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Evaluation of Decisions to Rehabilitate South African Dams in terms of the ANCOLD ALARP Criterion and SWTP for Human Safety

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ABSTRACT: Eleven case studies of dam rehabilitation projects in South Africa are evaluated in terms of quantitative risk assessment criteria (ANCOLD, 2003) and Society's Willingness to Pay (SWTP) (Pandey, et al., 2006). Inspection and design reports on which the decisions to rehabilitate were based were made available by the Department of Water and Sanitation, South Africa, from where estimates of pre- and posterior probabilities of failure, expected loss of human lives as well as cost of rehabilitation were obtained. In all cases, ANCOLD's ALARP criterion dictated that the (existing) dams be rehabilitated. Only one of the eleven cases requires rehabilitation based on the SWTP criterion. The other cases either had a prohibitively high rehabilitation cost, an already low probability of failure prior to rehabilitation or low expected loss of lives in case of failure.

1. INTRODUCTION

South African and international dam authorities base their decisions to rehabilitate dams on several criteria, of which risk to human lives is an important one. Internationally, the Australian National Committee on Large Dams' (ANCOLD's) risk to human lives criterion, based on the ALARP principle, may be considered the most widely accepted. This criterion accepts lower safety levels for existing dams, based on the argument that it is considerably more expensive to improve the safety of existing structures compared to new ones (ANCOLD, 2003).

Target safety levels, as defined by the Probabilistic Model Code (JCSS, 2001) are similarly differentiated based on the relative cost of implementing safety measures, with lower safety levels being accepted when the relative cost is large. These target safety levels have been derived based on monetary optimization (Rackwitz, 2000), while the ANCOLD criteria are based on engineering judgment and past experience.

The social acceptability of the structural design in terms of risk to human life is, however, not necessarily guaranteed when relying on the ANCOLD life safety criteria or the JCSS target reliabilities. Figure 1 shows the interaction between monetary optimization and an acceptance criterion for risk to life. Within the acceptable region the optimization may be performed by a private or societal decision maker, but the acceptance criterion always has to be evaluated from a societal point of view. The acceptance threshold can be defined based on the marginal life saving costs principle, using the Life Quality Index (LQI) net benefit criterion to judge the efficiency of life saving measures from a societal point of view. Only efficient investments into life safety have to be performed, as dictated by the LQI based Society's Willingness to Pay (SWTP), but higher safety levels are of course also acceptable and may be aimed at if required by monetary optimization or other considerations. SWTP is a utility function which may be used to determine the level of expenditure into life safety required by society (Pandey, et al., 2006) and applied in this study to determine the lower bound for acceptable investments in dam rehabilitation. The cost effectiveness of rehabilitation work to provide increased safety determines whether or not the investment is required. Economic optimization would often imply higher safety levels than required by SWTP (Rackwitz and Streicher 2002, Fisher et.al. 2012).

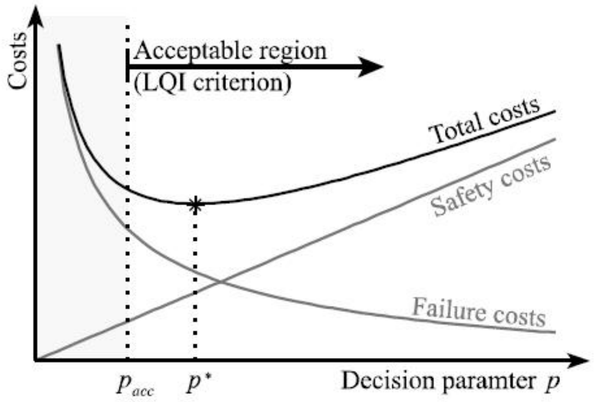

Figure 1: The LQI acceptance criterion as a boundary condition for monetary optimization

The content of the paper is outlined as follows: ALARP criteria and their application in decision making regarding dam rehabilitations are discussed in section 2. In section 3, SWTP is introduced as a lower bound to acceptable investments in dam safety. Data for eleven cases of actual dam rehabilitations that were carried out in South Africa is provided in section 4. Finally, in section 5 the decisions to rehabilitate are evaluated for these cases in terms of (a) internationally accepted ALARP criteria for existing dams, (b) the lower bound for acceptable safety as defined by SWTP. We conclude with short discussions on the acceptability of rehabilitation decisions taken, the factors that influence the SWTP boundary and a comparison of ALARP and SWTP criteria.

2. ALARP CRITERIA AND DAM REHABILITATION DECISION MAKING

The most commonly used format to quantitatively assess risk to human life is against risk acceptance criteria, presented as acceptance lines on a Farmer diagram, such as Figure 2. Farmer diagrams have a double-logarithmic scale with the x-axis representing the number of fatalities (N) and the y-axis representing the annual frequency (F) of N or more fatalities occurring (Kroon and Maes, 2008).

Risk located below the negligible line may be regarded as broadly acceptable, while risk located above the intolerable line should not be accepted. In between the two criterion lines risks are regarded as tolerable only if they are reduced to be As Low as Reasonably Practicable (ALARP). The joined term "reasonably practicable" can be interpreted as the degree of risk balanced against time, cost and physical difficulty of implementing risk reduction measures (Melchers, 2001).

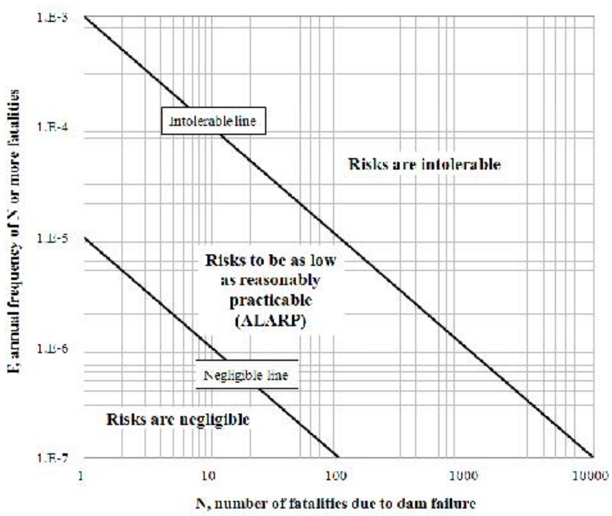

Figure 2: Illustration of typical implementation of quantitative risk acceptance criteria

Ball and Floyd (1998) presents an overview of the development and application of quantitative risk to human life criteria from the 1960's to the 1990's, focusing on developments in the UK, Hong Kong and the Netherlands: Acceptance lines are primarily defined by two properties, namely the intersection with the y-axis and the gradient of the line. The upper limit of tolerability is often set at 10^{-4} for 10 or more fatalities. The negligible acceptance line tends to be located two or three factors of 10 (100 or 1000) lower on the frequency (F) scale. For some criteria, such as the criteria developed in Hong Kong, the acceptance lines are truncated vertically and thus an upper limit for the potential loss of life is defined. The gradient of the line represents the degree of risk aversion of the society (Kroon and Maes, 2008). Risk aversion is the additional public opposition to an event which kills a large number of people over a series of smaller events which collectively result in the same number of fatalities. According to Ball and Floyd (1998), most acceptance lines have negative gradients of between -1 and -2. A gradient of -1, is termed 'risk neutral', while a steeper gradient implies risk aversion.

Current application of conventional acceptability criteria for risk to human life in international dam safety is reported in "Risk Assessment in Dam Safety Management" (ICOLD, 2005). In this survey the International Commission on Large Dams (ICOLD) collected responses from 24 member countries. Of these, nine (Australia, Canada, Czech Republic, Germany, the Netherlands, New Zealand, South Africa, United Kingdom and the USA) explicitly discuss risk criteria. Although many countries presented a view and acknowledge that risk-based tools are useful within dam safety, there are contradicting opinions on its application and many countries are hesitant to clearly define quantitative acceptance criteria for risk to human life.

2.1. ANCOLD Criteria

The Australian Committee on Large Dams (ANCOLD), proposes risk acceptance criteria for new and existing dams in their Guidelines on Risk Assessment (ANCOLD, 2003), as shown in Figure 3: The acceptance line for existing dams is one factor of 10 less stringent than for new dams, based on the argument that it is considerably more expensive to improve the safety of existing structures compared to new ones, i.e. it is not deemed reasonably practicable to reduce the risk of existing dams to the same levels as new dams. Also, acceptance lines are truncated horizontally, because current technology does not allow for the construction of dams with smaller probabilities of failure.

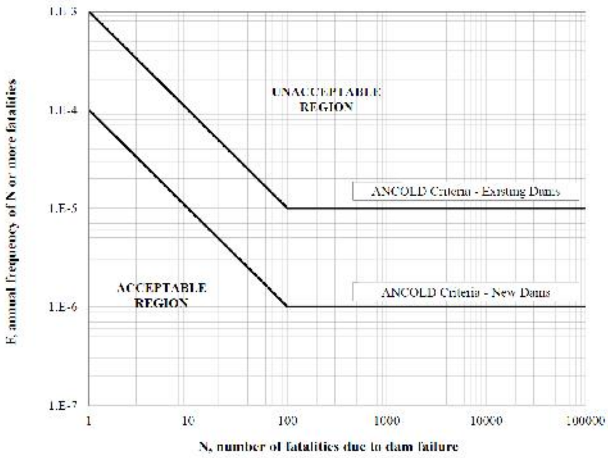

Figure 3: ANCOLD risk acceptance criteria for new and existing dams

3. SWTP AS A LOWER BOUND FOR DAM SAFETY

3.1. Background

Society's Willingness to Pay (SWTP) is a utility function which effectively determines the lower bound for investments in life safety required by society (Pandey, et al., 2006). It is based on the Life Quality Index (LQI) which jointly considers the social indicators of a nation to give a measure of the quality of life of a society (Pandey and Nathwani, 2004). In a simple form, the LQI can be written as

$$L = G^q E \qquad (1)$$

where G represents the Gross Domestic Product (GDP) per person, E the life expectancy at birth and q is a parameter which reflects the trade-off placed on consumption and the value attached to length of life. The parameter q depends on the fraction of time spent producing G, and the remaining time, the leisure time, available for the enjoyment of E.

An investment in life safety should lead to an improved life quality. A small change in the LQI due to the implementation of a safety measure is shown as

$$\frac{dL}{L} = \frac{dG}{G} + K\frac{dE}{E} \qquad (2)$$

where dG corresponds to the monetary cost of implementing the project (negative), dE the change in the life expectancy due to a change in the risk associated with the project and K = 1/q.

The LQI net benefit criterion requires that an investment into life safety, which influences both G and E, should lead to a positive change in the LQI, i.e. $dL/L \geq 0$. SWTP defines the lower boundary for acceptable decisions and may be obtained as the exact value (dL/L = 0) of Equation 2:

$$-\mathrm{dG} \geq \mathrm{SWTP} = \mathrm{GK}\frac{\mathrm{dE}}{\mathrm{E}} \approx \mathrm{GKC_x d\mu} \qquad (3)$$

Society requires that an investment, −dG, into a life-saving activity should at least be equal to the SWTP for a marginal increase in life expectancy (Fischer, et al., 2011). The parameter dE/E may not always be easily quantified and instead it may be calculated as the product of the mortality change ($d\mu$) and a demographic constant (C_x). The demographic constant takes age-averaging and discounting into account (Lentz, 2007).

3.2. Estimation of SWTP

Country specific values of SWTP may be derived, but South Africa does not conform well with the preferences underlying the LQI principle, i.e. the joint development of health and life safety (life expectancy at birth), economy (GDP per person) and the necessary time to work (described by q as the ratio of work time to leisure time) .

In this study the Earth value for SWTP (ESWTP) (Faber and Virgüez-Rodriguez, 2011) was used, assuming a 3% time preference rate for consumption and a uniform mortality reduction scheme. The ESWTP of $US 517,000/life amounts to R 4.048 million/life, based on the average R/$ exchange rate for the period 2006 to 2011, during which time the dam rehabilitations described in section 4 were carried out.

3.3. SWTP in dam safety

SWTP dictates that investments should be made into all life saving measures which are considered efficient by society, i.e. where the cost per marginal life saved is less than the SWTP threshold. In the dam rehabilitation projects considered here, rehabilitations would be efficient (and required) if

$$\frac{\Delta C}{\Delta N} \leq SWTP \qquad (4)$$

where ΔC is the annualized cost of rehabilitation over the design life and ΔN is the corresponding reduction in annual expected loss of life. The reduction in annual expected loss of life ΔN is realized based on the reduction in the annual probability of dam failure p_f achieved through rehabilitation, multiplied by the estimated loss of life (LL) in case of dam failure

$$\Delta \mathrm{N} = \left(\mathrm{p_{f,prior}} - \mathrm{p_{f,post}}\right).\mathrm{LL} \qquad (5)$$

The South African Department of Water and Sanitation (DWS) assumes the annual probability of dam failure after it has been rehabilitated $(\mathrm{P_{f,post}})$ to be between 10^{-5} and 10^{-6} per year, equivalent to a well-engineered dam with no known deficiencies (Oosthuizen et al., 2002).

For a given rehabilitation investment to be considered efficient, a minimum reduction ΔN in the expected loss of human lives are required (Eq.4). Equation 5 then implies that a rehabilitation investment may be considered inefficient because;

a) the achieved reduction in the probability of dam failure is too small. This may in turn be due to an ineffective rehabilitation strategy, or because the initial probability of failure is already small.
b) the expected number of lost lives (LOL) in case of failure is already so low that a change in failure probability does little to improve the expected ΔN

For a given dam rehabilitation project, with ΔC, $p_{f,prior}$ and $p_{f,post}$ known, a threshold value LL_{SWTP} may be calculated, which can be used together with $p_{f,prior}$ to locate an FN-SWTP-criterion line on the Farmer diagram, assuming a risk neutral gradient of one. For such a project, if the expected LL in case of dam failure is more than the threshold value (LL_{SWTP}) the rehabilitation project is required by society. Section 5.2 details this assessment for eleven dam projects.

4. CASE STUDIES

A 2004/05 the South African Department of Water Affairs study concluded that 166 of the 314 government owned dams was in need of rehabilitation. The study prompted spending on rehabilitations that amounted to over R1.5 billion by 2012 with 19 dams being rehabilitated in full (Segers, 2012). Initial inspection reports and rehabilitation design reports were made available for eleven of these and is used here as case studies.

Table 1: Estimated risk to human life for dams prior to rehabilitation

Dam	Estimated number of lives lost (LL)		Prior probability of failure ($p_{f,prior}$)	
	Min	Max	Min	Max
Bospoort (Sluice open)	9	13	$1e^{-3}$	$1e^{-2}$
Bospoort (Sluice fail)	9	13	$1e^{-2}$	$1e^{-1}$
Klein Maricopoort	3	5	$1e^{-4}$	$1e^{-3}$
Toleni	2	3	$5e^{-4}$	$5e^{-3}$
Lakeside	200	400	$2e^{-4}$	$2e^{-3}$
Vaalkop	35	350	$2e^{-5}$	$2e^{-4}$
Rust de Winter	13	13	$5e^{-5}$	$5e^{-4}$
Makotswane	5	8	$3e^{-4}$	$3e^{-3}$
Kromellenboog	18	19	$2e^{-4}$	$2e^{-3}$
Albert Falls	100	170	$1e^{-4}$	$1e^{-3}$
Glen Brock	21	29	$1e^{-3}$	$1e^{-2}$
Wentzel	156	312	$1e^{-3}$	$1e^{-2}$

DWA estimates of the initial probability of failure ($P_{f,prior}$) and loss of life (LL) in case of dam failure were obtained as intervals from DWA dam safety inspection reports, as shown in Table 1. Note that for Bospoort Dam two scenarios were considered in the DWA risk analysis, namely 1a) sluice gates function normally during dam failure, and 1b) sluice gate failure.

Rehabilitation design reports provided the estimated total costs of safety improvements, which were annualized over a 50 year design life at an interest rate of 7%, as detailed in Table 2.

Table 2: Estimated cost of rehabilitation

Dam	Estimated cost of rehabilitation	Annualised cost of rehabilitation (Rm/yr)
Bospoort	R 84 342 000	R 6.11m
Klein Maricopoort	R 39 330 000	R 2.85m
Toleni	R 23 662 000	R 1.71m
Lakeside	R 25 194 000	R 1.83m
Vaalkop	R 24 225 000	R 1.76m
Rust de Winter	R 21 318 000	R 1.54m
Makotswane	R 16 956 000	R 1.23m
Kromellenboog	R 19 157 000	R 1.39m
Albert Falls	R 16 530 000	R 1.20m
Glen Brock	R 17 600 000	R 1.28m
Wentzel	R 14 250 000	R 1.03m

5. EVALUATION OF REHABILITATION DECISIONS

5.1. Comparison to ANCOLD criteria

Risk to human life was estimated by DWS for eleven dams in need of rehabilitation, as detailed by the intervals reported in Table 1. These prior-to-rehabilitation intervals can be used to position the eleven South African dams on the ANCOLD FN-criteria graph, so that each project is depicted by a block, as shown on Figure 4.

Figure 4 can be used to evaluate these projects in terms of the ANCOLD acceptability criteria. It is clear that, according to ANCOLD, the decisions to rehabilitate are justified as none of the dams adhered to acceptable risk levels for existing dams prior to rehabilitation.

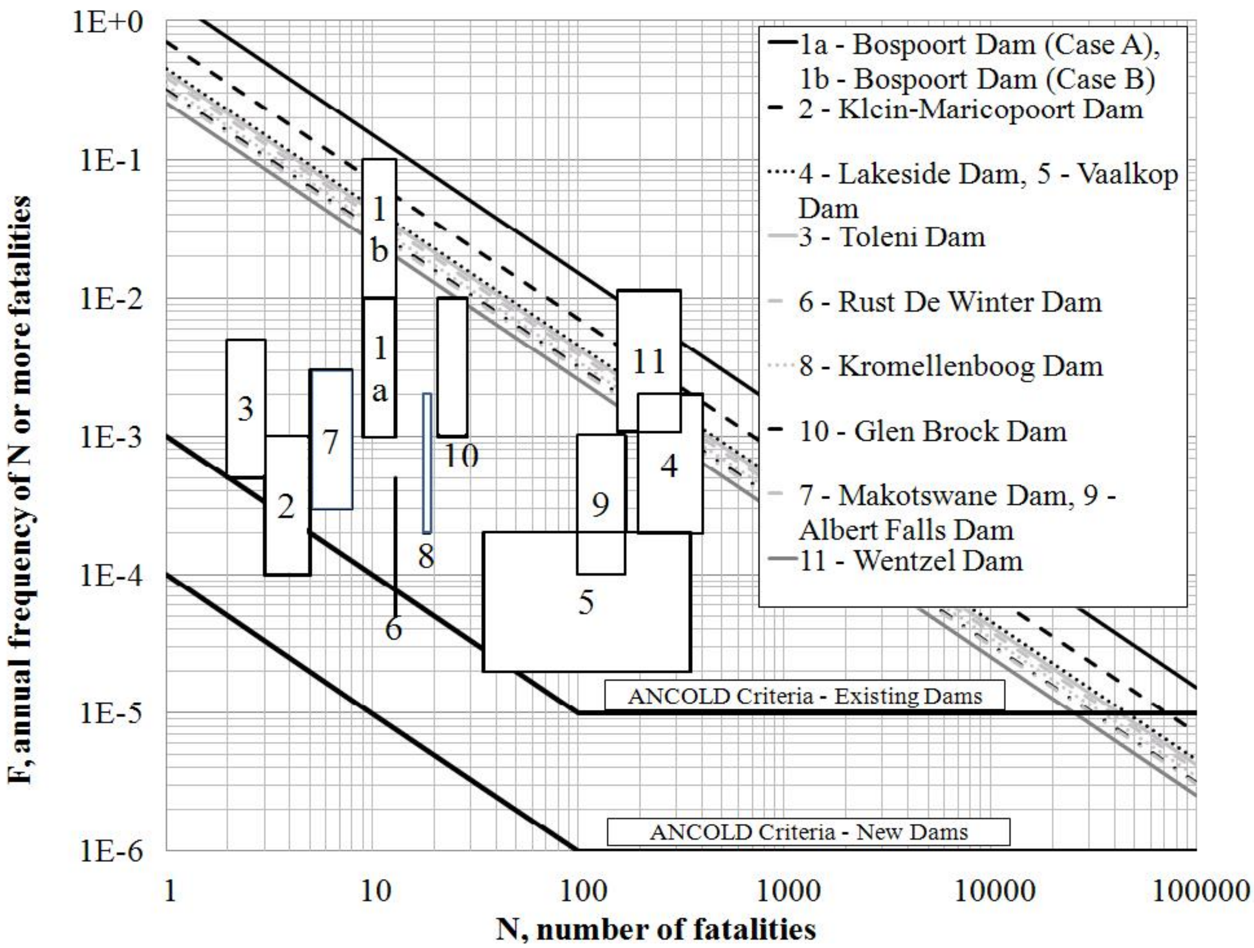

Figure 4: DWA rehabilitation projects compared to ANCOLD FN-criteria as well as to their project specific FN-SWTP-criteria lines

5.2. Comparison to SWTP criteria

FN-SWTP-criterion lines were generated for each of the eleven case studies, based on the procedure described in Section 3.3. Accordingly, it can be seen in Figure 4 that most of the rehabilitations were not required by society. Based on the average cost per marginal life saved ($^{\Delta C}/_{\Delta N}$), only the rehabilitation of Wentzel dam (11) is required by society. Table 3 provides the average cost per marginal life for the eleven case studies, ranging from R 0.8 million up to R 1 308 million per marginal life.

Of course, it should be reiterated here that even when dam rehabilitation work is not required by society, it may still be considered based on economic, environmental, or other considerations in addition to safety.

The position of each criterion line depends only on the rehabilitation cost and SWTP. Criterion lines would become more stringent with increased SWTP or decreased rehabilitation cost. Correspondingly, the most stringent FN-SWTP-criterion is associated with Wentzel Dam, which has the lowest annualized rehabilitation cost, while the least stringent FN-SWTP-criterion is associated with Bospoort Dam, which has the highest annualized rehabilitation cost.

It is interesting to note that, for Bospoort Dam, the FN-SWTP lines intersect the vertical axis at a positive value, which would imply that at these rehabilitation cost levels, society deems more than one expected death per annum acceptable. At very high values of expected loss of life, the

SWTP lower bound would require higher safety levels than currently accepted by ANCOLD.

Table 3: Average cost per marginal life saved through dam rehabilitation projects

Dam	Average Δ_N (lives/year)	Marginal liife cost ($\Delta C/\Delta N$) (R/life)
Bospoort	$6.04e^{-2}$	R 101m
	$6.05e^{-1}$	R 10m
Klein Maricopoort	$2.18e^{-3}$	R 1 308m
Toleni	$6.86e^{-3}$	R 250m
Lakeside	$3.28e^{-1}$	R 5.6m
Vaalkop	$2.01e^{-2}$	R 87m
Rust de Winter	$3.50e^{-3}$	R 441m
Makotswane	$1.07e^{-2}$	R 115m
Kromellenboog	$2.02e^{-2}$	R 69m
Albert Falls	$7.35e^{-2}$	R 16m
Glen Brock	$1.37e^{-1}$	R 9m
Wentzel	$1.29e^{-0}$	R 0.8m

6. CONCLUSIONS

The decisions to rehabilitate eleven South African dams were evaluated. The decisions are justified by comparison to ANCOLD risk acceptance criteria. However, SWTP indicates that only one of the eleven rehabilitations was required by society, with the SWTP threshold located two to three factors of 10 (100 or 1000) higher on the frequency (F) scale than the ANCOLD acceptance line for existing structures. The position of the FN-SWTP-criterion is dam dependant and influenced primarily by the cost of rehabilitation works and the SWTP value. Societal requirements for rehabilitation are then largely influenced by the initial probability of failure of the dam and the expected number of lost lives in case of failure. This in turn implies that a rehabilitation investment may be considered inefficient because the achieved reduction in the probability of dam failure is too small, typically because the initial probability of failure is already fairly small; or because the expected number of lost lives in case of failure is already so low that a change in failure probability does little to further reduce the expected number of lost lives.

In addition to life safety and economic considerations, the South African Department of Water Affairs also considered socio-economic, social and environmental impacts in their decision to rehabilitate (Reynolds, 2013). Surprisingly however, the cost of rehabilitation works does not form part of their decision. If and how this cost should be included in the decision framework needs consideration.

7. ACKNOWLEDGEMENTS

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