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Economic Optimization Considerations in South African Dam Rehabilitations

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ABSTRACT: Economic optimization is applied to eleven case studies of actual dam rehabilitation projects in South Africa. The optimization includes the cost of rehabilitation and damage- and compensation costs for lives lost in case of dam failure. Economic motivation for the existence of the facility is excluded from the optimization. Five of the eleven cases would require rehabilitation based on economic optimization. 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. Costs to improve safety for the different cases was typically between ZAR 0.5 and 5 million per percentage reduction in the probability of failure over a 50 year design life, but could be as high as R50m/%. A high cost per percentage reduction is typically associated with dams that already had a low probability of failure prior to rehabilitation. Interesting to note when the outcome is compared to other rehabilitation decision criteria is that ANCOLD's ALARP criterion dictated that in all of the eleven cases the dams be rehabilitated, while only one of the eleven cases would require rehabilitation based on the Society's Willingness to Pay utility function (Reynolds, 2013). Surprisingly, the cost of rehabilitation works is not considered as part of the South African Department of Water and Sanitation's (DWS's) decision framework. Rational incorporation of this cost needs consideration.

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. The economic efficiency of the proposed rehabilitation work seems to be of lesser importance and is often not explicitly considered. Ideally, these should be appropriately weighted in the decision process.

This paper takes a first step towards formulating how this may be possible, by first applying economic optimization principles to eleven case studies of actual dam rehabilitation projects, comparing these economically feasible decisions to what would be arrived at by alternative decision models, and discussing the influence of various contributing factors in the decision framework.

2. BACKGROUND

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 decision criterion to motivate rehabilitation. 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).

Society's Willingness to Pay (SWTP) is a utility function which may be used to determine the acceptable level of expenditure into life safety required by society (Pandey, et al., 2006). The cost effectiveness of rehabilitation work to provide increased safety determines whether the investment is required.

Investments for improved safety could also be made for economic reasons. Economic optimization would often imply higher safety levels than required by SWTP (Rackwitz and Streicher, 2002; Fisher et.al., 2012).

In addition to life safety and economic considerations, the South African Department of Water and Sanitation also considers socio-economic, social and environmental impacts in their decision to rehabilitate. Surprisingly however, the cost of rehabilitation works is not considered.

The eleven case studies considered here are dam rehabilitation projects carried out between 2006 and 2011 by the Department of Water and Sanitation (DWS) within South Africa. Inspection and design reports on which the decisions to rehabilitate were based were made available by DWS, from where estimates of pre- and posterior probabilities of failure, loss of human lives and damage in case of failure, as well as cost of rehabilitation were available.

3. MONETARY NET BENEFIT OF REHABILITATION

For typical engineering facilities the monetary net benefit function is expressed by Rackwitz (2002) as

$$Z(p) = B(p) - C(p) - D(p) \qquad (1)$$

In the case of a rehabilitation project, $B(p)$ is the benefit derived from the extended existence of the facility, C(p) is the cost of rehabilitation works, D(p) is the change in the expected cost of failure of the facility and p is the vector of all safety relevant factors particular to the rehabilitation project under consideration.

It is assumed here that rehabilitation does not extend the useful life of the facility, so B(p) is assumed to be zero, i.e. economic motivations for the existence of the facility is excluded from the optimization.

Rehabilitation should generally lead to a lowered probability of failure P_f of the facility, resulting in a reduction in the expected cost of failure. Thus, D(p) should be negative, calculated as shown in Section 3.1 (Eq.$D(p) = C_f(p_{post}) - C_f(p_{prior})$ (5) and making a positive contribution to the net benefit Z(p).

Positive net benefit $Z(p)$ implies rehabilitation alternatives that are economically feasible. In this study eleven actual dam rehabilitations are assessed to determine whether or not the decisions to rehabilitate were justified from an economic perspective.

3.1. *Expected cost of failure*

Direct- and indirect economic losses in case of dam failure are estimated as part of South African dam safety evaluations. Direct economic losses could include the damage to the structure, loss of agriculture and the costs of emergency relief, while the indirect economic losses could include the loss of future benefits of the facility (Oosthuizen, 2002). The number of lost human lives (LL) is also estimated as part of each dam safety evaluation.

According to Lentz (2007) compensation for lost lives should be included in the cost of failure. The Societal Value of a Statistical Life (SVSL) may be used as an estimate of appropriate compensation for a lost life, based on societal preferences. The societal preferences referred to here are those underlying the Life Quality Index (LQI) principle as defined by Pandey, et al. (2006), i.e. the joint development of health and life safety (life expectancy at birth), economy (GDP per person) and the necessary time to work.

Faber and Virguez-Rodrigues (2011) estimates an Earth value for SVSL ($ESVSL$) based on observations from 71 countries, representing more than 70% of the Earth population. The $ESVSL$ of $US 629,000 used in this work is based on a rate of time preference for consumption of 3% (Arrow, 1995) and a uniform mortality reduction scheme. It is converted to South African Rands at the average R7.83/$ exchange rate for the period under consideration.

The total cost of failure c_f is determined by combining the components above as follows

$$c_f = E_d + E_{id} + LL.ESVSL \qquad (2)$$

Table 1: Dam failure cost- and probability estimates from the relevant dam safety evaluation reports

Dam	Estimated economic cost of failure				Estimated number of lost lives (LL)		Prior probability of failure ($p_f(p_{prior})$)		Year of estimate (I)
	Direct (E_d)		Indirect (E_{id})						
	Min	Max	Min	Max	Min	Max	Min	Max	
Bospoort (Sluice open)	R 3m	R 6m	R 30m	R 60m	9	13	$1e^{-3}$	$1e^{-2}$	2005
Bospoort (Sluice fail)	R 3m	R 6m	R 30m	R 60m	9	13	$1e^{-2}$	$1e^{-1}$	2005
Klein Maricopoort	R 3.9m	R 39m	R 3m	R 3m	3	5	$1e^{-4}$	$1e^{-3}$	1999
Toleni	R 0.06m	R 0.6m	R 0.6m	R 5.8m	2	3	$5e^{-4}$	$5e^{-3}$	2000
Lakeside	R 6.7m	R 67m	R 67m	R 671m	200	400	$2e^{-4}$	$2e^{-3}$	1999
Vaalkop	R 15m	R 150m	R 150m	R 1500m	35	350	$2e^{-5}$	$2e^{-4}$	2000
Rust de Winter	R 2.1m	R 21m	R 21m	R 209m	13	13	$5e^{-5}$	$5e^{-4}$	1994
Makotswane	R 1.6m	R 18m	R 16m	R 180m	5	8	$3e^{-4}$	$3e^{-3}$	2005
Kromellenboog	R 70m	R 700m	R 700m	R 7000m	18	19	$2e^{-4}$	$2e^{-3}$	2005
Albert Falls	R 20m	R 40m	R 60m	R 2000m	100	170	$1e^{-4}$	$1e^{-3}$	2004
Glen Brock	R 5m	R 10m	R 20m	R 40m	21	29	$1e^{-3}$	$1e^{-2}$	2006
Wentzel	R 0.55m	R 5.5m	R 5.5m	R 55m	156	312	$1e^{-3}$	$1e^{-2}$	1994

The failure probability in year r is the product of the annual probability of failure p_f and the probability that no dam failure occurred up to year r, thus

$$p_f^r = p_f\left(1 - p_f\right)^{r-1} \tag{3}$$

The expected cost of failure C_f is then determined from

$$C_f(p) = c_f \sum_{r=1}^{n} \frac{p_f^r(p)}{(1+q)^r} \tag{4}$$

where the discount rate q is taken as 3% (Arrow, 1995) and the remaining service life n of the rehabilitated facility is assumed to be 50 years.

The change in the expected cost of failure of the facility is computed as

$$D(p) = C_f(p_{post}) - C_f(p_{prior}) \tag{5}$$

where is acknowledged that rehabilitation will improve the safety features of the dam, thus improving the probability of failure from its prior value $p_f(p_{prior})$ to its post rehabilitation value $p_f(p_{post})$, that respectively feeds into Equation 4.

The estimates of losses and $p_f(p_{prior})$ are summarized in Table 1, as determined from the various dam safety evaluations for the eleven case studies.

According to Oosthuizen (2002) it may be assumed that the probability of failure after rehabilitation $p_f(p_{post})$ may be assumed to be equivalent to that of a new dam, i.e. between $1e^{-5}$ and $1e^{-6}$.

3.2. Cost of rehabilitation

Once a decision to rehabilitate has been reached, the design of suitable rehabilitation works will commence. It is only at this stage that a cost estimate for C(p) becomes available, as provided in Table 2.

Table 2: Estimated cost of rehabilitation

Dam	Estimated cost of rehabilitation $C(p)$	Year of estimate (II)	Rehabilitation complete (III)
Bospoort	R 84 342 000	2007	2009
Klein Maricopoort	R 39 330 000	2008	2011
Toleni	R 23 662 000	2007	2010
Lakeside	R 25 194 000	2008	2009
Vaalkop	R 24 225 000	2006	2007
Rust de Winter	R 21 318 000	2008	2010
Makotswane	R 16 956 000	2006	2008
Kromellenboog	R 19 157 000	2008	2009
Albert Falls	R 16 530 000	2008	2010
Glen Brock	R 17 600 000	2009	2010
Wentzel	R 14 250 000	2007	2008

It is interesting to note therefore that the cost of rehabilitation is not considered by the South African Department of Water and Sanitation as part of their decision to rehabilitate.

3.3. Time value of money

Estimates of the different cost components mentioned in Sections 3.1 and 3.2 above are made at different times during the decision process, as indicated in Figure 1 and Tables 1 and 2.

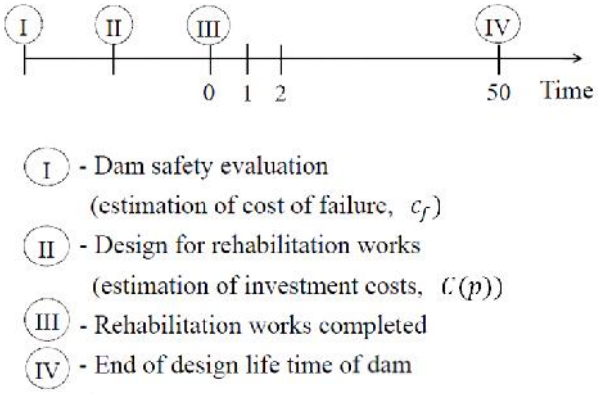

Figure 1: Timeline for dam rehabilitation project

All cost components (E_d, E_{id}, $ESVSL$ and $C(p)$) are discounted to their worth in the year in which rehabilitation works are completed (III), using basic economic principles, so that

$$c_{III} = c_R(1+i)^{III-R} \tag{6}$$

where R is the year in which the relevant cost component c_R was estimated. An inflation rate of $i = 5\%$ was used as appropriate for South Africa.

3.4. Results

The net benefit Z(p) as per Equation 1 was calculated for each of the eleven dams. However, since bands of possible values were estimated for several of the input parameters as indicated by the min/max columns in Table 1, three estimates of net benefit were made for each dam, namely a best case (B), worst case (W) and average (A). The best case net benefit $Z_B(p)$ was estimated using maximum estimates for $p_f(p_{prior})$ and c_f with the minimum estimate for $p_f(p_{post})$, to obtain a maximum estimate for D(p). Conversely, the worst case net benefit Z_W (p) was estimated using minimum estimates for $p_f(p_{prior})$ and c_f with the maximum estimate for $p_f(p_{post})$, to obtain a minimum estimate for D(p). The average net benefit $Z_A(p)$ was taken as the average of the two cases above.

The estimates for Z(p) are provided in Table 3. Positive net benefits Z(p) are highlighted and imply rehabilitation alternatives that are economically feasible.

Table 3: Estimated net benefit

Dam	Net Benefit		
	Best case $Z_B(p)$	Worst case Z_W (p)	Average $Z_A(p)$
Bospoort (Sluice open)	-R 62m	-R 91m	-R 77m
Bospoort (Sluice fail)	R 16m	-R 75m	-R 29m
Klein Maricopoort	-R 25m	-R 45m	-R 35m
Toleni	-R 24m	-R 27m	-R 26m
Lakeside	R 126m	-R 21m	R 52m
Vaalkop	-R 6m	-R 25m	-R 16m
Rust de Winter	-R 16m	-R 23m	-R 20m
Makotswane	R 1m	-R 18m	-R 9m
Kromellenboog	R 462m	-R 15m	R 224m
Albert Falls	R 74m	-R 17m	R 28m
Glen Brock	R 25m	-R 15m	R 5m
Wentzel	R 335m	R 4m	R 170m

Only five of the eleven dams require rehabilitation based on the average expected net benefit, with Wentzel dam being the only one for which rehabilitation is feasible even for the worst case estimate of net benefit.

The cases for which rehabilitation was not deemed feasible either had a prohibitively high rehabilitation cost, an already low probability of failure prior to rehabilitation or low estimated loss of lives in case of failure. In the case of Kromellenboog dam, the high economic losses in case of failure contributed significantly to its rehabilitation being economically feasible, in spite of fairly low values for $p_f(p_{prior})$ and LL.

It should be noted that rehabilitation projects will often extend the remaining useful life of a facility. This benefit $B(p)$ was ignored in this study, but will of course increase the monetary net benefit of such a project, thus making it more likely to be economically feasible.

3.5. Comparison to other criteria

3.5.1. 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 2: The acceptable annual probability of failure for existing dams is ten times 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.

Target safety levels for buildings, 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 and Streicher, 2000), while the ANCOLD criteria are based on engineering judgment and past experience.

The eleven South African dams are also shown on Figure 2, positioned based on their prior-to-rehabilitation data. Each block is highlighted in accordance with the findings of Table 3, i.e. the darker the highlight, the more economically feasible the rehabilitation.

It is clear that the decisions to rehabilitate were justified based on the ANCOLD safety criteria. Rehabilitation will decrease the dams' annual probabilities of failure, thus lowering each block to a position between $1e^{-5}$ and $1e^{-6}$, which would make them acceptable in terms of the ANCOLD criteria.

The ANCOLD criteria do not seem to resemble target safety levels that correspond to economically optimum values, although the inclusion of realistic estimates for $B(p)$ may bring these closer. It may be useful to derive target safety levels based on monetary optimization for dams, similar to what was done for buildings by Rackwitz and Streicher (2000).

From Figure 2 it seems that rehabilitation based on economic optimization becomes difficult to justify for dams with an annual probability of failure lower than $p_f \leq 1e^{-4}$, or with consequences of failure of less than fifteen lives.

3.5.2. SWTP criteria

The social acceptability of the structure in terms of risk to human life is not necessarily guaranteed when relying on the ANCOLD life safety criteria or the JCSS target reliabilities.

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.

The SWTP utility function (Pandey, et al., 2006) is applied by Reynolds (2013) 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) and this is confirmed here:

Only Wentzel dam required rehabilitation based on SWTP (Reynolds, 2013).

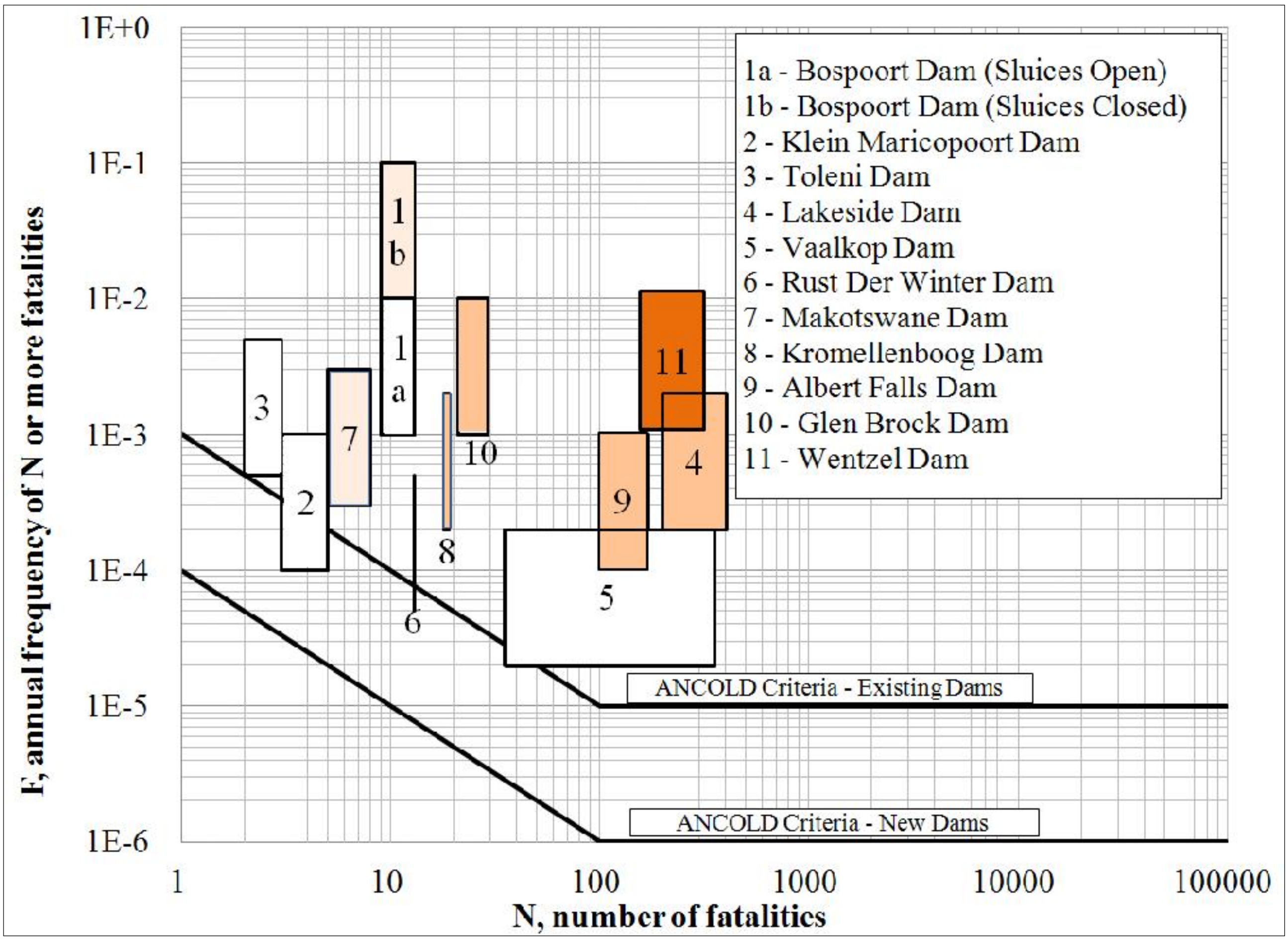

Figure 2: South African dam rehabilitation projects overlaid on ANCOLD safety criteria

4. REHABILITATION EFFICIENCY

The ANCOLD criteria acknowledges the fact that safety improvements for existing structures are less cost efficient than for new structures. An attempt is made here to quantify the cost efficiency of typical rehabilitation measures by considering the eleven South African case studies.

The rehabilitation costs were normalized with respect to the change in the 50 year probability of dam failure $P_{f,50}$ achieved through rehabilitation, where

$$P_{f,50} = 1 - (1 - p_f)^{50} \tag{7}$$

Since DWS provide a range (min, max) estimate respectively of the initial- and final annual probability of failure, the average value for each was used here.

Table 4 reports the cost per percentage reduction in the probability of dam failure over a 50 year remaining service life, for the eleven cases. The normalized cost varies typically between R0.5m- and R5m per percentage, but could be as high as R 50m/%. A high cost per percentage reduction is typically associated with dams that already had a low probability of failure prior to rehabilitation.

The wide range of normalized rehabilitation costs show that even within existing dams, significant differences exist in the cost effectiveness of rehabilitation measures. The current ANCOLD differentiation between "new" and "existing" structures aim to account for the difference in cost effectiveness of rehabilitation measures, but it may be prudent to refine this differentiation in risk acceptance criteria to something that can be better quantified.

Table 4: Normalised cost of rehabilitation

Dam	Cost of rehabilitation $C(p)$	Change in $P_{f,50}$ $\Delta P_{f,50}$	Normalised cost of rehabilitation $\frac{C(p)_{III}}{100.\Delta P_{f,50}}$
Bospoort	R 93m	$2.41e^{-1}$	R 3.9m/%
Bospoort	R 93m	$9.41e^{-1}$	R 1.0m/%
Klein Maricopoort	R 46m	$2.69e^{-2}$	R 17.0m/%
Toleni	R 27m	$1.28e^{-1}$	R 2.1m/%
Lakeside	R 26m	$5.33e^{-2}$	R 5.0m/%
Vaalkop	R 25m	$5.21e^{-3}$	R 48.8m/%
Rust de Winter	R 24m	$1.34e^{-2}$	R 17.6m/%
Makotswane	R 19m	$7.90e^{-2}$	R 2.4m/%
Kromellenboog	R 20m	$5.33e^{-2}$	R 3.8m/%
Albert Falls	R 18m	$2.69e^{-2}$	R 6.8m/%
Glen Brock	R 18m	$2.41e^{-1}$	R 0.8m/%
Wentzel	R 15m	$2.63e^{-1}$	R 0.6m/%

5. CONCLUSIONS

Only five of the eleven dams require rehabilitation based on the average expected net economic benefit. The cases for which rehabilitation was not deemed feasible either had a prohibitively high rehabilitation cost, an already low probability of failure prior to rehabilitation or low estimated loss of lives in case of failure.

The cost effectiveness of rehabilitations, as measured by the cost of rehabilitation per percentage reduction of the 50 year probability of failure, varied between R0.5m/% and R5m/%, but could be as high as R 50m/%. A high cost per percentage reduction is typically associated with dams that already had a low probability of failure prior to rehabilitation.

These are indications that current decision criteria for the rehabilitation of existing dams may be too stringent, leading to rehabilitation of dams which are neither economically feasible, nor required by society from a safety perspective.

However, rehabilitation projects will inevitably also extend the remaining useful life of a facility. This benefit was excluded in this study, but will of course increase the monetary net benefit of such a project, thus making it more likely to be economically feasible.

Rackwitz and Streicher (2002) determined target reliability levels for typical bridge- and building structures based on principles of economic optimization and using simplified load- and resistance models to estimate probabilities of failure. It may be useful to conduct a similar exercise for dam structures.

6. ACKNOWLEDGEMENTS

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