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Computational Structural Stability Analysis of Gravity Dams Using Franc-2d

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Abstract

This paper assesses the structural safety and sliding stability of a concrete gravity dam through a fracture mechanics–based methodology integrated with probabilistic analysis. A 47-meter-high dam model is developed using FRANC-2D, applying Linear Elastic Fracture Mechanics (LEFM) and quarter-point elements to simulate crack initiation and propagation under varying reservoir levels. Mode I and Mode II stress intensity factors (K_I and K_II) are computed to determine thresholds for unstable crack growth. To incorporate the inherent uncertainties in material properties and external loads, a probabilistic framework is implemented. Key parameters such as cohesion, internal friction angle, and applied loads are modelled as random variables. Monte Carlo simulations are conducted to estimate the probability of dam failure. Results indicate that fracture behavior is highly sensitive to changes in both loading and material characteristics, highlighting the importance of probabilistic tools in dam safety evaluations. This integrated approach enhances the accuracy of long-term performance predictions and supports informed maintenance and risk mitigation strategies.

Keywords: FRANC-2D; Linear Elastic Fracture Mechanics (LEFM); Probabilistic Analysis; Gravity Dam; Stress Intensity Factors; Monte Carlo Simulation

1. INTRODUCTION

Concrete gravity dams are essential infrastructure for water storage, flood control, and hydropower generation. However, their structural stability remains a major concern due to the risks associated with potential failure. These massive hydraulic structures rely primarily on their self-weight to resist external forces such as hydrostatic pressure, uplift, and seismic activity. Stability issues are especially critical for older dams or those subjected to harsh environmental conditions and degradation over time. Traditional stress-based analysis methods often struggle to accurately capture the complex fracture behavior that can lead to structural failure. To address this limitation, **FRANC-2D**—a powerful finite element analysis tool—is increasingly used for in-depth fracture-based stability assessment of concrete gravity dams. FRANC-2D allows for the simulation of crack initiation, propagation, and interaction with dam geometry and material interfaces using principles from both linear and nonlinear fracture mechanics. This enables engineers to calculate Stress Intensity Factors (SIFs), predict realistic crack trajectories, and evaluate the impact of fracture development on the dam's overall structural integrity. FRANC-2D provides a comprehensive framework for evaluating dam safety, whether for newly constructed dams or for assessing the residual life of existing structures undergoing rehabilitation or experiencing material degradation. By incorporating fracture behavior into the analysis, this method offers a more realistic and reliable basis for long-term safety evaluations.

The application of fracture mechanics to concrete gravity dams has significantly advanced understanding of crack behavior and structural safety. Ingraffea [1] demonstrated how Linear Elastic Fracture Mechanics (LEFM) could be applied to predict crack paths and assess repair strategies in real dam structures. Rescher [2] emphasized the role of fracture extension and the importance of considering seismic loading in the evaluation of aging dams.

Additionally, Saouma et al. [3] conducted parametric studies highlighting how loading conditions, concrete anisotropy, and material aging influence SIFs and fracture progression. These foundational works underscore the critical role of fracture mechanics in enhancing dam safety evaluations.

Significance: This work advances the assessment of crack propagation and sliding stability in concrete gravity dams by integrating Monte Carlo simulations within the FRANC-2D framework, grounded in Linear Elastic Fracture Mechanics (LEFM). By bridging deterministic fracture modelling with probabilistic analysis, the study moves beyond the limitations of traditional limit equilibrium methods. It highlights how variability in key material and loading parameters—such as cohesion, internal friction angle, and uplift pressure—influences the shear-friction factor of safety. The identification of critical fracture lengths under varying reservoir levels, along with the probabilistic estimation of failure, provides a more rigorous, risk-informed framework for evaluating dam performance and safety.

2. DESCRIPTION OF DAM

The analysis focuses on a 47-meter-tall concrete gravity dam with water maintained at the full reservoir level. The dam is modelled using reduced dimensions and cross-sectional geometry, as illustrated in Fig.1. The dam material is assumed to be linearly elastic concrete, characterized by mass density (ρ) of 2400 kg/m³; Poisson's ratio (ν) of 0.2and Modulus of elasticity (Ec) of 22,360 MPa. The analysis neglects the unit weight of the rock foundation, implying that all calculated stresses in the foundation are due to the self-weight of the dam and the hydrostatic pressure from the reservoir — referred to as in situ stresses.

The numerical simulation is conducted using the finite element software FRANC-2D [18], which enables fracture analysis in 2D domains. A detailed finite element mesh of the dam is developed and is shown in the associated figure.

Loads Considered in the Analysis:

1. Hydrostatic Pressure: Water level reaches the dam crest (47 m), generating pressure on the upstream face.
2. Self-Weight (Body Force): Gravity-induced stresses from the dam's own weight.
3. Full Uplift Pressure: Applied along the length of any potential crack path, simulating worst-case uplift conditions.

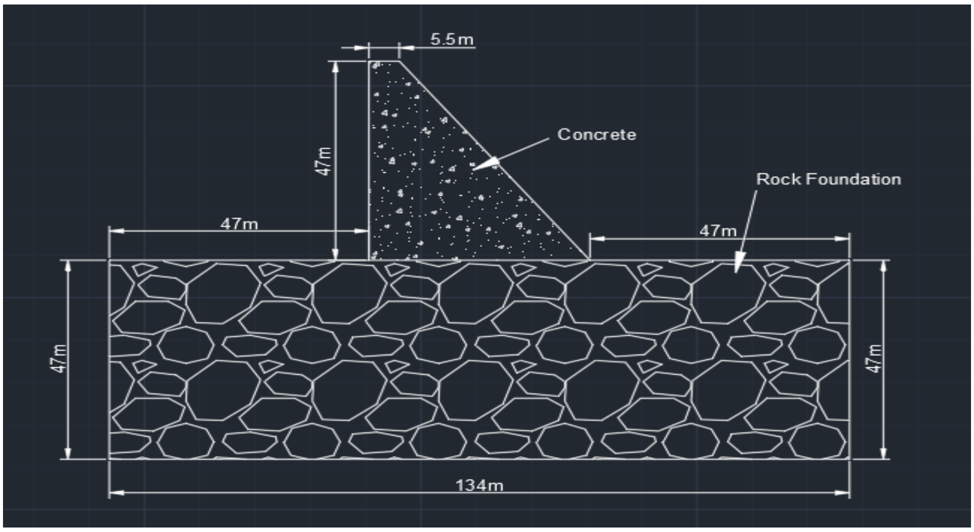

Fig.1 Description of dam

3. MATERIAL PROPERTIES

The gravity dam is modelled as a homogeneous, isotropic, and linear elastic concrete structure. Key material properties include a density of 2400 kg/m³, Young's modulus of 22,360 MPa, and Poisson's ratio of 0.20. The fracture toughness ($K\_IC = 4.5 \times 10^6$ MPa) is incorporated within a Linear Elastic Fracture Mechanics (LEFM) framework. To account for material variability, parameters such as cohesion, internal friction angle, and uplift pressure are treated as random variables following appropriate probability distributions. This probabilistic approach enables a more realistic assessment of stress intensity factors and overall structural safety.

4. METHODOLOGY

4.1 MODELLING

This study evaluates the fracture behavior and sliding stability of a 47-meter-high concrete gravity dam by integrating fracture mechanics with probabilistic analysis. The numerical modelling and simulations are performed using FRANC-2D, a finite element software specifically designed for crack growth and fracture mechanics studies.

The modelling process begins with constructing a detailed two-dimensional finite element model of the gravity dam in FRANC-2D. This model serves as the basis for simulating the dam's response under realistic loading conditions, including hydrostatic pressure exerted by the reservoir and the self-weight of the structure. By capturing these conditions, the model as shown in Fig.2 enables a comprehensive assessment of crack initiation, propagation, and the overall sliding safety of the dam.

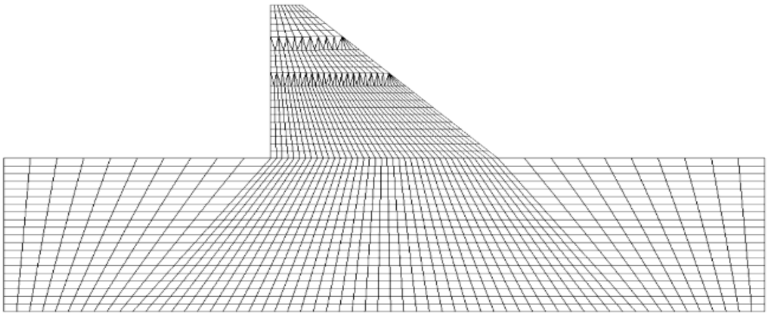

Fig.2 Modelling of Gravity Dam in FRANC-2D

4.2 MESH REFINEMENT NEAR TIP

A detailed two-dimensional model of the dam geometry was developed, with particular focus on mesh refinement in stress-concentrated regions such as the heel and toe of the dam. The concrete was modelled as a linear elastic, homogeneous, and isotropic material. Essential material properties including Young's modulus, Poisson's ratio, density, tensile strength, and fracture toughness were assigned based on established literature and experimental data. Mesh refinement near the crack tip is a critical aspect of accurate fracture mechanics analysis, especially when using finite element tools like FRANC-2D. Coarse mesh elements cannot accurately capture the steep stress gradients and singularity effects that occur near the crack tip (Fig.3). To overcome this, the mesh size was progressively reduced around the crack tip area, enabling precise resolution of stress intensity factors and realistic simulation of crack initiation and propagation.

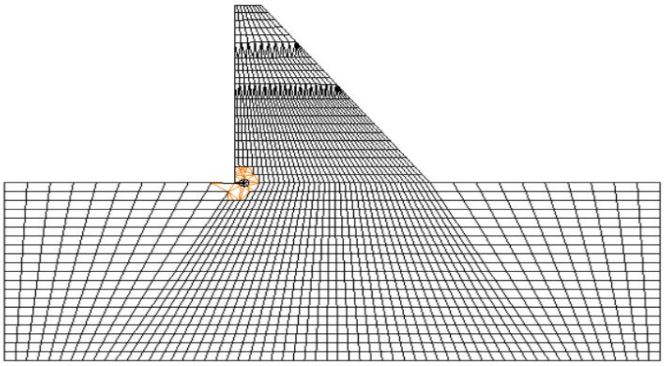

Fig.3 Crack at heel region

4.3. SINGULAR FINITE ELEMENT

To accurately capture the stress singularity near the crack tip in Linear Elastic Fracture Mechanics (LEFM), quarter-point (singular) finite elements as shown in Fig. 4 were implemented around the crack front. These specialized elements modify the standard iso-parametric formulation by shifting the mid-side nodes to one-quarter of the element edge length from the crack tip. This adjustment allows the element shape functions to replicate the characteristic $\sigma \propto 1/\sqrt{r}$ stress field, typical of Mode I crack behavior. The use of quarter-point elements significantly improves the precision of stress intensity factor (SIF) calculations (K I, K II) without requiring extensive global mesh refinement. In this study, such elements were carefully integrated around the crack tip in FRANC-2D to ensure high-fidelity simulation of crack initiation and propagation. Their application is especially critical for modelling brittle fracture in materials like concrete, where accurately predicting crack behavior hinges on capturing the localized stress distribution at the crack front.

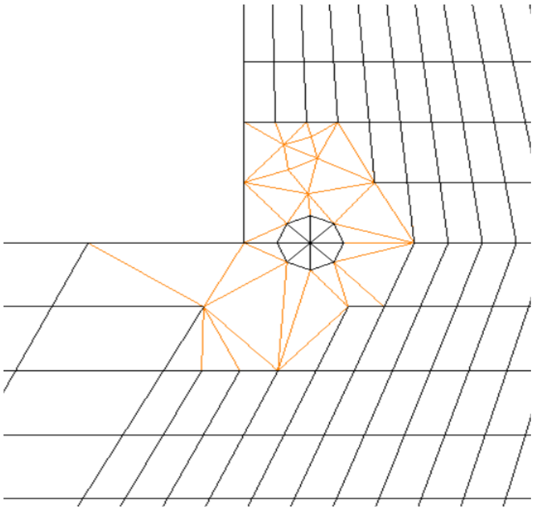

Fig.4 Quarter Point Elements

4.4. FORCES CONSIDERED

The analysis considered key loading conditions including self-weight, full uplift pressure, and hydrostatic pressure corresponding to reservoir levels of 42 m, 47 m, and 52 m. These forces were applied to the finite element model to assess both sliding stability and fracture behavior under varying hydraulic scenarios. To simulate realistic reservoir conditions, hydrostatic pressure was applied along the upstream face of the dam, increasing linearly with depth. Uplift pressure was applied uniformly at the dam–foundation interface, representing full uplift conditions. The dam's self-weight was automatically incorporated through body forces based on the specified material density. The shear friction factor (SFF) was evaluated for each loading case to assess sliding stability, while stress intensity factors (K_I and K_II) were calculated to evaluate fracture risk. By analyzing the variation of stress intensity factors with crack length, critical crack lengths were identified for each reservoir level. The intersection of K_I with the material's fracture toughness threshold (K_IC) indicated potential instability due to crack propagation. These loading scenarios were crucial for evaluating the dam's behavior under both normal and extreme hydraulic conditions, providing key insights into its fracture response and safety margins.

4.5 ANALYSIS

To more accurately reflect real-world variability, a probabilistic analysis was employed. Key parameters—cohesion, internal friction angle, and uplift pressure—were modelled as random variables characterized by appropriate probability distributions based on empirical data and literature. Monte Carlo simulations were conducted to estimate the probability of failure, providing a more comprehensive and statistically robust assessment of the dam's structural reliability under uncertain conditions.

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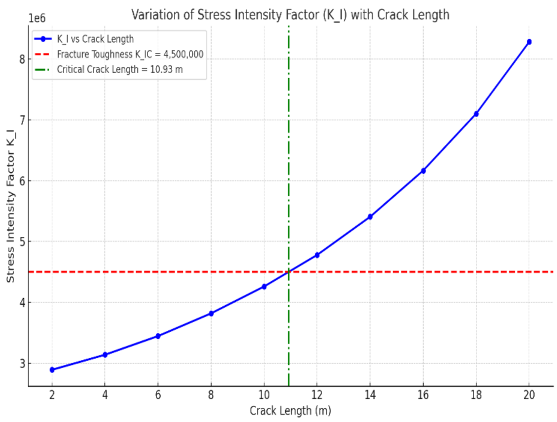
5. PROBABILISTRIC ANALYSIS

To incorporate the inherent variability and uncertainty present in real-world conditions, this study models key input parameters—pool elevation, fracture toughness, cohesion, and angle of internal friction—as random variables. Each parameter is defined by a mean (μ) and standard deviation (σ) based on literature values or empirical data.

- Fracture toughness ($\mu = 4.5 \times 10^7\ N/m^{3/2}$, $\sigma = 0.5 \times 10^7\ N/m^{3/2}$) represents the concrete's resistance to crack propagation.
- Pool elevation (μ = 47 m, σ = 5 m) accounts for the variability in hydrostatic loading due to fluctuating reservoir levels.
- Cohesion ($\mu = 1400\ N/m^2$, $\sigma = 50\ N/m^2$) and angle of internal friction (μ = 45°, σ = 10°) are key shear strength parameters within the Mohr-Coulomb failure criterion.

All variables are assumed to follow a normal distribution, allowing for consistent sampling in the probabilistic framework. Using this data, Monte Carlo simulations were conducted to quantify the impact of parameter uncertainty on structural performance, particularly in terms of sliding stability and fracture behavior. This approach supports a reliability-based evaluation of the dam, offering a more realistic and risk-informed assessment of its structural safety under uncertain loading and material conditions.

6. RESULTS AND DISCUSSION



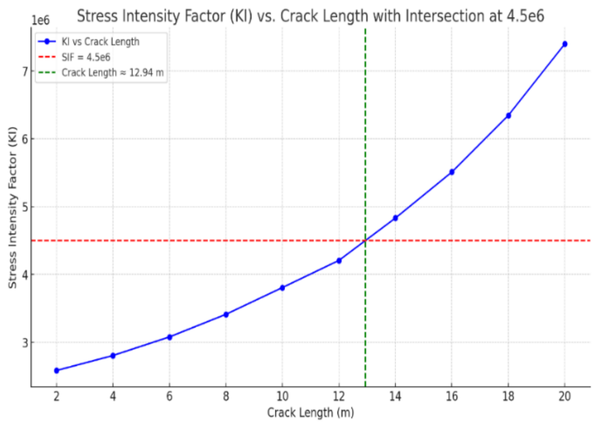


Fig.5 SIF vs Crack length in meters upto full water level **Fig.6** SIF vs Crack length in meters @ 42 m water

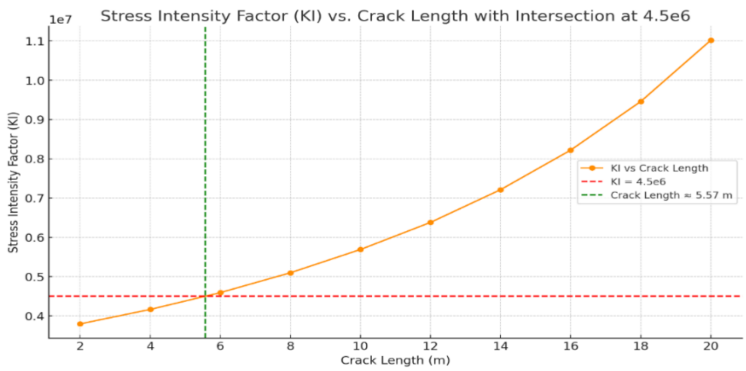


Fig.7 SIF vs Crack length in meters @ 52 m water

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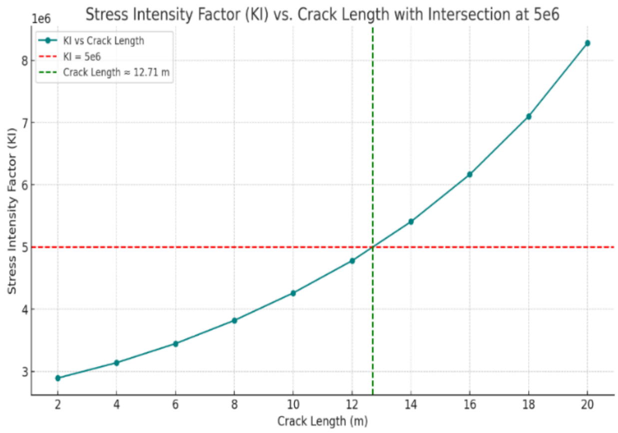
From Fig. 5, the relationship between the stress intensity factor KI and crack length is illustrated, highlighting the fracture behavior of the dam section under study. The curve demonstrates a nonlinear increase in KI with crack length, consistent with fracture mechanics theory, where longer cracks amplify stress concentration at the crack tip. The material's fracture toughness, KIC=4.5×10^{6} N/m$^{3/2}$ is shown as a horizontal threshold line. The intersection between the KI-crack length curve and this threshold defines a critical crack length of approximately 10.93 m. For crack lengths shorter than this critical value, the dam can sustain the existing stress without unstable crack growth. However, beyond this length KI exceeds KIC, indicating the onset of unstable fracture and potential failure. This fracture-based failure criterion emphasizes the importance of monitoring crack development, especially in aging or heavily stressed dams to ensure crack lengths remain below this critical limit for safe operation.

Figure 6 illustrates the variation of the stress intensity factor KI with crack length, emphasizing its intersection with the material's fracture toughness, KIC=4.5×10^{6} N/m$^{3/2}$. The KI curve (blue) increases nonlinearly with crack length, reflecting the rising stress concentration at the crack tip. The red dashed line marks the critical fracture toughness threshold, with the intersection at approximately 12.94 m defining the critical crack length. For crack lengths shorter than 12.94 m, KI<KIC, indicating stable crack behavior. Beyond this length, KI>KIC signaling the onset of unstable crack propagation and heightened risk of sudden structural failure. This finding is essential for establishing maintenance thresholds and preserving structural integrity amid varying loading and crack growth conditions.

Figure 7 illustrates the relationship between the stress intensity factor KI and crack length for the structural material, highlighting the critical condition for crack propagation. The orange curve shows a nonlinear increase in KI with crack length, reflecting the growing stress concentration at the crack tip. The red dashed line represents the material's fracture toughness, KIC=4.5×10^{6} N/m$^{3/2}$, beyond which the crack becomes unstable. The intersection of the KI curve with the KIC line occurs at a crack length of approximately 5.57 m, indicated by the green vertical dashed line. This defines the critical crack length, below which cracks remain stable and above which unstable fracture propagation is likely. The earlier intersection compared to other scenarios suggests a more vulnerable structural state where smaller cracks can lead to failure, emphasizing the importance of rigorous crack length monitoring and preventive maintenance.

Fig.8 SIF vs Crack length & Intersection @5x10^{6}



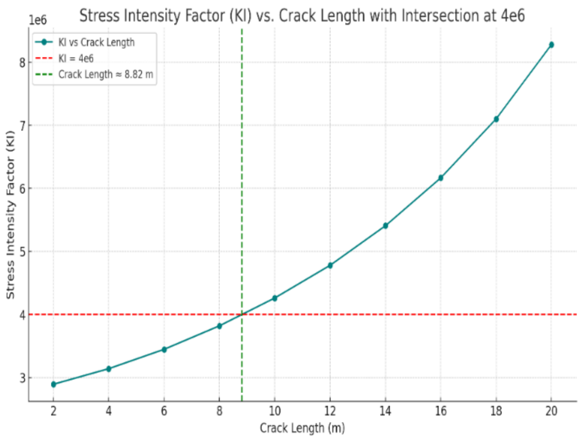


Fig.9 SIF vs Crack length & Intersection@4x10^{6}

at full water level | at full water level

From Figure 8, the graph depicts the variation of the stress intensity factor KI with crack length, emphasizing the critical crack length where failure may initiate. The teal curve shows a nonlinear increase in KI as the crack length grows, reflecting the increasing stress concentration at the crack tip. The red dashed line represents the material's fracture toughness, KIC=5.0×10^{6} N/m$^{3/2}$. The intersection of this line with the KI curve defines the critical crack length, approximately 12.71 m, marked by the green vertical dashed line. Crack lengths shorter than 12.71 m indicate stable conditions under the given loading, while cracks exceeding this length cause KI to surpass KIC, leading to unstable crack propagation and potential structural failure. This analysis provides essential insights for establishing safety thresholds and guiding maintenance strategies in fracture-sensitive structures.

Figure 9 illustrates the relationship between the stress intensity factor KI and crack length, highlighting the fracture threshold at a fracture toughness KIC=4.0×10^6 N/$m^{3/2}$, marked by the red dashed line. The teal curve shows a nonlinear increase of KI with crack length, consistent with the stress concentration behavior near the crack tip in fracture mechanics. The intersection between the KI curve and KIC occurs at approximately 8.82 m, indicated by the green vertical dashed line, representing the critical crack length. Cracks shorter than this value remain stable, whereas cracks exceeding 8.82 m led to KI>KIC, initiating unstable crack propagation. This critical length serves as a key design and inspection criterion, beyond which the dam may be at risk of rapid fracture and potential failure.

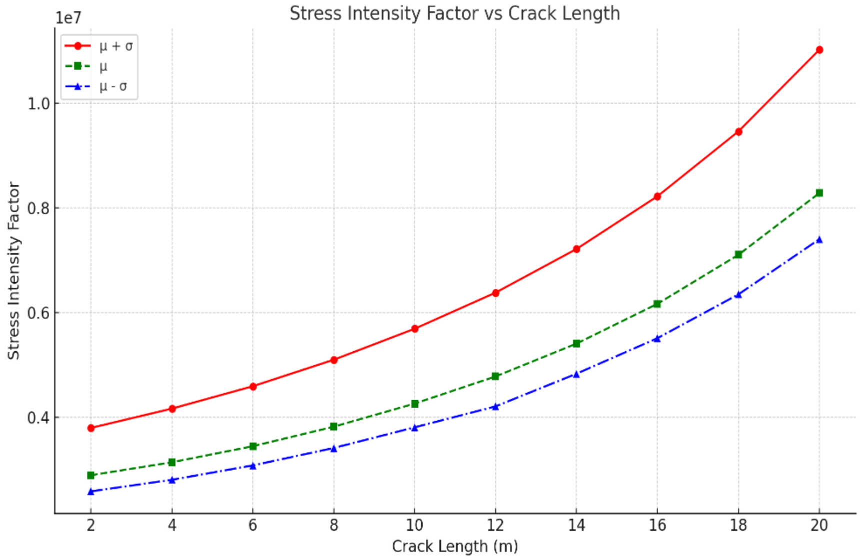


Fig.10 SIF Vs Crack length at all the three water levels

Figure 10 illustrates the probabilistic variation of the stress intensity factor KI with crack length, incorporating uncertainty through mean and standard deviation values. The green dashed line represents the mean KI at different crack lengths, while the red and blue curves depict one standard deviation above (μ+σ) and below (μ−σ) the mean, respectively, reflecting variability in input parameters such as loading and material properties. All three curves show a nonlinear increase in KI with crack length, emphasizing that longer cracks lead to significantly higher stress intensities. The shaded area between the red and blue curves represents the uncertainty envelope of the stress intensity factor, providing a visual tool crucial for reliability-based fracture analysis. This probabilistic representation allows engineers to better assess fracture risks under uncertainty and establish safety margins relative to the material’s fracture toughness.

7. PROBABILISTIC ANALYSIS DATA

Table 1. Material Properties of the Dam

RANDOM VARIABLE	MEAN (μ)	STANDARD DEVIATION (σ)
Pool Elevation in m	47	5
Fracture Toughness in N/$m^{3/2}$	4.5×10^7	0.5×10^7
Cohesion in N/m^2	1400	50
Angle of internal friction in degrees	45	10

8. SFF CALCULATIONS

Table 2. Tabulation of Shear Friction Factor (SFF) for Different Mean and Standard Deviation Values

RUN	H, m	K_IC, $N/m^{3/2}$	C, N/m^2	θ, degrees	Crack Length, m	Uncracked Length, m	SFF	Σm
1	47	$4.5*10^7$	1400	45	10.93	29.07	5.27	-
2	42	$4.5*10^7$	1400	45	12.94	27.06	6.27	2.14
	52	$4.5*10^7$	1400	45	5.57	34.43	1.99	
3	47	$4.0*10^7$	1400	45	8.82	31.18	5.5	0.25
	47	$5*10^7$	1400	45	12.71	27.29	5	
4	47	$4.5*10^7$	1350	45	10.93	29.07	5.1	0.13
	47	$4.5*10^7$	1450	45	10.93	29.07	5.36	
5	47	$4.5*10^7$	1400	35	10.93	29.07	0.91	0.54
	47	$4.5*10^7$	1400	55	10.93	29.07	1.99	

$$SFF = \frac{cL + \Sigma V \tan\theta}{\Sigma H}$$

where, c is the cohesive strength; L is the uncracked ligament length; ΣV is the resultant vertical force; **θ** is the angle of internal friction and ΣH is the resultant horizontal force.

9. CONCLUSIONS

1. The shear friction factor of safety effectively evaluates the sliding stability of the dam.
2. Shear friction factor of safety is used to assess the sliding stability of the dam.
3. The factor of safety is influenced by parameters including the uncracked interface length, internal friction angle, cohesion, normal force, and shear force.
4. Fracture toughness exhibits minimal sensitivity to changes in the shear friction factor of safety.
5. Cohesion remains largely unaffected by variations in the shear friction factor of safety.
6. The angle of internal friction and pool elevation significantly impact the shear friction factor of safety, exhibiting high sensitivity in the analysis.

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