Instrumented Becker Penetration Test

II: iBPT- SPT Correlation for Characterization and Liquefaction Assessment of Gravelly Soils

[In review for publication in ASCE JGGE]

Mason Ghafghazi, M.ASCE[1], Jason T. DeJong, M.ASCE[2], Alexander P. Sturm, S.M.ASCE[3], and Charles E. Temple[4]

[1] Assistant Professor, Department of Civil Engineering, University of Toronto, 35 St. George St., Toronto, ON M5S 1A4, +1 (416) 978 – 5972, mason.ghafghazi@utoronto.ca

[2] Professor, Department of Civil & Environmental Engineering, University of California at Davis, One Shields Ave., Davis, CA 95616, +1 (530) 754 – 8995, jdejong@ucdavis.edu

[3] Graduate Student, Department of Civil & Environmental Engineering, University of California at Davis, One Shields Ave., Davis, CA 95616, +1 (650) 580 – 2729, apsturm@ucdavis.edu

[4] Former Graduate Student, Senior Engineer, Shannon & Wilson, Inc., 1722 3rd Street, Suite 100, Sacramento California, 95811, +1 (916) 438 – 2300, cet@shanwil.com

ABSTRACT

The Becker Penetration Test (BPT) is a widely used tool for the characterization of gravelly soils, especially liquefaction assessment. An instrumented Becker Penetration Test (iBPT) was developed and integrated into the standard, closed-ended Becker drill string. The iBPT produces a continuous profile of energy normalized blow count values, N_{B30}, which are computed using the acceleration and strain measurements recorded directly behind the driving shoe. The N_{B30} profile is repeatable and unaffected by hammer driving energy or accumulated shaft resistance. This paper presents the correlation between iBPT N_{B30} and SPT N_{60} values which is necessary for performing liquefaction assessment in gravelly soils. In developing this correlation, field variability was addressed by comparing median iBPT N_{B30} and SPT N_{60} values from adjacent soundings over geologically consistent depth intervals. A framework was also developed to assess, and, when appropriate, correct for gravel influence on measured SPT blow count (N) values. This framework utilizes SPT blows-per-inch as well as physical evidence from SPT and adjacent Sonic samples. The correlation between iBPT N_{B30} and SPT N_{60} is shown to be a constant value of 1.8 and independent of soil type or penetration resistance magnitude.

INTRODUCTION

Penetration tests, namely the Standard Penetration Test (SPT) and Cone Penetration Test (CPT), have become the standard for characterizing the liquefaction potential of cohesionless soils. Assessing the characteristics of gravelly soils poses additional difficulties due to the large particle to probe diameter ratio (e.g. Daniel et al., 2004). In the case of the SPT, gravel particles can clog or block the split-spoon sampler, resulting in limited recovery and/or unrepresentative blow counts. Depending on the abundance of large particles during the CPT, gravel particles can either block the advancement of the cone, cause a misalignment in the rods, and/or adversely influence the measurements.

In order to obtain a representative penetration measurement in gravelly soils, current practice will often (1) use SPT blows-per-inch to detect and correct for the influence of large particles and/or (2) conduct large diameter in-situ testing such as the Becker Penetration Test (BPT). If the BPT is utilized, then equivalent energy normalized SPT blow count (N_{60}) values must be estimated using empirically developed correlations. The large diameter (168 mm, 6 5/8 in) diameter of the BPT is particularly applicable in these coarse materials, where it provides more repeatable results and fewer occurrences of refusals compared to smaller scale split-spoon penetrometers (e.g. SPT). Other site investigation tools are occasionally used to characterize gravelly soils (i.e. large penetration tests (e.g. California Modified Sampler, North American Large Penetration Test, etc. (Daniel et al. 2004) and the Chinese Dynamic Penetration Test (Cao et al., 2013)). However, these tools are only slightly larger than CPT and SPT and therefore influenced by large particles in a similar manner.

The first correlation between BPT and SPT N values by Becker Drills Inc. from the 1970s proposed a correlation factor of 1.0 based on data collected from side-by-side soundings at a number of sites around British Columbia, Canada (Harder and Seed, 1986). The use of the correlation became questionable after the effects of driving energy on both SPT and BPT were recognized. Harder and Seed (1986) proposed a correlation between SPT N_{60} and BPT blow count values corrected to a constant hammer combustion condition, N_{BC}. Sy and Campanella (1994) developed a set of correlations between energy normalized BPT blow count values, N_{B30}, and SPT N_{60} values. The correlations of Sy and Campanella (1994) are dependent on the amount of estimated static shaft resistance along the drill string, calculated using signal matching and wave equation analysis techniques.

The equivalent SPT N_{60} estimated by both Harder and Seed (1986) and Sy and Campanella (1994) are limited in accuracy and reliability due to the inherent limitations in how the contribution of shaft resistance is accounted for in the overall penetration resistance measured by the BPT. The limitations stem from their underlying assumptions and the datasets used to develop the correlations. Harder and Seed (1986) did not directly account for the influence of shaft resistance on the measured blow counts. The equivalent N_{60} values produced by the method are overly-conservative at low shaft resistance values and overestimated at high shaft resistance values. The Sy and Campanella (1994) method utilized a more rigorous approach to correct for the contribution of shaft resistance by using wave matching techniques (CAPWAP) to estimate the total static shaft resistance developed along the drill string. However, the shortcomings of wave matching techniques in modelling the drill string response from individual hammer impacts, non-uniqueness of the wave matching solutions in separating drill string shaft and tip contributions, the deficiency of static shaft resistance as a proxy for energy loss, and the limited field data used to develop the correlation have resulted in inconsistent results. The estimated N_{60} values from Sy and Campanella (1994) are generally overestimated at low shaft resistance and erratic at medium to high shaft resistance.

Sy and Lum (1997) presented a modified, mudded BPT, using reduced diameter drill strings and drilling mud circulated behind the driving shoe, in an effort to reduce or eliminate shaft resistance. The mudded BPT was shown to eliminate the shaft resistance, but its application has remained limited to research explorations because of the difficulties associated with circulating mud with the BPT in pervious, gravelly soils.

The instrumented Becker Penetration Test (iBPT) provides a solution to the problem of shaft resistance in Becker Penetration Test. The iBPT equipment (DeJong et al., 2016) measures the acceleration and strain directly behind the drill string tip in order to calculate the energy delivered to the soil beneath the tip from individual hammer blows. iBPT blow count values per 0.3 m (1 ft) of penetration, N_B, are normalized by the residual energy delivered to the tip:

$$N_{B30} = N_B \frac{E_{res,Tip}}{30\ (\%)} \qquad [1]$$

where $E_{res,Tip}$ is the residual energy transferred to the instrumented section above the drill string tip at the end of each blow, expressed as a percentage of the rated ICE 180 hammer energy (11 kJ), and normalized to a reference 30% hammer energy efficiency (similar to 60% for SPT N_{60}).

DeJong et al. (2016) demonstrated that the iBPT system provides repeatable, reliable N_{B30} profiles that are unaffected by the input hammer energy, accumulated shaft resistance, and other driving conditions. The iBPT is fully integrated with standard Becker drilling equipment and can be performed as deep as Becker driving is possible. The robust and reliable N_{B30} measurements obtained with the iBPT system provide the opportunity to develop a more reliable correlation to compute equivalent SPT N_{60} values.

The development of the correlation between iBPT N_{B30} and SPT N_{60} values is described in this paper. The correlation uses data from four, extensive, field exploration programs including SPT, iBPT, and Sonic soundings. The materials from the four sites encompass those soils commonly encountered in practice and range from low plasticity clays, silts, and sands to gravelly sands. Most of the materials were of alluvial origin; however, man-made, compacted and hydraulically-placed fills as well as residual soils were also encountered. In order to develop a reliable correlation, the first step was to ensure that the SPT N_{60} values used were of high quality. This resulted in the development of a framework to assess the quality of SPT data obtained in gravelly soils, and includes a systematic approach for quality evaluation and, when appropriate, blow count value correction. Next, the extent of spatial variability that typically exists in gravelly alluvia was evaluated and a consistent, geology-informed, methodology was used to handle the effects of spatial variability on the final correlation. A linear correlation was developed to convert iBPT N_{B30} values to equivalent SPT N_{60} values. This paper demonstrates that the correlation is independent of soil type and therefore applicable to all soils that may be encountered when characterizing sites with gravels.

FIELD MEASUREMENTS AND TEST SITES

The iBPT system was deployed at four sites providing data in a wide range of ground and drilling conditions. Data were obtained in residual and alluvial deposits as well as man-made compacted and hydraulically placed fills. A variety of soil types were encountered including mixtures of clays, silts, sands, gravelly sands and sandy gravels. Collectively, the particle size ranged from small cobbles to clays, the plasticity ranged from 0 to about 27, the percent gravel ranged from 0% to 50%, and the percent fines ranged from 0% to 90. Driving was performed from the ground surface and from various depths below grade (after pre-drilling) to avoid refusal stemming from high shaft friction when penetrating through the compacted dam embankment.

All testing was performed in clusters where one (or occasionally two) iBPT soundings were performed at a distance of 2 to 4 m (6 to 14 ft) from SPT and Sonic soundings. CPT soundings were also performed in many cases (at similar spacing), which provided additional data on stratigraphic layering and field variability. The positioning and spacing between the soundings was determined considering the depositional environment (i.e. aligning borings parallel to historic stream flow to enhance cross-correlation), the zone of influence of the different tests, the test sequence, and site access. Table 1 contains a summary of the tests performed at each site.

SPT data were obtained through rotary wash drilling at all sites. The procedures recommended by Idriss and Boulanger (2008) were used to correct measured N values to N_{60} values. Individual energy measurements, obtained per the procedures recommended in ASTM D4633-10, were used for energy normalization in two SPT borings at each site. For SPT borings where direct energy measurements were not available, the average energy of the hammer measured on the same site, was used, with the short rod correction applied when appropriate. The SPT samplers used at of the two sites had no inside clearance, while the SPT samplers used at the other two sites had clearance for liners with no liners installed. The liner correction recommended by Idriss and Boulanger (2008) was applied to the latter.

A summary of the four sites is presented here with additional details provided in DeJong et al. (2016). The first site, Headworks West Reservoir, is founded on alluvial gravelly and cobbly deposits from the original alignment of the Los Angeles River. The second site, the new alignment for North Haiwee Dam, is located in a relatively calm hydro-geologic depositional environment and comprised of silty sand and clean sand deposits with occasional gravel lenses. The third site, Stone Canyon Dam, is located within a narrow canyon and underlain by arroyo-alluvial foundation comprised of highly interlayered and intermixed low plasticity clays and sands with frequent gravel-sized, slate fragments. There is significant variability in the alluvium; however, the man-made, dam embankment units are relatively homogeneous and comprised of clayey silts and silty clays. The fourth site, Bouquet Canyon Dam, consists of a dam founded on an upper, sandy, alluvium and a lower, gravelly, alluvium which is underlain by highly weathered, schist bedrock.

DEVELOPMENT OF iBPT-SPT CORRELATION

Geotechnical design and analysis in general, and liquefaction assessment procedures in particular, often use SPT N_{60} as a proxy for the soil strength and denseness since sampling and laboratory characterization of cohesionless soils is impractical. The prevalence of SPT N_{60} data in sands has led to the development of numerous methodologies for estimating liquefaction susceptibility from SPT N_{60} values. iBPT N_{B30} values provide reliable penetration resistances in gravelly soils (DeJong et al, 2016); however, there are no direct methods to estimate liquefaction susceptibility from iBPT N_{B30} values. As such, iBPT N_{B30} values need to be converted to equivalent SPT N_{60} values in order to predict the liquefaction susceptibility of gravelly soils. This approach assumes that the SPT-based liquefaction triggering correlations, developed for sand, are applicable to sandy soils with gravels and to gravelly soils.

The correlation was developed by comparing iBPT N_{B30} values and SPT N_{60} values in adjacent soundings form the four project sites. The following steps were taken:

- All SPTs were screened for gravel influence through a conservative framework (described in detail below) with consideration of additional information from adjacent Sonic soundings. SPT blow counts which were determined to be adversely influenced by the presence of gravel particles were excluded from the correlation database.
- SPT N_{60} values were computed using Idriss and Boulanger (2008).
- iBPT N_{B30} values were computed using DeJong et al. (2016).
- SPT N_{60} and iBPT N_{B30} measurements were binned over geologically consistent depth intervals that had comparable penetration resistance trends and soil types. This was done in an effort to handle the spatial variability between two adjacent soundings, about 3 m (9.8 ft) apart, in alluvial deposits.
- Median values of the binned SPT N_{60} and iBPT N_{B30} values were compared to develop the correlation.

Screening for Gravel Influence on SPT

The presence of large particles (gravels and larger) can increase SPT blow counts (Rollins et al., 1998). Large particles may get trapped below the driving shoe, temporarily increasing the blow counts until they are pushed out of the way, moved into the sampler, or broken apart by subsequent hammer blows. Large particles may also clog the sampler, changing the penetration mechanism from open-ended to closed-ended (full displacement).

The occurrence and consequence of encountering large particles during an SPT test is dependent on the soil gradation, the soil density, the particle shape and hardness, and where along the SPT penetration length of 0.45 m (18 in) the large particles are encountered, among other factors. It is difficult to detect and quantify the gravel influence on SPT N values with a high level of certainty. It is, however, possible to identify circumstances where gravel influence is more likely, and develop a simplified framework to screen and, when possible, correct, the SPT *N* values for gravel influence.

A rigorous and conservative framework to assess gravel influence on SPT *N* values was developed. The framework conservatively separates SPT N_{60} values into high (HQ) and low quality (LQ) categories. HQ data represent measurements where little or no gravel influence occurred and LQ data represent measurements where the possibility of significant gravel influence could not be ruled out.

The framework uses the per-inch SPT blow counts (Figure 1), as well as any physical evidence for the presence of gravel. The physical evidence includes gradation of the samples retrieved in the split-spoon sampler and Sonic cores, photographs of the sample retrieved in the split-spoon sampler and Sonic cores, sample recovery, and field logs. When possible soil gradations from Sonic core samples should be considered as the SPT split-spoon sample can scalp large particles resulting in an under-estimation of the gravel content. This is evident in the ranges of gradations observed in gravelly soils from SPT (ID= 35 mm or 1 3/8 inch) and Sonic core (ID= 102 mm or 4 inch) samples from two sites (Figure 2). Sonic cores are not immune to scalping, but the larger diameter results in a more accurate (closer to in-situ) gradations.

Gravels often cause an increase in per-inch blows over a few inches of penetration (e.g. Figures 1b and 1c.ii). These “spike” features in the blows per-inch profile can be corrected by manually removing the “spike” feature from the per-inch blow count trend, as illustrated in Figures 1b and 1c. On the other hand, greater judgment is needed when a steady rise or consistently high values are observed (e.g. Figure 1c.i). When there are multiple changes in the blows per-inch profile (e.g. Figure 1d.i), or in cases of refusal (less than about 15 inch sampler penetration out of the standard 18 inch), the measurements are considered unreliable.

Every SPT test is assigned one of five different quality indices as defined in the following rubric:

I – No sign of gravel influence in per-inch blow counts. No signs of influential gravels in the physical evidence from SPT *and* Sonic testing.

II – No sign of gravel influence in per-inch blow counts. Sign(s) of influential gravels in physical evidence from SPT *and/or* Sonic testing.

III – Sign(s) of gravel influence in per-inch blow count which were reliably corrected. No sign of influential gravels in physical evidence from SPT *and* Sonic testing.

IV – Sign(s) of gravel influence in per-inch blow counts which were considered acceptable, or were reliably corrected. Sign(s) of influential gravels in physical evidence from SPT *and/or* Sonic testing.

V – Sign(s) of gravel influence in per-inch blow counts which cannot be reliably corrected. Sign(s) of influential gravels in physical evidence from SPT *and/or* Sonic testing.

The implication of indices I and II is that gravels were deemed not present in the vicinity of the SPT sampler (I), or the sampler did not encounter the gravel particles (II). Index III, which is seldom observed, accounts for cases where dense sand seams are encountered. Index IV pertains to cases where the presence of gravel is virtually certain, but its adverse influence on the blow count may be negligible, or eliminated by applying a reliable correction. Index V pertains to the cases where the presence of gravel is certain and its effects cannot be reliably corrected. Table 2 summarizes the five indices for assessing gravel influence on SPT results.

The intention behind the screening framework is to consider the blows-per-inch and physical evidence separately, and then combine them to make a final decision based on the strict index definitions. In some cases, the two factors may corroborate to better explain how large particles influenced the blow counts. One example is when a gravel particle is located within the sampler close to the penetration depth where a blow count 'spike' is observed. Another example is when *N* values are consistently high and the recovery is small, or the length of sample recovered is similar to the penetration distance up to the depth where a high blow zone begins. In other cases, physical evidence and per-inch blow counts may not necessarily align. The indices are specifically worded to methodically categorize various possibilities and facilitate the decision-making process.

After an Index (I – V) is assigned to each *N* value the data are separated into high quality (HQ) and low quality (LQ) categories. HQ data represent measurements where little or no gravel influence was expected and is defined as data with indices of I to III *and* less than 20% gravel present in the SPT spilt-spoon sampler. LQ data represent measurements where the possibility of significant gravel influence could not be ruled out and is defined as data with indices of IV and V, *or* more than 20% gravel present in the spilt-spoon sampler. This methodology was developed considering guidance from Idriss and Boulanger (2008), including a 'rule-of-thumb' 15-20% gravel threshold. The 20% gravel present in the SPT spilt-spoon sampler cutoff was applied as an objective and conservative criteria after applying the gravel screening framework presented above to be conservative in the data selected for use in the correlation development. As detailed below, subsequent evaluation verified that this level of screening was conservative (as intended for correlation development) with many HQ SPT data excluded. Appendix A presents a modified, less conservative, version of this SPT screening framework that may be used for general site investigations to evaluate the influence of gravel on SPT data.

The screening framework described above was applied to each SPT sample from the four sites in order to assess gravel influence on SPT N values. Only the SPTs identified as HQ were included in developing the iBPT-SPT correlation. The majority of these were obtained in soils that did not contain gravel (Index I). The remainder if the database was comprised of SPT N_{60} values obtained in soils where the presence of the gravel was determined to have not adversely influenced the SPT (Indices II and III, with less than 20% gravel).

Field Variability

The differences between the two measurements (i.e. iBPT N_{B30} and SPT N_{60}) obtained in adjacent soundings can be attributed to a combination of differences between the tests as well as field variability. In order to distinguish between the contributions of these two factors, and quantify the extent of field variability, results from identical tests performed in adjacent soundings can be compared. Figure 3 presents measurements made in the same horizons from four pairs of CPT soundings (spacing between pairs of soundings being 4.6 m (15 ft)) and from four pairs of iBPT soundings (spacing between pairs of soundings being between 2.8 and 4.0 m (9 to 13 ft)) from the North Haiwee Dam site. The CPT tip resistance, q_t, is widely recognized as the most repeatable in-situ penetration resistance measurement (e.g. Kulhawy and Trautmann, 1996). The per-foot average q_t values from pairs of CPT soundings are plotted in Figure 3a, and have a log-normal coefficient of variation (COV) of 0.40. iBPT N_{B30} values from adjacent soundings are plotted in Figure 3b, and have a log-normal COV of 0.37. The field variability bands from CPT and iBPT measurements are similar, which demonstrates that the iBPT N_{B30} measurement is as repeatable as the CPT q_t measurement. More importantly, ±40% variability bands reflect the range that can generally be expected when the comparing the results from adjacent soundings (3 to 4.5 m distance) in an alluvial deposit.

The same range of variability, about ±40%, is therefore expected in the correlation between iBPT N_{B30} and SPT N_{60} values as its development is based on the comparison of data from two adjacent borings/soundings. Further, the SPT is a less repeatable method compared to other in-situ penetration tests (e.g. Kulhawy and Trautmann 1996, Rogers 2006), and is therefore the likely source of additional scatter in the correlation.

Binning of Data for Correlation Development

The comparison of representative, median penetration resistance values obtained by two different methods (e.g. iBPT N_{B30} and SPT N_{60} values) over geologically consistent depth intervals enables evaluation of the relation between penetration resistances between the two methods. The basis for this approach is founded in the recognition that the soils encountered in two adjacent soundings at a specific horizon may not have been deposited simultaneously due to the spatial variability of the alluvial depositional processes. However, statistically similar soils will be deposited over a larger depth interval when the depositional environment is consistent over time; these geologically consistent depth intervals can be binned and the median values from these intervals used as representative values.

The application of this binning approach using iBPT N_{B30} and SPT N_{60} data for the correlation developed is illustrated in Figure 4. The consistency of the iBPT N_{B30} and SPT N_{60} signatures were considered in selection of internals for binning. For example, in each of the two bins at depths of 3.5 to 6.5 m (11 to 21 ft), and 8 to 13.5 m (26 to 44 ft), iBPT N_{B30} and SPT N_{60} trends are similar, and distinctly different from other intervals. The SPT and Sonic logs, grain size distributions, and photos are also compared within each potential bin to confirm that the interval generally consists of one material type. In general, there was consistency between the materials encountered in the iBPT, Sonic, and SPT soundings from a single cluster and this binning approach associated statistically similar materials in most cases.

For the correlation development the bins which include mainly high quality SPT data were classified as high quality (HQ) and those with low quality SPTs were classified as low quality (LQ) and were excluded from the correlation development. Transitional depth intervals or those without enough data were not assigned to a bin and were omitted from correlation development.

iBPT N_{B30} - SPT N_{60} Correlation

A linear correlation

$$N_{60} = 1.8\ N_{B30} \qquad [2]$$

exists between median SPT N_{60} and iBPT N_{B30} values from high quality (HQ) bins with a log-normal COV of 0.35. Figure 5 presents the median data pairs for the 122 HQ bins developed, with the symbol diameter representing the amount of data in each bin. These 122 bins are based on 349 individual HQ SPT measurements with an adjacent, continuous iBPT N_{B30} profile (Table 1). No clear bias is evident amongst the data from the four different sites, and the extent of variability was similar to that present at the test sites, as indicated by the ±40% variability bands in the figure.

The use of median bin values was effective at capturing the correlation between SPT N_{60} and iBPT N_{B30} values in the spatially variable, alluvial deposits. The effect of the binning procedure is evident in Figure 6 where bars that represent the range of SPT N_{60} and iBPT N_{B30} values present in each bin is plotted. The largest error bars are observed at Headworks West Reservoir which is the most geologically variable site in the database. The binning approach presented above appears to adequately curb the variability in more variable sites to the same level observed in Figure 3.

No material dependence is observed in the correlation. This is evident in Figure 7 where the data have been presented based on the dominant soil type present in each defined bin. The data are presented on log-log scale in Figure 7b for better visibility across their entire data range. Further evaluation of the data revealed no bias in the correlation with respect to depth or saturation conditions.

The correlation factor is constant across the full range of penetration resistances measured. To assess the sensitivity of the correlation factor, the cumulative distribution of the ratio of SPT N_{60} to iBPT N_{B30} median values are plotted in Figure 8. The correlation factor of 1.8 represents the median (50th percentile) value in the cumulative plot. SPT N_{60} values less than 40 ($N_{B30} < 23$) are specifically important to liquefaction assessment. If only data bins within this range of data are included in the cumulative plot, a nearly identical cumulative distribution curve is obtained. This confirms the robustness of the 1.8 correlation factor to the range of N_{60} values included in correlation development. A cumulative distribution curve is also plotted for the database after all bins with gravelly soils were excluded. The nearly identical curve confirms that inclusion of the SPT N_{60} values which were corrected for gravel influence did not influence the correlation.

The bins that were defined as LQ based on the SPT N_{60} measured are plotted on top of the high quality data in Figure 9. As expected, a significant portion of the LQ data lie above the field variability bands, which is consistent with the expectation that the presence of gravel typically increases measured SPT N_{60} values. A significant number of the LQ data also plot within the ±40% variability bands of the correlation, suggesting that the presence of gravel had little or no influence on median N_{60} values of these LQ bins, which confirms that the screening criteria applied to the SPT data was conservative.

The correlation produces very good agreement between the iBPT equivalent N_{60} profiles and those directly measured by the SPT in adjacent soundings. Figure 10 shows four iBPT equivalent N_{60} profiles, one from each site. The agreement between the N_{60} values from iBPT and SPT is evident. Also evident is the improved resolution of the subsurface stratigraphic provided by the continuous profile of iBPT equivalent N_{60} values. The iBPT based profile provides a representative N_{60} value for every foot of penetration, whereas SPT measurements are typically performed at 1.5 m (5 ft) vertical increments. This increased resolution improves detection of the transitions between layers, the presence of weak layers, and the vertical uniformity within individual layers. The plots in Figure 10 and these observations are representative and consistent in the 42 iBPT-SPT sounding pairs examined to date.

CONCLUSIONS

The instrumented Becker Penetration Test (iBPT) provides a continuous, normalized blow count profile (N_{B30}). The measurements allow for a high degree of repeatability and reliability by the directly measuring, and correction for, the magnitude of energy delivered to the drill string tip. The iBPT enables characterization of a wide range of soils, including clayey, silty, sandy, and clean gravels, as well as gravelly soils (DeJong et al, 2016). Analysis of SPT and Sonic data, in combination with the iBPT data has led to the following observations and conclusions:

- A systematic framework for the assessment of gravel influence and, when applicable, correction for its effects on SPT *N* measurements was developed. This method is based examination of the SPT blows-per-inch trend as well as physical information from SPT and

Sonic samples of the soil penetrated. The method was applied in development of the iBPT – SPT correlation and was demonstrated to be an effective, conservative approach for selecting SPT measurements that were not affected by gravel. A less conservative version of this framework can be used for evaluation of the influence of gravel on SPT data as described in Appendix A.

- The spatial variability in alluvial deposits was shown to be significant, and relatively consistent across the project sites. In general, identical measurements obtained in two soundings performed at ~3m spacing had approximately ±40% variability. This level of variability is due to the alluvial depositional process itself, and therefore should be expected when two measurements are compared at a similar spacing.
- A data binning approach was proposed to systematically handle the spatial variability of alluvial deposits. Bins were defined where vertical intervals of SPT N_{60} and iBPT N_{B30} values as well as encountered soil types were consistent. The median SPT N_{60} and iBPT N_{B30} values were used to represent the bin characteristics.
- A linear correlation with an empirical factor of 1.8 was developed to estimated equivalent SPT N_{60} from iBPT N_{B30} values. This correlation was evaluated and shown to be robust across all four project sites, applicable in the soils tested, and stable across the range of penetration resistances measured. Further, no bias with respect to measurement depth or soil saturation (above or below the water table) was evident. The bin data used to develop the correlation contained about ±40% variability; this is attributed to spatial variability of alluvial deposits, as opposed to a systematic difference between the iBPT N_{B30} and SPT N_{60} measurements.
- Representative soundings of the 42 SPT – iBPT soundings pairs examined show that the correlation produces very good agreement between the iBPT equivalent N_{60} values and those

directly measured by the SPT in adjacent soundings. In addition, the vertical continuity (relative to SPT measurements obtained every 1.5 m) in the stratigraphic profile produced by the iBPT improves the characterization and assessment of transitions between layers, and detection of critical, weak zones.

Appendix A. Practical SPT Screening Framework

When only SPT measurements are available (e.g. early in a site investigation) a practical screening framework for evaluating gravel influence may prove useful to guide the selection of subsequent site investigation tools (e.g. whether iBPT may be appropriate). As such, insights gained from the large iBPT dataset have been used to develop a practical framework for SPT screening.

The practical framework uses blows-per-inch SPT data as well as physical evidence from SPT, and if available Sonic soundings. A flowchart detailing the proposed practical SPT screening framework is presented in Figure A.1. The framework uses the indexing scheme defined in Table 2. Indices I to III are considered uninfluenced by gravel, and index V is considered influenced by gravel to the extent that a reliable correction cannot be applied. The SPT samples classified with an index IV are considered free of gravel influence if their gravel content is less than 20%.

In this practical SPT screening framework, the 20% gravel content threshold is used as an inclusion criterion for index IV samples as opposed to an exclusion criterion all samples, as is proposed in the conservative screening framework. This subtle change places more emphasis on the assigned indices and allows those samples which are influenced by gravel, but the influence is believed to be negligible or adequately corrected, to be used for characterization.

The practical framework may admit a number of the SPT measurements dismissed by the conservative framework. In Figure 10, those SPTs which were considered LQ, based on the conservative screening framework, but are considered unlikely to be influenced by gravel, based on the practical framework, are circumscribed by open circles. It is evident that most of the SPTs now pass the criteria, and all of those SPTs which pass agree with the iBPT profile. As expected, the SPTs which are still considered LQ (e.g. Figure 10.d at 10.5 m (35 ft) depth) have N_{60} values that are greater than the iBPT profile.

The application of this practical framework for screening of SPT values on a project without a companion iBPT profile does not provide a site-specific definitive confirmation of the SPT data quality. As such, this practical framework is appropriate for initial screening of SPT data to determine if there is sufficient gravel present such that the SPT data quality may be questionable and further testing may be warranted. In all cases the decision to use SPT data or perform more advanced testing is dependent on the project value, the societal consequences of failure, and the influence of the uncertainty in the (equivalent) SPT value on the predicted system performance.

ACKNOWLEDGEMENTS

The authors appreciated the funding and support provided by the Division of Safety of Dams (DSOD) of the California Department of Water Resources (David Gutierrez and Richard Armstrong) and Los Angeles Department of Water and Power (Craig Davis and Adam Perez). In addition, the support and collaboration of AMEC (Marty Hudson and Alek Harounian), AECOM

(Wolfgang Roth and S. Nesarajah), GeoPentech (Jon Barneich, Andrew Dinsick and Doug Wahl), and Great West Drilling (Jim Benson) is appreciated.

REFERENCES

ASTM D2487-10 (2011), Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA, USA.

ASTM D4633-10 (2010). Standard test method for energy measurement for dynamic penetrometers. ASTM International, West Conshohocken, PA, USA.

Cao Z., Youd L.T., Yuan, X. (2013). Chinese Dynamic Penetration Test for Liquefaction Evaluation in Gravelly Soils. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, 139(8): 1312-1333.

Daniel C.R., Howie J.A., Campanella R.G., and Sy A. (2004). Characterization of SPT grain size effects in gravels. Second International Conference on Site Characterization (ISC'2). Porto, Portugal.

DeJong J.T., Ghafghazi M., Sturm A.P., Wilson D.W., den Dulk J., Armstrong R.J., Perez A., and Davis C.A. (2016). Instrumented Becker Penetration Test I: Equipment, Operation, and Performance. Under review.

Harder L.F.Jr., and Seed H.B. (1986). Determination of penetration resistance for coarse-grained soils using the Becker Hammer Drill. College of Engineering, University of California, Berkeley. Report No. UCB/EERC-86/06. May 1986.

Kulhawy F., and Trautman C.H. (1996). Estimation of insitu test uncertainty. Uncertainty in the Geologic Environment: From Theory to Practice, Proceeding of Uncertainty '96, ASCE Geotechnical Special Publication No. 58.

Idriss I.M., and Boulanger R.W. (2008). Soil Liquefaction during Earthquakes. Earthquake Engineering Research Institute publication No. MNO-12. ISBN #978-1-932884-36-4.

Rogers J.D. (2006). Subsurface Exploration Using the Standard Penetration Test and the Cone Penetrometer Test. Environmental and Engineering Geoscience, 12(2): 161-179.

Rollins K.M., Diehl N.B., and Weaver T.J. (1998). Implications of Vs - BPT $(N_1)_{60}$ Correlations for Liquefaction Assessment in Gravels. Geotechnical Earthquake Engineering and Soil Dynamics III, 1:506-507.

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

Sy, A., and Lum, K.K.Y. (1997). Correlations of mud-injection Becker and standard penetration tests. Canadian Geotechnical Journal, 34(1): 139-144.

Table 1. Summary of field testing used for developing iBPT - SPT correlation

Project	*Number of Soundings*	*Total Linear Footage (m/ft)*	*Complimentary Drilling*	*High/Low Quality SPTs*	*High/Low Quality Bins*
Headworks West Reservoir	*16*	*400/1300*	*SPT, Sonic*	*94/103*	*25/28*
North Haiwee Dam	*10*	*250/800*	*SPT, CPT, Sonic*	*93/10*	*45/5*
Stone Canyon Dam	*8*	*165/550*	*SPT, CPT, Sonic*	*120/57*	*36/18*
Bouquet Canyon Dam	*8*	*100/330*	*SPT, CPT, Sonic*	*42/40*	*16/17*
Total	*42*	*915/2980*		*349/210*	*122/68*

Table 2. Rubric developed for assigning gravel influence indices to SPT data

Per-Inch SPT Blow Counts		*Physical Evidence**		*Index*
Is there a sign of Gravel Influence?	*Can a reliable correction be applied?*	*Are gravels present based on the physical evidence from SPT (and/or Sonic)?*	*Is the gravel present influential gravel**?*	
No	-	*No* *Yes*	- *No*	*I*
No	-	*Yes*	*Yes*	*II*
Yes	*Yes*	*Yes* *No*	*No* -	*III*
Yes	*Yes*	*Yes*	*Yes*	*IV*
Yes	*No*	*Yes*	*Yes*	*V*

** Physical Evidence refers to soil gradations, sample photos and field logs from SPT split spoon samples and/or Sonic cores in the vicinity of the SPT sample.*

*** Influential gravel is one of sufficient size and abundance to have plausibly affected SPT penetration measurement.*

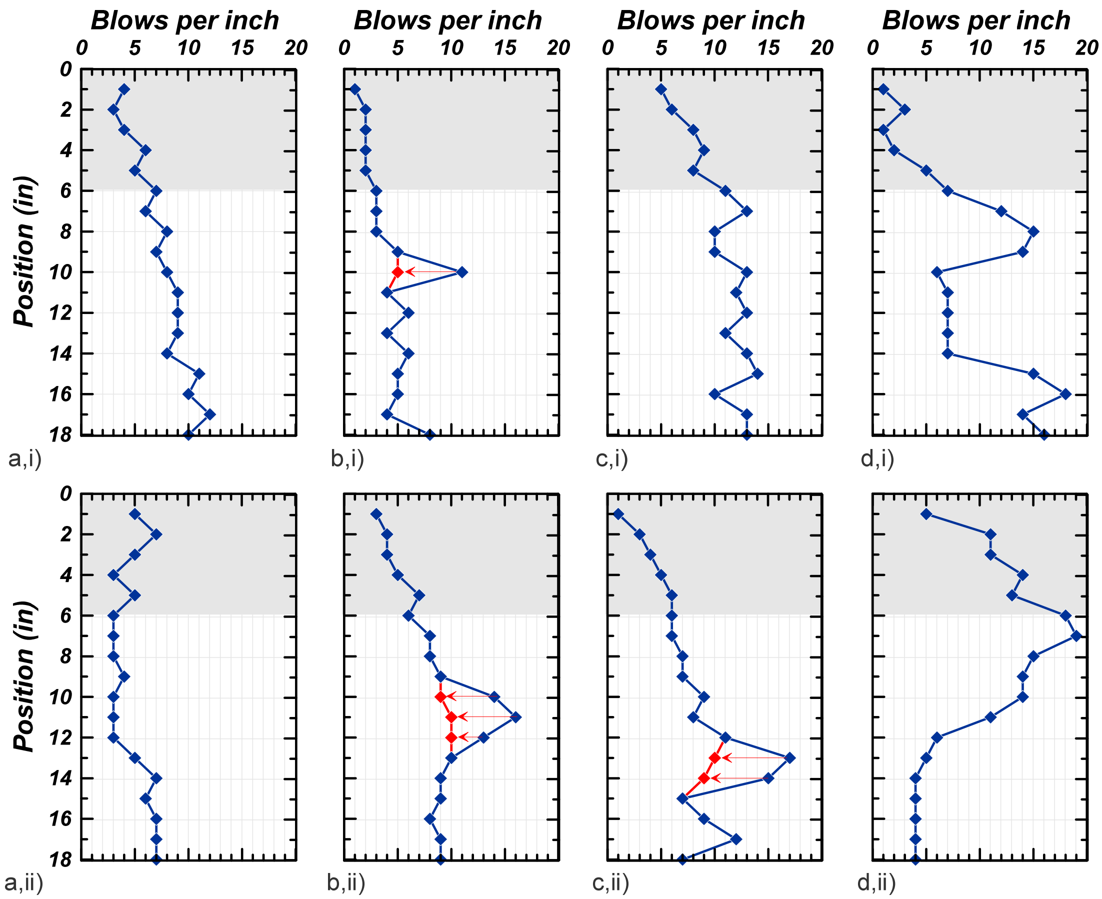

Figure 1. Per-inch SPT blow counts used to evaluate gravel influence; a) No influence (indices I and II); b) Potential influence with reliable correction (index III); c) Influence with reasonable trend or reliable correction (index IV); d) Influence, not correctable (index V)

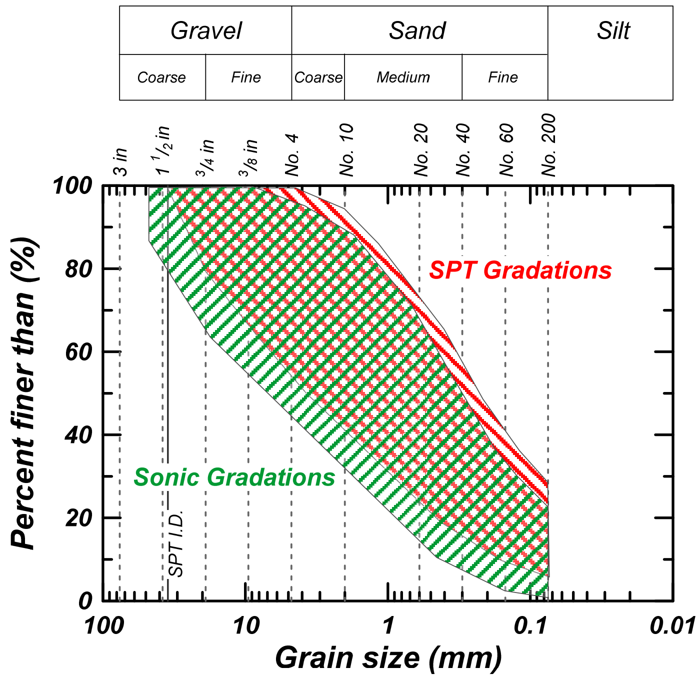

Figure 2. Effect of scalping on grain size distribution curves (ASTM D2487, 2011) of SPT samples; comparison to grain size distribution curves of Sonic cores; data from the Headworks West Reservoir

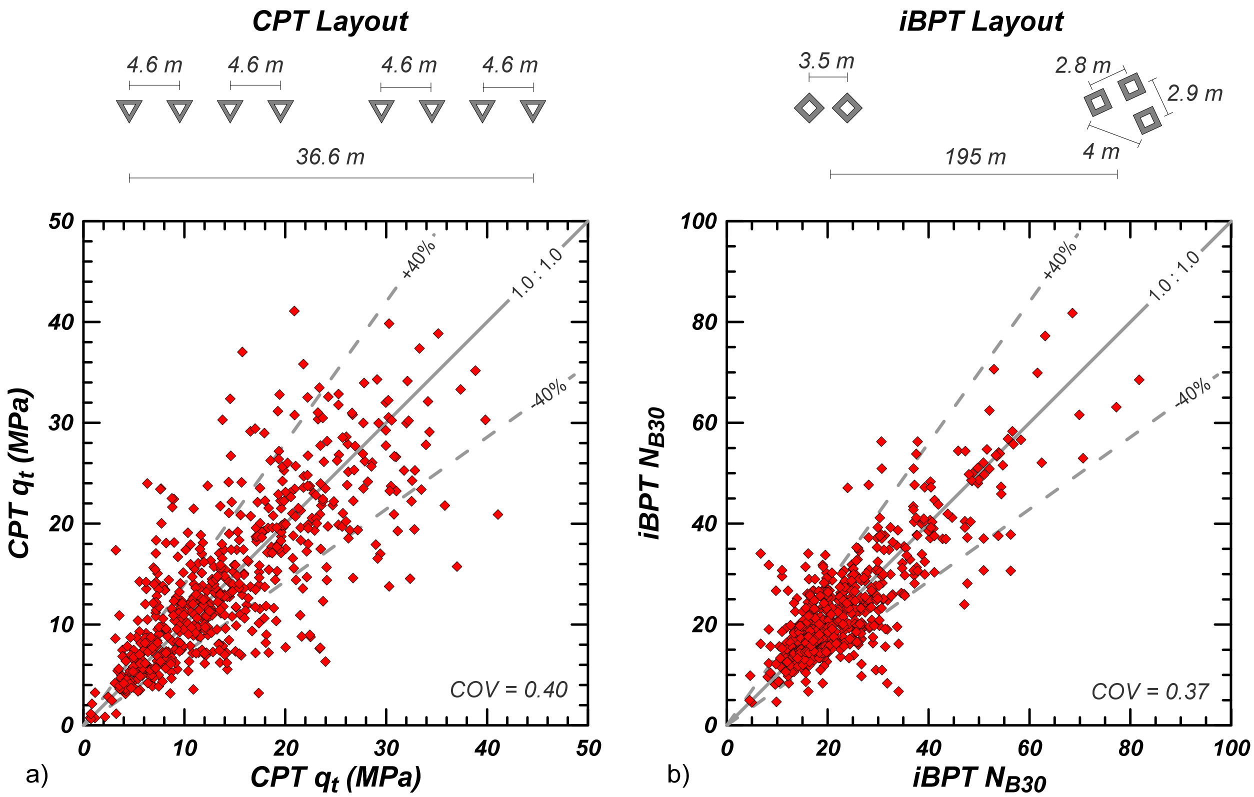

Figure 3. Field variability in adjacent soundings at North Haiwee Dam; a) Comparison of adjacent CPT tip resistances (q_t) averaged per foot of penetration b) Comparison of adjacent iBPT N_{B30} values per foot of penetration

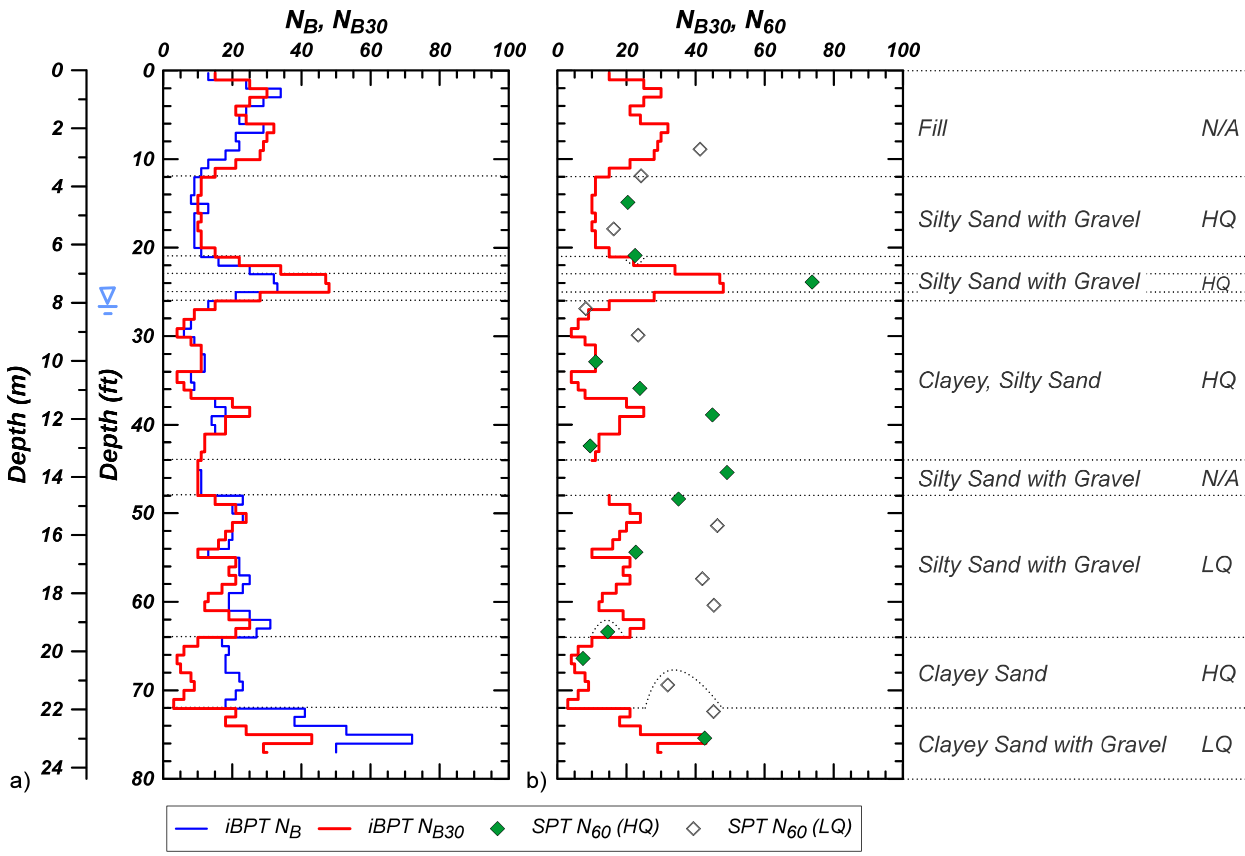

Figure 4. Example profile from the Stone Canyon Dam; a) iBPT raw blow counts N_B, normalized blow counts based on tip measurements N_{B30}; b) High and low quality SPT N_{60} and iBPT N_{B30}, and depth intervals and material types identified for binning

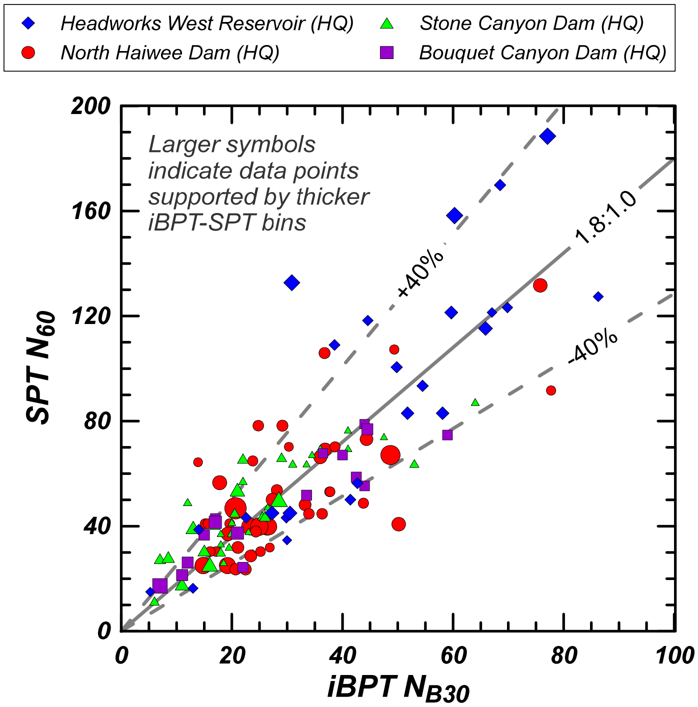

Figure 5. Correlation between medians of iBPT N_{B30} from tip measurements, and SPT N_{60}; high quality (HQ) data from four sites

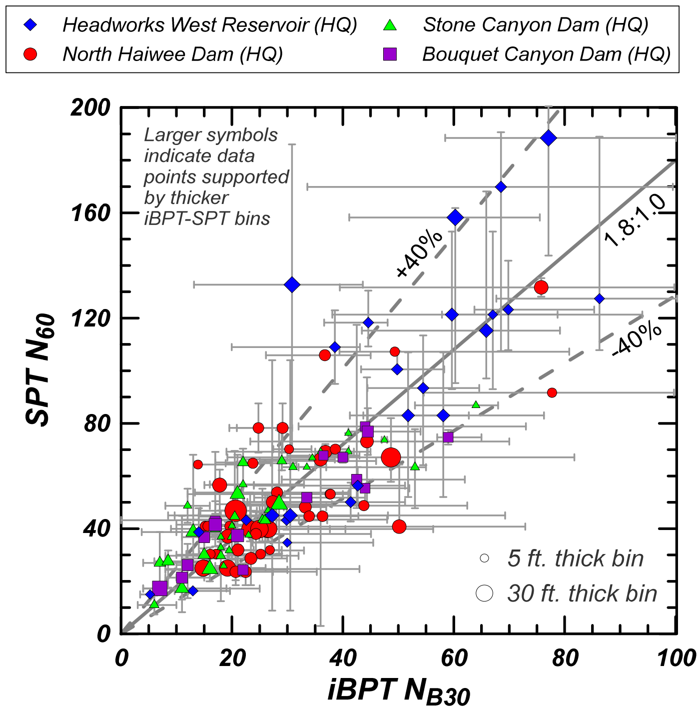

Figure 6. Range of data included in bins used to develop correlation between medians of iBPT N_{B30} from tip measurements, and SPT N_{60}; High quality (HQ) data from four sites

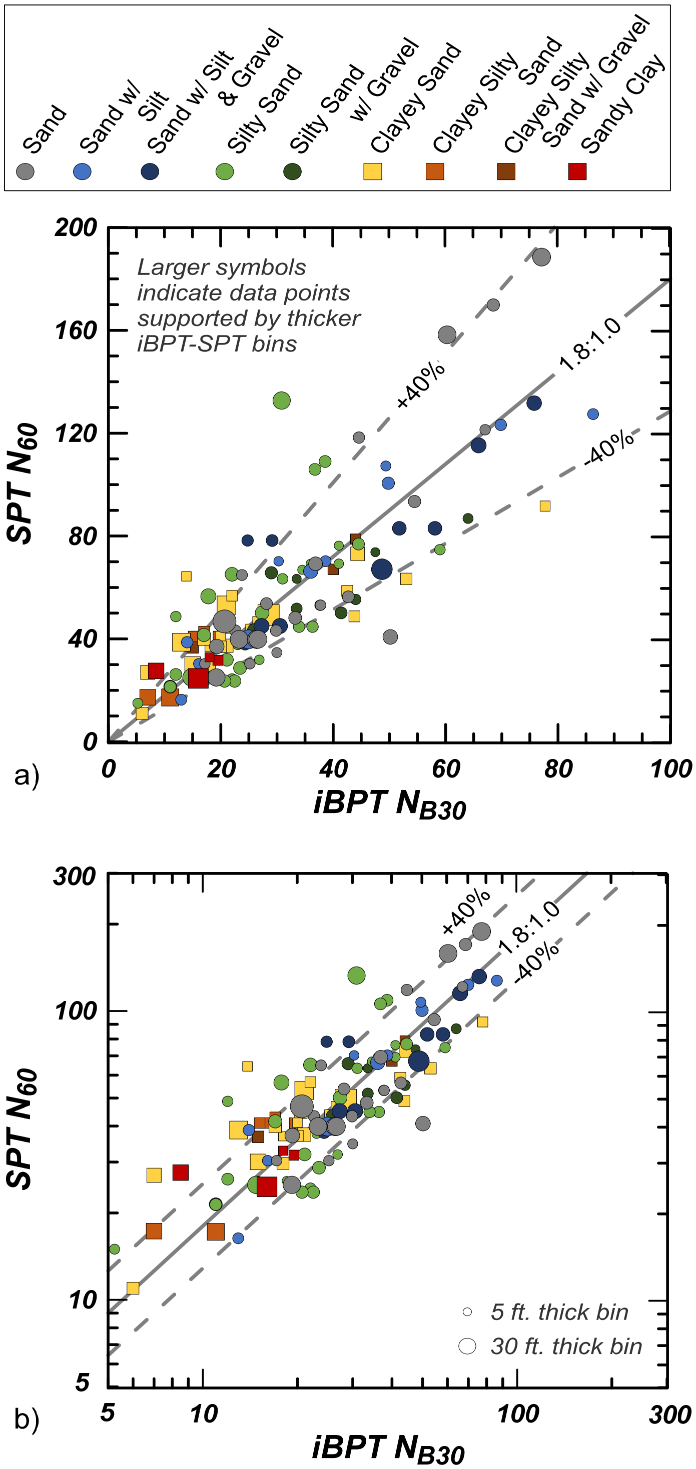

Figure 7. High quality (HQ) bins used to develop correlation between medians of iBPT N_{B30} from tip measurements, and SPT N_{60}; material types identified; data from four sites. a) Linear axes; b) Logarithmic axes

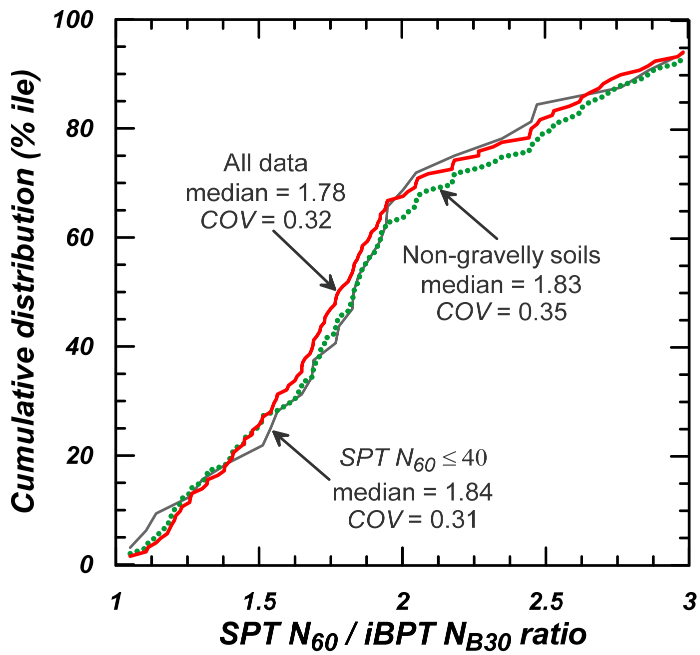

Figure 8. Cumulative distribution of iBPT-SPT correlation factor from high quality (HQ) bins

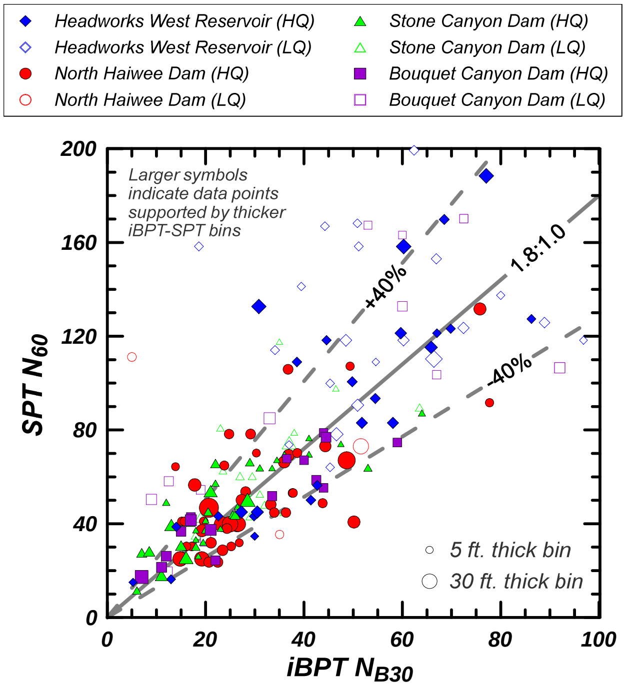

Figure 9. Correlation between medians of iBPT N_{B30} from tip measurements, and SPT N_{60}; low quality (LQ) and high quality (HQ) data from four sites

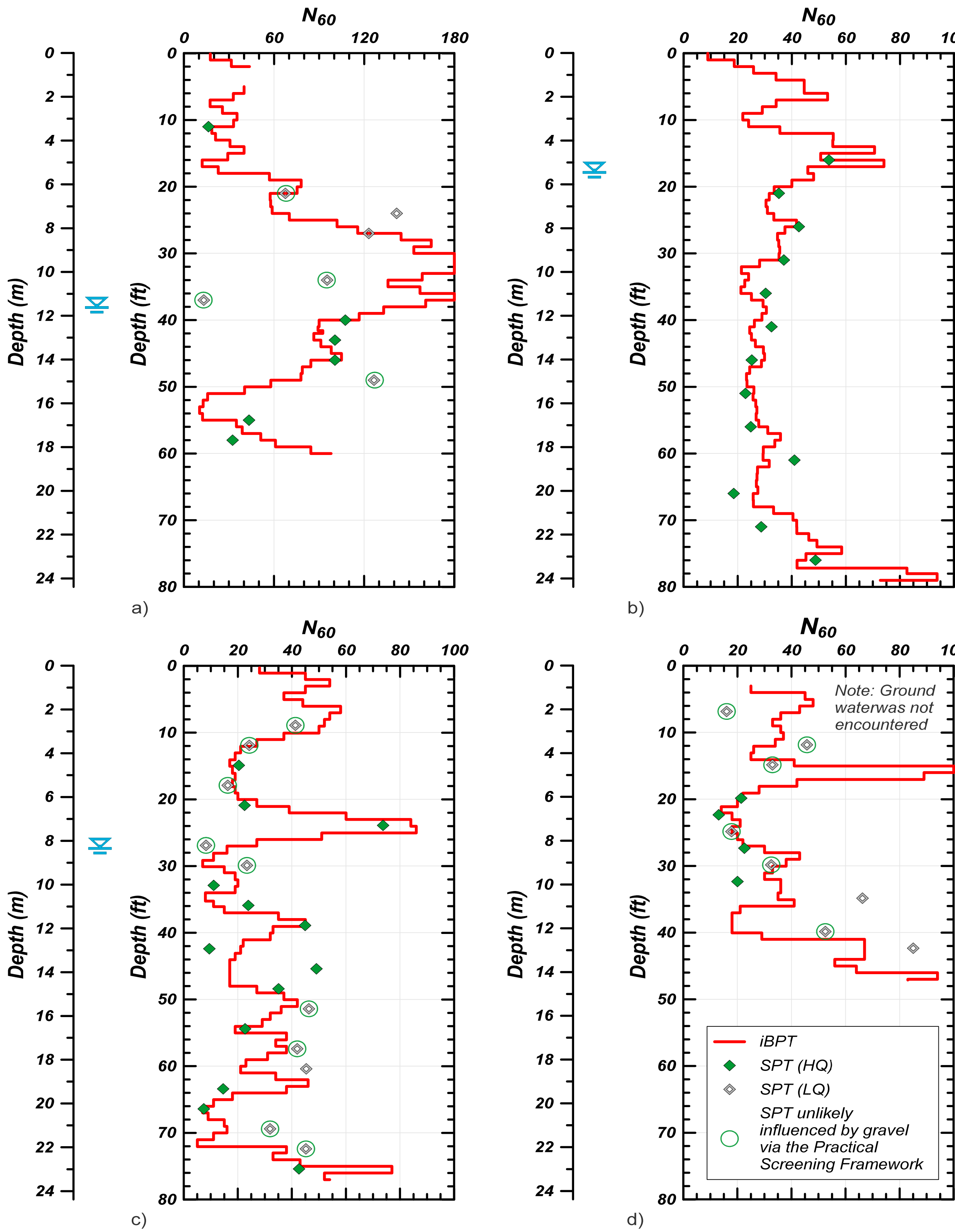

Figure 10. Equivalent iBPT comparison to SPT N_{60} : a) Example from Headworks West Reservoir; b) Example from North Haiwee Dam; c) Example from Stone Canyon Dam (see Figure 4); d) Example from Bouquet Canyon Dam; see Appendix A, for the practical screening framework

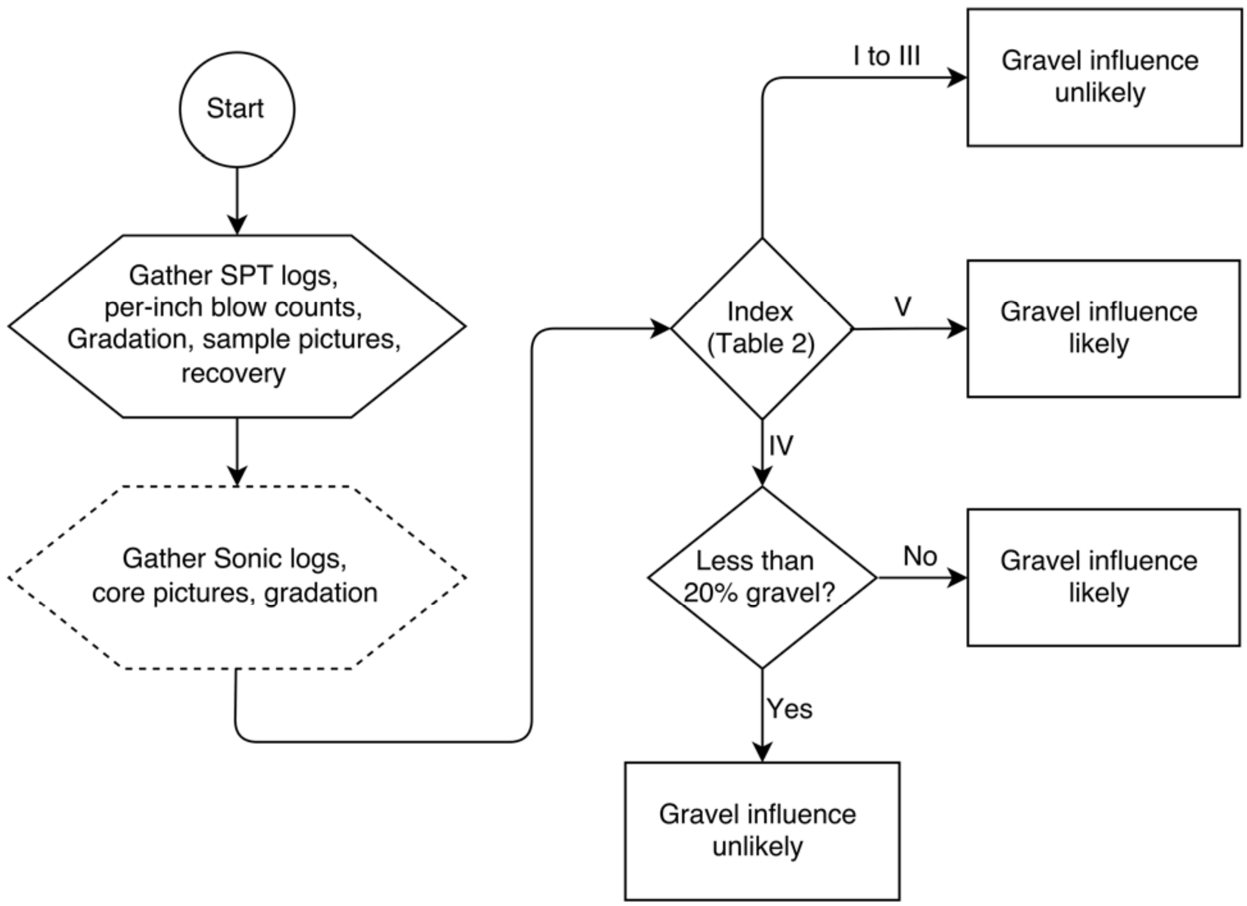

Figure A.1 . Flowchart for practical screening framework for gravel influence on SPT