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Case History Applications of Reliability Methods in Geotechnical Engineering: Lessons Learned and Future Opportunities

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ABSTRACT

The following lessons have been learned from the application of reliability methods in the practice of geotechnical engineering:

1. Establishing Goals Is Important;
2. Mitigating Consequences Can Be Effective;
3. Performance Depends on Systems;
4. Physical Factors Are Important in Statistical Models;
5. Too Much and Too Little Conservatism Are Both Problems;
6. Value of Information Depends on Decision Making; and
7. Effective Communication Is Essential.

While the potential for application of reliability methods in the future is unlimited, there are major needs related to each of these lessons that will have to be addressed in order to realize this potential.

INTRODUCTION

Application of reliability methods in the practice of geotechnical engineering has become more widespread in recent years. The objective of this paper is to present lessons that have been learned from practical applications. The lessons are illustrated with actual case histories coming from offshore and coastal engineering projects. The paper concludes with a discussion of future directions and needs in the application of reliability methods.

LESSON 1 - ESTABLISHING GOALS IS IMPORTANT

An important first step in performing a reliability analysis is to establish the goals of the analysis. The ultimate goal is to provide guidance for making decisions. The decisions can range from very narrow in scope, such as how long to make a driven pipe pile, to very broad in scope, such as how to manage the human risk associated with hurricanes in New Orleans. Within the context of a decision, the goals are expressed in terms of decision criteria. Two very common criteria are maximizing the expected monetary value for a decision where costs and benefits can readily be expressed in monetary terms and maximizing the expected utility value for a decision where additional factors, such as human safety or an aversion to risk, also affect the decision (e.g., Benjamin and Cornell 1970, Kenney and Raiffa 1976, and Ang and Tang 1984).

A tool useful in establishing goals is a risk evaluation chart (Fig. 1). These charts plot boundaries or thresholds for the tolerable frequency of failures with associated consequences. They are commonly referred to as F-N charts, where F stands for the frequency of failure and N stands for the number of consequences. The intent of these charts is to establish a benchmark level of risk that is considered tolerable by the stakeholders in exchange for benefits, such as economical energy. A risk is considered tolerable if the combination of frequency and consequence falls below the threshold. Excellent discussions concerning the basis for, applications of, and limitations with these types of charts are provided in Fischhoff et al. (1981), Whitman (1984), Whipple (1985), ANCOLD (1998) and Bowles (2001).

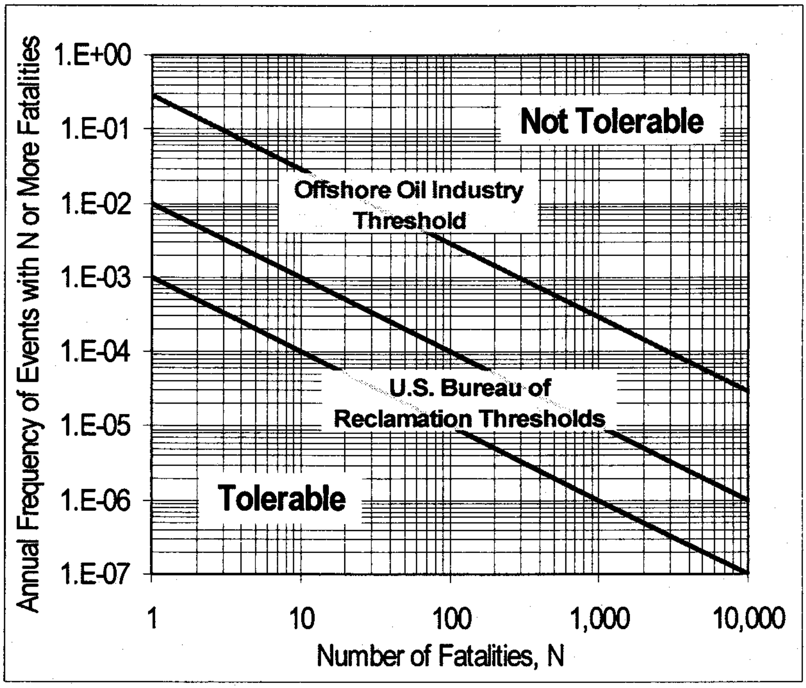


Figure 1 Published Risk Evaluation Guidelines for Human Fatalities (U.S. Bureau of Reclamation Thresholds taken from USBR 2003; Offshore Oil Industry Threshold taken from Bea 1991 and Stahl et al. 1998).

The F-N curve on Figure 1 shows three thresholds for comparison. The bottom two thresholds, which apply to public dam projects in the United States, were developed by the Bureau of Reclamation (USBR 2003). The lower USBR threshold provides a boundary above which the risk is not considered tolerable, while the upper USBR threshold provides a boundary above which the risk is not acceptable and urgent action is required (Fig. 2). The top threshold on Figure 1 applies to the offshore oil industry (Bea 1991 and Stahl et al. 1998). The differences in the thresholds for public dams and offshore facilities reflect a difference in the perspectives of the stakeholders. A major dam failure affects the general public and would generally not be tolerated well by society. In contrast, the failure of an offshore platform affects only the workers on the platform, who voluntarily and knowingly choose to work there.

A case history application of an F-N curve is shown on Figure 2, where the system of levees and floodwalls that protect New Orleans from hurricanes (known as the Hurricane Protection System) is evaluated in comparison to a major dam. The box labeled "Historical performance of Hurricane Protection System" is plotted from the following information: the number of fatalities due to the failure during Hurricane Katrina is shown as a range with a lower-bound at the number of bodies currently identified and an upper bound including the total number of bodies still not identified or missing (IPET 2006); the annual frequency of failure is shown as 95th percent confidence bounds on the estimated frequency based on one failure during Hurricane Katrina in 2005 in approximately 40 years of service.

The risk associated with the Hurricane Protection System is well above what would be considered to be acceptable for a major dam in the United States. In hindsight, a formal evaluation of the risk could have alerted the residents of New Orleans to the high risk to which they were exposed. With this knowledge, the residents may have evacuated more effectively; only 80 percent of the residents evacuated in advance of the hurricane (IPET 2006). In addition, the residents may have put pressure on politicians to devote more resources both to improving the system of levees and floodwalls and to developing an effective plan of evacuation. A formal evaluation of risk may also have alerted the government to a situation where "expedited action" to reduce the risk was warranted.

In moving forward with the Hurricane Protection System in New Orleans and with other similar protection systems along coasts throughout the world, evaluations like Figure 2 provide a basis to establish clear goals so that the risks from natural hazards are better managed.

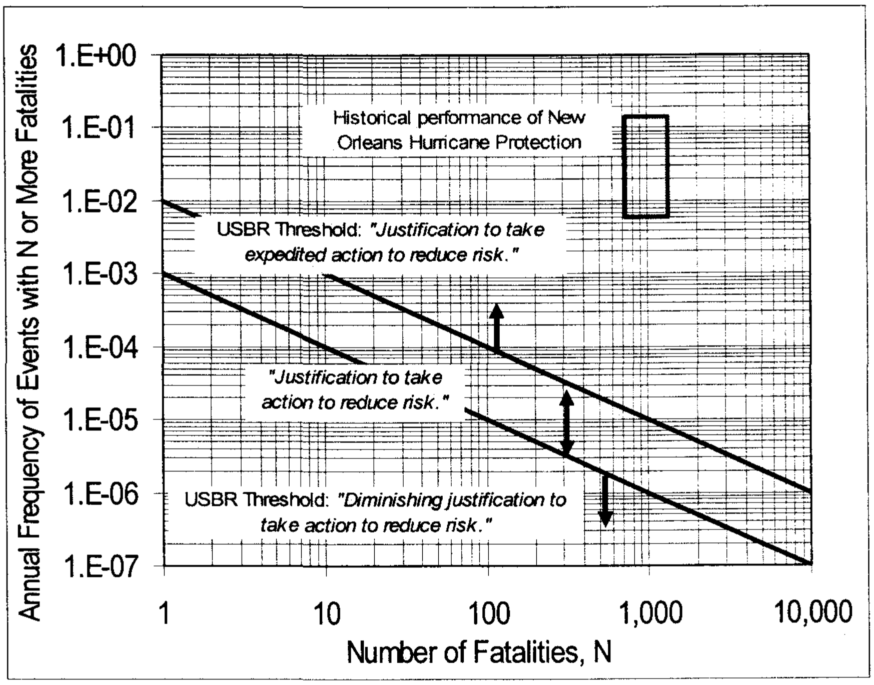


Figure 2 Evaluation of Hurricane Protection System in New Orleans

LESSON 2 - MITIGATING CONSEQUENCES CAN BE EFFECTIVE

With goals in mind, a reliability analysis provides an effective tool to achieve those goals. For example, if the New Orleans Hurricane Protection System is treated as a major dam, then the box in Figure 2 labeled “Historical performance of New Orleans Hurricane Protection System” needs to move down by increasing the reliability of the system. However, in many cases, mitigating consequences, that is moving the box to the left in Figure 2, is a more effective means by which to achieve goals.

In the case of New Orleans, mitigating consequences could be achieved with 100 percent evacuation in advance of a hurricane. This evacuation will come at a cost. It will require a concerted investment in planning, preparation, transportation and communication. It will also require patience by the public because for every evacuation that is truly needed, there will be many evacuations where the storm track will turn away from New Orleans after the city has been evacuated.

The offshore oil industry in the Gulf of Mexico provides a great example of managing risk by mitigating consequences. In 2005, offshore facilities were subjected to two of the largest hurricanes recorded, Hurricanes Katrina and Rita. The impacts were significant: more than 150 platforms were severely damaged or destroyed and direct costs are estimated at tens of billions of U.S. dollars (MMS 2006). In comparison, the direct costs due to damage onshore in New Orleans from Hurricane Katrina were very similar. However, in contrast to New Orleans, the evacuation of tens of thousands of offshore workers for both storms was 100 percent effective, and there were no lives lost or even injuries that resulted offshore.

LESSON 3 - PERFORMANCE DEPENDS ON SYSTEMS

The performance of a geotechnical system, including its reliability and the risk associated with a failure, depends on how individual components interact as a whole. Therefore, while design codes and standards tend to focus on the performance of components, it is important that the entire system be considered in design and decision making.

One example of how system effects govern performance is shown on Figure 3; this floating production system is moored in 1,000 m of water with a system of 14 mooring lines and anchors. The mooring lines consist of steel wire rope with segments of steel chain at the top where they connect to the hull and at the seafloor where they connect to the anchors. The anchors are 3-m diameter by 18-m long steel caissons that are inserted by suction (suction caissons).

The reliability of individual components along the most-heavily loaded mooring line is shown on Figure 4. The probability of failure for the anchor is more than two orders of magnitude smaller than those for the individual components in the mooring line itself; hence, failure of a mooring line during a storm is expected to be a break in the line itself versus a pull-out of the anchor. This information about system performance is significant for several reasons. First, there is a potential to make the anchor designs more efficient (e.g., using a lower factor of safety) without jeopardizing the performance of the mooring system. Second, the consequence of a failure may depend on how the failure occurs. Failure in the lines means that the hull could move off station by hundreds of kilometers during a storm and collide with other offshore facilities or coastal facilities. Failure by pull-out of the anchors means that the hull may not move off station as far due to the restoring force provided by the weight and dragging resistance of the anchors. However, the dragging anchors could damage seafloor facilities such as well heads and pipelines.

Another system effect for this offshore mooring system is shown on Figure 5. The probability that the system will fail given failure of a single line is shown for systems in three different water depths. The smaller this probability the more redundancy there is in the mooring system. While there are 14 lines, the redundancy is limited because failure of a single line is most likely to occur during a severe storm, meaning that failure of subsequent lines is more likely. However, the redundancy is still significant, particularly for the mooring systems in 2,000 and 3,000 m of water (Fig. 5). The effect of water depth on the redundancy is related to the pre-tension in the mooring lines. A larger pre-tension force is used for the deeper water depths, meaning that load redistribution in the event of a line failure is more effective. The lack of consistency in mooring system performance displayed on Figures 4 and 5 reflects that system effects are not considered fully in the current state of design practice.

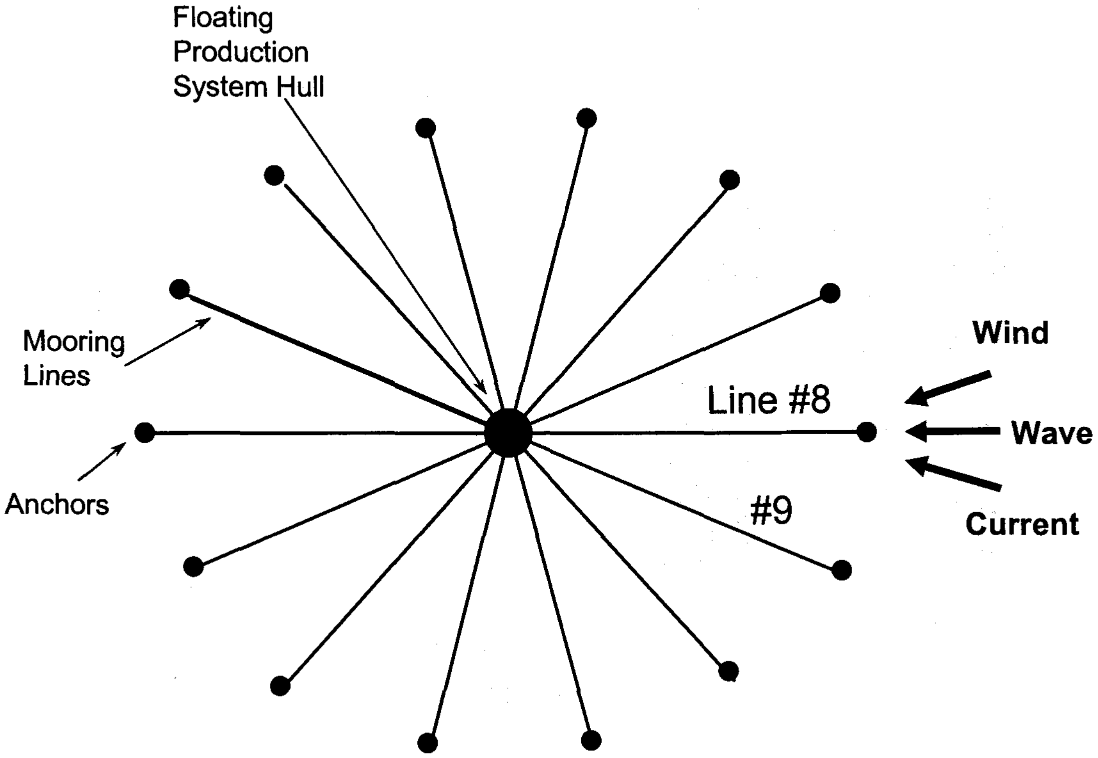


Figure 3 Plan View of Mooring System Spread for a Floating Offshore Production Facility (Choi et al. 2006).

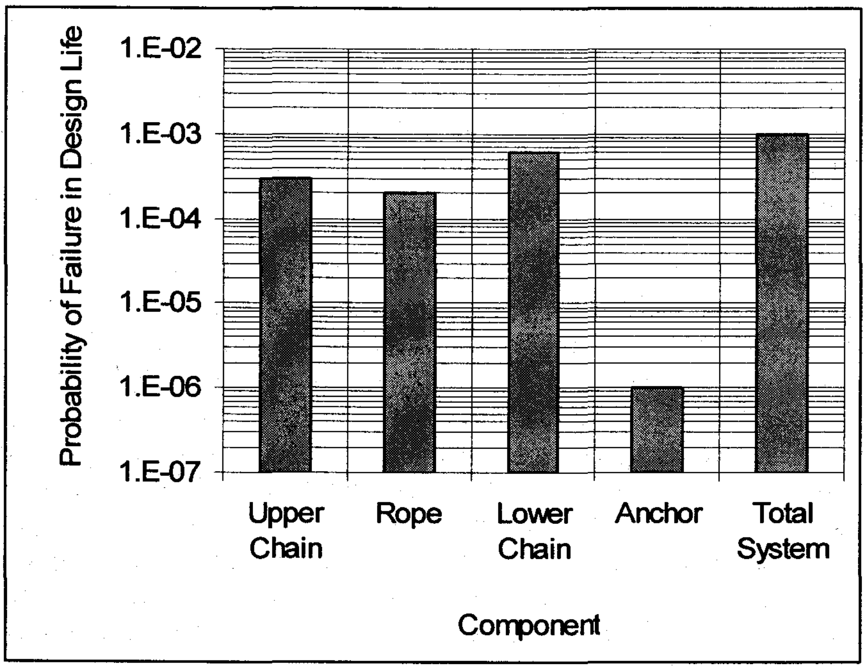


Figure 4 Reliability of Individual Components in the Most-Heavily Loaded Mooring Line (Line #8 in Fig. 3) (adapted from Choi et al. 2006).

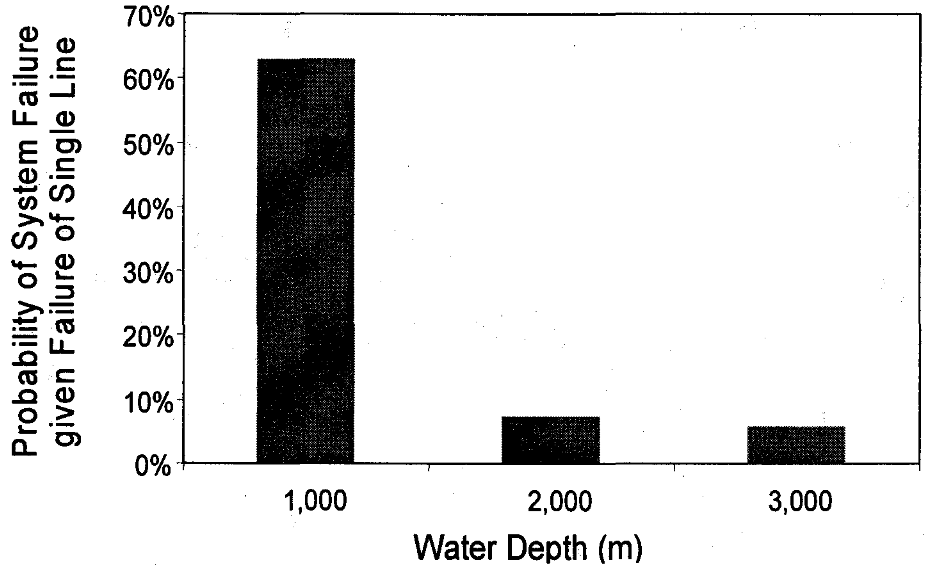


Figure 5 Mooring System Redundancy (Choi et al. 2006).

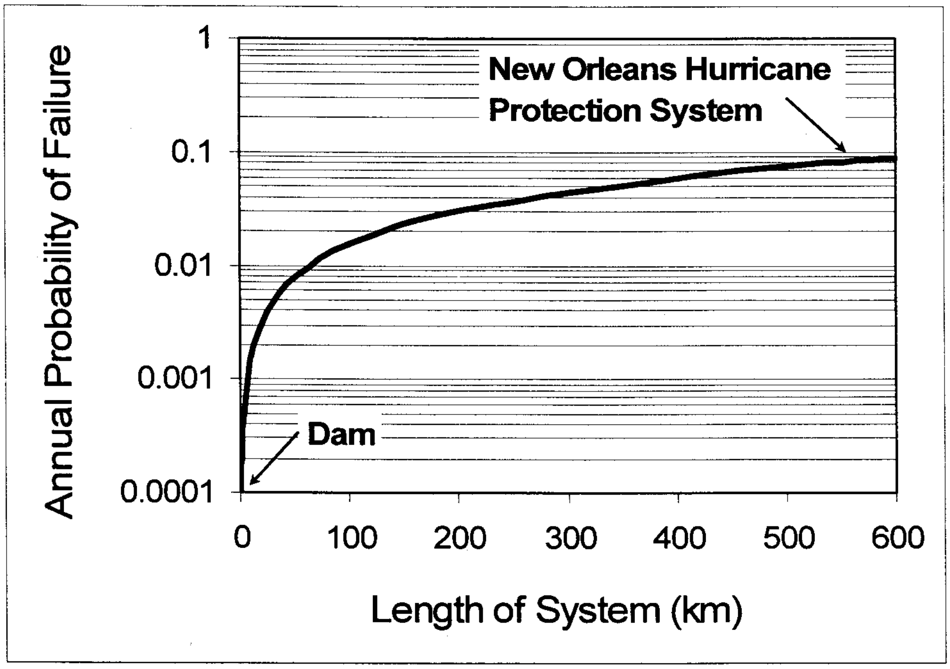


Figure 6 Example of System Reliability Assuming that Hurricane Protection System Consists of a Series of Independent Dams that Are Each 0.6 km in Length.

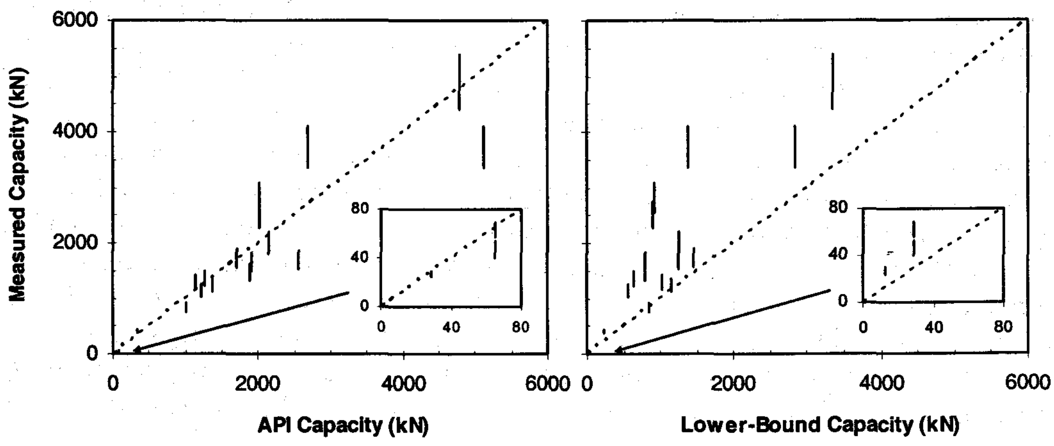
A second example of system effects is shown on Figure 6 for a hurricane protection system, like that in New Orleans. The levees and floodwalls surrounding the city form a series of components that all must perform successfully in order for the system to perform successfully; failure of any stretch of levees or floodwalls will lead to a failure of the system. One way to manage the risk associated with this system would be treat it as a dam and lower the probability of failure to something on the order of 1 in 10,000 per year (Fig. 2). However, in contrast to a dam that is generally less than 1 km in length and is designed and constructed at one time, the hurricane protection system is nearly 600 kilometers long, covers a wide range of geologic and hydrologic conditions, and is designed and constructed by numerous parties over many years. Therefore, even if a high level of reliability is achieved in each dam-like segment of the hurricane protection system, the probability of failure for the system will be substantially greater than that for a dam (Fig. 6). Consideration of system effects here underscores that mitigation of consequences (that is, evacuation of people in advance of a hurricane) may be the most effective means of risk management versus increasing the reliability of the system itself.

LESSON 4 - PHYSICAL FACTORS ARE IMPORTANT IN STATISTICAL MODELS

Physical factors are important in developing realistic statistical models, even when these factors are not mathematically convenient to model. Important physical factors can include upper or lower bounds on variables; correlations and even non-linear relationships between variables, particularly between extreme values; probability distributions that do not follow a convenient mathematical form such as a normal or lognormal distribution; and uncertainty in the statistical models themselves (i.e., epistemic uncertainty).

An example of a physical factor that is important in statistical modeling is shown on Figure 7 for the axial capacity of driven piles. The left-hand graph shows a commonly used relationship between the measured capacity from pile load tests and the predicted capacity using the American Petroleum Institute or API method. The information on Figure 7a has been used in practice to calibrate a lognormal distribution to describe uncertainty in the actual capacity for the purposes of design (e.g., Tang and Gilbert 1993; Gilbert et al. 2005).

One feature of a lognormal distribution that is not realistic in this application is that it has a lower-bound of zero. There is a physical lower-bound on axial pile capacity in normally consolidated clays related to the remolded undrained shear strength of the soil. Figure 7b shows a lower-bound capacity that is calculated using the remolded instead of the undisturbed undrained shear strength in the API method. The measured capacity is greater than or equal to this calculated lower-bound capacity in every single load test. Gilbert et al. (2005) and Najjar (2005) show that a mixed, truncated lognormal distribution (a truncated lognormal distribution with a probability mass at the lower bound equal to the truncated probability) models the physical data well in Figures 7a and 7b. The disadvantage to this mixed, truncated distribution model is that it is not mathematically convenient; it requires numerical integration to conduct a reliability analysis.



(a) Calculated Predicted Capacity (b) Calculated Lower-Bound Capacity

Figure 7 Measured versus Calculated Capacities for Axially Loaded, Driven Steel Pipe Piles in Normally Consolidated to Slightly Overconsolidated Clays (taken from Gilbert et al. 2005; each measured capacity is shown as a range to account for uncertainty in interpreting load test results).

Figure 8 shows the relationship between reliability and the lower-bound capacity for the pile foundation of an offshore facility in deepwater (greater than 1,000 m). A conventional reliability analysis was performed using a lognormal distribution with no lower bound (i.e., a lower-bound capacity at 0 percent of the median capacity on Fig. 8), and the probability of failure was above the target value. The consequence of this analysis was that longer piles were needed, which would cause significant cost and schedule overruns on the project.

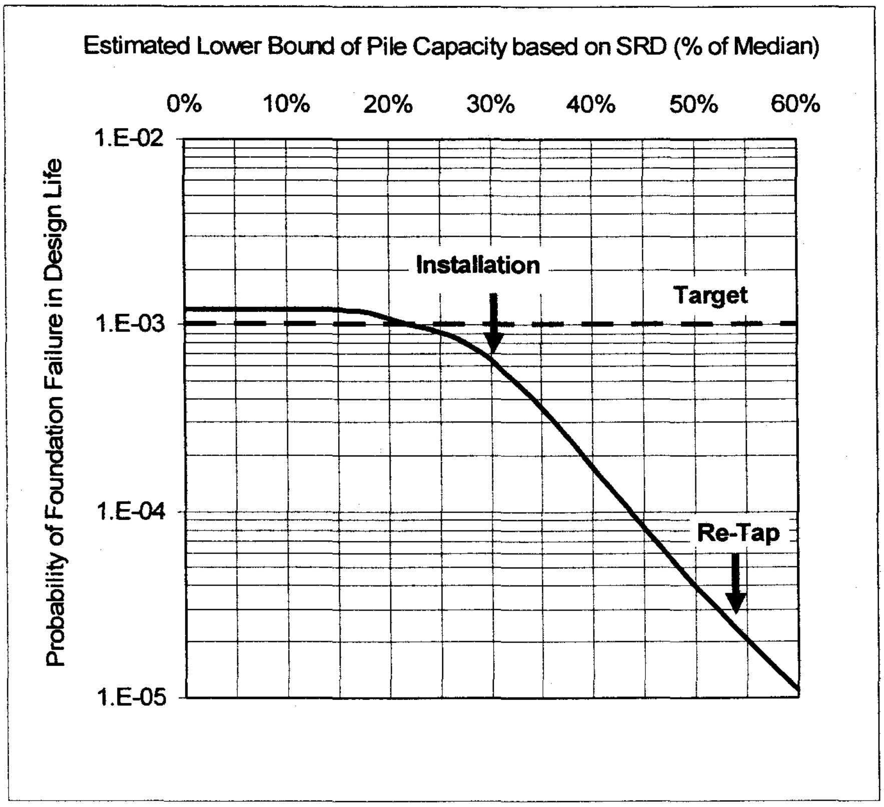


Figure 8 Effect of Lower-Bound Capacity on Reliability for an Axially Loaded Pile (taken from Gilbert et al. 2006a; note that SRD stands for Soil Resistance to Driving). Incorporating a lower-bound into the pile capacity can be very important in design and decision making.

Before ordering longer piles, the effect of a lower-bound on the capacity was considered. Based on the boring data, the lower-bound on the capacity was estimated to be at least 30 percent of the median capacity. With this lower-bound, the probability of failure for the foundation was acceptable (Fig. 8). In order for the owner to feel comfortable with this approach, they decided to instrument and monitor the pile during driving. This level of pile monitoring is not typically used offshore because the measured capacities during pile driving in normally consolidated clays are only 20 to 30 percent of the capacity after set-up and therefore generally of little use. However, in this case, the pile capacity measured during pile driving would provide a physical confirmation for the lower-bound capacity. The result is labeled "Installation" on Figure 8. For further confirmation, a re-tap analysis was performed several days after pile driving, and the resulting reliability for the pile was now well within the acceptable range (Fig. 8).

LESSON 5- TOO MUCH AND TOO LITTLE CONSERVATISM ARE BOTH PROBLEMS

Reliability analyses are useful both to make designs more efficient, that is to remove unnecessary over-conservatism from a design, and to make designs that manage the risk of failure adequately, that is to remove under-conservatism from a design.

Examples of problems with both over-conservative and under-conservative designs are shown on Figure 9. Here the form of the risk evaluation chart from Figure 1 has been adapted in two ways. First, the consequences of a failure on the x-axis are expressed in monetary value instead of human life. In these examples, a failure of the foundation would lead to economic damage but not fatalities. Second, the likelihood of failure is expressed as a probability of failure in the design life on the y-axis. Risk evaluation charts like that shown in Figure 1 were developed for hazards occurring randomly with time, such as earthquakes, hurricanes or explosions. However, the events that drive failure do not always occur randomly with time; the capacity of the foundation does not vary randomly with time and the maximum applied load may be a regularly scheduled maintenance activity and not a natural hazard. By expressing the likelihood of failure as a probability of failure in the lifetime of the facility, failure events that may or may not occur randomly with time can be considered on a consistent basis.

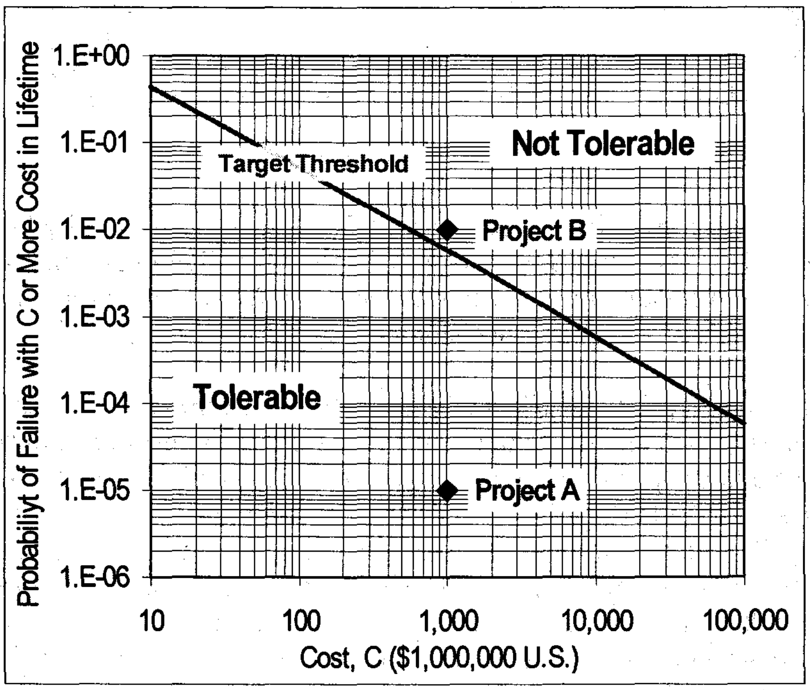


Figure 9 Risk Evaluation Chart for Two Projects.

The design labeled "Project A" on Figure 9 is for the anchors of a mooring system for a floating production system in deepwater. The reliability analysis indicated that the probability of failure was orders of magnitude smaller than what could be tolerated by the owner. The value in identifying this over-conservatism early in the design was that it could be used to improve the design. It is important to consider that removing over-conservatism is not necessarily just a matter of cost savings. In this case, an over-conservative design meant larger and longer suction caissons, which would be more difficult to install. Several cases have occurred recently where a failure to install a foundation (e.g., buckling the caisson) has meant that a facility was initially moored with fewer lines for months and consequently subjected to a much higher risk than was intended.

The design labeled "Project B" on Figure 9 is also for an anchor of an offshore facility. This case was not conventional in that the maximum load was a sustained tension load and not a storm load and in that the capacity was primarily from the weight of the foundation and not the shear strength of the soil. This unconventional case meant that conventional factors of safety in the design standard did not necessarily apply. The reliability was calculated using a design developed from the design standard, and the probability of failure was unacceptably high (Fig. 9). The design standard was then modified for this type of situation based on the reliability analysis.

LESSON 6 - VALUE OF INFORMATION DEPENDS ON DECISION MAKING

The value of information depends on how the information affects decisions that are made using the information. If a design will be same whether or not the information is obtained, then there is essentially no value to obtaining the information.

An example of an analysis to quantify the value of information in design is shown on Figure 10. The value of drilling site-specific borings was quantified for the design of new structures in a mature offshore field. Since considerable geologic and geotechnical information was already available, a site-specific boring for a new structure may not necessarily be worth the cost and time required to drill the boring. The trade-off for not drilling a site-specific boring was that an increased level of conservatism would be needed in design to account for the additional uncertainty. The decision tree in Figure 10 shows the decision alternatives and outcomes that were considered. The geotechnical design properties derived from the boring data are not known before drilling the boring. There is a range of possible design properties that could be obtained from the boring, and, therefore, a range of possible pile designs that would be needed for a given set of geotechnical properties.

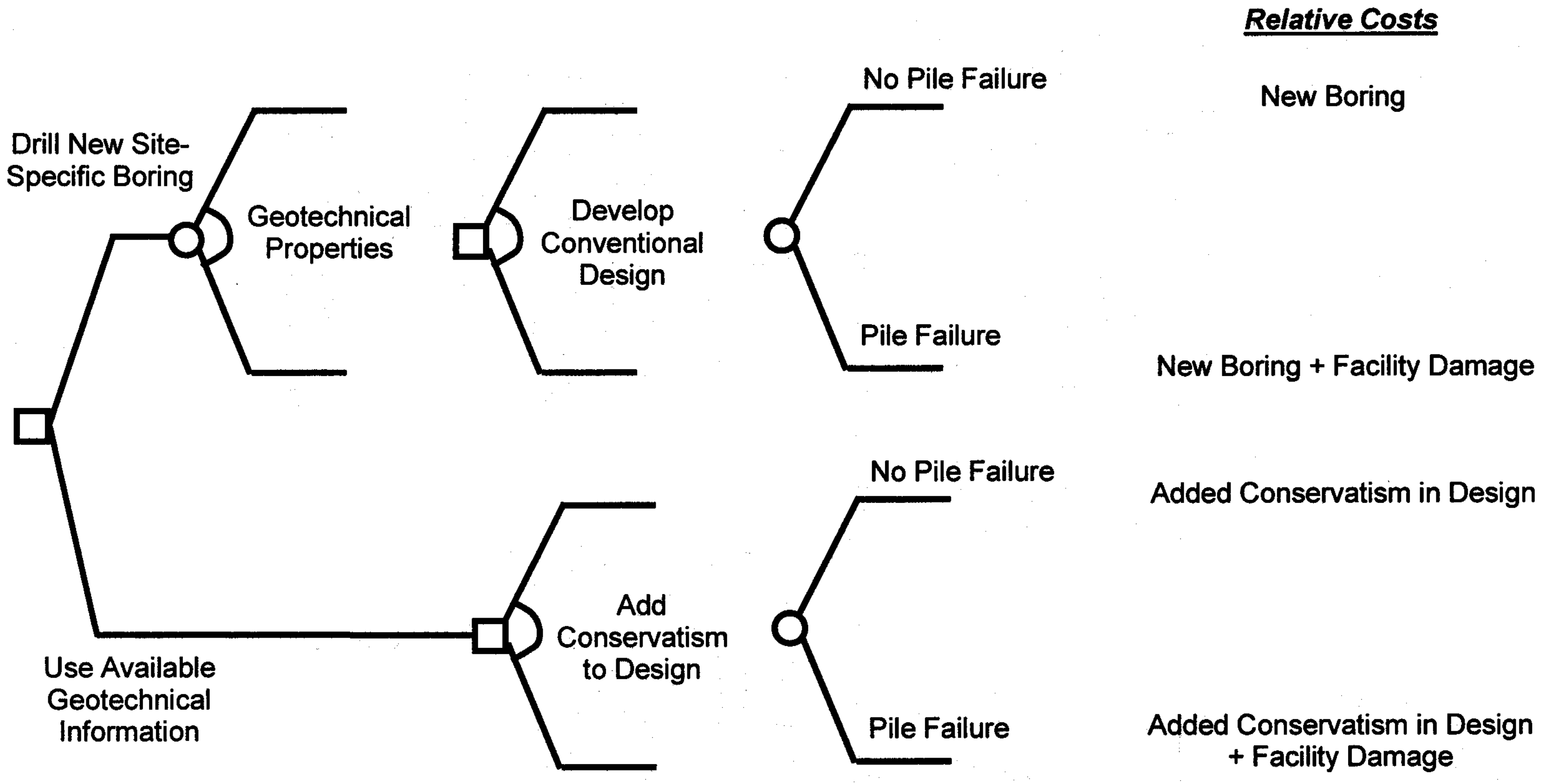


Figure 10 Example Decision Tree for Site Investigation in Mature Offshore Field (taken from Gilbert et al. 2006a).

One major input to the decision tree on Figure 10 is the magnitude of additional conservatism required from not having a site-specific boring. This conservatism is shown on Figure 11 for a variety of geologic settings. The amount of uncertainty in pile capacity arising from not having a site-specific boring is expressed as a coefficient of variation. The magnitude of conservatism required is expressed as a partial factor of safety (FS) that would be multiplied by the conventional factor of safety. As the uncertainty increases due to not having a site-specific boring, the required partial factor of safety to account for this uncertainty also increases (Fig. 11).

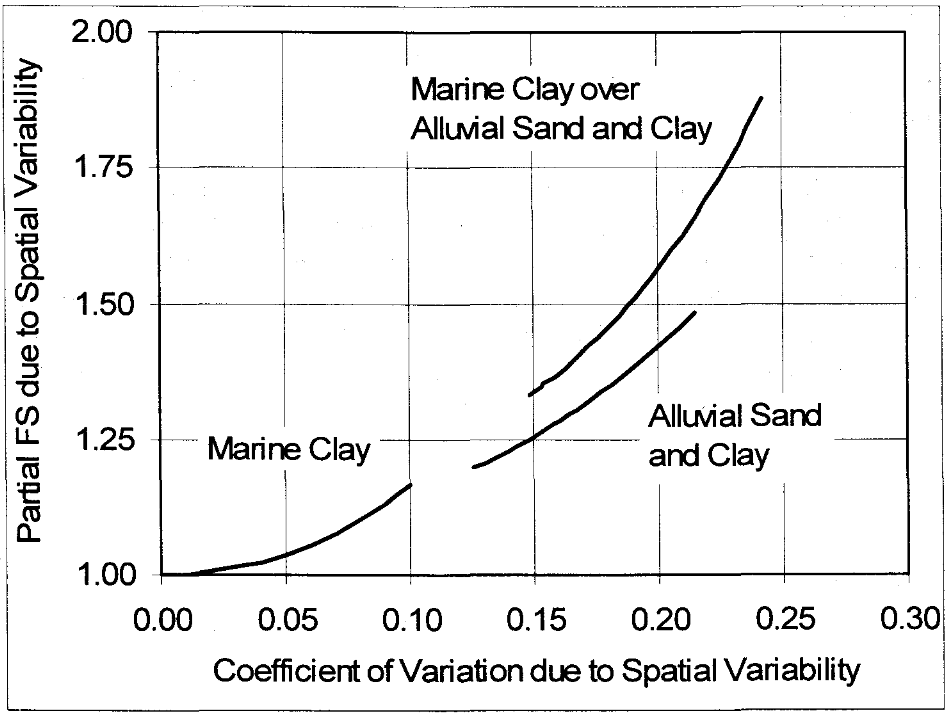


Figure 11 Increased Conservatism Required versus Uncertainty from Not Drilling a Site-Specific Soil Boring (adapted from Gilbert et al. 1999b; coefficient of variation is in axial pile capacity).

The three curves shown on Figure 11 correspond to three different offshore fields, each with unique geologic characteristics (Gambino and Gilbert 1998; Gilbert et al. 1999a and 1999b). In each field, all of the available geotechnical data were used to develop the relationships on Figure 11. The field with the geology labeled "Marine Clay" had the most homogenous geotechnical properties; in this field, a ten percent increase in the factor of safety would be adequate to compensate for not having a site-specific soil boring (Fig. 11). In the other two fields, the geotechnical properties were more variable and the required increases to the factor of safety to account for not having a site-specific soil boring were much greater ("Marine Clay over Alluvial Sand and Clay" and "Alluvial Sand and Clay" on Fig. 11). Therefore, the value of information from a site-specific soil boring depends on the geologic setting. Furthermore, the costs of drilling a boring and the costs of lengthening piles to account for not having a boring, which both vary from field to field and time to time, need to be considered on a project-specific bases in order to decide when a site-specific boring is warranted (Fig. 10).

LESSON 7 – EFFECTIVE COMMUNICATION IS ESSENTIAL

Communication for a reliability analysis is important both to elicit input information and to communicate the results to decision makers. The conventional means of communicating uncertainty through statistical parameters (e.g., a standard deviation) or narrative descriptions are not always effective. Once information is presented, such as the cross section in Figure 12 showing a conceptual geologic model, it tends to be interpreted as reality and certainty no matter how many qualifications are provided to account for uncertainty in the information.

One idea for improving communication is to use a graphical technique called multiples (Tufte 1990). Multiples are small-scale images positioned within the eye span on a single page or screen showing the range of possible interpretations of the information. The uncertainty multiples on Figure 13, which correspond to an area where two borings were drilled in a geologic environment depicted by Figure 12, show that there is uncertainty in the presence and thickness of a buried alluvial channel at the location of a proposed offshore platform. The possibility of encountering a buried channel is an important consideration for the platform designer and installer because it could slow or prevent pile driving.

Figure 13 shows a wealth of information about the uncertainty in encountering a buried channel at the platform site. Each small-scale image on Figure 13 represents an equally likely scenario in the range of possibilities. In this way, the probability of a scenario is conveyed directly to the viewer. For example, there is a 4/9 probability that a buried channel will be encountered at the platform site. It may be the same channel as that encountered at Boring B or a different channel. Also, there is a small chance (1/9) that the thickness of the channel at the location of Boring B is actually smaller than was measured due to sand caving into the hole during drilling (middle image in upper row of Fig. 13). Finally, if a channel is encountered its thickness is uncertain and ranges between 10 and 30 m. In summary, Figure 13 shows more information to the decision makers in a single glance than could possibly be conveyed in statistical parameters or in paragraphs of text. Therefore, uncertainty multiples provide a very effective means for conveying and visualizing uncertainty in all of its richness, even for a layperson.

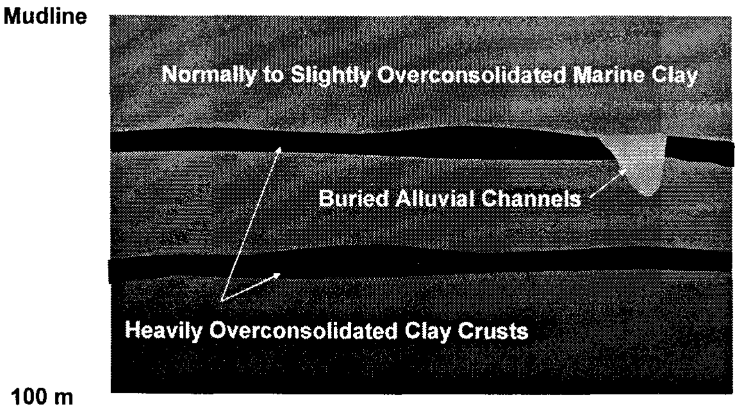


Figure 12 Geologic Setting for Illustrative Example (taken from Gilbert et al. 2006b).

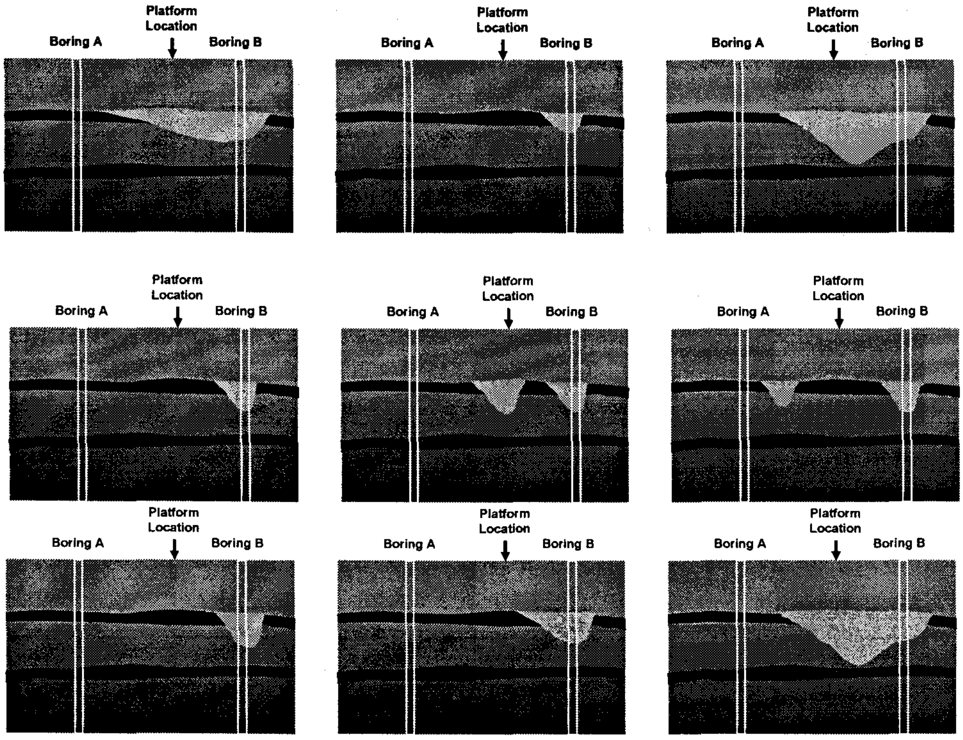


Figure 13 Uncertainty Multiples for Illustrative Example (taken from Gilbert et al. 2006b)

FUTURE DIRECTIONS AND NEEDS

The potential for the application of reliability methods in the practice of geotechnical engineering is unlimited. These methods are essential in advancing the state of practice, in increasing the value added by the profession, and ultimately in providing civilization with technically effective solutions that balance costs, benefits and risks (ASCE 2006). These methods are taking on even greater importance as the world becomes more interconnected and interrelated. Local failures now impact the entire world, such as the price of oil in the wake of Hurricane Katrina. Also, the available resources to manage risk in the world as a whole are severely limited.

The major needs to improve the state of practice in the application of reliability methods can effectively be summarized in terms of the lessons presented in this paper:

1. Establishing Goals Is Important: We, geotechnical engineers, need to become more involved in public policy and in interacting with decision stakeholders so that rational goals are set and expectations are clear.
2. Mitigating Consequences Can Be Effective: We need to consider consequences as well as probabilities in our analyses, and more importantly, in design and decision making.
3. Performance Depends on Systems: We need to consider how the performance of individual components affects the performance of the system as a whole, even when our design standards focus only on components and even when our project may only be a small piece of the overall system.
4. Physical Factors Are Important in Statistical Models: We need to establish what is important in the context of the decisions that need to be made and to include all available and relevant information in developing and applying mathematical models.
5. Too Much and Too Little Conservatism Are Both Problems: We need to work directly with decision makers so that they understand explicitly how conservative a design is and what the impacts would be of making it more or less conservative.
6. Value of Information Depends on Decision Making: We need to relate how information will benefit the decisions that need to be made on a project-specific basis and not simply pursue as much information as possible without considering the costs and benefits.
7. Effective Communication Is Essential: We need to make sure that the full richness of uncertainty is conveyed clearly in eliciting information for making decisions and in presenting the information to decision makers.

A significant theme in all of these needs is the role of humans. Effective management of risk requires considering that geotechnical systems are designed, built and used by humans.

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