Comprehensive Status Report: November 18, 2004

OTRC Project Title: Suction Caissons & Vertically Loaded Anchors
MMS Project 362 TO 16169
Project Subtitle: Suction Caissons: Seafloor Characterization for Deepwater Foundation Systems
PI: Robert B. Gilbert
MMS COTR: A. Konczvald

This report provides a comprehensive summary of the research completed in all prior Phases of this project (September 1999 – August 2004), and describes research being done in the present Phase (September 2004 – August 2005) to complete this project.

Note that this report addresses one of four related research areas on this project. The other three areas are reported separately under the subtitles – Suction Caissons: Model Tests, Suction Caissons: Finite Element Modeling, and Suction Caissons & Vertically Loaded Anchors: Design Analysis Methods.

Suction Caissons: Seafloor Characterization for Deepwater Foundation Systems

Robert B. Gilbert and Shadi S. Najjar (Graduate Research Assistant)

INTRODUCTION

The challenge of seafloor characterization for deepwater facilities is that the mooring foundations, subsea well trees and flowlines are spread over large areas (tens of thousands of feet across), while the cost of obtaining high-quality geotechnical data for the seafloor is high. Therefore, information from a handful of soil borings is typically extrapolated over thousands of feet to design foundations. This extrapolation leads to uncertainty that could potentially lead to excessively conservative designs or to unreliable designs.

The goal of this research is to develop a reliability-based methodology to design offshore foundations with limited seafloor characterization data and to apply this methodology to optimize geotechnical investigation programs. Specific research objectives are:

1. Develop models describing spatial variability in foundation design parameters for different geologic profiles encountered in deepwater fields.
2. Relate uncertainty in foundation design parameters to partial safety or resistance factors required to achieve target reliability levels for different foundation types and loading conditions.
3. Quantify the added value of geologic and geophysical information in reducing uncertainty in foundation design parameters.
4. Quantify the added value of foundation installation information in reducing uncertainty in foundation design parameters.

This research utilizes and synthesizes the results from a handful of related OTRC projects, including:

- Suction Caisson: Model Testing by Olson and Rauch;

- Suction Caisson: Design Analysis Methods by Aubeny and Murff;
- Suction Caisson: Finite Element Modeling by Tassoulas;
- Suction Caisson State-of-Practice by Murff (and API); and
- Mooring System Reliability by Zhang and Gilbert.

This report summarizes the results that have been obtained thus far and describes ongoing work. An emphasis in this report is put on the more recent work in this area.

SPATIAL VARIABILITY IN FOUNDATION DESIGN PARAMETERS

The initial work in this project focused on spatial variability in design parameters. Proprietary site investigation and design information was compiled and analyzed for a set of deepwater sites. These data were supplied by three different companies. Figure 1 provides an illustration of the type of results from this work; this figure shows variation in the calculated using the design method under development by Aubeny and Murff. The data on Figure 1 correspond to sites that are in a similar geologic setting, normally consolidated clays from deepwater in the Gulf of Mexico. References for details of this work include Gilbert and Murff (2001) and several industry reports. The major conclusions from this work are as follows:

1. The relative variability in the capacity of suction caissons versus conventional driven piles is larger because i) suction caissons depend less on side friction (a spatially averaged property) and more on end bearing (a local property) and ii) suction caissons depend more on shallow soils that tend to exhibit greater relative variability in strength than deeper soils.
2. The magnitude of variability in the capacity of suction caissons depends substantially on the geologic setting. In normally consolidated marine clays in deepwater in the Gulf of Mexico, the absolute variability is small with coefficients of variation between 0.1 and 0.2.

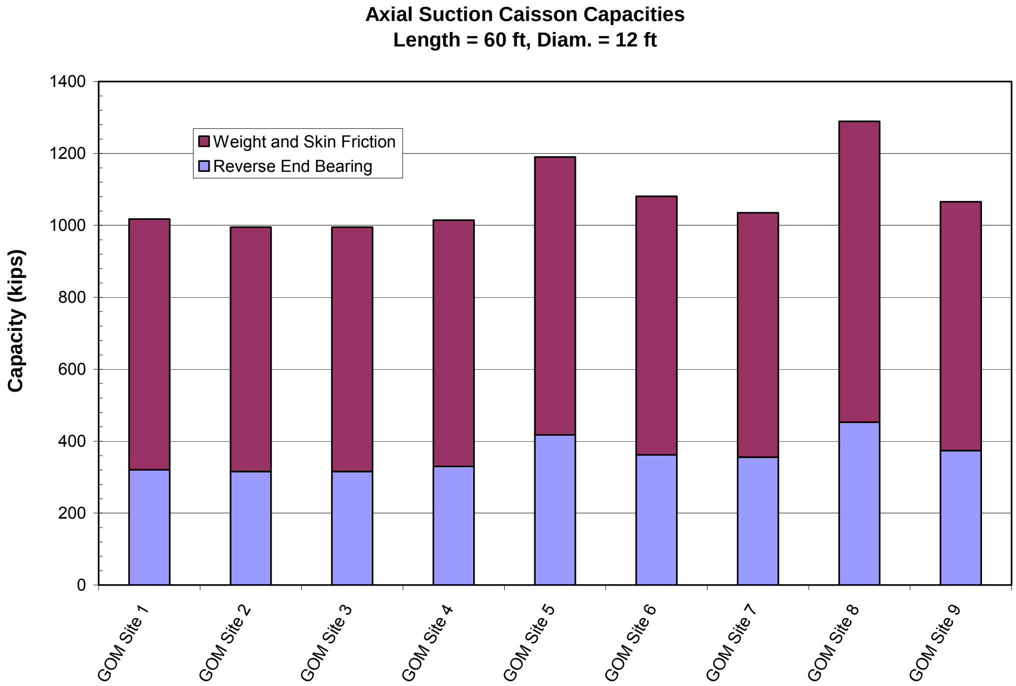


Figure 1. Example of Spatial Variability in Suction Caisson Capacity across Gulf of Mexico Deepwater Sites

CALIBRATION OF DESIGN MODELS

An effort is currently underway to analyze a load-test database containing model and field test results for suction caisson. The objective is to use these data to calibrate design models and to quantify the bias and uncertainty in using them.

An illustration of this work is shown on Figure 2. Ratios of measured to predicted axial capacities are plotted for 25 tests in the database. The load-test database shown here is comprised of seven lab-scale model tests (from the OTRC project by Olson and Rauch), fifteen centrifuge tests, and three full scale field tests. Diameters range from 4 inches (model tests) to about 50 feet (prototype scale for centrifuge tests) and ratios or length to diameter range from 2 to 10. The predicted capacities are obtained using the design model that is under development on the OTRC project with Aubeny and Murff.

The majority of the load tests in the database are conducted under rapid monotonic loading conditions to simulate undrained uplift under extreme loading conditions in the field. However, different loading rates are used in different studies thus introducing a source of uncertainty in the measured loads. Another source of uncertainty in the database is the different time periods that are allowed for the suction caissons to setup prior to undrained load testing. Load tests that are conducted prior to full equalization of excess pore water pressures can underestimate the ultimate capacity of the caisson. The last major source of uncertainty in the suction caisson database is the different methods used to measure the undrained shear strength. Direct simple shear tests, unconsolidated-undrained triaxial tests, cone penetrations tests, vane shear tests, and T-bar tests are used to measure the undrained shear strength in different studies analyzed.

To provide for a consistent analysis of the data, shear strength measurements that are obtained using the vane test (Clukey and Morrison 1993) and UU-triaxial tests (Cho et al. 2003) are reduced by 25% and used to calculate predicted capacities The ratio of measured to predicted capacities is evaluated for the 25 tests using an alpha of 1.0 (a model parameter that characterizes the efficiency of side friction from the soil along the caisson walls) and an N of 9.0 (a model parameter that characterizes the end bearing capacity of a foundation). Results indicate an average ratio of measured to predicted capacity of 1.04 and a coefficient of variation in the ratio of measured to predicted capacity of 0.28. Coefficients of variation of the ratio of measured to predicted capacity corresponding to combinations of alpha and N that result in a mean ratio of measured to predicted capacity of 1.0 are selected and presented in Table 1. For comparison purposes, the coefficient of variation from a similar analysis on a load-test database for driven pipe piles is about 0.2.

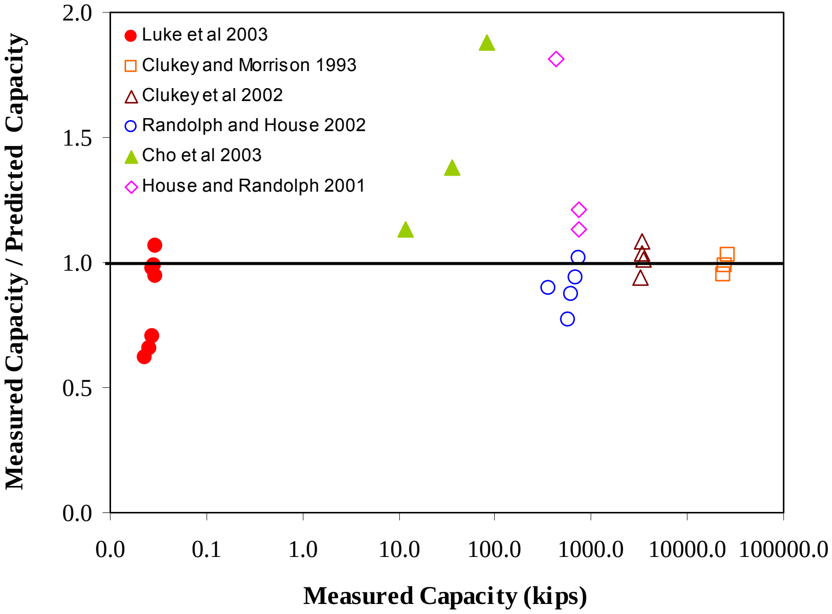


Figure 2. Comparison between Measured and Predicted Axial Capacities for Suction Caissons (corrected shear strength: DSS, α = 1.0, N = 9)

Table 1. Biases and Uncertainties in the Capacity Prediction Models (DSS Strength)

		Measured Capacity / Predicted Capacity	
α	N	Mean	Coefficient of Variation
1.0	10	1.0	0.28
0.9	11.5	1.0	0.28
0.8	13	1.0	0.29
0.7	15	1.0	0.31

As another example, measured and predicted capacities are shown on Figure 3 for load tests with a variety of loading inclinations. The test results shown here were generated from the OTRC project by Olson and Rauch. This figure shows remarkably strong agreement between the design predictions and the measured capacity.

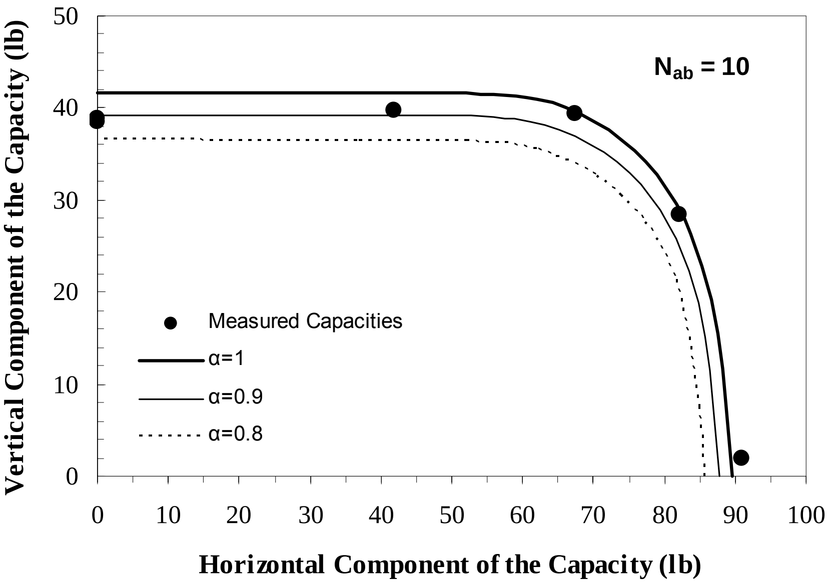


Figure 3. Comparison between Measured and Predicted Capacities for Axial, Inclined, and Lateral Loading

LOWER-BOUND CAPACITY

One general concern arising from the work on spatial variability and model calibration is that the magnitude of uncertainty for suction caisson design is generally larger than that for driven piles in normally consolidated clays. Therefore, we have recently been pursuing ways to reduce the effect of this uncertainty in design. One area of focus is on the effect of a lower-bound capacity in limiting the uncertainty (e.g., Gilbert 2003).

The first step in this work was to re-evaluate load-test databases with driven piles, since the design methods for suction caissons were derived from those for driven piles. These databases show clear evidence for the existence of a lower-bound capacity in both cohesive and cohesionless soils (Gilbert et al. 2005). This lower-bound capacity is a physical variable that can be calculated based on mechanics with site-specific soil properties. The calculated lower-bound capacity typically ranges from 0.5 to 0.9 times the calculated predicted capacity.

In order to explore the hypothesis of a lower-bound capacity for suction caissons in normally consolidated clay, an analysis is presented for the axial pullout tests available in the database. The predicted lower-bound capacity is calculated using the alpha method by replacing the undisturbed undrained shear strength with the remolded undrained shear strength of the soil. The remolded strength is calculated by dividing the undisturbed strength by the sensitivity of the soil. An alpha value of 1.0 and an end bearing factor of 9.0 is used in the analysis. In tests in which the top cap of the caisson is vented, 1-g model tests and centrifuge tests indicate a failure mode in which the caisson is pulled out without the formation of a plug. For these cases, the lower-bound side friction is calculated as the sum of frictional resistance acting on the inner and outer walls of the caisson and the lower-bound reverse end bearing is assumed to act on the annulus of the caisson. In tests in which the top cap is sealed, tests indicated the formation of a plug.

For these cases, the lower-bound side friction is calculated from the external skin friction and the lower-bound reverse end bearing is assumed to act on the full cross sectional area of the caisson.

The ratio of the predicted lower-bound capacity to the measured capacity is calculated and plotted on Figure 4 for the 25 load tests shown on Figure 2. For all the cases studied, the calculated ratio of the predicted lower-bound capacity to the measured capacity is less than 1.0, indicating clear evidence for the existence of a lower-bound axial capacity. The ratio of lower-bound capacities to measured capacities ranged from 0.25 to 1.0 and had an average value of 0.62. The incorporation of lower-bound capacities of this magnitude into reliability analyses can have a significant effect on the calculated reliability of suction caissons in normally consolidated clays. This effect is considered in the final section of this report.

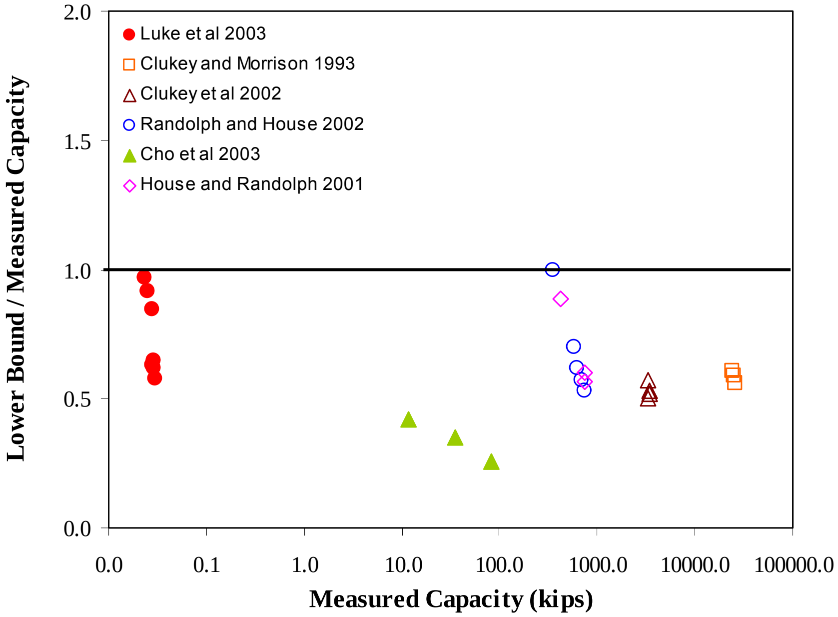


Figure 4. Evidence of Lower-Bound Capacity for 25 Suction Caissons

RELIABILITY-BASED DESIGN OF SUCTION CAISSONS

A convenient mathematical model for the probability distribution of suction caisson capacity is shown on Figure 5. For capacities greater than the lower bound, the distribution is a continuous probability density function that follows a lognormal distribution. Most reliability analyses for pile capacities have assumed lognormal distributions for the pile capacity based on the available database information, and the model on Fig. 6 is consistent with this conventional approach. For capacities at the lower bound, there is a finite probability (that is, a probability mass function) that corresponds to the probability of being less than or equal to the lower bound in the non-truncated lognormal distribution.

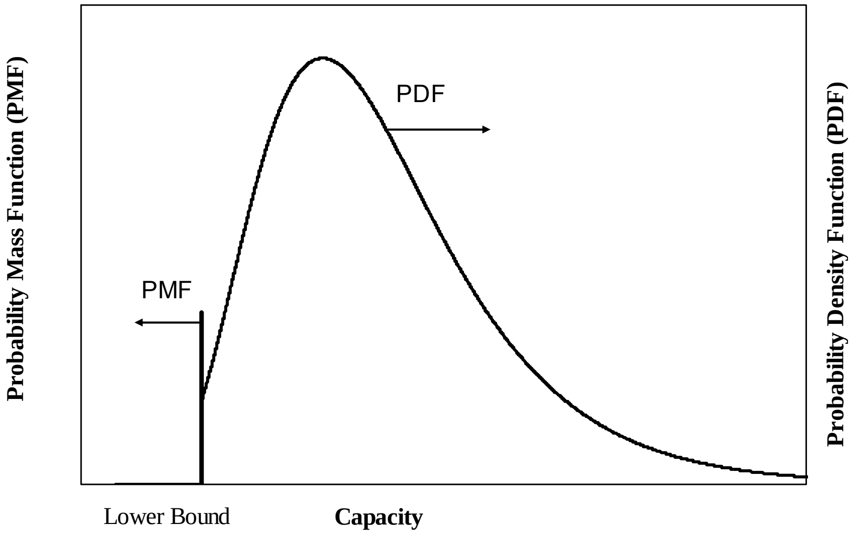


Figure 5. Mixed Probability Distribution for Modeling Suction Caisson Capacity

Curves showing the variation of the reliability of a suction caisson foundation as a function of the ratio of the lower-bound to median capacity are shown on Figure 6. The reliability index (β) is defined as $\beta = -\Phi^{-1}(p_f)$, where p_f is the probability that the load exceeds the capacity and $\Phi^{-1}()$ is the inverse of the cumulative standard normal function. The curves on Figure 6 represent the case were the uncertainty in the capacity (c.o.v. = 0.3) is relatively large compared to the uncertainty in the load (c.o.v. = 0.15), which is typical for deepwater mooring systems. The primary conclusion from Figure 6 is that a lower-bound capacity can have a significant effect on the calculated reliability.

To better illustrate the magnitude of the effect of the lower-bound capacity, the median factor of safety that is required to achieve different levels of reliability are plotted on Figure 7 as a function of the ratio of the lower-bound to the median capacity. To highlight the importance of the lower-bound capacity, consider a typical lower-bound capacity of 0.6 times the median strength and a target reliability index of 4. The required median factor of safety from a conventional reliability analysis (that is, one that doesn't incorporate the lower-bound capacity) is 3.7. However, if the lower-bound capacity is incorporated into the analysis, the required median factor of safety is reduced to 2.7 while still maintaining the same level of reliability ($\beta = 4$). Results on Fig. 8 indicate that resistance factors in a Load and Resistance Factor Design (LRFD), which control the median factor of safety, may need to incorporate information about the lower-bound capacity if they are to provide a consistent level of reliability.

Since a lower-bound capacity can have a significant effect on the reliability of a design, a reliability-based LRFD design code should include information on the lower-bound capacity. Two alternative formats are currently under development for including information about a lower-bound capacity in a LRFD design code: (1) a conventional design checking equation where the resistance factor is adjusted according to the lower-bound capacity and (2) a second design checking equation to include information about the lower-bound capacity.

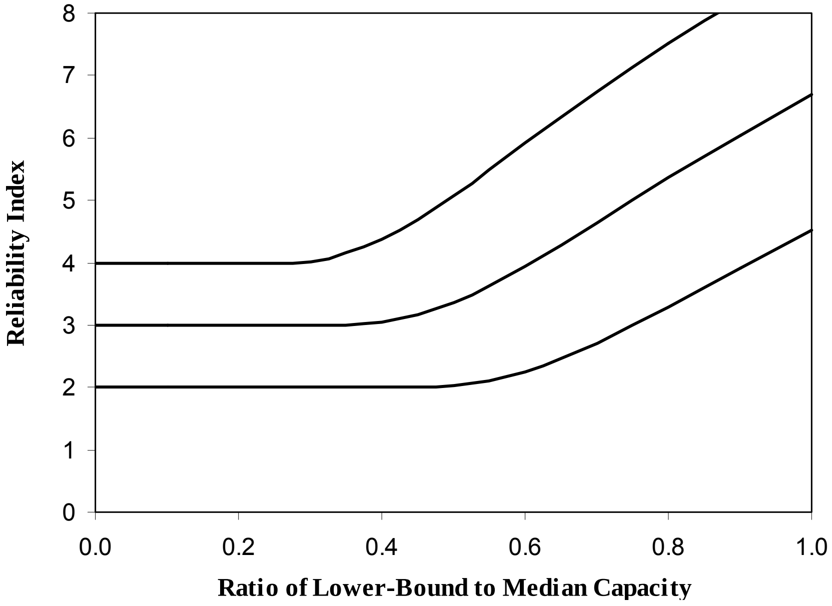


Figure 6. Effect of lower-bound capacity on reliability index
(c.o.v.$_{Load}$ = 0.15, c.o.v.$_{Capacity}$ = 0.3)

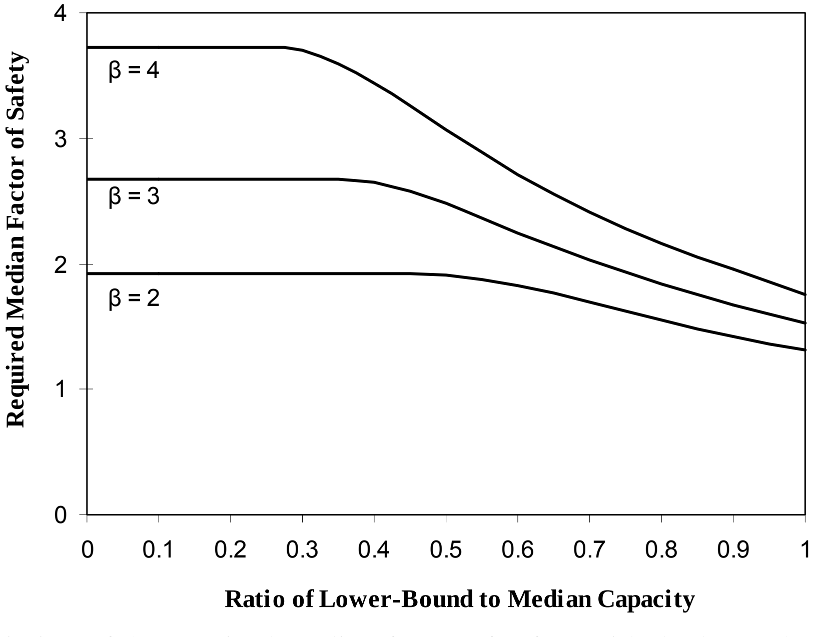


Figure 7. Variation of the required median factor of safety with the lower-bound capacity
(c.o.v.$_{Load}$ = 0.15, c.o.v.$_{Capacity}$ = 0.3)

Adjusted Resistance Factor for Lower-Bound Capacity

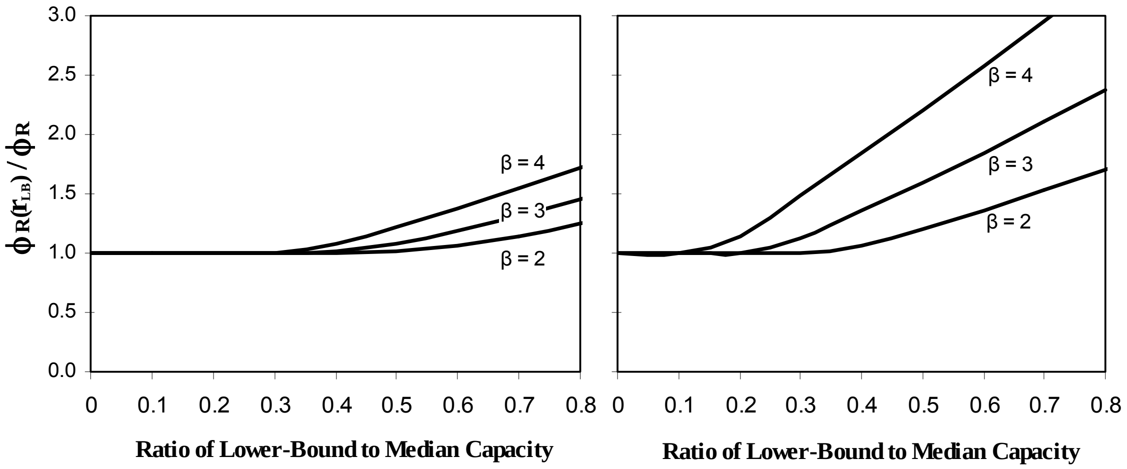
The conventional design checking equation has the following general form:

$$\phi_R r_{nominal} \ge \gamma_Q q_{nominal} \tag{1}$$

where $r_{nominal}$ is the nominal capacity calculated using a design method, ϕ_R is the resistance factor, $q_{nominal}$ is the nominal load for design, and γ_Q is the load factor. In order to incorporate the effect of a lower-bound capacity, this design checking equation is modified as follows:

$$\phi_{R(r_{LB})} r_{nominal} \ge \gamma_Q q_{nominal} \tag{2}$$

where the resistance factor, $\phi_{R(r_{LB})}$, is a function of the lower-bound capacity. The ratio of the resistance factor incorporating a lower-bound capacity with the conventional resistance factor, $\phi_{R(r_{LB})} / \phi_R$, is shown as a function of the lower-bound capacity on Figure 8 for different target values of the reliability index. For reasonable values of the ratio of the lower-bound to median capacity, 0.4 to 0.9, the effect of the lower bound on the required resistance factor is significant.



(a) c.o.v.$_{Capacity} = \delta_R = 0.3$ (b) c.o.v.$_{Capacity} = \delta_R = 0.5$

Figure 8. Variation of the increase in the nominal resistance factor with the lower-bound capacity (c.o.v.$_{Load} = \delta_Q = 0.15$).

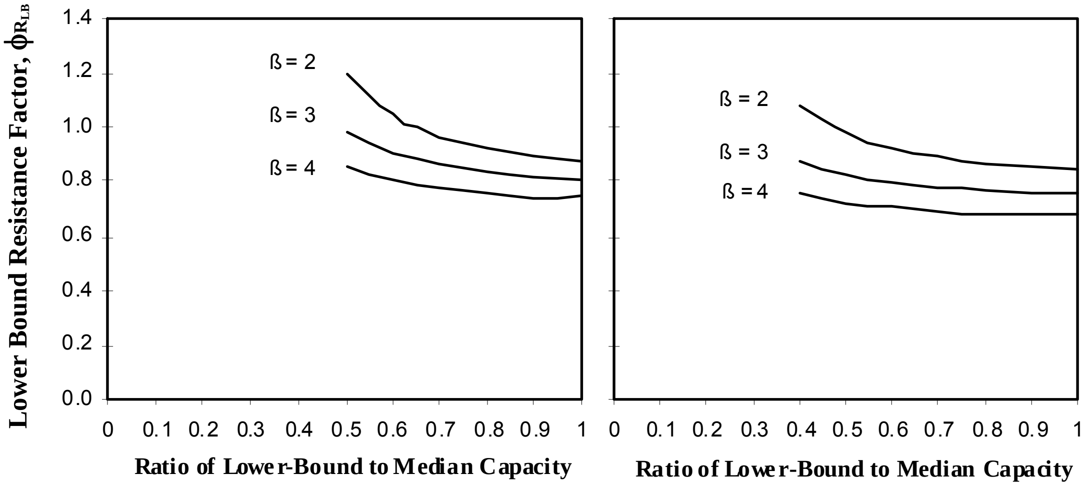
Added Design Checking Equation for Lower-Bound Capacity

An alternative code format would be to have two design checking equations:

$$\begin{gathered} \phi_R r_{nominal} \ge \gamma_Q q_{nominal} \\ \text{OR} \\ \phi_{R_{LB}} r_{LB} \ge \gamma_Q q_{nominal} \end{gathered} \tag{3}$$

where the first design checking equation is the conventional equation and the second equation includes a resistance factor, $\phi_{R_{LB}}$, that is applied directly to the lower-bound capacity. Providing that one or the other of the two equations is satisfied, a design will provide the specified level of reliability. The motivation for this form of the design checking equation is that the conventional approach is incorporated and does not need to be modified, whether or not there is a lower-bound capacity; the effect of a lower-bound capacity is reflected entirely in the second equation.

A plot of $\phi_{R_{LB}}$ versus the lower-bound capacity is shown on Figure 9 for different target reliability indices. The curves begin at values of the lower-bound capacity, specifically r_{LB}/r_{median}, where the second design checking equation in Equation (3) governs. One advantage of this approach with two design checking equations (Equation 3 versus Equation 2) is that $\phi_{R_{LB}}$ is not very sensitive to either the magnitude of the lower-bound capacity or the target reliability index (Fig. 8). In fact, a conservative value of around 0.75 for $\phi_{R_{LB}}$ could be used to cover a wide range of possibilities.



(a) c.o.v.$_{\text{Capacity}} = \delta_R = 0.3$ (b) c.o.v.$_{\text{Capacity}} = \delta_R = 0.5$

Figure 9. Variation of the lower-bound resistance factor to account for a lower-bound capacity (c.o.v.$_{\text{Load}} = \delta_Q = 0.15$).

SUMMARY

This report provides a summary of the ongoing work in the area of seafloor characterization for deepwater foundation systems. Major conclusions thus far as follows:

1. The relative variability in the capacity of suction caissons versus conventional driven piles is larger.
2. The magnitude of variability in the capacity of suction caissons depends substantially on the geologic setting. In normally consolidated marine clays in deepwater in the Gulf of Mexico, the absolute variability is small with coefficients of variation between 0.1 and 0.2.

3. The uncertainty in design models for suction caissons is comparable to but slightly higher than that for driven piles in normally consolidated clays.
4. There is a physical lower-bound to the range of possible capacities, and this lower-bound can have a significant affect on the reliability of the foundation.
5. The lower-bound capacity should and can be incorporated into conventional design methods.

Future work will focus on assessing spatial variability in the lower-bound capacity and in using installation data to estimate the lower-bound capacity.

REFERENCES

Aubeny, C. P., Han, S., and Murff, J. D. (2003). Refined model for inclined load capacity of suction caissons. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering*, OMAE, pages-5.

American Petroleum Institute: *Recommended Practice for Planning Designing, and constructing Fixed Platforms-Load and Resistance Factor Design*, RP 2A-LRDF, Washington D.C., 1993.

Cho, Y., Lee, T. H., Chung, E. S., and Bang, S. (2003). Field tests on pullout loading capacity of suction piles in clay. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering*, OMAE, pages-7.

Clukey, E. C. (2001). Suction caisson design issues. *Proceedings of the OTRC International Conference*, 163-181.

Clukey, E. C. and Phillips, R. (2002). Centrifuge model tests to verify suction caisson capacities for taut and semi-taut legged mooring systems. *Proceedings, International Conference on Deepwater Offshore Technology*.

Clukey, E. C. and Morrison, M. J. (1993). A centrifuge and analytical study to evaluate suction caissons for TLP applications in the Gulf of Mexico. *Geotechnical Special Publication No. 38,* ASCE, 141-156.

Clukey, E. C., Aubeny, C. P., and Murff, J. D. (2003). Comparison of analytical and centrifuge model tests for suction caissons subjected to combined loads. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering*, OMAE, pages-6.

Gilbert, R. B. and Murff, J. D. (2001), "Identifying Uncertainties in the Design of Suction Caisson Foundations," *Proceedings,* International Conference on Geotechnical, Geological and Geophysical Properties of Deepwater Sediments Honoring Wayne A. Dunlap, OTRC, Houston, Texas, 231-242.

Gilbert, R. B. (2003), "Reliability-Based Design as a Decision-Making Tool," Proceedings, International Workshop on Limit State Design in Geotechnical Engineering Practice, Phoon, Honjo and Gilbert (eds.), Cambridge, Massachusetts.

Gilbert, R. B., Najjar, S. S., Choi, Y. J. (2005). Incorporating lower-bound capacities into LRFD codes for pile foundations. *Proceedings, GeoFrontiers Conference,* ASCE, inpress.

House, A. R., and Randolph, M. F. (2001). Installation and pullout capacity of stiffened suction caissons in cohesive sediments. *Proceedings, 11th International Offshore and Polar Engineering Conference.*

Luke, A. M., Rauch, A. F., Olson, R. E., and Mecham, E. C. (2003). Behavior of suction caissons measured in laboratory pullout tests. *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering*, OMAE, pages-9.

Murff, J. D. and Hamilton, J. M. (1993). P-Ultimate for undrained analysis of laterally loaded piles. *Journal of Geotechnical Engineering,* ASCE, Vol. 119, No. 1, 91-107.

Randolph, M. F., and House, A. R. (2002). Analysis of suction caisson capacity in clay. *Proceedings, Offshore Technology Conference*. OTC 14236.

Watson, P. G., Suemasa, N., and Randolph, M. F. (2000). Evaluating Undrained Shear Strength Using the Vane Shear Apparatus. *Proceedings, 10th International Offshore and Polar Engineering Conference,* 485-493.