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GEOTECHNICAL ENGINEERING ORGANIZING AND EVALUATING UNCERTAINTY

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ABSTRACT: The four stages of a typical project—site characterization and evaluation, design evaluation, decision-making, and construction control—could all benefit from the employment of probabilistic approaches. The ability to quantify risk numerically might be helpful when evaluating initiatives. Reliability theory may be applied when uncertainties can be measured and model errors are understood. Event-tree analysis can serve as a framework for applying judgement regarding uncertainty in an efficient manner. Standards for acceptable risk limit the use of measured risk in decision-making; effective client communication is crucial. Engineers will continue to use conventional approaches unless clients or regulators are interested in assessing risks as part of decision making. Clients are interested in talking about risks when the risks are high and the price of total safety are high. Risk assessment is receiving attention due to concerns over the sufficiency of existing structures like earth dams, and advances in earthquake engineering will have an impact. There is a need for more and better illustrations of probabilistic technique applications.

INTRODUCTION

Uncertainty is pervasive in geotechnical engineering. Practicing engineers, of course, worry about such questions as Will we get the job?, When will it start?, Will the driller show up as promised?, When will we be paid?, etc. I am afraid this Conference won't help with those important uncertainties. We will have enough on our plate as we focus questions having to do with uncertainty in the engineering aspects of a project.

Engineers face uncertainties at all phases of a project: Is it possible that a site is so poor or contains unrevealed defects that make it unsuitable?; Is a proposed field investigation adequate for characterizing the materials at a site?; What values should be assigned to soil parameters (strength, permeability, etc.) required for analyses?; How accurate is an analysis leading to an important derived quantity (e.g., safety factor); and — most important— How confident are we that a proposed design is safe, and adequate in other ways? There are also uncertainties as to just how well a design is being implemented during actual construction.

The founders and leaders of our profession have spoken and written extensively concerning the importance of recognizing uncertainties and taking them into account in design. Casagrande's well-known Terzaghi Lecture (1965) was specifically about ''calculated risk,'' by which he meant very careful consideration of risk. Casagrande was not optimistic that risks could literally be calculated or even quantified.

During this conference, we *are* interested in ''quantifying'' risk— that is, using numerical and analytical characterizations and methods to assist in making decisions concerning uncertainties such as those I just listed. In the years since Casagrande's lecture, there have in fact been advances in enumerating uncertainties in geotechnical engineering. There are new ''tools'' for use in guiding site exploration and characteriza-

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Note. Discussion open until December 1, 2000. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on October 29, 1997. This paper is part of the ***Jour-***

There are now examples in which risks have literally been calculated as part of engineering projects, and others where subjective judgments have been used to assign numbers to the risks. Increasingly, quantified risk is being used as the basis for engineering decision making.

The subject matter of this conference has been covered in the report ''Probabilistic Methods in Geotechnical Engineering'' [National Research Council (NRC) 1995]. Morgenstern (1995) has dealt with managing risk in geotechnical engineer- ing. I will mention a few other recent state-of-the-art papers. The plenary papers to this conference, and other papers as well, are state-of-the-art summaries covering portions of the subject. I will strive only to indicate the scope of useful prob- abilistic methods, referring to but a very limited segment of recent literature.

The comments I offer to begin this discussion are aimed at four questions:

- What do probabilists mean by all the words they use?
- How can probabilistic methods be used in geotechnical engineering?
- When, and for what type of projects, is it appropriate to use probabilistic methods?

UNCERTAINTY WHEN TALKING ABOUT UNCERTAINTY

Fell (1994), in an excellent state-of-the-art paper concerning risk assessment relative to landslides, reports:

> ''Unfortunately, there are no generally accepted definitions of the terms used in risk assessment . . . shortly after its formation in 1981, the United States Society for Risk Analysis established a committee to define risk. After 3 or 4 years of work the committee published a list of 14 candidate definitions and reported that it could not reach agreement. They recommended that a single definition of risk not be established but that everyone be free to define it as appropriate to his or her own work.''

I certainly will not attempt to change this situation, but I must attempt to explain what I mean by various terms I will use.

I have already used the phrase *probabilistic methods*. This is a very loose concept, intended to cover a diverse range of techniques for expressing and dealing explicitly with uncertainty.

I have spoken of *quantifying risk*. This is meant to imply using numbers to express risk. Thus *quantified risk* is more explicit than Casagrande's *calculated risk*, which according to the American Heritage dictionary means ''estimated with forethought.'' To me, *risk evaluation* is the process of arriving at *quantified risk*. However, a different meaning for *risk evaluation* is becoming more accepted. However, *quantified risk* can be arrived at either by means of (a) theory and numerical calculations or (b) using subjective judgments. I have tried to think of simple phrases to distinguish between these two approaches, but I have been unsuccessful. Actually, both approaches may be used together in a *risk evaluation*.

Risk assessment is broader. It includes identification of hazards, risks, and consequences; investigation of possible steps to reduce risks and consequences; and prioritization of reme- dial actions. Risk assessment may or may not involve quantification of risks.

I will strive to distinguish consistently between *hazard* and *risk*, using meanings that are widely if not universally accepted. When expressed in probabilistic terms, *hazard* expresses the likelihood that some event— such as piping or a flood— may occur. *Risk* expresses the likelihood that some loss occurs, and is often in the form of a product of the prob- ability that a *hazard* occurs and the probability of a loss given that the hazard occurs. (Be warned, it is fairly certain that a strict probabilist will disagree with my use of the word *like- lihood*. I use it merely to express a concept.)

Lastly, *probabilistic thinking* is another loose concept. It implies use of concepts from formal probability theory, reliability theory, statistics, etc., and possibly the actual use of some theoretical tools from these sciences— but without becoming a slave to formalism.

There is a moral: We must all be patient and diligent in our communications with each other, sparing no effort in our attempts to understand the message being sent.

PROBABILISTIC METHODS IN GEOTECHNICAL ENGINEERING

The scope of the papers being presented to this conference makes clear the diversity of probabilistic methods that are being applied in geotechnical engineering. Different approaches are commonly used for different types of projects: landslides, foundations for offshore structures, environmental problems, etc. Different types of analysis are suitable for the several stages of a project. For the purposes of my discussion, it is convenient to divide a project into four stages: (1) site evaluation and characterization; (2) design evaluation; (3) decision making, and (4) construction control. The following sections discuss each of these stages. My aim is to indicate the types of questions that probabilistic methods can contribute at each stage, without going into technical detail. However, it must be recognized that, from the standpoint of probabilistic methods, it may or may not be appropriate for these stages to proceed independently. For example, the choice of method for assessing the reliability of a design depends both upon the availability of data concerning the site and upon the way in which acceptable risk is judged.

SITE EVALUATION AND CHARACTERIZATION

A variety of probabilistic methods have been developed that can be useful during this stage of a project. The following discussion aims to suggest the range of possibilities, and is not exhaustive. Some, such as searches for ''flaws'' and construction of profiles, may be the end of using probabilistic methods for the project; others may aim to provide specific data required for further probabilistic analysis.

Designing a Search to Look for ''Flaws'' at Site

In this stage, the general nature of the site is established. A vital question is, Is the exploration program adequate to detect and reveal the extent of any flaws that might present unusual design problems or possibly make the site unsuitable for some intended purpose? Typical flaws are strata of especially weak or liquefiable soil or the presence of an adversely sloping joint in rock, solution cavities, or channels of exceptionally high permeability. *Search theory* can be used to guide selection of patterns of borings and to help decide how many borings are necessary to reduce probability of an undetected flaw to below an acceptable limit. Application of search theory to geotechnical problems was pioneered by Baecher (1979) two decades ago. Halim and Tang (1993) present a recent contribution to this theory.

Characterizing Variability over Site

It is common practice to prepare soil profiles across a site, based upon soil types recorded in borings spaced some distance apart. Various probabilistic approaches can aid in this task, by systematically identifying possible correlations of soil types with depth and among boreholes. A mathematical technique known as Kriging is useful for this purpose. One common application is mappping of the elevation of the top of a soil type of particular interest. Nobre and Sykes (1992) provide one relatively recent example of using this approach to mapping the elevation of bedrock. Johnson and Dreiss (1989) and Poeter and Townsend (1991) present examples of using probabilistic techniques to develop profiles for complex alluvial sediments, as aids to study of ground-water pollution.

Spatial variability of soil properties, both horizontally and vertically, is an especially important problem. Accounting for this variability can be important in such diverse problems as estimating risks of slope failures with long embankments, study of the dispersion of plumes of pollutants, and evaluation of a site's resistance to liquefaction— all of which are mentioned subsequently. The work of Vanmarcke (1983) has provided a starting point for the characterization of spatial variability.

A very interesting application, described by Tang (1979), concerns the penetration of skirts for an offshore gravity platform. At the proposed site, layers of dense sand and hard clay occur at some locations, and the exact location at which the platform sets down cannot be controlled precisely. Cone penetration data were analyzed to take into account possible variations of skirt penetration resistance with depth and laterally. The analysis led to estimates for the mean $\pm$ 1σ range for total resistance and the central 50% band for the unbalanced moment. Such information provides important guidance both for planning the sinking operation and monitoring and controlling the actual sinking.

Choosing Values for Material Properties

A classic geotechnical engineering task is the selection of the value for a soil parameter to be used in some analysis. In some problems it is necessary and appropriate to rely upon judgment in making this decision. Increasingly, however, values are better selected systematically employing statistical and probabilistic methods. For reliability analyses (to be discussed subsequently), it is at a minimum necessary to estimate the mean and standard deviation (or variance) for key parameters. In other situations (see subsequent discussion of codes), it may be desirable to select a value with some stated probability of not being below (or above, as the case may be) the selected value.

There are several different types of uncertainties regarding

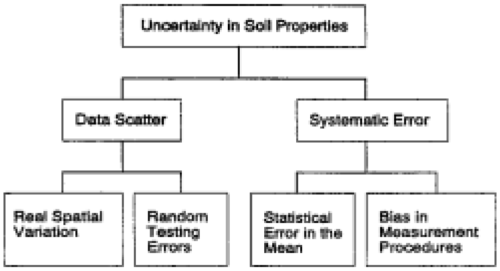

FIG. 1. Categories of Uncertainty in Soil Properties (Christian et al. 1994)

the properties of soil as measured either in the field or in the laboratory (Fig. 1):

- Data scatter, consisting of (1) real spatial variability and (2) random testing errors. Random testing errors should not be allowed to influence parameter selection; the magnitude of such errors should be identified and screened out of further analysis. Real spatial variability can be important, depending upon the distances over which it occurs compared to the scale of the project.
- Systematic errors, resulting from (1) errors because tests do not actually measure accurately the desired parameter, and (2) too few tests to average out random testing errors. The first of these difficulties (akin to model errors in analysis, to be discussed shortly) can be very important and require particular attention.

The literature contains techniques for dealing with all of these difficulties in systematic ways. Christian et al. (1994) give a brief summary as applied to problems with slope stability. The classic work by Vanmarcke (1977) provides methods for dealing with the possible consequences of spatial variability. The problem of deciding when enough tests have been performed to reduce random errors is similar to that of searching for ''flaws.'' Wu et al. (1989) present an interesting example of evaluating alternative exploration programs so as to choose the program that will most effectively define the site characteristic for a project. A reliability analysis (see below) provides the framework for this particular evaluation.

EVALUATION OF RISK

There is no one procedure for evaluating risk that is appropriate for all types of projects. The choice of method depends upon the approach that is most acceptable for the type of project, the data available, the degree to which there is reliance upon subjective judgment, and the criteria that will be used to judge whether or not the risk is acceptable.

Reliability Analysis

A *reliability analysis* evaluates the probability that *capacity* (e.g., bearing capacity) exceeds *demand* (e.g., loading), where either or both capacity and demand are uncertain. This probability is called *reliability*, and

$$\text{Probability of failure} = (1 - \text{reliability})$$

If probability distribution functions can be established for both capacity and demand, in principle an exact (but very tedious) calculation of reliability may be made. An alternative is to make many simulations, drawing random numbers to choose appropriate values for demand and capacity. Generally well-developed approximate methods are available that depend only upon characterization of capacity and demand by their means and standard deviations. Reliability analysis has often been applied to structural systems. There currently is considerable interest in the application of this approach to geotechnical engineering problems. A brief discussion of the method from the standpoint of geotechnical engineering appears in NRC (1995). In the Sixth Casagrande Memorial Lecture to the Boston Society of Civil Engineers Section of ASCE, Kulhawy (1996) gives important insight and guidance concerning the applicability of reliability-based design.

Since reliability analysis has frequently been used for the structural portions of large offshore structures, it is natural that the method has been applied to the foundations for such structures. The recent literature contains several good examples; a brief review of one will illustrate the key aspects of such an analysis.

Ronold and Bysveen (1992) evaluate the reliability of the foundation for a deep-water gravity platform resting on soft clay (Fig. 2). A standard for design of such structures is the worst six-hour sea state during the lifetime of the platform. The largest significant wave height during this storm is uncertain. The capacity is determined from a stability analysis using the failure surface shown in Fig. 2, which was found to be the critical failure surface. The uncertainties concerning this capacity are

- The undrained strength for active loading conditions, as evaluated from triaxial compression tests
- The relation between undrained strength for active, plane

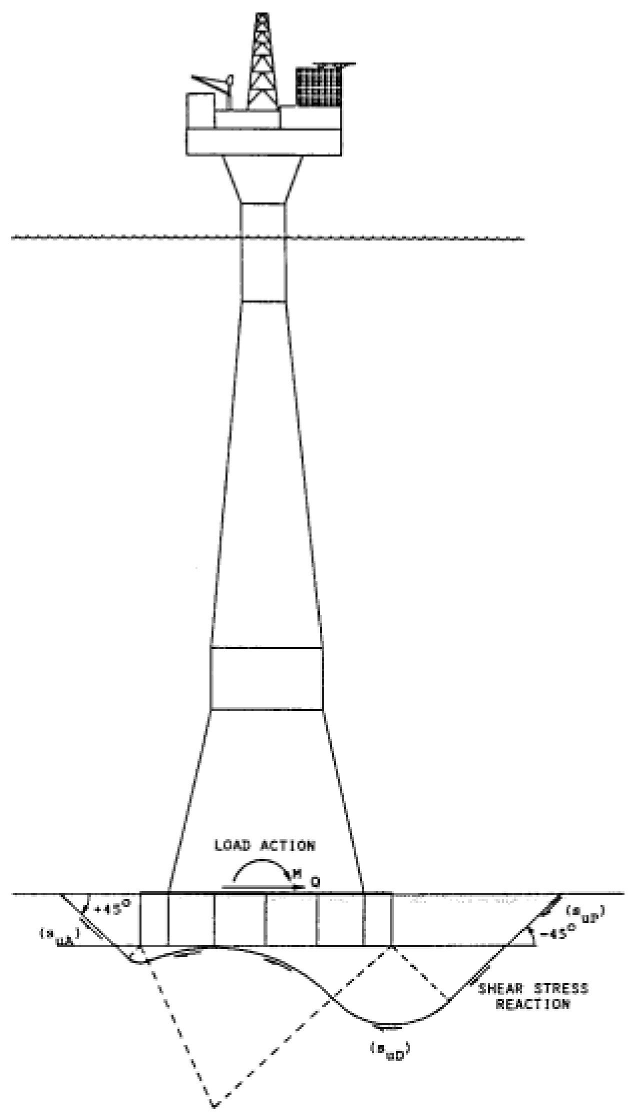

FIG. 2. Deep-Water Platform on Soft Clay, with Critical Shear Surface Configuration through Soil (Ronold and Bysveen 1992)

strain, and passive loading conditions (used for different portions of the failure surface)
- The effect of cyclic degradation of strength during cyclic loading
- Model error: how well the stability calculation gives the actual capacity, assuming strengths are known accurately

Mean values and standard deviations were evaluated for all of these factors, using statistical techniques where adequate data existed (especially for active undrained strength) and subjective judgment otherwise (as for model error). Calculations then led to a probability of failure of 0.4×10^{-4}, which was deemed sufficiently small and in line with safety levels typical for good deterministic designs. (Note that this is the probability of failure given that the worst six-hour sea state actually occurs. The corresponding probability of failure during the lifetime of the structure is much less.) The dominating part of the total uncertainty came from uncertainty regarding details of the wave loading. Uncertainty in soil strength parameters was of little importance for the total uncertainty, except for that associated with cyclic degradation. Model uncertainties associated with the stability calculations were also found to contribute significantly to the total uncertainty. Nadim and Lacasse (1992) report a similar analysis for a jack-up platform, and also emphasize the importance of uncertainty in the loading.

The recent literature also contains reliability analyses for liners of landfills (Gilbert and Tang 1995; Rowe and Fraser 1995, the latter using Monte Carlo simulations), for an anchored sheet-pile wall (Cherubini et al. 1992), and for stability of slopes (Christian et al. 1994). These analyses are characterized by careful attention to evaluating the uncertainty in the strength of soil, using statistical techniques plus some judgment as necessary, and to model errors. Uncertainty in the demand (i.e., loading) is typically less important in these studies. Some studies were primarily research to illustrate possible applications, while some have been used as input to actual decision making.

I want to emphasize especially the importance of model errors— that is, potential errors in the deterministic calculations used to evaluate capacity for specified material properties. The uncertainties that can be associated with such calculations are often ignored or badly underestimated. By comparing predictions from a standard model for predicting flow through liners with actual measurements, Rowe and Fraser found it necessary to introduce a bias factor of 0.18 — that is, to account for a average error of more than a factor of 5! Lacasse and Nadim (1994) report on the use of model tests to evaluate the mean and standard deviation for bearing capacity calculated by standard methods. Ronold and Bjerager (1992) suggest a method that may be used to evaluate model uncertainty from test programs. One warning that perhaps is obvious: a soil parameter (e.g., strength) must be chosen in the same way (e.g., the mean value) in a reliability analysis as when analyzing results of tests to calibrate the model used for calculations.

Model errors, in the broadest sense, are not just an affliction of probabilistic reliability analysis. Anytime a key feature of a problem is overlooked and not considered in decision making, there is a model error. Morgenstern (1995) provides just such an example.

Event-Tree Analysis

Fig. 3 shows part of an event tree used as part of a risk evaluation for an earth dam. The spillway for this dam was capable of passing large flood flows, but the unlined channel downstream of the spilling basin had experienced erosion. The concern was that headward erosion of this channel might lead

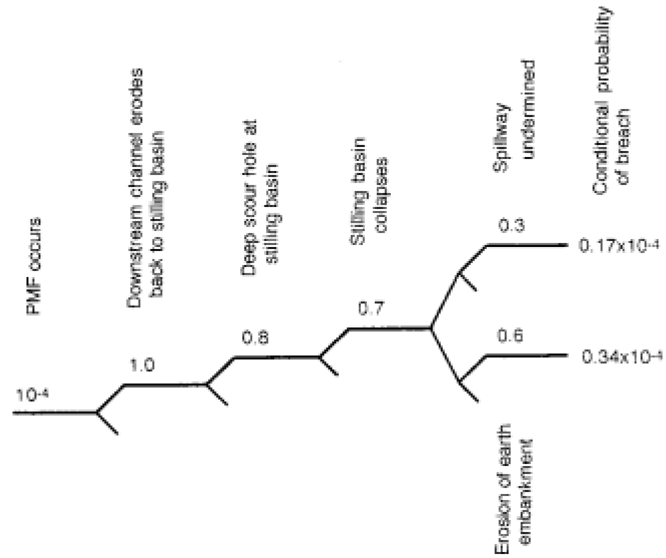

FIG. 3. Event Tree for Breaching of Earth Dam

to collapse of the stilling basin and thence to possible destruction of the spillway and/or erosion of the adjacent earthen embankment— and thus possible breaching of the dam. (This example is hypothetical though similar to a case from my files.) The ''event'' in this case is a flood flow of specified magnitude (actually, for a small range of flows centered on the probable maximum flood). Successive branch points account for the possibilities that

- The downstream channel erodes back to the stilling basin, causing scour holes of different depths.
- The foundation for the stilling basin collapses as a result of the scour hole.
- Collapse of the stilling basin leads to undermining of the spillway and breaching of the dam.
- Collapse of the stilling basin leads to erosion of the adjacent earthen embankment and breaching of the dam.

The probability of the flood flow was established from hydrologic studies. The probabilities at the branch points were estimated subjectively by engineers, based upon prior experience with erosion at the site, model hydraulic tests concerning erodibility of rip-rap, calculations concerning stability of a bulkhead wall at the toe of the stilling basin, and model hydraulic tests concerning scour-induced currents near the toe of the earthen embankment. Multiplying probabilities along the successive branch points gives the probability that this particular flood flow causes breaching of the dam. For this particular event tree, the probability of a failure is not much different from the probability of the initiating event. A set of similar event trees for different magnitudes of flood flows was used. For smaller and more likely flows, the probabilities of erosion, developing a scour pool, etc., are smaller. The sum of the probabilities from the set of event trees, which thus reflect the contributions from all magnitudes of flow, gave the overall probability of failure.

Used in this way, the event-tree analysis is in effect a crude form of reliability analysis, where subjective judgments take the place of formal treatment of uncertainties. A similar example, concerning possible breach of a dike resulting from sinkhole collapse, is described by Vick and Bromwell (1989). The construction of an appropriate event tree is by itself an important exercise, one that requires engineers to identify the sequence of events that might lead to a failure. Often the event tree is modified as the study progresses and certain sequences of events clearly become much less likely than others. Obvi-

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ously, the numerical result is only as good as the subjective judgments, and engineers— who by nature typically are conservative— often need guidance in forming these judgments. Roberds (1990) has discussed methods for developing subjective probability assessments. One key is preparing tables for translating verbal statements concerning probability (e.g., ''low'') into numerical values.

Landslides

Reliability analysis is potentially appropriate for assessing the probability of failure of a particular slope— based upon geometry, shear strength, and pore pressures. The major question always is whether or not the possible presence of weak, inclined strata has been taken into account properly.

There is extensive literature concerning zoning against landslides and estimating possible slide-caused losses on a regional basis. Einstein (1988) presents an excellent general summary of mapping techniques, especially those used in Europe. He deals with techniques used to assess probabilities of sliding, although the emphasis is upon general measures of likelihood rather than upon specific numerical measures. Fell (1994) has an excellent summary of methods for assessing probability of sliding and concerning allowable risks, together with numerical examples. Included in the methods are the use of historical data, relating risk of sliding to rainfall, and of geomorphological and geotechnical data. Fell claims ''it is practical in many, if not all cases, to assign a probability to landsliding. In many cases it will be subjective, and approximate, but it is better than not trying.''

One recent, interesting paper by Evans and Hungr (1993) assesses the rockfall hazard at the base of talus slopes. The analysis is primarily theoretical. One conclusion is that a strip development, 200 m along and 50 m from the margin of a talus slope, would be struck by a damaging boulder once in 95 years. Another interesting study (Bunce 1994) deals with the risk to automobiles of being struck by rockfall onto highways.

Risks Associated with Earthquakes

Given the infrequent occurrence of earthquakes, it is not surprising that probabilistic methods play a major role for characterizing *demand*; e.g., the probability of exceeding some intensity of ground motion. There are debates as to whether a facility should be evaluated for a ''500-year'' or ''2,500-year'' earthquake. But even with earthquake problems there is not universal acceptance of probabilistic methods. Ground-shaking hazard maps, being prepared during 1996 by the U.S. Geological Survey as a basis for new building code provisions, are using probabilistic analysis for the Eastern United States but deterministic approaches for the West.

There is a school of thought holding that the design of critical projects (large dams, for example) should never be based upon probabilistic analysis of the earthquake threat, because there is so much uncertainty as to values for the parameters going into such analyses. This school argues that all such facilities should be designed for a *maximum credible earthquake*. However, the word *credible* itself implies some judgment involving uncertainty. In addition, methods used to evaluate ground motions caused by the maximum credible event generally are not based upon the absolutely largest values that have been measured. Thus the so-called deterministic methods for specifying earthquake motions for design involve some unquantified uncertainty.

Indeed there are uncertainties with regard to the accuracy of probabilistic ground-shaking hazard analyses. Given the short history of direct experience with earthquakes in the United States, it would be overly bold to claim that a ''2,500 year earthquake'' can be evaluated precisely. However, this fact does not by itself mean that society should not decide to agree upon adoption of such events— calculated according to accepted rules— as a basis for design. At the same time, for some types of projects society may continue to opt to follow conservative, deterministic rules. The choice ultimately is made depending upon the costs of conservatism versus the potential for consequences as a result of a failure.

Even when the ground shaking used for evaluation of a site is the result of a probabilistic analysis, the subsequent assessment of *capacity* most commonly is deterministic. Liquefaction typically is evaluated using the well-known plot in Fig. 4 (Note: An up-to-date version of this diagram has $(N_1)_{60}$ as the abscissa, as in Fig. 5), which leads to a decision that a site either will or will not liquefy.

Liao et al. (1988), applying statistical methods (logistics) to many case histories where liquefaction did or did not occur, developed the plot in Fig. 5, which gives the probability of liquefaction for different combinations of shaking intensity and site resistance. It then is possible to multiply the probability of earthquake occurrence with the probability of liquefaction given the earthquake, so as to obtain an overall probability of liquefaction as a result of that particular level of shaking. The calculation can be repeated for different earthquakes with different probabilities of occurrence, and the individual results can be summed to give the overall probability of liquefaction.

There has been growing interest in this approach to evaluating the risk of liquefaction. In developing Fig. 5, no physical constraints were placed upon the combinations of shaking and blow count that might cause liquefaction. In addition, case studies where liquefaction did not occur are much scarcer in the literature than in actuality. Hence it seems likely that the probability of liquefaction is overestimated for points lying well below the 50% probability curve. Loertscher and Youd (1994) have applied logistics to study the influence of magnitude upon the probability of liquefaction. Fenton and Van-

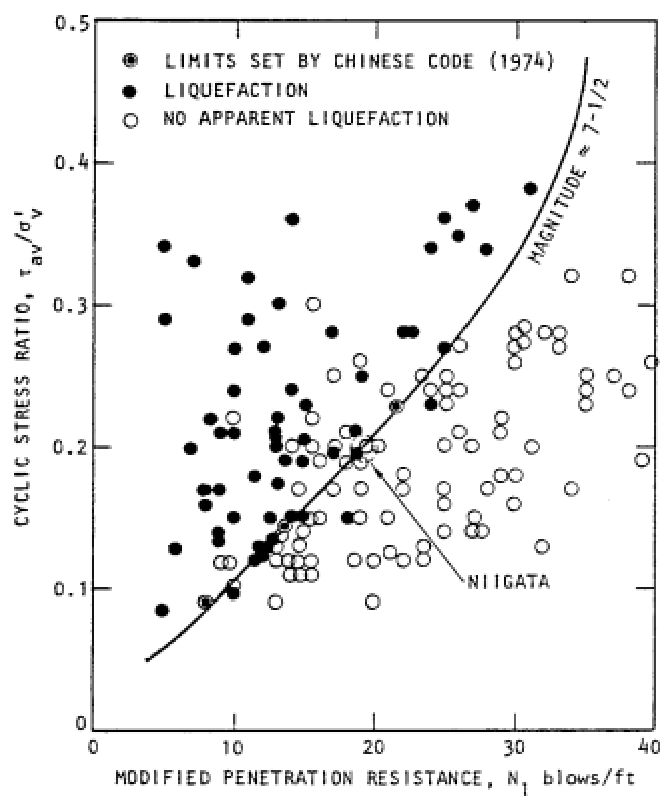

FIG. 4. Empirical Plot for Evaluation of Liquefaction (from Liao et al. 1988, Based upon Work by H. B. Seed and Others)

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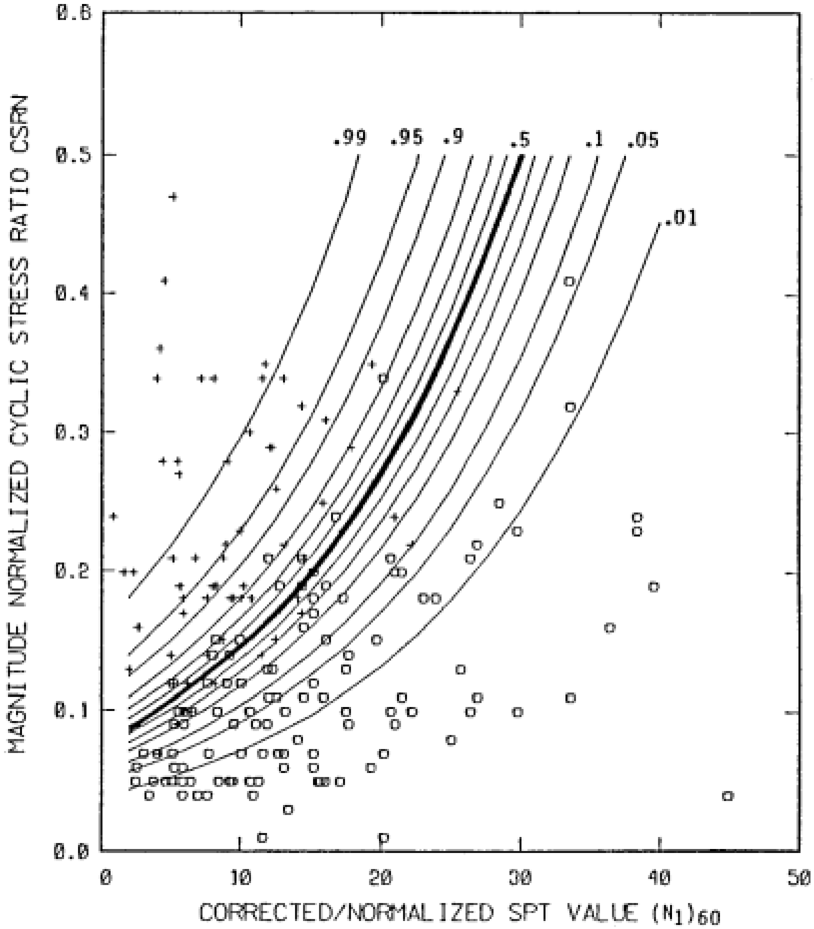

FIG. 5. Probability of Liquefaction by Regression of Case Studies. (Liao et al. 1988)

marcke (1991) have analyzed implications of spatial variability at a site upon the site's susceptibility to liquefaction. Data are being accumulated concerning the consequences of liquefaction— e.g., the resulting lateral displacement or settlement— and this information potentially can be combined into an analysis leading to the probability of some damaging amount of movement. Thus probabilistic analysis of damage caused by liquefaction is a particularly fruitful area for research.

Environmental Problems

I have no professional experience with environmental problems. Hence I can only offer a few observations based upon a superficial reading of a limited portion of the literature.

The word *risk* — in the form of information concerning the likelihood that a given degree of exposure to some substance will cause harmful consequences in humans— is commonly encountered when dealing with environmental problems. However, geoenvironmental engineers evaluating sites or designing waste repositories generally must follow very prescriptive rules with little opportunity for applying probabilistic methodologies. For example, the EPA scheme for ranking of hazardous sites uses a checklist of factors to establish a ''likelihood of release value '' that then goes into a simple equation and is combined with other similarly evaluated factors. Thus, probabilistic studies concerning hazardous sites are today mainly of value in pointing the way to more rational approaches that might appear in the future.

One major problem facing the analysis of pollutant movement through soils is the heterogeneity of typical soils. There is a long literature concerning the stochastic modeling of ground-water flow (Thompson and Gelhar 1990). In words from that paper:

> ''Research . . . has been devoted to the development of more systematic and predictive modeling techniques which explicitly account for natural heterogeneity in a parsimonious statistical fashion . . . these stochastic approaches are aimed at the quantitative description of bulk hydraulic behavior over large temporal and spatial scales while accounting for the influence of small-scale material variabilities.''

In other words, the effect of randomness in local properties (such as permeability) upon the spreading of contaminant plumes is studied, and rules for accounting for these effects are developed. This particular paper uses multiple random-walk simulations.

These studies have assumed a medium that is ''uniform'' on a scale large compared with the local variability of soil properties. A paper published just prior to this conference by researchers at the hosting university (Webb and Anderson 1996) deals with the more difficult problem of large-scale heterogeneities, particularly those associated with braided stream channels. The practical inability to actually map such buried channels is accounted for by multiple simulations.

Here and there, there are isolated examples where probabilistic methods have been used to guide detailed choices during design of remediation measures. For example, Massmann et al. (1991) describe a study concerning a pumping scheme to extract contaminated ground water. The choice of a rate was optimized, using subjective judgments concerning the relative success of different pumping rates. Gilbert and McGrath (1996), in a paper to this conference, present guidelines for managing uncertainties in design of remediation schemes— using probabilistic calculations to bolster their common sense reasoning. Examples of reliability analysis applied to waste containment have been mentioned above.

ACCEPTABLE RISK

There is a considerable body of data that implicitly suggests acceptable risk. Fell (1994, quoting Reid 1989) summarizes risk statistics for persons voluntarily or involuntarily exposed to various hazards, expressed as probability of death per person per year. They range from 0.00014×10^{-3} for structural failure, through 0.009×10^{-3} for air travel and 0.3×10^{-3} for road accidents, to 1.9×10^{-3} for parachuting and 2.8×10^{-3} for deep-sea fishing as an occupation.

For comparison, the average 30-year-old male has, statistically, a chance of 10^{-3} of dying this year. It has been inferred that people, by their actions, implicitly accept a voluntary risk up to 10^{-3} and tolerate involuntary but recognized risks up to perhaps 10^{-5}. The tolerance for risks they suddenly discover or do not understand is lower yet. It is also well documented that risks that may affect a large number of people simultaneously (i.e., air crashes) are less tolerable than risks of individual accidents.

Failure rates can be collected for classes of structures. For example, the average annual failure rate of earthen dams, from all causes, is about 10^{-4}. By no means does this constitute an acceptable rate.

Another approach is to evaluate theoretically the risk of a common class of structures, such as steel-framed buildings. This was done when limit-state codes were being developed for such buildings. The risk of failure, during the lifetime of a structure, implied by accepted designs was found to be on the order of 10^{-4}. (This is for any type of unsatisfactory behavior; the risk of a collapse would be less.)

The vexing question, of course, is How can this information be used to establish allowable risks for specific projects? There is no general answer to this question. Fig. 6 reproduces a first attempt to assemble information to assist with such discussions and negotiations. (Note: Of all the figures with which my name is associated, this is perhaps the most often cited. I had a call about it as recently as the fall of 1995. Greg Baecher, from whom I originally borrowed the figure, laments that he seems best known for a figure he never published himself.) Relations of this general type have been developed in several countries. British Columbia Hydro, as part of an effort to review multi-hazard threats to dams and other facilities (Nielsen et al. 1994), have assembled the information shown in Fig. 7. The proposed criterion limits risk to any one individual to 10^{-4}/year, with

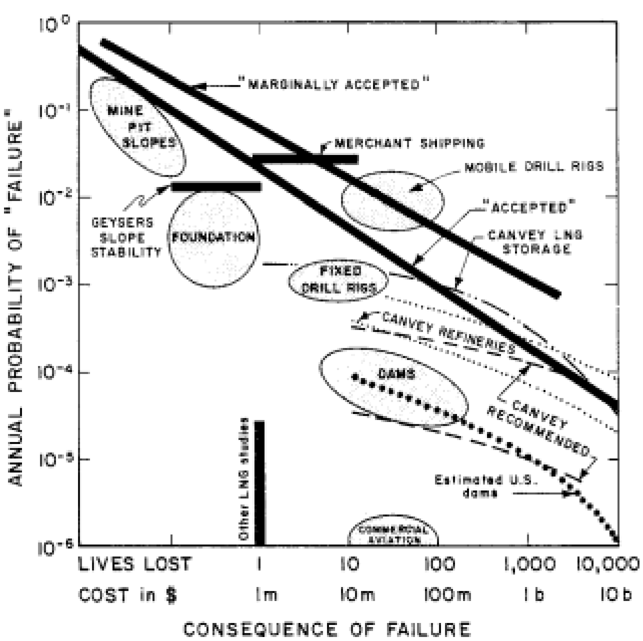

FIG. 6. Risks for Engineering Projects (Whitman 1984)

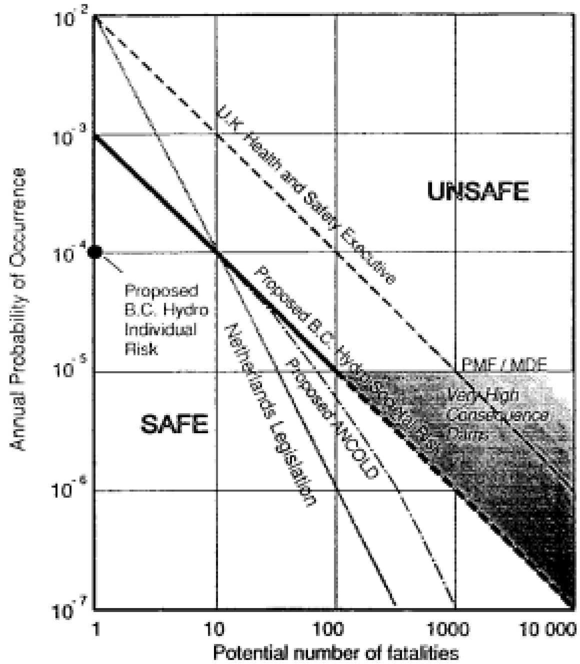

FIG. 7. Various Risk Criteria (Courtesy of BCHydro)

smaller risk levels when potential multiple fatalities are involved. In addition, there is a maximum organizational financial risk for projects whose failure cost exceeds $100 million: The annual expected (i.e., best estimate) risk should not exceed $10,000/year. BCHydro's approach to risk analysis for dams is discussed in a paper to this conference by Vick and Stewart (1996).

In a few problems, the risk calculated for an engineering solution may be compared with an absolute limit to risk. More commonly, quantified risk becomes a vehicle for communication between engineer and client or regulator— to express the degree of riskiness and to compare the relative risk among possible alternative solutions. In any project where geotechnical engineering deals with a significant portion of the effort (which will mean most important projects), it is vital that the geotechnical engineer be part of these communications— to understand how much geotechnical engineering solutions contribute to the overall risk and to explain how this risk might be altered. Obviously, in such discussions a geotechnical engineer must feel comfortable with probabilistic concepts.

Human Errors

As mentioned above, there have been reliability analyses for classes of structures that have actually been built and are in service. It is typically found that actual failure rates exceed predicted failure rates, perhaps by as much as two orders of magnitude. Further examination reveals that most of the failures are the result of human error, e.g., structures not built according to plans, materials not meeting specification, some loading not considered in the reliability analysis, etc. An obvious question then is this: If failures result from oversights not considered in a reliability analysis, why perform such an analysis for judging adequacy of design? The answer is that engineers want to make sure that the probability of failure from things under their control is well less than the failure probability associated with things they cannot control. Not only is this attitude in the best interest of the engineer, but of society as well.

CONSTRUCTION CONTROL

Controlling compaction using field sampling has long been a part of geotechnical engineering, and rules concerning sampling rates and criteria governing acceptability are to some extent influenced by statistical concepts. There continue to be new contributions motivated by new types of problems. For example, specifications typically require that the overall hy- draulic conductivity of a compacted landfill liner be less than some specified limit. Benson et al. (1994a) have developed a procedure for selecting the number of samples that must be tested to ensure a high probability that this criterion is met, and Benson et al. (1994b) demonstrate how borrowed material can be evaluated for potential as a compacted liner. Quality control for membrane liners has also become a geotechnical engineering problem.

Morgenstern (1995) emphasizes the importance of the *ob- servational method*. For any who are not familiar with this concept, it implies adjusting construction procedures and de- tails depending upon observations and measurements made as construction proceeds. Practicioners of this method understand the importance of identifying, in advance of construction, the range of possible soil conditions that may be encountered— and of having plans to cope with possible eventualities. Just describing the observational method suggests opportunities for using probabilistic concepts and methods. If the uncertainties and risks have been quantified before construction begins, then updated information obtained during construction can be used to revise risk estimates and to guide decisions made during construction.

WHEN TO USE PROBABILISTIC ANALYSIS

Ralph Peck participated in the workshop concerning Prob- abilistic Methods in Geotechnical Engineering (NRC 1995). As usual, he was a brave soul, since almost all others attending were certified probabilists. Here is how he summarized the state of the profession:

> ‘‘We see geotechnical engineering as developing into two somewhat different entities: one part still dealing with tra- ditional problems such as foundations, dams, and slope sta- bility, and another part dealing with earthquake problems, natural slopes, and, most recently, environmental geotech- nics. Practitioners in the first part have not readily adopted reliability theory, largely because the traditional methods have been generally successful and engineers are comfort- able with them. In contrast, practitioners in environmental geotechnics and to some extent in offshore engineering re- quire newer, more stringent assessments of reliability that call for a different approach. Therefore, we may expect re- liability methods to be adopted increasingly rapidly in these areas as confidence is developed. It is not surprising that those engineers working in environmental and offshore problems should be more receptive to new approaches, and it should not be surprising that there may be spillback into the more traditional areas.’’

It is difficult to improve upon this characterization of the pres- ent status of utilization of probabilistic methods. I would add that studies for evaluation and remediation of existing facili- ties— such as dams— originally designed by traditional ap- proaches is a fertile field for risk evaluation.

I do want to suggest an alternate classification that looks to the future as well as the present. For the sake of simplification, I will divide geotechnical engineering problems into two broadcategories.

1. Those where the client relies upon codes, regulations, and ‘‘accepted practice’’ to ensure that he receives a sat- isfactory product. This category includes the vast major- ity of ‘‘routine’’ projects.
2. Those where the client, and/or a regulator, is active in a

discussion of potential risks and ultimately assumes at least most of whatever risk is implied by the final choice of design. Such projects are characterized by either the impossibility of eliminating risks completely or by a very high cost of reducing risks to an insignificant level. Thus it is in the interest of the client to become actively en- gaged in decision making. Projects of this type are less common, and typically are large in scale or involve un- usual types of buildings or facilities, or both. However, there is no reason why probabilistic methods cannot be utilized in traditional problems— if a client believes that doing so can be of potential benefit.

When involved in the first type of project, an engineer is unlikely to make use of quantified risk analysis— or of prob- abilistic thinking or statistics, except possibly in connection with planning details of site exploration and characterization or during construction control. However, probabilistic analysiscan be of use when developing requirements of codes and regulations.

Involvement in the second type of project will certainly re- quire an engineer to engage in probabilistic thinking. In some instances, acceptable risk may be specified numerically, and the engineer must choose a design and demonstrate that the specification is met. Even here the client, or at least a regu- lator, will be involved in a significant way, since seldom will there be clear, accepted procedures covering all aspects of the evaluation of risk. More likely, a number of design schemes will be discussed by the engineer and client, until the client (and likely the cognizant insurance company) is satisifed that there is an acceptable balance between cost and risk. Evalua- tion of risk, whether in quantitative terms or merely by words, becomes an important means of communication between clientand engineer.

Role of Probabilistic Methodologies in CodeDevelopment

The NRC report suggests that probabilistic methods can be useful in the development of codes. Indeed, such methods have been used in the process of developing the limit-state codes now common for the structural portions of buildings. During the past decade, there has been an effort to standardize codes within the European Community and to bring geotechnics codes in line with the reliability-based approach to structural codes. These codes emphasize ''limit states'' and partial factors (akin to safety factors) applied to both loads and resistances. The approach often is referred to as Limit-States Design (LSD).

In Canada there has been considerable discussion re LSD. *Geotechnical News* for March 1995 has a piece entitled ''Limit States Design on Trial,'' reporting on a mock trial with argu- ments against and for LSD. The unanimous opinion of the judges constitutes a recommendation to the profession and reads:

> ''The Working Stress Design (WSD) approach is still the common and accepted touchstone for most geotechnical en- gineers. It marries experience to judgement. However, in itself, it does not wholly fit the need for a design approach consistent for both structural and geotechnical engineers. The LSD approach, when utilized in its broadest and most practical sense, namely using factored resistance rather than using partially factored strength parameters, goes far to meet this need and with time and accumulated experienceby practicioners in both structures and foundations will im- prove its quality of practical applications.

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In the United States, where for the most part geotechnical engineers are deeply suspicious of codes, there as yet has been relatively little debate on this matter.

A reading of drafts of the geotechnics portion of the Eurocode actually reveals a quite limited emphasis upon probabilistic methods and thinking. There is a section describing how partial resistance factors for pile design are selected based upon a pile-load test program and on the pile type adopted for design (this section is discussed in NRC 1995).

Eurocode also introduces the concept of a characteristic value, described as follows:

> ''Characteristic values shall be selected with the intention that the probability of a more unfavorable value governing the occurrence of a limit state is not greater than 5%. For parameters for which the values governing field behavior are well established with little uncertainty, the characteristic value may be taken as the best estimate of the value in the field. Where there is greater uncertainty, the characteristic value is more conservative It might sometimes be helpful to use statistical methods. However, it is emphasized that this will rarely lead directly to characteristic values, since these depend upon an assessment of the field situation.''

Safety factors (actually material resistance factors) are then to be applied to characteristic values. Eurocode suggests a factor of 1.2 to 1.25 for friction angle and 1.5 to 1.8 for cohesion — but provides exceptions and ''outs''. There are some complicated concepts here that require considerable thought.

The draft chapter on retaining walls contains primarily a lot of good, well-accepted advice concerning good design. Here and there is specific guidance regarding partial safety factors and load conditions (such as location of a water table). Simpson (1992) has written a very thoughtful critique concerning the use of partial factors for the design of retaining walls. In his conclusion he states:

> ''At present, the best available tool is engineering judgement; there is danger that formal procedures, if they are sufficiently simple to be prescribed, will jettison valuable information. However, it is sensible to provide objective checks on judgement whenever possible The best way to combine these requirements is to make the designer directly responsible for design values adopted in the calculations. In addition, codes should specify how design values should be checked against values derived using characteristic values and partial factors. Both the characteristic and design values should be defined in terms of the expected probability that the values will occur in the field situation in such a way as to govern the occurrence of limit states. Numerical analysis of soil test results alone will often be an inadequate basis for selection of these values.''

No matter how one feels concerning the wisdom of codes governing geotechnical practice, these are important ideas and questions. I hope that they will be discussed vigorously at this conference.

FURTHERING USE OF PROBABILISTIC METHODOLOGIES

The NRC report's principal recommendation is that ''education of new geotechnical engineers, as well as practicing engineers, in probabilistic methods should be undertaken.'' A retired professor cannot possibly resist commenting on such a matter.

In the MIT Department of Civil and Environmental Engineering, we have for years required a subject in probability theory, taught by faculty from the Department. This requirement has proved less than a great success, primarily because it is rarely followed up by applications in subsequent subjects, whether they be oriented to engineering science or to design. Actually, the same problem tends to exist with much of the material taught in other beginning subjects in engineering science. Observations such as these are stimulating a rethinking of engineering curricula, with a gradually increasing trend toward teaching material as it is needed for some application. This stimulates student interest in the basic material, but means that students may not get as thorough a grasp of basics and appreciate the potential application of this material beyond the particular context within which it is taught. In other words, the issue of teaching probabilistic methods to geotechnical engineers will inevitably be caught up in an ongoing debate concerning the pedagogy of teaching.

Morgenstern (1995) argues that it is the principles of *risk management* that should be taught at a fundamental level and then illustrated through applications. In his words, *risk management* relies on rational analyses and involves situation appraisal, problem and potential problem analyses, and decision analyses. I agree with this perspective. I would prefer to see a subject covering the practice of risk management taught early in a curriculum, rather than a subject in probability theory. Of course, some basic concepts concerning probability must be incorporated into this type of subject.

The NRC report also urges that major geotechnical projects should involve a probability expert as part of the project team to provide opportunities for close interaction between that expert and the other team members. Following on from the thoughts in the last paragraph, I would recommend rather that an expert in risk management should be included as a member of the team. Of course this expert should be well grounded in probability theory and its application.

Having made these arguments, I certainly do agree that geotechnical engineers as a whole should become better versed in the important basic concepts of probability theory, reliability theory, and risk analysis. The NRC report contains, in an appendix, an excellent primer concerning these matters. In my Terzaghi Lecture (Whitman 1984), I urged the need for examples showing how risk can be quantified and used for decision making. As has been noted above, a number of such examples has now been published. This is a good start, but more are needed, especially those illustrating clearly the role played by probabilistic methods in actual decision making. The ready availability of examples will go a long way in piquing the interest of practicing engineers.

Perhaps the key question is What can be done to interest clients in designs based upon probabilistic thinking rather than traditional approaches? I believe a client will always become interested in different approaches if it appears there is potential for financial benefit, for satisfying regulators, or even for public relations purposes. A client may receive such stimuli from various sources, but a key stimulator is the engineer for the project. A phrase in the middle of Peck's summary holds the key: Traditional methods are used ''because engineers are comfortable with them.'' Clearly there will continue to be projects that are best engineered using traditional approaches. A challenge for this conference is to identify types of projects where the ''spillback'' predicted by Peck should begin to occur in the near future.

There are at least two relatively recent developments that will inevitably lead to more widespread use of risk assessment. One is increasing concern about existing buildings and infrastructure that do not meet modern standards of design with regard to natural hazards. Major examples are dams designed to pass flood flows well less than required today and with little or no regard for the potential effects of earthquakes. It will be very expensive to ''fix'' all such dams, and some represent greater risks than others. Prioritizing remedial actions is a necessity. The U.S. Bureau of Reclamation and organizations in Canada and Australia have begun to develop procedures for dealing with these problems (Note: A rich literature has begun to appear since the Conference. For example, see Bowles et al. (1998) and other papers in the proceedings of that meeting), and it seems clear that there will be at least some role for quantitative risk assessment.

In earthquake engineering, there is beginning to be emphasis upon performance-based design, taking into account the likelihood of significant earthquakes. Increasingly there are building owners who do want to understand the risks that their investments may become damaged and nonfunctional. Potential site failures and foundation movements will often be part of the potential problems.

FINAL REMARKS

Traditional engineers rightly worry that too much emphasis upon analysis might drive out engineering judgment and lead to unsatisfactory designs. Wu et al. (1975) long ago provided a thoughtful example of how a probabilistic analysis might go wrong: a slope that contains a plane of weakness but is assumed to be homogeneous when conducting a statistical analysis of data for strength. This potential problem exists with any analysis, whether deterministic or probabilistic, until it is well calibrated to experience. This is why I have emphasized the importance of model errors. Thoughtful probabilists always emphasize that probabilistic methods do not replace traditional methods. Rather, probabilistic methods are tools that can effectively supplement traditional methods for engineering geotechnical projects, providing better insights into the uncertainties and providing an improved basis for interaction between engineers and decision makers.

All this is particularly true concerning a methodology especially popular at the moment: reliability analysis. Christian et al. (1994) offer some valuable insights concerning this tool:

> ''Reliability analysis is especially useful in establishing design values for factor-of-safety representing consistent risks for different types of failures The most effective applications of probabilistic methods are those involving relative probabilities of failure or illuminating the effects of uncertainties in the parameters.''

Similar perspectives are needed concerning all of the existing and yet-to-be-developed probabilistic methods.

I hope I have helped you appreciate, in general terms, how the quantification of uncertainty can play a useful and important role in engineering projects. I also hope I have stimulated you to learn about the available examples of practical application. With Peck, I agree that probabilistic methods are now playing important roles in a number of engineering problems, and that there will be increasing spillover into problems now engineered by traditional methods. The continued challenge is to recognize problems in which probabilistic thinking can contribute effectively to the engineering solution— while at the same time not trying to force these new approaches into problems best engineered with traditional methods and viewpoints.

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