Exploring the potential use of a risk-based approach to assessing the geotechnical well-being of the slopes of old embankment dams

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SYNOPSIS. Historically many aspects of geotechnical design have tended in favour of the deterministic methods of analysis based on the concept of Factors of Safety over probabilistic methods. This is particularly the case when considering the slope stability of dams. In recent years, with the introduction of Eurocode 7, the geotechnical community in the UK has been coming to terms with the use of the Limit State approach to geotechnical design which defines the relationship between design parameters and performance criteria. This generally involves factoring up loads and factoring down calculated soil parameters such as shear strength. The factors are statistically calculated to produce a design that has an acceptably low probability of failure although the approach gives no indication of what the value might actually be.

Using statistical methods to determine the characteristic values may only be performed effectively when data comes from sufficiently homogenous identified populations or when sufficient data is available. It is rarely possible and relevant to adopt statistics particularly when investigating old embankment dams where it is sometimes suggested that the actual process of undertaking major intrusive investigations with boreholes could have a detrimental effect on the performance of the dam and where internal erosion could have an influence on overall slope stability.

The paper explores the potential application of a risk based approach, assisted by the use of quantified risk profiles used in flood risk management, to better understand the current performance of the slopes of old embankment dams.

INTRODUCTION

Owners of large stocks of ageing embankment dams need to focus spending and balance risk, whilst seeking to maximise the overall return on investment and achievement of other performance targets. A targeted approach needs to be informed by an improved understanding of the overall risk associated with potential failure modes, the attribution of risk to

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individual assets and the likely change in risk that would result from an engineering intervention. This approach has been advocated in flood risk assessment and management for a number of years. A key component in this approach is the derivation and representation of asset fragility in the form of fragility curves. Fragility curves quantify the relationship between the loading on an asset and the conditional probability of failure of the asset given that loading. In UK flood risk management, probabilities are typically determined by reliability analysis. This paper reviews the traditional Factor of Safety approach to assessment of embankment dam slope stability and compares it to probabilistic/reliability approaches. It then goes on to discuss how a risk based approach can be applied to slope stability risk assessments.

FACTORS OF SAFETY APPROACHES

The geotechnical design of new dams and associated structures and the safety of existing dams is normally assessed using “lumped” limit state Factors of Safety as acceptance criteria. Fell (2005) indicates that the Factors of Safety adopted for embankment dams are reasonably universal with, for example, similar values used by the US Bureau of Reclamation (USBR, 1984), US Corps of Engineers (2003) and the Building Research Establishment in the UK (Johnston *et al*, 1990). A recent survey of six US State and Federal Agencies made similar findings (USSD 2007). Typical minimum acceptable values for new dams with high consequence of failure are 1.3 for end of construction and multistage loading, 1.5 for normal long-term loading conditions and 1.1 to 1.3 for rapid drawdown in cases where rapid drawdown represents an infrequent loading condition. Fell (2005) also recognised that a lower minimum factor of safety may be adopted for an existing dam which is well monitored and is performing well.

The US Army Corps (2003) recognises that when the uncertainties and the consequences of failure are both small, it may be acceptable to use lower factors of safety, of the order of 1.3 or less in some circumstances. Duncan and Wright (2005) indicate that Factors of Safety for slopes generally can vary from between 1.25 (when the geological setting is well understood, the soil conditions are uniform and thorough investigation provide a consistent, complete and logical picture of conditions at the site) to 2.0 and above where the geological conditions are complex and poorly understood, soil conditions vary sharply from one location to another, and investigations do not provide a consistent and reliable picture of the conditions at the site.

Guidance on factors of safety for slope design of new embankment dams in the UK is given in “An engineering guide to the safety of embankment dams in the UK” (Johnston *et al*, 1999). This approach was used by Rigby *et al* (2002) in developing a methodology with a panel of dam experts to investigate existing embankment dams. The methodology has factors of safety varying from 1.3 to 1.7 depending on the level of confidence in the data available. Worst credible values of shear strength are used in the analysis. These are the worst that a designer could realistically believe might occur, bearing in mind the limited amount of data available from investigations of existing embankments compared to the level of quality control that would be applied to a modern new build embankment.

As more data becomes available from geotechnical site investigations it is possible to refine preliminary conservative assessment, with a number of dams initially being considered to be potentially at risk shown to be acceptable as more reliable data is collected. This staged approach to risk assessment was also suggested by McCann and Castro (1998) moving to different levels from screening, ranking, detailed assessment to detailed design of remedial work and implementation of operational safety measures.

A tiered approach to risk assessment is currently being proposed in the UK Guide to Risk Assessment in Reservoir Safety Management presently under development by the Environment Agency in conjunction with a panel of UK and international dam risk practitioners. This progresses from screening and qualitative risk assessment through to simple then detailed quantitative risk assessment.

Other industries in the UK use different approaches. In the UK BS6031, the Code of Practice for Earthworks (1981), suggests that for first-time slides with a good standard of investigation a safety factor between 1.3 and 1.4 should be used for designed. For a slide involving entirely pre-existing slip surfaces, but otherwise of similar status, a safety factor of about 1.2 should be provided. The Highways Agency Design Manual for Roads and Bridgeworks (1991) Volume 4 (HA44/91) does not specify prescriptive values for factor of safety but states that “in determining acceptable factors of safety for slopes the designer must carefully consider the consequences of failure (i.e. the risk to life and property), the reliability (and conservatism) of the parameters used in the analysis and the accuracy of the analysis”. It states that “the most reliable factor of safety is likely to be based on parameters derived from back analysis, by the same method of a failed slope in the same soil strata”. Parry *et al* (CIRIA C591 2003a, CIRIA C592 2003b) considered the factors that need to be addressed in assessing the condition of infrastructure cuttings and embankments respectively.

CIRIA 591 states that the discussion of design life and factor of safety for embankments included in CIRIA C592 is applicable to cuttings. The factors of safety used in the examples of remedial works given in C591 are between 1.2 and 1.3. CIRIA C592 states that a lumped factor of safety 1.3 is often used for conventional drained analysis but also gives suggested minimum ultimate limit state factors of safety for use in embankment assessment depending on the parameters adopted in slope stability analysis varying from 1.1 and 1.3 for deep slips with worst credible and moderately conservative parameters respectively. Moderately conservative is defined as a cautious estimate of the values used in any slope stability analysis, e.g. soil parameters, groundwater pressures, loads and geometry. It is considered to be equivalent to representative values as defined in BS 8002 (1986). Worst credible soil parameters are the worst conditions that the designer reasonably believes might occur - a value that is very unlikely and safety factors lower than moderately conservative are therefore applied. CIRIA Reports C580 and 104 (Gaba *et al*, 2003 and Padfield and Mair, 1984) dealing with retaining wall design further clarify these three levels of design parameters for different situations as indicated in Figure 1.

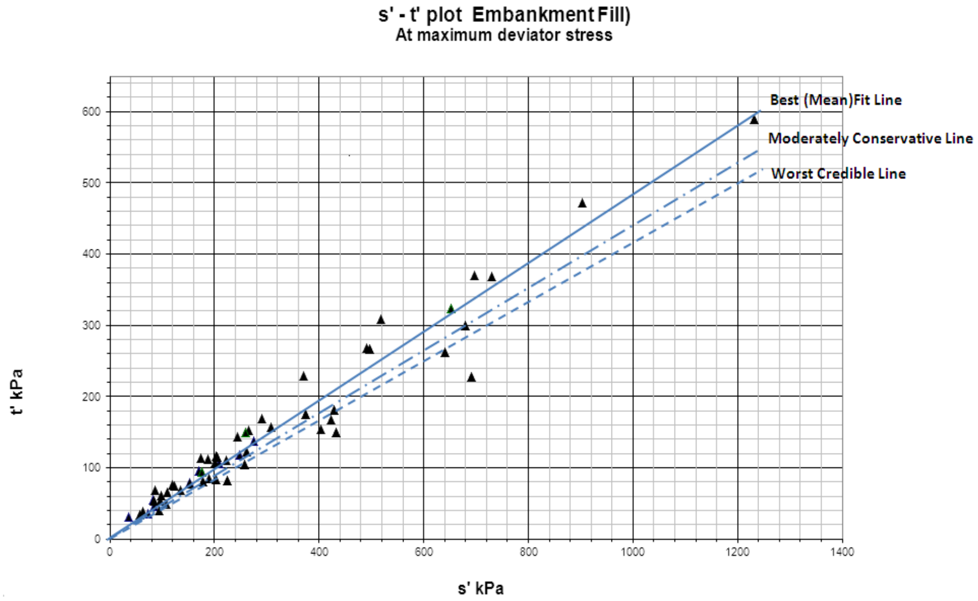

Figure 1. Use of s and t plots from consolidated undrained triaxial tests to design parameters to CIRIA Report 104, Padfield and Mair et al, (1984)

The approach adopted by Rigby *et al* (2002) uses s and t plots from consolidated undrained triaxial tests with pore pressure measurement to derive shear strength parameters. The use of the worst credible concept allows for engineering judgment in the choice of the parameters to be used in the analysis. For example the data used in Figure 1 is from an investigation of a dam with an average downstream slope of 1 in 2. (26.5^{o}) whereas the lowest measured effective angle of shearing resistance was recorded as 24^{o} which, if valid, would mean the slope would have a factor of safety close to or less than one even though it had been standing for over 150 years. In which case, a review of the data followed by an appropriate choice of parameters using engineering judgment would be required as recommended in Rigby *et al*, 2002.

In “An engineering guide to the safety of embankment dams in the UK”, Johnston *et al*, (1999) state that it is common in stability calculations to use c = 0, even when it would appear that the fill and foundation possess some cohesion. This is an empirical strength reduction which allows for uncertainties and some progressive failure, but it may lead to unrealistically low factors of safety on shallow surfaces. However, the USSD report on the Strength of Embankment Materials (2007) indicated that it is a common practice for US Consultants and Government Agencies to include cohesion for impervious or semi-pervious fine-grained soils.

Eurocode 7 brings in the concept of characteristic value for material properties, which does not usually appear in deterministic assessments. The characteristic value is a cautious measurement of the material property under consideration, for example soil shear strength, based on the strength probability distribution. In Eurocodes, such cautiousness in measuring the parameters is generally taken into account by a 95% fractile (or 1.64 standard deviations from the mean) based on the soil strength probability distribution, although a variety of statistical approaches are available to derive appropriate design parameters. Cautious measurements therefore often rely on an expert assessment produced from available test results and from guideline values found in the literature. The characteristic value is then a cautious assessment of the material load or strength causing limit-states to appear.

It has been suggested (Day, 2001) that the parameters used in designs are therefore mathematical concepts that have no real physical interpretation. For the data set of shear strength results represented by Figure 1 the average derived effective angle equates to 28^o with a standard deviation of 4.3^o. This would equate to a characteristic value of 21.5^o. These results however relate to the embankment slope of 1 in 2.25 or 24^o which is clearly unrealistic as stated above. A similar level of conservatism was applied to the design of one of the latest dams built with similar materials in the UK which was designed with the embankment fill having an effective angle equating to 23^o and a downstream slope of 1 in 5 (Hughes *et al*, 2001). For many of these reasons Eurocode 0 (EN 1990) provides that, for the design of special construction works (nuclear installations, dams, etc.), provisions other than those in EN 1990 to 1999 might be necessary, although recommendations on the specific provisions that may apply are not given.

Deterministic analyses suffer from limitations such as the failure to consider variability of the input parameters and inability to answer questions such as "how stable is the slope?" There is no direct relationship between the factor of safety and the probability of failure. Therefore a slope with a higher factor of safety may be no more stable than another slope with a lower factor of safety; it is dependent upon the nature and variability of the slope materials. For example, a slope with a factor of safety of 1.5, with a standard deviation of 0.5^o on the angle of shearing resistance used in the analysis, could have a much higher probability of failure than a slope with a factor of safety of 1.2 with a standard deviation of 0.1^o on angle of shearing resistance.

Interestingly in the classic text on the stability of slopes by Professor Eddie Bromhead in 1986 he stated "My view is that the calculated factors are meaningless (except for those that imply failure). They only exist as a relative index when considering remedial measures e.g. if *this* is done, rather than *that*, which gives the better (more reliable/cost effective/permanent result?". This would be termed as an "As Low As Reasonably Practicable" approach in current terminology. A very important consideration when assessing what action, if any, to implement on an old embankment dam that may have been operationally satisfactory for many years but whose consequence of failure may be high.

PROBABILISTIC APPROACH

Probabilistic slope stability analysis allows for the consideration of variability in the input parameters and it quantifies the probability of failure of a slope. Probabilistic slope stability analysis can be performed using the Monte Carlo method. Basically, the method as detailed in Eddleston *et al*, (2004) consists of re-running the analysis many times by inputting new parameters estimated from the mean and standard deviation values of the chosen parameters. For a general and conservative approach to align with the deterministic approach, which could be considered in parallel with consequence of failure considerations more stringent criteria is suggested for use in preliminary analyses than for when more comprehensive data is available. It must also be appreciated that shear strength is not the only parameter that should be considered when using probabilistic methods. Variations in groundwater conditions, inundation of downstream slope due to heavy rainfall, poor drainage, potential for internal erosion or overtopping and the effects of climate change will all need to be taken into account.

Although a comprehensive investigation programme can be undertaken on a portfolio of dams this takes time. In many instances it is appropriate to make a high level screening of dam stability for input into a Portfolio Risk Assessment (PRA) of a number of dams. This can be achieved using a method developed at the University of Stanford, McCann *et al* (1985). The approach uses a Bayesian probabilistic model to evaluate the probability of failure (PoF) for four modes of failure including slope stability. The model draws on US dam data and practices to estimate the frequency of failure for a number of dam conditions. An engineer's assessment of the current condition of the dam is undertaken and the numerical measure is incorporated into estimates of probability of failure as detailed in Table 1 (RAC Engineers and Economists and Atkins, 2007). This is a similar to the approach originally advocated by Bromhead (1986).

Table 1. Modified University of Stanford Evaluation of Slope Stability Probability of Failure (PoF) for screening a portfolio of dams.

Evaluation Scale	PoF	Desk Study FoS	Description
1	1.1×10^{-6}	> 1.5	Good condition of dam. No unanticipated movements or performance. Mild operating conditions and climate.
2	2.8×10^{-6}		Good condition of dam, but dam subjected to extreme weathering or drawdown cycles are likely.
3	3.3×10^{-6}		Minor erosion of slope face.
4	5.9×10^{-6}	1.3 to 1.5	Evidence of weak material or organic matter.
5	9.2×10^{-6}		Evidence of minor erosion and weak material.
6	1.3×10^{-5}		Excessive erosion or undercutting of side slopes.
7	2.1×10^{-5}		Poor compaction of embankment, steep side slopes with a low calculated factor of safety.
8	3.7×10^{-5}	1.0 to 1.3	No unusual surface movement, but evidence of high pore pressures (if available).
9	4.8×10^{-5}		No tension cracks, but evidence of settlement and misalignment, or ruptured conduits. Unusual and sudden change in pore pressure instrumentation.
10	1.5×10^{-4}		Longitudinal tension cracks at crest along with misalignment, sloughing, and bulging of embankment or tilting of roadway or inlet structures. Sinkholes.

RISK BASED APPROACHES

Geotechnical risk analysis differs significantly from structural and hydrological practice in its strong reliance on subjective probability to assess both the impact of data scatter and bias uncertainties. Risk assessment methods involving formal elicitation of expert opinion allows the inclusion of bias uncertainties that might otherwise be difficult to calculate or quantify. Experienced engineers have evaluated opinions on many of these uncertainties, and can incorporate these opinions in a risk analysis. This practice is not without pitfalls as noted by Baecher and Christian (2000) who quote Casagrande (1965), “we would like to pick these numbers out of the ground, not out of the air”. There is a difference between a subjective probability and the first number that pops into an expert’s head. Baecher and Christian (2000) also suggest that many criticisms of risk analysis are based on anecdotal quotes by famous engineers, who stressed the importance of judgment, experience, and conservative design as the rudiments of risk management. This plays well with the engineering community, but unfortunate experiences with technology have made the public as a whole sceptical of “the experts know best” approach to safety and suspicious of reliance on “engineering judgment”. There is a preference today for a more informed approach utilising expert elicitation to gain a consensus view of a panel of experts. Outcomes of risk analyses reflect the combined opinion of a set of experts and analysts at an instant in time based on evaluation of uncertainty represented for example in the form of fragility curves and operational and soil property data from similar dams in an overall portfolio of dams of a similar age and type of construction and geology. Risk analysis then becomes logically consistent, and as comprehensive as practicable.

The value in risk analysis lies in its systematic, explicit approach, and in its replacing “conservative” assumptions, the real safety of which is unknown, with best estimates and explicit statements about uncertainty, Baecher and Christian (2000). Risk analysis will never replace the wizened-but-wise expert knowledge of All Reservoir Panel Engineers, but it is an accounting scheme to support the genuine exercise of informed judgment. This can then be included in overall dam risk assessments by considering a range of results from analyses and the level of confidence in the results as suggested in the USBR Risk Framework to Support Dam Safety Decision-Making (2011).

It is generally recognised that uncertainty can be described as one of two types as defined by Baecher and Christian (2000) as shown in Figure 2.

- Data scatter, which can be attributed to inherent randomness, natural variation or chance outcomes; in principle, this uncertainty is irreducible because it is assumed to be a property of nature.
- Bias Uncertainty is attributed to lack of knowledge about events and processes; in principle, this uncertainty is reducible because it is a function of information.

In view of the inherent uncertainty in the determination of reliable material parameters for existing old embankment dams it was decided to explore the merits of utilising existing uncertainty and fragility approach to understand the performance of existing embankments.

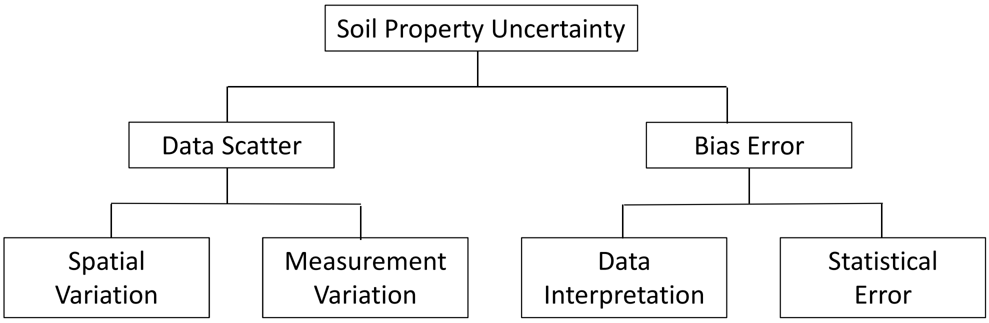

Figure 2. Contributions of uncertainty in soil parameter estimates

A recent report (Schultz *et al*, 2010) by the US Army Corps of Engineers entitled “Beyond the Factor of Safety” explores the use of fragility curves in probabilistic risk assessments. In general fragility curves describe how the reliability of a structure changes over the range of loading conditions to which a structure might be exposed. Simm *et al* (2009) have recently made a comparison between geotechnical factor of safety approaches and fragility curves in relation to flood embankments in the UK where different water levels impose different loadings on the embankment. A similar approach was adopted in the production of this paper to explore the possible application of a fragility approach as part of a dam risk assessment involving expert elicitation to evaluating the stability of the existing old embankment dam. The data in Figure 1 above is used to explore the uncertainties inherent in the interpretation of site investigation data. The dam used in the analyses for this paper was shown to have critical slips contained within embankment material and consistent data on the phreatic surface in the embankment. The variation in strength properties of the embankment fill was therefore used to produce "fragility" curves for a range of angles of shearing resistance based on deterministic and probability assessments as indicated in Figures 3 and 4 respectively.

The results from the deterministic analysis indicate that for a variety of parameters ranging from worst credible to moderately conservative the factor of safety of the downstream varies from 1.1 to 1.15 indicating that remedial works may be required on the dam. If cohesion of 5kN/m² is included in the analysis the factors of safety rise to between 1.25 and 1.3.

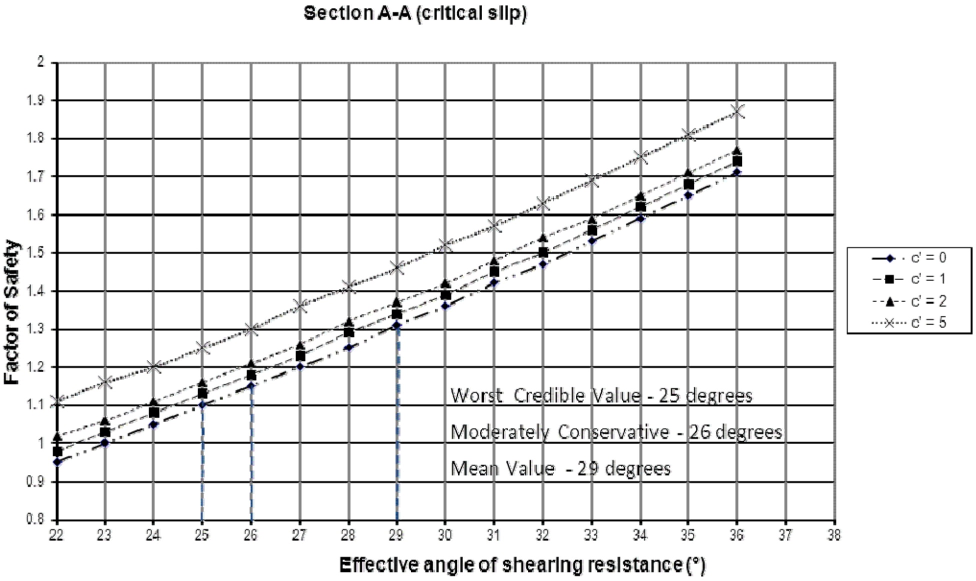

Figure 3. Variation of Factor of Safety with effective angle of shearing resistance and cohesion

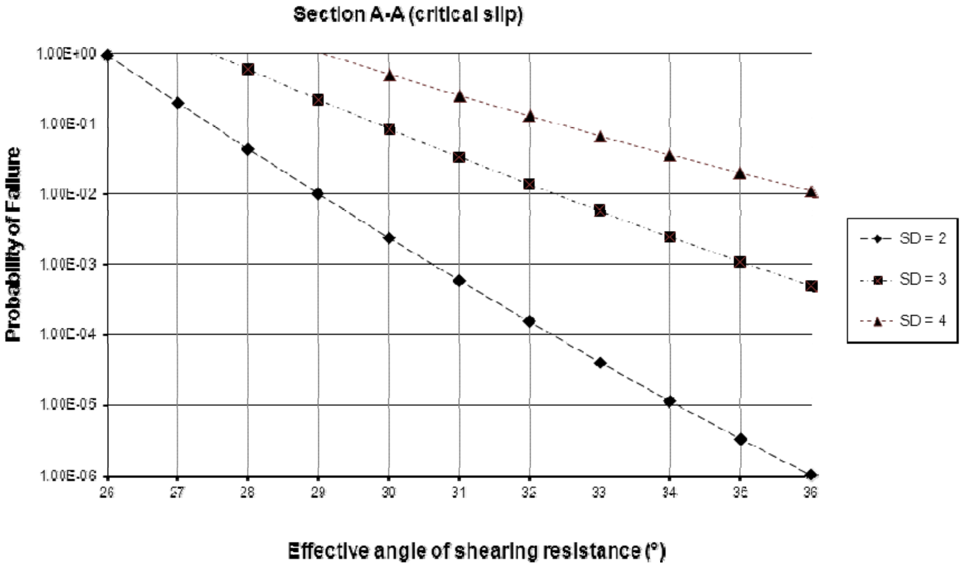

Figure 4. Fragility curve showing variation in estimated Probability of Failure with effective angle of shearing resistance

The probabilistic assessment is based on analyses using standard deviations of 2, 3 and 4 which represent typical variations of parameters reported for a range of similar material on other dams in the North West of England (Eddleston *et al*, 2004). The results indicate that for a data set with relatively low variation the probability of failure would fall in the "intolerable" range of less than 1 x 10^{-4} (HSE, 2001) but would be unrealistically high based on the wide variation in the data set of the test results available. The results for a reliable data set demonstrate parity with the deterministic analysis. A high degree of uncertainty (represented by a higher standard deviation) serves to increase the probability assessments significantly to levels that indicate the dam is potentially under threat of failure. In most instances this is not matched by the known operational performance of the dam over its service history.

The significance of the information presented in fragility curves offers the expert review panel taking part in a risk assessment process the opportunity to balance the theoretical evaluations with variations and uncertainties in known properties of the dam against its historical performance to assign a document a balance view of the probability of failure on well-being of the dam in relation to slope stability. For old dams this often requires an understanding beyond just knowing what factor of safety is obtained by inputting a strength property from often limited numbers of laboratory test results. This can then be combined with assessment of other geotechnical threats posed by internal erosion and hydrological and hydraulic threats which are also assessed on a probabilistic basis.

CONCLUSION

Investigation of old embankment dams provides limited information on the properties of embankment materials on which to make judgments when compared to the level of both investigation data and Construction Quality Assurance that would be expected of a new build dam. Methods of assessment of the stability of existing dams to current design codes and practices assist in making assessments of the existing well-being of the dam. However, there are many inherent uncertainties with the application of these approaches. The simple application of uncertainty analysis in the form of risk assessments utilising fragility curves offers the opportunity to make more informed judgments on the well-being of a dam based on the available information and the level of uncertainty associated with the information. This can be used as a means of prioritising potential remedial works for a portfolio of dams similar to the “indexing” approach original proposed by Bromhead (1986).

In many instances embankment dams with a good track record of operation and with no evidence of instability are shown to have relatively low factors of safety when analysed to modern design standards. In such circumstances it is important for dam owners to consider the consequence of failure and the ALARP principle when assessing the need for improvements to stability in line with modern standards. Consideration must also be given to the potential for more likely modes of failure such as internal erosion. As dam risk assessment techniques become increasingly widespread it is more generally accepted that it is an ongoing process of assessment, prioritised interventions to close gaps and demonstration of continuous improvement to manage risk (Vreugdenhil *et al*, 2011).

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