RISK ASSESSMENT AND RELIABILITY FOR LOW LEVEL RADIOACTIVE WASTE DISPOSAL

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ABSTRACT

The reliability of critical design features at low-level radioactive waste disposal facilities is a major concern in the licensing of these structures. To date, no systematic methodology has been adopted to evaluate the geotechnical reliability of Uranium Mill Tailings Remedial Action (UMTRA) disposal facilities currently being designed and/or constructed. This paper discusses and critiques the deterministic methods currently used to evaluate UMTRA reliability. Because deterministic methods may not be applicable in some cases because of the unusually long design life of UMTRA facilities, it is proposed that a probabilistic risk assessment-based methodology be used as a secondary method to aid in the evaluating of geotechnical reliability of critical items. Similar methodologies have proven successful in evaluating the reliability of a variety of conventional earth structures. In this paper, an "acceptable" level of risk for UMTRA facilities is developed, an evaluation method is presented, and two example applications of the proposed methodology are provided for a generic UMTRA disposal facility. The proposed technique is shown to be a simple method which might be used to aid in reliability evaluations on a selective basis. Finally, other possible applications and the limitations of the proposed methodology are discussed.

INTRODUCTION

The reliability of low-level radioactive waste disposal facilities is a major concern in the licensing of these structures. Prior to issuance of a license, the Nuclear Regulatory Commission (NRC) must be convinced that a given disposal facility is acceptably reliable. For the UMTRA project, reliability engineering is therefore included as an integral part of the quality assurance program. To date, UMTRA reliability engineering has consisted solely of deterministic evaluations. It is agreed that such evaluations should be used as the primary method of determining reliability. However, because of the 1000-year design life of UMTRA facilities, the precedents required to make completely accurate deterministic evaluations may, at times, be lacking. Therefore, it is proposed that a risk assessment-based methodology be used as a supplementary, secondary means of evaluating geotechnical reliability. An acceptable level of risk for UMTRA facilities can be developed based on what is considered acceptable for other critical engineering applications. Lifetime failure probabilities can be estimated, and reliability quantitatively assessed, by comparing estimated levels of failure probabilities to the acceptable levels of risk.

EVALUATING UMTRA RELIABILITY

Existing Methods

Geotechnical reliability has been evaluated historically using methods based solely on past precedents. Similarly, the reliability of UMTRA disposal facilities generally has been evaluated in qualitative terms only. In these qualitative evaluations, past performances of earth structures are considered and then used to extrapolate the future performance and reliability of specific design features at the disposal facilities. This method is the most simple and practicable way to evaluate reliability for earth structures. The continued use of such methods is therefore recommended as the primary means of evaluating reliability for UMTRA facilities.

However, as discussed by DeMello[1], dependence on precedents alone can be potentially dangerous in geotechnical engineering. Moreover, because of the relative lack of precedents for long-term low level waste disposal facilities, the application of deterministic methods to UMTRA facilities is subjective and should be supplemented by a secondary, less subjective method.

Proposed Secondary Method

A probabilistic risk assessment-based quantitative analysis can be used as a supplemental method to provide additional assurance that precedents assumed in qualitative evaluations are applicable. The use of such methods in evaluating geotechnical reliability has been recognized and accepted[1,2,3] and is considered by many to be the best method available to evaluate high-level nuclear waste disposal[4]. However, because of the nature of geotechnical engineering, practioners advise that for most applications probabilistic methods be used for supplementary purposes only[2,5]. Therefore, for UMTRA facilities, it is proposed that probabilistic methods be used as a secondary means of evaluating reliability. Deterministic evaluations currently being used are recommended as the primary means.

In general, the secondary method involves performing a quantitative comparision of calculated lifetime failure probabilities to "acceptable" failure probabilities for a variety of design features. If the probability of failure for a given feature is calculated to be less than the acceptable level, the design is said to be relatively reliable. The overall scheme for evaluating reliability, as proposed in this paper, is illustrated in Fig. 1.

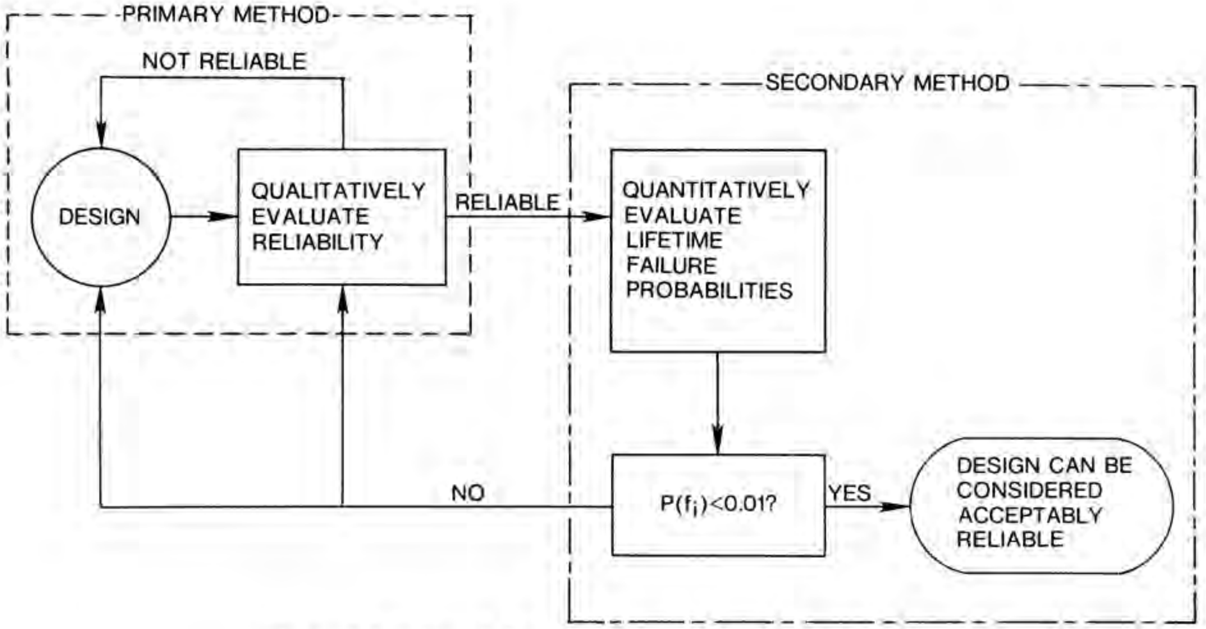

Fig.1 Schematic of Proposed Methodology for Evaluating Reliability of Applicable Design Features.

Acceptable Levels of Risk

To evaluate the reliability of design features for UMTRA facilities, an estimate of the acceptable (or allowable) level of risk is required. A comparison of failure consequences of an UMTRA facility to those of conventional earth structures (for example, water retention dams) must be made in order to identify an acceptable level of risk.

For conventional earth structures, failure consequences are generally assessed in monetary terms or in terms of design life mortalities[2,5]. However, for UMTRA facilities (and for remedial works in general), design life economics and consequential mortalities are not easily quantified. Unlike conventional structures, remedial works create the potential for saving lives which would otherwise be lost. Therefore, failure of a remedial design results in potential saving not being realized. This is particularly true for the UMTRA project, for which applicable standards require that the disposal facilities be designed and built such that no active maintenance is required. For these reasons, it is most appropriate to express failure consequences for UMTRA facilities as the number of savings not realized if failure occurs. Estimates of these savings have been made previously[6] and were assumed for comparative purposes. (This method of calculation assumes that failure occurs instantaneously at the beginning of the design life. Such an assumption is conservative, given the fact that failure of an UMTRA facility is inherently a non-instantaneous process.) A comparative plot of acceptable risk is presented in Fig. 2.

The values of acceptable risk, expressed as lifetime failure probability, are shown to be on the order of 10^{-2}. This value is identical to that suggested by Junge and Dezman[7] as reasonable for UMTRA sites. For the analyses presented herein, 10^{-2} will therefore be used as a threshold value in the evaluation of the relative reliability of a design feature.

Calculating Lifetime Failure Probabilities

The probability that failure will occur during the design life of a structure can generally be expressed in terms of conditional and prior probabilities as[3]

$$p(f_i) = p(a_i)p(f/a) \qquad (1)$$

where:

$p(f_i)$ = the lifetime failure probability for a given failure mechanism over the design lifetime of i years.

$p(a_i)$ = The lifetime prior probability that a given loading event will occur over the design life of i years. [For constant loading events, such as gravity forces, $p(a_i) = p(a_o) = 1$.]

$p(f/a)$ = The conditional failure probability that a failure will occur if the specified loading event occurs.

i = design life, in years

Annual prior probabilities are most often expressed in terms of the annual probability of occurrence, or the average inverse of the return period of the loading event[3]. Lifetime prior probability can be expressed as

$$p(a_i) = 1 - [1-p(a_o)]^i] \qquad (2)$$

where:

$p(a_o)$ = annual prior probability of a loading event (average inverse of the loading event return period)

For instance, if an earthquake with a recurrence interval of 10,000 years is used as the loading event in a dynamic stability analysis for an embankment

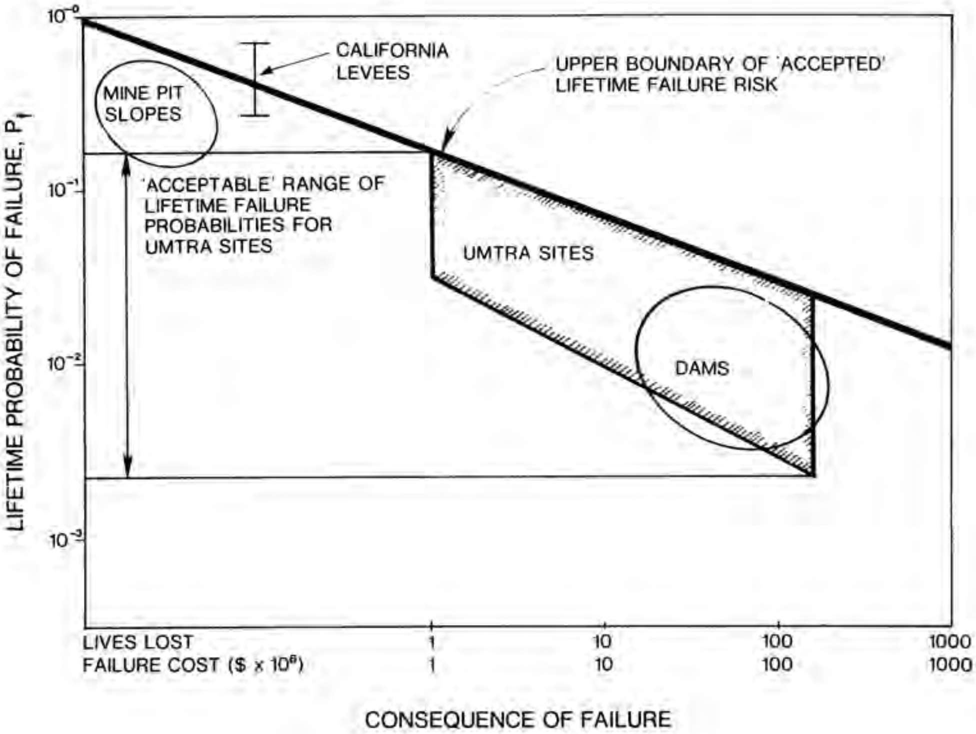

Fig.2 Acceptable Level of Risk for UMTRA Facilities[2]

with a design life of 100 years, then

$$p(a_o) = \frac{1}{10,000} = 0.0001, \text{ and}$$

$$p(a_i) = 1 - [1-0.0001]^{100} = 0.01$$

Conditional failure probabilities can be evaluated in a variety of ways. For the purposes of this exercise, it is assumed that failure mechanisms are such that the mean factor of safety $(\overline{FS})$ is proportional to the ratio of mean demand forces $(\overline{D})$ to mean capacity reactions $(\overline{C})$, so that $FS \propto \frac{\overline{C}}{\overline{D}}$. For such a relationship, conditional failure probabilities can be calculated as follows[5]:

$$p(f/a) = 1 - \phi\ (\beta) = 1 - \phi \left[\frac{\overline{C} - \overline{D}}{(\sigma_C^2 + \sigma_D^2)^{1/2}} \right] \qquad (3)$$

where:

ϕ = The standard normal cumulative distribution function (CDF) of a normal variable with zero mean and $\sigma = 1$

σ_C or σ_D = The standard deviation of capacity or demand quantities

β = the reliability index

To simplify matters, the uncertainty in demand forces (D) can be ignored relative to the uncertainty in capacity reactions (C). The reliability index can then be expressed as[5]

$$\beta = \frac{1 - 1/\overline{FS}}{V_c} \qquad (4)$$

where V_c is the coefficient of variation of C. Eq.(3) simplifies to[5]

$$P(f/a) = 1 - \phi \left[\frac{1 - 1/\overline{FS}}{V_c} \right] \qquad (5)$$

This equation can be applied to calculate conditional failure probabilities for various design elements which exhibit the $F \propto \frac{C}{D}$ relationship and for which C is assumed normally distributed.

APPLICATIONS

The equations presented above can be used to calculate lifetime failure probabilities for a variety of design elements. To illustrate their applicability, failure probabilities are calculated below for seismic slope stability and erosion protection stability for a generic UMTRA facility. For seismic slope stability, there is a design loading event for which a recurrence interval, and therefore a prior probability, can be estimated. For erosion protection stability, the design loading event is extreme and a recurrence interval is difficult to assess. Therefore, the threshold failure probability is assumed and a hypothetical "allowable" recurrence interval is back calculated. In both cases, the uncertainty in capacity (C) is greater than the uncertainty in demand (D) and the capacity forces of each can be considered to be normally distributed. Thus, the two failure mechanisms considered provide examples of situations for which quantitative evaluation of reliability is possible.

Seismic Slope Stability

Seismic stability of UMTRA disposal embankments is necessary over the 1000-year design life of the facilities. Although most of the disposal sites are located in low seismicity zones, pseudostatic seismic stability analyses of the disposal embankments are needed as a minimum. Seismic slope stability analyses require three main elements: soil parameters, seismic parameters, and embankment geometry. For each site, appropriate site-specific seismic studies are performed and seismic parameters are developed from these studies. The seismic parameters generally consist of 1) a design earthquake with a given magnitude, 2) the distance from the site at which the earthquake occurs, 3) an estimated peak ground acceleration at the site, and 4) a probabilistic estimate of the return period for the design event. For UMTRA sites, the design earthquake is invariably the Maximum Credible Earthquake (MCE). While the MCE represents an extreme event, estimates of its recurrence interval are possible and are routinely performed as a part of most seismologic studies. The development of soil parameters is based on field and laboratory testing. The development of embankment geometry is based on required capacities and/or topographic considerations.

If it is assumed that the method of stability analysis used is relatively correct, the lifetime probability of seismic slope failure can be calculated for each UMTRA embankment. The seismic and soil parameters developed for the pseudostatic analysis and the results of the analysis are needed to perform the calculation.

A generic UMTRA site was considered in an example calculation. The following parameters were assumed for the fictitious site.

- Seismic Parameters
  - Earthquake Magnitude: 7.5
  - Distance: 40 km
  - Site Peak Ground Acceleration: 0.18 gals
  - Estimated Return Period of Design Earthquake: 10,000 years
- Soil Parameters
  - Coefficient of variation for strength data: 0.15
- Pseudostatic Analysis Results
  - Mean minimum factor of safety: 1.2

For a 1000-year design life, application of these values to Eq.(2) and Eq.(5) yield the following:

$P(f/a) = 0.16$

$P(a_i) = 0.095$

$P(f_i) = (0.095)(0.16) = 0.015$

The resulting $P(f_i)$ is in the range of the acceptable value of 10^{-2}, so it might be said that the ficticious embankment will be seismically reliable over the 1000-year design life. Qualitative evaluation would indicate the same, as a factor of safety of 1.2 (or even less) is normally considered adequate for seismic loading in the design of earth structures. Because the secondary method of evaluation validates the primary qualitative evaluation, it can be concluded that the design is reliable.

Erosion Protection Stability

Erosion protection for UMTRA facilities is designed so that erosion will not result if the design storm occurs during the 1000-year design life. Erosion protection analyses require three elements: geologic paramenters, hydrologic parameters, and embankment and/or ditch geometries. The geologic parameters are developed from field and laboratory testing and are used in the chosen design method. Hydrologic parameters consist of a design storm, usually taken as the probable maximum precipitation (PMP), or a lesser storm if the PMP is impracticable. The development of embankment and ditch geometries are based on required capacities, topographic considerations, and available materials.

Assignment of a return period to a PMP design storm is not an accepted practice. Therefore, slight modification of the analytical technique discussed above is required. First, the threshold failure probability, $P(f_i) = 0.01$, is assumed. An estimate of the conditional failure probability P(f/a) was then calculated based on design parameters and results. From these two quantities, an allowable hypothetical return period can be back calculated for the PMP. If the calculated return period is greater than that which might be considered believable for an extreme event such as PMP, the design is considered reliable.

A sample calculation was carried out for a ditch at a generic UMTRA facility[8].

- Design Storm
  - Probable Maximum Precipitation: 21cm/hr (8.3 in/hr)
- Rock Parameters
  - G_S: 2.68
  - Porosity: 0.3
  - Rock Friction Angle: 40°
- Results
  - D_{50} (min) = 4.7cm (1.85 in), FS = 1.0
  - D_{50} (ave) = 6.4cm (2.5 in), FS = 1.3

For a 1000-year design life, application of these values to Eq.(2) and Eq.(5) yield the following:

$P(f/a) = 0.15$

$P(f_i) = 0.01$ (assumed threshold failure probability)

$P(a_0) = 6.83 \times 10^{-5}$

Hypothetical Return Period = 14,600 years

The calculated hypothetical return period can be considered to be within the "believable" range. In other words, in order for the erosion protection to not meet the reliability criteria, the PMP would have to occur more than once every 14,600 years on the average. Insofar as the PMP represents "the theoretically greatest depth of precipitation for a given duration that is physically possible"[9], the likelihood of the PMP occurring more often than once every 14,600 years is low. Therefore, the ditch erosion protection for the ficticious embankment can be considered relatively reliable. Again, primary qualitative evaluations in this case tend to agree with these results. Realistically, designing against an extreme event with a safety factor of 1.3 would, in most cases, be as reliable as is practicable.

SUMMARY

As illustrated in the above examples, probabilistic analyses can be useful as a secondary method in evaluating the reliability of some design elements at UMTRA facilities. These analyses are most applicable to critical design elements for which primary deterministic methods cannot confidently provide reliability evaluations. Slope stability and erosion protection stability have been discussed as possible applications of the proposed methodology. In addition, various probabilistic techniques are available which could be used to evaluate the reliability of failure mechanisms such as settlement[10], seepage[11], and liquefaction[12]. These analyses might be applied to UMTRA facilities in a manner similar to that discussed for slope stability and erosion protection stability.

For any of the possible applications mentioned above, the analyses should not be used as a sole-source indication of geotechnical reliability, but as a secondary tool to validate primary qualitative evaluations of reliability. If applied properly, probabilistic methods should provide a useful means of supplementing deterministic reliability evaluations of low-level waste disposal facilities and ensure that the facilities meet applicable standards and thus expedite the licensing of these structures.

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