CECW-EW   5 March 2003

Errata Sheet

No. 1

Engineering and Design

RISK-BASED ANALYSIS IN GEOTECHNICAL ENGINEERING
FOR SUPPORT OF PLANNING STUDIES

ETL 1110-2-556

28 May 1999

Extend expiration date to 30 June 2004.

CECW-EG Engineer Technical Letter 1110-2-556	Department of the Army U.S. Army Corps of Engineers Washington, DC 20314-1000	ETL 1110-2-556 28 May 1999
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DEPARTMENT OF THE ARMY
U.S. Army Corps of Engineers
CECW-EG **Washington, DC 20314-1000**

Technical Letter
No. 1110-2-556 28 May 1999

EXPIRES 30 June 2002

Engineering and Design
RISK-BASED ANALYSIS IN GEOTECHNICAL ENGINEERING FOR SUPPORT OF PLANNING STUDIES

1. Purpose

This engineer technical letter (ETL) provides guidance on the application of probabilistic methods to geotechnical aspects of water resource planning studies. This cover letter and Appendix A provide an overview of the reliability analysis in geotechnical engineering. Appendix B provides methods for the evaluation of levee reliability and for the procedure to evaluate the probable failure point (PFP) and the probable non-failure point (PNP) for benefit determination involving existing levees (Ref 3.b.).

2. Applicability

This ETL is applicable to all USACE Commands having Civil Works responsibilities. It applies to all studies for major rehabilitation projects, flood damage reduction studies, and levee planning studies.

3. References

a. ER 1105-2-100. Guidance for Conducting Civil Works Planning Studies.

b. Policy Guidance Letter No. 26 (1991).

4. Distribution

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5. Background

a. *Risk-based analyses in water resource planning.* Budget constraints, increased customer cost-sharing, and public concern for project performance and reliability are issues that must be addressed in the assessment of Federal water resource investments. Explicit consideration of risk and uncertainty helps address these issues and improve investment decisions. To this end, risk-based analyses have been increasingly applied to planning of Corps water resource projects in recent years. This approach captures and quantifies the extent of the risk and uncertainty in the various planning and engineering components of an investment project. The total effect of risk and uncertainty on the project's engineering and economic viability can be examined and conscious decisions made reflecting explicit trade-offs between risks and costs. Risk-based analysis can be used to compare plans in terms of the likelihood and variability of their physical performance, economic success, and residual risks.

b. Risk and uncertainty. Risk and uncertainty are intrinsic in water resource planning and design. In the planning domain, they arise from the inherent uncertainty and variability of complex physical, social, and economic situations. In the engineering domain, there are components of uncertainty and variability in the frequency and magnitude of loadings, in the analytical models used to assess performance, in the variables used in those models, in the frequency and magnitude of physical changes in the lifetime of components, and in the condition of unseen features. These are further discussed in paragraph 7. In Corps planning studies, the framework for assessing risks associated with alternative plans is an event tree and a probabilistic simulation model, an approach often referred to as the Monte-Carlo method. This is summarized in paragraph 6.

6. Framework of Economic Risk Assessment

The framework of a risk assessment for Corps planning studies is an *event tree*. For each improvement alternative, as well as the base condition or without-project alternative, possible events of unsatisfactory performance are identified along with the events leading to their occurrence and the consequences of their occurrence. The relationships between precursor events and unsatisfactory performance events are established and illustrated in a tree diagram. Probability values are assigned to one or more initiating events, which usually have an associated time increment (e.g., water rises to elevation 152.4 ± 0.3 m (500 ± 1 ft) with probability 0.01 per year). Conditional probabilities (e.g., probability of piping given water at elevation 500) are assigned to events between the initiating events and the unsatisfactory performance events. Several probabilistic approaches can be used to assign these values as described in paragraph 7. Once the event tree and required probability values have been established, a series of random numbers is generated to define a single excursion (or iteration) through the event tree and it is noted which outcome (a satisfactory or unsatisfactory performance event) is reached. The process is repeated for numerous iterations (often several thousand), each modeling a life cycle (typically 50 years) with a series of time increments (often a year). Where conditional probabilities vary with time within the life cycle, a *hazard function* provides the conditional probability of event occurrence for each time increment given non-occurrence up to the modeled time. For example, if the hazard function for a component has a value in year 10 of 0.01, this means that a component that has survived for 9 years has a 1-percent chance of failure in year 10. In year 11, the hazard function applies only to components that have survived year 10, and its value may be smaller, equal to, or greater than the value from the previous year, depending on the lifetime characteristics of the component. The probability of an unsatisfactory performance event per year or over a life cycle can then be estimated by dividing the number of generated events by the number of iterations. The probability of unsatisfactory performance can be multiplied by the expected value of the consequences to develop a risk cost associated with the event.

7. Sources of Uncertainty and Methods of Probabilistic Modeling

Uncertainty in performance arises from a number of sources, and the selection of an appropriate probabilistic method to develop conditional probability values may vary with the type of uncertainty. The following paragraphs provide an overview; additional considerations are discussed in Appendix A.

a. Uncertainty in loadings. Loadings such as floods, earthquakes, and impacts are random events for which magnitude and time of occurrence may be modeled by probabilistic methods. This often involves the use of binomial or Poisson distributions fit to observed event data.

b. Uncertainty in parameter values. Geotechnical parameters such as soil strength and permeability have several components of uncertainty. The value of a parameter at any point and the average value over any distance are inherently uncertain because of soil's natural spatial variability. Secondly, there is uncertainty due to testing errors and uncertainty in estimating the mean and variance of the properties due to the finite number of tests performed. The normal and lognormal distributions are often used to model parameter values, which may be the value at a point or the spatially averaged value calculated over some distance or area.

c. Uncertainty in analytical models. Analytical models such as slope stability analysis methods, seepage equations, etc., have an inherent model uncertainty arising from the fact that they are mathematical simplifications of more complex problems, and unsatisfactory performance such as slope instability or piping may occur in the prototype at factors of safety above or below the limit state FS = 1.0 corresponding to these conditions in the model. Model uncertainty has not been systematically considered in most Corps studies to date. Where probabilistic methods are used to make economic comparisons of alternatives, probability values calculated using consistent models should provide a consistent basis for comparison even though model uncertainty is not included.

d. Uncertainty in performance. As parameter values and analytical models both have inherent uncertainty, the performance of a structure with respect to some quantifiable performance mode (slope stability, seepage, settlement, etc.) is likewise uncertain. The probability of satisfactory or unsatisfactory performance for modes with well-defined models and parameters is often calculated using first-order, second-moment (FOSM) methods, such as the Taylor's series method, which yield a *reliability index* β or probability of unsatisfactory performance Pr(U). This approach quantifies uncertainty in performance as a function of uncertainty in parameter values and the analytical model.

e. Performance modes without defined limit states. In some cases, engineering models may not be formulated to include limit states (e.g., FS = 1) and hence may not be easily reformulated to provide a reliability index or probability of unsatisfactory performance. Instead, satisfactory performance is expected to be attained by the adoption of experienced-based practices. An example is the design of filter materials, where equations can be used to design filters expected to perform adequately and prevent internal erosion, but there is no measure such as the factor of safety on which to base a mathematical procedure for comparing the relative reliability of filters. These situations are not directly compatible with FOSM methods. To obtain required probability values for these modes, one must either use frequency models based on observed events or judgmental values based on expert elicitation.

f. Frequency and magnitude of physical changes or failure events. Physical conditions may change at some uncertain time within the lifetime modeled in a simulation. These may directly lead to unsatisfactory performance or may require changing the values of parameters in an analytical model. Examples include scour of foundations, plugging of well screens by incrustation, failure of well screens by corrosion, development of seepage windows in sheet piling, and dislodging of fill material in rock joints. The occurrence of such events cannot be easily predicted by a model based on physical parameters. The occurrence may be modeled using a frequency-based approach such as those based on the exponential and Weibull distributions where sufficient data exist.

g. Condition of unseen features. The condition of unseen features is inherently uncertain. Examples include the effects of unknown cracks, burrows, or other defects in levees, and the adequacy of grout cutoffs under dams. A similar uncertain, but non-calculable, situation would be determining the probability of locating and plugging the source of a piping channel in a foundation before destructive erosion occurs. Such situations may contribute considerable uncertainty regarding performance but often can only be accounted for in a risk assessment or reliability analysis by quantifying the experience and judgment of experts rather than estimating uncertainty in parameters or fitting distributions to historical data.

8. Examples of Risk-Based Analysis

Despite the evolving nature of guidance for geotechnical aspects of engineering reliability analysis and risk-based economic analysis, a number of planning studies are already under way, and some have been completed. Geotechnical reliability analyses for these studies have been based on recent and ongoing research by the Corps and others; consulting reports prepared in support of both guidance development and specific project studies; workshops and training; and ongoing discussions among engineers in Corps districts and Headquarters, researchers, and consultants.

a. Appendix A. Appendix A provides a broad overview of methods and issues in geotechnical reliability analysis, with emphasis on application to Corps problems. It includes a bibliography of related literature and reports that provide a perspective on how probabilistic models have been applied.

b. Appendix B. Appendix B is a research report prepared by Thomas F. Wolff, Ph.D., P.E., of Michigan State University, for the Corps of Engineers, titled *Evaluating the Reliability of Existing Levees*. Note that, in Chapter 2, the comments on the rescinded Corps document that appeared in the original report have been edited and deleted during the preparation of this ETL. This report presents a framework for developing functions to quantify the reliability of existing levees as a function of floodwater elevation, a necessary input to the economic planning process. A number of performance modes are identified, such as underseepage, through-seepage, surface erosion, etc. For each mode, one or more examples are provided to illustrate calculation of the reliability index and probability of failure using first-order second-moment methods. Each example is worked for a series of floodwater elevations to obtain a conditional probability function. Uncertainty in parameter values is considered; model uncertainty and spatial correlation are not considered. A total probability of failure versus floodwater elevation function is calculated by combining the functions for each mode assuming they form an independent series system. For some of the modes, such as slope stability and underseepage, analytical models are fairly well developed and there is some experience basis for estimating coefficients of variation. Some other modes, such as interior erosion (through-seepage) and surface erosion, do not have well-established analytical models and the necessary coefficients of variation may be difficult to estimate. For these latter modes, an expedient model was used in the research; the examples provided should not be taken as definitive methodology but rather should be considered illustrations of how the methodology framework can be used as better models and their required random variables become available.

c. Application of examples. Both appendices provide overviews and examples of probabilistic methods, but should not be construed as definitive "how-to" guidance. The general approach in Appendix B, however, shall be used as the framework for evaluating the reliability of existing levees, including the probable failure point (PFP) and probable non-failure point (PNP) as defined and required in Ref 3.b. The experience of both the Corps of Engineers and the geotechnical profession with probabilistic methods continues to evolve. Published research includes a variety of methods, some elegant, but difficult to implement, and some overly simple. Furthermore, the appropriate choice of methods may be very problem-dependent. Hence, methodology should be developed on a case-by-case basis, using these examples as a reference point.

9. Action Required

For studies which require characterizing the reliability of existing levees, functions relating the probability of failure to the floodwater elevation, including the evaluation of Probable Non-failure Point (PNP) and Probable Failure Point (PFP) required in Policy Guidance Letter No. 26, shall be developed consistent with the approach in Appendix B.

FOR THE COMMANDER:

Appendix A - An Overview of Probabilistic Analysis for Geotechnical Engineering Problems.

Appendix B - Evaluating the Reliability of Existing Levees.

CARL F. ENSON, P.E.
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