ESTIMATING OVERALL RISK OF DAM FAILURE: PRACTICAL CONSIDERATIONS IN COMBINING FAILURE PROBABILITIES

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ABSTRACT

With the move to a risk based approach to dam safety there has been a concomitant focus on estimating the probability of failure of dams. The majority of risk guidelines relate to the total probability of failure and therefore the individual probabilities estimated for different components and loading conditions need to be combined. In most cases the failure modes of various components of a dam are not mutually exclusive and therefore the failure probabilities are not simply additive. This paper discusses the requirements for estimating probabilities in dam safety risk analysis both for assessing the risks associated with an existing dam and the justification for upgrades. The approach taken to calculating probabilities of failure in the risk analysis model can have a significant influence on the magnitudes of key inputs to decisions about dam safety upgrades. Ignoring adjustment for common cause failure modes can lead to overestimation of the estimated total probability of failure and the annualised incremental loss of life, and underestimation of the cost per statistical life saved. A worked example is used to illustrate the importance of appropriate combination of probabilities in quantitative risk analysis.

Keywords: dam safety, risk analysis, risk assessment, dam failure, event tree analysis.

1 INTRODUCTION

With the move to a risk based approach to dam safety there has been a concomitant focus on estimating the probability of failure of dams. Event trees and other techniques are increasingly being used to determine the probability of failure of a particular component of a dam for a specific loading condition (e.g. earthquake, flood or normal operating).

The majority of risk evaluation guidelines however relate to the total probability of failure for the reservoir and therefore the individual probabilities estimated for different dam sections or components, failure modes and loading conditions need to be combined. In most cases the failure modes of various components of a dam are not independent and therefore the failure probabilities are not simply additive. This is important not only for assessing the current probability of failure but also changes in the probability of failure resulting from upgrades and hence the justification for these upgrades.

For example, a fix to a saddle dam, which is the most vulnerable section to failure, can increase the probability of failure for the main dam, although the total reservoir probability of failure would be reduced. If the consequences associated with main dam failure are greater than those for the saddle dam, then overall risk in terms of the likelihood of higher levels of life loss and economic losses or annualised measures of those consequences could be increased by the saddle dam fix. Clearly it is important to understand such interactions in performing risk assessments for dams.

The ANCOLD Guidelines on Risk Assessment (ANCOLD, 2003) recognise the need to combine the estimated probabilities in different manners depending upon the requirements.

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The guidelines give the following examples of different methods for combining probabilities:

- *"The estimated overall total probability of failure per annum over all components of the dam, overall load states[5]/scenarios and over all failure modes*
- *The estimated total probability of failure per annum for each component of the dam (for example, concrete gravity section, main embankment or saddle embankment);*
- *The estimate total probability of failure per annum by load state/scenario;*
- *The estimated total probability of failure per annum by failure mode."* (G7-3 ANCOLD, 2003)

This paper discusses the requirements for estimating probabilities in dam safety risk analysis both for assessing the risks of dam failure and the justification for safety upgrades. The different methods available for estimating probabilities for given failure modes of a dam are briefly summarised and then two methods for combining these estimated probabilities of failure are discussed. A worked example is used to illustrate the importance of appropriate combination of probabilities in quantitative risk analysis.

2 REQUIREMENTS FOR ESTIMATING PROBABILITIES IN DAM SAFETY RISK ANALYSIS

Estimates of probability are required in dam safety risk analysis for estimating both the probability of failure and the consequences of failure (e.g. life loss). These estimates can then be used to assess the risks of an existing dam and the justification for upgrades using risk evaluation guidelines.

[5] The term load state is generally applied to a discrete interval of flood or earthquake loading. However, Hill et al. (2001) demonstrate the importance of using numerical integration principles including convergence criteria for estimating probability of failure and other risk measures in dam safety risk assessment.

For flood and earthquake loading, event trees are applied to each interval of peak loading (Hill et al., 2001). It is important to keep in mind that these event tree calculations do not track successive loading levels for a single flood event, but rather they consider all magnitudes of different flood events as represented by peak reservoir level. This perspective is important to understand when considering the case of multiple breaches, which is discussed in Section 4.4.

2.1 RISK GUIDELINES

There is a range of Australian and international risk evaluation guidelines and criteria that can be used to assess the risk of a dam. These risk guidelines vary in how probability and risk are defined and assessed. Some guidelines are based upon the probability of an outcome occurring, whereas others are based upon the cumulative probability distribution for a type of outcome.

The ANCOLD (2003) Guidelines on Risk Assessment recommend that the assessment of tolerable risk is based upon an assessment of probability of loss of life for the person or group which is most at risk (individual risk) and the societal risk criteria (F-N Curve) which incorporates the ALARP principle (refer below). Both of these measures require the combination of probabilities from different failure modes and dam sections to estimate the total probability of loss of life.

Some risk guidelines apply to the total probability of failure. For example the USBR (2003) Tier 2 Public Protection Guidelines are based upon the total probability of failure exceeding 1×10^{-4} per annum.

Other risk guidelines refer not just to the probability of failure but rather to the annualised risk[6]. For example the USBR (2003) Tier 1 Public Protection Guidelines are based upon the annualised life loss levels for

[6] Annualised risk is defined as the product of probability of failure and consequences integrated over the entire range of each type of initiating event (loading) and summed over all types of initiating events.

earthquake, flood and normal operating of 1 x 10^{-2} and 1 x 10^{-3} lives per annum. The risk for each loading condition is assessed separately.

The majority of guidelines relate to total probability of reservoir failure and therefore probabilities for each dam section and component and for all types of initiating events and failure modes need to be appropriately determined. When the outcome of interest is related to the consequences of failure, then the different types of population at risk (PAR) exposure conditions should also be considered.

In the event tree analyses an exposure event subtree (see Figure 1) can be appended to the failure mode event tree to characterise the day-night, weekday-weekend and seasonal differences in exposure of the PAR. The combined event tree can then be used to estimate the probability of consequences; particularly the probability of life loss.

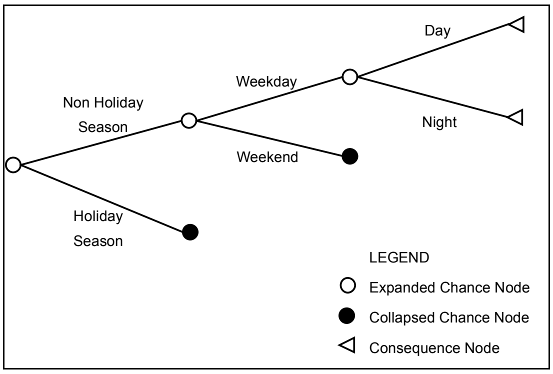


Figure 1 Example of exposure time subtree

2.2 ASSESSING SAFETY UPGRADES

The appropriate combination of probabilities is also important for understanding and assessing the justification of upgrades. Understanding of the relative significance of different failure modes is enhanced through comparing estimates of probabilities of failure and other risk measures. The contribution of gate reliability and spillway plugging factors to dam failure risk must be estimated through comparing risk model runs made with and without these processes contributing. This is because they increase the probability of failure by mechanisms such as overtopping, but do not by themselves constitute a failure mode. Thus the increase in risk due to the estimated level of gate reliability, for example, must be obtained by comparing results from a run made under the assumption that the gate system is perfectly reliable.

The ANCOLD (2003) Guidelines on Risk Assessment recommend that societal risk should be reduced to as low as reasonably practicable (ALARP). Measures of reasonableness include the adjusted cost per statistical life saved (ACSLS) and the related concept of a Disproportionality Ratio (R), which is based on HSE (2001) Tolerability of Risk Guidelines (Bowles, 2003).

Probabilities from different failure modes and dam sections need to be carefully combined over all types of initiating events and exposure conditions to estimate the total probability for deriving estimates of life loss and economic loss risk reductions that contribute to ACSLS and R, and hence to assessing the justification of upgrades. Inappropriate treatment of probabilities can lead to bias in the assessment of justifying upgrades.

3 ESTIMATING PROBABILITIES

A full discussion of the available methods for estimating probabilities for dam safety risk analysis is outside the scope of this paper.

Fell et al. (2000) provides a summary of the status of methods for the estimation of failure of dams for use in quantitative risk assessment. They recognise the following two broad categories of methods:

1) *Historic performance methods* - These methods use the historic performance of dams similar to the dam being analysed to assess a historic failure frequency, and assumes that the future performance of such dams will be similar. These methods do not directly account for the reservoir loading, nor do they allow for the detailed characteristics of the dam or for particular intervention. Generally speaking, these methods are only applicable for initial or portfolio risk assessments, and for

checking more detailed event tree methods, and should not be used alone for detailed assessments.

2) *Event tree methods* - Event tree methods have the advantage that the mechanics of the failure, from initiation to breach can be modelled; the details of the dam and its foundation and the ability to intervene to prevent breaching. However, sometimes there is little objective basis for estimation of the conditional probabilities within the event tree and therefore it may be necessary to relate back to historic performance data as a "credibility check" on the answers.

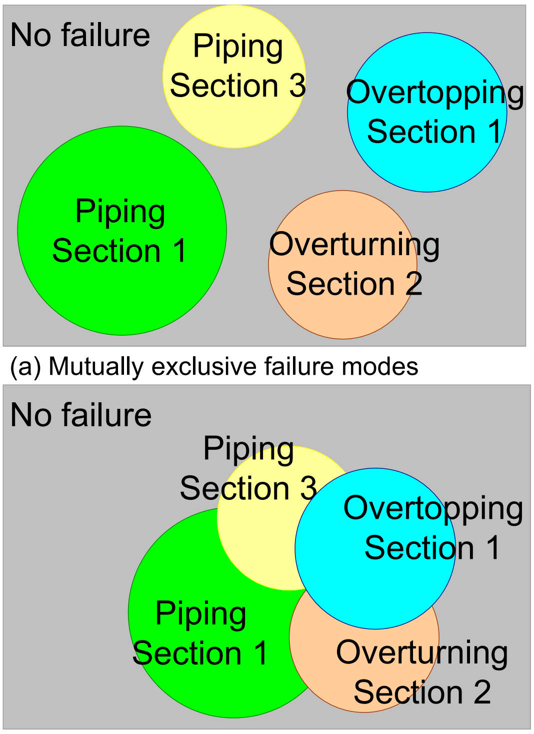
4 COMBINING PROBABILITIES

4.1 COMMON CAUSE FAILURE MODES

Common cause failure modes are failure modes that can occur simultaneously at a single dam section due to a single initiating event, and failure modes that can occur simultaneously at multiple sections of a dam due to a single initiating event. The total probability of dam failure is some combination of the probabilities of dam failure that are associated with each of the possible modes.

Figure 2 shows two hypothetical Venn diagrams for a particular point on the flood loading system response curves (i.e. for a particular peak reservoir level). The hypothetical case has three sections and the significant failure modes are flood induced piping through the embankment and overtopping for Section 1, overturning of a concrete gravity section for Section 2, and piping through the embankment in Section 3.

Figure 2a shows the Venn diagram for the case that the failure modes are mutually exclusive. For this case the probabilities for the individual failure modes are simply additive. However, in the majority of cases the different failure modes are not mutually exclusive and therefore the probabilities are not additive. This is depicted in Figure 2b. For these cases the probabilities need to be carefully combined to correctly account for the common cause failure modes, represented in the Venn diagram by the intersection of each failure mode event.



(b) Common cause failure modes

Figure 2 Hypothetical Venn diagrams showing conditional probability of failure for different failure modes for a given peak reservoir level

It is important to avoid incorrectly inflating the estimate of probability of failure and other risk measures for the entire project by neglecting to make adjustments for common cause failure modes at the various sections.

Improper handling of common cause failure modes in event tree calculations can also be important because different failure modes at different dam sections might lead to significantly different dam failure characteristics (e.g. breach geometry and time), and hence different failure consequences to the owner or third parties. In some cases a saddle dam failure might result in a significantly smaller failure flood in an entirely different downstream area, at least in the near field. For this reason, it is often necessary to keep a track of the consequences, usually at least in terms of economic losses and estimated loss of life, that are associated with the probability of each particular failure mode, dam component and loading condition.

Thus incorrect handling of common cause failure mode can also distort the relative estimates of risk for dam sections and components under existing conditions and for proposed fixes. It can therefore distort estimates of risk reduction and hence the justification for fixes.

A common cause adjustment (CCA) approach should be used when failure modes are not mutually exclusive. This recognises that a failure in one section by a particular mechanism can take place simultaneously with failure of another section or failure of the same section by a different mechanism. Once the conditional probability of failure based on the intersection of all failure mechanism in the Venn diagram becomes 1.0, two cases can pertain. The first is when the breach discharge is sufficient to pre-empt an additional breach from occurring. The second is when reservoir levels remain high enough to complete development of other breaches.

In the second case, as additional breaches occur at higher peak reservoir levels, additional consequences must be considered as a result of discharges through the each breach. These additional discharges may increase flows in the same river that is affected by the first breach or they may result in flooding in a different river below a breach that occurs within another section of the dam and possibly caused by a different mechanism. An example of this would be a dam where multiple pipes are able to fully develop to breaches in the embankment. Such an approach would be applicable where, for example, the release of water via a breach would not be sufficient to significantly reduce the driving head for other piping breaches.

The occurrence of more than one breach does not change the probability of "a" failure occurring. However, the risk model calculations can be used to track the probability of different numbers of breaches and of breach flows in different rivers below a single reservoir.

4.2 UNI-MODAL BOUNDS THEOREM

The conditional probabilities for the failure modes that are not mutually exclusive can be adjusted for common cause occurrence by using the uni-modal bounds theorem. The uni-modal bounds theorem (Ang and Tang, 1984) states that for *k* positively correlated failure modes, with conditional branch failure probabilities (system response probabilities, or SRPs), p_i, the system (total) branch failure probability, p_f, lies between the following upper (*u*) and lower (*l*) bounds:

$$\max_i\,[p_i] \;\leq\; p_f \;\leq\; 1-\Pi_{i=1}^{k}(1-p_i)$$

$$p_f^l \;\leq\; p_f \;\leq\; p_f^u$$

While the uni-modal bounds theorem provides an approach to bounding the total branch failure probability, it does not provide a direct means of bounding individual failure mode probabilities. This latter adjustment is needed because the consequences associated with each failure mode may differ. While there is no unique approach to adjusting each system response probability, the following approach is proposed by Bowles et al. (2000).

The upper (*u*) bound can be used to adjust the branch failure probabilities for each failure mode as follows:

$$p_i^u \;=\; p_i\,(p_f^u/p_f)$$

This adjustment should be made simultaneously over all sections of a multi-section dam. It should be calculated and applied separately in each probability interval for a loading type.

However, for flood and normal operating (static) failure modes, the adjustment should "frozen" at the value that is calculated for the first loading interval, proceeding from the smallest to the largest magnitudes of loading, for which the unadjusted sum of the branch failure probabilities equals or exceeds 1.0. This "freezing" of the adjustment factor avoids unrealistic adjustments being used for higher magnitude floods or normal operating (static) loading conditions when failure would have already occurred at lower loading magnitudes.

Freezing of the adjustment factor is not necessary for earthquake loading, since it is short lived and does not progressively increase in magnitude and PGA like flood and static loading. In some cases, when failure probabilities are very small, the CCA may make no significant difference to risk analysis results and can be ignored.

To adjust branch failure probabilities using the lower (*l*) bound, one can set all branch failure probabilities for each failure mode (simultaneously over all sections of a multi-section dam) to zero, except for the maximum one which should retain its value without adjustment. For flood and static failure modes "freezing" should be exercised in a similar manner to that described for the upper bound case.

4.3 PHYSICAL DOMINANCE

In some situations, it might be possible to use an argument of the physical dominance of one failure mode over all others that are due to the same common cause (Tarbox et al 1988). Using the probability of the physically dominant mode, is appropriate where the probability of one particular mode and section develops a breach so rapidly that it causes discontinuation of development of the other breach by reducing the reservoir level and "starving" the other breach of the driving head. In this case, the conditional probability of failure will be equal to that of the physically dominant mode from the point on the range of loading at which the physical dominance takes over.

As an example, consider the overtopping of a main embankment section and a saddle embankment section, which both have the same crest elevation, but where the saddle dam is constructed from significantly more erodible materials than the main dam. Erosional failure of the saddle dam might be considered to have physical dominance over failure of the main dam because it is far more erodible and because as it breaches it reduces the reservoir level sufficiently to arrest the breach process at the main dam section. The dominance situation might turn out differently in this example if the breach of the saddle dam does not significantly reduce the reservoir level, in which case both sections might fail, although likely sequentially.

Dominance relationships can be accounted for as follows:

1) Make estimates of conditional probabilities (system response probabilities, or SRPs) of failure over the entire range of loading for each failure mode as if they are mutually exclusive of all other failure modes.
2) Reduce the conditional probabilities of failure for the dominated failure mode(s) to reflect the effect of the dominant failure mode.

Care should be taken to review such dominance relationships when representing a risk reduction measure using the event tree. For example, if downstream slope protection is added to the saddle dam, dominance might shift to the failure of the main dam section. Clearly each situation should be carefully considered over the entire range of loading.

4.4 POTENTIAL FOR MULTIPLE BREACHES

For most dams, failure of one section of the dam in a particular failure mode is likely to preclude further breaches in the dam. In these cases, a large breach would cause a relatively rapid release of water and a correspondingly rapid reduction in the water level in the reservoir. In this scenario, the first breach quickly removes the loading conditions on the rest of the dam and virtually eliminates the probability of further breaches.

For a relatively low dam that retains a very large volume reservoir, the rate of reduction in water level after occurrence of the first breach may be insufficient to pre-empt additional breaches from occurring. In this case, the failure probabilities do not increase with the occurrence of additional breaches, but consequences do because of the increased discharge capacity and possibly a new flow pathway created by subsequent breaches.

Research is being undertaken at Utah State University, to develop a physically-based three-dimensional computer simulation model for the multiple breach location problem. The model includes flood routing and overtopping/breach hydraulics, wind setup and wave effects, sediment transport and stability processes associated with multiple breach initiations for an embankment dam and reservoir system. This work seeks to provide a basis for estimating the probability of the location of a breach for a varying crest level and improved estimates of breach flood waves from multiple locations and hence their associated consequences. An uncertainty analysis approach is being incorporated.

5 WORKED EXAMPLE

The impact of the methods of computing dam failure probabilities on decisions regarding dam upgrades is demonstrated by considering a worked example for a notional dam. The notional dam has a main embankment composed of earth and rockfill with an ungated concrete overflow spillway. A preliminary engineering risk assessment identified that there were three significant failure modes that would contribute to the total probability of failure:

- overtopping of the earth and rockfill embankment;
- piping through the earth and rockfill embankment; and
- piping into or through the alluvial foundation material.

Overtopping failure is likely to occur once the water level in the reservoir reaches the crest level of the embankment. The conditional probability of failure due to overtopping increases with the maximum flood level in the dam.

The conditional probability of piping failure also increases with the reservoir level. Elevated reservoir levels, which occur during floods, increase the driving head on potential piping failure paths within the embankment and foundations. Elevated reservoir levels may also expose new potential piping failure paths within the embankment that are otherwise not exposed during non-flood periods.

Because of the variations in zoning of the earth and rockfill material, the notional dam can be subdivided into several sections. The crest level of the embankment and the potential for wind setup and wave effects vary along the embankment, so that some sections have a higher conditional probability of failure in the event of overtopping than others. Variation in embankment zoning and foundation materials also result in variations in the conditional probability of piping failure between the sections of the embankment.

The total probability of failure was computed, incorporating CCA between:

- the three failure modes of overtopping, piping through the embankment and piping through or into the foundations; and
- the sections of the embankment, determined according to variations in zoning of material, composition of foundation and level of embankment crest.

The total probability of failure for the existing dam incorporating CCA is estimated to be 1.4×10^{-4}, or 1 in 7,400 per annum.

If no adjustment for common cause of dam failure is made, the estimate of the total probability of failure increases to 1.8×10^{-4}, or 1 in 5,500 per annum. Ignoring the CCA thus overestimates the total failure probability for the notional dam in its existing state by about 35%.

The risks associated with dam failure were also computed for the existing notional dam, in terms of incremental annual loss of life and incremental annual economic costs. These computations were performed both with and without CCA. Annualised economic losses and loss of life are about 40% lower in using CCA than without CCA.

For our notional dam, there are three possible stages of works to upgrade the dam. The impact of incorporating CCA on the probability of failure, annualised incremental consequences, and ACSLS is shown in Figures 3 to 5, which are discussed below.

Figure 3 shows the reduction in probability of failure with the stage of dam upgrade. For a given stage of dam upgrade, the probability of failure estimated with CCA is lower than the estimate made without adjustment for common cause. The differences in estimated probabilities of failure between calculations made with and without CCA are also likely to influence the arc of the F-N curve, which may overstate the justification for a particular stage or stages of the dam upgrade.

Figure 4 shows that the annualised incremental loss of life also reduces as stages of the upgrade are implemented. For a given stage of dam upgrade, the annualised incremental loss of life estimated with CCA is lower than the estimate made without adjustment for common cause. After implementation of stage 2, the incremental annualised loss of life estimated without CCA is almost three times the value estimated with CCA.

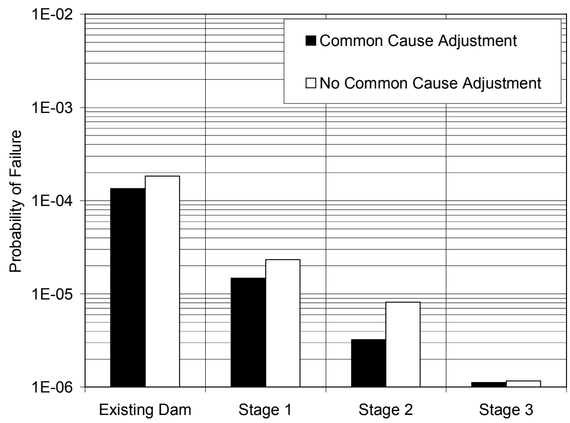


Figure 3 Impact of Common Cause Adjustment on total probability of failure for notional dam and upgrades

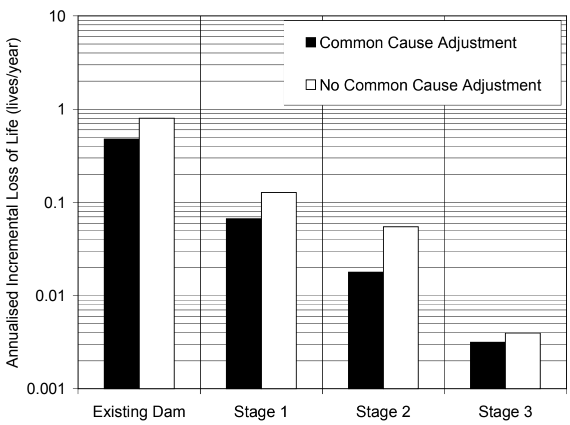


Figure 4 Impact of Common Cause Adjustment on annualised incremental loss of life for notional dam and upgrades

To illustrate the impacts of these different estimates it may be assumed that the three stages of dam upgrade have capital costs of $ 10.0 M, $ 7.0 M and $ 7.0 M respectively. In this example, a discount rate of 6% per annum and an economic life of 50 years have been assigned for capital costs associated with upgrades to the dam.

Adjusted cost per statistical life saved (ACSLS) is used to demonstrate reasonableness under the ALARP principle. Figure 5 shows that the ACSLS is low enough for Stage 1 of the upgrade, when computed with or without CCA, that Stage 1 would likely be considered to be easily justified under ALARP.

However, the CCA has a considerable influence on the CSLS for both Stages 2 and 3 of the upgrade, which may well influence the decisions that are made on proceeding with these stages. The ACSLS of $ 4.3 M/statistical life, computed without CCA, would probably provide good justification for Stage 2 under ALARP. However, the ACSLS of $ 7.2 M/statistical life computed with CCA would be reduced, although not significantly in this case.

The contrast is more prominent for Stage 3, with an ACSLS of $ 9.2 M/statistical life without CCA providing some support for Stage 3 of the upgrade; but when CCA is included the justification for Stage 3 would be reduced based upon an ACSLS of $ 32 M/statistical life.

Such differences in ACSLS could also have a significant effect on the prioritisation of risk reduction measures for a single project or across dams in a portfolio.

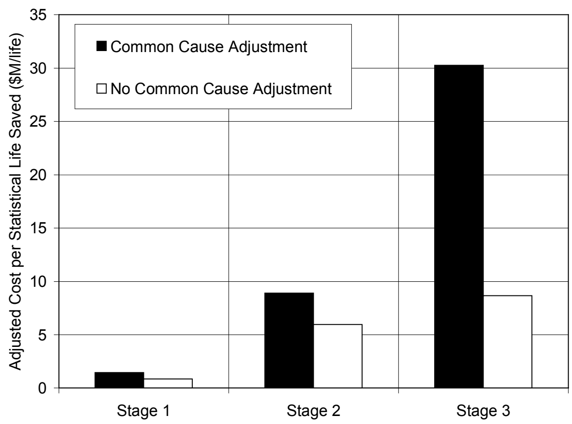


Figure 5 Impact of Common Cause Adjustment on adjusted cost per statistical life saved for notional dam and upgrades.

6 CONCLUSIONS

Estimates of probability are required in dam safety risk analysis for estimating both the probability of failure and the consequences of failure (e.g. life loss). These estimates can then be used to assess the risk associated with an existing dam and the justification for upgrades using risk evaluation guidelines.

The majority of risk guidelines are based upon the total probability of failure or loss of life and therefore this requires the appropriate combination of probabilities from different failure modes and dam sections. Examples of common cause failure modes include multiple failure modes that can occur simultaneously at a single dam section due to a single initiating event, and failure modes that can occur simultaneously at multiple sections of a dam due to a single initiating event.

The Uni-Modal Bounds Theorem provides a method for adjusting conditional probabilities for the failure modes that are not mutually exclusive. This adjustment should be made simultaneously over all sections of a multi-section dam. It should be calculated and applied separately in each probability interval for a loading type.

It is important that the method of combining probabilities is chosen that reflects the physical conditions in the system being modelled. In some situations, it might be possible to use an argument of the physical dominance of one failure mode over all others that are due to the same common cause. Using the probability of the physically dominant mode, is appropriate where the probability of one particular mode and section develops a breach so rapidly that it causes discontinuation of development of the other breach by reducing the reservoir level and "starving" the other breach of the driving head.

It is clear from the worked example that the approach taken to combine probabilities can have a significant influence on the key risk estimates that are used in decisions about dam upgrades. In the worked example, ignoring adjustment for common cause of dam failure leads to:

- Overestimation of the total probability of failure;
- Overestimation of the annualised incremental loss of life; and,
- Underestimation of the adjusted cost per statistical life saved.

The underestimation of the adjusted cost per statistical life saved for two of the stages could be important in risk-based decisions about dam upgrades and their prioritisation. Stages that would be justifiable under the ALARP principle using the ACSLS values without CCA are less justifiable when the ACSLS values are more realistically computed using CCA.

The differences in estimated probabilities of failure between calculations made with and without CCA are also likely to influence the arc of the F-N curve, with computations made ignoring CCA also overstating the justification for a particular stage or stages of the dam upgrade.

7 ACKNOWLEDGMENTS

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