Important Role of Uncertainty in Forensic Geotechnical Engineering

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ABSTRACT

Uncertainty plays a significant role in forensic geotechnical engineering. There is generally uncertainty in the available evidence and there is subsequently uncertainty in any conclusions drawn from it. Probability theory highlights the following principles when drawing conclusions from evidence:

1. If evidence can be explained by multiple hypotheses, then it is impossible to draw conclusions with certainty;
2. Additional evidence does not necessarily reduce and can actually increase uncertainty in the conclusions drawn from it; and
3. Neglecting hypotheses from the set of all possibilities can lead to erroneous conclusions.

Three case histories are presented to demonstrate these principles in practice. These case histories underscore the importance in considering uncertainty carefully and in communicating uncertainty clearly in conducting forensic analyses.

INTRODUCTION

Uncertainty plays a significant role in forensic geotechnical engineering. There is generally uncertainty in the available evidence and there is subsequently uncertainty in any conclusions drawn from it. It is important to consider uncertainty carefully in conducting a forensic analysis and it is equally important to communicate uncertainty clearly in presenting conclusions.

Probability theory provides valuable insight into the role of uncertainty in drawing conclusions. Bayes' theorem is a mathematical representation of learning from evidence:

where is the probability of interest, the probability that a conclusion is true given the available evidence; is the probability for the evidence if the hypothesis is true; and the summation in the denominator includes all possible hypotheses.

Bayes' theorem highlights three useful principles:

1. If evidence can be explained by multiple hypotheses, then it is impossible to draw conclusions with certainty;
2. Additional evidence does not necessarily reduce and can actually increase uncertainty in the conclusions drawn from it; and
3. Neglecting hypotheses from the set of all possibilities can lead to erroneous conclusions.

Consider simple examples to illustrate these principles. Figure 1 shows a case with two possible hypotheses, A and B. The probabilities for these hypotheses without the evidence are weighted heavily toward Hypothesis B (Fig. 1a). However, the probability of obtaining the evidence is three times greater for Hypothesis A versus Hypothesis B (Fig. 1b). Subsequently, the updated probabilities for the hypotheses from applying Bayes' theorem reflect uncertainty (Fig. 1a); both hypotheses are still possible and a conclusion cannot be drawn with certainty given the evidence. Furthermore, since the evidence contradicts the prior expectation that Hypothesis B is more probable, the evidence actually increases the uncertainty in the conclusion; instead of the updated probabilities moving closer to certainty [P(Hypothesis A) = 0 and P(Hypothesis B) = 1 or P(Hypothesis A) = 1 and P(Hypothesis B) = 0], the updated probabilities move closer to maximum uncertainty [P(Hypothesis A) = 1/2 and P(Hypothesis B) = 1/2] when the evidence is considered (Fig. 1a). Figure 2 shows a case with three possible hypotheses, A, B and C. If the probabilities for these hypotheses without evidence neglect the presence of Hypothesis C (Fig. 2a), even though the probability of obtaining the evidence is greatest with this hypothesis (Fig. 2b), then the updated probabilities are weighted heavily toward Hypothesis A being correct. However, if the probabilities for these hypotheses without evidence include the presence of Hypothesis C (Fig. 2c), then the updated probabilities indicate that Hypothesis C is more likely to be correct than either A or B (Fig. 2c).

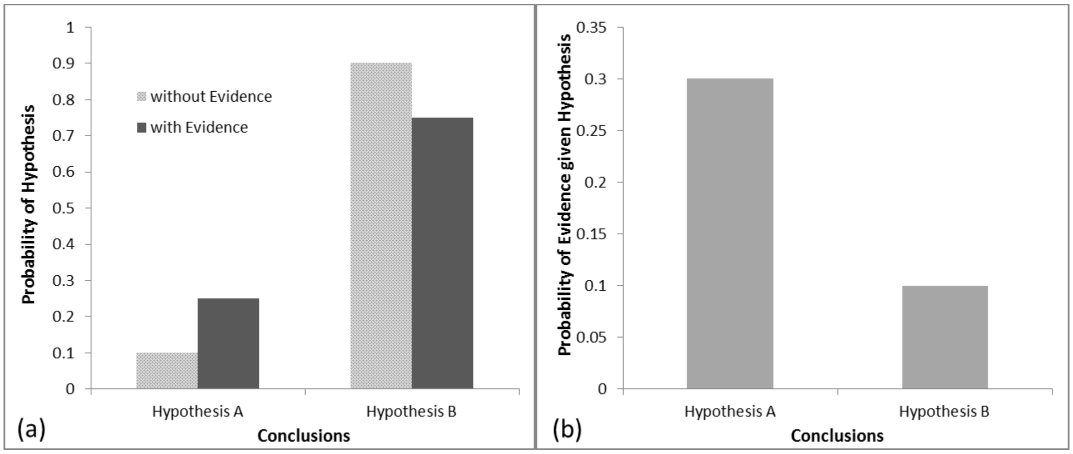

Figure 1. Example illustrating that evidence does not necessarily reduce and can increase uncertainty.

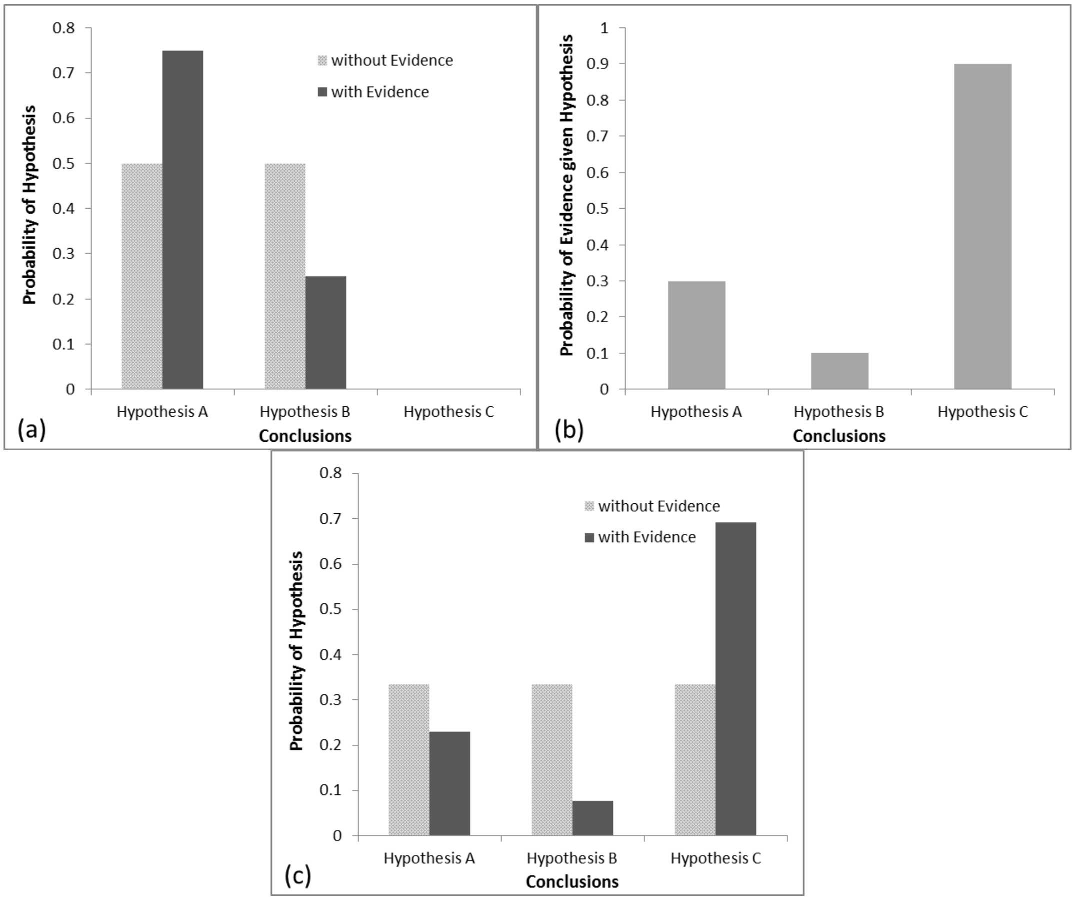

Figure 2. Example illustrating that neglecting a possible hypothesis can lead to an erroneous conclusion.

Three case histories are presented in the following sections to demonstrate these theoretical principles in practice.

KETTLEMAN HILLS SLOPE FAILURE

The Kettleman Hills slope failure occurred on March 18, 1988 in Cell B-19, Phase 1A of the Kettleman Hills landfill in Kettleman City, California (Figs. 3 and 4). An initial forensic analysis obtained a factor of safety for the slope of about 1.2 at the time of failure based on a conventional, two-dimensional, limit equilibrium analysis and using residual shear strengths. The investigators hypothesized about two possible mechanisms that may have caused the actual factor of safety to be smaller and more consistent with the failure. First, they hypothesized that the strength of the interface between a geomembrane and a compacted clay layer on the base of the landfill may have been reduced by "wetting," a migration of moisture in the clay to near the interface after it was constructed. They concluded that this "wetting" may have reduced the factor of safety by about 10 percent. They also hypothesized that the three-dimensional geometry of the slip surface was not captured in the conventional two-dimensional analysis and that these three-dimensional effects may have reduced the factor of safety by 10 to 15 percent. These conclusions were reported in two papers that have been highly cited, Mitchell et al. (1990) and Seed et al. (1990).

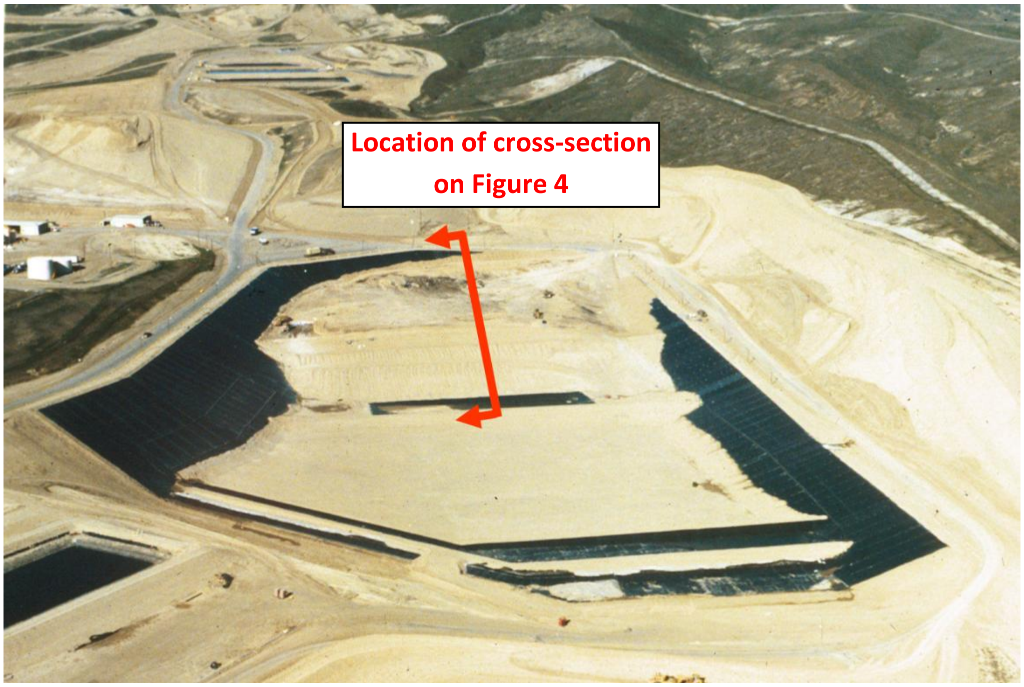

Figure 3. Aerial photograph of Kettleman Hills Landfill before slope failure (photo provided by Chemical Waste Management, Inc.).

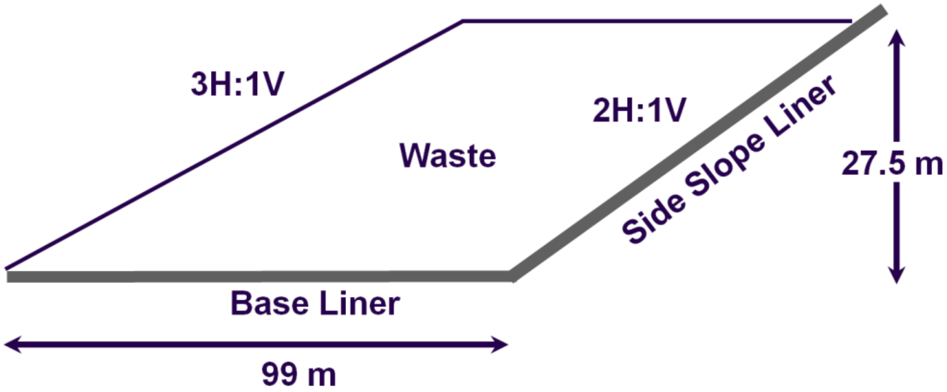

Figure 4. Cross-section through Kettleman Hills Landfill before slope failure.

Subsequent to the initial forensic analysis, a more comprehensive analysis was conducted based on information collected after the waste was removed and samples from the slope were obtained and tested. In addition, Construction Quality Assurance data were analyzed to establish the compacted moisture content achieved during construction of the clay liner. The actual compaction moisture contents during construction were generally higher than those used in the laboratory testing for the initial forensic analysis by Mitchell et al. (1990) and Seed et al. (1990). Consequently, the measured shear strengths for the interface between the geomembrane and compacted clay liner on the base of the landfill were less than those obtained in the initial analysis. The primary conclusion from the subsequent analysis was that the calculated factor of safety from a conventional, two dimensional, limit equilibrium analysis was about 1.0 and consistent with the failure (Byrne et al. 1992). A second conclusion from this analysis was that three-dimensional effects did not reduce the factor of safety and, if anything, probably increased the factor of safety. A third conclusion from this analysis was that the shear strengths mobilized at the time of failure were probably close to the peak shear strength on the side slope and the residual shear strength on the base. This conclusion was further reinforced by Stark et al. (1994).

This slope failure was analyzed further to better understand the relationship between the mobilized shear strengths at failure and the peak and residual shear strengths. Numerical analyses were conducted to maintain compatibility between stresses, strains and displacements. An analysis was then performed with all of the evidence using a formal implementation of Bayes' theorem to account for uncertainty (Gilbert et al. 1998). The conclusion from this analysis was that the average strength mobilized along the base of the landfill was probably between the peak and residual strength (Fig. 5).

In summary, initial forensic analyses that did not fully capture the uncertainty in the evidence led to unsubstantiated conclusions about the Kettleman Hills Landfill failure. In addition, even with considerable information obtained from a variety of investigations into the failure, there is still significant uncertainty in the actual shear strength that was mobilized at the time of the failure.

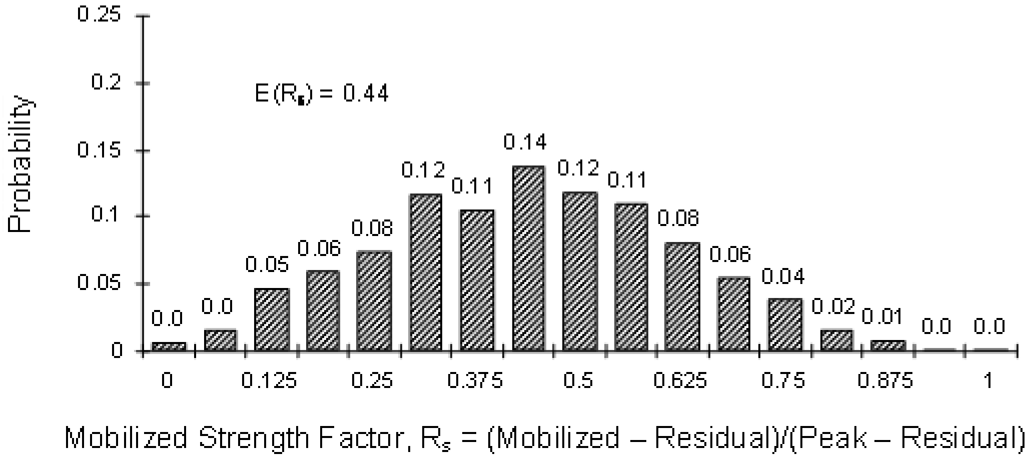

Figure 5. Probability distribution for mobilized shear strength on base of Kettleman Hills Landfill based on Bayesian analysis of evidence (from Gilbert et al. 1998).

OFFSHORE PLATFORM FOUNDATION PERFORMANCE IN HURRICANE IKE

In 2008, Hurricane Ike loaded many offshore platforms in the Gulf of Mexico to beyond their design capacity and some platforms even to their ultimate capacity (Energo 2010). One platform loaded to its ultimate capacity was an eight-leg structure located in about 30 m of water (Fig. 6). The foundation system for this structure is eight steel pipe piles that are driven on a batter 52 m into the sea floor. The stratigrahpy over the length of the piles consists of 50 m of soft to stiff clay with a 10-m thick layer of medium to very dense sand near the pile tips.

For the purposes of continuing to use this structure after the hurricane, a forensic analysis was performed of its performance during Ike. First, the hindcast oceanic and atmospheric data from the hurricane were analyzed to develop the maximum sea state conditions at the location of the platform. Then, the entire structural system including the steel pipe piles was analyzed using a three-dimensional, non-linear Finite Element Method model.

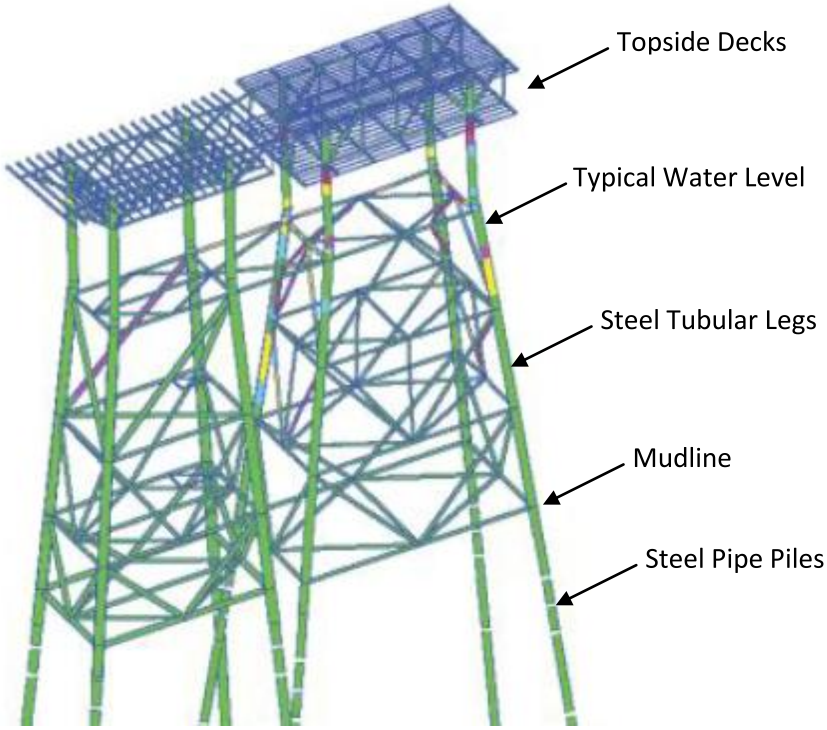

Figure 6. Schematic rendering of 8-leg jacket loaded to ultimate capacity in Hurricane Ike.

The results of the analysis are shown on Figure 7. This figure shows an interaction curve for combinations of base shear and overturning moment on the foundation system that lead to collapse; the flatter left-hand side of this curve corresponds to a shear-dominated failure where the piles are failing laterally, while the steeper right-hand side of this curve corresponds to an overturning-dominated failure where the piles are failing axially. Figure 7 also shows the maximum load in Hurricane Ike estimated from the hindcast analysis. This forensic analysis indicates that the foundation system was expected to fail during the hurricane (Fig. 7). However, the structure was intact with only minor structural damage above the mudline when it was inspected after the hurricane. Therefore, further forensic analyses were required in order to explain its survival and update its capacity before the platform could be used again.

Since the “failure” of the structure in the structural analysis was taking place in the foundation system, the structural engineers analyzing the platform focused on the shear strength of the soil to explain the survival. The structural engineers incrementally increased the undrained shear strength of the soft to stiff clay until the capacity of the foundation system exceeded the load in Hurricane Ike. An increase of 300 percent to the profile of undrained shear strength versus depth was required to explain the survival. While a 300-percent increase in the undrained shear strength explains the survival of this platform, it is not considered to be plausible or realistic (particularly to a geotechnical engineer).

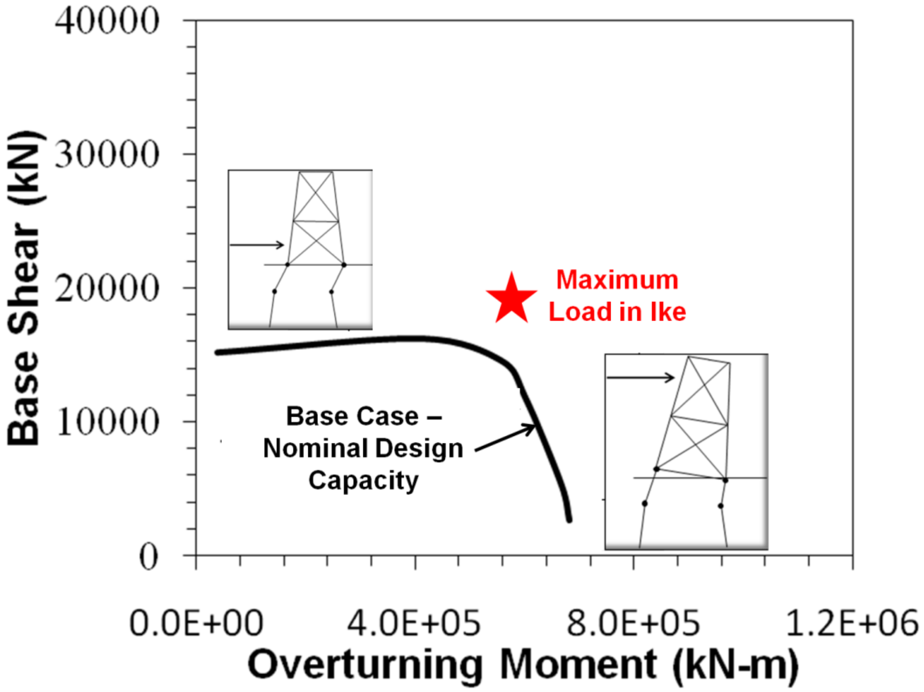

Figure 7. Interaction curve for capacity of jacket foundation system loaded in Hurricane Ike.

The potential failure mechanism for the foundation system in the Hurricane Ike loading is dominated by shear versus overturning (Fig. 7). The lateral capacity of the pile system is relatively insensitive to the shear strength of the soil (e.g., Gilbert et al. 2010), which is why a 300-percent increase in the shear strength of the soil is required to produce a relatively modest increase in the capacity of the foundation system. However, the lateral capacity is sensitive to the structural capacity of the piles (i.e., the yield strength of the steel) and to the structural details at the pile heads near the mudline. In addition, when the ultimate capacity of the foundation system is mobilized, the piles will push laterally into soil that has not been degraded by previous cyclic loading during the storm. Therefore, an ultimate lateral resistance corresponding to static loading is more reasonable than one that reflects cyclic degradation. Figure 8 shows the capacity of the foundation system using a mean versus a nominal yield strength for the steel piles, accounting for jacket leg stubs that extend several meters below the mudline and using static rather than cyclic p-y curves. With these small and plausible adjustments to the structural analysis, the survival of this foundation system in Hurricane Ike can be readily explained (Fig. 8).

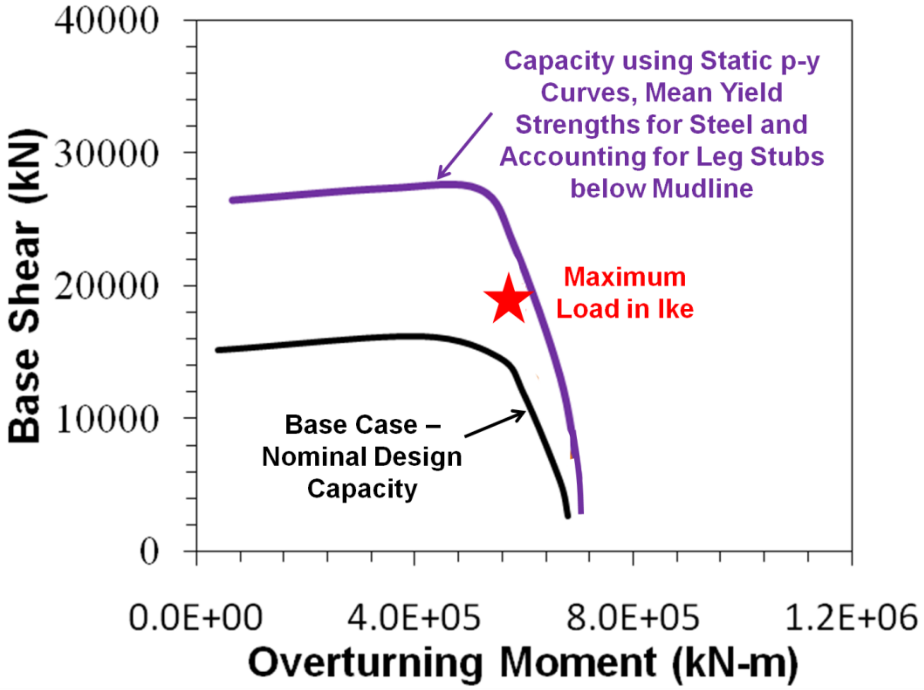

Figure 8. Updated interaction curve for capacity of jacket foundation system loaded in Hurricane Ike.

In summary, by not considering plausible hypotheses to explain the survival of this offshore platform loaded to its capacity in Hurricane Ike, unrealistic conclusions were drawn from the evidence.

LANDFILL COVER FAILURE

A failure of a landfill cover slope occurred during construction (Fig. 9). A 0.6-m thick soil cover layer slid about 7 m down a 3H:1V slope along the interface between a geocomposite drainage layer and a textured geomembrane. The geocomposite drainage layer ruptured in tension at the head scarp, and the cover soil layer bulged at the toe of the slide.

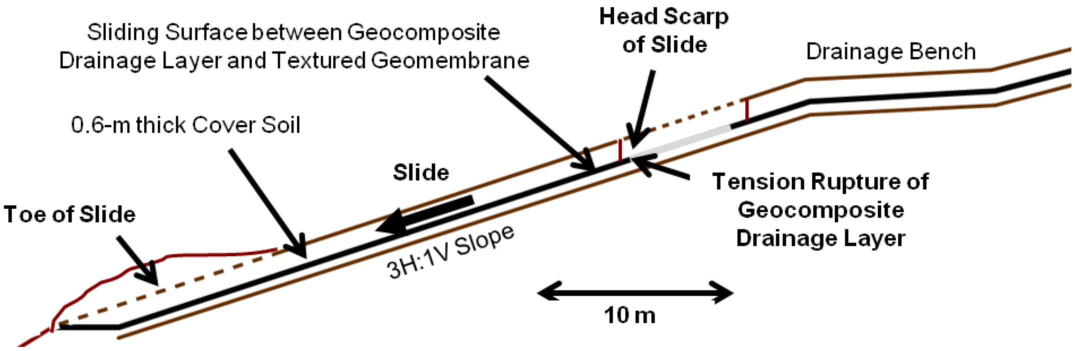

Figure 9. Cross-section through failure of a landfill cover slope during construction.

The initial forensic analysis focused on the shear strength of the failure plane. First, data from the Construction Quality Assurance testing were compiled and additional direct shear tests were conducted by the same laboratory (Laboratory A). Next, the contractor hired Laboratory B to conduct additional tests on samples from the site. These test data are summarized in Figure 10. The results from Laboratories A and B were very similar and, while there is variability in individual tests results due apparently to spatial variability in the texturing of the geomembrane, there was a relatively high degree of confidence in the average shear strength for this interface. Subsequently, the design engineer hired Laboratories C and D to conduct additional shear tests (Fig. 10). These new data were statistically similar to one another but statistically different than those obtained from Laboratories A and B. Therefore, the uncertainty increased in the average shear strength for this interface as additional information was obtained. Furthermore, a hypothesis was formulated that spatial variability in the shear strength of the interface led to the failure. An assessment of the average shear strength envelope together with 95-percent confidence bounds is shown in Figure 11.

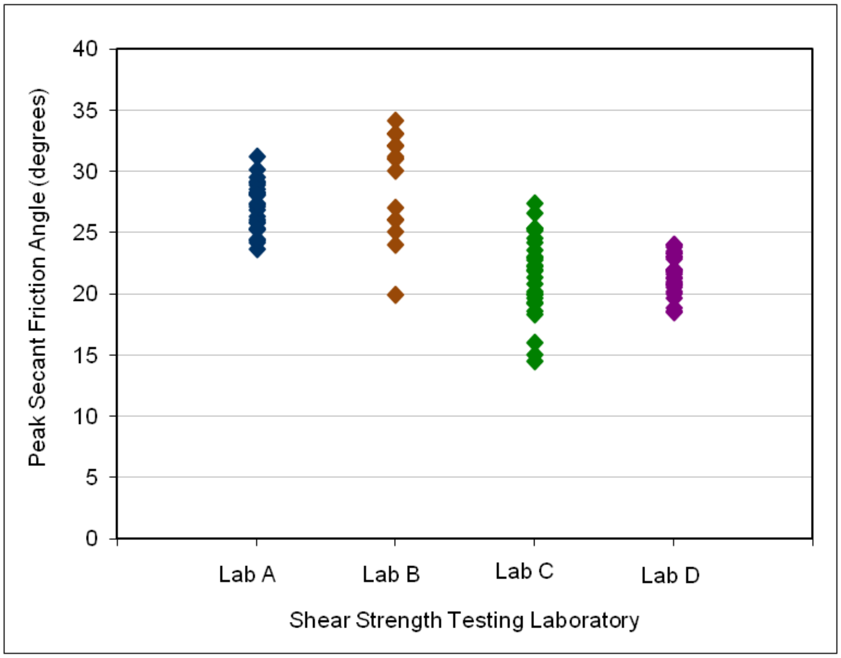

Figure 10. Test data for shear strength of interface between geocomposite drainage layer and textured geomembrane from landfill cover slope failure.

There was additional evidence beyond test data for the shear strength of the sliding surface. First, a limit equilibrium stability analysis was conducted, accounting for a range of possible contributions to sliding resistance from the tensile capacity of the geocomposite drainage layer at the head of the slide and the compressive capacity of the cover soil layer at the toe of the slide (Fig. 9). This analysis was used to establish a range of average shear stress mobilized on the slip surface at the onset of failure, represented by the height of the box labeled "Average Shear Stress in Failure" in Figure 11.

Second, there was a small amount of rainfall, about 10 to 20 mm, shortly before the failure. The geocomposite drainage layer was designed to accommodate a much greater rainfall event than 10 to 20 mm; consequently, this evidence was initially dismissed as being irrelevant. However, the cover slope was under construction and not in its final design configuration at the time of the failure. The cover soil layer had not been placed all of the way up the slope, meaning that there was a 3 to 5-m wide section of exposed geocomposite drainage layer at the crest of the slope. Also, the cover soil layer had not been graded at the toe of the slope, meaning that it was at least partially blocking the drainage outlet of the geocomposite drainage layer. Hydraulic analyses showed that even a small amount of precipitation under these conditions could readily lead to average water heads on the slide surface that exceeded the thickness of the cover soil. The range of possible water pressures is represented by the width of the box labeled “Average Shear Stress in Failure” in Figure 11.

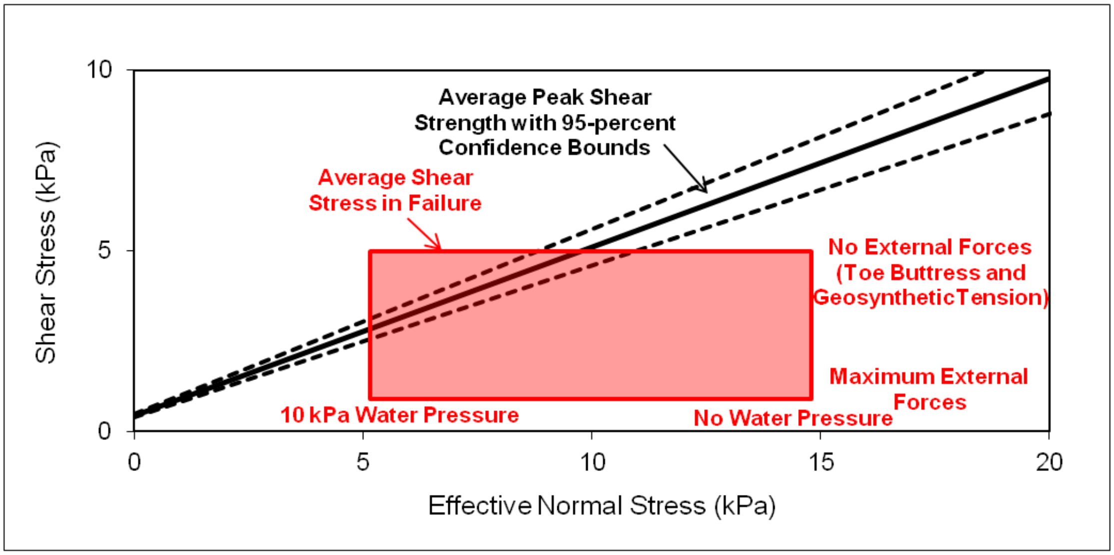

Figure 11. Strength envelope for sliding surface from landfill cover slope failure.

The mobilized average shear stress on the sliding surface is compared in Figure 11 to the average peak shear strength for the sliding surface based on the shear testing. This comparison indicates first that, even with no water pressure acting on the interface and no external forces resisting the sliding, it was improbable that variations in the shear strength of the interface were the cause of the failure. This comparison also indicates that there was probably at least 5 to 10 kPa of average water pressure acting on the interface at the time of the failure. While 5 to 10 kPa of water pressure is small in absolute terms, it is enough to reduce the effective normal stress acting at the base of this thin cover layer by 50 percent or more (Fig. 11).

As further evidence that water pressure contributed to this failure, shear tests were conducted on samples from the sliding surface obtained after the failure. If an effective normal stress of 15 kPa had been acting on this interface in the field (i.e., no water pressure), then a residual shear strength for this effective normal stress would have developed after about 7 m of shear displacement in the field. Tests on fresh samples of the interface at this effective normal stress produced residual shear strengths that were about 60 percent of the peak shear strengths. However, shear tests on the interface tested at an effective normal stress of 15 kPa after the failure showed no evidence of post-peak strength loss, consistent with shearing in the failure having occurred at a much smaller effective normal stress.

In summary, this landfill cover slope failure illustrates that uncertainty does not necessarily decrease with additional evidence. It also illustrates that it is important to consider all of the evidence in formulating and evaluating hypotheses as to the cause of a failure.

CONCLUSION

Probability theory highlights the following principles when drawing conclusions from evidence:

1. If evidence can be explained by multiple hypotheses, then it is impossible to draw conclusions with certainty;
2. Additional evidence does not necessarily reduce and can actually increase uncertainty in the conclusions drawn from it; and
3. Neglecting hypotheses from the set of all possibilities can lead to erroneous conclusions.

Three case histories were presented to demonstrate these principles in practice. The Kettleman Hills Landfill slope failure showed that there was significant uncertainty in the shear strength mobilized in the failure even after numerous forensic analyses. The offshore platform survival in Hurricane Ike showed that unrealistic conclusions were drawn when plausible hypotheses were neglected. The landfill cover slope failure showed that uncertainty increased with additional evidence and that all evidence needed to be considered holistically in drawing conclusions.

In conclusion, it is important to consider uncertainty carefully in conducting a forensic analysis and it is equally important to communicate uncertainty clearly in presenting conclusions from that analysis.

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