A CASE STUDY OF RISK ANALYSIS
IN DAM DESIGN

by

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ABSTRACT

The balancing of risks and costs is inherent in geotechnical practice. Traditionally, the likelihoods and consequences of failure of geotechnical project components are seldom quantified, and alternative design measures to mitigate risks are not usually presented to the project owner in advance. Should litigation later occur, the geotechnical engineer may be held solely accountable for risk tradeoffs made in the owner's perceived interest. Probabilistic risk analysis (PRA) provides a systematic method to communicate the engineer's judgment about uncertainties and their effects, and to present and compare alternative risk reduction strategies. The use of PRA is illustrated for a case study of a dike on karst. Here, the technique documented the rationale supporting selection of design and exploration strategies that would not likely have been apparent from more customary approaches. In this way, PRA documented risk-related design decisions and provided for informed owner review and participation in the decision making process.

INTRODUCTION

TRADITIONAL APPROACHES TO RISK IN GEOTECHNICAL ENGINEERING

Risks are a staple of everyday geotechnical practice and the profession has developed customary, though seldom explicitly stated, methods to address them. Risks are spawned by uncertainties, usually related to subsurface conditions but also due to imperfect knowledge and idealizations in analytical modeling.

In practice the geotechnical engineer typically attempts to reduce uncertainties to the greatest extent possible within budgeted constraints, for example by further subsurface investigations or higher levels of analytical precision. Having done so, he will present to the client or project owner a design solution based on the best available information and judgment, incorporating a degree of conservatism felt to be justified by the level of remaining uncertainty and the consequences of adverse or unpredicted behavior of the design.

Having identified the design solution, caveats are sometimes included to point out the limitations of the data upon which it is based. However, there is a traditional reluctance to explicitly identify any residual risk associated with the design or consequences of adverse behavior. The following are often cited in support of this position:

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1) a reluctance to needlessly alarm the client/owner by describing "worst case" scenarios whose likelihood is extremely remote

2) an appearance of not having solved the owner's problem, or an appearance of inadequate professional abilities

3) an appearance of being more concerned with liability-related self interest than with solving the client's problem

4) a reluctance to impart the perception to third-parties (regulators, project opponents, or the public) that the design might not incorporate an adequate degree of safety

The traditional approach to risk in geotechnical engineering has served the profession remarkably well, and may continue to do so in the great majority of cases. However, there are some conditions for which conservative design or exploration methods to reduce uncertainty and risk do not exist or are not feasible in the context of project time and economic constraints. Inevitably, some unanticipated failures will occur, and standards of legal accountability are increasingly divergent from those of traditional practice. The failure on the part of the engineer to have explicitly identified risks, consequences, or risk-mitigating alternatives is being more commonly cited in U.S. courts in cases of geotechnical-related litigation.

An example involves a cement plant at a site having collapsible soils. Initial subsurface investigations identified the presence of some such soils, but with no clear pattern in their depth, extent, or magnitude of collapse on saturation. Several phases of subsequent exploration only revealed the same pattern of data inconsistency. With the need to proceed on the basis of available data, the geotechnical engineer recommended shallow foundations for structures felt to be located in areas of lower collapse potential, with some provisions for control of surface infiltration. Large-scale collapse subsequently occurred over major portions of the site with damages on the order of $20 million.

Among the issues in the ensuing litigation was that the engineer had not identified to the owner the risk associated with shallow foundations. It was also shown that deep pile foundations could have carried loads to non-collapsible strata for an additional $11 million, but that this option had been discarded as too costly without formally presenting it to the owner.

By contrast, another case involved a landslide that occurred during excavation of a dam spillway. Conditions related to possible landslide occurrence were identified in feasibility investigations, and several other spillway alignments were addressed in the feasibility report but found to be much more costly. Here, the identification of potential risk and systematic study of alternatives were felt to be factors that contributed to out-of-court settlement of the claim against the geotechnical engineer.

ROLE OF RISK ANALYSIS IN GEOTECHNICAL PRACTICE

If legal standards demand greater accountability in the way risk is treated in geotechnical engineering, then the engineer must become more specific in addressing risks for projects where unavoidable uncertainties remain even after applying accepted standards of professional practice. Probabilistic risk analysis (PRA) provides one method to do so.

PRA consists of three basic elements:

1) identifying various alternative measures to reduce risk, and their associated costs

2) estimating the extent to which failure consequences would be reduced by each alternative

3) estimating the degree to which failure likelihood would be reduced for each alternative by means of failure probability

Of these components only the third, estimating the probability of failure, represents an extension of procedures that would otherwise be carried out for many geotechnical projects. Here, it is important to distinguish probability concepts from statistical procedures. Statistical evaluations, for example, are an important element in establishing seismic risk (Weichert and Rogers, 1987) and flood overtopping likelihoods for dam spillway upgrading (Von Thun, 1988), and the recent geotechnical literature contains many examples of statistical characterization of soil properties (Bowles and Ko, 1984). While statistical methods may aid in establishing failure probabilities, PRA does not require them. At the basis of PRA is the use of subjective probability, which can be viewed as the engineer's degree of belief that a particular outcome of an uncertain event might occur (Baecher, 1983). Such judgment-based expressions of uncertainly as "possible," "likely," and "probable" are well established in geotechnical practice, and estimating subjective probability requires only that this judgment be scaled to a likelihood range of 0 to 1 for various component events in a failure sequence. While subjective probabilities may legitimately vary from one engineer to another, this makes them no more arbitrary or imprecise than the engineering judgments upon which they are based.

By quantifying likelihoods in this way, PRA provides a vehicle to communicate engineering judgment about uncertainties to the owner. PRA procedures inform the owner of options available to mitigate risk and provide him with the opportunity to participate in establishing appropriate levels of risk, or at least to be informed about the risk associated with a proposed design strategy. According to current practice, courts often view a "good" design decision as one that is successful and a "bad" decision as one that is not. By providing a systematic procedure, identifying risk-reducing alternatives, and communicating uncertainties, PRA procedures can demonstrate after the fact that decisions were not made in an arbitrary or uninformed way, and can evaluate a design decision more according to its support at the time it was made rather than its outcome with the benefit of hindsight.

UNCERTAINTIES IN DAM DESIGN

PRA APPLICATIONS

Accounting for uncertainty in dam design is especially difficult because the consequences of failure can be immense both in terms of economic cost and loss of life. For major dams this is reflected by well-supported conservatism in design.

However, PRA is finding growing application to dam safety retrofitting of existing structures, for which costs can be extremely high, and to smaller or lower-hazard dams where extreme conservatism may be economically unacceptable.

The analytical framework for using PRA techniques in problems of dam design and dam safety is well developed (Benjamin, 1983; Gruetter and Schnitter, 1982). Methods to estimate dam failure probabilities have been developed for concrete dams (Bury and Kreuzer, 1985) and for levees on soft foundations (Duncan and Houston, 1983). The application of PRA techniques to design of dams and embankments has generally been in two categories - optimization of design features, and selection among design alternatives. The former class is represented by optimization of embankment slopes for dikes on soft soils of the James Bay Project (Societe d'Energie de la Baie James, 1983), for dikes crossing the Great Salt Lake (Whitman, 1984), and for two rockfill dams in Romania (Priscu, et al., 1982). These applications have in common the balancing of failure risks associated with varying degrees of conservatism in slope design, by the associated differences in cost. For the other category, an example of PRA for selecting among design options is provided by Vick, et al. (1985) for alternative tailings dam designs with varying seismic resistance.

UNCERTAINTIES IN KARST TERRAIN

Of foundation uncertainties encountered in dam design, those posed by karst are among the most difficult. For large dams, two classes of problems are presented: impounding capability of the reservoir, and structural integrity of soluble foundation rock. In the former case, for example Hales Bar Dam in Tennessee and Anchor Dam in Wyoming, the reservoir may fail to fill despite extensive sealing efforts. In the latter case, the ability of cavern roofs to withstand stresses imposed by the dam, and the hydraulic stability of cavern infillings under high reservoir head are of principal concern. Required foundation treatment can be extreme in both cost and difficulty, as illustrated by Kentucky Dam (Moneymaker, 1950) and more recently Khas Laem Dam in Thailand (Bergado, et al., 1984).

For lower dams both the nature of the problem and its diagnosis are somewhat different. Because excavating the foundation to bedrock is seldom economically feasible, upward stoping of cavities by ravelling and piping in overlying foundation soils is of primary concern as depicted on Figure 1. This mechanism, rather than structural collapse of the cavity itself, has been responsible for loss of impoundment in small reservoirs and lagoons (Warren, 1974). Aley, et al. (1972) also describe several instances of sinkhole collapse within and around reservoir areas induced by reservoir infilling. It is notable, however, that documented structural failures of dams attributed to sinkhole collapse are very rare despite the widespread nature of reservoir impoundment problems in karst terrain. Therefore, the presence of karst features cannot itself be taken as evidence that dam safety problems will necessarily occur.

Unlike high dams where intensive explorations can be concentrated within relatively limited foundation and abutment areas, lower dams frequently span greater distances making them poorly suited to economical cavity detection by such conventional means as extensive drilling or exploration adits. Heavy reliance must instead be placed on various geophysical or remote sensing methods (Ruth and Degner, 1984) but considerable uncertainty in the presence, location and size of cavities inevitably remains.

The PRA case study subsequently described involves such a low dike with typical uncertainties in subsurface information regarding the presence of sinkholes. In this case, however, the performance of several kilometers of existing dikes in an immediately adjacent area provided key, but conflicting, judgmental inferences. PRA was used as a tool to better quantify and evaluate the uncertainties, and to aid in selecting among several alternatives identified to reduce the risk of sinkhole-induced dike failure.

CASE STUDY

PROJECT DESCRIPTION

The project site is located in central Florida in a region containing both active sinkholes and older (paleokarst) solution features. A mining operation and processing plant at the site have produced extensive impoundments containing waste clays (slimes) from rock washing operations. Current expansion of this facility will require a large fresh water impoundment adjacent to the existing slimes ponds. The principal confinement of this impoundment, designated the North Dike (ND), is the main focus of the case study. These primary project features are shown on Figure 2(a).

The North Dike will span a distance of 1200 m. with a maximum height of 12 m. The design contemplates a homogeneous section of compacted clay fill. A cutoff will penetrate a stratum of near-surface sands, which have been shown by local experience to provide adequate underdrainage of the downstream portion of the embankment. A typical section of the North Dike is shown on Figure 2(b).

SUBSURFACE CONDITIONS

Limestones beneath the project site include the uppermost Miocene Tampa Formation and the underlying Oligocene Suwannee Limestone. Erosion and solutioning have reduced the Tampa Limestone to a thickness of 3 to 6 meters. Extensive mining-related exposures show it to be soft, with vugular porosity consisting of extensive but isolated fist-sized inclusions of stiff, highly plastic clay. Degradation of the limestone characteristically leaves a layer of clay residuum overlying a comparatively uniform weathered rock surface. Typical soil conditions in the North Dike foundation shown on Figure 3 include a thin layer of alluvially-deposited sands and clayey sands overlying the residual clays.

Distribution and Occurrence of Karst Features

Surface reconnaissance and mining-related exposures at the site show solution features to be of two types. Ancient infilled sinkholes or "paleokarst" features are those caused by collapse of weathered, erosion-weakened Tampa Limestones and overlying soils into cavities in the underlying Suwannee Limestones. These conical sinkholes typically range from 15 to 30 m. in diameter at the ground surface, tapering to an apex on a slope of about 45 degrees. Such paleokarst features are distributed throughout mined-out areas on an estimated mean spacing of 150 to 300 meters. All are infilled with clay and rubble soil to unknown depths.

Active solution features, on the other hand, are those which accept water and control local drainage patterns. The largest such feature within the proposed reservoir area is approximately 60 m. in diameter, with well-established vegetation and trees on its sideslopes. Other active solution features designated "solution pipes" are those where collapse has not yet occurred. They consist of clustered, rubble-filled surface depressions several centimeters up to a meter across. The distribution of known karst features within the reservoir area is shown on Figure 4.

These solution features observed at the site reflect in a general way their wider geographic distribution. Local data show 15 recorded sinkhole collapse events in the county, several within 4 to 5 km. of the site. In a nearby and geologically similar area Littlefield, et al. (1984) studied two quadrangles of high sinkhole density. In one, 537 paleokarst features were identified from photoimagery with 45 reported collapses. In the other, 181 ancient sinkholes and 10 collapses were documented.

Subsurface Investigations

Various remote sensing and geophysical methods were applied to supplement information on known solution features within the reservoir area and North Dike foundation. Since regional sinkhole distribution may correspond to large-scale fracturing and structural trends, a primary exploration strategy was to attempt to identify lineations projecting from known sinkhole locations through the North Dike foundation. In this attempt, both black-and-white and thermal infrared imagery were examined. No evidence of additional solution features or photolineations was found. A radar survey to detect subsurface cavities was also attempted, but the radar was unable to penetrate clay layers overlying the limestone. Consequently, a microgravity survey was conducted in the area having the largest and highest density of known solution features. Although several gravity anomalies were identified, they failed to conform with regional structure or to allow for extrapolation of directional trends.

Performance of Existing Dikes

The behavior of existing slimes ponds adjacent to the proposed reservoir shown on Figure 2(a) provides important information. These ponds cover almost 10 times the area of the proposed water impoundment. They are enclosed by 13 km. of internal and external dikes generally similar in height and composition to the proposed North Dike, and reasonably uniform geologic conditions are present throughout the vicinity. Sinkholes are known to exist within the slimes ponds from reports of periodic rapid drops in fluid level of up to a meter. Yet it is significant that no distress or failure of the existing dikes has occurred despite such convincing evidence of sinkholes in the slimes pond reservoir.

PROBABILISTIC FORMULATION

The possible presence of sinkholes in the North Dike foundation poses a potential dam safety concern, but one clouded by conflicting inferences that can be drawn from available information. It is clear that sinkholes could exist in the North Dike foundation. However, the successful performance of existing slimes pond dikes suggests either that sinkholes in the foundation of these dikes are fortuitously absent, or that the dikes are able to successfully withstand whatever structural effects the presence of foundation sinkholes may impose. Further, it is not clear what additional exploration efforts feasibly can or should be undertaken for the North Dike when available subsurface information fails to support the existence of directional trends in spatial sinkhole distribution, and when the cost of a conventional sinkhole drilling program could exceed the cost of the North Dike itself without any guarantee of unambiguous results.

To better address these issues a probabilistic formulation of the problem was undertaken. The probability of North Dike failure due to sinkholes, p[f], can be expressed according to the expression:

$$p[f] = p[s] \; p[f/s] \tag{1}$$

where:

p[f] = probability of dike failure (defined as rapid breach leading to uncontrolled reservoir release)

p[s] = probability of at least one sinkhole in the dike foundation

p[f/s] = conditional probability that dike collapse will occur given the presence of one or more foundation sinkholes

The component probabilities p[s] and p[f/s] can be estimated separately on basis of field observations.

Probability of Sinkhole Occurrence, p[s]

The presence of sinkholes is treated as a series of spatially independent random events, such that prior knowledge of the presence of a sinkhole at one location would not alter the assessed probability of sinkhole occurrence in any adjacent area. This assumes that sinkholes are not interconnected or influenced by preferential directional trends. Another assumption is that sinkhole occurrence is not time-dependent. The random variable representing sinkhole presence at a particular location has only two possible states: either a sinkhole is present, or it is not.

Observations in and around the proposed reservoir show major sinkholes or solution pipe clusters at spacings ranging from 60 to 600 m., with 300 m. taken as a representative mean spacing. This compares reasonably well to mean spacing ranging from about 500 to 1000 m. in geologically related areas (Littlefield et al., 1984). Further, site observations of both active and paleokarst features suggest that a reasonable estimate of the surface diameter of sinkholes or solution pipe clusters is about 30 m. Given a mean sinkhole diameter of 30 m. and mean spacing of 300 m., the ratio of sinkhole area to coverage area is 0.0079. This defines the probability of occurrence of a sinkhole in any area increment equal to that of the sinkhole (730 $m.^2$).

This simplified statement of sinkhole occurrence can be represented as a series of independent Bernoulli trials for sinkhole presence within discrete segments of the North Dike foundation. Taking the North Dike as an average of 46 m. wide and 1220 m. long, the probability of at least one sinkhole in the foundation according to the binomial distribution is:

$$p[s] = 1 - [(1 - p)^n] \tag{2}$$

where p = probability of sinkhole occurrence in one 730 $m.^2$ foundation area increment n = number of Bernoulli trials, equal to number of area increments in dike foundation (76)

Substituting appropriate values, it is found that p[s] = 0.45. In other words, probabilistic formulation of geologic observations suggests that there is about a 50/50 chance that at least one sinkhole will exist in the North Dike foundation.

Conditional Probability of Failure, p[f/s]

For dike failure to result from the presence of sinkholes, a series of events must occur. First, sinkhole overburden must either structurally collapse by upward stoping, or cavity infilling must be eroded or extruded to produce a void capable of carrying concentrated seepage. The dike must then be incapable of structurally responding to these events. Soil properties such as plasticity, cracking resistance, and piping resistance of the clayey foundation and dike fill materials suggest that the dike will possess some degree of resistance to at least moderate foundation deformation produced by sinkhole collapse or subsidence. Experience derived from the performance of existing slimes pond dikes aids in estimating this resistance, expressed as the conditional probability of dike failure given the presence of sinkholes, p[f/s].

If the average base width of the existing dikes is taken as 46 m., and if sinkholes are assumed to occur on a mean spacing of 300 m., then sinkhole occurrence beneath the 13 km. of existing dikes can be modeled as a series of Bernoulli trials, as previously described. According to equation (2) the probability of at least one sinkhole being present beneath the existing dikes is 0.99. Also, the mean value of the binomial distribution is n(p), or 6.5 in this case. So it is virtually certain that the existing slimes pond dikes have successfully spanned at least one sinkhole, with the most likely number being 6 or 7. Using this estimate, the probability that no dike failures are observed can be computed on the basis of equation (1) for various trial values of conditional failure probability, as shown in Table 1.

TABLE 1
CONDITIONAL FAILURE PROBABILITIES,
EXISTING DIKES

Assumed Conditional Probability p[f/s]	Resulting Probability That No Failure Occurs
0.1	0.01
0.5	0.51
0.1	0.90
0.05	0.95
0.01	0.99

Table 1 does not allow unambiguous determination of p[f/s]. It does, however, provide a judgmental context for interpreting existing dike performance. It can be said, for example, that the possibility that p[f/s] is less than 0.5 is relatively remote, and that p[f/s] consistent with observed behavior is more likely to be in the range of 0.10 to 0.01.

Another approach to estimating p[f/s] is the fault-tree method. By this procedure, the failure sequence is decomposed into component events, each conditional on its precursor. The fault tree for North Dike failure shown on Figure 5 has been constructed to a level of detail such that component probabilities can be reasonably assessed. Table 2 represents the author's probability estimates. The conditional probability that sinkhole collapse will occur given that a sinkhole is present, derives from the previously-described regional observations showing ratios of collapses to sinkholes ranging from 0.055 to 0.08. The remaining probabilities quantify the author's judgment and experience in evaluating the factors shown on Figure 5.

TABLE 2
FAULT TREE COMPONENT PROBABILITIES

Event Probability	Author's Estimate
E_1 - p[collapse/sinkhole]	0.07
E_2 - p[cracking/collapse]	0.8
E_3 - p[piping/cracking]	0.5
E_4 - p[breach/piping]	0.7

$$p[f/s] = (p_1)\ (p_2)\ (p_3)\ (p_4) = 0.02$$

The results of the fault tree approach according to the author's best estimate supports p[f/s] of about 0.02. This value lies within the range of 0.10 to 0.01 previously indicated to be most likely from evaluation of existing dike performance.

Probability of Dike Failure, p[f]

From previous estimates of p[s] and p[f/s], by equation (1) p[f] = (0.45)(0.02) = 0.01. In other words, there is roughly a one-in-one hundred chance of North Dike failure due to sinkholes according to the foregoing synthesis and interpretation of available information. It is instructive to compare this probability to that for other potential failure causes. The failure rate from all non-hydrologic causes for eastern U.S. earth dams less than 50 feet high is approximately 1.4×10^{-3} (U.S. Bureau of Reclamation, 1987). Hence, failure of the North Dike due to sinkholes alone would be almost 10 times more likely than failure of similar dams due to all other structural causes combined. This assessment is consistent with intuitive judgments and provides a useful comparison in gauging and validating sinkhole risk estimates. Such a comparatively simple risk statement also provides meaningful information to the non-engineer.

SINKHOLE RISK ANALYSIS

Alternative Design Strategies

Having quantified the risk of failure from sinkholes, several methods were identified to reduce the hazard either by reducing the likelihood of failure or by mitigating failure consequences. From these options, three of the most feasible and practical were culled: to proceed with North Dike construction without mitigation measures; to construct a secondary dike immediately downstream; or to provide a warning system.

To construct the North Dike without any specific mitigation of sinkhole hazard provides a base case to which other alternatives can be compared, and implies that the likelihood of failure constitutes an acceptable risk. This interpretation might be supported on the basis that the incremental risk posed by North Dike failure is small compared to that which has been implicitly accepted for some time from the existing slimes pond dikes. Hence, this alternative is to proceed with North Dike construction on the basis of existing information, without further measures to mitigate sinkhole hazard. The estimated cost of North Dike construction would be $1.6 million.

Another alternative is to construct a secondary retaining dike immediately downstream from the North Dike whose function would be to temporarily retain water from North Dike failure. A secondary dike would have foundation dimensions approximately the same as the North Dike, and it too would have a corresponding probability of failure from sinkholes. However, uncontrolled reservoir release would require failure of both the North Dike and the secondary dike. Because the secondary dike could be conveniently constructed using mine waste from ongoing operations its cost would be less, about $600,000.

A warning system represents a non-structural alternative to mitigate loss of life in the event of North Dike failure, but economic losses would still occur. The site configuration is such that reservoir failure would inundate the mine and plant, but there would be no off-site inundation hazard to downstream residents or the general public. It is estimated that a sensor and alarm system could be installed in the dike crest to detect rapid deformation at a cost of about $200,000. Although the effectiveness of a warning system is uncertain, many documented sinkhole collapses have developed over periods of several hours to several days, and complete reservoir release in the event of North Dike failure would also take place over some period of time. Considering these factors, it is estimated that there would be a 50/50 chance of at least several hours' warning time prior to full reservoir release. Given this warning time, it is also estimated that there would be a 50/50 chance of complete evacuation of project personnel, a 30% chance that evacuation would be 50% effective, and a 20% chance that no evacuation would occur.

Failure Consequences

In the event of full reservoir release, failure consequences would be of two types: economic losses both direct and indirect, and loss of life. It is estimated that mine and plant repair, cleanup, and lost revenue might total on the order of $20 million. To this would be added the cost of repairing the North Dike, estimated at full replacement cost.

Various approaches have been used to account for loss of life in cost-benefit analyses by assigning a dollar value per life saved by hazard reduction strategies. A full discussion is beyond the scope of this paper, but two comparatively recent examples provide useful guidance for the North Dike study. Draft guidelines for PRA studies of nuclear reactor safety have proposed standards corresponding to $5 million per life saved (U.S. Nuclear Regulatory Commission, 1982). Also, the need to perform cost-benefit assessments for proposed safety regulations have led the U.S. Occupational Health and Safety Administration and the U.S. Office of Management and Budget to establish a range of $2 million to $5 million per life saved in the construction industry (ENR, 1985). It has been noted that these values are high in comparison to the range of $200,000 attributable to other safety measures such as highway and auto safety improvements (O'Donnell and Mauro, 1979; Okrent, 1980). Nevertheless, a value of $2 million per life saved is believed to represent an applicable value for purposes of the North Dike study. It is estimated that up to 50 mine and plant personnel would be at risk from North Dike failure.

Decision Tree

The three alternative strategies and their associated component probabilities are portrayed in decision tree format on Figure 6. Component probabilities are multiplied to obtain the probability of occurrence for each branch. For each alternative it is convenient to express the expected cost as the sum of initial cost and risk cost, where initial cost is that for North Dike construction and sinkhole hazard mitigation, and risk cost is the sum of the products of branch probability and the corresponding potential loss. Figure 6 shows that of the three options considered, constructing a secondary dike has the lowest expected cost and would be the preferred option on this basis.

Additional Exploration

In view of the limited available data, one might also consider the option of performing a more extensive subsurface investigation - logically, an intensive and deep drilling program to detect limestone cavities. A modest extension of the PRA was used to evaluate further exploration.

If it were possible to obtain perfect subsurface information that could precisely define the location and extent of foundation sinkholes, the cost of obtaining this information would define the upper limit for any future exploration program. Given certain knowledge of sinkhole locations a grouting program would be conducted to fill the cavities, but some uncertainty would still remain regarding effectiveness of the grouting itself. In this case, it is estimated that a grouted sinkhole might be 10 times less likely to cause dike failure, or in other words that $p[f/s] = 0.002$. It can also be shown that the expected number of sinkholes in the North Dike foundation is one, and a cost of $200,000 is estimated for surface treatment and grouting of this sinkhole.

This set of conditions is represented by an additional branch of the decision tree shown by the preposterior analysis on Figure 7. The probability that grouting would be required is the prior probability of sinkhole presence, or 0.45. The expected cost of perfect exploration in conjunction with North Dike construction is then $1.8 million. The maximum expenditure justified for any exploration program would equal the difference between the expected cost of perfect exploration from Figure 7 and the expected cost of $2.22 million for the secondary dike, or $420,000. In other words, further subsurface exploration is worthwhile only to the extent that it reduces risk more than other available means to do so. Considering that even an intensive drilling program would not likely provide definitive sinkhole information and that the cost to construct a secondary dike is only slightly more than the cost of such a program, further subsurface exploration was not pursued for the North Dike.

SUMMARY AND CONCLUSIONS

The selection of basic design concepts often involves implicit tradeoffs between risks and project cost, and design decisions must be made at an early stage of project planning when only preliminary data are available and corresponding uncertainties are greatest. The design problem of evaluating sinkholes in a dam foundation and interpreting their effects presents an extreme example of the difficulty in accurately gauging risk and selecting design and exploration strategies on a purely judgmental basis. In the North Dike case, the presence of sinkholes together with the successful performance of existing slimes pond dikes were conflicting factors in the intuitive assessment of risk. To have proceeded with North Dike construction on the basis of the satisfactory performance of existing dikes would not have addressed the known presence of sinkholes in the vicinity. On the other hand, a very conservative North Dike design strategy would not have been supported by the fact that dikes in a similar setting have not failed. The instinctive reaction, to call for further exploration, would commit the owner to a very costly program with questionable success in fully laying the problem to rest. It is unlikely that either this design paradox or its liability implications would have been resolved with great confidence without systematic treatment of risks.

For the North Dike, interpreting observations in a probabilistic context provided more clearly defined statements of likelihoods and risks. PRA allowed for selecting among a suite of various mitigative measures, incorporating the important components of failure consequences. The North Dike case also shows that judicious interpretation of the kinds of data ordinarily available from preliminary geologic and geotechnical studies may provide a great deal of probabilistic information. One can often translate ordinary observations into simple probability statements and models to effectively apply PRA to difficult design decision-making problems.

Tradeoffs between acceptable risk and project cost are inherent in the practice of geotechnical engineering, and in many if not most cases the experience and judgment of the engineer may best qualify him to make them. However, for inherently high-risk cases such as that illustrated, calling upon the engineer to be solely responsible for such tradeoffs may exceed the requirements of professional responsibility, not to mention prudent liability exposure. Since the project owner ultimately bears the risks and pays the costs of the facility, it is appropriate that the owner should have an informed involvement in risk-related decision making. For the North Dike case, detailed descriptions of failure scenarios, probabilities, alternatives, and consequences effectively and quantitatively communicated to the owner the best judgment of the geotechnical engineer. PRA also provided guidance on whether to embark on an exhaustive exploration program. It provided a rational basis for establishing that other available options would provide a more cost-effective vehicle for risk reduction, a decision that might otherwise have been perceived as an unsupported departure from more traditional geotechnical practice.

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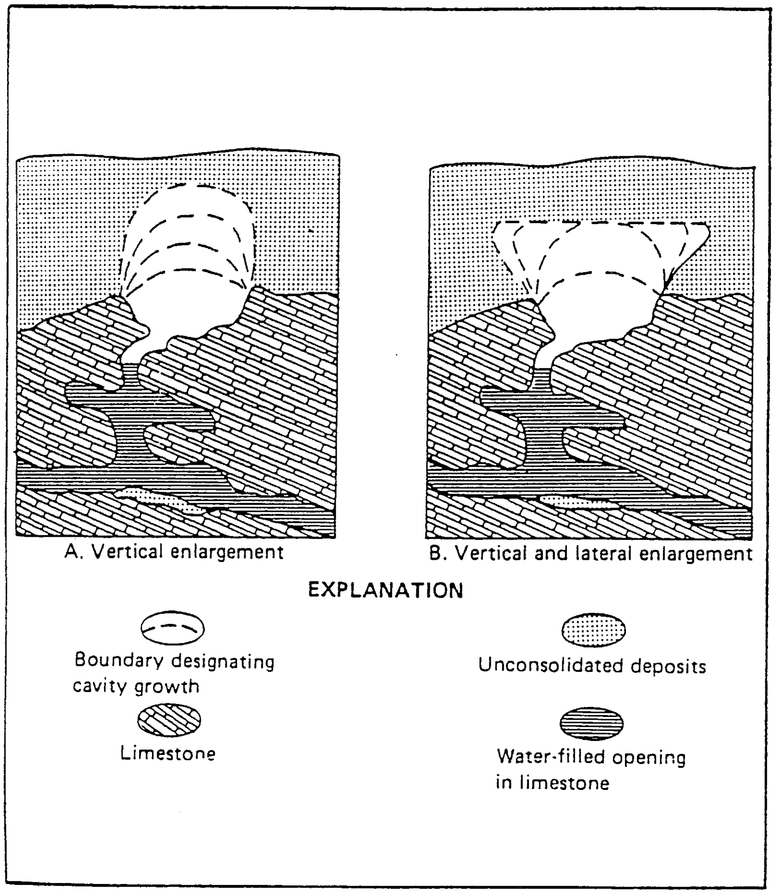


Figure 1 - Mechanism of Cavity Development in Soils (after Newton, 1984)

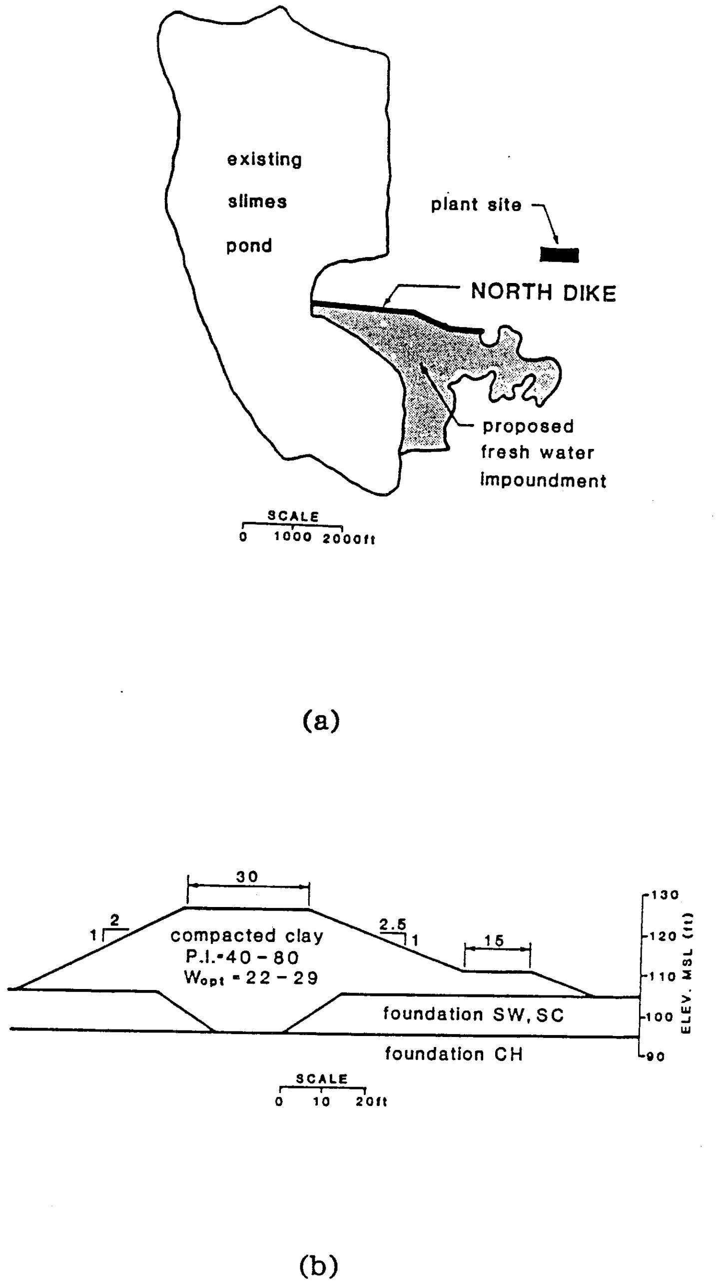


Figure 2 - (a) Project Components; (b) Typical Section, North Dike

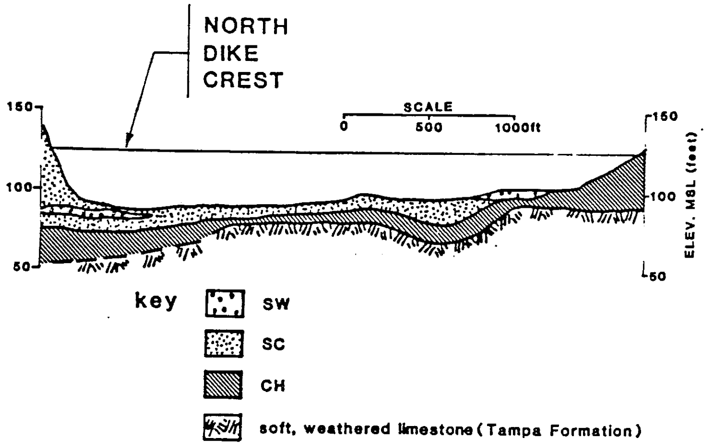


Figure 3 - Subsurface Soil Profile, North Dike Foundation

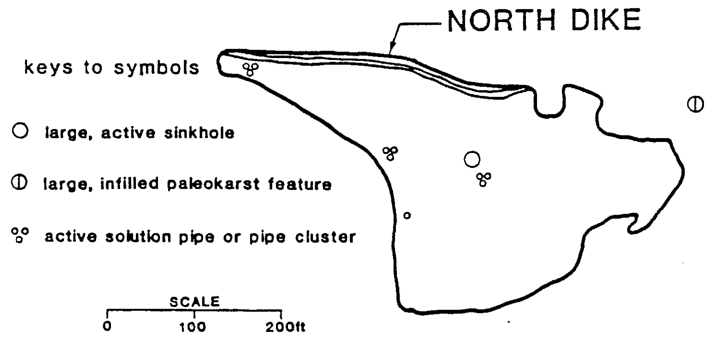


Figure 4 - Distribution of Known Karst Features in Reservoir Area

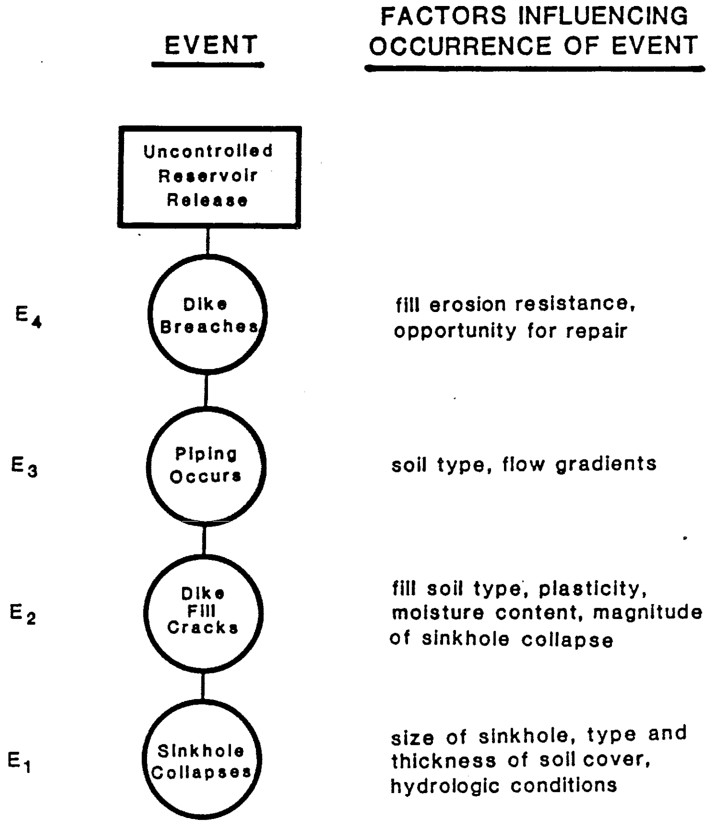
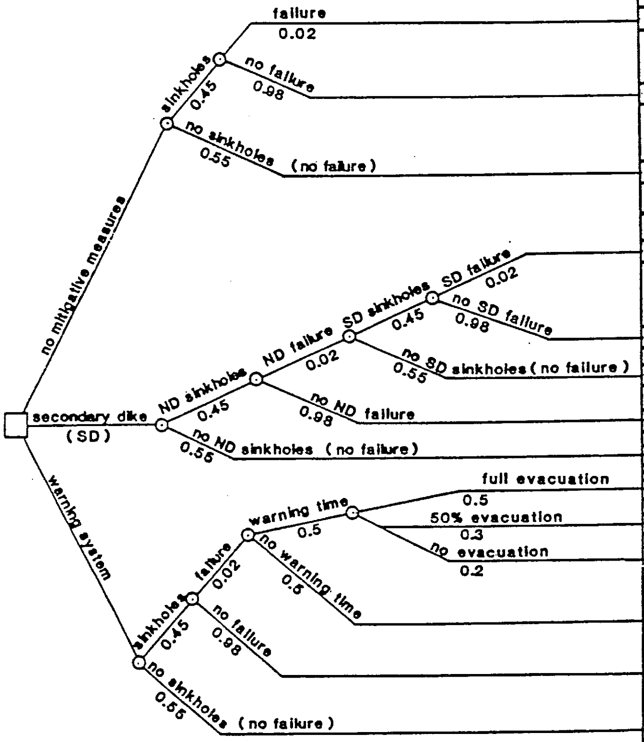
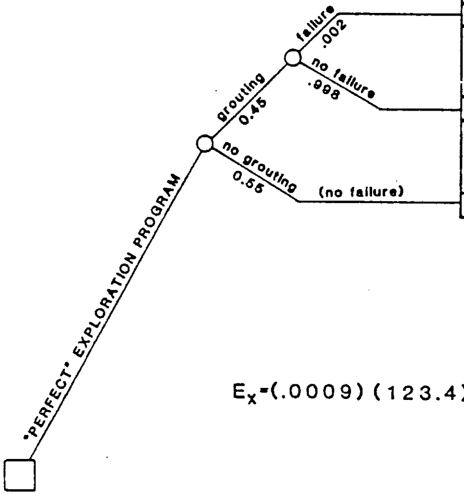


Figure 5 - Event Tree for North Dike Failure, Given Sinkhole Presence



branch prob.	$ losses x 10^6			risk cost	ND cost	mitigation cost	expected cost-$\$ x 10^6$
	economic	life	total				
.009	21.6	100	121.6	1.09	1.6		$2.69
.441	–	–	–	–			
0.55	–	–	–	–			
.00008	21.6	100	121.6	.010	1.6	0.8	$2.22
.004	1.6	–	1.6	.006			
.005	1.6	–	1.6	.008			
0.44	–	–	–	–			
0.55	–	–	–	–			
.002	21.6	–	21.6	.003	1.6	0.2	$2.61
.001	21.6	50	71.6	.072			
.001	21.6	100	121.6	.122			
.005	21.6	100	121.6	.608			
0.44	–	–	–	–			
0.55	–	–	–	–			

Figure 6 - Decision Tree for North Dike Alternatives



BRANCH PROB.	LOSSES		INITIAL COST		TOTAL COST $\$ x 10^6$
	ECONOMIC	LIFE	ND	GROUTING	
.0009	21.6	100	1.6	0.20	123.4
.449	—	—	1.6	0.20	1.8
0.55	—	—	1.6	—	1.6

$$E_x = (.0009)(123.4) + (.449)(1.8) + (0.55)(1.6) = \$1.80 \times 10^6$$

Figure 7 - Decision Tree for "Perfect" Exploration