Applied Mathematics & Information Sciences
An International Journal

http://dx.doi.org/10.18576/amis/190110

A Reliability-Based Risk Analysis of a Roller Compacted Concrete Dam – A Case Study

Zakaria Che Muda[1,], Mohamed Hafez[1], Lariyah Mohd Sidek[2], Hidayah Basri[2], Zaher Almkahar[1], and As'ad Zakaria[3]*

[1] Faculty of Engineering and Quantity Surveying, INTI-International University, Nilai, Malaysia
[2] Institute of Energy Infrastructure, Nasional Energy University, Selangor, Malaysia
[3] Institute of Energy Systems, School of Engineering, University of Edinburgh, Edinburgh EH9 3FB, UK

Received: 7 Jun. 2024, Revised: 1 Aug. 2024, Accepted: 12 Aug. 2024.
Published online: 1 Jan. 2025

Abstract: In this paper we investigate the suitability of using first-order reliability method (FORM) analysis in design practice against a more vigorous Monte Carlo Simulation (MCS) for reliability-based analysis of the roller compacted concrete (RCC) dam in compliance with ICOLD (2005) requirements. Extreme rainfall events due to climate change critically impact the reliability and safety of the dams, making it an important consideration in dam risk analysis to prevent dam failure. A simplified first-order reliability method (FORM) with a first-order Taylor Series expansion involving a simple reliability analysis requires very little effort beyond the conventional dam stability analysis without any unfamiliar terms and can be used in routine engineering practice. Case applications to stability problems of the RCC dam against sliding and overturning modes of failures illustrate the simplicity and practical usefulness of the method. The sliding failure was the dominant failure mode then the overturning failure with the friction angle influential random variable has the highest sensitivity of 90.6% and lastly density of concrete with only 9.4%. A strong linear correlation between the reliability index and the factor of safety for sliding has been established. An excellent linear correlation between the FORM-Taylor Series and Monte Carlo analysis for sliding has been obtained. The overturning failure mode has the least significant effect where its probability of failure is almost nil as compared with the sliding mode of failure. The Taylor Series method is based on a simplified first-order probabilistic analysis, although somewhat conservative but adequate to be used in design stage whereas the Monte Carlo method provides a more rigorous and precise form of analysis suited for the construction and operation stages to be used in practice. The unconditional and conditional (combined) probability of failure for different modes of failure for all the scenarios were evaluated against the ICOLD (2005) requirements.

Keywords: climate change, roller compacted concrete dam, reliability analysis, first-order reliability method, Monte Carlo analysis.

1 Introduction

Since the early 1980s, Roller Compacted Concrete (RCC) has gained acceptance as a construction material for dams, and over 550 RCC dams were constructed worldwide since 2012 (Ashtankar and Chore, 2014). RCC dam has a promising trend due to its fast construction process (Hu et al., 2019; Huang & Wan, 2018; Zheng et al., 2020), low engineering cost (Nagayama & Jikan, 2003; Warren, 2013), similar strength to conventional concrete (Kokubu et al., 1996) and good durability and low maintenance requirements (McDonald and Curtis, 1997). ICOLD (2003) provides a comprehensive review of the state of the art of the design and construction of RCC dams. The sliding mode of failure along the dam interface are key factors that must be addressed in the design stage of the RCC dam. (Ma et al.,2018).

Flood, earthquake and uplift loads are generally larger today due to climate change with extreme and abnormal events than assumed in the previous design of most gravity dams while the required factors of safety remain unchanged. As a result, many existing dams have marginal or unsatisfactory calculated stability using modern guidelines. On the opposite spectrum, the forecasting of drought plays a critical role in the operational management of hydroelectric power dams. Khan et al.'s (2018) review paper presented the impacts and analyzing indices associated with drought in the Asian mainland. Presently, a lack of reliable and quantifiable data concerning drought incidences and forecasting methods exists in major river basins in Malaysia. The findings from Khan et al.'s (2020) study indicate that the coupled Wavelet-Autoregressive Integrated Moving Average with Artificial Neural Network models is the preferred method for short-term drought prediction.

The conventional design of concrete gravity dams still follows the deterministic method, which does not directly account for the effect of uncertainties of the input variables on the safety of structures (Pires et al., 2019). The usual engineering design code of practice is still using the normal deterministic approach with the given factor of safety to determine the elemental or overall stability of structures. Safety factors have been based on a deterministic approach based on the mean values of the data obtained regardless of the variance of the data that has been widely incorporated in

*Corresponding author e-mail: zakaria.chemuda@newinti.edu.my

© 2025 NSP
Natural Sciences Publishing Cor.

the design criteria all over the world. The argument is that the project meeting the higher safety factors would be sufficiently safe than the one with the lower safety factor, unfortunately this is not always true. The wide variance of data with a higher safety factor is not the same as a narrow variance of data with a lower safety factor. The probability of failure for a given safety factor is influenced by its variance, which, in turn, is contingent upon uncertainties in input data such as the coefficient of variation, number of tests, quality of investigations, measurement techniques, and others. This variability in safety factors contributes to a broad range of probability of failure values for structural safety, as indicated by ICOLD (1993).

Pires et al. (2019) exemplify the application of structural reliability theory through a case study involving a concrete gravity dam. The study delineates the prominent failure modes and design parameters exerting significant influence on dam safety. The probability of failure (Pf) is determined through structural reliability analysis, a method employing probabilistic approaches to assess the safety of a structure (Garcia et al., 2012). The analysis, integral to the calculation and prognosis of the probability of failure at any stage of a structural system's life cycle, is a key aspect of structural reliability (Melchers and Beck, 2018).

Christian et al. (1994), Tang et al. (1999), provide clear underlying theories and examples of the use of reliability in geotechnical engineering. The conventional factor of safety approach to limit state problems provides very limited insight into the failure probability of the structural system. Reliability calculations offer a mechanism for assessing the cumulative impact of uncertainties and serve as a tool for discerning variations in conditions characterized by either elevated or diminished uncertainties (Duncan, 2000). The use of structural reliability methods in concrete dams is not widespread in its use in practice as mentioned by Pires et al., 2019. This reliability analysis sometimes mentioned as the probability of failure should not be viewed as a replacement for the traditional deterministic approach using the factor of safety but rather as a supplement to each other that will add values to the analysis. The design and safety check of concrete gravity dams using the reliability analysis can effectively overcome the shortcomings of the safety factor method (Pei et al., 2011, Sharafati et al., 2020). The reliability analyses provide more reliable results and a more logical framework than the factors of safety when the relationship between the probability of failure, and its consequences of failure in terms of life and economic need to be established with a higher degree of accuracy. Probabilistic analyses yield more comprehensive estimates than deterministic analyses due to the range associated with the input variables. This requires a lot more information than required in a deterministic analysis in terms of expected variable behavior and the likely variable probability distributions (Muench, 2010). In contrast to a deterministic analysis, the undertaking necessitates a more extensive amount of information pertaining to the anticipated behavior of variables and the probable distributions of these variables (Muench, 2010).

First Order Reliability Method (FORM) can be applied to stability analysis of the dam block through simple procedures and need not require more data than is required for conventional analyses using the factor of safety. The value of analyses can be increased considerably at a relatively small additional effort (Yang and Ching, 2020). Monte Carlo Simulation (MCS) requires a large number of calculations to obtain the results with high accuracy, where the computational cost is relatively large.

Risk is defined as the product of the probability of a critical event, a system of failure of the given event and its consequences according to Equation (1).

Risk= ∑P(Critical event) x ∑P(System of failure of the event) x C (consequences) (1)

The risk related to dam failure measures the likelihood or probability against the consequences on life and cost of damage on the property and the environment.

ICOLD (2005) described that risk analysis can be used as an appropriate tool in the process of risk management. Dam risk analysis requires the identification of potential failure modes and quantification probabilities of the structural system responses to different loading demands.

During the construction and operation stage, the use of instrumented measured uplift and shear strength with thorough knowledge of site geology will reduce the uncertainty in stability evaluations of risk analysis and economic cost. Uplift pressures over the maximum design have been reported in some dams (Spross, J. et al., 2014). Degradation phenomena in dam-foundation contacts have been also reported in some cases that are needed for remedial actions. Some dams have been documented to experience uplift pressures exceeding their maximum design levels (Spross, J. et al., 2014). Instances of degradation phenomena occurring in dam-foundation contacts have also been reported, necessitating remedial actions in certain cases (Barpi and Valente, 2008).

The aimof this paper is to assess the suitability of the simplified FORM-Taylor series analysis to be used in design practice for RCC Dam and compare its accuracy against a more vigorous Monte Carlo simulation. Further to evaluate the results of the probability of failure modes against the ICOLD (2005) guideline.

2 Reliability-Based Design Methods

The reliability-based analysis of a typical cross-section of the RCC dam is analyzed by First Order Reliability Method (FORM) using first-order Taylor series approximation and compared with a more complex Monte Carlo Simulation (MCS) approach. FORM-Taylor Series approximation is mathematically simpler, though somewhat less precise, that can be performed using an excel spreadsheet that is used by the design practitioners. MCS which is coded in MATLAB

© 2025 NSP
Natural Sciences Publishing Cor.

provides a more rigorous and precise analysis which is suitable for construction and operation stage assessment and a research-based environment.

2.1 First-Order Reliability Method (FORM)

First-Order Reliability Method (FORM)" originates from the approximation of the performance function g(X) by the linearization of first-order Taylor expansion.

A performance function or limit state function, $g(x)$ is defined as the failure state ($g(x) < 0$) and safety state ($g(x) > 0$) where $x = (x_1, x_2... _n)$ is a random variable vector.

The performance function (Phoon, 2019) is widely adopted:

$$g(x) = g(x_1, x_2... _n) = F_s(x_1,x_2,...,x_n) - 1.0 \quad (1)$$

where F_s is the factor of safety and the prescribed acceptable safety factor is 1.0 (Liang et al., 1999).

The probability of failure can be defined as

$$Pf_{FORM} = P(g(x) < 0) = \int g(x) \leq 0 \, f(x)\, dx \quad (2)$$

where $f(x)$ is the joint probability density function of x.

Due to the inherent complexity of the multidimensional integral in equation (2), the reliability index β is typically computed in engineering practice and the failure probability is subsequently estimated by

$$Pf_{FORM} \approx \Phi(-\beta) = 1- \Phi(\beta) \quad (3)$$

where $\Phi(\cdot)$ is the standard normal cumulative distribution function.

Since FORM only gives a linear approximation of the limit-state function at the design point, the reliability index may be over- or underestimated for the functions with considerable curvature as such Monte Carlo Simulation provide a more accurate solution for a multi-number of the variable of a large complex model with non-linear limit state functions.

2.2 Monte Carlo Simulation

Monte Carlo simulation (MCS) provides a versatile approach capable of solving large complex models with multi-variables, whether linear or nonlinear of single or multiple limit state functions. This method involves sample trials of random variables, taken from the joint density function f(x) in Equation 2. The probability of failure is then estimated as in Equation 4.

$$P_{fMCS} = \frac{1}{N}\sum_{i=1}^{N} I[X_i] = \frac{N_f}{N} \quad (4)$$

where P_{fMCS} is the estimated probability of failure. I[ ] denotes the indicator function, Xi represents the sample vector i, Nf signifies the points within the failure domains, and N stands for the total number of trials. The number of trials must be sufficiently large to attain a precise estimation of the probability of failure with minimum statistical errors.

$$I(X_i) = \begin{cases} 1 \text{ if } g(x) \leq 0 \\ 0 \text{ if } g(x) > 0 \end{cases}$$

Finally, the MCS-based reliability index is expressed as:

$$\beta_{MCS} \approx -\Phi^{-1}(Pf_{MCS}) = \Phi^{-1}(1- Pf_{MCS}) \quad (5)$$

3 Tolerable Risk Guidelines

A risk matrix provides a valuable tool for the likelihood of failure and the consequences arising from identified risk drivers associated with significant potential failure modes. In Figure 1, a dam risk matrix is depicted, employing general categories of failure likelihood and severity of the consequence.

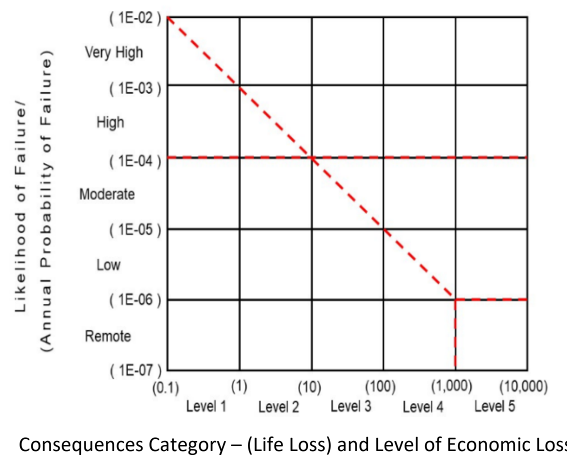


Fig. 1: Dam Risk Matrix (USBR-USACE, 2019)

The vertical axis of the matrix delineates the likelihood of failure and the annual probability of failure (APF), while the horizontal axis delineates the corresponding consequences, including loss of life and economic impacts categorized as follows: Level 1 <$10 million, Level 2 $10-$100 million, Level 3 $100-$1 billion, Level 4 $1-$10 billion, and Level 5 >$10 billion (USBR-USACE, 2019). However, further studies need to be carried out on the life and economic loss as a consequence of the probability of failure associated with the dams. ICOLD (2005) uses the horizontal dashed line value for the probability of failure of 10^{-4} for the high-risk dams.

For existing dams, the APF for an individual risk to the identifiable person or group, defined by a location should be limited to the value of less than 10^{-4} per year, except in exceptional circumstances (ANCOLD, 2003). The USACE (2014) policy for the estimated APF of greater 10^{-4} per year is unacceptable except in exceptional circumstances with the justification to implement risk reduction actions. If the APF is less than 10^{-4} per year, the other tolerable risk guidelines are met, and the implementation of the risk reduction actions diminishes.

© 2025 NSP
Natural Sciences Publishing Cor.

4 RCC Gravity Dam – A Case Study

The RCC gravity dam under this study has a maximum height of 71.0 m, a base width of 57.15m and a top width of 5.0 m. The upstream face is vertical, and the downstream face has a slope of 1.0:0.8 (V: H). Figure 1 illustrates the geometry, water level and forces of the RCC Dam main block cross-section of the RCC dam under the case study.

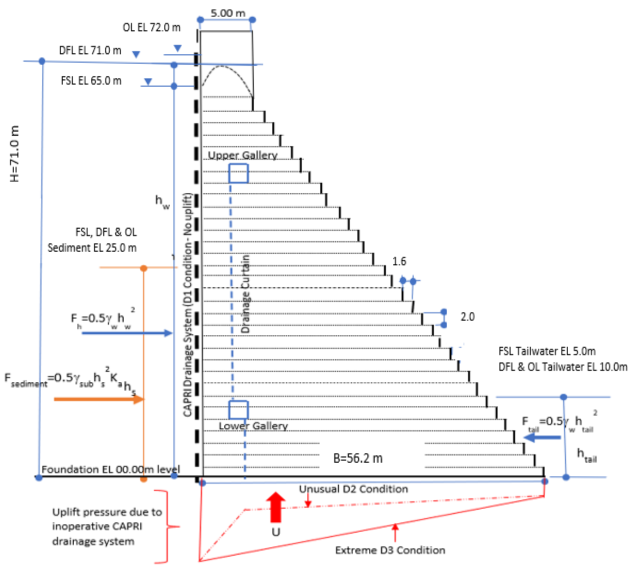


Fig. 2: A typical overflow cross-section of the RCC Dam – water level and its forces

The dam has two drainage upper and lower galleries to relieve uplift at the concrete-rock foundation interface and interstitial pressure of the mass of concrete at the lift joints. The RCC dam has also been installed with the CAPRI drainage system resulting in no uplift water pressure at the base and at the lift joint interfaces of the RCC dam.

4.1 Design Data of Hollow Buttress Dam

The design data of the aging hollow buttress dam which was constructed in the early 1960's is given in Table 1.

Table 1: Design Data of the Dam

General	*SI units*
Full supply level (FSL)	65.00 m EL
Design flood level (DFL)	71.00m EL
Overtopping level (OL) – PMF level	72.00m EL
Silt level	25.00m EL
Foundation level	00.00m EL
Width of base	56.20 m
Height of Dam at Spillway	71.00 m

4.2 Variability of Design Parameters

Variable material parameters involved in the reliability risk analysis of gravity dam include 1. density of concrete, shearing friction coefficient and cohesion of dam concrete-rock interface. The volume weight of concrete, friction angle and cohesion were determined by site-specific laboratory test samples. The sample size must meet the statistical requirements and be treated as a random variable (Xin and Chongshi, 2016).

Economic and safety reasons made it desirable to use the actual site-specific values of shear strength and uplift based on the actual monitoring system rather than generic values as specified in the guidelines for concrete dam stability analyses. The use of instruments measured uplift and shear strength with thorough knowledge of site geology will reduce the uncertainty in stability evaluations of the risk analysis and economic cost. Uplift pressures over the maximum design have been reported in some dams (Spross, J. et al., 2014). Degradation phenomena in dam-foundation contacts have been also reported in some cases that are needed for remedial actions (Barpi and Valente, 2008).

4.2.1 Density of Concrete Material

CIB (1991) gives the density mean value of 23.5 kN/m^3 with a standard deviation, σ of 0.940 kN/m^3 or the coefficient of variation (COV) of 0.04 for concrete of compressive strength 20 MPa, and 24.5 kN/m^3 with a standard deviation, σ of 0.735 kN/m^3 or COV = 0.03 for concrete of compressive strength greater than 40 MPa. Assume the compressive strength for the RCC dam is 30 MPa.

4.2.2 Friction Angle Parameters of Concrete to Rock and Concrete to Concrete Interface

Category III rock mass of medium sound was adopted with the friction angle, ϕ with the value of 45.0° and standard deviation, σ of 11.5°. These pro-rated values are based on the China Electric Council (2010) recommendation for the rock-concrete interface at the foundation level as given in Table 2.

Table 2: Friction Angle and Cohesion Parameters of Rock Interface

Rock properties of dam foundation	Friction angle ϕ °		Cohesion C, MPa	
	Mean	Standard Deviation, σ	Mean	Standard Deviation, σ
Category I: dense and sound, the distance between cracks > 1 m	56.31 52.43	16.70 14.57	1.5 1.3	0.54 0.47
Category II: sound, weakly weathered massive rock with crack spaces distance between 0.5-1m	52.43 47.73	14.57 11.86	1.3 1.1	0.47 0.40
Category III: Rock mass of medium sound with crack spaces distance between 0.3-0.5m	47.73 41.99	11.86 11.31	1.1 0.7	0.40 0.28

The case history study of the existing roller compacted concrete dam in France reveals that a lift joint with the concrete-concrete interface friction angle ϕ is 46° with a standard deviation, σ is 4.57° using instrumental data from the construction records and engineering tests performed in the course of construction (Carvajal et al., 2011). The above value is marginally close to the concrete-rock interface

© 2025 NSP
Natural Sciences Publishing Cor.

friction angle, ϕ of 45° chosen in the study. Based on RIDAS (2017) guideline, the characteristic cohesion value along the sliding surface is neglected in the sliding calculation.

4.3 Load Cases

The event load case scenarios are based on the usual operational full supply level CAPPRI drainage system with no uplift, unusual design flood level and extreme overtopping level with the normal (100% drainage efficiency) and extreme (100% drainage efficiency) uplift conditions were used in the reliability-based analysis. The following load case scenarios - S1 Usual, S2 Unusual and S3 Extreme - with three drainage conditions - D1 Usual , D2 Unusual and D3 Extreme - are adopted in the analyses as follows;

1. Usual Load Case Scenario S1: Full supply level (FSL) with usual silt level.

   S1-D1: Design Flood Level with D1 drainage condition - CAPRI operative (no uplift).

   S1-D2: Design Flood Level with D2 drainage condition – CAPRI inoperative with unusual uplift (100% efficiency).

   S1-D3: Design Flood Level with D3 drainage condition - CAPRI inoperative with extreme uplift (0% efficiency).

2. Unusual Load Case Scenario S2: Design Flood Level (DFL) with unusual silt level.

   S2-D1: Design Flood Level with D1 drainage condition - CAPRI operative (no uplift).

   S2-D2: Design Flood Level with D2 drainage condition – CAPRI inoperative with unusual uplift (100% efficiency).

   S2-D3: Design Flood Level with D3 drainage condition - CAPRI inoperative with extreme uplift (0% efficiency).

3. Extreme Load Case Scenario S3: Overturning Level (OL) with extreme silt level.

   S3-D1: Design Flood Level with D1 drainage condition - CAPRI operative (no uplift)

   S3-D2: Design Flood Level with D2 drainage condition - CAPRI inoperative with unusual uplift (100% efficiency).

   S3-D3: Design Flood Level with D3 drainage condition - CAPRI inoperative with extreme uplift (0% efficiency).

Three silt-level conditions are being considered as follows;

- Usual silt Level of 42 m above the foundation level
- Unusual Silt Level of 52 m above foundation level
- Extreme Silt Level of 66 m above foundation level

The tailwater level conditions are as follows;

- Tailwater at FSL is 5.0 m from the foundation level
- Tailwater at DFL and OL is 10.0m from the foundation level

The reliability-based using FORM-Taylor Series Approximation and Monte Carlo Simulation (MCS) are carried out based on the above conditions to determine the annual probability of failure for the sliding and overturning failure modes that are applied to the RCC dam main spillway section.

5 Methodology

Two methods of reliability risk analysis - the simplified FORM with Taylor Series approximation and Monte Carlo analysis - have been used in this paper. The first Taylor Series method is a probabilistic simplified analysis, though somewhat less precise, and was used by USACE (1997 and 1998) and Duncan (2000). The second Monte Carlo probabilistic analysis was carried out using a 10 million sample population provides a more rigorous and precise form of analysis than the FORM-Taylor Series method.

5.1 Reliability-based analysis using FORM-Taylor Series Approximation.

A simplified reliability analysis using the FORM-Taylor series approximation as proposed by Duncan (2000) is carried out for the RCC concrete dam for the stability checks against sliding and overturning, mathematically simpler, though somewhat less precise but adequate for design practice, that can be performed using excel spreadsheet. The terms involved in computing the sliding factor of safety FOS [C, $W_{concrete}$, tan ϕ] and overturning factor of safety FOS [$W_{concrete}$] all involve some degree of uncertainty. Therefore, the computed value of the sliding and overturning factor of safety also involves some uncertainty.

It is useful to be able to assess the Reliability of sliding and overturning factors of safety, as well as the best estimate of its value. Therefore, the computed value of the sliding and overturning factor of safety also involves some uncertainty. It is useful to be able to assess the Reliability of sliding and overturning factors of safety, as well as the best estimate of its value.

The calculation steps using the reliability-based FORM-Taylor Series approximation are as follows:

Step 1. Determine the most likely values of the parameters involved and compute the factor of safety by the normal (deterministic) method for sliding and overturning. This is sliding F_{MLV} or overturning F_{MLV}.

$$F_{MLV} = \frac{\{(\sum W_{conc} + \sum W_{water} + \sum W_{silt} - \sum U_{uplift}) \tan \emptyset\}}{F_h + F_{silt} - F_{tail}} \quad (5)$$

$$F_{MLV} = \frac{\{\sum W_{conc} \cdot x_{conc} \cdot + \sum W_{water} \cdot x_{water} + \sum W_{silt} \cdot x_{silt} + F_{tail} \cdot \frac{h_{tail}}{3}\}}{F_h \cdot \frac{h_w}{3} + F_{silt} \cdot \frac{h_{silt}}{3} + \sum U_{uplift} x_u} \quad (6)$$

The above deterministic analysis using the above factor of

© 2025 NSP
Natural Sciences Publishing Cor.

safety can be easily extended into the first-order reliability analysis using first-order Taylor Series approximation.

Step 2. Estimate the mean and standard deviations of the parameters that involve uncertainty. i.e., angle of friction, ϕ and Density of concrete, γ_{conc} are considered as random variables with normal distributions.

1 CIB (1991) gives the concrete Density, γ_{conc} of a mean value of 24.5 kN/m^3 with a standard deviation, σ of 0.735 kN/m^3 for concrete of compressive strength of 40 MPa.

2 China Electric Council (2010) Category III rock mass of medium sound with the friction angle value, ϕ of 45.0^o and standard deviation, σ of 11.5^o.

Step 3. Use the Taylor series technique (Wolff, 1994; USACE 1997, 1998 and Duncan, 2000) to estimate the standard Deviation and the coefficient of variation of the factor of safety for cohesion, weight of concrete and friction angle using these formulas:

$$\sigma_F = \sqrt{\left(\frac{\Delta F_1}{2}\right)^2 + \left(\frac{\Delta F_2}{2}\right)^2 + \left(\frac{\Delta F_3}{2}\right)^2} \quad (7)$$

$$V_F = \frac{\sigma_F}{F_{MLV}} \quad (8)$$

Compute the factor of safety with each parameter increased by one standard Deviation and then decreased by one standard Deviation from its most likely value, with the values of the other parameters equal to their most likely values. These calculations result in N values of F^+ and N values of F^-. Using these values of F^+ and F^-, compute the values of ΔF for each parameter and compute the standard deviation of the factor of safety (σ_F) using (7) and the coefficient of variation of the factor of safety (V_F) using (8). To calculate β, the First Order Reliability Method (FORM) method uses a Taylor series expansion as above, simplified by using only the first term (hence, "First Order").

Step 4. Use an Excel spreadsheet to determine the value of FMLV from the first step and the value of VF from the third step to determine the value of Pf. The key to computing more precise values of P_f is to compute the value of the lognormal reliability index, β_{LN}, using the following formula (Scott et al. 2001):

$$\beta_{LN} = \frac{\ln\left(F_{MLV}/\sqrt{1+V^2}\right)}{\sqrt{ln(1+V^2)}} \quad (9)$$

where β_{LN} = lognormal reliability index; V = coefficient of variation of a factor of safety; and F_{MLV} = most likely value of factor of safety.

Step 5 When β_{LN} has been computed using (9), the value of P_f can be determined accurately using the built-in function NORMSDIST in Excel. The argument of this function is the reliability index, β_{LN}. In Excel, under "Insert Function," "Statistical," choose "NORMSDIST," and type the value of β_{LN}.

The Excel spreadsheet is been developed of the reliability-based analysis using FORM-Taylor Series approximation for all the load and drainage cases.

5.2 Reliability-based analysis using Monte Carlo Simulation

A practical alternative is to develop probability distributions for the various parameters and apply a more rigorous Monte Carlo Simulation (MCS) with a higher degree of accuracy to determine the probability that the safety factor is below some threshold value associated with instability or other types of bad performance.

The basic procedure using the Monte Carlo analysis coded in MATLAB for the RCC dam is listed below:

Step 1 Build a probabilistic model of limit state analysis for a safety factor for sliding and overturning moment as given in Equations 5 and 6, respectively.

Step 2 Assign the mean and probability distributions to the model inputs for uncertainty in material properties, i.e., angle of friction ϕ and Density of concrete, γ_{conc} are considered random variables with normal distributions with no correlation.

1 CIB (1991) gives a concrete density of a mean value of 24.5 kN/m^3 with a standard deviation of 0.735 kN/m^3 for concrete of compressive strength of 40 MPa.

2 China Electric Council (2010) Category II rock mass of medium sound with a friction angle value of 45.0^o with standard deviation, σ the value of 13.26^o, was used for the concrete dam foundation concrete-rock interface.

Step 3 Sample the model inputs based on their normal distributions and constraints using the 3-sigma rule.

Step 4 Input all the constant or determinate values.

Step 5 Run the model for the safety factor for sliding and overturning.

Step 6 Record the model output factor of safety.

Step 7 Repeat for the specified samples of the model inputs. Ten million input samples are used.

Step 8 Compute the number of samples with the factor of safety < 1.0; however, the safety factor is a constraint to be greater than zero.

Step 9 Evaluate the probability distribution for the model outputs with N=10^6.

$$P_f = \frac{1}{N}\sum_{i=1}^{N} I[X_i] = \frac{N_f}{N} \quad (10)$$

Probability of Failure = No of samples with the factor of safety < 1.0 / Total No of Samples.

Matlab Code for Sliding Mode of Failure

© 2025 NSP
Natural Sciences Publishing Cor.

```
for i=1:MCS_Sample
W_Concrete(i) =
Area_of_Concrete*Density_of_Concrete_distribu
tion(i);
Sliding_FOS(i) =
(((W_Concrete(i)+W_Water+W_Silt-
Total_Uplift_Force)
*tand(Friction_Angle_distribution(i)))))
/((Horizontal_Hydraulic_Force_Upstream+Horizo
ntal_Force_Silt-
Horizontal_Hydraulic_Force_Downstream));
end
FOS_Below_One = nnz(Sliding_FOS<1);
Probability_of_Failure =
FOS_Below_One/MCS_Sample;
```

Matlab Code for Overturning Mode of Failure

```
for i=1:MCS_Sample
    W_Concrete(i) =
Volume_of_Concrete*Density_of_Concrete_distr
ibution(i);
    Overturning_FOS(i) =
(Cohesion_distribution(i)*Area_of_Contact+(W
_Concrete(i)*Lever_arm_Xconcrete)+(W_Water*L
ever_arm_Xwater)+(W_Silt*Lever_arm_Xsilt))/(
(Horizontal_Hydrostatic_Force_Upstream*Lever
_arm_Ywater_Upstream)+(Horizontal_Force_Silt
*Lever_arm_Ysilt)+Total_Uplift_Moment-
(Horizontal_Hydrostatic_Force_Downstream*Lev
er_arm_Ywater_Downstream));
end
FOS_Below_One = nnz(Overturning_FOS<1);
Probability_of_Failure =
FOS_Below_One/MCS_Sample;
```

Step 10 Calculate the Reliability Index. β. Set $\beta > 8$ if the number of samples with a safety factor < 1.0 is zero, i.e., probability of failure = 0.

Matlab Code for Reliability Index

```
% Calculate the reliability index (Beta) using
the inverse CDF of the standard normal
distribution
Beta = -norminv(Probability_of_Failure);
```

Step 11 Display the output and plot the number of samples against the safety factor graph.

The MATLAB coding has been developed for MCS analysis for the sliding and overturning failure modes for all load and drainage cases.

6 Results and Discussion

The RCC gravity dam's two predominant probabilities of failures – sliding and overturning modes have been analyzed and discussed in this section.

6.1 Sliding Factor of Safety, Probability of Failure, and Reliability Index at Concrete-Foundation Level

The summary of the hollow spillway section results for FORM-Taylor Series and Monte Carlo simulation probability of sliding failure is shown in Table 3.

The above sliding factor of safety for full supply level (FSL), design flood level (DFL), and overtopping level (OL) are compared with the minimum sliding factor of safety for usual, unusual, and extreme floods are 1.5, 1.3, and 1.1 respectively for a well-defined friction only as given Table C.8 of MyDAMS (2017). The sliding safety factor for DFL (2.11) and OL (2.00) is greater than 1.5 and 1.3, respectively. The sliding factor of safety for the S1 scenario under S1-D1, S1-D2 is greater than 1.5 except for S1-D3. The sliding factor of safety for the S2 scenario under S2-D1, S2-D2 is greater than 1.3 except for S2-D3. The sliding factor of safety for the S3 scenario under S3-D1, and S3-D2 is greater than 1.1 except for S3-D3.

The S1-D1 scenario has the highest reliability index (β_{TS} Taylor = 2.026, β_{MCS} =2.025) and S3-D3 is the lowest (β_{TS} Taylor = -0.192, β_{MCS} MCS = - 0.014). The values of the reliability index, b_{TS} in the FORM-TS are slightly lower than β_{MCS} MCS values. The values of the reliability index, β_{TS} in the FORM-TS are slightly conservative than MCS values.

The highest probability of failure is 2.138E-02 (P_{fTS} FORM-TS) and 2.143E-02 (P_{fMC} MCS) is S1-D1 whilst the lowest is 5.763E-01 (P_{fTS} FORM-TS) and 5.054E-01 (P_{fMC} MCS) is S3-D3. The values of the probability of failure in the FORM-TS are slightly conservative than MCS values. This unconditional sliding probability of failure is greater than 10^{-5} as required under ICOLD (2005). These values indicate the suitability of using FORM-Taylor Series in the reliability risk assessment and design of the RCC dam.

Figure 3 indicates the sliding factor of safety and reliability index β for the FORM and Monte Carlo.

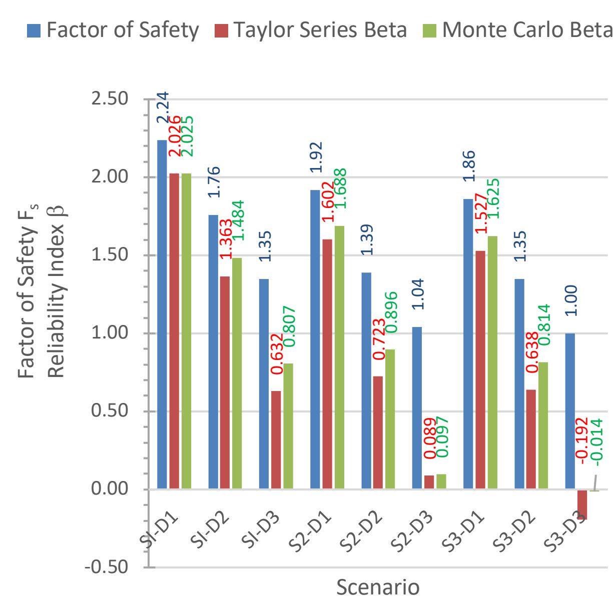


Fig. 3: Sliding Factor of Safety and Reliability Index β

The sliding factor of safety follows the same trendline as the reliability index, (β_{TS} - FORM-TS and (β_{MCS} - MCS) as the

© 2025 NSP
Natural Sciences Publishing Cor.

scenario changes from S1 to S3 and drainage conditions change from D1 to D3. As the factor of safety increases, the reliability index increases accordingly. The factor of safety decreases accordingly when the scenario changes from normal S1-D1 to extreme S3-D3 loading conditions ranging from 2.24 to 1.00. The safety factor for sliding follows the same trend line as the reliability index, β_{TS} of FORM-Taylor Series, and β_{MCS} of MCS. β_{MCS} values of MCS are slightly higher than β_{TS} values of the FORM-Taylor Series.

The reliability index, β for both FORM-Taylor Series and MCS, decreases as the scenario event changes from S1 Usual through S3 Extreme. Scenario S1 event has a higher reliability index, β as compared with scenarios S2 and S3 event. Also, the drainage D1 condition has a higher reliability index, β as compared with D2 and D3 conditions.

The rate of decrease of the reliability index, β from the D1 to D3 condition is higher than the rate of increase from the S1 to S3 event. As such, the reliability index, β more sensitive due to changes in drainage conditions D1 to D3 than the increase in the water level in S1 to S3 event. The reliability index of MCS ranges from 0%-8.8% higher than the FORM-Taylor Series when $\beta > 1$ and 9.0%-27.7% higher when $0<\beta<1$. FORM-Taylor Series reliability index has better accuracy with MCS when $\beta > 1$.

Figure 4 shows the relationship between the reliability index β and sliding factor of safety between the FORM-Taylor Series and Monte Carlo Simulation.

The results indicate a very strong linear correlation between the reliability index β and sliding factor of safety, F_s with $R^2 > 0.97$ for both FORM-Taylor Series and Monte Carlo Simulation with the following relationship;

The results indicate a very strong linear correlation between the reliability index β and sliding factor of safety, F_s with $R^2 > 0.97$ for both FORM-Taylor Series and Monte Carlo Simulation with the following relationship;

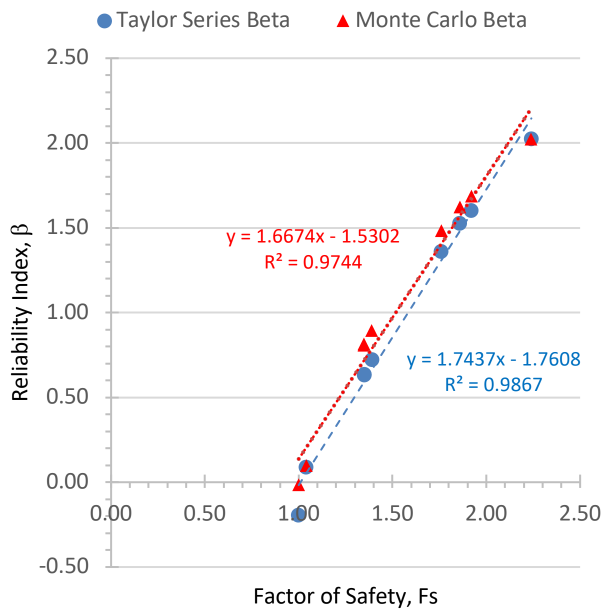


Fig. 4: Relationship between Reliability Index, β and Sliding, FoS for Taylor Series-Monte Carlo

- FORM-Taylor Series

$$= 1.667F - 1.532 \text{ with } R^2 = 0.9961 \quad (11)$$

- Monte Carlo Simulation

$$\beta_{MCS} = 1.7437F_S + 1.7608 \text{ with } R^2 = 0.9969 \quad (12)$$

The reliability index β increases linearly with the increase in the safety factor, Fs, for both the FORM-Taylor Series and Monte Carlo analysis. The FORM-Taylor Series, β_{TS} is slightly lower than the Monte Carlo β_{MCS} for the given sliding factor of safety.

Figure 5 illustrates the sliding probability of failure P_f of Taylor FORM and Monte Carlo for all the load cases with its normalized value.

Table 3: Sliding Factor of Safety and Probability of Failure of RCC Dam

			D1: CAPRI (No Uplift)		**D2: Unusual Uplift - 100% Efficiency**				**D3: Extreme Uplift - 0% Efficiency**		
Scenario	h_w (m)	Silt Level	Sliding F_{MLV}	Taylor Series $P_{fTS}(\beta_{TS})$	Monte Carlo $P_{fMC}(\beta_{MC})$	Sliding F_{MLV}	Taylor Series $P_{fTS}(\beta_{TS}))$	Monte Carlo $P_{fMC}(\beta_{MC})$	Sliding F_{MLV}	Taylor Series $P_{fTS}(\beta_{TS})$	Monte Carlo $P_{fMC}(\beta_{MC})$
S1 Usual FSL	65.00	25.0m	2.24	2.138E-02 (2.026)	2.143E-02 (2.025)	1.76	8.651E-02 (1.363)	6.890E-02 (1.484)	1.35	2.637E-01 (0.632)	2.099E-01 (0.807)
S2 Unusual DFL	71.00	25.0 m	1.92	5.462E-02 (1.602)	4.573E-02 (1.688)	1.39	2.348E-01 (0.723)	1.851E-01 (0.896)	1.04	4.644E-01 (0.089)	4.641E-01 (0.090)
S3 Extreme OL	72.00	25.0m	1.86	6.341E-02 (1.527)	.206E-02 (1.625)	1.35	2.616E-01 (0.638)	2.077E-01 (0.814)	1.00	5.763E-01 (-0.192)	5.054E-01 (−0.014)

FSL is full supply level, DFL is design flood level, OL is overtopping level, h_w is upstream head of water, and *P_f Probability of Failure* and *β Reliability Index are given in bracket.*

© 2025 NSP
Natural Sciences Publishing Cor.

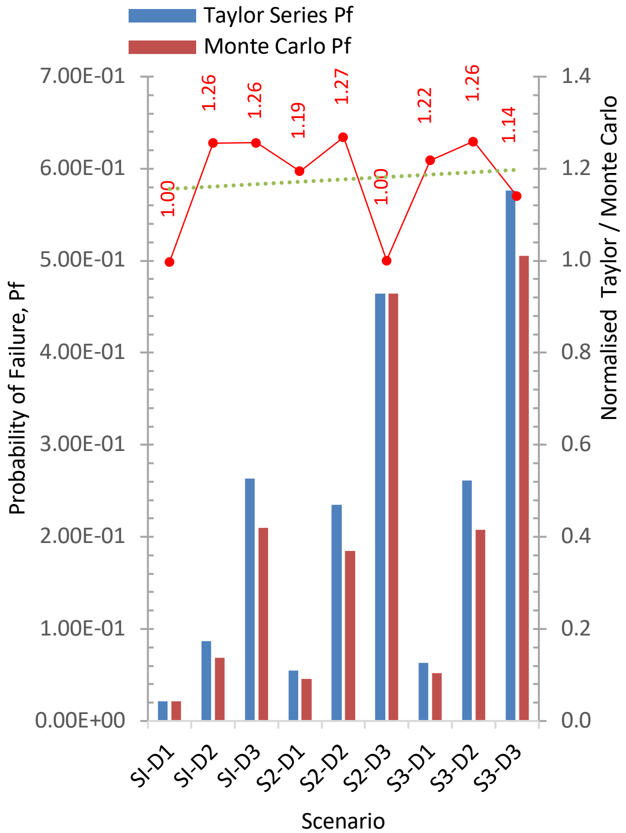


Fig. 5: Sliding Probability of Failure, P_f and Normalized Taylor Series / Monte Carlo Values

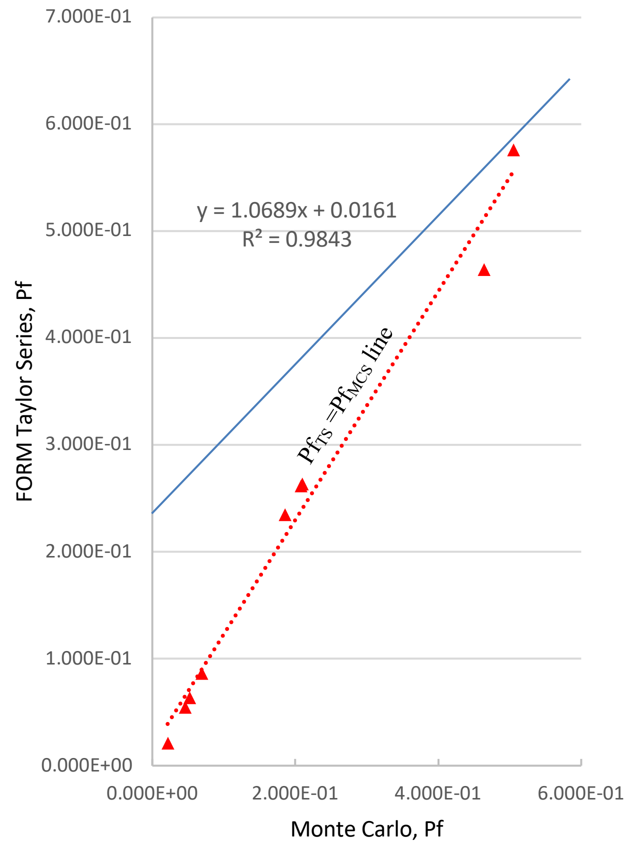


Fig. 6: Sliding Probability of Failure – Correlation between FORM-TS and Monte Carlo Analysis

The risk of probability of failure for both FORM-Taylor Series and MCS increases as the scenario event changes from normal S1 to extreme S3 under different increase uplift drainage conditions from D1 to D3. Scenario S1 event has a lower probability of failure as compared with scenarios S2 and S3. Also, drainage D1 conditions have a lower probability of failures as compared with D2 and D3 conditions. The rate of increase in the probability of failure from the D1 to D3 condition is higher than the rate of increase from the S1 to S3 event. As such, the probability of failure is more sensitive due to changes in drainage conditions D1 to D3 than the increase in water level in S1 to S3 event. However, uplift drainage conditions are dictated by the height of water level conditions predominantly at the upstream and to a lesser extent at the downstream.

The normalized FORM-Taylor to MCS probability of failures ranges from 1.00 to 1.27. FORM-Taylor P_{fTS} values are slightly more conservative than MCS P_{fMCS}. Thus FORM-Taylor probability can safely be used at the design stage, however, a more accurate MCS analysis is required in the construction and operation stage to evaluate the risk on the probability of failure.

Figure 6 illustrates the correlation between the FORM-Taylor Series and Monte Carlo analysis for the sliding probability of failure.

The results indicate an excellent linear correlation between the FORM-Taylor Series, P_{fTS}, and Monte Carlo analysis P_{fMCS} for sliding with $R^2 = 0.9843$ with the following relationship.

$$P_{fTS} = 1.0689\, P_{fMCS} + 0.0161 \quad (13)$$

FORM-Taylor Series, Pf_{TS} values are more conservative by 1.07 times or 7% more than Monte Carlo analysis Pf_{MCS} for sliding as this equation is above the $Pf_{TS} = Pf_{MCS}$ line.

Thus, FORM-Taylor probability values are slightly conservative and adequate enough to be used in evaluating the risk on the probability of failure at the design stage than the more precise MCS reliability analysis for RCC Dam.

6.2 Overturning Factor of Safety, Probability of Failure, and Reliability Index at Concrete-Foundation Level

The summary of the hollow spillway section results for FORM-Taylor Series and Monte Carlo simulation probability of overturning failure is shown in Table 4.

S1-D1 scenario has the highest overturning factor of safety of 3.96 and reliability index $\beta_{TS} = 45.912$, $\beta_{MCS} > 8$). S3-D3 has the lowest overturning factor of safety of 1.29 and reliability index ($\beta_{TS} = 3.055$, $\beta_{MCS} > 8$).

© 2025 NSP
Natural Sciences Publishing Cor.

Table 4: Overturning Factor of Safety and Probability of Failure of RCC Dam

			D1: CAPRI (No Uplift)			**D2: Unusual Uplift - 100% Efficiency**			**D3: Extreme Uplift - 0% Efficiency**		
Scenario	h_w (m)	Silt Level	Overturning F_{MLV}	Taylor Series $P_{fTS}(\beta_{TS})$	Monte Carlo $P_{fMC}(\beta_{MC})$	Overturning F_{MLV}	Taylor Series $P_{fTS}(\beta_{TS})$)	Monte Carlo $P_{fMC}(\beta_{MC})$	Overturning F_{MLV}	Taylor Series $P_{fTS}(\beta_{TS})$	Monte Carlo $P_{fMC}(\beta_{MC})$
S1 Usual FSL	65.00	25.0m	3.96	0.000E+00 (45.912)	0.000E+00 (>8)	2.16	0.000E+00 (25.594)	0.000E+00 (>8)	1.57	0.000E+00 (9.777)	0.000E+00 (>8)
S2 Unusual DFL	71.00	25.0 m	3.06	0.000E+00 (37.296)	0.000E+00 (>8)	1.71	0.000E+00 (17.945)	0.000E+00 (>8)	1.32	4.794E-05 (3.901)	0.000E+00 (>8)
S3 Extreme OL	72.00	25.0m	2.94	0.000E+00 (35.918)	0.000E+00 (>8)	1.67	0.000E+00 (17.008)	0.000E+00 (>8)	1.29	1.124E-03 (3.055)	0.000E+00 (>8)

FSL is full supply level, DFL is design flood level, OL is overtopping level, h_w is upstream head of water, and *P_f Probability of Failure* and *β Reliability Index are given in bracket.*

All the overturning probability of failure is zero except for the S2-D3 and S3-D3 FORM-Taylor Series P_{fTS}. The number of samples run is 10 million and no failures are recorded in the Monte Carlo Simulation. β= 7.87375 with its Pf = 1.7764 x 10^{-15} are related to the computational representation of the standard Gaussian cumulative distribution function (Φ) and its inverse (Φ -1). In the MATLAB coding for MCS, the operational limit where no probability of failure occurs is set at β > 8 i.e. Pf = 00.000E+00.

The unconditional overturning probability of failure under the FORM-Taylor Series for all load case scenarios S1, S2, and S3 is less than 10^{-5} except for S2-D3 and S3-D3 scenarios is greater than 10^{-5} as required by ICOLD 2005. The unconditional overturning probability of failure under MCS is nil for all load case scenarios (S1, S2, S3) and less than 10^{-5} as required by ICOLD 2005 as such not a critical mode of failure.

The results of β and Pf from Table 3 and Table 4 show that the dominant failure mode is the sliding mode as compared with the overturning failure mode. The overturning failure shows a very low probability of failure and not a very critical mode of failure.

Figure 7 shows the results of the overturning factor of safety and reliability index, β_{TS} for Form-Taylor Series (TS) and β_{MCS} for Monte Carlo Simulation.

The overturning factor of safety follows the same trendline as the reliability index, β_{TS} - FORM-TS and β_{MCS} - MCS) as the scenario changes from S1 to S3 and drainage conditions change from D1 to D3. As the factor of safety increases, the reliability index increases accordingly. The factor of safety decreases accordingly when the scenario changes from usual S1-D1 to extreme S3-D3 loading conditions ranging from 3.96 to 1.29.

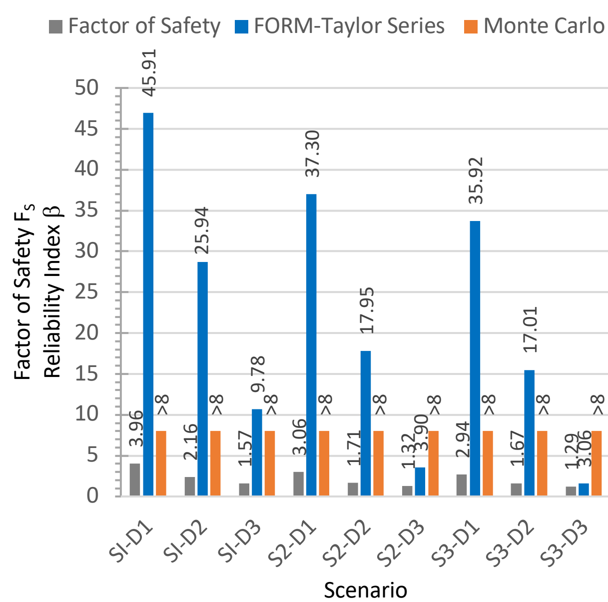


Fig. 7: Overturning Safety Factor and Reliability Index β

No direct comparison can be made between the reliability index, β_{TS} for FORM-Taylor Series and β_{MCS} for MCS. In the MATLAB coding for MCS, the operational limit where no probability of failure occurs is set at β > 8 i.e. Pf = 00.000E+00.

The reliability index, β_{TS} for FORM-Taylor Series, decreases as the scenario changes from S1 Usual through S3 Extreme. Scenario S1 event has a higher reliability index, β_{TS} as compared with scenarios S2 and S3 event. Also, the drainage D1 condition has a higher reliability index, β_{TS} as compared with D2 and D3 conditions.

The use of safety factors for safety quantification of

© 2025 NSP
Natural Sciences Publishing Cor.

Table 5: Sensitivity Analysis for Sliding

Input	FSL - Swing ΔF			DFL - Swing ΔF			OL - Swing ΔF			Average	Sensitivity
Variable	S1-D1	S1 -D2	S1-D3	S2-D1	S2 -D2	S2-D3	S3-D1	S3 -D2	S3-D3	ΔF	%
Angle of friction, ϕ^o	1.68	1.32	1.01	1.44	1.05	0.78	1.40	1.01	0.75	1.16	90.6
Density of concrete, γ_{conc}	0.13	0.13	0.13	0.11	0.11	0.11	0.11	0.11	0.11	0.12	9.4

structures should be used with limitations and caution as the structure with the same safety factors but different coefficients of variation can result in the variation in probabilities of failure in the order 10^{-5} (ICOLD, 1993).

From the reliability analysis, the sliding failure mode was the dominant mode over the overturning mode of failure. The most probably been friction angle is the most influential random variable in this failure mode. The overturning had a significantly lower probability of occurrence than sliding. The overturning modes had a very low probability of occurrence with the most probable reason being that the concrete density and coefficient of hydraulic inefficiency presented balanced contributions.

6.3 Sensitivity Analysis

Sensitivity analysis measures how the impact of one or more input variables can lead to uncertainties in the output variables. Table 5 and Figure 8 indicate the sensitivity analysis on the independent input variable friction angle and concrete density for sliding. No sensitivity analysis is carried out for overturning as it has only one input variable, i.e., density of concrete.

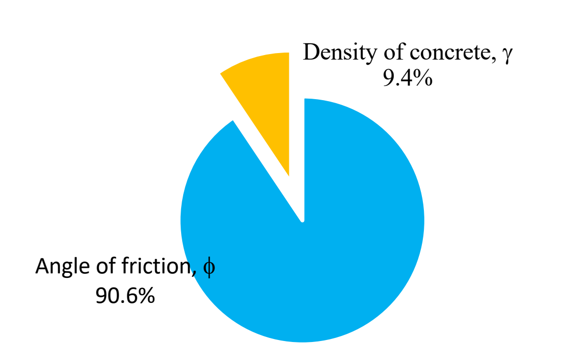


Fig. 8: Sensitivity Analysis for Sliding

The friction angle swing ΔF ranges from 0.75 to 1.68 and concrete swing ΔF density ranges from 0.11 to 0.13. The ΔF values measure the swing on the safety factor, or the friction angle and the density of concrete taken from the FORM-Taylor Series analysis for sliding. sensitivity for the friction angle is 90.6% and the density of concrete is 9.4%. It can be seen that the sliding mode of failure is very sensitive to friction angle and the density of concrete has very minor effect. In this sense, the Taylor Series Method can be viewed as a structured sensitivity analysis or parametric study.

6.4 Conditional Probability of Failure

The annual exceedance probability (AEP) of water for full supply level (FSL) under usual operating conditions and design flood level (DFL) and overtopping level (OL) is assumed 1, 10^{-3} and 10^{-4}.year^{-1} respectively

The AEP for silt level is assumed as 1.0 x10^{-1}.year^{-1} for usual, unusual and extreme silt levels.

The AEP for drainage is assumed as 1, 2.0x10^{-2} and 1.0x10^{-2}.year^{-1} for usual CAPRI in operation, unusual 100% drainage (CAPRI inoperative) and 0% drainage (CAPRI inoperative) respectively.

$$\text{Conditional probability of failure}, Pf combined = \sum P(Unconditional) \times \sum P\,(Water) \times \sum P\,(Silt) \times \sum P(\,Drainage\,) \quad (14)$$

The conditional probability of failure provides insights into the susceptibility of a dam to specific triggers, while the unconditional probability of failure offers a broader assessment of the overall failure likelihood. These probabilities assist in prioritizing risk management strategies, determining maintenance needs, and making informed decisions regarding dam safety measures. Table 6 shows the results of the sliding unconditional probability of failure for the FORM-Taylor Series and Monte Carlo simulation.

Table 6 shows the results of the sliding conditional probability of failure for Taylor Series (TS) and Monte Carlo simulation.

Example for Scenario S1-D1, S2-D2 and S3-D3 calculations for MCS as shown in Table 6.

1. Scenario S1-D1: MCS P_{fc} = 2.143 x10^{-02} x 1 x 1.0x10^{-1} x 1 = 2.143 x10^{-03}
2. Scenario S2-D2: MCS P_{fc} = 1.851 x10^{-01} x 10^{-03} x 1.0x10^{-1} x 2.0x10^{-2} = 3.702 x10^{-07}
3. Scenario S3-D3: MCS P_{fc} = 5.054 x10^{-01} x10^{-04} x 1.0x10^{-1} x 1.0x10^{-2} = 5.054 x 10^{-08}

The sliding failure mode has the maximum failure probabilities under S1-D1 unconditional (Pf Taylor = 2.143E-02, Pf MCS =2.143E-02) and S1-D1 conditional (Pf Taylor = 2.143E-03, Pf MCS =2.143E-03) probability of failures. All the conditional failure probabilities under S2 (S2-D1, S2-D2, S2-D3) and S3 (S3-D1, S3-D2, S3-D3) load case scenarios are less than 10^{-4} probability of occurrence as required by ICOLD (2005) except for S1 load case scenario (S1-D1, S1-D2, S1-D3) under the usual FSL event.

Table 7 shows the results of the overturning combined (conditional) probability of failure for Taylor Series (TS) and Monte Carlo simulation.

© 2025 NSP
Natural Sciences Publishing Cor.

Table 6: Conditional Sliding Probability of Failure - Taylor Series (TS) and Monte Carlo Simulation (MCS)

Scenario	**Water Level** AEP Event	**Silt Level** AEP Event	**Drainage Conditions** D1 AEP Event	D2 AEP Event	D3 AEP Event	**D1 TS *MCS*** *Pf*	**D1 TS *MCS*** *Comb Pf*	**D2 TS *MCS*** *Pf*	**D2 TS *MCS*** *Comb Pf*	**D3 TS *MCS*** *Pf*	**D3 TS *MCS*** *Comb Pf*
S1 **Usual FSL**	1	$1.0x10^{-1}$	1	$2.0x10^{-2}$	$1.0x10^{-2}$	2.138E-02 *2.143E-02*	2.138E-03 *2.143E-03*	8.651E-02 *6.890E-02*	1.730E-04 *1.378E-04*	2.637E-01 *2.099E-01*	2.637E-04 2.099E-04
S2 **Unusual DFL**	10^{-3}	$1.0x10^{-1}$	1	$2.0x10^{-2}$	$1.0x10^{-2}$	5.462E-02 *4.573E-02*	5.462E-06 4 4.573E-06	2.348E-01 *1.851E-01*	4.696E-07 *3.702E-07*	4.644E-01 *4.641E-01*	4.644E-06 *4.641E-06*
S3 **Extreme OL**	10^{-4}	$1.0x10^{-1}$	1	$2.0x10^{-2}$	$1.0x10^{-2}$	6.341E-02 *5.206E-02*	6.341E-07 5.206E-07	2.616E-01 *2.077E-01*	5.232E-08 *4.154E-08*	5.763E-01 *5.054E-01*	5.763E-08 *5.054E-08*

Table 7: Conditional Overturning Probability of Failure - Taylor Series (TS) and Monte Carlo Simulation (MCS)

Scenario	**Water Level** AEP Event	**Silt Level** AEP Event	**Drainage Conditions** D1 AEP Event	D2 AEP Event	D3 AEP Event	**D1 TS *MCS*** *Pf*	**D1 TS *MCS*** *Comb Pf*	**D2 TS *MCS*** *Pf*	**D2 TS *MCS*** *Comb Pf*	**D3 TS *MCS*** *Pf*	**D3 TS *MCS*** *Comb Pf*
S1 **Usual FSL**	1	$1.0x10^{-1}$	1	$2.0x10^{-2}$	$1.0x10^{-2}$	0.000E+00 *0.000E+00*	0.000E+00 *2.0.000E+00*	0.000E+00 *0.000E+00*	0.000E+00 0.000E+00	0.000E+00 0.000E+00	0.000E+00 0.000E+00
S2 **Unusual DFL**	10^{-3}	$1.0x10^{-1}$	1	$2.0x10^{-2}$	$1.0x10^{-2}$	0.000E+00 *0.000E+00*	0.000E+00 4.0.000E+00	0.000E+00 0.000E+00	0.000E+00 *0.000E+00*	4.794E-05 *0.000E+00*	4.794E-11 *0.000E+00*
S3 **Extreme OL**	10^{-4}	$1.0x10^{-1}$	1	$2.0x10^{-2}$	$1.0x10^{-2}$	0.000E+00 *0.000E+00*	0.000E+00 1.0.000E+00	0.000E+00 0.000E+00	0.000E+00 0.000E+00	1.124E-03 *0.000E+00*	1.124E-10 *0.000E+00*

All the conditional overturning probability of failure is nil except for S2-D3 FORM-Taylor Series (Pf_{TS} = 4.794E-11) and S2-D3 FORM-Taylor Series (Pf_{TS} =1.124E-10). In accordance with Table 7, there is no likelihood of the combined overturning probability of failure for the RCC dam for all the scenarios (S1, S2, and S3) where its condition probability of failure is less than 1.0 x 10^{-4} (ICOLD, 2005, ANCOLD, 2003, USBR-USACE, 2019, USACE, 2014).

7 Conclusions

1. The probabilistic FORM-Taylor Series approximation is slightly more conservative and fit to be used at the design and even at operation stages as a degradation phenomenon in dam-foundation contacts and uplift pressures over the maximum design and has been reported in some dams.
2. A more highly accurate Monte Carlo analysis is advisable to be used at the construction stages when test data for friction angles and density of the materials are available based on actual site conditions is used.
3. A strong linear correlation with $R^2 > 0.97$ between the reliability index, β and the sliding factor of safety, F_s for FORM-Taylor Series and Monte Carlo analysis has been established.
4. An excellent linear correlation with R^2=0.9843 between the FORM-Taylor Series, P_{fTS} and Monte Carlo analysis P_{fMCS} for sliding has been obtained. FORM-Taylor P_{fTS} si 1.07 times or 7% more conservative than Monte Carlo analysis P_{fMCS} for sliding.
5. Sliding is the most dominant mode of failure than the overturning mode. The most probably been friction angle is the most influential random variable in this failure mode. The overturning modes had a very low probability of occurrence with the most probable reason being that the concrete density and coefficient of hydraulic inefficiency presented balanced contributions.
6. Unconditional overturning probability of failure under MCS for all load case scenarios S1, S2, S3 are null and there is no likelihood of the overturning mode of failure occurring.
7. Sensitivity analysis indicates for the sliding mode of failure that the friction angle has a very high sensitivity of 90.6% whereas the density of concrete has a very low sensitivity of 9.4% only.
8. Conditional sliding probability of failure for S1 scenario is greater than 10^{-5} whilst S2 and S3 scenario are less than 10^{-4} as required by ICOLD (2005). Unconditional sliding probability of failure for all load case scenarios S1, S2, S3 > 10^{-5}.
9. Conditional overturning probability of failure under FORM-Taylor Series for all load case scenarios S1, S2, and S3 is less than 10^{-5} except for S2-D3 and S3-D3 scenario is greater than 10^{-5} of ICOLD 2005.

© 2025 NSP
Natural Sciences Publishing Cor.

Acknowledgements

The authors would like to thank INTI International University, Malaysia for the financial support for the publication of this article.

References

[1] ANCOLD (2003), *Australian National Committee on Large Dams, "Guidelines on Risk Assessment,"* October 2003. http://www.ancold.org.au/publications.asp

[2] Ashtankar, V. B., & Chore, H. S. (2014). Development of design mix roller compacted concrete dam at Middle Vaitarana. *Advances in Concrete Construction,* 2(2), 125–144. https://doi.org/10.12989/ACC.2014.2.2.125.

[3] Barpi, F.and Valente, S. (2008), Modeling water penetration at dam-foundation joint. *Eng. Fract. Mech.* 2008, 75, 629–642.

[4] Brian, F. (2008), RCC-New developments and innovations, *Proceedings of the Brazilian International Roller Compacted Concrete (RCC) Symposium*, pp. 1–18, Salvador, Brazil, 2008.

[5] Carvajal, C., Peyras, L., Bacconnet, C. and Bécue, J-P (2011), Probability modelling of shear strength parameters of RCC gravity dams for reliability analysis of structural safety. *European Journal of Environmental and Civil Engineering*, Taylor & Francis, 2011, 13 (1), pp.91-119.

[6] CEB-FIP Model Code 1990 (1991), *Comite Euro-International du Beton. Bulletin d'information, No. 213/214,* Lausanne. Cederström, M. (2009) Personal communication.

[7] CEN 2001, European Committe for Standartization - CEN, *"Basis of structural design. EN 1990."* Brussels, Belgium, 2001.

[8] China Electric Council (2010), *The Standards Compilation of Power in China.*

[9] Christian, J. T., Ladd, C. C., and Baecher, G. B. (1994), Reliability applied to slope stability analysis, *J. Geotech. Engr*., 20, Dec., 2180–2207.

[10] Duncan, J. M. (2000). Factors of Safety and Reliability in Geotechnical Engineering, *Journal of Geotechnical and Geo-environmental Engineering April 2000*

[11] Garcia, L.A, Bueno, I.E, Lombillo, A.S. and Ortuno M.G.M, (2012) Methodology for estimating the probability of failure by sliding in concrete gravity dams in the context of risk analysis, *Struc. Saf. Vol 36, pp. 1-13, 2012.*

[12] Hu, W., Zhong, D., Wu, B., & Li, Z. (2019). Construction phase oriented dynamic simulation: taking RCC dam placement process as an example. *Journal of Civil Engineering and Management,* 25(7), 654-672.

[13] Huang, Y., & Wan, Z. (2018). Study on Viscoelastic Deformation Monitoring Index of an RCC Gravity Dam in an Alpine Region Using Orthogonal Test Design. *Mathematical Problems in Engineering*, 2018

[14] ICOLD (1989), International Commission on Large Dams, Bulletin 72: *Selecting Seismic Parameters for Large Dams.* Paris 1989.

[15] ICOLD (1993), International Commission on Large Dams, Bulletin 88 : *Rock foundations for dams* !COLD, Paris, 1993.

[16] ICOLD (2005*),* International Commission on Large Dams, Bulletin 130: *Risk assessment in dam safety management*, Paris 2005.

[17] ICOLD (2003), International Commission on Large Dams, Bulletin 126 *: Roller-Compacted Concrete Dams: State of Art and Case Histories,* ICOLD, Paris, 2003.

[18] Khan, M.D.H., Nur, S. M., El-Shafie, A. (2018), A Review of Fundamental Drought Concepts, Impacts and Analyses of Indices In Asian Continent, Journal of Urban and Environmental Engineering, 12,1,106-119, 2018. doi: 10.4090/juee.2018.v12n1.106119.

[19] Khan, M.D.H., Nur, S.M., El-Shafie, A. (2020), Wavelet based hybrid ANN-ARIMA models for meteorological drought forecasting, Journal of Hydrology, 590 (2020) 125380.

[20] Kokubu, K., Cabrera, J.G., Ueno, A (1996), Compaction properties of roller compacted concrete. *Cement & concrete composites*, 1996, Vol.18 (2), p.109-11.

[21] Ma,J., Lingqiang Yang, L., Yan Wang,Y. (2018) Safety Evaluation of roller compacted concrete dam, *Advances in Engineering Research*, volume 163, 671-674.

[22] McDonald, J.E and Curtis, N.F. (1997), *Applications of Roller-Compacted Concrete in Rehabilitation and Replacement,* Technical Report REMR-CS-53, US Army of Corps of Engineers, 1997

[23] Melchers, R.E and Beck, A.T (2018), *Structural reliability: analysis and prediction.* 3rd Edition, John Wiley & Sons, 2018.

© 2025 NSP
Natural Sciences Publishing Cor.

[24] Muench, S. (2010). *Probabilistic User's Guide. Seattle: University of Washington.*

[25] Nagayama, I., and Jikan, S. (2003). 30 Years' History of Roller-compacted Concrete Dams in Japan. *Fourth Int. Symp. on Roller Compacted Concrete Dams*. 17-19 November 2003, Madrid, Spain.

[26] Pei, L.; Chen, C.; He, K.; Lu, X. (2022) System Reliability of a Gravity Dam-Foundation System Using Bayesian Networks. *Reliab. Eng. Syst. Saf.* 2022, 218, 108178.

[27] Pires, K.O, Beck, A.T., Bittencourt, T.N and Futai, M.M (2019) Reliability analysis of built concrete dam, *Ibracon Structures and Materials Journal,* Vol 12, Number 3 (June 2019) p 551-579. ISSN 1983-4195.

[28] Phoon, K.K (2019) *Reliability-Based Design in Geotechnical Engineering Computations and Applications,* Published December 12, 2019 by CRC Press, 544 Pages ISBN 9780367864132

[29] Reclamation (2003), United States Department of the Interior, Bureau of Reclamation, *"Guidelines for Achieving Public Protection in Dam Safety Decision Making,"* 15 June 2003.

[30] RIDAS (2017). Swedish Hydropower Companies Guidelines for Dam Safety. In Application Guideline 7.3 Concrete Dams. Stockholm, Sweden: Svensk Energi.

[31] Scott, G.A., J.T. Kottenstette, and J.F. Steighner. 2001. "Design and Analysis of Foundation Modifications for a Buttress Dam." *Proceedings, 38th U.S. Symposium on Rock Mechanics, Washington, D.C. pp. 951-957.*

[32] Sharafati, A.; Yaseen, Z.M.; Pezeshki, E. (2020) Strategic Assessment of Dam Overtopping Reliability Using a Stochastic Process Approach. *J. Hydrol. Eng.* 2020, 25, 04020029.

[33] Spross, J., Johansson, F. and Larsson, S. (2014), On the use of pore pressure measurements in safety reassessments of concrete dams founded on rock. *Georisk: Assess. Manag. Risk Eng. Syst. Geohazards* 2014, 8, 117–128.

[34] Tang, W. H., Stark, T. D., and Angulo, M. (1999), Reliability in back analysis of slope failures, *J. Soil Mech. and Found.,* Tokyo, October 1999.

[35] USACE (1997). *'Engineering and design introduction to probability and reliability methods for use in geotechnical engineering.* Engr. Tech. Letter No. 1110-2-547, Department of the Army, Washington, D.C., 30 Sept. 1997.

[36] USACE (1998), *Risk-based analysis in geotechnical engineering for support of planning studies,* Engrg. Circular No. 1110-2-554, Department of the Army, Washington, D.C., 27 Feb. 1998.

[37] USACE (2000), *Planning Guidance Notebook.* United States Army Corps of Engineers, ER 1105-2-100, 2000.

[38] USACE (2014) *Safety of Dams – Policy and Procedures,* US Army Corps of Engineers*,* ER1110-2-1156, 31 March 2014

[39] USBR-USACE (2019) *Best Practices in Dam and Levee Safety Risk Analysis*, USBR-USACE Joint Publication, Version 4.1, July 2019

[40] Wolff, T. F. (1994), *Evaluating the reliability of existing levees,* Rep., Res. Proj.: Reliability of existing levees, prepared for U.S. Army Engineer Waterways Experiment Station Geotechnical Laboratory, Vicksburg, Miss.,USA.

[41] Nagayama, I., & Jikan, S. (2003). 30 Years' History of Roller-compacted Concrete Dams in Japan. *Fourth Int. Symp. on Roller Compacted Concrete Dams,*2003

[42] Warren, T. (2013). Roller-compacted concrete dams: a brief history and their advantages. *Dams and Reservoirs,* 22(2), 87-90.

[43] Xin, C. and Chongshi, G. (2016), Risk analysis of gravity dam instability using credibility theory Monte Carlo simulation model. *SpringerPlus* 5, 778 (2016). https://doi.org/10.1186/s40064-016-2508-7

[44] Yang, Z.; Ching, J. A (2020), Novel Reliability-Based Design Method Based on Quantile-Based First-Order Second-Moment. *Appl. Math. Modell*. 2020, 88, 461–473.

[45] Zheng, X., Zhou, J., Chen, G., & Chen, S. (2020). Exposure Assessment for Roller Compacted Concrete Dam Construction Integrated Real-Time Location Information. *KSCE Journal of Civil Engineering*, 24(3), 703-714.

Biography:

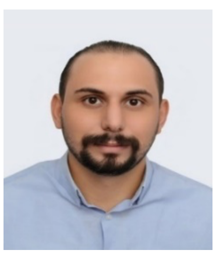
Zakaria Che Muda earned his Ph. D. degree in Built Environment from University of Malaya. He is currently a Professor at the Department of Civil Engineering, INTI International University. He has published over 100 papers in international journals. His research interests are focused on approximate analytical methods, numerical analysis, reliability-based analysis, fibre-reinforced concrete and energy-efficient buildings.

© 2025 NSP
Natural Sciences Publishing Cor.

Mohamed Ahmed Hafez earned his Ph. D. degree in Civil Engineering from University of Malaya. He is an Assoc. Prof. at the Department of Civil Engineering, INTI International University. He has published over 55 papers in journals. His research interests are focused on Dam risk, slope stability and soft ground improvement.

Lariyah Mohd Sidek earned her Ph. D. degree in Civil Engineering (Urban Drainage) from Kyoto University, Japan in 2005. Currently, she is a Professor and Head of Centre for Sustainable Technology and Environmental at University Tenaga Nasional. She has published about 350 papers in international conferences and journals. Her research interests include Water Resources Engineering, Dam Break Study, Risk Informed Decision Making on Dam Safety.

Hidayah Basri is earned her Ph. D degree in Civil Engineering from University Tenaga Nasional, Malaysia in 2022. She is currently a Senior Lecturer at the Institute of Energy Infrastructure, and Civil Engineering Department at University Tenaga Nasional. She has published about 175 papers in conference proceedings and journals. Her research interest includes hydrological forecasting, dam safety and emergency response plan. She is a Member of Young Professional Forum of the International Commission of Large Dams (ICOLD).



Zaher Almakahal is currently a graduate research assistance and master student at the Department of Civil Engineering, INTI International University. He has published several papers in international journals. His research interests are focused on approximate analytical methods, numerical analysis, and reliability-based analysis.

As'ad Zakaria is currently a Ph. D student at the Institute of Energy Systems, School of Engineering, University of Edinburgh, Edinburgh, UK. He has published over 10 papers in the Q1 and Q2 journals. His research interest is in Stochastic Optimization, Monte Carlo Simulation, power system analysis and renewable energy systems.

© 2025 NSP
Natural Sciences Publishing Cor.