APPLICATION OF RISK ASSESSMENT TO DAM SAFETY MANAGEMENT IN NEW SOUTH WALES, AUSTRALIA

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Abstract: The Dam Safety Committee (DSC) operates under the Australian New South Wales (NSW) Dams Safety Act 1978 to ensure the safety of dams. DSC prescribes dams whose failure could cause loss of life. A dam owner is responsible for the safety of a dam and must meet the DSC's requirements. In 2006 the New South Wales Government endorsed the DSC's Risk Management Policy Framework for Dam Safety, which allowed the DSC to shift from the old standard-based approach to a less prescriptive risk-based approach. This new approach is goals-based regulation. It defines the minimum level of safety that will adequately protect the community. A dam owner must keep the risks of a dam under review and demonstrate that risks are tolerable and As Low as Reasonably Practicable (ALARP).

One of the challenges in the application of risk assessment in dam safety management is the estimation of the probability of failure of a dam and its appurtenant structures. In this paper, the Authors will share their experience in the estimation of the probabilities of failure in dams by presenting an example on the use of reliability theory in estimating the probability of slope failure in an embankment dam. Another example is presented on the use of Monte Carlo simulations in assessing the probability of failure of a gravity dam.

Key words: dam safety; risks; gravity dam; probability of failure; Monte Carlo simulations.

1 Introduction to NSW Dams Safety Committee

In the 1970's, international concern following dam failures, led to the Australian National Committee on Large Dams raising the need for dam safety regulation. The NSW Government thus enacted the Dams Safety Act in 1978, which constituted the NSW Dams Safety Committee (DSC).

The DSC consists of nine part-time members experienced in dam engineering. It formulates measures to ensure the safety of dams in NSW. It prescribes dams whose failure could threaten life or cause extensive property or environmental damage. There are 363 prescribed dams. The Committee adopts a watchdog role to ensure the dam owners conform to appropriate safety requirements for the life of these dams. This aims to ensure that the risks of failure are tolerably low. Thus a "safe" dam complies with the DSC's requirements. Since 1978, 47 deficient dams have been upgraded at a cost of over A$1 billion.

The DSC's approach is goals-based; its prime goal is that dams meet its requirements in its guidance sheets. These goals include

- risks are identified, assessed, managed, and reduced, for the life of a dam;

- needed safety upgrades are undertaken as soon as practicable.

The dam owner must determine how he achieves these goals and demonstrate to the DSC they have been achieved, or will be achieved following improvements to their dams.

2 DSC's Requirements

The DSC's requirements are based on the Consequence Category of the dam, which is based on potential damage if the dam was to fail. The categories are in Table 1.

Table 1. Consequence Categories (DSC1B June 2010)

Population at Risk (PAR)	**Severity of Damage and Loss**			
	Negligible	**Minor**	**Medium**	**Major**
< 1	Very Low	Very Low	Low	Significant
1 to 10	Low	Low	Significant	High C
10 to 100		Significant	High C	High B
100 to 1000			High A	High A
> 1000				Extreme

All Extreme, High and Significant Category dams, and Low Category dams over 15m high are prescribed. For all prescribed dams the DSC requires Surveillance Reports at 5 year intervals. Safety Reviews are required at regular intervals or where Surveillance Reports indicate a dam may be unsafe. They provide vital input for any decisions on remedial measures and involve a conclusive assessment of dam safety.

3 Dam Owner Requirements

For new dams, the DSC's wishes to ensure they are designed and built to appropriate safety criteria. Thus, owners must provide details of proposed dams to the DSC at an early stage. After construction, dam safety is managed by owners arranging for

- proper operation and maintenance by trained personnel
- regular surveillance by trained personnel and annual inspections by a dams Engineer
- dam safety emergency plans
- ongoing assessment of dam behaviour
- periodic review of the dam's compliance with current DSC requirements
- actions, in response to dam assessments, to ensure the dams are safe

Because the safety of a dam is affected by many things (changes in downstream development, new assessment methods and criteria) the DSC will not "sign-off" on a dam's safety but will judge whether a dam meets current safety criteria. However, if the DSC considers a dam is unsafe, or may become unsafe, it can give notice, under S.18 of the Dams Safety Act requiring the dam owner to do what is necessary to ensure the dam's safety.

4 DSC Risk Management Framework

Originally the DSC had a ‘Standards-based’ approach (SBA) to dam safety, wherein risks to dams were controlled by following established design, loading, and event rules which ensure the risk of failure is very low. This changed in 2006 when the NSW Government signed-off on the Risk Management Policy Framework for Dam Safety, which shifted the focus to a ‘risk-based’ approach.

4.1 The DSC Normal Safety requirements

The DSC’s normal safety requirements or “starting points” are the levels of safety of the SBA. If a dam satisfies the SBA, it will be acceptable.

Flood Capacity for Dams

Under the SBA if a dam complies with Table 2 it will satisfy the DSC. If it does not comply, the owner must demonstrate compliance with the Public Safety Guidelines.

Table 2. Starting Point Acceptable Flood Capacity (AFC) (DSC3B 2010)

Flood Consequence Category Rating	**Flood or AEP**
Extreme	Probable Maximum Flood, (PMF), (reservoir full)
High A	Probable Maximum Precipitation Design Flood, (PMPDF) (reservoir full)
High B	Max. of Annual Exceedance Probability (AEP) of PMPDF, or 10^{-6} not necessary to use PMP Design Flood, as PMPDF was used in the previous row for HIGH A
High C	Max of AEP of PMPDF, or 10^{-5}
Significant	10^{-4}
Low	10^{-2} to 10^{-3}
Very Low	No requirements

4.2 DSC Public Safety Guidelines

Risk to the Individual

Where the safety is judged on the DSC public safety risk guidelines, the requirement is that risk to the individual be below 1 in 10,000 per annum, but that the risk must also be ALARP (As Low As Reasonably Practicable). For all dams, the DSC’s negligible risk is 1 in 1,000,000 per annum.

Societal Risk

Where safety is judged on the DSC public safety risk guidelines, the requirement for the long- term is that societal risk be below the limit of tolerability shown at Figure 1 as dictated by ALARP. For societal risk, the DSC has adopted a negligible level two orders lower than the limit of tolerability.

ALARP (As Low As Reasonably Practicable)

The DSC requires owners to demonstrate that risks are ALARP based on

- disproportion between sacrifice (money, time, trouble and effort) in making the safety improvement and the risk reduction achieved
- the level of risk in relation to the limit of tolerability and the negligible risk

- An indicator for cost-effectiveness of safety improvements is Cost to Save a Statistical Life.

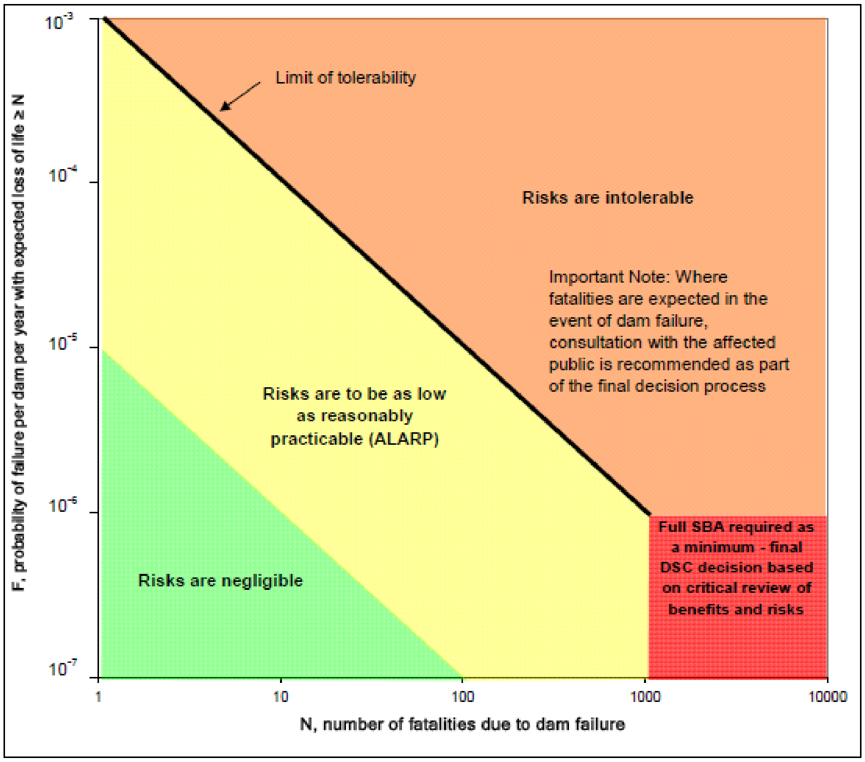

Figure 1. DSC Societal Risk Requirements: Existing Dams (DSC1B, June 2010)

5 Meeting Dam Safety Requirements

A dam owner may use risk assessment to support submissions to the DSC on dam safety. Owners are to use the ANCOLD Guidelines on Risk Assessment. The need for risk assessment could be

- to review the risks to a dam
- to better clarify the safety status of a dam, where the SBA provided no guidance (e.g. piping risk)
- where the DSC’s starting point SBA is not met
- to justify a shift from the DSC normal level of safety

A dam owner must make risks comply with the DSC’s requirements as soon as reasonably practicable. Safety improvements required by the DSC may be implemented progressively where that would promote more effective risk reduction. For guidance on acceptable progressive improvement to a deficient dam’s safety, an owner may comply with the following

- in the short term to maximise safety whilst planning for the later stages of improve-ments a structural fix must start within 2 years and a non structural fix (warning and evacuation plans) must be complete within 1 year.
- in the medium term to reach risk levels below the limit of tolerability but not ultimate low level of risk, improvement must be complete within 10 years.

- in the long term to satisfy ALARP and the DSC’s negligible risk level, work must be complete within 20 years.

6 Demonstration of Safety

Demonstrating a dam’s safety starts with a 5-year Surveillance report which assesses if the dam does or does not meet the DSC requirements. If not, or if the dam is older than 15 years, a safety review is required. This covers all hazards, loads and failure modes on a risk based approach for comparison with the DSC’s public safety risk guidelines. Any safety review must have an independent peer review. In a safety review, if the dam complies with the Standards Based Approach or recognised good practice, this demonstrates the dam’s long term safety.

6.1 Risk Assessment

A Risk assessment is required where there are aspects not adequately addressed by traditional standards or where an owner wishes to demonstrate that less costly improvements, than those required by standards, would adequately protect public safety. For the risk assessment the failure consequences are estimated in terms of potential loss of life (PLL) based on dambreak analyse. When the risk analysis is complete the total risk and the PLL are entered into Figure 1 and if the societal risk is in the negligible region DSC is satisfied. If the societal risk is in the intolerable region, the DSC requires the societal risk be reduced as soon as reasonably practicable in a short-term, and/or medium-term improvement to at least the limit of tolerability. If the societal risk is in the region of tolerability review, the DSC requires the risk to be reduced to the negligible level on a program agreed with the DSC unless the owner can demonstrate that a higher risk is tolerable. To be tolerable, the risk must be ALARP. The urgency for improvement is significantly lower than for risks in the intolerable region. Without improvement, or a demonstration that the existing risk is tolerable, the dam does not meet DSC requirements. If the societal risk is lower than the limit of tolerability and the loss of life exceeds 1,000, the DSC requirement is that the dam must compliy with all relevant standards, including PMF capacity, and with currently recognized defensive design measures. If improvement is needed it is to be made as soon as practicable. Without compliance the dam does not meet DSC requirements. When a dam falls below the DSC’s requirements the owner must demonstrate that his recommended options for upgrading the dam has reduced the risk to tolerable levels either in a staged approach or in a single upgrade.

7 Estimating the Prospective Probability of a Shear Failure in an Embankment Dam

The analysis of the stability of Embankment No. 1 at Lake Hume at the border between New South Wales and Victoria in Australia is used to demonstrate the use of reliability theory in estimating the prospective probability of a major shear failure in an embankment dam. Prospective probability means that the probability of failure is predicted in a design situation before an embankment is constructed, or the embankment has not yet experienced its design loading.

7.1 Some Basic Relationships from Reliability Theory

The following relationships from reliability theory are used for estimating the probability, P_F, of a shear failure in Lake Hume Embankment No. 1:

$$F = g(x_i) + e \qquad \text{.....} \quad (1)$$

$$E[F] = g(E[x_i]) + E[e] \qquad \text{.....} \quad (2)$$

$$V[F] \cong \sum_{i=1}^{k} \left(\frac{\Delta F}{\Delta x_i} \right)^2 V[x_i] + V[e] \qquad \text{.....} \quad (3)$$

$$\beta = \frac{E[F] - 1.0}{\sigma[F]} \qquad \text{.....} \quad (4)$$

$$P_F = 1 - \Phi(\beta) \qquad \text{.....} \quad (5)$$

where	F	a performance indicator, in this case the Factor of Safety (FOS)
	g	denotes a function of random influencing variables
	x_i	one of the various variables, upon which the value of F depends
	e	represents modeling error
	$E[\ ]$	signifies the expected value
	$V[\ ]$	denotes the variance of a variable
	$\Delta F / \Delta x_i$	is the slope of the curve which describes how F varies with x_i, all other variables being kept at their mean values
	β	is the Reliability Index
	$\sigma[\ ]$	is the standard deviation of a parameter.
	P_F	is the probability of failure
	Φ	denotes the standard normal cumulative distribution function.

The probability density function (pdf) of F, the factor of safety, is taken to be a normal distribution. This is considered valid on account of the Central Limit Theorem, notwithstanding that some of the influencing variables may not be normally distributed. Whitman (1984) points out that, regardless of variable distributions, the probability of failure will be reasonably accurate, provided that β is less than 2.5 and the variance of F is not very large.

7.2 Probability of a Major Shear Failure in Lake Hume Embankment No. 1

Figure 2 shows the stability analysis of Embankment No. 1. The minimum factor of safety, F, for shearing through the critical failure surface shown in Figure 2, is equal to 0.969, calculated using the mean values of the variables listed in Table 3. The incremental changes in F due to variations in the input variables are given in Table 4, and the variance in F is computed in Table 5.

Christian et al. (1994) commented that the effect of modeling error is to increase F by 5% and to add to variance by a coefficient of variation of 0.07 (i.e. a variance of 0.0049 for a value of F close to 1.0). For the base case F equal to 0.969, a 5% increase brings the value of F to 1.017. Given $E[F]$ = 1.017 and $\sigma[F]$=0.206, equation (4) gives β = 0.08471. The probability of failure of a major shear failure for the base case, based on equation (5), is 1 - $\Phi(0.08471)$ = 0.466.

There are two major components contributing to the variance of a variable, namely spatial variance and systematic variance, as shown in Table 5. Spatial variance is due mainly to the fluctuation in the value of a variable, e.g. the unit weigh of fill materials with location, and to random errors in the measuring the values of the variable. Systematic variance is due to the statistical variance related to the sample size of the measured variable, and/or a systematic bias in measuring the values of the variable. Christian et al. (1994) discussed methods for assessing the spatial and systematic variances of variables.

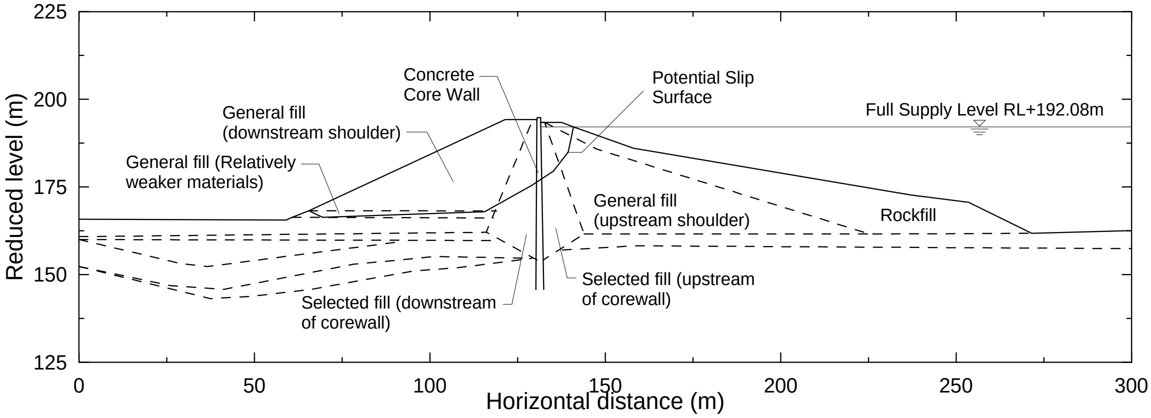

Figure 2. Base case for reliability analysis of slope stability of Lake Hume Embankment No. 1

Table 3. Mean values of input variables for stability base case of Lake Hume Embankment No. 1

Zone	Contributes to Sliding Resistance	Cohesion/ Undrained Strength c' (kPa)	Friction Angle, ϕ' (deg.)	Unit Weight γ (kN/m^3)
Rip-rap (Upstream rockfill)	Yes	0.0	45.0	20.0
Zone A - General fill upstream shoulder	Yes	10.0	20.0	20.0
Zone B – Upstream selected fill 14.6 – 20.8m below crest	Yes	71.8	0.0	20.0
Concrete core wall	Yes	0.0	45.0	24.0
Zone D – General fill downstream shoulder	Yes	105.0	0.0	20.0
Zone C – Downstream selected fill 18 – 24m below crest	Yes	42.1	0.0	20.0
Zone D – Downstream shoulder 16.4-18.6m below upper berm	Yes	79.3	0.0	20.0
Zone C – Downstream selected fill below slip surface	No	25.0	0.0	20.0
Ditto but 10 – 18m below crest		50.0	0.0	20.0
Zone D – Downstream general fill 21 – 22m below berm.		114.8	0.0	20.0
Other foundation soil/rock layers				

Table 4. Effect on Factor of Safety of Variations in the Input Variables

Variables	New Value	New F (Note base case F = 0.969)	$\Delta F/\Delta x_i$	$(\Delta F/\Delta x_i)^2$
Fill unit weight, γ_f	19.0 kN/m^3	1.016	0.047	0.00221
Rip-rap, ϕ'	44^{o}	0.969	0.0	0.0
Zone A, c'	9 kPa	0.968	0.001	0.000001
Zone A, ϕ'	19^{o}	0.969	0.0	0.0
Zone B, c'	70.8 kPa	0.968	0.001	0.000001
Concrete corewall, ϕ'	44^{o}	0.968	0.001	0.000001
Corewall unit weight, γ_c	23 kN/m^3	0.969	0.0	0.0
Zone C, c'	41.1 kPa	0.967	0.002	0.000004
Zone D, c'	78.3 kPa	0.961	0.008	0.00006

Table 5. Variance of Factor of Safety

Variables	$\Delta F/\Delta x_i$	Variance		$(\Delta F/\Delta x_i)^2\ V[x_i]$		
		Spatial	Systematic	Spatial	Systematic	Total
Fill unit weight, γ_f	0.047	0.20	0.006	0.00044	0.00001	0.00045
Rip-rap, ϕ'	0.0	0.0	1.56	0.0	0.0	0.0
Zone A, c'	0.001	0.0	9.0	0.0	0.00001	0.00001
Zone A, ϕ'	0.0	0.0	6.25	0.0	0.0	0.0
Zone B, c'	0.001	228.31	56.88	0.00023	0.00006	0.00029
Concrete corewall, ϕ'	0.001	0.0	6.25	0.0	0.00001	0.00001
Corewall unit weight, γ_c	0.0	0.0	0.09	0.0	0.0	0.0
Zone C, c'	0.002	396.38	28.74	0.00159	0.00011	0.0017
Zone D, c'	0.008	482.85	104.75	0.02897	0.00629	0.03526
Sub-total of $V[F]$:						0.03772
Modeling error:						0.0049
Total $V[F]$:						0.04262
Standard deviation, $\sigma[F]$:						0.206

8 Estimating the Probability of a Gravity Dam using Monte Carlo Simulations

Attempts to estimate the probability of shear friction failure for concrete gravity sections at Lake Hume using First Order Second Moment (FOSM) reliability analysis as explained in the preceding Section, in conjunction with traditional two-dimensional cantilever beam bending analysis, proved unsatisfactory. Results were erratic apparently due to the dramatic change in the value of the Shear Friction Factor that occurs once the concrete section cracks. Monte Carlo simulations were used instead of FOSM analysis to estimate the probability of shear friction failure for concrete gravity sections. The simulation techniques had been extensively used by one of the Authors in estimating the probabilities of failure of the concrete gravity sections and concrete training walls at Lake Hume, and for some other gravity dams in Australia (MacDonald, Cooper and Wan 2000).

8.1 Monte Carlo Simulations

Monte Carlo simulations select values of various input variables randomly based on the assumed pdf of the individual input variables, such as the unit weight of concrete in the dam body, concrete strength parameters, uplift pressure profile, etc. The mathematical model of the gravity dam, typically a 2-dimensional cantilever beam bending model set up in an electronic spreadsheet, is repeatedly analysed for thousands of times each time using a set of randomly selected input variables. The analyses produce pdf of output variables, namely the Shear Friction Factor, or the Factor of Safety (FOS) against overturning of the dam. The area under the pdf curve of the FOS for values of FOS less than 1.0 represents the probability of failure. Figures 3 and 4 illustrate the concept of Monte Carlo simulations used in the stability analysis of a gravity dam for various loading scenarios (e.g. Operating Basis Earthquake (OBE), Maximum Design Earthquake (MDE), Normal Operation at Full Supply Level (FSL), etc.).

9 Conclusions

Implementing risk-based safety policies are more cost-effective and will deliver a greater overall reduction in risks to life, property and community interests. The Benefits include a less prescriptive, holistic goals-based approach to dam safety; a more consistent relationship of dam safety levels to dam failure consequences; and the introduction of a concept of progressive improvement of dam safety to better apply the available resources to reducing risks to the community. It also ensures the elimination of safety improvements with very low cost-effectiveness through the adoption of less stringent requirements for the flood capacity of dams that threaten small populations. This frees-up resources to address intolerable risks on other dams, whilst still retaining an almost negligible risk of failure in line with levels accepted for facilities such as Airports, nuclear reactors and petrochemical plants.

Estimating the probability of failure of a dam in the risk assessment process presents a challenge to dams engineers. The Authors presented an example in estimating the prospective probability of a major shear failure in an embankment dam using the FOSM reliability analysis. The Authors found that the use of the FOSM method in estimating the probability of shear friction failure in a gravity dam was unsatisfactory, and described the alternative method of using Monte Carlo simulations to estimate the probability of shear friction failure of gravity dams.

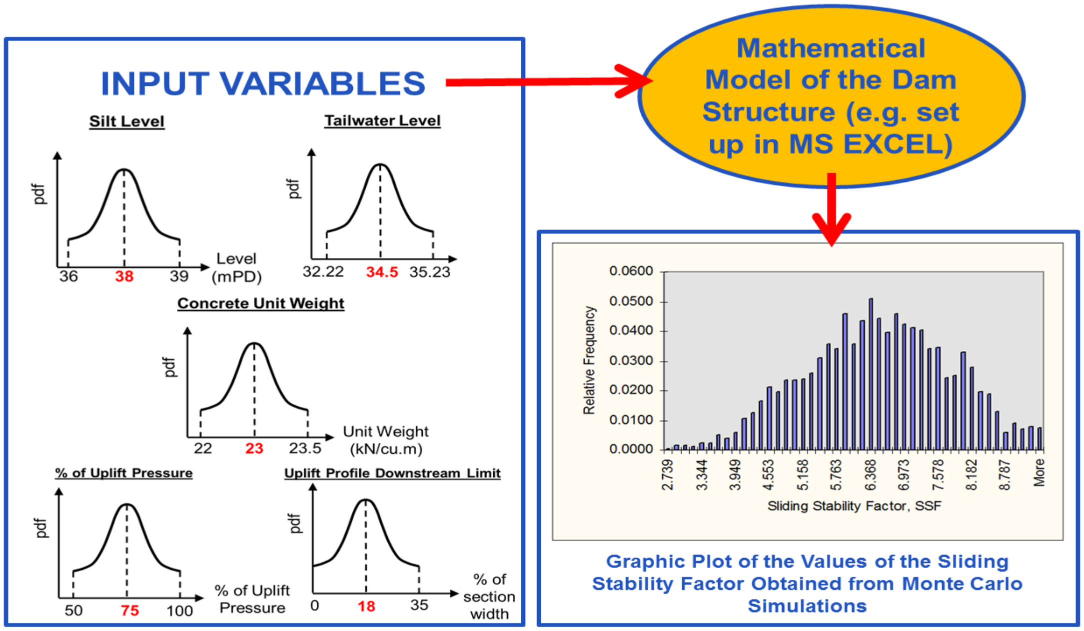

Figure 3. Conceptual Model of the Use of Monte Carlo simulations in Gravity Dam Analysis

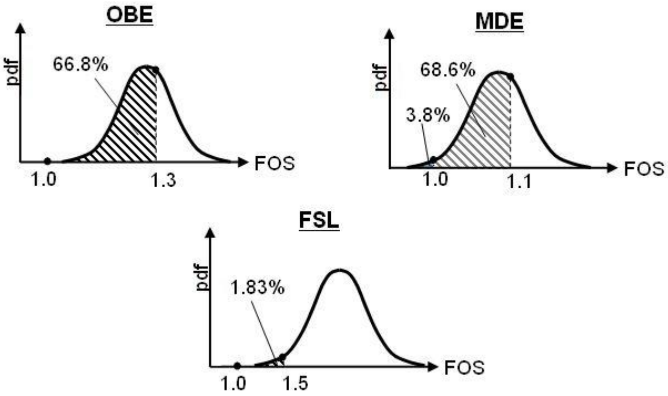

Figure 4. Typical results of Monte Carlo Simulations showing the Probability Density Functions (pdf) of the Shear Friction Factor for various loading scenarios

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