPT), through correlations with the Standard penetration test (SPT), is widely used in practice to assess the liquefaction resistance of gravelly soils. In this paper, two methods of interpreting BPT blow counts are applied to two sites underlain by gravelly soils. The Harder approach uses bounce chamber pressure measurements to correct BPT blow counts, but it does not explicitly consider soil friction acting on the Becker casing. The Sy approach uses measured energy to correct the BPT blow counts, and it considers casing friction. The two case studies illustrate the importance of considering casing friction during the BPT. In addition, independent shear wave velocity measurements at the second site appear to support the equivalent SPT N-values determined by the Sy method which are very different to those determined by the Harder approach.

INTRODUCTION

The damaging earthquakes of 1964 in Niigata, Japan and in Alaska focused the geotechnical engineers' attention to liquefaction as a major problem caused by

---

[1] Klohn-Crippen Consultants Ltd., Richmond, British Columbia, Canada
[2] University of British Columbia, Vancouver, British Columbia, Canada
[3] B.C. Hydro and Power Authority, Burnaby, British Columbia, Canada

earthquake shaking. Since then, liquefaction-induced ground failures have been observed in every significant earthquake around the world. The field observations of the performance of sites during earthquakes have formed the basis for the widely used Seed's simplified method of liquefaction potential assessment for level ground (Seed et al. 1985). The Seed procedure uses the Standard penetration test (SPT) N-value as the soil density index and is applicable to sand and silty sand sites for which the performance data base was compiled.

Although relatively rare compared to liquefaction of sands and silty sands, liquefaction of saturated gravelly soils has been observed at several well-documented sites, including during the 1983 Borah Peak earthquake and the 1988 Armenian earthquake. Liquefaction of gravelly soils is now a recognized hazard, particularly for design of large earth structures.

Because the SPT is unreliable in gravelly soils, the current practice in North America is to use the Becker penetration test (BPT) and to correlate its blow counts to SPT N-values to make use of the extensive liquefaction performance data base available for SPT in sandy soils. The BPT is essentially a large scale dynamic penetration test. Harder and Seed (1986) proposed a BPT-SPT correlation procedure for liquefaction assessment in gravelly soils, and showed that the results were in general agreement with the observed performance of several gravelly soil sites during the 1983 Borah Peak earthquake. Their procedure, however, is limited to a few "calibrated" Becker drill rigs and does not quantify nor explicitly account for soil friction acting on the casing during the BPT.

A more rational approach to BPT-SPT correlation based on stress wave measurement of the BPT was recently proposed by Sy and Campanella (1994). This method uses the energy transferred into the top of the Becker casing to correct the BPT blow count to a reference energy level, similar to the procedure currently used in SPT energy correction. It further considers casing friction, which can be significant at large depth, in the estimation of equivalent SPT N-values.

Applications of the BPT-SPT correlations to two case studies of liquefaction potential evaluation in gravelly soils are described in this paper, and the results of BPT interpretations by both the Harder (1988) and Sy (1993) methods are compared.

OBSERVED LIQUEFACTION IN GRAVELLY SOILS

Liquefaction-induced ground failures in saturated gravelly soils have been reported in the literature at several sites as summarized in Table 1. The best-investigated liquefaction sites are those in Idaho during the 1983 Borah Peak earthquake (Youd et al. 1985; Harder, 1988; Stokoe et al. 1988; Andrus and Youd, 1989; Andrus, 1994), in Armenia during the 1988 Armenia earthquake (Yegian et al. 1994), and in southern Hokkaido during the 1993 Hokkaido-Nansei-Oki earthquake (Kokusho et al. 1995). In fact, the field observations from the 1983 Borah Peak earthquakes formed the basis of at least two Ph.D. dissertations, one by Harder (1988) and the other by Andrus (1994).

Table 1. Observed Liquefaction in Gravelly Soils

Year	M	Earthquake	Reference
1891	7.9	Mino-Owari, Japan	Tokimatsu & Yoshimi (1983)
1948	7.3	Fukui, Japan	Ishihara (1985)
1964	9.2	Valdez, Alaska	Coulter & Migliaccio (1966)
1975	7.3	Haicheng, China	Wang (1984)
1976	7.8	Tangshan, China	Wang (1984)
1978	7.4	Miyagiken-Oki, Japan	Tokimatsu & Yoshimi (1983)
1983	7.3	Borah Peak, Idaho	Youd et al (1985), Harder (1988)
1988	6.8	Armenia	Yegian et al (1994)
1992	5.8	Roermond, Netherlands	Maurenbrecher et al (1995)
1993	7.8	Hokkaido, Japan	Kokusho et al (1995)

The main conclusions from studies of the liquefaction case histories in gravelly soils are:

(1) Loose to medium dense gravelly soils, with SPT N-values less than about 20, are susceptible to liquefaction.
(2) In a "matrix-supported structure" where the larger particles (gravel) float in a matrix of finer-grained material (silt and sand), the finer matrix material controls liquefaction resistance of the gravelly deposits.
(3) Sandy and silty gravels have significantly low permeabilities compared to clean gravels and, therefore, do not dissipate excess pore pressures as quickly to prevent liquefaction.
(4) Boundary drainage conditions are important, e.g. presence of an impervious surface layer can impede drainage leading to liquefaction of the underlying gravelly soils.
(5) Seed's liquefaction chart developed for sands is also applicable to gravelly sands.

Until more earthquake performance data from gravelly sites are available, the current practice is still to use the Seed's SPT-based liquefaction method to evaluate liquefaction potential in gravelly soils. Recent laboratory tests of sand-gravel composites (Evans and Zhou, 1995) are providing further insights into the liquefaction phenomenon of gravelly soils.

DYNAMIC PENETRATION TESTS

An important limitation of the SPT is that the N-values (blows per 305 mm) in gravelly soils are unreliable, and, often too high, due to the large particle size relative to the diameter of the sampler (51 mm o.d. by 35 mm i.d.). To overcome this deficiency, some investigators have suggested using the lowest recorded N-value as representative of the gravelly soil stratum or formation (e.g. Fletcher, 1965). Others have recorded blow counts for small increments (e.g. for each 25 mm or 30 mm) of the sampler penetration to assess the effect of gravel particles as a basis to reject or accept the measured SPT results, or to infer the N-value for the finer grained matrix of the gravelly deposits (e.g. Stokoe et al. 1988; Valera and Kaneshiro, 1991; Lum and Yan, 1994). These subjective approaches of interpreting SPT results in gravelly soils rely heavily on the investigators' judgement and intuition.

An alternative approach to SPT for in-situ characterization of liquefaction resistance of gravelly soils is to use a larger scale penetration test and to correlate its blow counts to SPT N-values. Several large scale dynamic penetration tests have been proposed and their basic features are compared to the SPT in Table 2.

Table 2. Dynamic Penetration Tests

	Standard Penetration Test	Large Penetration Test (Japanese)	Large Penetration Test (Italian)	Becker Penetration Test
Symbol	SPT	LPT	LPT	BPT
Drive Method	Drop Hammer	Drop Hammer	Drop Hammer	Diesel Hammer
Hammer Weight (N)	623	981	5592	7670
Drop Height (mm)	760	1500	500	varies
Maximum Energy (kJ)	0.47	1.47	2.80	11.0
Sampler O.D. (mm)	51	73	140	170*
Sampler I.D. (mm)	35	50	100	closed end

* Most common casing size used

The large penetration test (LPT) is widely used in Japan (Yoshida et al. 1988) and in Italy (Crova et al. 1993). It is simply a larger scale version of the SPT and, similar to the SPT, it requires a hole to be predrilled before conducting the test. Conventional rotary or diamond drilling through coarse gravelly deposits is often difficult and time consuming. Even more difficult is cleaning of the borehole before lowering the sampler to the bottom of the hole for testing the undisturbed in-situ soils. These difficulties are avoided by use of a close-ended continuous dynamic probe, such as the BPT.

The BPT consists of driving a specially-designed, close-ended casing into the ground using a double-acting diesel hammer and recording the blow count for each 0.3 m of casing penetration. The test simulates the driving of a displacement pile. The drive casings (or pipes) come in 2.4 m or 3.0 m lengths with threaded ends, and are available in three sizes, viz. 140 mm o.d., 170 mm o.d. and 220 mm o.d. The 170 mm o.d. casing is becoming the most commonly used size for penetration testing. There are two basic drill rig types: the older and more compact HAV180, and the newer and more elaborate AP1000. Both types of drill rigs, however, use the same International Construction Equipment (ICE) Model 180 diesel hammer. More details of the Becker hammer drill are given in Harder and Seed (1986) and in Sy and Campanella (1993).

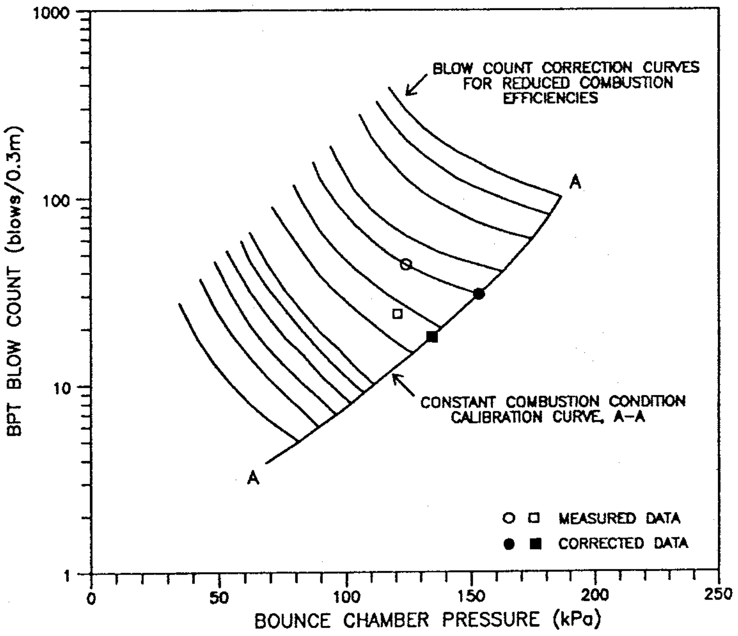
BPT-SPT CORRELATIONS

Harder Approach

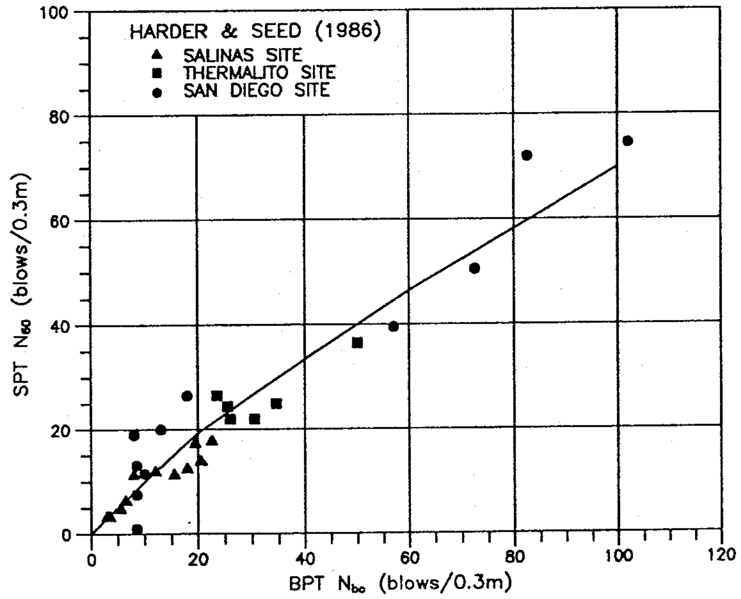
Harder and Seed (1986) proposed an empirical BPT-SPT correlation procedure based on hammer bounce chamber pressure measurements. Their procedure involves two basic steps. Firstly, the field measured BPT blow count is corrected to a reference combustion condition, and secondly, the corrected blow count is used to estimate equivalent SPT N-value.

The Harder approach is illustrated in Fig. 1. The field data point is first located, using the measured blow count (N_b) and corresponding peak bounce chamber pressure at sea level, on the blow count correction chart in Fig. 1a. Then following the appropriate correction curve or path down to the rating curve A-A (reference calibration curve for AP1000 type rig), the corrected blow count, N_{bc}, is obtained. Two examples are shown in Fig. 1a, the empty circle and empty square representing two measured data, and the filled circle and filled square giving the corresponding blow counts after correction. The corrected BPT blow count, N_{bc}, is then used to determine the equivalent corrected SPT blow count, N_{60}, using the correlation shown in Fig. 1b.

The attractiveness of the Harder approach is that peak bounce chamber pressure can easily be measured in the field without sophisticated equipment. The method, however, has some limitations. Since the reference combustion line in Fig. 1a is



(a) **BPT blow count correction chart**



(b) **BPT-SPT correlation chart**

Fig. 1 BPT-SPT correlation procedure proposed by Harder and Seed (1986)

specific for the particular drill rig/hammer used, the method could not be generally applied to different Becker rigs or hammers (Sy and Campanella, 1993). Also, the empirical BPT-SPT correlation in Fig. 1b was based on test data from three sand sites to only 15 m, and did not explicitly consider soil friction on the Becker casing which could be very different at other sites.

Sy Approach

An alternative and more fundamental approach to BPT-SPT correlation, based on experimental and numerical studies of the SPT and BPT, was proposed by Sy and Campanella (1994). In this approach, a Pile Driving Analyzer (PDA) is used during the BPT to determine the energy transferred into the top of the drive casing, similar to dynamic monitoring of pile driving (ASTM D4945-89). The transferred energy is then used to correct the measured field blow count to a reference energy of 30% of the manufacturer's rated energy for the ICE 180 hammer using:

$$N_{b30} = N_b \frac{ENTHRU}{30} \qquad [1]$$

where N_{b30} is the BPT blow count normalized to the 30% reference energy level, N_b is the measured blow count, and ENTHRU is the measured maximum transferred energy expressed as percent of the rated hammer energy of 11.0 kJ. Note that Eq. [1] is analogous to that used for energy correction of SPT blow counts.

The Sy approach further considers soil friction acting on the Becker casing. The soil friction and its distribution along the casing are estimated from the PDA stress wave measurements by a signal-matching wave equation analysis program, CAPWAP (Rausche et al. 1985). The energy-corrected N_{b30}, together with the computed shaft resistance value (Rs), is then used to estimate the equivalent SPT N_{60} value from the BPT-SPT correlations in Fig. 2.

Effect of Casing Friction

The BPT-SPT correlations proposed by Harder (1988) and by Sy (1993) are fundamentally different, due mainly to the effect of casing friction in the BPT. The Sy correlation curves (Fig. 2) are bending upward or convex, and they represent contours of equal shaft resistances (or casing friction). The Harder correlation curve (Fig. 1b), however, is bending downward or concave, and has unknown embedded casing friction.

Lum and Yan (1994) obtained correlations between bounce chamber pressure and transferred energy measurements at a dam site in British Columbia and compared the Sy and the Harder BPT-SPT correlations as shown in Fig. 3. Although this direct comparison is valid only for the actual Becker hammer and site conditions existing at the calibration site, the trend clearly shows that the Harder correlation line cuts through increasing shaft resistance contours as the BPT blow count increases.

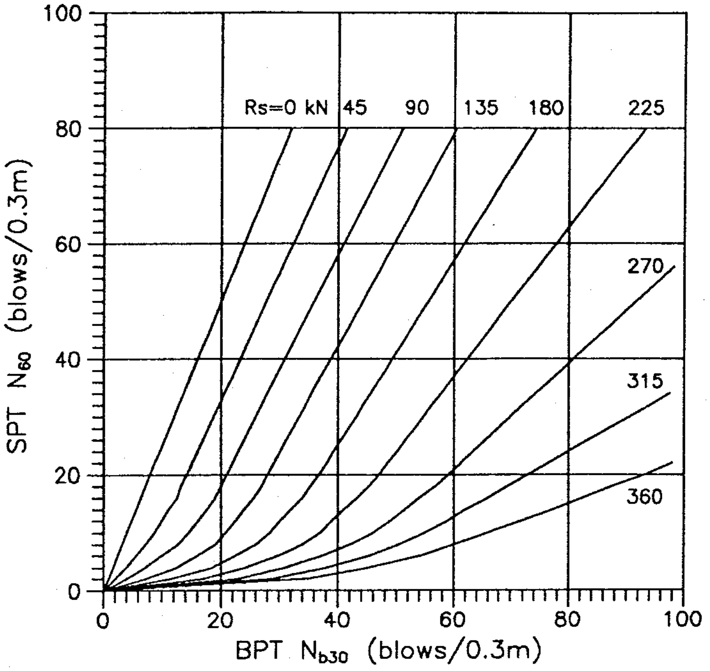


Fig. 2 **BPT-SPT correlation chart proposed by Sy and Campanella (1994)**

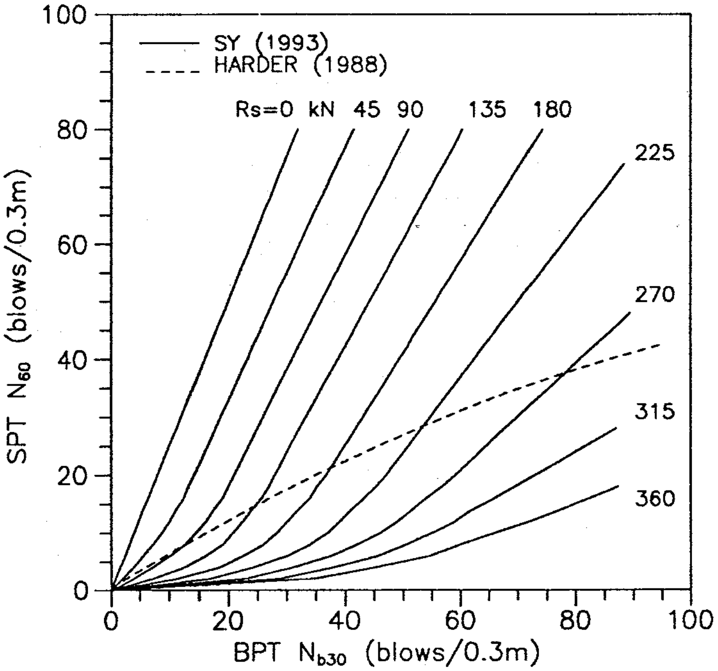


Fig. 3 **Comparison of BPT-SPT correlations by Sy and by Harder (after Lum and Yan 1994)**

Figure 3 indicates that the Harder correlation has significant embedded casing friction, the magnitude of which increases with increasing BPT blow count. Because the Harder correlation was developed empirically from test data to 15 m depth at three sand sites, the embedded casing friction effects are specific to the conditions at the test sites. Application of this correlation to other sites with different frictional characteristics, e.g. gravelly sites, could give unreliable results.

The Harder (1988) and Sy (1993) methods of BPT-SPT interpretations are applied to BPT data from two gravelly sites as described below. At both sites, dynamic monitoring of the BPT was performed with a PDA, in addition to measurement of hammer bounce chamber pressures.

CASE STUDY NO. 1

The first case study is a proposed waterfront development in downtown Vancouver on a site which was filled sometime in the last century to extend the shoreline. The 9 to 13 m thick uncontrolled fill consists of loose to compact sand and gravel with some silt and occasional cobbles, boulders and construction debris. The fill overlies 11 to 14 m thick deposits of loose silty sand and soft sandy silt above dense glacial till stratum.

The BPTs at this site were performed using an HAV180 Becker drill rig to drive 170 mm diameter casings. The dynamic measurements from BPT93-4 to 20 m depth are summarized in Fig. 4, which shows the measured blow count (N_b), bounce chamber pressure, and maximum transferred energy (ENTHRU) plotted against depth. The latter two quantities are average values for each 0.3 m of casing penetration. The ENTHRU is expressed as % of the hammer rated energy of 11.0 kJ. The soil profile shown on the right hand side of Fig. 4 was determined from an adjacent sampling hole drilled with the Becker casing driven open-ended.

Note the apparently high recorded blow counts, up to 60 blows/0.3 m, in the top 5 m of BPT93-4. This was due to an inefficient hammer condition, which was later found to be caused by a problem in the fuel control system. The inefficient driving was detected early in the test by the unusually low recorded transferred energies, less than 10%. The driller made several attempts to correct the problem, but it was not until the casing had penetrated 9 m that the actual problem was finally found and rectified. After hammer repair, the ENTHRU values jumped to about 30% (Fig. 4), clearly confirming the need for correcting measured BPT blow counts to a common reference energy level for design.

Figure 5 summarizes the dynamic measurements from another test, BPT93-5, to 32 m depth at the same site. With the hammer operating at constant combustion, the measured blow count (N_b) in BPT93-5 generally increases with depth. The bounce chamber pressure also increases with increasing depth or blow count. The

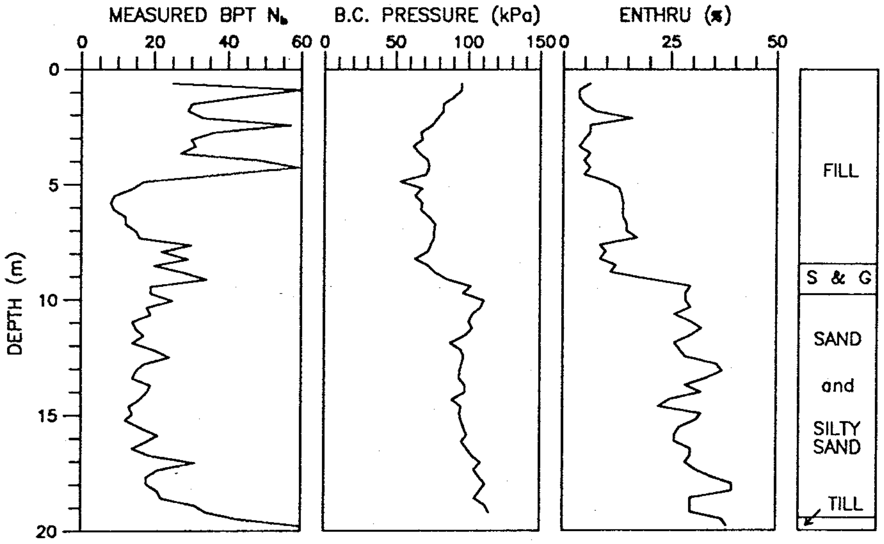


Fig. 4 Site 1 BPT93-4: measured blow count (N_b), bounce chamber pressure, and ENTHRU

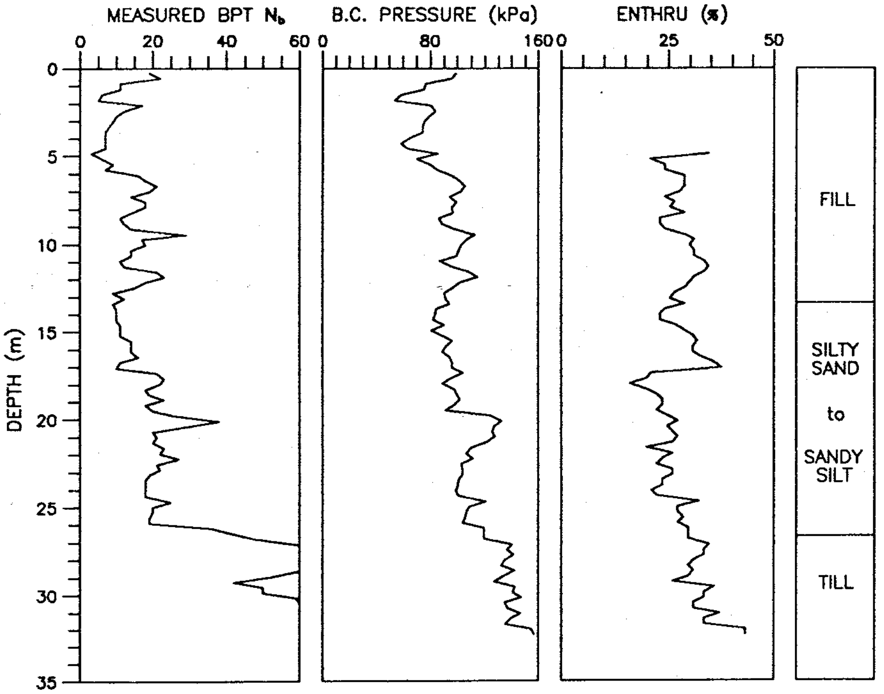


Fig. 5 Site 1 BPT93-5: measured blow count (N_b), bounce chamber pressure, and ENTHRU

transferred energy, however, is relatively constant, with an average value of about 25%.

Figure 6 shows the energy-corrected BPT blow count (N_{b30}), the estimated shaft resistance distribution, and the equivalent SPT N_{60} determined by the Sy method for BPT93-5. The N_{b30} is calculated using Eq. [1]. The shaft resistance (casing friction) profile is estimated based on CAPWAP-derived soil/casing friction values and by reviewing the PDA force and velocity wave traces. As expected, the shaft resistance increases with increasing embedment or length of casing in the ground. Finally, the equivalent SPT N_{60} is determined from the correlations in Fig. 2. The results indicate equivalent N_{60} values of about 10 to 20 in the 13 m thick gravelly fill and about 5 to 10 in the underlying native sand and silt.

Figure 7 compares the equivalent SPT N_{60} values determined by the Sy and the Harder methods. The equivalent N_{60} values from the Sy method are higher than those from the Harder method in the top 13 m of the soil profile, where shaft resistances are relatively low. However, below 13 m where shaft resistances are large, the equivalent N_{60} values by the Sy method are generally lower than those of Harder's, except for some high blow counts where the trend is opposite. These differences are due mainly to the effect of casing friction. As illustrated earlier in Fig. 3, the Harder correlation curve has embedded friction which increases with increasing blow count, whereas the Sy method explicitly considers casing friction. Thus at shallow depth where shaft resistance is usually low, the Harder procedure would underpredict equivalent N_{60} if the BPT blow count is relatively high. At depth where shaft resistance is usually large, and if the blow count is relatively low, the Harder procedure would overpredict equivalent N_{60}.

CASE STUDY NO. 2

The second case study is from Terzaghi Dam in interior British Columbia in which a series of BPTs were conducted as part of the seismic deficiency investigation of the dam. At the downstream toe, the foundation consists of sand and gravel with some silt and boulders, remnant of ancient slide debris or talus materials.

The dynamic measurements from BPT91-11 to 49 m depth in the downstream area of the dam are shown in Fig. 8. The BPT was performed with an AP1000 type drill rig driving 170 mm diameter casings. The measured blow counts are high, generally above 20 or 30 in the top 15 m of the soil profile, and above 50 below 15 m depth. The measured bounce chamber pressures average about 100 kPa, and the ENTHRU values are typically 20 to 24%.

Figure 9 shows the energy-corrected N_{b30}, estimated shaft resistance and equivalent SPT N_{60} values from the Sy method plotted against depth for BPT91-11. The shaft resistance profile is estimated based on four CAPWAP analyses performed at

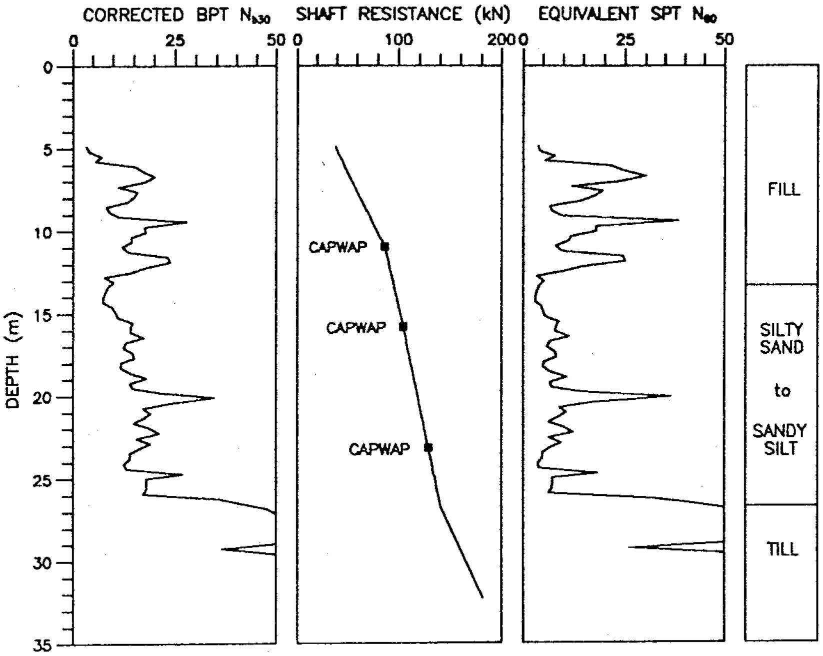


Fig. 6 Site 1 BPT93-5: energy-corrected blow count (N_{b30}), shaft resistance, and equivalent SPT N_{60}

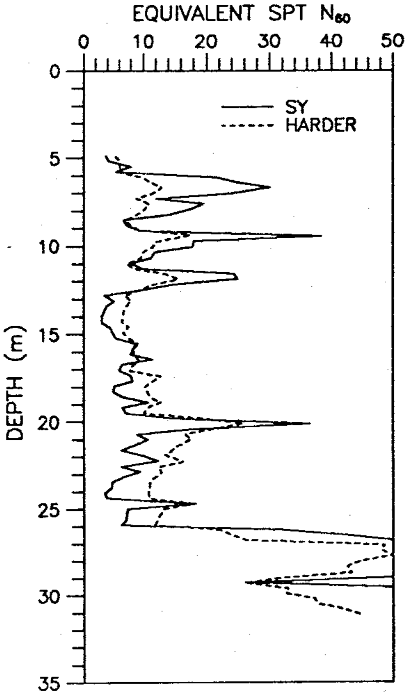


Fig. 7 Site 1 BPT93-5: equivalent SPT N_{60} values by Sy and Harder methods

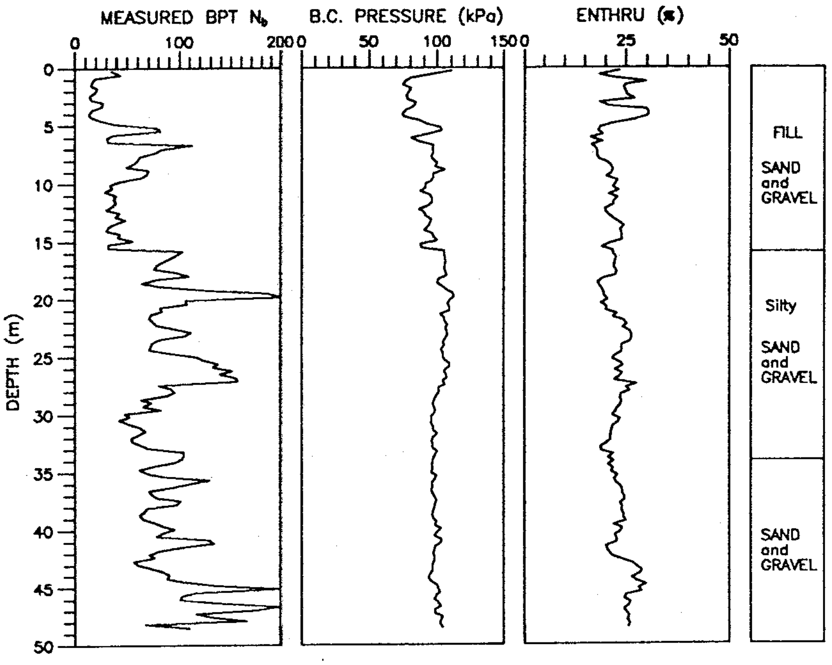


Fig. 8 Site 2 BPT91-11: measured blow count (N_b), bounce chamber pressure, and ENTHRU

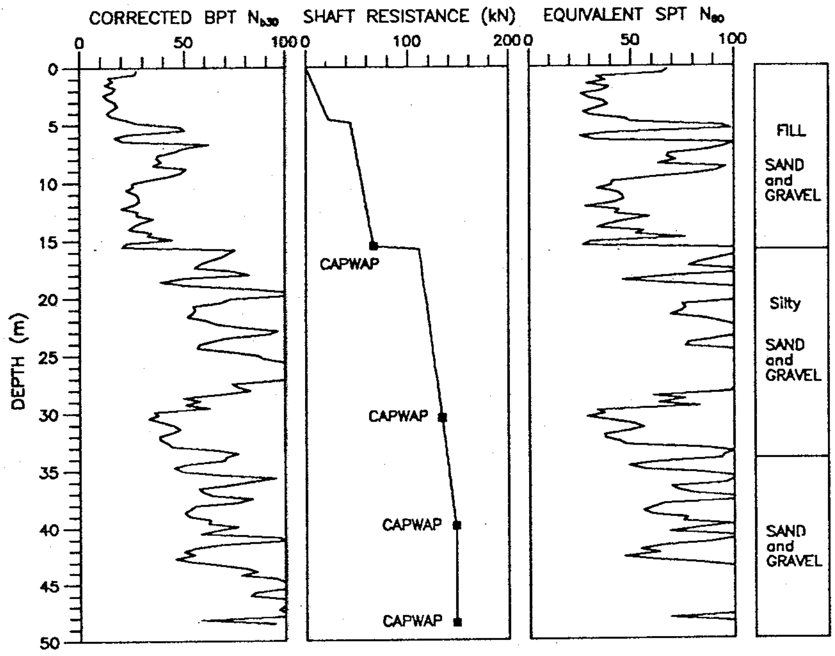


Fig. 9 Site 2 BPT91-11: energy-corrected blow count (N_{b30}), shaft resistance, and equivalent SPT N_{60}

selected depths and from a review of the PDA wave traces. As shown in Fig. 9, the estimated N_{60} values are high, generally above 30 blows/0.3 m.

The equivalent SPT N_{60} values from the Sy and Harder methods are compared in Fig. 10a. The N_{60} values from the Sy method are 2 to 3 times higher than those from the Harder method. Again, this difference is due to the effect of casing friction. At this site, because the blow counts are relatively high and the shaft resistance relatively low, the large embedded friction in the Harder correlation results in the low interpreted N_{60} values compared to the results by the Sy approach (Fig. 3). Fortunately, cross-hole shear wave velocity (Vs) data are available at a location close to DH91-11 that can be used, through published SPT-Vs correlations, to compare with the BPT-interpreted SPT N_{60} values. Figure 10b shows the shear wave velocity profiles measured by two separate testing contractors in the same set of test holes close to DH91-11. Both testing contractors used the crosshole technique.

Sykora and Koester (1988) reviewed and compared various empirical correlations relating Vs to SPT N-values. The two field-based correlations developed for gravelly soils are:

1. Imai and Tonouchi (1982)

$$Vs = 75.4 \quad N_{67}^{0.351} \qquad [2]$$

2. Ohta and Goto (1978)

$$Vs = 94.2 \quad N_{67}^{0.34} \qquad [3]$$

where Vs = shear wave velocity (m/s)
N_{67} = SPT N-value obtained by Japanese rope and cathead method with donut hammer, having estimated energy ratio of 67% (Seed et al. 1985)

The above correlations represent the latest in a series of correlative studies conducted by the respective investigators. The data base, however, is still small, being 28 data points for Eq. [2] and only 8 for Eq. [3].

As part of their seismic deficiency investigation of the Hugh Keenleyside Dam in British Columbia, Lum and Yan (1994) examined several SPT-Vs correlations for gravelly soils, including Eqs. [2] and [3]. They conducted BPTs and crosshole Vs measurements at several sites. Figure 11 from Lum and Yan (1994) shows the

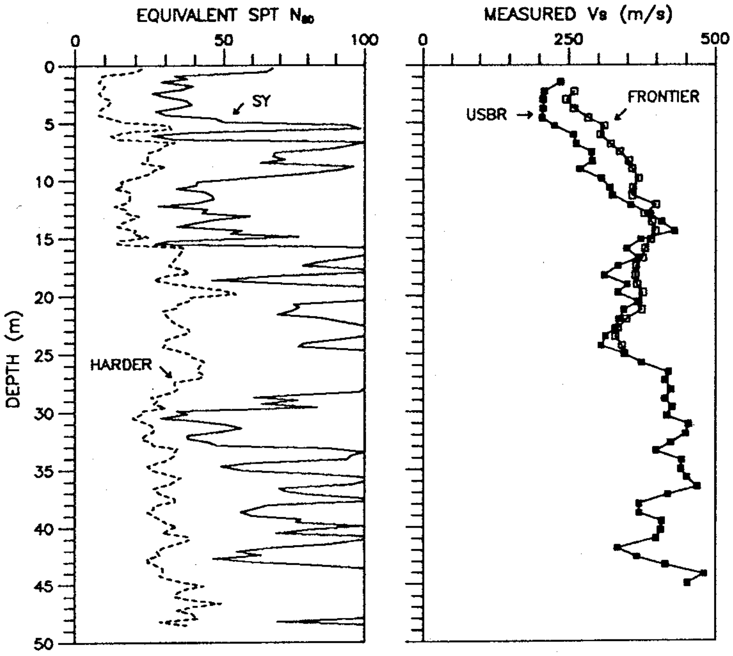


Fig. 10 Site 2 (a) BPT91-11 equivalent SPT N_{60} values by Sy and Harder methods; (b) measured shear wave velocities

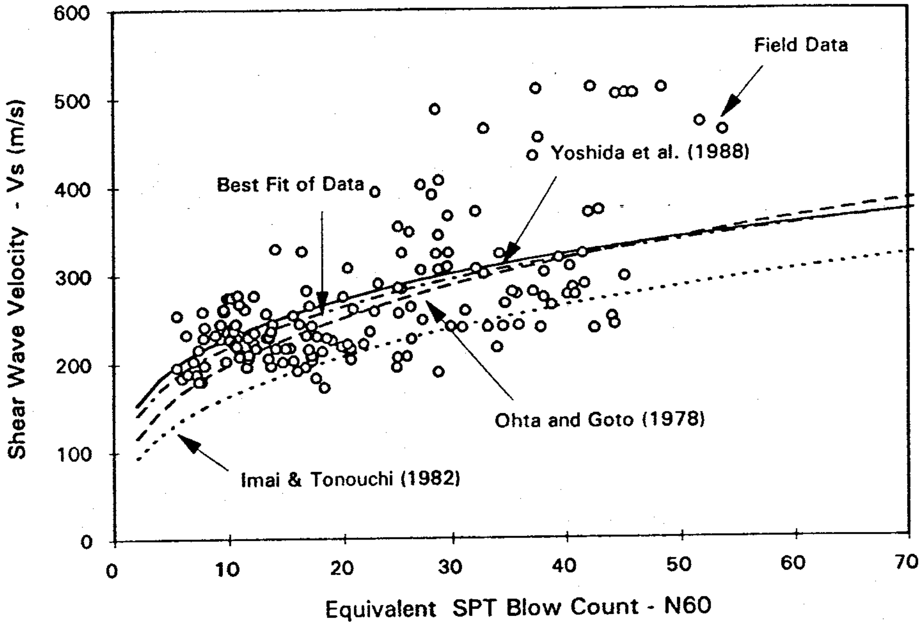


Fig. 11 Correlations between shear wave velocity and equivalent N_{60} values in gravelly soils (from Lum and Yan 1994)

published correlations plotted against the Vs data and equivalent N_{60} values from BPT using the Harder approach. Despite data scatter, they found that the Ohta and Goto (1978) correlation fits the data set well, but the Imai and Tonouchi (1982) correlation gives lower Vs values. These same two empirical SPT-Vs correlations are applied to the data at Terzaghi Dam below.

The equivalent N_{60} values derived from the Sy and Harder methods in Fig. 10 are converted to equivalent Vs values using Eqs. [2] and [3], and the interpreted results are compared in Fig. 12 with the measured Vs values. As shown, the equivalent Vs values calculated from the Sy approach are in good agreement with the measured Vs values. The calculated upper limit Vs values are due to an imposed maximum equivalent N_{60} value of 100. The equivalent Vs values from the Harder approach, however, are consistently lower than the measured values below about 10 m. Although the use of SPT-Vs correlation is subject to uncertainties, these results confirm the importance of accounting for casing friction in the BPT.

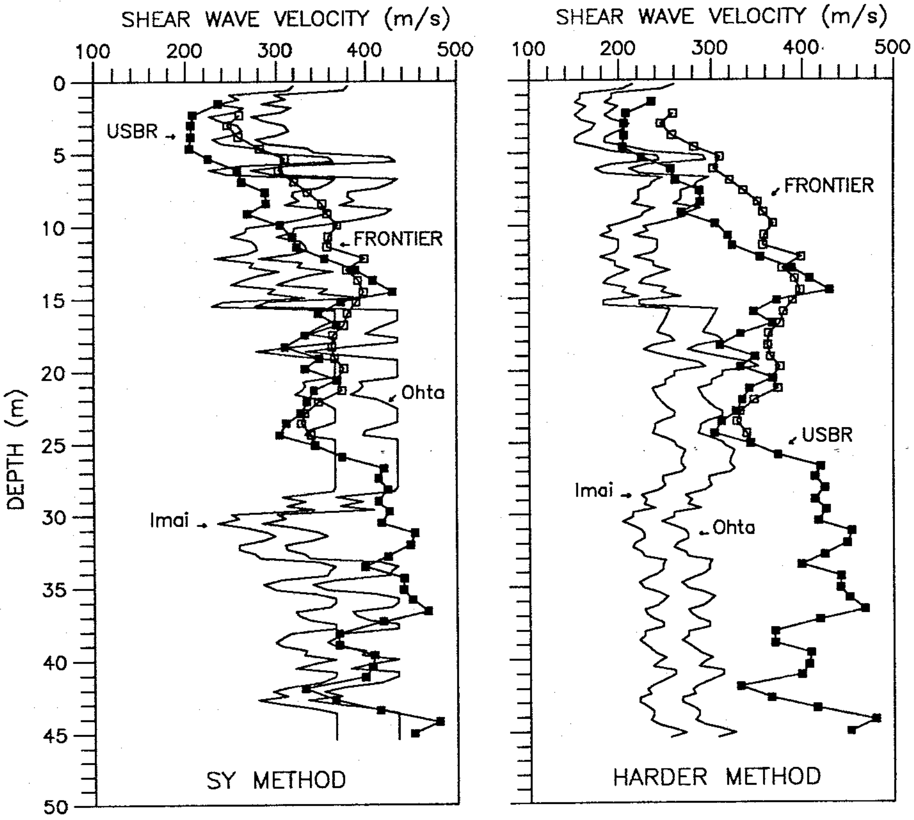


Fig. 12 Site 2: comparison of measured and BPT-derived equivalent shear wave velocities

SUMMARY AND CONCLUSIONS

Several case histories of seismic liquefaction in saturated gravelly soils have been reported in the literature. Field observations and investigations of these case histories indicate that loose to medium dense saturated gravelly soils are susceptible to liquefaction, and that the Seed's SPT-based liquefaction procedure for sands is applicable to gravelly sands. Because the SPT is unreliable in coarse-grained soils, the current practice is to use the BPT, through correlations with the SPT, to assess the liquefaction resistance of gravelly sites.

Two BPT-SPT correlations have been proposed in the literature. The Harder approach uses measured bounce chamber pressure to correct the field blow count to a reference constant combustion condition, but it does not explicitly consider soil friction acting on the Becker casing. The Sy method uses measured transferred energy to correct the BPT blow count, similar to energy correction of the SPT, and it accounts for casing friction. These correlations are applied to two gravelly sites in British Columbia.

In the first case study, the equivalent N_{60} values determined by the Sy method are higher in the top 13 m, but generally lower below 13 m, than those from the Harder method. In the second case study, the equivalent N_{60} values by the Sy method are significantly higher than those by the Harder method throughout the 48.5 m profile. In the second site, independent cross-hole shear wave velocity measurements, through correlations with the SPT, appear to support the results determined by the Sy method. Both case studies illustrate the importance of considering casing friction in the BPT.

ACKNOWLEDGEMENTS

The authors acknowledge BC Hydro for permission to publish data from Terzaghi Dam. The opinions expressed in the paper are those of the authors and do not necessarily represent opinions of any other individual or organization. The authors also thank the ASCE reviewers for helpful comments.

REFERENCES

Andrus, R.D. 1994. In-situ characterization of gravelly soils that liquefied in the 1983 Borah Peak earthquake. Ph.D. Dissertation, University of Texas at Austin.

Andrus, R.D. and Youd, T.L. 1989. Penetration tests in liquefiable gravels. Proc. 12th Int. Conf. on Soil Mech. and Found. Eng., Rio de Janeiro, 679-682.

ASTM Standard D4945-89. Standard test method for high-strain dynamic testing of piles. ASTM Standards, Vol.04.08, 1018-1024.

Coulter, H.W. and Migliaccio, R.R. 1966. Effect of the earthquake of March 27, 1964 at Valdez, Alaska. U.S. Geological Survey Professional Paper 542-C.

Crova, R., Jamiolkowski, M., Lancellotta, R. and Presti, D.C.F. 1993. Geotechnical characterization of gravelly soils at Messina site: selected topics. Predictive Soil Mechanics, Thomas Telford, London, 199-218.

Evans, M.D. and Zhou, S. 1995. Liquefaction behavior of sand-gravel composites. ASCE Journal of Geotech. Eng., 121(3): 287-298.

Fletcher, G.F.A. 1965. Standard penetration test: its uses and abuses. ASCE Journal of Soil Mech. and Found. Div., 91(SM4): 67-75.

Harder, L.F. Jr. 1988. Use of penetration tests to determine the liquefaction potential of soils during earthquake shaking. Ph.D. Dissertation, University of California, Berkeley.

Harder, L.F. Jr. and Seed, H.B. 1986. Determination of penetration resistance for coarse-grained soils using the Becker hammer drill. Report No. UCB/EERC-86/06, University of California, Berkeley, 118 pages.

Ishihara, K. 1985. Stability of natural deposits during earthquakes. Proc. 11th Int. Conf. on Soil Mech. and Found. Eng., San Francisco, Calif., Vol. 1, 321-376.

Imai, T. and Tonouchi, K. 1982. Correlation of N value with S-wave velocity and shear modulus. Proc. 2nd European Symp. on Penet. Testing, Amsterdam, 67-72.

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.

Lum, K.K.Y. and Yan, L. 1994. In-situ measurements of dynamic properties and liquefaction resistances of gravelly soils at Keenleyside dam. Ground Failures under Seismic Conditions, ASCE Geotech. Special Publication No. 44, 221-240.

Maurenbrecher, P.M., Den Outer A. and Luger, H.J. 1995. Review of geotechnical investigations resulting from the Roermond April 13, 1992 earthquake. Proc. 3rd Int. Conf. on Recent Advances in Geotech. Earthquake Eng. and Soil Dyn., St. Louis, Missouri, 645-652.

Ohta, Y and Goto, N. 1978. Physical background of the statistically obtained S-wave velocity equation in terms of soil indexes. Butsuri-Tanko (Geophysical Exploration), 31(1):8-17. (in Japanese)

Rausche, F., Goble, G.G. and Likins, G.E. Jr. 1985. Dynamic determination of pile capacity. ASCE Journal of Geotechnical Engineering, 111(3): 367-383.

Seed, H.B., Tokimatsu, H., Harder, L.F. and Chung, R.M. 1985. Influence of SPT procedures in soil liquefaction resistance evaluations. ASCE Journal of Geotechnical Engineering, 111(12): 1425-1445.

Stokoe, K.H., Andrus, R.D., Rix, G.J., Sanchez-Salinero, I., Sheu, J.C. and Mok, Y.J. 1988. Field investigation of gravelly soils which did and did not liquefy during the 1983 Borah Peak, Idaho, earthquake. Geotech. Eng. Report GR87-1, Civil Engineering Department, University of Texas at Austin.

Sy, A. 1993. Energy measurements and correlations of the Standard penetration test (SPT) and the Becker penetration test (BPT). Ph.D. Thesis, Department of Civil Engineering, University of British Columbia, Vancouver, B.C.

Sy, A. and Campanella, R.G. 1993. Dynamic performance of the Becker hammer drill and penetration test. Canadian Geotechnical Journal, 30(4): 607-619.

Sy, A. and Campanella, R.G. 1994. Becker and standard penetration tests (BPT-SPT) correlations with consideration of casing friction. Canadian Geotechnical Journal, 31(3): 343-356.

Sykora, D.W. and Koester, J.P. 1988. Correlations between dynamic shear resistance and standard penetration resistance in soils. Earthquake Engineering and Soil Dynamics II - Recent Advances in Ground-Motion Evaluation, ASCE Geotechnical Special Publication No. 20, 389-404.

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.

Valera, J.E. and Kaneshiro, J.Y. 1991. Liquefaction analysis for rubber dam and review of case histories of liquefaction of gravels. Proc. 2nd Int. Conf. on Recent Advances in Geotech. Earthquake Eng. and Soil Dyn., St. Louis, Missouri, 347-356.

Wang, W.S. 1984. Earthquake damages to earth dams and levees in relation to soil liquefaction and weakness in soft clays. Proc. of the Int. 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. ASCE Journal of Geotech. Eng., 120(3): 581-596.

Yoshida, Y., Kokusho, T. and Motonori, I. 1988. Empirical formulas of SPT blow counts for gravelly soils, Proc. ISOPT-1, Orlando, Florida, Vol. 1, 381-387.

Youd, T.L., Harp, E.L., Keefer, D.K. and Wilson, R.C. 1985. The Borah Peak, Idaho earthquake of October 28, 1983 - liquefaction. Earthquake Spectra, EERI, 2(1): 71-89.