

## IMPACT OF VARIATION IN SEISMIC PARAMETERS ON THE BASE WIDTH OF DAM BODY

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**ABSTRACT:** Large concrete gravity dams are normally designed for seismic combination of 100% horizontal component (H) with 0% vertical component (V). This research provides the guidelines for use of realistic seismic load combinations in the design of large concrete dams. The current study involves the impact of variation of seismic parameters on the base width of the dam. In addition to 100% H with 0% V, 100% H with 30% V and 100% H with 67% V and vice versa of all three (03) combinations are also considered. Total six (06) seismic load combinations have been considered to analyse the dam body using rigid body analysis approach using CADAM software. Three (03) dam base widths are studied for six (06) horizontal and vertical seismic combinations. The analysis results showed that increase in dam base width of 20m (Study-I) was okay for seismic combination EQ-(1,2 & 3,4) by taking some extra measures. Increase in dam base width of 30m (Study-II) was okay for seismic combination EQ-(1,2 & 3,4) without taking any extra measures. Whereas, increase in dam base width of 40m (Study-III) was okay for all seismic combinations EQ-(1,2, 3,4, 5,6).

**Keywords:** Concrete gravity dams, Horizontal & vertical earthquake component, Stability, CADAM.

### 1. INTRODUCTION

Concrete gravity dams are the most important structures constructed to preserve the large quantities of water. The safety of a dam during earthquake ground motion must be carefully verified. Failing to do so will have disastrous consequences in the form of sudden release of the stored water. Recently a large number of concrete dams have been constructed and more are expected to be built on high seismic regions and are expected to face major earthquake events during their design life. Because of life damage to millions of people living in the floodplains downstream of these dams, their prediction under dynamic solicitations become an important aspect [1]. The ability to evaluate the effects of earthquake ground motion on concrete dams is essential in order to assess the safety of existing dams and to evaluate the proposed designs for new dams to be constructed [2]. One potential failure mode of concrete gravity dam during an earthquake is extensive cracking and deformation in the zone between the base of the dam and the foundation rock (dam foundation interaction). Failure of the zone can result in relative displacement between the dam and the foundation rock, a displacement which is often called a sliding displacement. The stability assessment of an earth dam in case of static loading is quite straightforward, and the methodology is well recognized and accepted [4]. However, static stability criterion is not appropriate for evaluating the base sliding displacement of a dam due to oscillatory and transient ground motion [3]. The dams can also be

affected by dynamic loading coming from natural earthquakes or induced by mining operations. To account for the dynamics of dam systems various analyses of the base sliding response have been performed. Leger and Katsouli (1989) studied the stability of concrete gravity dams using a finite element formulation for the dam, water, and foundation rock, and gap-friction elements to model the sliding at the base interface [5]. Ridha and Ikram (2014) studied the stability analysis of dam foundations and found that soil liquefaction has been the cause of most geotechnical hazards during earthquake events [6]. However, most of the previous studies have been performed considering only the horizontal (H) component of seismic forces. In process of generating synthetic accelerograms matching target spectra for the purpose of evaluating the seismic safety of structures through time-history analyses, the problem of incorporating vertical (V) components in a simple and realistic way arises. Also, the occurrence of the maximum responses for each of the components must be evaluated realistically to avoid too severe or insufficient correlation between these components [7]. Canadian Dam Safety Association (CDSA) guidelines commentary state that "It is a good practice to consider the impact of concurrent H & V components of seismic input on the concrete structures, though not necessarily to include both in the calculation of sliding safety factors" [8]. U.S. Army Corps of Engineers (USACE) guidelines for gravity dams state that "earthquake loading should be checked for horizontal earthquake acceleration and, if included in the stress analysis, vertical

acceleration” [9]. Federal Energy Regulatory Commission (FERC) mentions that vertical accelerations must be considered for buttress dams [10]. Vertical accelerations alter the resistance of load-carrying systems designed to counter horizontally induced forces in many structures e.g. shear strength of reinforced concrete columns etc. International Committee on Large Dams (ICOLD) recommends that peak V accelerations be generally assumed equal to 2/3 of the peak H accelerations at sites close to the assumed epicenter [11]. The rule of seismic load combination (100% H + 0% V) component is commonly used in practice and yield a good approximation of the minimum factor of safety against sliding for large concrete gravity dams. However, the effect of an increase in vertical component on dam geometry is still not studied much. Some studies recommend that load combination consisting of the vertical peak ground acceleration (PGA) applied simultaneously with 30% of the horizontal PGA was more critical than the usual combination (100% H + 30% V) and represented more realistically the maximum response predicted from the time-history analyses.

This research involves the variation of seismic parameters to study the impact of variation on dam geometry. In addition to 100% horizontal component with 0% vertical component, 100% horizontal component with 30% vertical component and 100% horizontal component with 67% vertical component and vice versa of all three (03) combinations are also considered. The seismic load was applied according to ICOLD (2016) latest guidelines for safety evaluation earthquake (SEE) corresponding to 84th percentile level [11]. Finally, the effect of variation in seismic parameters on the base width of the dam is studied and discussed.

## 2. DESIGN PARAMETERS FOR RIGID BODY ANALYSIS

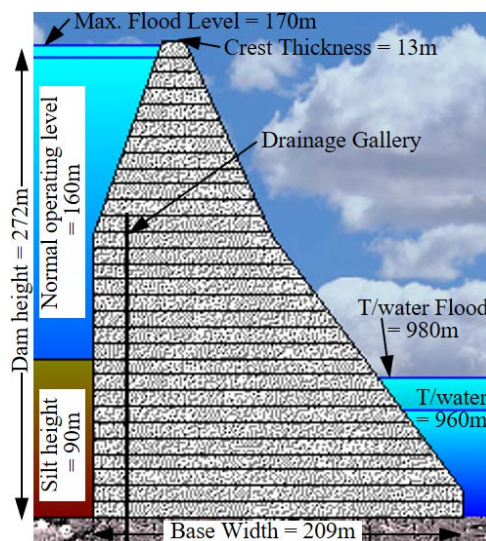


Fig.1 Basic dam geometry

Stability & safety of concrete gravity dam has been studied using rigid body analysis approach using CADAM software, primarily designed to provide support for learning the principles of structural stability evaluation of gravity dams [12]. The basic dam geometry considered for analysis is shown in Fig. 1. In the design of concrete gravity dams, it is essential to determine the loads required in the stability analysis. The following are the forces used in the rigid body analysis of dam geometry.

### 2.1 Dead Load

The dead load includes the self-weight of the dam body and dam accessories. The unit mass of concrete is taken as 25.5 kN/m<sup>3</sup>.

### 2.2 Hydrostatic Pressure

Hydrostatic pressure acts on both upstream and downstream face from reservoir water level and tailwater level.

$$P = W_0 h \quad (1)$$

Where, P = Hydrostatic pressure (kN/m<sup>2</sup>)

W<sub>0</sub> = Unit weight of water (9.81 kN/m<sup>3</sup>)

H = Water depth at reservoir and d/s of dam (m)

### 2.3 Hydrodynamic Pressure

The basic Westergaard [13] added mass formulation for vertical upstream faces assumes earthquake acceleration normal to the dam face.

### 2.4 Silt Pressure

Silt pressures have been considered in the design. Method for computing the silt pressures is discussed below:

$$P_e = C_e W_1 d \quad (2)$$

Where, C<sub>e</sub> = Silt pressure coefficient

P<sub>e</sub> = H<sub>z</sub>. silt pressure acting u/s dam face (kN/m<sup>2</sup>)

W<sub>1</sub> = Submerged unit weight of silt

### 2.5 Uplift Pressure

Uplift is applied as shown in Fig. 2 & 3 as per Engineering Manual USACE EM1110-2-2200 [9].

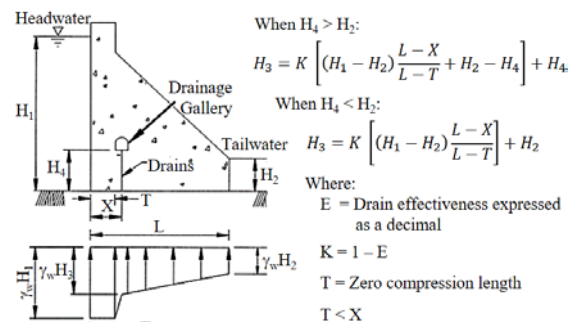


Fig.2 Uplift distribution with drainage gallery

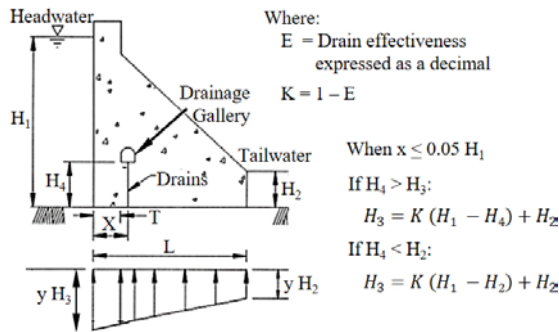


Fig.3 Uplift distribution with foundation drains

## 2.6 Seismic Static Load

The seismic static load is calculated by the following relation.

$$I = W k \quad (3)$$

Where,

$I$  = Inertial force by EQ on dam body ( $\text{kN/m}^3$ )

$W$  = Dead load of dam concrete ( $\text{kN}$ )

$k$  = Seismic coefficient

## 2.7 Load Combinations

Load combinations employed for rigid-body analysis of the dam is listed in Table 1.

Table 1 Load combinations

Load class	Load combination name	Symbol	Self wt.	Static Load			Seismic Load SEE 0.57g
				Hydrostatic Max. storage	Flood	Silt	
Usual	Long term Max. Level	U	✓	✓	-	✓	-
Unusual	Long-term Safety-Flood	US	✓	-	✓	✓	-
Extreme	SEE – Usual Max. level	E	✓	✓		✓	✓

## 2.8 Stability Requirements

The dam stability was checked as per the stability requirements listed in Table 2.

Table 2 Stability requirements

Loading Cases	Load Combination name	Results	
		Min. Sliding FOS	Min. Overturning (O/T) FOS
Usual	Long term max. level	> 3.00	> 2.00
Unusual	Long-term safety check-flood	> 2.50	> 1.50
Extreme-1	Pseudo-static	> 1.00	> 1.00
Extreme-2	Pseudo-dynamic	> 1.00	> 1.00

## 3. SEISMIC ANALYSES

Two types of analyses namely Pseudo-static & Pseudo-dynamic have been performed in this study.

### 3.1 Pseudo-static Seismic Analysis (Extreme-1)

In a pseudo-static seismic analysis, the inertia forces induced by the earthquake are computed from the product of the mass and the acceleration. The dynamic amplification of inertia forces along the height of the dam due to its flexibility is neglected. The dam-foundation-reservoir system is thus considered as a rigid system with a period of vibration equal to zero.

### 3.2 Pseudo-dynamic Seismic Analysis (Extreme-2)

A pseudo-dynamic seismic analysis is based on the response spectrum method and is conceptually similar to a pseudo-static analysis except that it recognizes the dynamic amplification of the inertia forces along with the height of the dam. However, the oscillatory nature of the amplified inertia forces is not considered. That is the stress and stability analyses are performed with the inertia forces continuously applied in the same direction.

### 3.3 Seismic Loads

The seismic load was applied as per ICOLD guidelines for safety evaluation earthquake (SEE) corresponding to 84th percentile level [11]. The peak ground acceleration ( $\text{PGA}=0.57\text{g}$ ) is calculated from TABAS response spectrum, shown in Fig. 4.

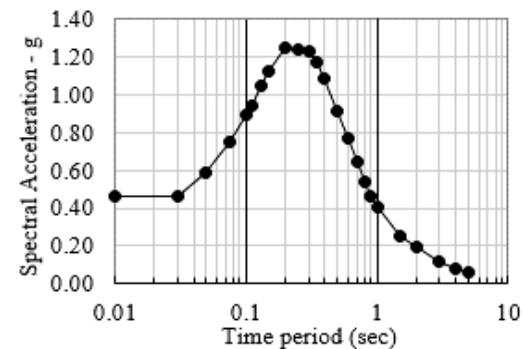


Fig.4 TABAS seismic response spectra

### 3.4 Analysis Assumptions

Following assumptions are made in the assessment of dam stability:

- Seepage has been assumed to be unchanged under seismic conditions.
- In cases where the desired factor of safety was not achieved through pseudo-static analysis, pseudo-dynamic approach was followed being relatively more accurate.
- Peak ground acceleration in the horizontal direction is  $0.57\text{g}$  while peak ground acceleration in the vertical direction has been assumed to be  $2/3$  of peak ground acceleration in the horizontal direction.
- Sustained acceleration has been assumed to be

- 2/3 of peak ground acceleration (0.57g).
- v. Stability analysis has been carried out for various combinations of horizontal sustained ground acceleration HSGA ( $0.38g = 2/3$  of  $0.57g$ ) and vertical sustained ground acceleration VSGA ( $0.253g = 2/3$  of HSGA).

### 3.5 Seismic Load Combinations

Following six (06) combinations of HSGA and VSGA have been used to study the stability of dam,

- EQ-1: 100% HSGA ( $0.38g$ ) + 0% VSGA  
 EQ-2: 0% HSGA + 100% VSGA ( $0.253g$ )  
 EQ-3: 100% HSGA ( $0.38g$ ) + 30% VSGA ( $0.076g$ )  
 EQ-4: 30% HSGA ( $0.114g$ ) + 100% VSGA ( $0.253g$ )  
 EQ-5: 100% HSGA ( $0.38g$ ) + 67% VSGA ( $0.17g$ )  
 EQ-6: 67% HSGA ( $0.253g$ ) + 100% VSGA ( $0.253g$ )

## 4. ANALYSIS RESULTS

The legends used describing the test results in Figures are shown below,

- Peak Sliding Factor of Safety (FOS)
- Overturning Factor of Safety towards Upstream (U/S)
- ◆ Overturning Factor of Safety towards Downstream (D/S)
- - - Min. Factor of Safety against Sliding for Usual loading Case (3.0)
- - - Min. Factor of Safety against Sliding for Unusual loading Case (2.5)
- - - Min. Factor of Safety against Overturning for Usual loading Case (2.0)
- - - Min. Factor of Safety against Overturning for Unusual loading Case (1.5)
- - - Min. Factor of Safety against Sliding and Overturning for Extreme-1 & 2 loading Case (1.0)

### 4.1 Analysis Results with Basic Dam Geometry

The basic dam geometry with a base width of 209m as shown in Fig. 1 was first analyzed for seismic load combinations EQ-(1,2 & 3). The analysis results are shown in Fig. 5 to 7.

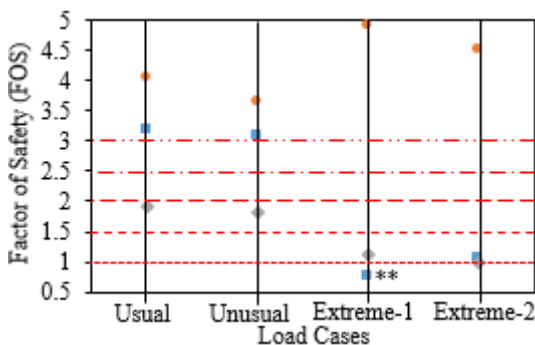


Fig. 5 FOS under different load cases for EQ-1

Fig. 5 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-1.

\*\*Sliding stability factor achieved for load case

Extreme-1 is 0.77 which is less than 1.00. A safety factor of less than 1.00 during Extreme-1 obtained through rigid body pseudo-static analysis does not mean that the dam is unsafe. It requires that pseudo-dynamic analysis should be performed to verify the stability of the dam. Results of pseudo-dynamic analysis in the above Figure show a sliding safety factor of more than 1.00.

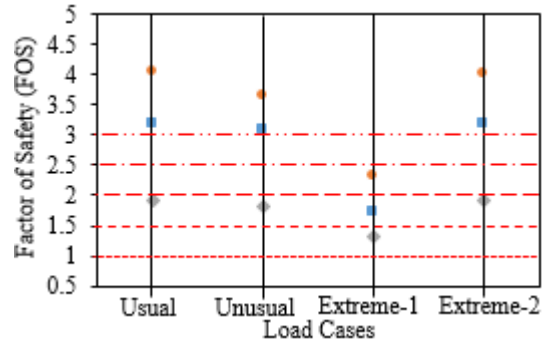


Fig. 6. FOS under different load cases for EQ-2

Fig. 6 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-2.

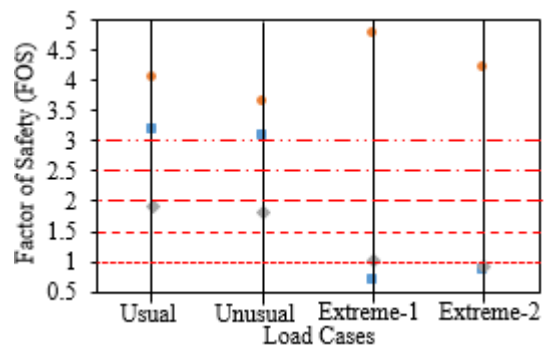


Fig. 7 FOS under different load cases for EQ-3

Fig. 7 shows that factor of safety (FOS) in sliding and overturning are not satisfied. The analysis results show that the basic dam geometry is okay for seismic combinations EQ-(1,2). Whereas the factors of safety for sliding and overturning are not satisfied with EQ-3. This shows that the basic dam geometry was is not okay for higher VSGA component, therefore, further analyses are performed by increasing the dam base width.

### 4.2 Analysis Results By Increasing the Dam Base Width Of 20m

The stability of the dam can be improved by providing the base key. However, due to limitation of software the base key cannot be modeled. Therefore, this research was kept limited to change in base width of dam body only. In Study-I, the dam was analyzed by increasing base width of 20m for all six (06) seismic load combinations. The dam geometry with increased base width is shown in Fig.8. The analysis results are shown in Fig. 9 to 14.



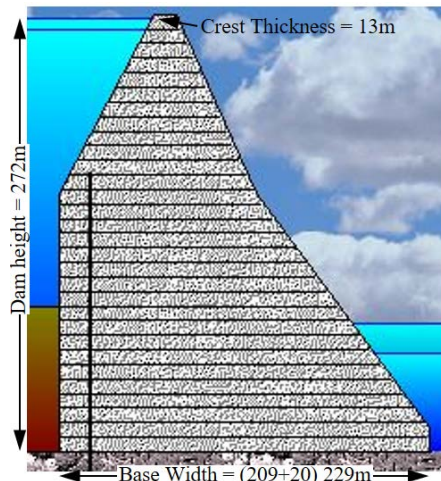


Fig.8 Dam geometry with inc. base width of 20m

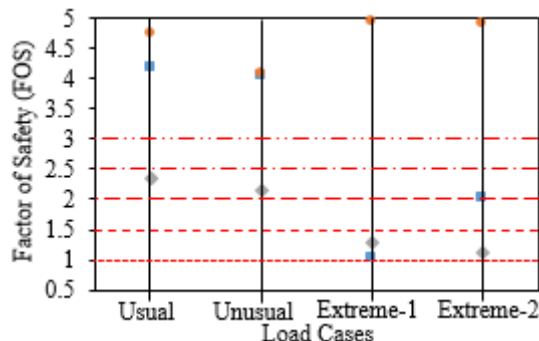


Fig. 9. FOS under different load cases for EQ-1

Fig. 9 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-1.

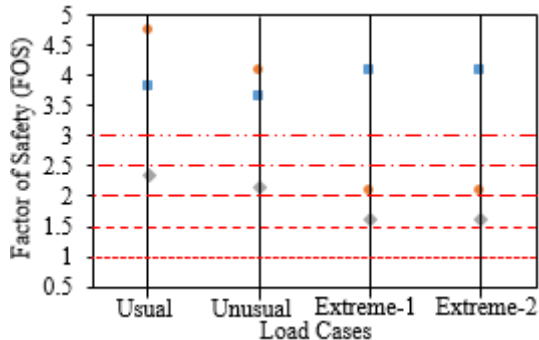


Fig. 10. FOS under different load cases for EQ-2

Fig. 10 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-2.

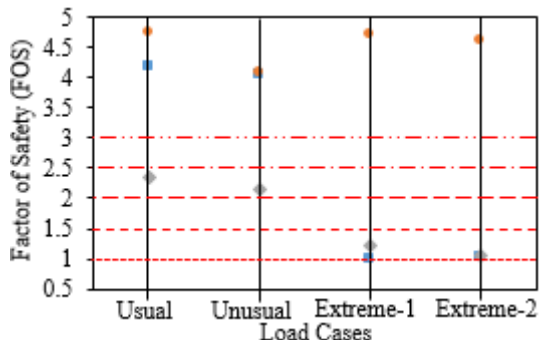


Fig. 11. FOS under different load cases for EQ-3

Fig. 11 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-3.

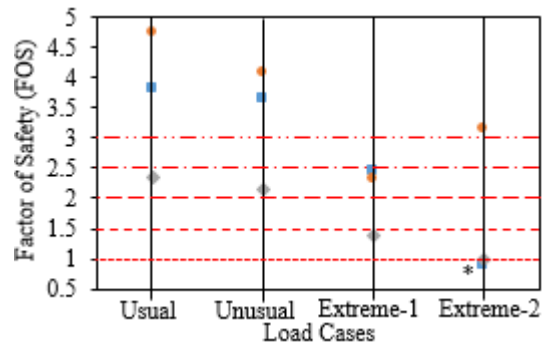


Fig. 12. FOS under different load cases for EQ-4

Fig. 12 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-4.

\*Sliding Factor of Safety can be achieved more than 1.00 by considering the effect of normal stress or increasing cohesion. This can be done by providing the proper bedding material to ensure concrete monolithic behavior at lift joint locations.

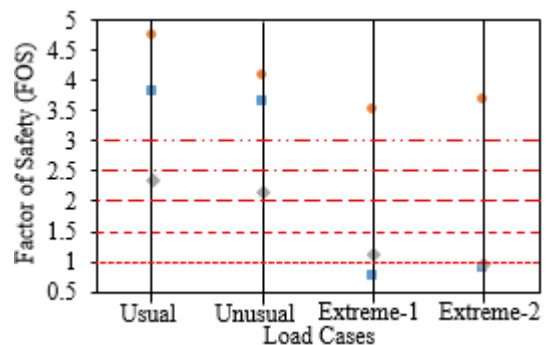


Fig. 13. FOS under different load cases for EQ-5

Fig. 13 shows that factor of safety (FOS) in sliding and overturning are not satisfied for EQ-5.

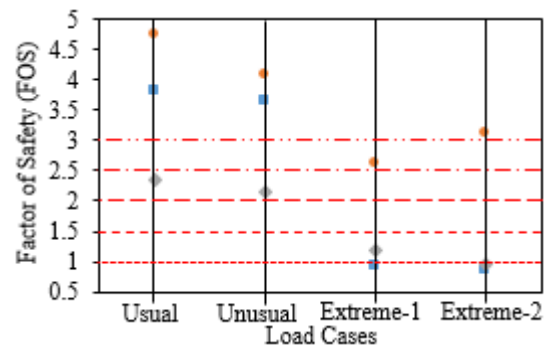


Fig. 14. FOS under different load cases for EQ-6

Fig. 14 shows that factor of safety (FOS) in sliding and overturning are not satisfied for EQ-6. As per stability evaluation, the increase in base width of 20m is okay for seismic combination EQ-(1,2 & 3,4) by taking some extra measures. However, the base width of dam needs to be further increased for seismic combinations EQ-(5,6).

#### 4.3 Analysis Results by Increasing the Dam Base Width of 30m

In Study-II, the dam was analyzed by increasing base width of 30m for all six (06) seismic load combinations. The dam geometry with increased base width is shown in Fig.15. The analysis results are shown in Fig. 16 to 21.

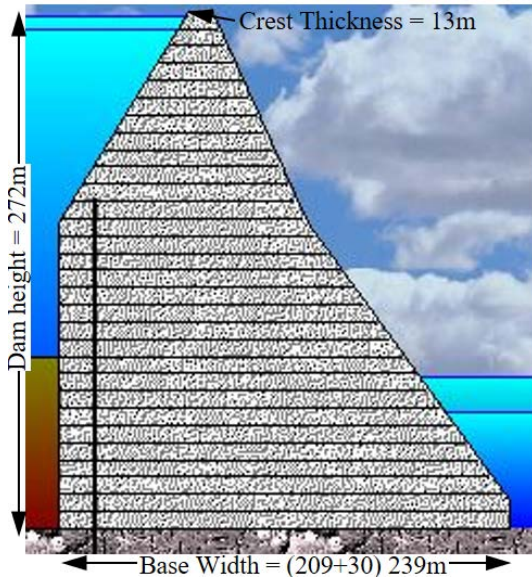


Fig.15 Dam geometry with inc. base width of 30m

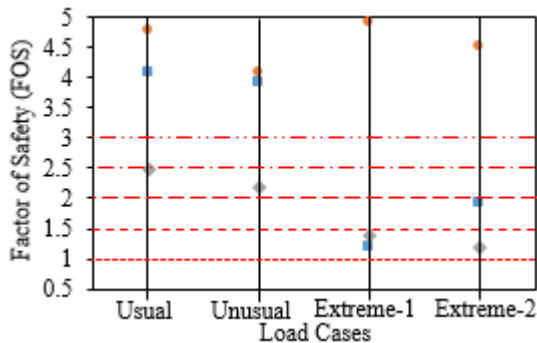


Fig. 16. FOS under different load cases for EQ-1

Fig. 16 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-1.

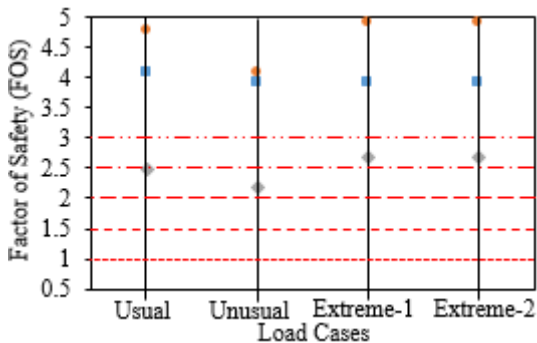


Fig. 17. FOS under different load cases for EQ-2

Fig. 17 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-2.

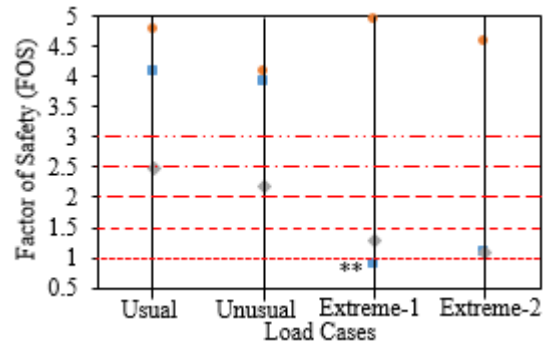


Fig. 18. FOS under different load cases for EQ-3

Fig. 18 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-3.

\*\*Sliding stability factor achieved for load case Extreme-1 is 0.89 which is less than 1.00. A safety factor of less than 1.00 during Extreme-1 obtained through rigid body pseudo-static analysis does not mean that dam is unsafe. It requires that pseudo-dynamic analysis should be performed to verify the stability of dam. Results of pseudo-dynamic analysis in the above Figure show a sliding safety factor more than 1.00.

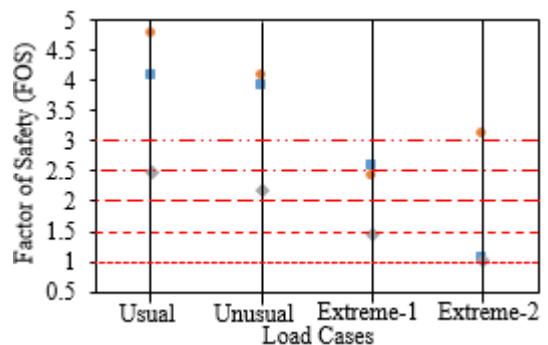


Fig. 19. FOS under different load cases for EQ-4

Fig. 19 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-4.

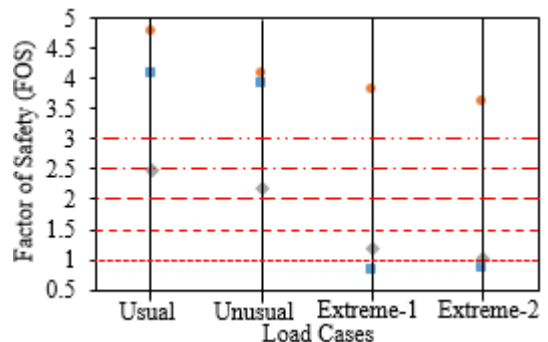


Fig. 20. FOS under different load cases for EQ-5

Fig. 20 shows that factor of safety (FOS) in sliding and overturning are not satisfied for EQ-5.

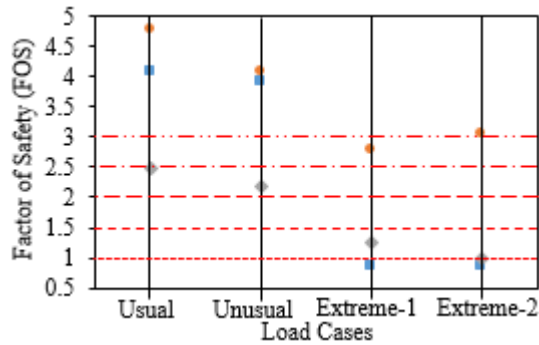


Fig. 21. FOS under different load cases for EQ-6

Fig. 21 shows that factor of safety (FOS) in sliding and overturning are not satisfied for EQ-6. As per stability evaluation, the increase in base width of 30m is okay for seismic combination EQ-(1,2 & 3,4) without taking any extra measures. However, base width of dam needs to be further increased for seismic combinations EQ-(5,6).

#### 4.5 Analysis Results by Increasing the Dam Base Width of 40m

In Study-III, the dam was analyzed by increasing base width of 40m for all six (06) seismic load combinations. The dam geometry with increased base width is shown in Fig.22. The analysis results are shown in Fig. 23 to 28.

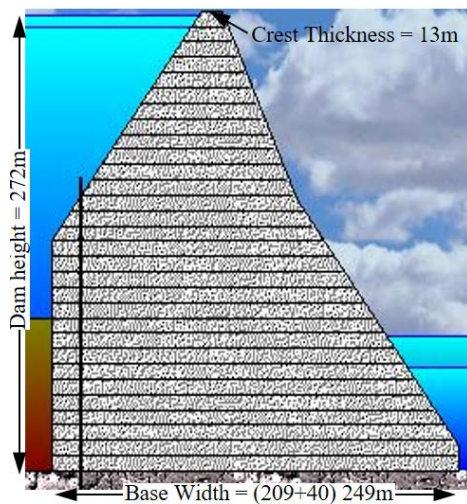


Fig.22 Dam geometry with inc. base width of 40m

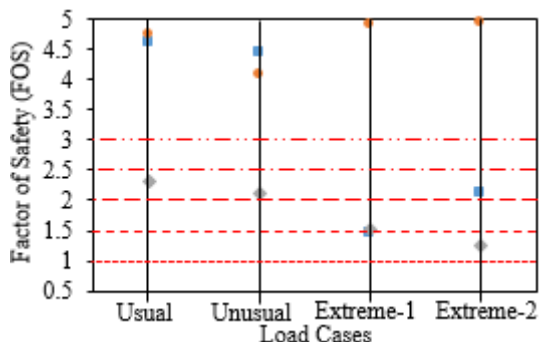


Fig. 23. FOS under different load cases for EQ-1

Fig. 23 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-1.

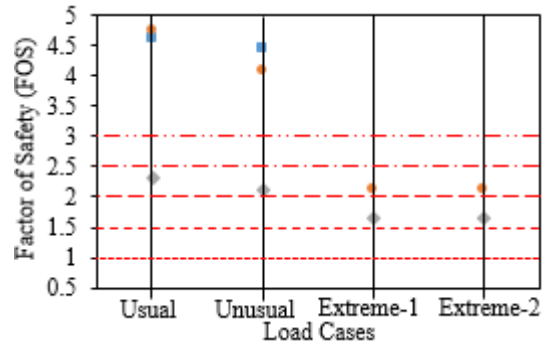


Fig. 24. FOS under different load cases for EQ-2

Fig. 24 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-2.

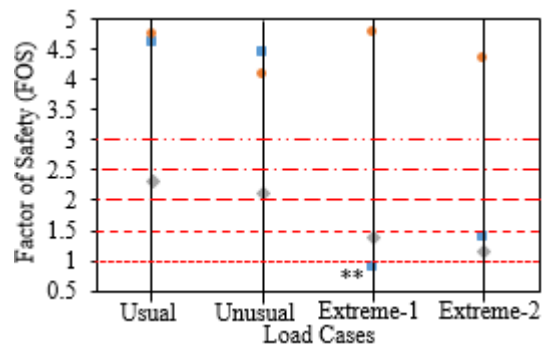


Fig. 25. FOS under different load cases for EQ-3

Fig. 25 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-3.

\*\*Sliding stability factor achieved for load case Extreme-1 is 0.97 which is less than 1.00. A safety factor of less than 1.00 during Extreme-1 obtained through rigid body pseudo-static analysis does not mean that dam is unsafe. It requires that pseudo-dynamic analysis should be performed to verify the stability of dam. Results of pseudo-dynamic analysis in the above Fig. show FOS more than 1.00.

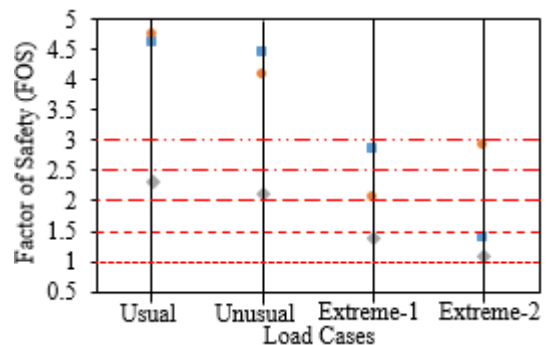


Fig. 26. FOS under different load cases for EQ-4

Fig. 26 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-4.



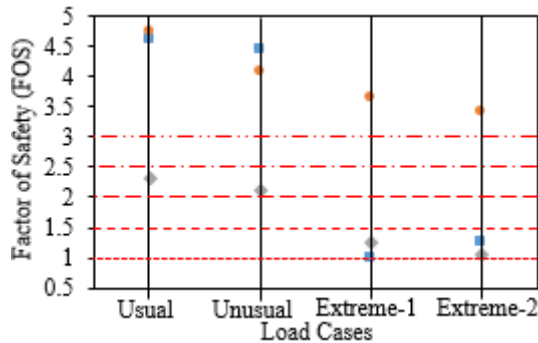


Fig. 27. FOS under different load cases for EQ-5

Fig. 27 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-5.

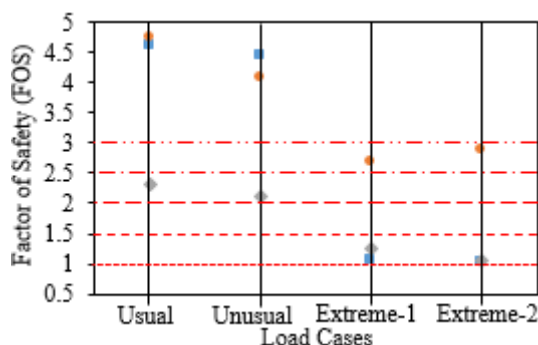


Fig. 28. FOS under different load cases for EQ-6

Fig. 28 shows that factor of safety (FOS) in sliding and overturning are satisfied for EQ-6. The results of the stability evaluation study also shows that the increase in base width of 40m is okay for all six (6) seismic combinations.

#### 4.6 Discussion

The analysis results show that the basic dam geometry with base width of 209m was not okay for EQ-(3,4 & 5,6). The Seismic combination EQ-(3,4) 100% HSGA+30%VSGA and vice versa is more critical and represents more realistic response predicted from response spectrum analysis. The same combination is commonly used in design of various concrete structures. An increase in base width of 30m showed satisfactory results for factor of safety against sliding and overturning without taking any extra measures. However, considering EQ-(3,4) increased the base width of dam body by 14.35%. EQ-(5,6) is likely to consider on the structures which need to be constructed near the epicentre. Taking the effect of EQ-(5,6) in stability analysis increased the dam base width by 19.15%.

#### 5. CONCLUSION

The impact of variation in seismic parameters have been studied on the base width of dam body. The results demonstrated that variation in horizontal and vertical seismic components have

significant impact on the base width of dam body. According to analysis, increase in base width of 30m is adequate for realistic and predicted seismic load combinations with reasonable factor of safety.

#### 6. ACKNOWLEDGMENTS

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