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Correlation of In Situ Test Data with Shear Strength for Deep Foundation Design

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Correlation of In Situ Test Data with Shear Strength for Deep Foundation Design

Final report submitted to the

Nevada Department of Transportation

by

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RELATED PUBLICATIONS

- Samuel, R.A., 2015, Geotechnical Surrogates for Sediment Shear Behavior in Southern Nevada, MS thesis, University of Nevada, Las Vegas.
  Permalink:
  https://unlv.summon.serialssolutions.com/#!/search?bookMark=ePnHCXMw42JgAfZbU5khpykZg_Z1AhutRhxoPWhOBjf31HzIOaVAxygUlxYV5YMGjooVgI01hWJgyQ0aHVMoBt3rrADbsq6QmadQnA9e-p2n4JdalpgCrE-U3VxDnD10YSVpPDQSiuOBdbOppQHoRDZj4lQBAKuAOm8

- Samuel, R., Badrzadeh, Y., Luke, B., Lawrence, A.J., Siddharthan, R., and Bafghi, A., 2015. Seismic site characterization in support of drilled shaft design in Southern Nevada. *Proceedings, IFCEE*, ed. M. Iskander, M. T. Suleiman, J. B. Anderson, D.F. Laefer. ASCE, pp 939-950. doi: 10.1061/9780784479087.

ACRONYMS

IGM	Intermediate geomaterial (a category that includes caliche)
LVV	Las Vegas Valley
N	Blow count
$N_{1,60}$	Blow count corrected to 1 ton/ft^2 overburden pressure and also hammer efficiency
N_{60}	Blow count corrected for hammer efficiency
PMT	Pressuremeter test
SPT	Standard penetration test
s_u	Undrained shear strength
VS	Shear wave velocity
ϕ	Angle of internal friction
σ_v'	Vertical effective stress

INTRODUCTION

The project addresses drilled shaft foundation design for Nevada, especially for the population center of Las Vegas Valley. Specifically, we address overconservatism due to challenges in characterizing deformability and strength of dense, hard-to-sample sediments such as gravel, sand and mixed materials; and carbonate-cemented sediments of all types (which are identified as caliche when cementation is heavy). Sampling is a problem for these materials because of disturbance during collection (in cases of low-cohesion sediment or weak, brittle cement) or high costs of coring (caliche). Blow counts (N) from a standard penetration test (SPT; ASTM D1586) are not informative in caliche once the sampler meets refusal.

Direct, in situ measurements of stiffness and shear strength (shear stress at failure, τ_f), particularly using the pressuremeter test (PMT), can help reduce overconservatism in design. However, these would not be so effective in very stiff sediments and especially caliche. And questions have arisen as to representativeness / interpretation of results of such a localized test in our strongly heterogeneous sediments <ref>. Further, considerations for time and dollars limit use of in situ tests of strength / stiffness. Thus, foundation designers must make best use of those relevant datasets that are easiest and most economical to capture.

To accompany PMT and laboratory strength / stiffness tests conducted on some readily sampled soils, correlations might be developed that relate shear strength or stiffness with readily measured in situ parameters. For weaker soils, the correlation is logically with cone penetration resistance <ref>; however, the cone penetration test is rarely viable in southern Nevada because of the soils' intermittent zones of high stiffness, particularly due to cementation. The next logical choice for correlations is N. This approach is widely used. In one of many examples, Coduto et al. (2011) present correlations of N with the angle of internal friction (ϕ) of uncemented coarse-grained soils and with the undrained shear strength (s_u) of fine-grained soils. For stronger materials for which the SPT meets refusal, shear wave velocity (VS) might be a valuable indicator. VS information might also improve robustness of correlations to shear strength in weaker soil types.

BACKGROUND

We understand that current practice for design of foundations for roadway structures is overconservative because strengths and deformabilities of strong but difficult-to-sample strata are underestimated. Site-specific evaluation of VS variation with depth might allow for more efficient (less overconservative) design. Techniques to determine in situ VS non-intrusively are becoming more sophisticated and results are more reliable (e.g., Nazarian, 2012). Vertical profiles and even vertical slices of VS can be back-analyzed from Rayleigh-type surface wave measurements, which, as the name implies, are gathered on the ground surface, averting the need to drill costly boreholes. (See example illustration in Figure 1.) Author Luke, working through UNLV's Applied Geophysics Center, has extensive experience using surface wave methods to characterize the subsurface, to depths as great as several hundred meters, using both active sources (hammers, dropped weights, vibrators) and ambient vibrations ("passive sources") (e.g., Luke et al. 2010, Calderón-Macías and Luke 2010, Jin et al. 2009, Casto et al. 2009, Luke and Liu 2008, Luke and Calderón-Macías 2007, Calderón-Macías and Luke 2007).

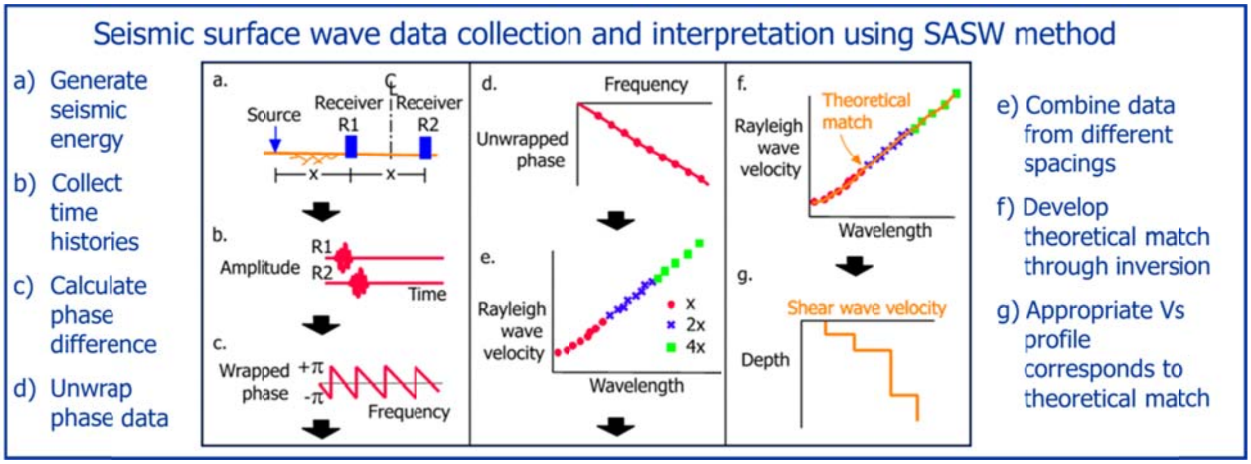

Figure 1. Diagrammatic explanation of the SASW method which is one of several used to generate detailed VS profiles nonintrusively by capitalizing on the dispersive characteristic of Rayleigh-type surface waves when moving through layered media.

Correlations of N to s_u are widely available (e.g., Coduto et al., 2011), however, users are warned against directly applying a correlation without testing it for the location of interest. We are not aware of any Nevada-specific correlation. Correlations of VS to either N or s_u are less common. One general correlation of the three, N, VS and s_u, is found in the NEHRP seismic site classification system that is adopted in the International Building Code. In that system, a site is assigned to one of five site classes according to any one of these three characteristics. Similarly, Andrus and Stokoe (2000) correlate VS to N in assessing liquefaction potential of coarse-grained soils.

Prior research at UNLV's Applied Geophysics Center has successfully addressed VS characterization of the Las Vegas Valley's caliches. We have generated a database and 3-D model of VS for the Las Vegas Valley (Luke et al. 2009, Luke et al. 2010, Murvosh et al. 2011, Murvosh et al. 2013). We have also investigated characterizing VS of sediment columns having large fluctuations in shear stiffness, focusing on conditions peculiar to Las Vegas (Tamrakar et al. 2011, Casto et al. 2009, Jin et al. 2009, Luke et al. 2008, Calderón-Macías et al. 2007, Luke and Liu 2007). Solving this problem using surface-collected data is challenging yet tractable. An important finding of the research is that all available independent information must be called upon in order to address potential non-uniqueness; in other words, to mitigate for the fact that for a complex stiffness profile (having one or more high-impedance-contrast boundaries), multiple, widely varying soil parameterizations exist that satisfy constraints imposed by the field data.

Drilled shafts are the most often used deep foundation element in the Las Vegas Valley. The shafts derive resistance from both components of resistance, skin and bearing. Although caliche is ubiquitous in the Las Vegas Valley, it is not common in other major US cities and as a result there are few established design guidelines (e.g., AASHTO recommendations) available to quantify these resistance components. Caliche fits AASHTO's categorization of "intermediate geomaterial", meaning that mechanical characteristics are intermediate with respect to soil and rock. Specifically, a cohesive IGM is defined having s_u in the range of 10 ksf to 100 ksf (FHWA 2010).Shaft designs are further complicated by the fact that the depth, thickness, frequency of occurrence, and lateral extent of caliche lenses vary widely. This means that capacities of the caliche relative to both bearing and skin resistance must be quantified. (If a caliche layer is thin, then only its skin resistance is of interest.) We understand that past designs by NDOT were generally based on applying existing design recommendations for caliche. One well-documented case study is the pile load field test carried out by Kleinfelder at the Spaghetti Bowl (I-15/ US 95 /I-515). In addition, the Pile Driving Analyzer (PDA) program has also been used. These studies have yielded upper limits for skin friction in the caliche layer; these are valuable starting points from which applicability of such recommendations, along with bearing capacity limits, to Las Vegas Valley soils can be investigated.

RESEARCH

The primary objective of the research was to collect in situ data (N and VS) that can be directly paired with laboratory s_u data to generate one or more correlations (N and/or VS to s_u). Emphasis is on Nevada soils with particular focus on cemented soils. Data were to be collected from NDOT records, published literature and new field testing. Resulting correlation(s) would be applied to address impact upon expectations for vertical static pile/shaft capacity.

The research program was organized into the following tasks. The task descriptions are copied verbatim from the project proposal. *With each description is a brief statement of how the work followed or deviated from the plan.*

Task 1: Planning and coordination: Communicate with NDOT personnel to coordinate plans, learn of existing relevant NDOT datasets, and discuss field testing opportunities. This task continues throughout the project. Emphasis is on lessons learned from past field testing. We look to develop correlations with special emphasis upon those sites where field pile load tests have been undertaken. *No significant deviation. Communication lines remained open throughout the project. Two in-person meetings were held at NDOT offices in Carson City. The researchers worked in tandem with NDOT personnel (Bafghi, Lawrence) on field testing and analysis of results; the team co-authored a conference paper.*

Task 2: Literature review: Using available Nevada-specific data and other relevant data, compile database of complementary data pairs or triads: s_u, N and VS. In particular, new VS profiles obtained from the pile load field test sites will be scrutinized to establish the correlations that are required for pile design calculations. *No significant deviation. NDOT personnel provided some key literature and data (Bafghi, Lawrence).*

Task 3: Field campaign: At locations specified by NDOT, collect intrusive (e.g., downhole, crosshole, in-hole) compression and VS data, and surface-based Rayleigh wave data using active and also passive sources. NDOT to provide lithologic logs, N and laboratory shear strength test results. NDOT to core representative cemented sections for transmittal to research team for laboratory characterization of shear strength and VS. Field tests will be conducted at new/additional locations in order to contribute to the database of parameters that will dictate the correlation. Such an undertaking is designed to improve the applicability of the correlations and also to establish the range for the variables that dictate the correlations. *Testing was conducted at one location only, the US 95/CC 215 interchange. No* *heavily cemented sediments suitable for coring were encountered. A complementary surface wave dataset was collected by UNLV Applied Geophysics Center (not part of this project; discussed below under Synergistic Activities).*

Task 4: Data processing: Process seismic datasets to generate profiles of shear and compression wave velocities with depth as well as Poisson's ratio. Include uncertainty measures. *As planned except that the analysis did not delve as deeply into uncertainty measures as anticipated because scatter in the data was so large that correlations were not valuable as predictors.*

Task 5: Synthesis: Compile test results to compose correlations. Check the database for accuracy and quality. Compare findings with statewide and broader databases. Consider both coupled and independent correlations of VS and N. Investigate the impact of uncertainty in the correlations on deep foundation capacity. Investigate the impact of uncertainty in the correlations on surface seismic response spectra, for example using the program SHAKE, for representative soil sites in Las Vegas and Reno. Use relevant seismic excitations to compute soil amplification, strain level, and liquefaction potential. Compare the seismic design criteria obtained by site-specific analysis against results obtained using code-based expedient methods. *The compilations were completed as planned. Local results were compared against local and global compilations. Local results demonstrated a distinct bias toward higher velocities/ greater stiffness/strength. Still, correlations were too poor to be of much use. (Scatter was tremendous.) Earthquake aspects were not addressed.*

Task 6: Report: Compose a technical report documenting research findings, recommending correlations for adoption in design, and stating implications for deep foundation design and seismic design. *This report encompasses by reference a thesis addressing the field tests and correlations work, and includes (Appendix A) a subordinate report addressing analyses of effects of caliche on axial capacity of drilled shafts.*

SYNERGISTIC ACTIVITIES

With help from the Applied Geophysics Center, UNLV graduate student Ms. Yasaman Badrzadeh collected seismic data along a long linear array at the US95/CC215 interchange site, not as part of this project. The source was an accelerated drop weight. The data underwent preliminary interpretation using the MASW method for fundamental-mode surface waves (Badrzadeh) and full waveform inversion (Professor Khiem Tran, Clarkson University). Plans to also interpret the data using seismic refraction tomography were not realized. Preliminary results were presented by Luke at IFCEE (Samuel et al. 2015).

Undergraduate student Ms. Jesse Basinski won an NDOT summer research award and used it to add a large and high quality dataset to the regional VS/N/sediment class database (refer to Samuel thesis) – that of the High Roller observation wheel at Project Linq in Las Vegas. Mr. William Sublette, a new BSCE and starting graduate student, added those data to the overall correlation built by Ms. Rinu Samuel. This compilation is presented in this report.

RESEARCH PRODUCTS

To date, the research has yielded the following written and oral outcomes.

- A thesis by Ms. Rinu Samuel (Samuel, 2015)
- A research report led by Prof. Siddharthan (Appendix A to this report), Samuel thesis
- A conference paper and presentation (Samuel et al. 2015)
- Graduate student posters by Ms. Samuel and by Ms. Yasaman Badrzadeh
- This final report

Future plans include one or more journal manuscripts, co-written by the authors of this report and their NDOT partners, for submission to Transportation Research Record.

DISCUSSION

A brief discussion of key findings follows. Further detail is contained in the research products listed above.

The work in Rinu Samuel's thesis (Samuel 2015) addresses most of the Tasks. From the Abstract: "… there is a need for investigating methods to assess the shear behavior of sediments that occur in the [Las Vegas Valley, LVV] *in situ* in working ranges of stress/strain, with the end goal of improving abilities to predict the capacity of drilled shafts in the LVV. To this end, global correlations of readily measured *in situ* tests – specifically, Standard Penetration Testing (SPT), shear wave velocity (VS) testing, and pressuremeter testing (PMT), with laboratory-measured shear parameters of sediments are reviewed to evaluate their applicability in the LVV. Direct measurements of [VS] are conducted using downhole testing at a site in the LVV known to have cementation and dense gravels. Local LVV datasets of aforementioned *in situ* tests and laboratory tests used to determine shear strength parameters are obtained from local consultants and government entities and are analyzed to detect possible relationships between *in situ* tests and shear parameters (such as ϕ, cohesion (c), s_u) beneficial for deep foundation design. Despite the high sediment heterogeneity across the LVV, variations in testing procedures, and lack of laboratory data, results show that readily measured in situ test data can be valuable for deep foundation design in the LVV when complemented with each other and laboratory data. In the datasets analyzed, blow counts are highly variable. Some local data show weak trends of increasing ϕ and c with increasing blow count. Comparisons of blow counts with VS did not yield any useful correlations. Neither seismic velocities nor N_{60} [blow count from SPT corrected for hammer efficiency] is more informative than the other, but when complemented with each other they provide valuable insight regarding stiffness and relative density of sediments and their variability with respect to depth. Most correlations from other sites considered in this study are not representative of the shear [characteristics] of the local sediments that were studied. Local VS profiles correspond better with local reference profiles than with others studied."

Correlations research

Samuel (2015) noted that blow count data are not informative in cemented sediments once the sampler meets "refusal". Because the stiff, cemented layers are not expected to fail under service loading, their stiffness at small strains will govern design. For these reasons, we looked to using

VS, a fairly readily measured, small-strain representative of mechanical stiffness, to supplement blow count data.

A literature review yielded correlations for various sites / soil types:

- N_{60} with ϕ for sandy soils
- N_{60} with s_u for clayey soils
- N_{60} with VS for both clayey and sandy soils (Fig. 1)
- VS with s_u for clayey soils

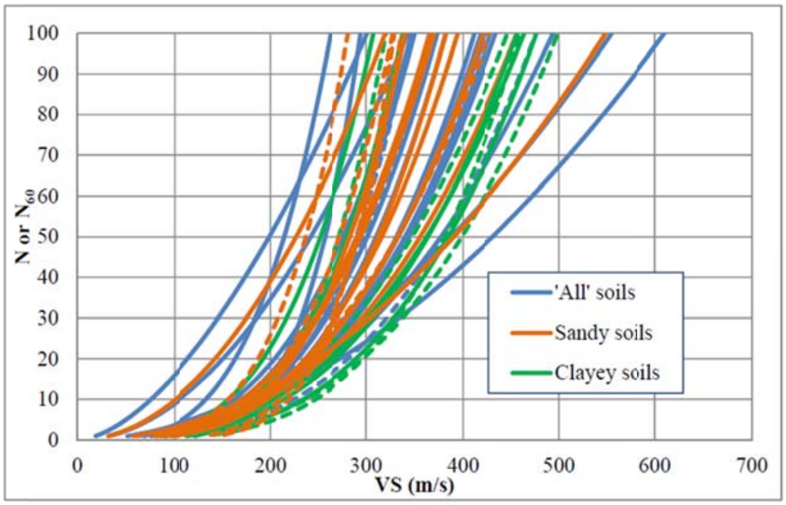

Figure 1. Literature review yielded many analytical relationships between N or N_{60} and VS. Variation is large; trends for sandy and clayey soils intermix. (Figure 2.7 from Samuel 2015.)

Few examples were found correlating VS with ϕ (for sandy soils). Cha and Cho (2007) explored this relationship for three such sites, relating the two through void ratio and effective stress.

The correlations show large variability. For example, considering only the mathematical fits to the data (ignoring the scatter inherent in each fit), N or N_{60} equal to 30 corresponded approximately to ranges of ϕ from 35° to 50°, s_u from 40 to 500 kPa, and VS from 140 to 330 m/s.

No correlations (relating N or VS to shear strength parameters) specific to dense sands and gravels or cemented soils were found.

This work does not incorporate the effect of vertical effective confining pressure, σ_v'. Comparing VS to N_{60} at California bridge sites, Bellana (2009) found that factor to be significant, especially for sands. The purpose of that work was to determine whether VS, which was needed for seismic site investigation, could be estimated from N_{60}. Under well controlled conditions and with a fairly rich dataset (918 pairs of VS - N_{60} data at about 20 different bridge sites), the author quantified uncertainty statistically. Even under such ideal circumstances, the author cautioned that "the correlations should only be used as a rough estimate of V_s to prioritize site investigation resources by identifying whether directly measuring V_s would be worthwhile." (Bellana 2009, p. *x*.)

Following this unsatisfying literature search, we turned attention to the PMT. That method too is problematic in the LVV's challenging sediments. Reporting on their PMT work for Project Neon in LVV, In Situ Engineering (2012) reported poor correlation of PMT results with soil type. Citing huge material variability, they noted "no discernible trend for modulus values" with respect to depth. "Sampling was performed before and after each test pocket to help clarify the material being tested. Unfortunately, these samples do not accurately represent the material being tested. Dealing with materials that are continuous or have small variation between tests within a test pocket, a lower bound modulus trend can be demonstrated by plotting the modulus values with respect to depth. However, this is not the case on this site. The soil strength and stiffness is highly variable with depth which is evidenced by the large spread in values, even in closely matched pairs of testing." (In Situ Engineering (2012), page 20.)

Direct comparison testing

Two direct-comparison tests were conducted at the CC215 / US95 interchange site in the LVV (Samuel et al. 2015; Samuel 2015). The logged sediment type, N_{60}, compression wave velocity (VP) and VS from downhole testing, and VS from surface wave (MASW method) testing were observed and compared. Summary results from one of two drillholes (NDOT Test Shaft 2, Boring 3/3A) are shown in Fig. 2. A pattern of steadily increasing N_{60} with increasing depth, which would have implied a direct correspondence with overburden pressure, is absent. Resolution of VS is coarse compared to N_{60} data. A single, 14-m thick upper layer in the VS profile corresponds to strongly varying sediment types and N_{60} values. Below this depth, a sharp increase in VS corresponds to a thick layer of very dense clayey gravel with sand. The transition beneath to a thick layer of lean clay matches a sharp decrease in VS. N_{60} values are still quite variable in both of those layers (ranging from ~20 to 100-plus; see Samuel (2015) for the mechanism we used to characterize N_{60} values at "refusal"). There is a thin cemented layer beneath, indicated well by N_{60} but too deep to be resolved by the downhole testing.

Poisson's ratio values, derived from VP and VS, were reasonable. VP profiles indicated depth to moist soil, which was well above the depth to water surface in the borehole. The VS profiles are compared to two sets of representative profiles differentiated by soil type, one general and one local to the LVV (Fig. 3). The local set has consistently higher velocities than the general one. VS measured for the deep gravel layer fits the scatter from which the local representative profiles were created (Fig. 4; ref. Murvosh et al. 2013). The same is true for the MASW measurement in the underlying clay, while the downhole VS values are slightly beyond those bounds.

Even for this one-on-one test, the correlation of VS to N_{60} was weak. According to our NDOT partners, the Osterberg cell (O-cell) drilled shaft test at this location demonstrated relatively weaker material in the upper ~10 m and intermediate strength at greater depth (Fig. 5). (More detail of the O-cell tests is given in Appendix A.) The weakness at shallow depths corresponds more strongly to the VS data than the N_{60}, which demonstrated quite high values in the upper six meters. Conferring with our NDOT partners, we understand that the O-cell test results confirmed that a drilled shaft foundation design for this site that followed AASHTO in selecting soil parameters for the design that were based only on soil classification and standard penetration values from exploratory borings would have been overly conservative. The estimated cost differential between drilled shaft foundations designed following standard AASHTO guidelines for Intermediate Geomaterials (IGMs –such as caliche) and other soils using only soil classifications and blow counts and those designed using the load test information combined with the extensive seismic and laboratory testing reflected roughly $2.3M in savings for a single flyover structure. Still to be determined is whether incorporating VS in a site investigation along with sediment classification and N_{60} in the absence of expensive O-cell testing would improve the design (by safely reducing overconservatism). Fig. 4 indicates that incorporating VS would be beneficial for the case studied.

We found interpretation of the downhole data, particularly VS, to be challenging. The process is probably complicated by scattering of the wave train as it passes through the many layers of contrasting stiffness. We suspect that in-hole (suspension) VS logging would be a preferable approach, because (1) scattering and signal attenuation have smaller impact and (2) measurements are more representative of local volume and therefore more comparable to N.

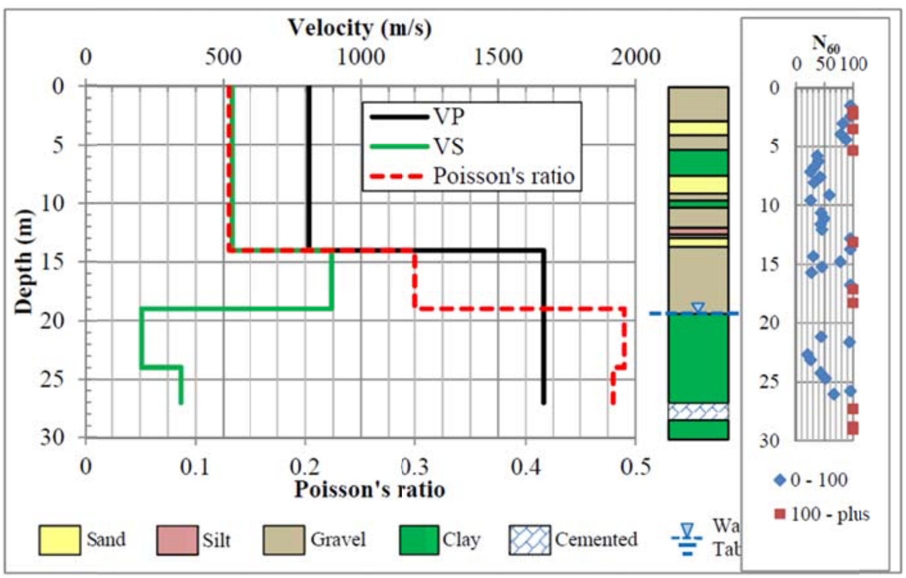

Figure 2. VP, VS, Poisson's ratio, sediment log and N60 for Hole 2 at CC215/US95 site. (Figure 3.13 from Samuel 2015.)

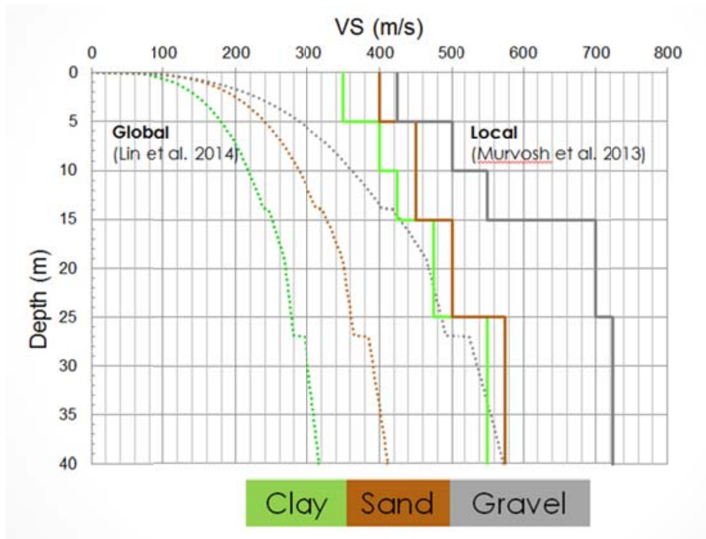

Figure 3. Representative profiles by sediment type, both global and local to LVV.

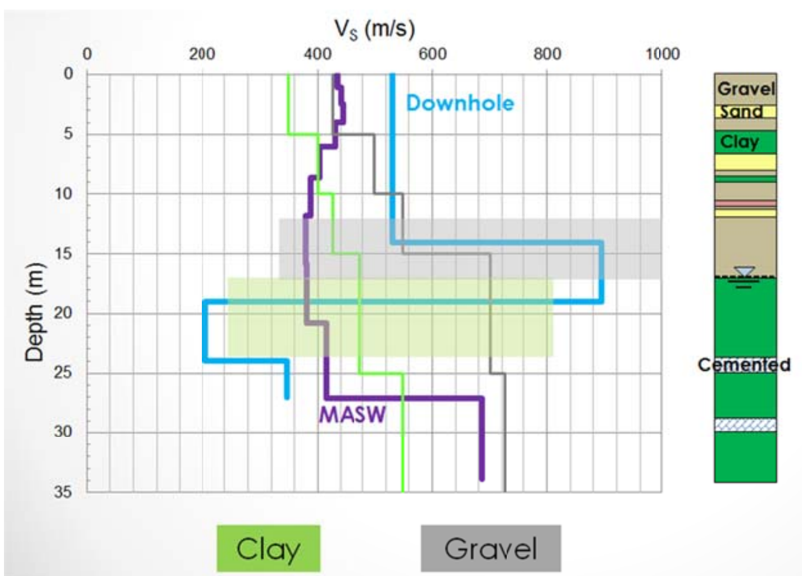

Figure 4. Hole 2: Measured VS compared against local representative profiles (green for clay, gray for gravel), and sediment lithology. Color-coded rectangles reflect variability of data from which representative profiles were created, at depths of interest for this site (gravel layer at ~12-17 m and clay layer at ~17-24 m).

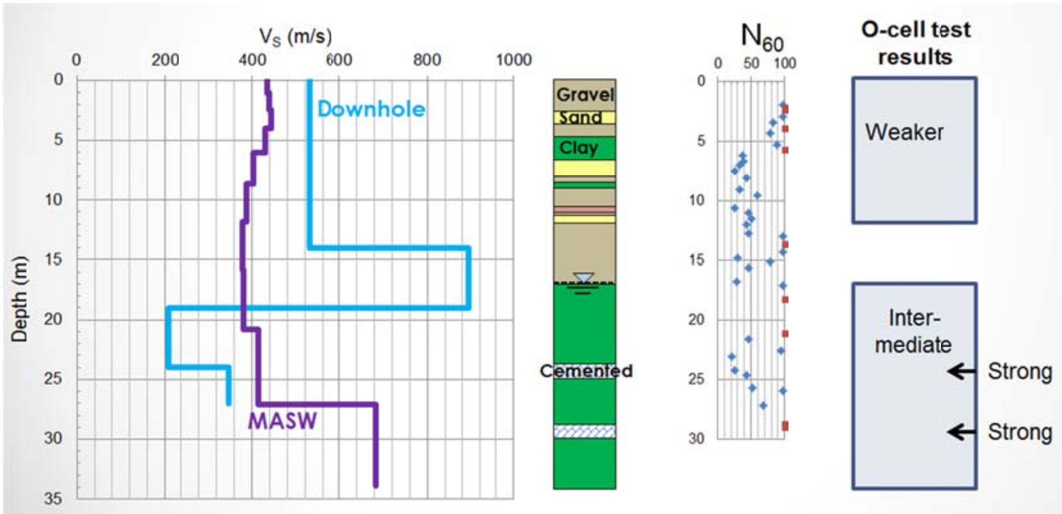

Figure 5. Hole 2: Measured VS, sediment lithology, N_{60} and general observations from Osterberg cell (O-cell) test.

Regional correlations

Samuel (2015) amalgamated N, VS, pressuremeter test results, sediment class, and shear strength data from projects around the LVV to look for patterns. Local practitioners provided data from several major projects. Clark County provided a pre-filtered selection from their database. Results were generally supportive of the conclusion that there is no simple correlation; the weak patterns that were seen for specific sites did not bear out at other sites. Samuel (2015) summarized this work as follows (pp 91-92): "This chapter analyses relationships between shear parameters and *in situ* tests for the LVV using two datasets: a) major-projects dataset and b) Clark County valley-wide dataset. The major-projects dataset provides *in situ* and laboratory strength data, while the Clark County dataset provides randomized N and VS. Overall, clay is the predominant sediment type within the datasets analyzed in this chapter; cementation is prevalent as well. No strong general correlations between laboratory strength tests and *in situ* tests are observed for the LVV. Although laboratory strength data is sparse, some weak trends are observed between shear parameters and *in situ* tests within the major projects dataset. As expected, sand mostly has higher friction angles and lower cohesion than clay, while clay and cemented sediments usually have higher undrained shear strength and cohesion than sand. Generally, shear parameters c and ϕ increase with increasing blow counts. Blow counts are highly variable in all predominant sediment types with respect to shear wave velocity within both datasets; very weak trends of increasing shear wave velocity with increasing blow counts are observed, if any."

We carried this study slightly farther by incorporating one more high quality major-project dataset, from Project Linq on the LV strip, provided to us by Arup (2011). This work was done by Ms. Jesse Basinski, undergraduate summer intern funded separately by NDOT. She drew the following conclusions after studying that dataset:

- Cemented layers contribute greatly to the stiffness of the site.

- In non-cemented layers, VS increases as N_{60}, corrected for field procedures *and overburden stress*, increases.
- Non-cemented dense gravel can exhibit stiffness greater than other non-cemented layers.
- Cemented layers are less predictable than non-cemented layers in respect to N_{60} and VS.
- In non-cemented layers, clay exhibits the lowest N_{60} and VS and sand exhibits higher N_{60} and VS.

The VS measurements in this dataset were made using the in-hole suspension method.

This investigation/dataset demonstrates that if we limit scope to a single, fairly small site and carefully sort the data (cemented versus non-cemented, depth of burial), more useful correlations can be found.

Graduate student Mr. Will Sublette, funded by this project, incorporated Basinski's work into an overall plot from Samuel (2015) comparing VS to N or N_{60} (Fig. 6). The three curves on the plot that show VS values at 1200 m/s or greater are second-order polynomial fits to the regional dataset, and are distinguished further in the figure caption. The plot also includes the correlations from literature that were shown in Fig. 1. The plot demonstrates (1) large variability in the data; (2) higher values for LVV than for the global datasets; (3) the dataset is not yet large enough to represent conditions Valleywide (demonstrated by the significant effect that the additional Project Linq data holds on the overall correlation). Further, note that there are no VS values below ~150 m/s. This outcome is likely affected by the fact that many of the VS values used came from ReMi-type surface wave measurements collected mainly to determine 30-m depth averaged VS and so the reported velocities are heavily averaged. Also note that there are many N values at 100 or greater. (As explained in Samuel (2015), we chose to saturate the N scale at 100; all values measured or computed from refusal counts above that number are plotted at 100). We also computed the curve fits to the dataset without considering the N=100 data (not shown). Those curves also showed considerable differences when the Project Linq data were included. Samuel (2015) provides similar plots to Fig. 6 for N compared to ϕ for sandy soils and N compared to s_u for clayey soils.

Samuel (2015) draws nine conclusions from her work, all of which are touched upon in this final report. The ninth, a key conclusion, is as follows: "Due to the heterogeneity of sediments, varying degrees of cementation, sampling difficulty, variability in volumes of sediments tested, and lack of standardization in testing in the LVV, joint sets of *in situ* and lab test results should be analyzed with careful consideration. Neither seismic velocities nor N_{60} is more informative than the other, but when complemented with each other [they] provide valuable insight regarding stiffness and relative density of sediments and their variability with respect to depth. Any test by itself may not be representative of the soils in the area, or may not be the best tool to understand the shear strength properties of the sediments in question. Therefore, the use of readily measured *in situ* test data is valuable for deep foundation design in the LVV as long as it is complemented with other data…. However, there are limitations associated with quantifying correlations of readily-measured *in situ* test data with shear behavior of sediments due to reasons such as high sediment heterogeneity, lack of standardization in testing, and differences in sediment volumes tested." (Samuel 2015, pp 134-135.)

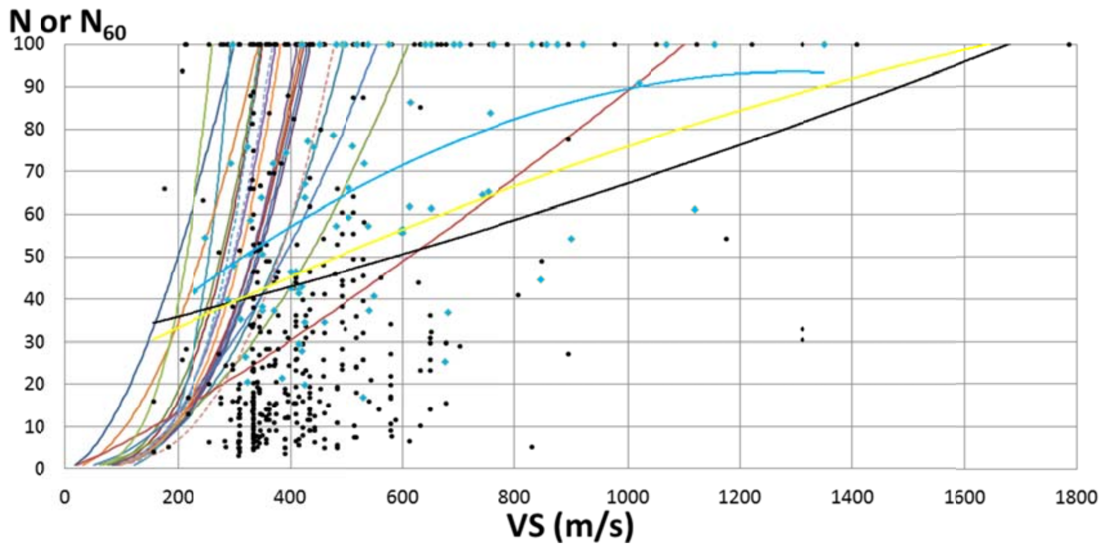

Figure 6. LVV regional N - VS data pairs compiled by Samuel (2015) (black dots) and for Project Linq compiled by Basinski (blue dots). Second-order data fits for Samuel's dataset (black), Basinski's dataset (blue) and all (yellow), computed by Sublette, are superimposed. (These are the three curves that show values at VS>1200 m/s.) Similar curves from literature review (also shown in Fig. 1) are included.

Foundation design research

Raj Siddharthan with support from Mahdi Nasimifar and in consultation with Barbara Luke analyzed the role of caliche layers on axial capacity of drilled shafts. The final report is included here as Appendix A. The authors conducted analyses using the program DFSAP, which incorporates the strain wedge model. Results were compared to design conducted following AASHTO LRFD procedures for IGMs. Analyses were conducted for two actual locations and one hypothetical one. Results demonstrated consistently that the caliche layer provides significant axial resistance. Thickness of the caliche layer strongly affects capacity, while depth does not. Analysis using DFSAP predicted much higher capacities than did the AASHTO procedures.

CONCLUSIONS

From this work we offer the following major conclusions related to drilled shaft foundation design for the strongly heterogeneous Las Vegas sediments:

- A useful Valley-wide correlation of readily measured soil characteristics (blow count, shear wave velocity, sediment classification) with shear behavior of soils (stiffness, strength) remains elusive. Jobsite-specific correlations may be useful, but only if cemented zones are identified and treated separately from the uncemented sediments.

- In the absence of in-place full scale load tests, considering shear wave velocity along with blow count and sediment lithology will help reduce uncertainty in deep foundation design. The three datasets do not always corroborate one another and therefore help to indicate level of confidence. Regarding shear wave velocity, results improve when it is measured locally (over small volumes that are more comparable to the volume of soil affected in a blow count) – in-hole measurements are preferable to surface-based measurements. Suspension logs are expected to be preferable to downhole measurements for the same reason; the Project Linq data appear to bear this out.
- Axial capacity of drilled shaft foundations is indeed enhanced by presence of caliche layers. Thickness of the caliche layer is a key parameter, while depth is less important.

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