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Risk Reduction Versus Risk Assessment: A Case for Preventive Geotechnical Engineering

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The topic of risk analysis has become greatly sophisticated in recent years. Owners and regulatory agencies have the ultimate concern of cost-effective risk reduction. Uncertainty and risk do not lend themselves to precise quantification, a fact that has resulted in some risk analyses finding a less than enthusiastic response from clients. All facilities rest on geologic materials and thus have a degree of uncertainty that often expresses itself most strongly in geotechnical elements of the project. This "natural" problem, and consideration of synergy and entropy, logically leads one to emphasize prevention rather than precise prediction of event sequences. Other professions, notably medicine and dentistry, have recognized the importance of preventive efforts and have formulated formal preventive programs. The size, complexity, and cost of many modern facilities suggest that a prudent approach to continuing acceptable facility performance should include formal preventive efforts, even in the planning stages of the project. A conceptual outline of a preventive geotechnical engineering program for a constructed facility is presented.

The field of risk analysis has grown rapidly in recent years, incorporating sophisticated mathematics, theory of probability, and modeling techniques (1). The costs of failures remain so high that owners and regulatory agencies demand a good understanding of risk in allocating funding for all project phases. In light of current environmental concerns and the growing size and complexity of projects, this need to understand risk has a foundation in prudence. Actual failures, such as the Teton Dam, suggest that we need to improve our understanding of risk for engineered facilities.

This paper looks briefly at the concept of risk, adding a few relevant comments regarding the ultimate source of risk. The paper suggests that a majority of the ultimate users of risk analyses remain either confused by the results or unconvinced of the merits of such studies. It is suggested that one way to bring a modicum of clarity to the subject lies in the consideration of formal risk reduction and how such an approach varies from the assessment mode. A brief conceptual outline of a preventive engineering approach for geotechnical aspects of facilities concludes the paper.

ENTROPY AND SYNERGY AND THE CONCEPT OF RISK

The presence of uncertainty (doubt or lack of absolute sureness) in a situation gives rise to risk (chance of loss or degree of probability of loss). Much recent work in risk analysis has rightly focused on reducing the uncertainty in the data needed to analyze risk in various situations (2). Frequently, probabilistic models assist in actually carrying out risk analyses. These models seek to identify and quantify sources of uncertainty and then incorporate the results into the variance of key aspects of the model. Often, the outcome of such a study results in a numerical assessment of the probability that some event will occur, a "number" many clients have some difficulty in evaluating or using.

In geotechnical engineering, we often assign the major uncertainties to the vagaries of the geological setting and ask the client for more exploration funds to "reduce" uncertainty. Some engineers overemphasize numerical predictions of performance and, again, exhaust large amounts of funds in sampling, testing, analyzing, and evaluating small (usually nonrepresentative) soil samples to arrive at the "perfect" prediction (3).

Perhaps we might help to keep these many (often conflicting) factors in proper perspective by considering the more fundamental aspects of uncertainty and thus arrive at a more efficient and cost-effective approach to dealing with risk. The terms synergy and entropy offer important insight into the concept of risk.

A general definition of synergy states that one cannot predict the behavior of complete systems by using as a basis only the known behavior of one or more subsystems. We can often come close, for a variety of reasons, but a degree of uncertainty exists regarding all predictions. Another definition of synergy states that the sum of the combined effects of a group of subsystems can greatly exceed, or greatly fall short of, the simple algebraic total of the separate effects. These definitions, and their general ramifications, provide strong incentive to workers whose mission seeks cost-effective prevention of adverse performance and should provide a measure of reason to those who seek to assess risk. Some suggest that synergy, or the concept represented by the term synergy, constitutes one of the natural laws of the universe. These two definitions suggest that we cannot make totally accurate predictions, even when experts try (3), and that the combined effects of groups of subsystems can produce "unusual" results.

When engineers deal with geotechnical aspects of constructed facilities, they face uncertainty. The size of samples tested in the laboratory and the "disturbance" of those samples render it difficult to produce truly accurate design parameters. Three key geotechnical parameters--strength, compressibility, and permeability--all change with time and with variations in effective stress. More and more data will never remove the uncertainty. Frequently, more data only confuse the issue.

Another problem in this regard stems from the second law of thermodynamics--i.e., the "entropy law". Others have discussed in great detail the role of the entropy law in economics (4) and in the current battle of preserving certain environmental standards (5). The entropy law remains involved in every aspect of behavior. A "simple" definition states that the entropy of the universe, or of an "isolated" structure, increases constantly and that this increase remains continuous and irrevocable. The modern interpretation of this degradation of energy consists of a continuous turning of order into disorder. The notion of introducing "outside" information into a system represents the basis of preventive measures. Some interest in entropy and soil behavior has taken place (6); however, the results of this work have not found application in practical engineering problems.

Some consider that the entropy law does not express a natural law but instead reflects the difficulty of the human mind in describing a state that involves a large number of details. Certainly this law has a unique place in science in that it marks the recognition by that most trusted of all sciences, physics, that qualitative change exists in the universe. The entropy law does not determine when the entropy of a closed system will reach a certain level nor exactly what will happen at that point; however, it does determine the general direction of the entropic process of any isolated system.

The concept of synergy remains linked to the concept of entropy because of another principle: the emergence of novelty by combination. Most of the properties of water do not logically follow from universal principles applied to the elemental properties of the components of water, oxygen, and hydrogen. If we look around us, we see many physical examples of the entropy law. Things do generally wear out--systems tend toward a condition of high probability, i.e., failure--if external energy is not applied.

Entropy and synergy remind us of the most fundamental sources of uncertainty in the universe. A proper appreciation of the role of these two factors in all endeavors, especially geotechnical engineering, will force us to carefully evaluate the marginal utility of additional soils or geologic data and will also force us to consider the difference between risk assessment and risk reduction.

COMPLEXITY OF CURRENT SITUATION

In our very complex world, we seem to have reached a point where owners, operators, policymakers, and regulators often remain somewhat polarized from the designers and constructors of large facilities. High inflation rates have put tremendous pressure on engineers to come up with efficient and cost-effective systems (facilities), but they often lack the up-front money from the owners to permit the kind of studies necessary to generate needed design data. For owners, the financial losses (and/or political problems) associated with unplanned outages, or "failures", remain very large for some facilities (large power plants, for example). Some owners find it difficult to know quite what to do with the results of a study (by a competent, well-meaning engineer) that states that the owner's new dam has a probability of $2x10^{-4}$ of failing in the next year. The owner doesn't want it to fail--ever! And he is willing to pay a "reasonable" amount to ensure that it does not fail. Clearly, the clients want to prevent (avoid) problems at a reasonable cost. Many design engineers do not have experience with their "products" long after they are built and thus have not had the blessing of important feedback. Formal preventive efforts, especially during the project design and planning phases, remain relatively new to much engineering.

Most engineers want to do a good job but resent what they consider unfair cost restrictions on their creativity and competence by short-sighted owners. Few owners actually understand the complex nature of the building process for large projects and seldom realize the risk that they take in carrying forward projects that have significant geotechnical aspects. Some clients ask, "Why do I have to pay so much for an 'assessment' of risk? Can't we just spend the money and begin reducing risk in the beginning?" This remains a difficult question to deal with because of the interdependent nature of risk factors.

SUCCESSFUL PREVENTIVE TECHNIQUES

Other professionals have considered prevention an important element in their delivery of services and have made great strides in formalizing effective preventive techniques. The latest piece of evidence that strongly supports this attitude is the major change of emphasis on the part of the American Cancer Society (after Congressional urging) from seeking cancer cures to preventing cancer. The force of circumstance acts very strongly, but some organizations resist far beyond what a practical person would consider reasonable. A brief look at several of these efforts can give good insight into how engineers could pursue similar tasks.

The approach of the dental profession has changed significantly over the years. Early practice focused primarily on reparative dentistry. Over the years, in addition to new reparative techniques, dentists have introduced the use of regular checkups by a professional; better cleaning methods, i.e., with dental floss; better toothbrushes and toothpaste; and the use of fluoride in drinking water and as a mouthwash. The general public has an increased awareness of the importance of better dental care. In addition, the use of oral surgery and orthodontia, along with X-rays, has made the practice of dentistry more sophisticated. The profession slowly adopted the prevention concept, and people even more slowly believed that prevention would pay dividends above its cost. Some dental problems do not show up for years, when it remains too late to really do anything about them. Dr. G.B. Black spoke to a class of dental students as follows: "The day is surely coming, and perhaps within the lifetime of you young men before me, when we will be engaged in practicing preventive dentistry rather than reparative dentistry." Dr. Black made this statement in 1896. Now, in 1979, I think we see excellent evidence that preventive dentistry does work, remains cost effective, and results in better overall general health and fewer serious dental problems. Quite clearly, however, it has not cured (or prevented) all dental problems. An explanation for this "shortcoming" may lie in the continued high intake of processed sugar by people in developed countries.

Preventive dentistry has four key features:

1. Formal examination by a professional, for purposes of monitoring and control;
2. Simple, regular tasks that the patient performs, such as cleaning and flossing;
3. Recordkeeping of performance and written notes by the professional; and
4. Special diagnostic and reparative techniques, such as X-rays.

Despite significant improvements, no dentist would guarantee a cavity-free patient.

The medical profession has used the term preventive medicine since the 1930s; however, the essential features of this concept have existed for many years. The earliest preventive measures employed in medicine consisted largely of nonmedical items--i.e., immunization, water purification, sewage separation, adequate housing, and a reasonably well-balanced diet. These measures remain quite effective, have not improved significantly with time, and also require no participation by a physician. In fact, the plumber, the public health inspector, the building inspector, and the civil engineer rank alongside the physician when one considers preventive medicine in its broad aspects. In the United States, the medical profession has made relatively good progress in the prevention of infectious diseases, accidents, wide-scale poisoning, etc. However, in the case of more complicated diseases, such as cancer, heart disease, stroke, genetic defects, and diabetes, essentially nothing is done in the way of prevention. Some of these more complicated diseases can be prevented only through changes in personal life-style, changes that generally come very reluctantly. In many areas, particularly in sports medicine, the emphasis remains on prevention rather than on predicting events (7).

The medical profession recognizes the need to develop incentives to cause people to carry out preventive efforts on their own. Apparently, massive data will not alone turn the tide. In view of this, the medical profession also suggests that essentially nonmedical efforts can have highly effective results (8, p. D10). The importance of diet to general health has received much recent attention. In addition, the importance of the environment (air and water pollution) in promoting general health has gained much acceptance. Periodic medical checkups will not alone prevent heart attacks, but a relatively stress-free employment, good diet, plenty of exercise, and freedom from air and water pollution will have a measurable effect on lowering the incidence of heart attacks for the general population. Perhaps the engineering profession should think of more effective ways to encourage "behavior" that will result in specific decreases in the number of failures noted.

Several key features of most preventive medical efforts are (a) a "healthy" environment; (b) periodic evaluations by trained professionals; (c) records of performance "data" such as blood pressure, pulse rate, and weight; (d) direct involvement of the "user" (patient) in the process; and (e) a simple method of evaluating results.

Note also, however, the great difficulty in truly preventing very complicated diseases--i.e., the difference between cancer and a broken leg.

PRUDENCE AND COST-EFFECTIVENESS: A MARRIAGE OF NECESSITY

Many owners of large facilities take more prudent care of their cars and power lawn mowers than they do of their multi-million-dollar facilities. Capital investments and the consequences of adverse performance justify a certain attitude toward preventive maintenance of one's automobile or lawn mower. The same logic (with roughly the same reasoning) should apply when one deals with bigger numbers. Many geotechnical engineers find a strange dichotomy in this area when they ask for money for a few more piezometers to monitor the post-construction behavior of a project.

Forget geology for a moment and the uncertainty it brings to our work. Time remains one of our enemies, especially in geotechnical aspects, where a change only in moisture content can drastically alter the safety factor for a project. Prudence suggests that we monitor pore pressures (continually) in certain key areas. Cost-effectiveness demands that we not have too many sampling stations. Who remains the best judge of how many sample locations and how often to sample? Most likely the job requires an "experienced" geotechnical engineer--one who has had design, construction, and post-construction experience. Because of the organization of many firms, people with such qualifications remain relatively uncommon.

Cost-effectiveness does not lend itself to simple evaluation, especially when we have "success" at preventing problems. We "learn" a lot from failures, and they provide data in assigning uncertainty, risk, and "costs" to current projects. The key to successful programs lies in a continual evaluation of data, full and open disclosure to the client regarding their meaning, and effective involvement of the client's personnel in the entire process of obtaining and evaluating the data. The engineer needs to continually convey to the client the meaning of his or her careful deliberations, and the client has the right to both question the engineer's conclusions and inform him or her of the current level of risk that seems appropriate to the client's present and future business goals. Good communication remains the key to actually getting a cost-effective response to a prudent action.

RISK REDUCTION VERSUS RISK ASSESSMENT

Some facility owners have had a less-than-enthusiastic response to risk-assessment studies. The U.S. Army Corps of Engineers has designed and constructed many dams without (as of July 1980) a single catastrophic failure (no failures in 7900 dam years). Despite this enviable record, some researchers find it appropriate to assign a degree of probability for failure to the Corps of Engineers inventory (9). The power of statistics can sometimes overwhelm even circumstance.

The Florida phosphate industry builds literally miles of new "dams" each year. State legislation has raised the level of general design input for these dams, which, in turn, has reduced the frequency of adverse performance. Mine owners, ever cautious of costs, generally respond to the logic of risk reduction rather than risk assessment. Risk reduction strikes them as a positive step, while some experiences with risk assessment have resulted in a beautifully bound report that still leaves them with tough decisions to make and the sinking feeling that the report does not help in making them.

I believe that we understand the fundamentals of geotechnical engineering well enough to offer positive suggestions to clients that will reduce risk almost immediately while at the same time generating data that will permit the continual assessment of risk. Focusing on water control seems a logical place to begin. Granted, we do have complex problems in geotechnical engineering, but simply understanding and using the principle of effective stress will go a long way toward preventing adverse behavior. I believe that much of the adverse geotechnical performance noted occurs because of the inability of a number of engineers (even self-styled geotechnical types) to grasp the essentials of this most elementary of our powerful fundamentals. The plea is, Emphasize risk reduction first and keep an open mind regarding what you will then "learn" about risk analysis. Observe reality and discover the obvious.

PREVENTIVE GEOTECHNICAL ENGINEERING: A MODEST PROPOSAL

My concept of preventive geotechnical engineering (directed primarily at risk reduction) has grown out of a number of years of experience on a wide variety of civil engineering projects, experience that includes the areas of planning, design, construction, and post-construction evaluation. The work includes a fair number of failure studies as well as court litigation over the cause, responsibility, and liability for the failures. This experience has led to the formulation of Neff's Laws of Failure:

1. Without external actions focused on prevention, all facilities will eventually fail.
2. Failures (unplanned adverse behavior) cost a lot.
3. Many failures need not happen.
4. Preventing most failures involves a small fraction of the cost of the actual failure.
5. Preventing failures involves a continual assessment and evaluation by a multidisciplinary team (designer, constructor, and owner-operator) of changing conditions that can affect desired performance.

Other professions, notably medicine and dentistry, have recognized the efficiency and cost-effectiveness of preventive measures and have developed formal preventive programs. For large, complex civil works projects, especially ones with significant geotechnical aspects, it appears prudent to consider preventive engineering efforts from the conceptual planning stage for the project. The demand for efficient use of resources, the incredibly high cost of unplanned outages, and increased emphasis on not violating the environment all reinforce the need for such programs. An outline of the elements of a preventive geotechnical engineering program is given below:

1. Clear statement of desired performance (owner-operator-designer)--(a) During construction, (b) shortly after construction, and (c) long after construction;
2. Identification of a single person in responsible charge of each concerned group--(a) Owner, (b) designer(s), (c) contractor(s), (d) operator(s), and (e) maintenance;
3. Review and evaluation of precedence with previous similar projects (especially identification of how previous failures could have been prevented)--(a) Risks, (b) failures, (c) uncertainty, (d) remedial tasks, and (e) costs;
4. Review for owner by independent designer--(a) Value engineering and (b) safety engineering;
5. Review for owner by independent contractor--(a) Construction methods, (b) construction sequence, and (c) cost estimate;
6. Formal written document by designer and reviewers--(a) Major uncertainties in design, (b) key assumptions in design, (c) key parameters that control performance, (d) critical values of key parameters at each stage of construction (including post-construction), (e) possible consequences of adverse performance and operation, and (f) method(s)

to obtain values of key parameters;

7. Identification of method(s) to provide incentive and increase awareness of all team members--(a) Awareness of key aspects of desired performance and (b) incentives to cost-effectively achieve desired performance;

8. Formation of geotechnical task force--Inclusion of staff from owner, designer, contractor (after chosen), consultants, and contracts group;

9. Development and implementation of a construction monitoring and control system--Input from owner, designer, contractor, and consultants; and

10. Development and implementation of continuing evaluation plan for expected life of the project--(a) Cost, (b) responsibility, and (c) accountability.

As more experience and field data appear, the work tasks in this list will change to reflect reality and circumstance. I do not consider the outline all-inclusive for very complex projects nor that every project will require all of the items listed in this outline. I encourage comments from readers to help modify this list and add to its usefulness and effectiveness.

I fully acknowledge the preliminary and somewhat elementary nature of the remarks put forward in this paper. A great deal of work must occur before such preventive geotechnical programs can find effective application on a wide variety of projects. A critical review of these ideas and concepts should promote further discussion on their merit. We need to carry out research (funded by government or other policy-setting groups) to help develop the tools necessary to perform such work effectively.

Successful studies will require the integration of multidisciplinary effort that focuses on key fundamentals that control the behavior of geologic materials as well as the more general principles, procedures, and methods that affect facility performance from a geotechnical point of view. A list of primary subject areas would include (a) engineering; (b) applied research; (c) geology; (d) system analyses; (e) soil-rock-structure interaction; (f) data collection, manipulation, and portrayal; (g) motivation and behavior modification, and (h) economics. I have begun to assemble such a team and have initiated planning sessions to outline project work scopes. I have also begun to integrate preventive concepts into design courses at both the graduate and undergraduate levels.

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