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Characterization of Gravelly Alluvium

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ABSTRACT

Characterizing project sites where gravelly alluvium is present poses particular challenges. Conventional field and laboratory techniques are significantly limited when large gravel particles either prevent their operation or adversely influence their measurements. The deposition of gravelly alluvium often involves complex, energy and sediment load dependent processes that can result in highly spatially variable deposits comprised of gravel to clay sized particles. This pervasive variability warrants a comprehensive site characterization approach that begins with developing a thorough understanding of the geological formation processes and the expected controlling deformation/failure mechanisms of the geotechnical system. In this context, the site investigation becomes a confirmatory process, allowing the subsequent idealization of site conditions for analysis and design to have a firm basis in geology. Recent work at several gravelly alluvium sites has allowed the development of new approaches and techniques for improved characterization. In particular, the benefit of continuous sonic sampling is demonstrated and a systematic method for determining gravel influence on SPT *N* values is outlined. Finally, the instrumented Becker Penetration Test (iBPT), a new closed-ended, large diameter penetrometer with direct energy measurement at the drill string tip is presented.

Introduction

Characterizing project sites where gravelly alluvium is present poses particular challenges. Despite these challenges, documented liquefaction of gravelly alluvium in historical earthquake events (e.g. Harder, 1994; and Cao et al., 2013) has demonstrated the importance of reliable liquefaction assessment for these materials. Additional liquefaction case history sites, including many in Christchurch, NZ (Cubrinovski et al. 2011a,b), have involved liquefaction of gravel-free, sand-like layers deposited directly above or below such alluvial gravel layers. As a result, proper characterization of gravelly alluvium is a persistent need when assessing the liquefaction potential of a site. The need for characterization extends beyond liquefaction assessment, and includes static design of deep foundations, tunnels, bridges, levees, dams, and many other structures founded upon alluvial deposits.

Geologic Depositional Characteristics of Gravelly Alluvium

Deposition of gravelly alluvium is a complex process that can result in highly interlayered deposits comprised of gravel to clay sized particles from varying geologic source materials. In broad valleys these alluvial gravels are commonly deposited within a braided river architecture,

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an example of which is presented in Figure 1a (Christchurch, NZ). Aerial views capture the current river structure while the coloring and vegetation of the bounding lands provide insight regarding historical depositional mechanisms and the lateral extent of river migration. During high river flow a high-energy depositional environment is present, allowing larger gravel particles to be transported downstream. Subsequent deposition of gravel particles is an energy and sediment load dependent process, with deposition occurring as the energy and/or sediment load decreases. As a result, the deposition of gravel layers is typically concurrent with high water levels associated with flash flooding and spring snow melt.

Over time, the highly variable depositional process results in subsurface conditions similar to that sketched in Figure 1b. The braided river architecture consists of a series migrating gravel layers (commonly referred to as bars when still exposed). Near the end of a depositional cycle, low-energy flow conditions allow finer sand, silt, and clay size particles to infill the exposed void space in the gravel layers. This process often results in high fines contents near the top of gravel layers. Exceptionally high flow events that cause overtopping of the existing channel results in the formation of overbank deposits. The rapid decrease in energy in this depositional environment leads to larger particles being deposited close to the existing channel while finer grained sediments may fall out of suspension in pools of trapped water further away.

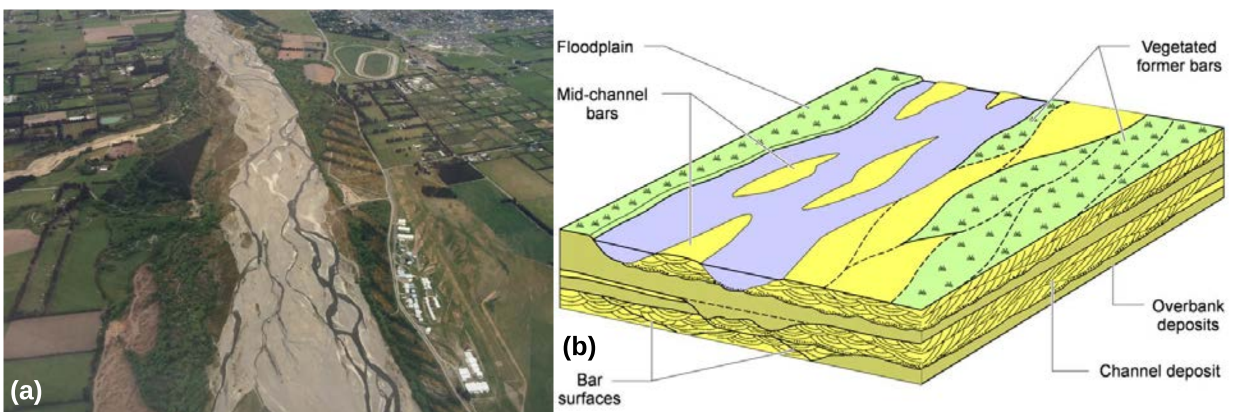


Figure 1 – (a) Arial image of braided gravel river deposit west of Christchurch, NZ and (b) depositional architecture of braided river deposit (from Nicols 2009).

The deposition of gravelly alluvium in narrower valleys and canyons, where dams are typically constructed, generally consist of similar depositional architecture, albeit with additional complications. The extent of lateral river migration is typically reduced due to steep valley walls, which provide geographic bounds, and a larger river gradient (slope), which are both inversely related to the extent of river meander. The water flow level may also be more extreme, possibly ranging from valley-wide flooding at its highest, to no flow after extended periods of drought. In addition, colluvium (debris from slope instability of the valley walls) can be deposited at the valley edges; the colluvium may further constrain river migration and be mixed with the sediment being transported from upstream.

Spatial Variability

The actual complexity of a natural braided alluvial deposit is more variable and chaotic than conceptually indicated above. Figure 2a and b present a photograph and a geologic map, respectively, from a 9 m deep excavation within a braided river deposit, cut perpendicular to the historic river alignment. Large gravel/cobble sized particles exist in lenses that extend up to 1 m in thickness and 5 m laterally (their continuity parallel to the river alignment is unknown, but likely greater). These lenses are interspersed within sandy layers/pockets, which contain up to 30% fine to medium gravel, as well as more continuous layers of silty sand. The extents of most layers are variable and fingering, with abrupt transitions between some layers and gradual transitions between others. Collectively, these layers reflect the changing deposition, migration, and energy of the river, with similar lenses reflecting several realizations of a depositional process across time and space.

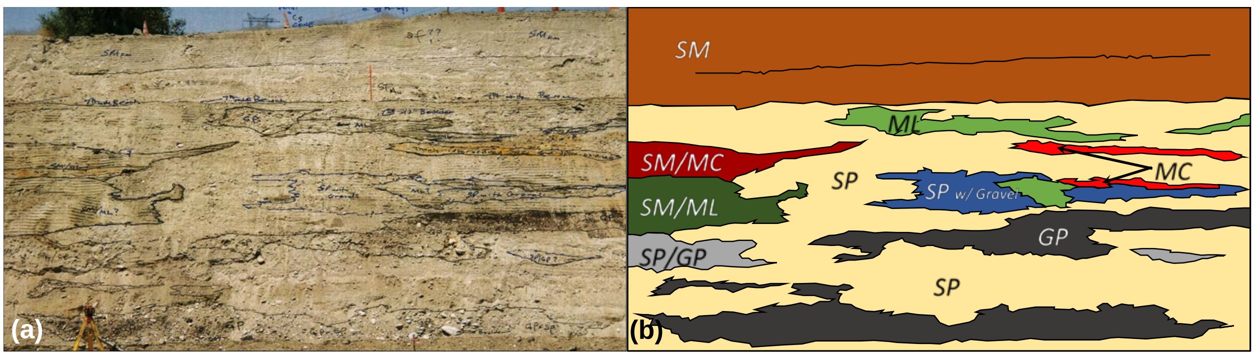


Figure 2. (a) photograph and (b) geologic map of 9 m deep excavation within a braided river deposit cut perpendicular to the historic river alignment (Permission from LADWP. Photograph and geologic map provided by Amec Foster Wheeler).

The composition of gravelly alluvium is highly variable within a given project site and between different project sites. Expectedly, its composition also differs significantly from more uniform natural materials and artificial fills. Figure 3a presents the percentages of gravel, sand, and fines present in SPT samples obtained at several different project sites using ternary plots. Site 2, for example, is a relatively clean sand site with largely less than 20% gravel or fines (as discussed in more detail later, the SPT test could be expected to perform well at this site). Site 1, in contrast, includes a substantial number of the samples that contain significant gravel (up to 50%), indicating that conventional methods for field characterization will not be applicable. Collectively, the alluvium differs significantly from the natural soft clay deposit and hydraulic fill materials that have a noticeably small fraction of gravel and significant fines content (Figure 3b). The compacted embankment material, which exists on the downstream side of a dam, contains a higher percentage of gravel but also a modest percentage of (plastic) fines for effective compaction and low permeability.

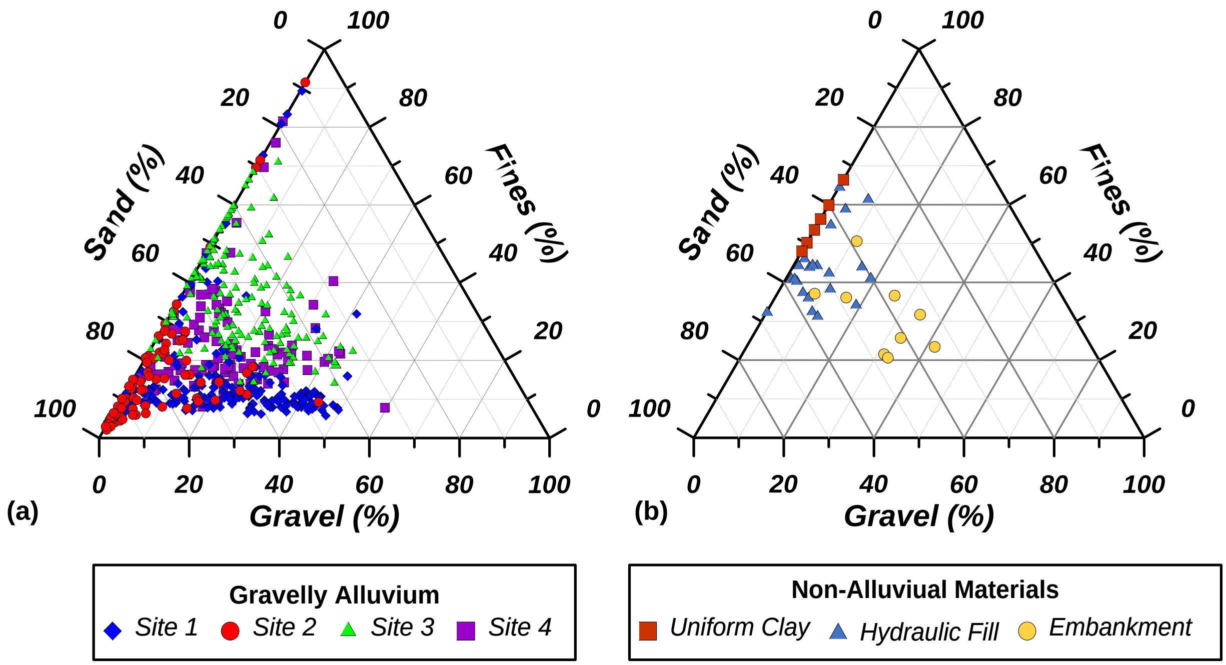


Figure 3. Ternary plots indicating the percent gravel, sand, and fines in (a) gravelly alluvium at four different project sites as well as for (b) uniform clay, hydraulic fill, and compacted dam embankment soils.

The natural spatial variability of gravelly alluvial deposits makes it difficult to compare and evaluate the applicability of different field techniques for characterization of a given deposit. Consider two borings/soundings performed at 4 m spacing in the alluvial deposit mapped in Figure 2. At nearly any depth it is unlikely that the exact same material will be encountered. As a result, it can be very difficult to assess the suitability of one technique relative to another as the two techniques may encounter different soils at the same exact depth. However, by recognizing that the same geologic depositional processes formed the subsurface of interest, it may be possible to identify larger depth intervals where both the materials encountered and penetration resistances measured, are consistent; therefore, the median penetration resistances between the two tests may be compared over these larger, consistent intervals. This approach has been outlined by Ghafghazi et al. (2016) and used successfully in selecting representative soil property values for liquefaction potential analysis.

The extent of spatial variability that exists within alluvial deposits is often greater than that recognized by engineers. This is exemplified using two cone penetrometer soundings performed in an alluvial sand deposit (gravel influence not of concern) at 4 m spacing. As evident in Figure 4a, the two cone tip resistance profiles are relatively similar to each other, generally following the same trends and containing characteristics typically observed in sand deposits. Presentation of the same data plotting the pair-wise data points at each measurement depth (Figure 4b) and then averaged over 0.3m depth intervals (Figure 4c) reveals a significant amount of variability, with logarithmic coefficient of variation (COV) values of 0.40 and 0.33, respectively. As expected, averaging of data over 0.3 m (1 ft) depth intervals reduces the COV values. Nonetheless, it is evident that at a lateral spacing of 4 m the penetration resistance can be expected to be up to ±40% the value measured at the reference location. This observation extends to, and has been confirmed in, gravelly alluvium as well; variations in penetration resistance of up to ±40% may be expected across lateral distances of 4 m.

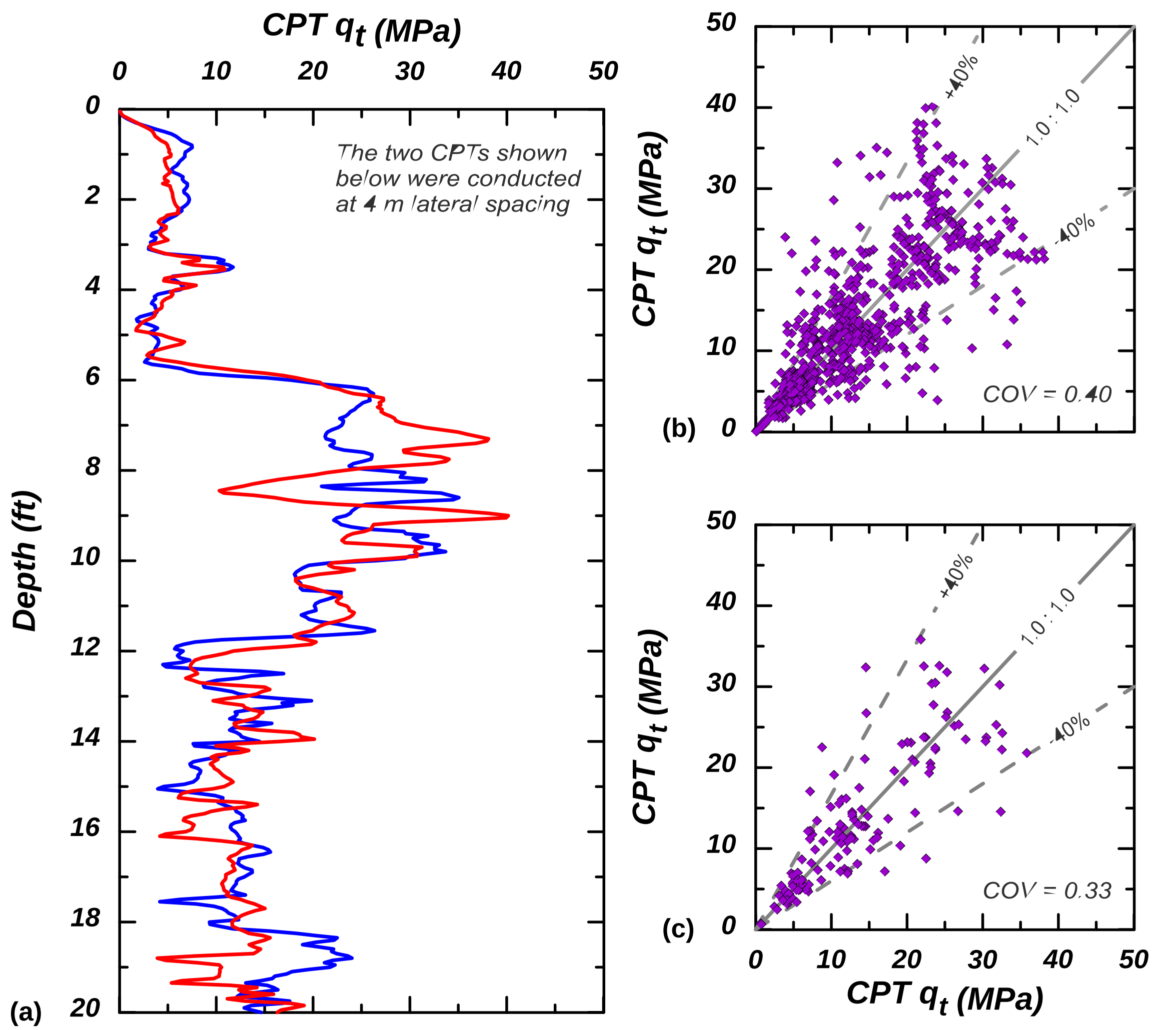


Figure 4. (a) Example of two cone penetrometer sounding profiles performed in a sandy deposit at a lateral spacing of 4 m. Reprocessing of the data by plotting depth specific data pairs from the two soundings for (b) each measurement depth (5 cm increments) and (c) averaged over 0.3m intervals to illustrate spatial variability and the effect of averaging.

Methodology for Characterization of Gravelly Alluvium

The spatial variability of gravelly alluvium, primarily due to its highly variable energy and sediment load dependent depositional process, presents challenges not often encountered when characterizing soils deposited by more stable and widespread processes (e.g. marine clay deposits). Implementing conventional site characterization practices typically employed in uniform materials, for example performing a few cone profiles at large spacing across the site, will be less effective in gravelly alluvium. In fact, this approach may provide unique soil profiles at every location tested with little or no clear correlation between these different soundings. Understanding site conditions, in this case, can only be achieved by first developing a site-specific geologic understanding and determining how the geotechnical system being analyzed/designed interacts with the geologic deposit.

A systematic methodology for site characterization of gravelly alluvium, or any project with complex subsurface conditions, is outlined in Figure 5. It contains the primary five steps of *Inductive Reasoning*, *Scenario Assessment*, *Site Investigation*, *Site Idealization*, and *Analysis & Design*. The steps of *Inductive Reasoning* and *Scenario Assessment* are focused on developing and preliminarily evaluating hypotheses of expected subsurface conditions and controlling performance mechanisms. The *Site Investigation* step utilizes techniques to develop a database while the *Site Idealization* step is focused on capturing the controlling factors in a simplified representation that can later be used in detailed analysis. The final *Analysis & Design* step consists of a detailed study, eventually leading to project completion.

While the methodology outlined here builds on prior recommendations (e.g. Clayton 1995, USACE 2001, Mayne et al. 2004, Clayton and Smith 2013), emphasis is placed on the extensive and detailed analysis of the site project prior to mobilization of equipment for in situ testing, and drilling and sampling for complimentary laboratory testing. In particular, *Site Investigation* is only a single step in the much larger site characterization process, a step that often begins prematurely, prior to developing a clearly articulated hypothesis of expected site conditions. The *Site Investigation* step also often incurs the largest expense of the geotechnical project budget; delaying the *Site Investigation* step until after the first two steps are completed may simultaneously serve to improve characterization and reduce costs by refining the testing efforts and reallocating a portion of the funds towards more detailed analysis and interpretation.

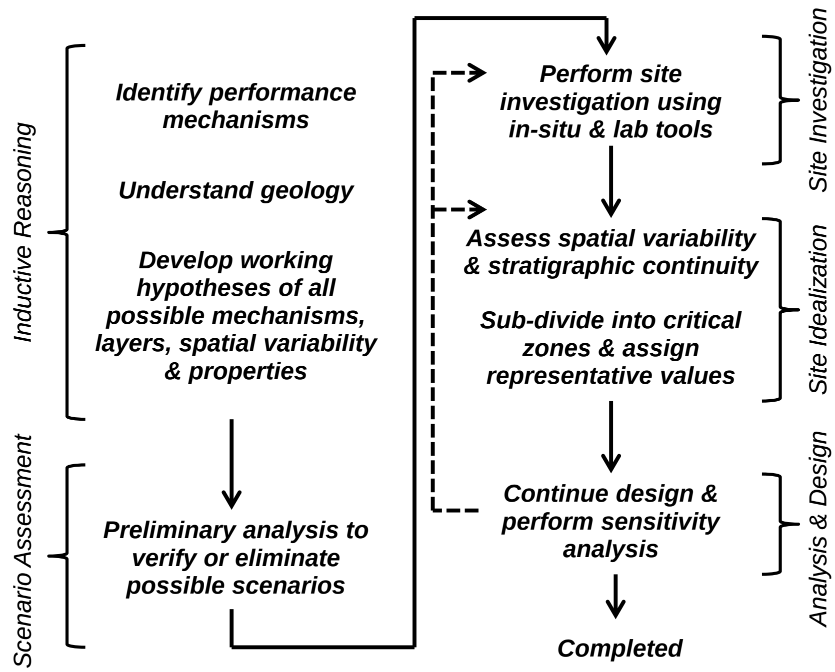


Figure 5. Systematic methodology for site characterization of gravelly alluvium.

Inductive Reasoning

The site characterization process begins by outlining the required performance of the geotechnical system being analyzed, the geologic setting that the project is being constructed upon/through, and how the length scales of these compare. The controlling performance mechanisms are often capacity or deformation based, and their requirements often differ for loading conditions (static, dynamic) and duration (short term, long term). Once identified, the potential deformation/failure zones for each mechanism can be estimated, revealing the mechanism scales and subsurface characteristics that are relevant for the investigation.

The geologic formation processes (as well as subsequent anthropogenic activities) that have led to the current site conditions dictate system performance. Therefore, the geology must be understood in detail by leveraging reference sources (e.g. geology reports, aerial/satellite photos, adjacent geotechnical project documents, etc.) and working closely with local geologists. This enables estimation of the number, thickness, variability, and soil properties of each of the geologic strata likely to exist at the project site. It is important to recognize that geotechnical engineers are typically over-optimistic about the uniformity of soil properties (Duncan 2000). Therefore, when estimating variability, it is useful to consult values obtained in prior studies (e.g. Phoon et al. 1995, Phoon and Kulhawy 1999a, 1999b, Baecher and Christian 2003) and to employ systematic, quantitative methods for estimating variability to the extent possible (e.g. Duncan 2000).

This collective effort enables development of a set of working hypotheses of all possible mechanisms that will govern performance, including identification of the particular strata that are engaged in and influence these mechanisms. Assessing the contribution of particular strata to different mechanisms requires hypotheses on the expected thicknesses, lateral continuity, material variability, and soil properties.

Scenario Assessment

The suite of hypotheses, when defined in sufficient detail, can then be analyzed to assess which scenarios will ultimately control performance. Sensitivity studies, where controlling conditions/parameters are systematically varied across ranges of uncertainty (based on geology and/or literature values), can help identify which aspects are controlling performance and how reducing uncertainty in these areas can improve the estimation of performance. In many respects this approach has similarities to the Potential Failure Modes Analysis (PFMA) often conducted for dams (USDOI 2012, USACE 2011). For smaller projects, this stage may consist of a relatively straight forward spreadsheet analysis, while for larger projects this stage may entail a suite of finite element simulations.

The outcome of the *Scenario Assessment* step includes a geologically-based hypothesis of the subsurface conditions that exist at the site (including major units, vertical and lateral variability, soil property ranges), a detailed understanding of the primary mechanisms controlling performance, and knowledge of which conditions/parameters control the governing mechanisms.

When understanding is sufficiently developed at this step the subsequent steps (*Site*

Investigation, Site Idealization) become a process of confirmation instead of discovery. It is not that revisions to the developed hypotheses will not be necessary; on the contrary, they may be expected as more site-specific information is gathered and further analysis is performed. This revision process, however, corrects and refines the understanding gained during hypotheses development instead of being the first detailed examination of the site.

Site Investigation

Site investigation, encompassing in-situ testing, drilling and sampling (with complimentary laboratory testing), is the middle step in the overall site characterization process. It focuses on obtaining an experimental, site-specific database of conditions/parameters expected to control system performance and design. The methods and tools employed in this step are extensively described in the geotechnical literature, with books, manuals, and publications detailing many different techniques available (e.g. Clayton 1995, USACE 2001, Mayne et al. 2004, Clayton and Smith 2013).

The primary challenge in *Site Investigation* is selecting the most appropriate techniques and determining where they should be performed at the site. The extent of expected spatial variability will guide the balance between the quantity versus quality of in-situ and laboratory tests performed; as the site hypotheses are confirmed/refined, the number and type of tests can be adjusted to optimize collection of critical data. In addition, in-situ and laboratory tests should follow stress paths similar to those induced by the expected deformation/failure mechanisms (e.g. Kulhawy and Mayne 1990) to the extent possible, and site specific factors for in-situ test correlations (e.g. CPT based estimate of *Su*) should be calibrated to appropriate shearing modes.

The *Site Investigation* step concludes by compiling the data collected, including interpretation of measured data to estimate engineering properties, and separation of data by geologic strata and/or similar soil properties. Normalization of properties with respect to overburden stress, for example by using normalized strength ratios (Su / σ_v') and normalized penetration resistance values ($(N_1)_{60}$ and q_{c1N}), are particularly useful when compiling data across borings/soundings for a particular stratum.

Site Idealization

The *Analysis & Design* of a project requires, as input, idealization of project site conditions into simplified representations. *Site Idealization* requires reduction of the site investigation database into representative parameters that appropriately account for the range in properties measured and the connectivity of the layers (or weaker zones within a layer). Binning of data from multiple borings/soundings into geologic strata and sub-intervals where properties (rather than materials) differ and then plotting cumulative distributions of overburden normalized parameters is effective in selecting representative percentiles and bounding (e.g. $\pm 1\sigma$) values for subsequent analysis.

It is recommended that the *Site Idealization* step, to the extent possible, be separated from the *Site Characterization* step in order to explicitly and systematically document each decision as an idealized representation (representative values, layer thicknesses, ground water table elevations) is formed. Each step of idealization may build conservatism in the subsequent analysis. Conservatism is built in, for example, when the 30th percentile value of $(N_1)_{60}$ is selected to be the representative value for a uniform, liquefiable layer underneath a dam; however, this may be representative if the layer's $(N_1)_{60}$ values are highly variable (see Boulanger and Montgomery 2015). The series of decisions made during site idealization can then result in compounding conservative or unconservative decisions that may not otherwise be clearly conveyed and documented.

Analysis & Design

The idealized site conditions, with upper/lower bound parameters for sensitivity studies, form the primary inputs for analysis and design. The methods employed at this stage are often more sophisticated and advanced, but do build on, those used during the earlier *Scenario Assessment* step. During detailed design and analysis, it may be necessary to revisit the *Site Idealization* phase in order to redefine the stratigraphic units and their representative properties or to evaluate the effects of uncertainty by analyzing multiple realizations of the idealized site conditions. In some cases, it may be necessary to expand the *Site Investigation* step, either by performing additional laboratory tests on samples already obtained or re-mobilizing equipment to site. Eventually the analysis and design is completed, and hence the overall process of site characterization is complete.

Summary

A comprehensive approach to charactering alluvial deposits is recommended to properly understand the geologic formation processes, interpret data from the site investigation, and to synthesize all of the information into an idealized site representation that will be used for analysis and design. Extensive effort should be placed in the early *Inductive Reasoning* and *Scenario Assessment* steps of the site characterization process in order to develop detailed hypotheses of site conditions and controlling deformation/failure modes. When performed well, the subsequent stages of S*ite Investigation* and *Site Idealization* become a process of confirmation and refinement of the original hypotheses rather than a process of discovery. Overall, following this approach can result in a more accurate prediction of performance, explicit measures of conservatism, better documentation of critical decisions, reduced project costs, and increased reliability.

Challenges & Recent Advances in Characterization Techniques

Characterizing gravelly alluvium is one of the outstanding challenges facing geotechnical engineers as the large particle size can adversely affect drilling and penetration processes. Mud rotatory drilling methods for disturbed sampling are typically employed; however, borehole stability and mud circulation loss, due to high soil hydraulic conductivity, are common issues. The coarsest materials are often fractured or missing (scalped) when disturbed samples are obtained. Additionally, the penetration resistance measured during drive sampling (e.g. N_{60} for SPT) can be unrepresentatively high, causing problems in analyses such as liquefaction triggering susceptibility. When in situ penetrometers, such as the CPT, penetrate gravelly alluvium, there is a persistent concern of refusal and cone damage; furthermore, it is not known whether the large particles have altered the penetration mechanism resulting in elevated tip resistance values. Laboratory testing of gravelly samples either requires scalping of the coarse particles or custom large-scale equipment in order to meet particle-to-specimen-size diameter ratios (such as those recommended in ASTM standards). In both cases preparation of the reconstituted specimen is a challenge, as gravelly alluvium is often widely graded and may have some level of plasticity. Overall, the majority of conventional field and laboratory techniques used to characterize soils are either not possible or adversely affected by the presence of a sufficient amount of gravel particles.

Recent work on a series of projects has enabled the development of alternate strategies for evaluating the potential influence of gravel on different conventional methods and advances in technology have enabled the development of a new continuous penetration technique in gravelly alluvium.

Sonic Drilling & Sampling

The sonic drilling technique is useful when characterizing gravelly alluvium as it provides rapid, disturbed, continuous core samples, essentially bringing an uninterrupted stratigraphic sample to the surface for the geologists and geotechnical engineers to inspect (Figure 6). This enables approximate delineation of the stratigraphic layers, identification of layers where gravel is present, information to guide selection of in situ and laboratory testing techniques, and disturbed bulk samples without significant scalping of coarse fraction materials for laboratory testing.

In North America, the “core and case” sonic drilling technique is typically employed to provide a continuous sample; its use in the characterization of gravels has increased in recent years though it was developed more than 40 years ago in Canada. The hydraulic oscillator induces vibrational resonance (Figure 6a), enabling the core barrel (typical 125 mm inside diameter) to easily penetrate into soil and weak rock (vibration frequency adjusted between 50 and 140 Hz to optimize penetration as soil density/hardness varies). An over casing is then advanced around the core barrel to the driven depth to prevent borehole collapse, followed by retraction of the core barrel for sample recovery; the process is repeated in 3 m intervals to the depth of interest (Figure 6b). A continuous sample core to 50 m depth (with less than 1% deviation from vertical) can typically be achieved in one day.

The vibratory sonic drilling technique induces vibrations that can disturb surrounding soil and heat the soil sample obtained. As a result, common practice is to perform all subsequent soundings/borings 3 m (10 ft) from the sonic location; if sonic drilling is performed after other methods then it can be positioned much closer (e.g. 1 m). Heating of the soil sample due to vibrations can vaporize water in the soil, resulting is sample water contents that are less than in situ conditions. Vibrations, which are effective in displacing soil, can also pulverize weak rock and damage/destroy soil structure, cementation, and laminations. Inferred sample depths within each 3 m core sample can drift by up to 0.3 m due to vibrations and sample handling.

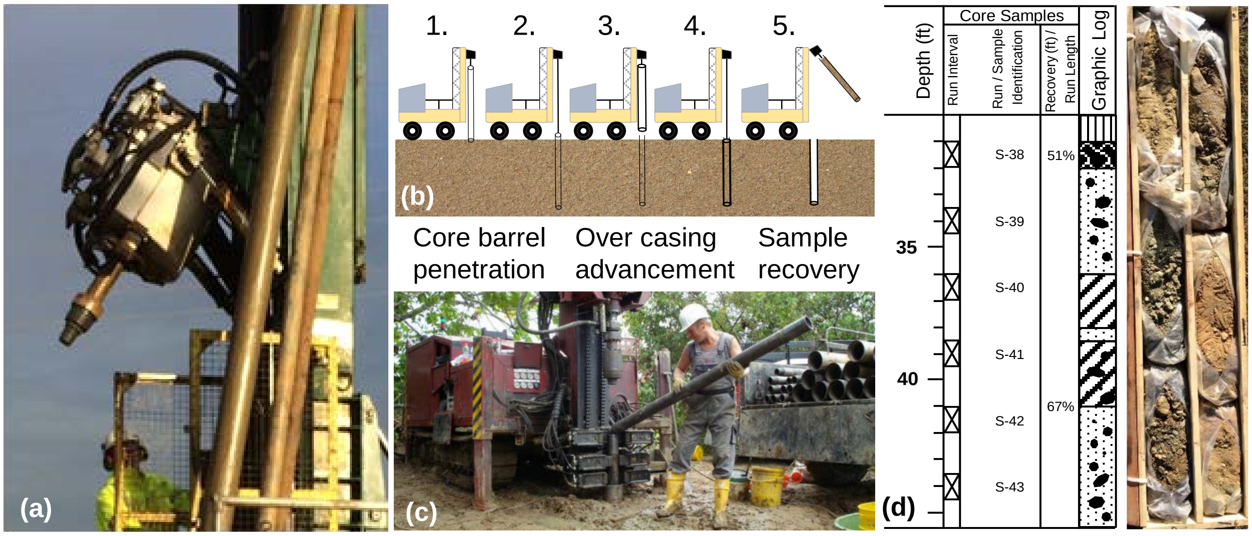


Figure 6. Images of sonic drill equipment (a) head, (b) drilling schematic (c) rods and clamping system (image from sonicsampdrill.com), and (d) continuous soil sample core.

Core barrel samples are sleeved in plastic (Figure 6d) and laid out, much like a rock core, to map the formation. As evident, a continuous profile enables identification of primary geologic strata as well as subtle variations in the material characteristics within each layer.

The sonic sample can provide valuable information for confirming/refining the geologic hypotheses, determining which subsequent drilling, sampling, and in situ testing techniques are appropriate, and developing a rational basis for defining stratigraphic layers in the site idealization stage. As a result, it can be particularly effective as the first tool mobilized to site.

Penetrometer Measurements

Penetrometer resistance measurements often form the basis for characterizing gravels as undisturbed sampling and laboratory testing are prohibitive in practice. Relying on penetrometer measurements for property characterization requires confidence that the measurements obtained be representative of the soil behavior when mobilized by the controlling deformation/failure mechanisms. As a result, it is imperative that the gravel particles do not artificially increase the penetrometer resistance, giving a false measure of material competence.

The conditions at which gravel particles influence penetrometers depend on the gravel properties (size and percent gravel), penetrometer geometry (outer diameter, inner diameter and/or annulus area), and penetration mechanisms (open-ended sampler penetration versus closed-ended penetration). Despite the complexities, several ‘rule of thumb’ recommendations exist. For example, Mejia (as reported in Idriss and Boulanger 2008) suggested that gravel content above 20% will likely result in elevated SPT blow counts (no specification on gravel size was given). Bolton et al. (1999) suggested that the penetration resistance changes when the cone penetrometer diameter to particles size ratio is less than 20:1. Others, such as Daniel et al. 2004 have also provided recommendations. While the exact parameter ratio (e.g. particle size to inner sampler diameter) values are not agreed upon, there is consensus that gravel particles can influence the standard penetration test (SPT). This is reflected in the wide range of alternate larger samplers/penetrometers that have been developed and tested in gravels.

The range of large penetrometer tests (LPT) developed is summarized in Figure 7 (discussion of the CPT is not included in the figure due to its steady state penetration mechanism). As evident, the sampler/penetrometer diameter ranges from the SPT (5.0 cm) up to the Becker penetration test (16.8 cm) (Figure 7a). The reference energy for a given method correspondingly increases with sampler diameter. The LPTs, like the SPT, use an open-ended sampler and suffer from unrepeatable results due to an inconsistent penetration mechanism in the presence of large particles. Large particles may arch across the inner diameter of these probes and change the penetration mechanism from partial to full displacement, they may slide inside the probe without causing additional resistance, or they may be encountered by the probe and increase the blow counts while they are pushed aside or crushed. Closed ended probes such as the CPT, DPT or BPT are less susceptible to this aspect as the penetration mechanism is always full displacement.

The additional amount of gravel content (in terms of both percent and size) that can be successfully sampled by these larger penetrometers without influencing blow counts is still limited. Many of the large penetrometers have diameters approximately 150% of the SPT diameter, which is still comparable to larger gravel particles (relative scales indicated in Figure 7b). Only the BPT has a diameter that significantly exceeds the gravel particle size range and provides the driving energy necessary for advancement in both loose and dense deposits.

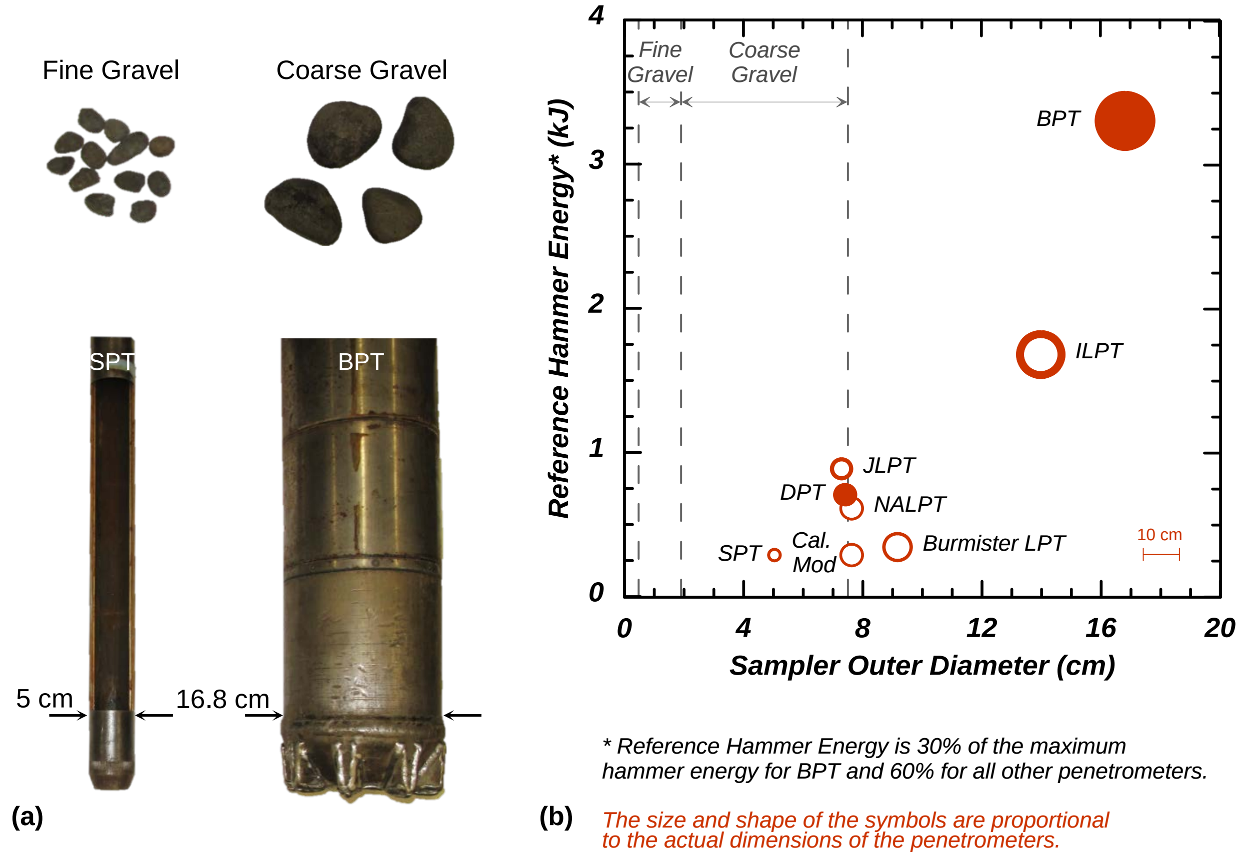


Figure 7. (a) Images of the SPT sampler and Becker drill tip compared to fine and coarse gravel and (b) comparison of large scale penetrometers (sampler shape and particle size also indicated for reference; expanded from Daniel et al. 2004).

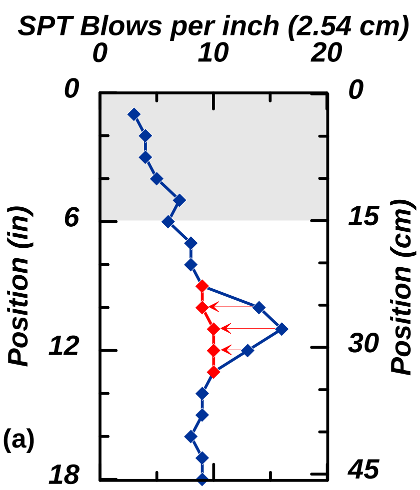
The following sections build on this insight. Presented first is a systematic, practical methodology for assessing the extent to which, if any, gravel present in the soil may adversely influence SPT penetration resistance. Second, a recently developed instrumented Becker Penetrometer method for estimating equivalent SPT N_{60} values in gravelly soils is presented.

Assessing Gravel Influence on SPT Measurements

A practical, repeatable framework for assessing gravel influence on SPT measurements was developed based on the analysis of nearly 600 individual SPT measurements (and complimentary information) in gravelly alluvium from four project sites. Two screening information categories were used to infer where there was sufficient gravel to adversely influence the SPT measurement: SPT blows-per-inch (per 25.4 mm of penetration) and physical evidence (encompassing sample gradation, photos, and logs from the SPT test and/or adjacent Sonic soundings).

The per-inch (per 25.4 mm) blow counts are used to detect gravel influence, which often manifests as an increase in per-inch blows over a few inches of penetration. Often these “spikes” can be corrected for, as depicted in Figure 8a, when either a thin gravel layer is penetrated or a gravel particle temporarily increases penetration resistance until it is pushed aside. Multiple changes in the blows-per-inch trend, consistently high penetration resistance, or incomplete penetration often prohibit the measurements from being salvaged. Detailed guidelines and examples can be found in Ghafghazi et al. (2016).

(a)



(b)

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 an 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*

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

Figure 8. (a) Example of an Index III SPT sample showing blows per inch (per 25.4 mm) and the applied correction, and (b) a table summarizing the five indices describing SPT sample quality.

The second screening category, physical evidence, is necessary to identify the abundance and size of the gravel particles in the soil being penetrated and to assess whether it is sufficient to adversely influence the SPT measurement. The mere presence of gravel sized particles (as indicated by the physical evidence) is not sufficient to infer gravel influence on SPTs; it is plausible that small amounts of coarse gravel can influence SPTs while larger amounts of finer gravel may not influence the SPT blow counts. Therefore, the framework suggests using the physical evidence from SPT and sonic testing to screen for the presence of 'influential gravels' – gravel particles of sufficient size and abundance to plausibly affect SPT penetration.

Collectively, the two screening categories are used to assign each SPT measurement an Index of I to V based on the framework outlined in Figure 8b. Once an Index has been assigned, the measurements are categorized as either high quality (HQ) or low quality (LQ), with HQ measurements representing those free of adverse gravel influence. Any sample with an Index of I-III is considered HQ while Index V samples are rated LQ. Index IV samples having less than 20% gravel content are rated HQ while those containing more than 20% gravel are rated as LQ.

Application of this method is intended to improve the ability to detect whether gravel has influenced the SPT measurement, provide a reliable process for correcting the influence when possible, and to increase certainty as to whether or not SPT measurements can be used in characterizing a given gravelly alluvial deposit.

instrumented Becker Penetration Test (iBPT)

The Becker Penetration Test (BPT), developed in Canada in the late 1950s, uses a 180 ICE double-acting diesel hammer to drive a 168 mm diameter, closed-ended steel pile. The BPT, out of the extensive set of penetrometers presented in Figure 7, is least likely to be adversely influenced by gravel particles and as such is the most promising tool for characterizing gravelly alluvium.

Unlike common penetrometers which are performed in over-bored open holes (often using drilling mud), the BPT's drive shoe (a closed-ended, 8 toothed, crowd-out bit) is the same diameter as the drill string, therefore, shaft friction accumulates during driving, contributing to the measured blow counts (N_B). Utilizing prior methods of interpreting BPT measurements (e.g. Harder and Seed, 1986; Sy and Campanella, 1994) leads to unreliable results that primarily stem from the inadequate methods employed to account for the effects of shaft friction on BPT penetration resistance.

Recent technological advances have enabled the development of the instrumented BPT (iBPT, DeJong et al. 2014, 2016, Ghafghazi et al. 2016), which directly measures the energy delivered to the drill string head and penetrometer tip (Figure 9a). Downhole sensors (force and acceleration) and a vibration-isolated data acquisition system continuously record measurements of hammer blows and digitally transmit them above ground to a data control unit (Figure 9c).

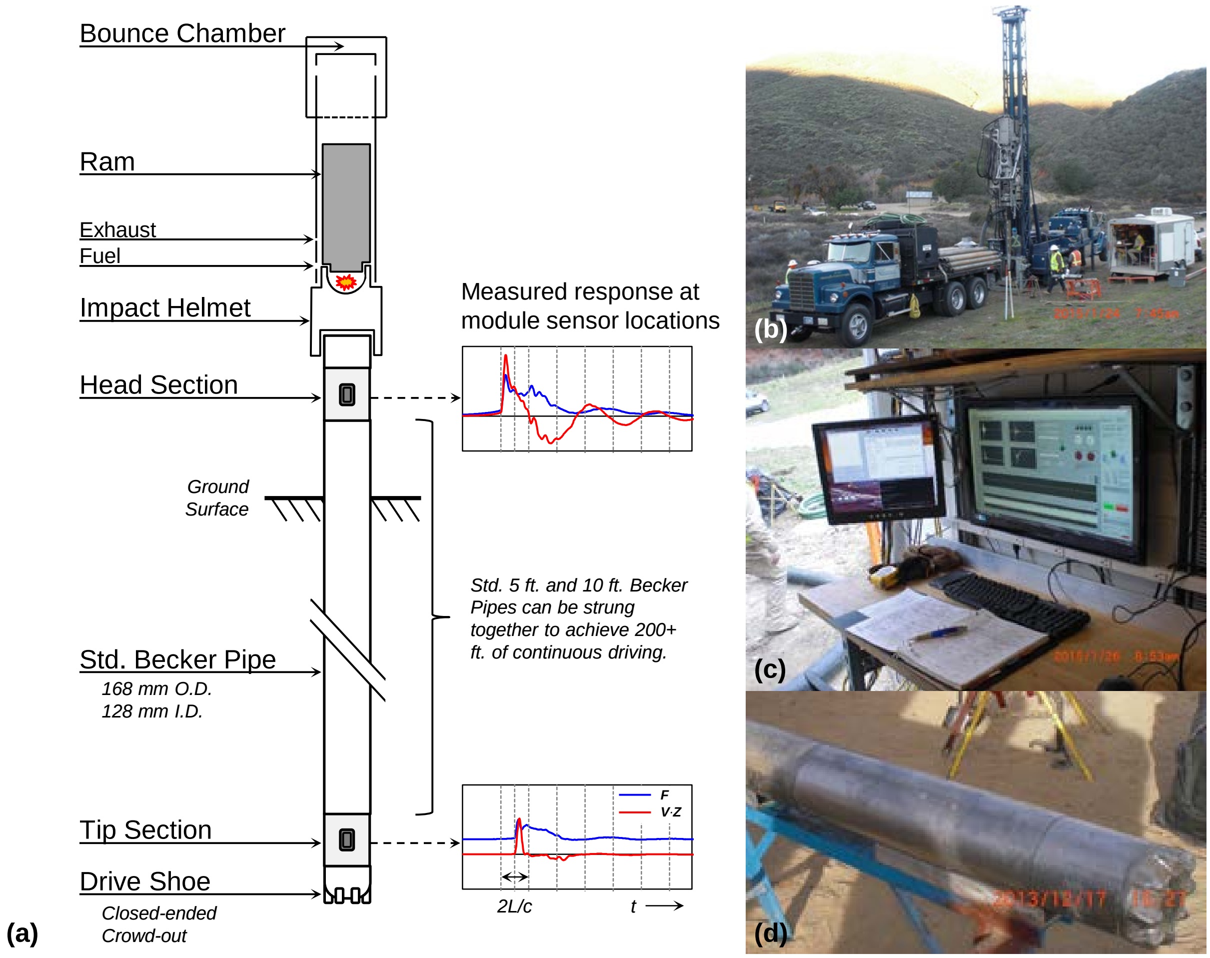


Figure 9. (a) Schematic of the iBPT system including the diesel hammer and sample measurements at the head and tip, (b) drill rig used to conduct Becker testing, (c) above-ground data control system for the iBPT, and (d) iBPT tip section and closed-ended drive shoe.

iBPT operation generates a continuous profile of both the per-foot blow count (N_B) and average, per-foot residual energy arriving at the penetrometer tip ($E_{res,tip}$) (Figure 10a,b). The delivered energy ratio ($ER_{T/H}$), the residual energy delivered to the drill string tip relative to the energy delivered by the hammer, provides insight into how much energy is absorbed by shaft friction with penetration depth (Figure 10c); the $ER_{T/H}$ often decreases to less than 25% within 10 m of driving.

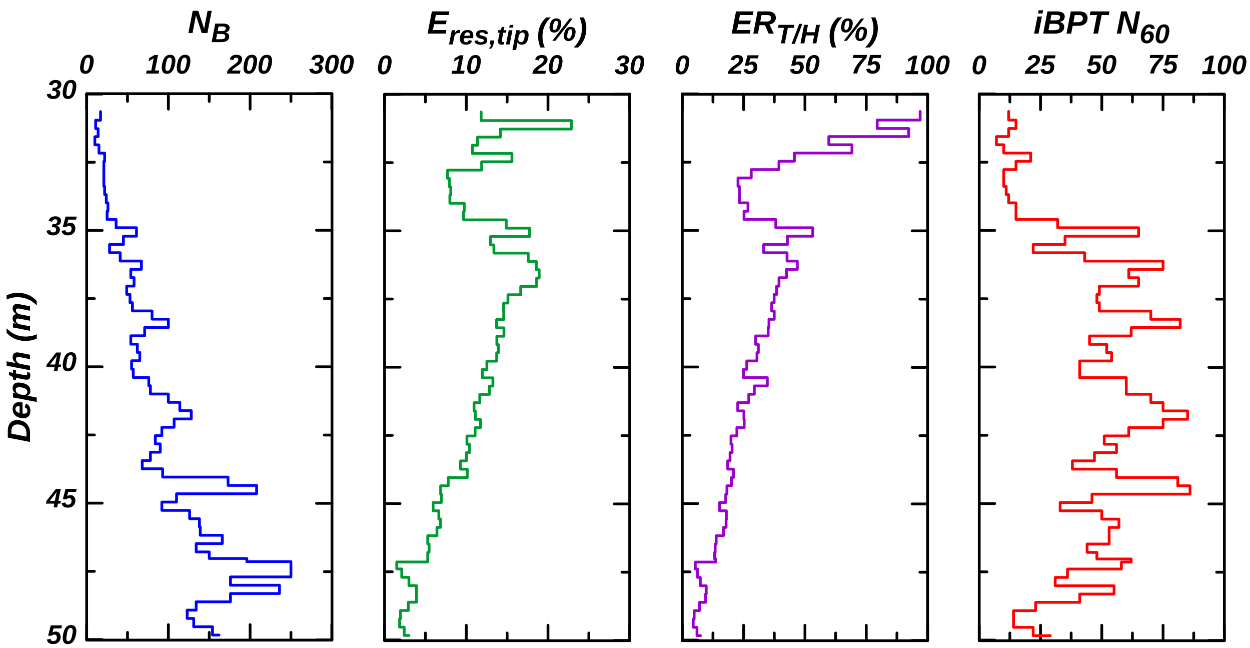


Figure 10. Example iBPT data output and conversion to equivalent iBPT N_{60} profile. Note that iBPT penetration started at 31 m depth after predrilling the boring through a compacted embankment.

An energy normalized tip penetration resistance can be directly calculated using the energy arriving at the tip and per-foot blow counts:

$$N_{B30} = N_B \frac{E_{res,tip}}{30}$$

where N_B is the measured blow count, $E_{res,tip}$ is the per-foot average residual energy delivered to the tip as a percentage of the nominal hammer energy (11 kJ), and 30 is the standardized efficiency of the Becker hammer as a percentage. Since N_{B30} values from iBPT are normalized based on the energy arriving at the tip, the influence of shaft friction has been accounted for.

The empirical correlation used to convert iBPT N_{B30} values to equivalent N_{60} values is presented in Figure 11. Each data point on the correlation figure compares the median iBPT N_{B30} and SPT N_{60} values over geologically consistent depth increments, from adjacent, closely spaced borings. The geologically consistent depth increments are not of consistent thickness for every data pair, therefore, the size of each point depicts the amount of data supporting it, with larger points carrying more weight. Overall, a linear correlation factor of 1.8 exists between iBPT N_{B30} and SPT N_{60} values regardless of material type or saturation conditions, albeit with ±40% scatter. As shown previously (Figure 4), this scatter is characteristic of the alluvial deposits in which the correlation was developed.

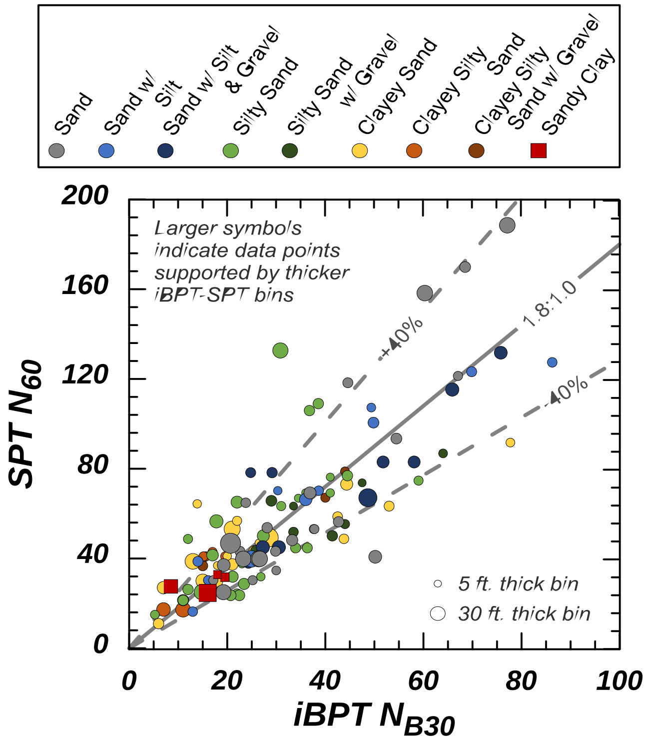


Figure 11. Correlation between iBPT N_{B30} and SPT N_{60} values based on 110 data points from four different project sites.

The iBPT provides repeatable, continuous N_{60} profiles not adversely influenced by the presence of gravel. Figure 12 compares iBPT equivalent N_{60} values to SPT measured and CPT estimated N_{60} values (Robertson, 2012) across three profiles from three different alluvium sites. The iBPT consistently trends with either SPT or CPT, with departures attributed to spatial variability. It is noted that there are instances where LQ, gravel influenced, SPT measurements (open '+' symbols) are much higher than the equivalent iBPT measurements.

The iBPT system provides a new, reliable method for the characterization of gravelly alluvium. The iBPT provides energy normalized penetration resistance using energy measured at the drill tip during driving. A robust correlation, used to estimate equivalent SPT N_{60} values, is based on more than 1,000 m of driving, 100,000 recorded hammer blows, and 600 corresponding SPTs. Itis applicable for gravelly deposits whose composition ranges from gravels to sandy clays.

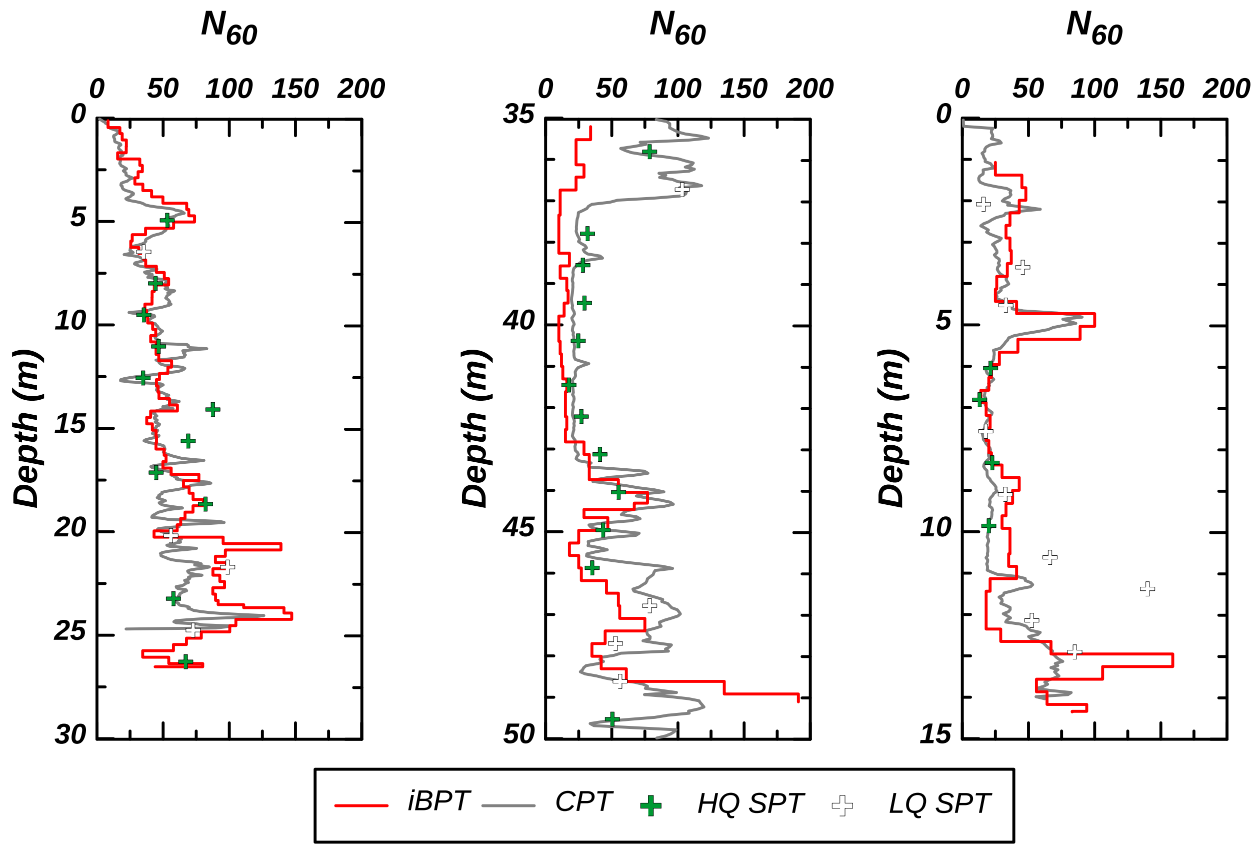


Figure 12. Example iBPT profiles from three different project sites. Agreement between iBPT N_{60} prediction and high quality SPT N_{60} data and estimated CPT N_{60} values (using Robertson 2012 conversion). Low quality SPT measurements are due to high gravel content, generally occur where variation increases, confirming gravel influence.

Conclusions

The characterization of project sites where gravelly alluvium is present poses particular challenges, but is simultaneously of critical importance for liquefaction potential evaluation as well as for conventional geotechnical analysis and design. The following observations have been made:

- The depositional process of gravelly alluvium is a complex, energy and sediment load dependent process that can result in highly interlayered deposits comprised of gravel to clay sized particles transported downstream and downslope from different geologic source materials. As a result, a high level of spatial variability, both horizontally and vertically, should be expected.
- The extent of spatial variability in alluvial deposits is larger than what many engineers would estimate, based on examining CPT sounding trends versus depth, for example. Quantitative analysis indicates that coefficient of variation values on the order of 0.3 to 0.4 are common. It is critical to recognize and rigorously estimate the extent of variability (particularly when the site-specific data population is limited) as property values towards the lower part of the range are often selected as representative values for analysis/design since they often control performance.
- A comprehensive approach to the characterization of alluvial deposits is recommended to

properly understand the geologic formation processes, interpret data from the site investigation, and synthesize the collective information to develop an idealized site realization that will be used for analysis and design. This is particularly important in highly variable gravelly alluvial deposits as the range of in situ and laboratory tools that are feasible and appropriate can differ significantly from those conventionally used for sands and clays.

- Extensive effort can be placed in the early *Inductive Reasoning* and *Scenario Assessment* steps of the site characterization process in order to develop a detailed hypothesis of expected site conditions and the likely deformation/failure modes that will control geotechnical performance and design. When performed well, the subsequent steps of *Site Investigation* and *Site Idealization* become confirmatory and refinement processes instead of discovery processes.
- Sonic drilling provide continuous (disturbed) samples in gravelly alluvium that enable delineation of geologic sequences and stratigraphic layering. The larger sample size captures gravel size particles and provides less scalping relative to the standard penetration test. The continuous samples are valuable for confirming initial hypotheses and justifying stratigraphic delineations during site idealization as well as for selecting other investigation techniques.
- The standard penetration test (SPT) N value, an industry standardized drive sampling index commonly used to assess liquefaction triggering potential, can be adversely affected by gravel. A method for systematically evaluating the quality of SPT data, based on blows-per-inch data as well as sample images, gradations, and soil descriptions, enables evaluation of gravel influence, if any, and identification of high quality data that can be used with confidence in analysis and design.
- A novel, robust instrumented Becker Penetration Test (iBPT) that directly measures the energy delivered to the drill string drive shoe provides a continuous profile of energy normalized soil resistance with depth that can be used to estimate equivalent SPT N values for soil characterization and liquefaction potential evaluation. The large diameter equipment can penetrate gravelly alluvium without concern for particle size influence and can also be deployed through existing dams and embankments.

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