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It Is All About Decisions

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Abstract: This paper addresses the importance of conducting reliability and risk analyses with the aim to support decision making. It presents geotechnical case histories from offshore applications to demonstrate how reliability and risk analyses can be used to inform project-specific design decisions, design practice and public policy. It offers the following lessons: (1) Taking a top-down perspective on how the analyses will be used in decision making fosters efficiency by focusing on the aspects of the problem that are most relevant; (2) There is a continuous need to keep track of and make use of what happened once a decision was made so that what was learned can be leveraged for future decisions; (3) Having frank, open and thoughtful discussions with stakeholders about consequences is valuable in providing useful information; and (4) Assessing and managing risk effectively requires a system perspective and multi-disciplinary collaboration.

Keywords: Decision analysis; Reliability-based design; Risk assessment; Offshore facilities.

1 Introduction

Dr. Suzanne Lacasse and the Norwegian Geotechnical Institute (NGI) have been instrumental in advancing the use of reliability methods for geotechnical applications. Much of this work has been applied to the offshore oil and gas industry, for example Lacasse and Goulois (1989), Lacasse and Nadim (2007), Lacasse et al. (2007) and Lacasse et al. (2013). Amongst the earliest examples of applying reliability methods to offshore geotechnical problems is work performed by Drs. Kaare Hoeg and Wilson Tang when Dr. Tang was hosted by NGI for a sabbatical (Hoeg and Tang 1978). I was first exposed to geotechnical reliability for offshore structures working with Dr. Tang as an undergraduate student in the mid-1980's. That initial exposure has led me on a career working on reliability and risk for a variety of applications, including offshore problems, having the opportunity to collaborate with Suzanne Lacasse, and even getting hosted by NGI on my own sabbatical 40 years after Dr. Tang. And now here I am with the great honor of delivering the 2022 Suzanne Lacasse Lecture.

The focus of this paper is on the importance of keeping the perspective of decision-making at the forefront when conducting reliability and risk analyses. It will describe geotechnical case histories from offshore applications to demonstrate how reliability and risk analyses can be used to inform decisions, including project-specific design decisions, decisions about design practice, and public-policy decisions. The paper will conclude with lessons learned from risk-based decision making in practice and opportunities to improve its value in the future with big data, machine learning and climate change.

2 Project-Specific Design

Project-specific design decisions can be informed by reliability and risk analyses when the design is outside of the typical practice that has been used to develop design standards, guidelines and codes. Several common situations are (1) unusual loads, such as sustained tension loads on deep foundations; (2) new foundation types, such as hybrids of shallow and deep foundations; and (3) applications in which the consequences of a foundation failure are outside of the norm, such as a structural system with little redundancy in the foundation.

A common decision in design is how to account for not having as much site investigation data as desired and whether or not to obtain more data. Figure 1 shows results from a reliability model that accounts for spatial variability in design undrained shear strength for a development region in deep water (Cheon and Gilbert 2014). The geologic conditions consist of normally to slightly over-consolidated, high-plasticity marine clays. The model of spatial variability was calibrated over a 100,000-km^2 region based on geotechnical data from 16 project sites that each included a variety of soil borings, jumbo piston cores and cone penetration tests. The model predicts both the design undrained shear strength at a point, which is used for estimating the bearing capacity of a deep foundation, and the depth-averaged design undrained shear strength, which is used for estimating the total side shear capacity of a deep foundation. The spatial variability in the design shear strength is relatively small in this rather homogenous geologic setting, with coefficients of variation of 0.16 in the point strength and 0.13 in the depth-averaged strength at a depth of 30 m. The horizontal correlation structure is anisotropic with a larger correlation distance perpendicular to the continental shelf in the direction of sediment transport and deposition from rivers versus parallel to the shelf: at a depth of 30 m, the horizontal correlation distance off the shelf is 6,000 m and along the shelf is 4,000 m for the depth-averaged strength. The horizontal correlation distance is smaller for the point strength than the depth-average strength, and all horizontal correlation distances increase linearly with depth. The vertical correlation distance is 7.5 m and independent of depth.

The objective for these models of spatial variability is to support decision making. Figure 1 illustrates how the model of spatial variability for this deep-water region is used to extrapolate beyond available data for design purposes; it shows curves of the factored pile capacity that would be used in a design check (i.e., compared to the factored load) versus the length of a suction caisson for different amounts of information. For a generic site within the geologic setting of this region but far (i.e., many horizontal correlation distances) from available data, the curve labeled "Factored for Generic Site to Account for Spatial Variability" shows the axial pull-out capacity factored by both the traditional resistance factor of 0.8 and an additional partial resistance factor of about 0.9 (it varies with length) calculated to give the same reliability as a design with site-specific geotechnical data (a reliability index of 4.0 in this case). If the factored design load is 12,000 kN, then the required caisson length would be 28 m (Figure 1). For a site with geotechnical data from a 20-m log jumbo piston core, added uncertainty due to spatial variability plays a role for caisson lengths greater than 20 m; in this case, a 25.8-m long caisson would be required for the design load (Figure 1).

This model can also be used to quantify the value of additional information. At the generic site far away from available geotechnical data within the same geologic setting, the expected design strength profile ("Expected for Generic Site") would lead to needing a 26.4 m long caisson (Figure 1). Therefore, the value of a site-specific geotechnical investigation is expected to be a savings of 28.0 – 26.4 = 1.6 m of caisson length. Likewise, at the site of the jumbo piston core, the expected value of savings associated with a deeper geotechnical investigation is 25.8 – 24.5 = 1.3 m of caisson length (Figure 1). The design team, including the owner/operator, can then decide whether the cost of obtaining additional site investigation data is worth the benefit of these savings in caisson length.

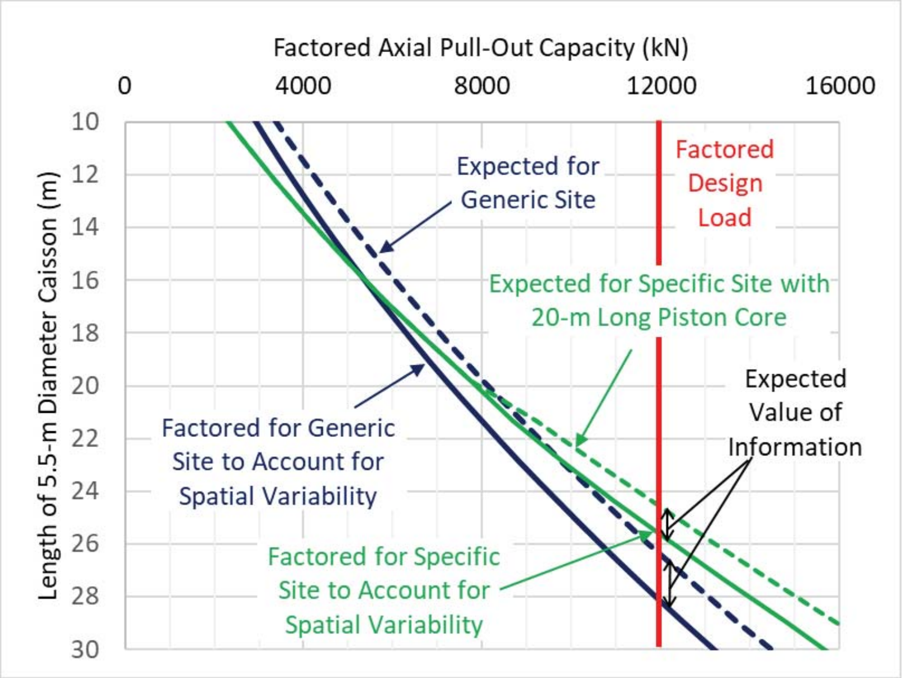

Figure 1. Reliability-based design example for an offshore region in deep water showing factored axial capacities to be used in design given different available quantities of site-specific geotechnical data for a 5.5-m diameter suction caisson. The curves labeled "Factored" have a partial resistance factor incorporated to achieve a reliability index of 4.0 with the additional uncertainty due to spatial variability. The curves labeled "Expected" are what is expected if a site-specific geotechnical investigation is performed to establish the design capacity.

There are several observations to offer after helping with these types of design decisions in a variety of applications. First, it is commonplace that site investigation data is not available at the exact location of offshore foundations and there is a need to extrapolate from the available data in one way or another on most projects.

Second, the “cost” of conservatism in extrapolating beyond existing data is very dependent on the geologic setting. The cost of extrapolation is relatively small in trying to predict axial capacity in homogenous marine clays (e.g., Figure 1) because the spatial variability is small and the effect of spatial averaging is significant for foundations that derive most of their capacity from side shear. However, the cost of extrapolation is relatively large in trying to predict pile drivability, which depends largely on end bearing, in alluvial/fluvial geologic settings with mixtures of coarse- and fine-grained soils and buried channel features.

3 Design Practice

Design codes, standards and guidance documents can be informed by reliability and risk analyses to (1) calibrate design factors (i.e., load factors, resistance factors, material factors and factors of safety) and (2) to update design practice based on experience gained by analyzing the actual performance of designs.

Starting in 1992 with Hurricane Andrew, the offshore energy industry has used reliability analyses to assess the performance of platforms in hurricanes (e.g., Aggarwal et al. 1996). This work explores the appropriateness of and the implicit bias in the design guidelines by comparing predicted with actual performance. It uses a Bayesian approach in a multi-disciplinary collaboration to update model bias factors on wave loads, structural system and capacities and foundation system capacities. It accounts for spatial and temporal variability and model uncertainty. The most recent iteration of this work includes analyses of 18 platforms and five hurricanes in the Gulf of Mexico that all produced wave loads exceeding design loads (Chen et al.2020). The product of this work is probability distributions for the mean bias factors that have been updated based on the observations (Figure 2).

The results indicate that the existing API/ISO design recipe is close to being unbiased for assessing the safety margin (i.e., capacity divided by load) for the jacket superstructure performance, slightly overpredicting both superstructure capacity and wave load by about the same amount (Figure 2). On the geotechnical side of the problem, the design recipe tends to underpredict pile system lateral capacity for piles in clay by nearly 20%, slightly underpredict axial pile capacity for piles in clay (pile system overturning), and significantly underpredict axial pile capacity for piles in sand by nearly 50% (Figure 2). The updated bias is most certain for axial pile capacity in clay with a coefficient of variation or c.o.v. of 0.19 and least certain for axial pile in sand with a c.o.v. of 0.37 (Figure 2). The results also show that a jacket system with four or more legs/piles is less likely to fail in the foundation system than in the superstructure (Chen et al. 2020).

This work has contributed to updating design practice in the following ways:

- It has motivated and guided efforts to improve design practice by updating the methods used to predict lateral pile capacity in clay (Jeanjean et al. 2017) and axial pile capacity in sand (Lehane et al. 2020). Both of these updates are now addressed in draft API/ISO documents.
- It has shown that system effects implicit in the design recipe, which involves component checks, lead to foundations being less likely to fail than superstructures in a hurricane for jackets with four or more legs. This result has dispelled a common perception that the foundations are designed more conservatively than the superstructures.
- It has motivated the introduction of a system check in addition to component checks in the design of new offshore structures.
- It has been used in calibrating the newest load and resistance factor design guideline, API RP2A-LRFD 2nd edition (2019).
- It provides useful information for assessing the reliability of existing structures, which helps inform decisions about extending design lives and re-purposing structures.
- It demonstrates the importance of considering the performance of the system holistically by assessing the loads (metocean engineering), superstructure (structural engineering) and foundation (geotechnical engineering) together.

This work further supports decision making by turning what had been referred to as “notional” probabilities of failure, which were calculated for offshore structures in the 1980’s during calibration of the first edition of API RP2A-LRFD (e.g., Moses and Larrabee 1988), into probabilities that reflect our best estimates for the actual frequencies of failures.

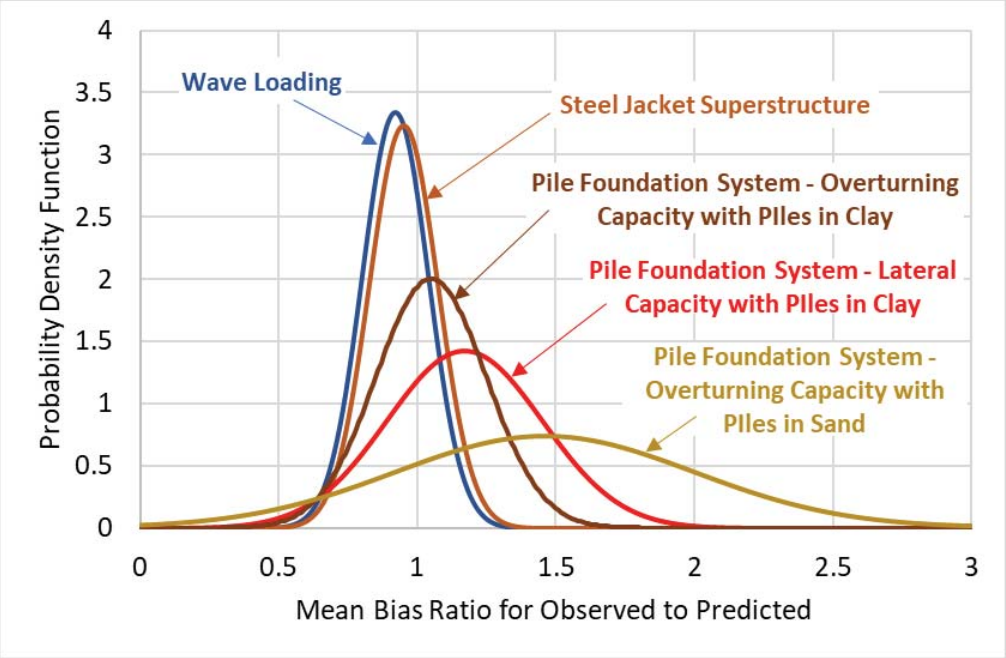

Figure 2. Updated probability distributions for mean bias ratios of offshore platform performance based on observed performance in hurricanes. Mean bias ratio greater than one indicate that the mean performance based on observations is greater than that predicted based on design practice. Results are taken from Chen et al. (2020).

4 Public Policy

The most significant impact that reliability and risk analyses can have is by informing public policy. A general principle in crafting public policy is that a new policy should not impose additional risk on the public. Therefore, a quantitative risk analysis comparing the risks associated with new versus existing policies can provide valuable input to policy makers.

After the Exxon Valdez oil spill in 1989, the U.S. government decided to prohibit the use of shuttle tankers to transport oil from offshore production facilities to the coast. Since all of the produced oil had been transported using pipelines in U.S. waters up until this time, this policy did not alter existing practice. However, as industry moved into deeper water, the option of using shuttle tankers rather than pipelines became more appealing. Therefore, a risk analysis was conducted to compare the risk of oil spills for pipelines, the conventional technology for oil transport from offshore production facilities in U.S. waters, with the risk of oil spills for shuttle tankers (Gilbert et al. 2001).

The comparative risk analysis was conducted with the following goals: 1) provide the government with information that can be used for a consistent and objective comparison of the risks associated with pipelines versus shuttle tankers and 2) incorporate available data, experience and expertise to the greatest extent possible in assessing the risks. The approach used to achieve these goals involved assembling teams of experts with a wide range of expertise, from operators to engineers to contractors, and conducting a series of workshops to identify available information, to evaluate its relevance to predicting future performance, and to review results. One set of results from this work is shown in Figure 3. Confidence intervals were assessed based on the quantity (or lack thereof) of relevant data and information available. In general, the risk of oil spills from pipelines is comprised of more frequent but smaller volumes, while the risk of oil spills from shuttle tankers is comprised of less frequent but larger volumes (Figure 3). The expected volume of oil spilled in a facility life that uses pipelines versus shuttle tankers is about the same with the 90-percent confidence intervals nearly overlapping (Figure 3). This work was used by the government together with other studies, including an Environmental Impact Statement, to craft a new policy published in the U.S. Federal Register on December 31, 2001 that allows for the use of shuttle tankers in transporting produced oil from offshore facilities.

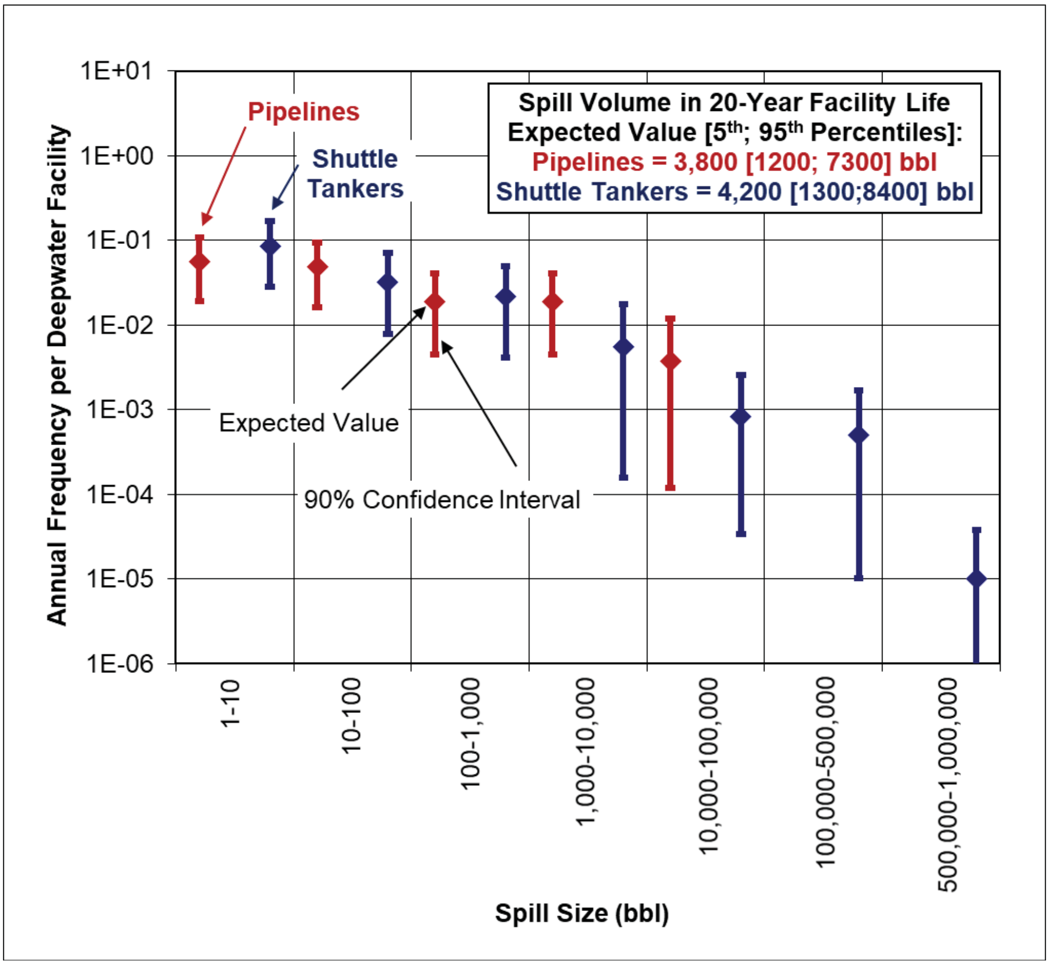

Figure 3. Comparison of oil spill risks for two technologies to transport oil from an offshore production facility in the Gulf of Mexico (results taken from Gilbert et al. 2001).

5 Summary

The objective of this paper is to underscore the importance of considering how reliability and risk analyses can and will be used in making decisions. The questions to ask at the outset include what are the decision alternatives, what are the consequences of interest, what information is available, and what is uncertain about what will happen when a decision is made. Based on my experiences in trying to inform decision making with reliability and risk analyses on real-world problems, I offer the following lessons:

- Taking a top-down perspective on how the analyses will be used in decision making fosters efficiency by focusing on the aspects of the problem that are most relevant. In the application of modeling spatial variability, we focused on modeling spatial variability in the design strength rather than spatial variability in the measured data. This approach leverages the expertise that the practicing engineers put into the problem in processing the different types and quantities of data (i.e., geologic setting, geophysical measurements, index properties, laboratory tests and in situ measurements) to establish a profile of design strength versus depth at each location. This approach simplifies the problem by not having to explicitly consider how to combine and adjust multiple types of disparate information. This approach provides the decision makers directly with what they want – what would the design strength be if a site-specific geotechnical investigation was conducted.
- There is a continuous need to keep track of and make use of what happened once a decision was made so that what was learned can be leveraged for future decisions. The work to update design model biases based on the performance of structures during hurricanes is never ending because we keep getting new information and raising new questions. We are currently re-analyzing and refining that information to investigate a hypothesis from observations in the North Sea that our models of waves may underpredict the height and steepness of, and therefore the force imposed by, large waves. This topic has taken on even greater relevance now with the proliferation of offshore wind turbines across the world.

- Having frank, open and thoughtful discussions with stakeholders about consequences is valuable in providing useful information for decision making. The work to assess risks of oil spills from pipelines and shuttle tankers raised an interesting and common question: is there a difference between an alternative that results in frequent but smaller volume spills versus one that results in rare but larger volume spills if both give the same expected volume of oil spilled? Since there was no single perspective amongst the stakeholders, the results of the risk assessment were presented in a variety of ways so that all perspectives could be considered.
- Assessing and managing risk effectively requires a system perspective and multi-disciplinary collaboration. All three applications described in this paper highlight this need. While adding several meters of length to a suction caisson to account for uncertainty due to spatial variability may not seem significant, it could be very significant if it means that a larger handling vessel will be needed for installation. While structural engineers were convinced that geotechnical engineers were being “overly” conservative in designing foundations, a collaborative analysis of the entire structural system including the pile foundations showed that the component reliabilities were similar and differences in observed performance were caused by different levels of redundancy in the structural system versus the foundation system. The causes of spills from both pipelines and shuttle tankers are contributed as much or more by human factors in how they are operated as they are by geotechnical or structural events.

The opportunities to utilize risk-based decision making in the future are increasing on many fronts. We are collecting and able to make use of greater amounts of data, we are improving models to use data in making predictions, and we are facing significant decisions with increased uncertainty due to changing climatic conditions. In order to meet these opportunities, we need to follow Suzanne Lacasse’s lead in constantly striving to apply the theory for reliability and risk to real-world problems.

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