Percentage of model error from production of negative random variable of x and y in joint normal density function can be calculated by following formula.

$$Error(\%) = \int_{-\infty}^{0}\int_{-\infty}^{0} f(x,y)dydx \qquad \textbf{(5)}$$

Similar to joint uniform distribution, assessed PDF of H_{dr}^2 can be converted into PDF of H_{dr} as shown in Fig. 5 (a) and (b).

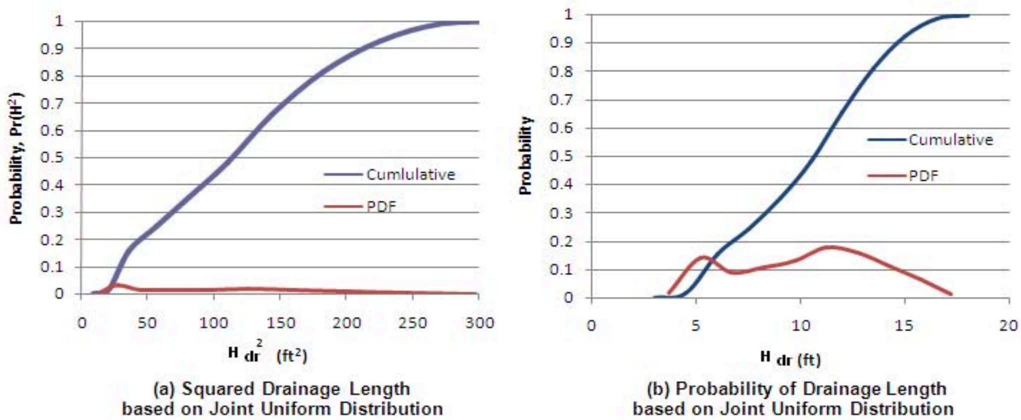

Figure 4 Probability Function of Drainage Length for Joint Uniform Distribution with Non-correlation between C_v and t_{60}

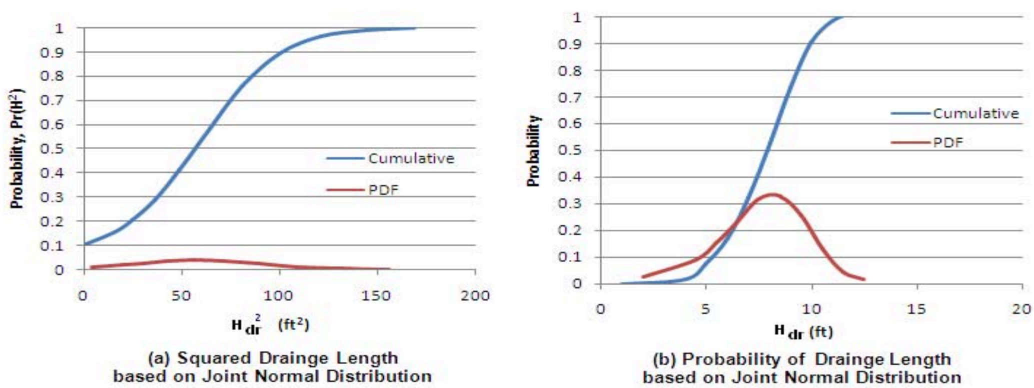

Figure 5 Probability Function of Drainage Length for Joint Normal Distribution with a Correlation Factor of -0.7 between C_v and t_{60}

From the site soil observations, double drainage is considered more appropriate for compressible layer drain condition since sandy fill and sandy till material overlies and underlies the compressible soil at each top and bottom. Fig. 6 shows comparison of probability function and PDF of estimated compressible soil layer thickness (2 H_{dr}), each based on uniform distribution and normal distribution. Model error of joint normal distribution was calculated to be 10.4 %, thus up to10 % of calculated layer thickness should not be convinced.

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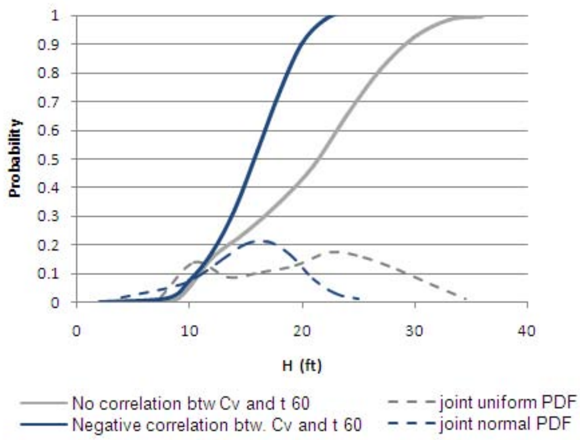

Figure 6 Results of Compressible Soil Thickness (H) Probability Function

CONCLUSION

Probability of compressible soil thickness could be estimated with data sets of consolidation time, estimated from preloading data and coefficient of consolidation, measured from one-dimensional consolidation tests. The data sets of consolidation time and coefficient of consolidation were characterized with a best fit probability density function. For the practicality of simplified approach, joint uniform and normal distributions were only considered to present the field and lab test data sets. From the project site, apparent negative co-relationship was observed between consolidation times and coefficients of consolidation, thus analysis result using joint normal distribution function is considered more appropriate to represent thickness of compressible soil layer below future site grade. Maximum likelihood of compressible soil layer thickness was estimated to be 18 to 22 feet for the organic soil, each estimated based on joint normal distribution and joint uniform distribution. The existence of organic soil layer with over 30 feet thickness was estimated less than 10% of entire project area. Those estimates are only confined to native organic soils in preloading area, excluding additional weak/soft fill or soil layers exhibiting local presidency.

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A Novel Application of Risk Analysis Methods to Evaluate the Future Viability of Two Large Concrete Stormwater Detention Tanks

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ABSTRACT

Many aspects of geotechnical design, such as the analysis of slopes using slip circles and the evaluation of imposed earth pressure, whether active, passive or at-rest, can be made fairly precisely. These lend themselves to the application of safety factors for use in design. However, problems involving groundwater flows and seepage often require an understanding of the security of the structure with respect to resistance to soil erosion. Such evaluations are complex and necessitate the use of quantitative risk analysis methodologies to provide an estimation of failure probabilities involving groups of experienced engineers providing subjective judgement through elicitation panel methods.

The paper describes the application of the Quantitative Risk Analysis (QRA) approach using event trees to assess the piping failure risk around two massive submerged, underground, concrete storage tanks in the UK. This process highlighted the most significant risks, their potential mitigation and the likelihood of the risks actually occurring in terms of a "Probability of Failure" within a particular time scale.

INTRODUCTION

Two Wastewater Storage Tanks were constructed in 1999 in North West England, UK to provide 60,000m3 of stormwater storage to prevent unsatisfactory stormwater overflow discharges during each annual Bathing Water Season. The asset comprises two very large diameter (36m) and deep (40m) buried tanks constructed as circular diaphragm walls with an interconnecting tunnel and associated infrastructure, See Figure 1.

NEED FOR A QUANTITATIVE RISK ASSESSMENT (QRA)

Since 2001 groundwater has been reported flowing into one of the tanks, Tank 2 around the joint between the base and a corbel ring beam which transfers loads from the base to the walls as shown in Figure 2.

Investigation and monitoring of these inflows has been undertaken and due to the local geology consisting of Triassic Mudstone and Halite Beds it was considered that inflows into Tank 2 were likely to have initiated potential solution and the possibility failure mechanisms including fines loss, gypsum dissolution and halite (rock salt) dissolution.

Figure 1 Aerial View of the Detention Tanks

Figure 2 – Ingress into the Tank

There is a possibility that these mechanisms could lead to structural damage to the asset, including the interconnecting tunnel and Tank 2 base, as well as the surrounding infrastructure. It is likely that the consequences of such a failure would be significant and include the asset being out of use. Suggestions for permanent works to reduce risk to the asset include ground stabilisation grouting and a new corbel ring beam to counter uplift forces on the base

Due to the uncertainties attached to the failure mechanisms the client recognised need to be able to prioritise the risks and have a better understanding of their urgency before funding can be sought for either investigative, permanent or temporary works.

To do this it was recommended that Quantitative Risk Assessment (QRA) be undertaken for the asset, to be based, where appropriate, on a recognised methodology. An approach similar to one used on embankment dams was proposed. This 'Toolbox' methodology is based on the guidance document 'Risk Analysis for Dam Safety: A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping, 2008' which has been jointly developed by the U.S. Bureau of Reclamation, US Army Corps of Engineers, The University of New South Wales and URS (Fell R., 2008).

AIM OF THE QUANTITATIVE RISK ASSESSMENT

It was intended that the QRA would:

- Identify and document all significant potential modes of failure in a logical manner.
- Form a consensus of opinion as to the most significant risks
- Assess the need and potential for improved evidence and investigations
- Identify and quantify the probability of each failure mode based on the evidence presented

- Form a consensus of opinion with regard to the effectiveness of mitigation methods and the best way to proceed
- Indicate the likelihood of risks occurring within a timeframe, albeit in a highly subjective manner

It was recognised that the results and conclusions of the QRA represent the best efforts of the team to form a consensus of opinion, to quantify the likelihood of failure events and draw conclusions which are of use to the asset owner.

QRA METHODOLOGY

Event Trees. The methodology adopted is based on the use of Event Trees which:

- represent progressions of events that could result in adverse consequences
- consist of a series of linked nodes and braches, each node representing an uncertain event or condition
- provide a graphical representation of the logic structure for the progression of each failure mode and a template for the assignment of event probabilities and calculation of risk
- identify where the greatest potential risks are
- foster common knowledge and understanding of failure modes, and synergetic discussion of various issues associated with failure modes

For the purposes of the QRA a failure event was be considered to be a progression of events which could lead to any or all of the following:

1. Death or serious injury.
2. The asset can no longer be used for its intended purpose without major remediation.
3. Significant damage to infrastructure external to the asset, including third party assets.

An event tree is constructed from left to right, starting with some initiator event and proceeding through events describing the response of the structure to each level of the initiator. These event sequences are developed all the way to a recognised failure mechanism. In the case of the Dam "Toolbox" standard event node descriptors have been used. These are Initiation, Continuation, Progression, Intervention and Failure.

Following consideration and trial runs the standard event tree node descriptors in Table 1 were developed for the QRA. These enable a clear and logical methodology to be followed, which is appropriate to all event trees. By considering one initiation node at a time and exploring the different routes to failure associated with it, it was considered to be possible to create a reasonably comprehensive list of potential failure events.

Table 1 . Description of Event Tree Nodes Developed for Bloomfield Road Storage Tanks QRA

	Event Tree Node Descriptor	Definition
1	Initiation	Consideration of the effect of a flow path on a particular stratum within the zone of influence of part of the asset, e.g. flow from the Sands & Gravels through the base / corbel joint causing fines loss around the tunnel.
2	Continuation	Consideration of the probability that the initiated effect (1) will stop of its own accord, i.e. without mitigation.
3	Progression	The series of events which need to occur for failure to happen e.g. describing how fines loss can eventually cause tunnel collapse.

Risk Estimating Team (RET). An important part of the Toolbox application on the dams is the use of a Risk Estimating Team (RET) formed from a consistent group of suitably qualified and experienced experts. This concept is appropriate for Bloomfield Road Tanks for which the responsibility of the RET is to agree the event trees and score the probabilities for each event node following discussion, consideration and challenging of the evidence and conclusions drawn to date. For the purposes of Bloomfield Road Tanks QRA the RET should:

- be small enough so as to be conducive to detailed and comprehensive discussions
- have sufficient knowledge and experience to be able to draw independent and, as far as is reasonably practical, correct conclusions from the evidence presented
- contain sufficient engineering expertise to be able to consider all parts of the asset in question, e.g. structural, geotechnical etc

Probability Scoring. Probability is defined in the Toolbox method (Fell R., 2008) as “a measure of the degree of certainty. This measure has a value between zero (impossibility) and 1.0 (certainty). It is an estimate of the … likelihood of the occurrence of the uncertain future event. There are two main interpretations:

1. Statistical – frequency or fraction – the outcome of a repetitive experiment of some kind and is in principle measurable by doing the experiment.
2. Subjective probability (degree of belief) – Quantified measure of belief, judgment, or confidence in the likelihood of an outcome, obtained by considering all available information honestly, fairly and with a minimum of bias. Subjective probability is affected by the state of understanding of a process, judgement regarding an evaluation, or the quality and quantity of information. It may change over time as the state of knowledge changes.

Due to the nature of the evidence available and the unique situation of the Bloomfield Road Tanks asset, this QRA will be almost entirely based on subjective probability.

Where there is not a basis (i.e. appropriate statistical information) for estimating statistical probability the Toolbox method uses verbal descriptors to assign response probabilities relative to the scale of verbal descriptors as shown in Table 2 (Fell R., 2008).

Table 2 Probability Mapping Scheme (Fell R., 2008)

Verbal Descriptors	Descriptor Probability
Virtually Certain	0.999
Very Likely	0.99
Likely	0.9
Neutral	0.5
Unlikely	0.1
Very Unlikely	0.01
Virtually Impossible	0.001

The total probability of a particular event occurring is simply the product of the scores allocated to each node of its event tree. To prevent abortive effort a virtually impossible score of 0.001 was allocated by the RET as 'de-minimus' in the workshop records.

QRA WORKSHOP

It is essential that prior to assigning a probability score to a particular event node the RET are all given the opportunity to comprehend, challenge and discuss the same evidence. Where possible this should be done with all the RET present, ideally in a workshop event. To improve its effectiveness the workshop should include a facilitator and recorder. The Toolbox approach (ref. Fell R., 2008) recommends that "the group (RET)... 'brainstorms' any and all information that is pertinent to the event node being discussed. Each piece of information is listed on a flip chart in either a 'factors leading to a higher probability' or 'factors leading to a lower probability' column depending on whether the information can be used as evidence to support or oppose belief in the event. The terms 'factors leading to a higher probability' and 'factors leading to a lower probability' are used in terms of the event node, as described, actually happening. The purpose of this step in the process is to display all the information that will be used in making the estimate for all team members to see and discuss. The team members can judge for themselves the importance of the information being listed as they make their estimates". The factors and evidence considered on the flip chart notes must be recorded for reference in the workshop notes. Figure 3 summarises the workshop process.

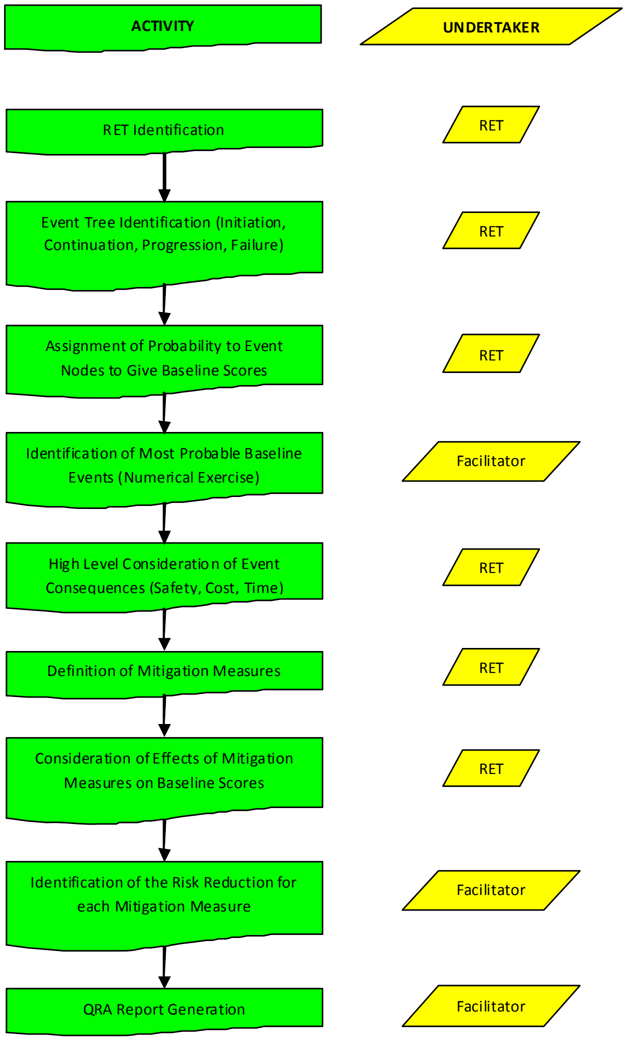

Figure 3 Summary of the Workshop Process

The following consequences will be of concern to asset owner and were estimated by the RET:

- Likelihood of injury / death (low, medium, high) as a result of failure;
- Immediate consequences of failure, e.g. tanks full, loss of mechanical and electrical equipment etc;
- Possible remedial works necessary to bring asset back into use and the associated cost;
- Possible duration for which the asset cannot be used;

- Possible impact on surrounding infrastructure for example the car park, road and sewer.

TOLERABILITY OF RISK USING THE QRA METHOD

In order to assess whether levels of risk are tolerable to UU, users of the Toolbox method on UU dams have adopted guidance from the HSE document r2p2, 2001. This outlines the HSE's tolerability of risk (TOR) framework in which risk is split into ranges as follows:

- Broadly acceptable – 'Risks falling into this region are generally regarded as insignificant and adequately controlled' (HSE, 2001)
- Unacceptable – 'a particular risk falling into that region is regarded as unacceptable whatever the level of benefits associated with the activity' (HSE, 2001)
- The zone between the unacceptable and broadly acceptable regions is the tolerable region. Risks in that region are typical of the risks from activities that people are prepared to tolerate in order to secure benefits.

An individual risk of death of one in a million per annum should be used as a guideline for the boundary between the broadly acceptable and tolerable regions' (HSE, 2001). For members of the public who have a risk imposed on them 'in the wider interest of society' this limit (between tolerable and acceptable) is judged to be\ 1 in 10 000 per annum.' (HSE, 2001)

CONCLUSIONS

The RET undertook a comprehensive QRA covering 97 potential failure events. Of these 25 were identified as having unacceptable or tolerable (ALARP) probabilities of occurrence, based on tolerability limits suggested by the HSE for per annum events involving fatalities. As it is not anticipated that any failure events have a high risk of causing fatalities these tolerability limits for probability may have to be amended by UU to be applied meaningfully for this specific asset. Within the most probable 25 failure events, 8 modes of failure have been identified. Within each mode events are differentiated by assumptions regarding groundwater pressure and timeframe. These modes are listed below, in order of the most probable events:

1. Gypsum Dissolution (Mudstone) Allowing Base Movement
2. Fines Loss from the Mudstone Allowing Base Movement
3. Chemical Attack of Corbel Ring Beam Shear Connectors Allowing Base Movement
4. Gypsum Dissolution (Mudstone) Allowing Tunnel Failure
5. Fines Loss from Sands and Gravels through Tunnel / D-wall Joint Allowing Tunnel Failure

6. Fines Loss from Sands and Gravels beneath Toe of D-wall and Through Base Joint Allowing Tunnel Failure

7. Halite Dissolution Allowing Base Movement

8. Halite Dissolution Allowing Tunnel Failure

In terms of immediacy the first seven modes were deemed to be unacceptable in the immediate (2 year) timeframe. Although the eighth is within the tolerable range in the immediate timeframe it cannot be deemed as acceptable until reasonably practicable measures, or mitigations, have been applied to reduce the risk (ALARP principle). The RET considered and priced, at a very high level, 4 mitigation options:

1. Bulk grouting of mudstone plug/halite, new corbel ring beam and new tunnel headwalls

2. Bulk grouting to consolidate connecting tunnel supporting stratum and new tunnel headwalls

3. Combination of mitigations 1 and 2

4. Mechanical seal to corbel/base joint

According to the reduction in probabilities calculated the most effective mitigation measure is Mitigation 3 which improves all probabilities to within the acceptable or tolerable (ALARP) range. Mitigation 4 is the next most effective mitigation measure however the design and costs for this option could not be determined as part of this exercise.

To conclude, the QRA exercise has been successful in achieving a credible consensus of opinion as to risks affecting the asset, considering the limited evidence available and subjective nature of the interpretation. The QRA also provides a consensus opinion of the relative effectiveness of mitigation measures, as determined by a reduction in probability. It has also created a logical and comprehensive framework for assessing possible failure events that can be used in the future as improved evidence becomes available.

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