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Effects of safety factors on the deflections in a concrete gravity dam

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The aim of this study was to determine the effects of safety factors on the deflections of a concrete gravity dam. Overturning and sliding safety factors for a selected concrete gravity dam with base width *b* and height *H* were specified, using pseudo analysis for the *b/H* ratios and earthquake acceleration values between 0.1 g and 0.4 g. Deflection values for specified parameters were obtained from the structural analysis program *SAP2000*. Deflection safety factor curves, determined from the *b/H* ratios, were obtained, as well as the earthquake acceleration values. The results of this analysis showed that safety factors reduced while strain values increased.

INTRODUCTION

Rapid developments in computer technology over the last few decades have made it possible to apply advanced structural analysis techniques to predict the behaviour, and therefore the safety, of concrete dams during earthquakes. However, many uncertainties remain in predicting the behaviour of dams during severe earthquakes. Amongst these are crack formation and propagation in the concrete body of the dam, nonlinear behaviour of the foundations, and the interaction of the water body in the reservoir with the dam structure (Ghrib *et al* 1997; Chopra 1998; Kreuzer 2000). Static and dynamic approaches, and linear or nonlinear finite element models have been combined with statistical methods in studies of stability analysis to evaluate the safety of dams (Hall 1998; Tinawi *et al* 2000; Leclerc *et al* 2003). A further issue is determining the most appropriate definition for seismic input, as this has a very significant effect on the seismic design and seismic safety evaluation of dams. Many uncertainties still exist in this regard, but progress has been made in defining the maximum credible earthquake (MCE), maximum design earthquake (MDE) and safety evaluation earthquake (SEE). With more seismic records available now, the effects of the very short duration peak ground acceleration (PGA) (which may be from 0.5 g to 1.0 g, or even higher in severe earthquakes), and the sustained effective seismic acceleration (which could be about 0.5 – 0.67 of PGA), are now better understood. An indirect result of seismic activity is the effect of increased seepage on uplift forces, due to increasing pressure acting through cracks in the concrete body or under the foundations. This must be taken into account in the stability analysis for seismic design, as it may have a very significant effect on the safety of the dam. Opan and Temiz (2007) reported that safety factors decrease with earthquake acceleration and pressure reduction.

The aim of this study was to determine the relationship between the deflections and safety factors at topping, and at toe, for a concrete gravity dam (CGD) during an earthquake. A CGD with base width *b* and height *H* was specified, using pseudo analysis for the *b/H* ratio and earthquake acceleration values between 0.1 g and 0.4 g. Deflection values for specified parameters were obtained from the structural analysis program *SAP2000*. Graphs were plotted for the selected dam from the results of the *b/H* ratio and earthquake acceleration, and the deflection and safety factors were evaluated.

FORCES ON A CONCRETE GRAVITY DAM DURING AN EARTHQUAKE

The forces on a CGD under earthquake conditions are the horizontal hydrostatic load, the horizontal hydrodynamic load, the vertical pore water pressure force, the weight of the CGD and the earthquake force due to the CGD weight. These forces are shown in Figure 1, where F_E is the horizontal hydrodynamic load, F_x is the horizontal hydrostatic load, F_u is the vertical pore water pressure load, W is the weight of the concrete dam, W_E is the concrete dam weight and earthquake load on the horizontal direction, and b, c, h and H are the parameters of the concrete dam.

The horizontal hydrostatic load is:

$$F_x = \frac{1}{2}\gamma_W h^2 \tag{1}$$

The horizontal hydrodynamic load is:

$$F_E = a\alpha\gamma_W h^2 \tag{2}$$

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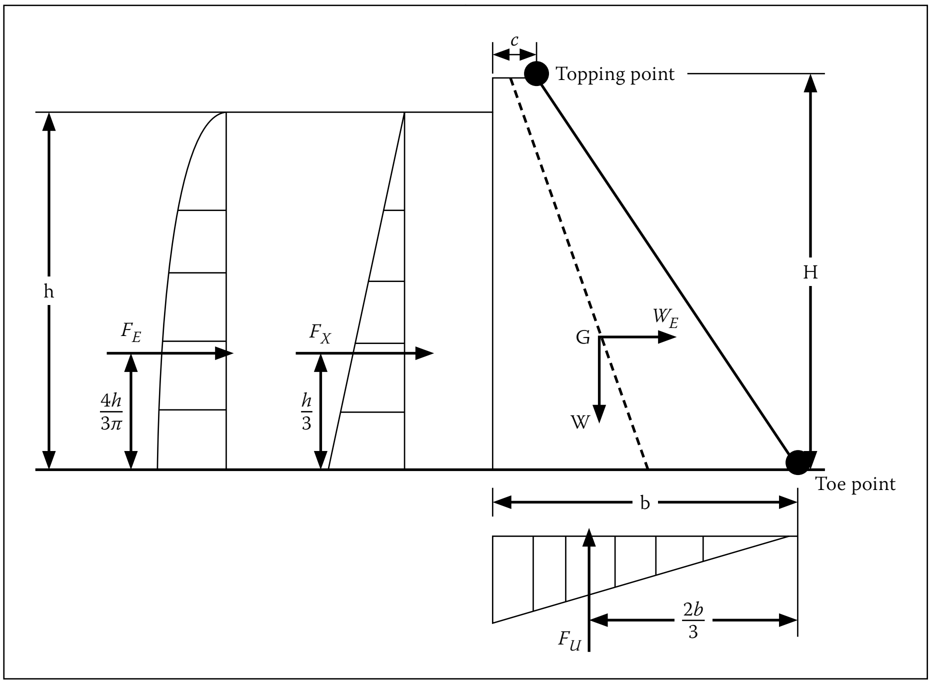

Figure 1 The forces on a concrete gravity dam under earthquake conditions

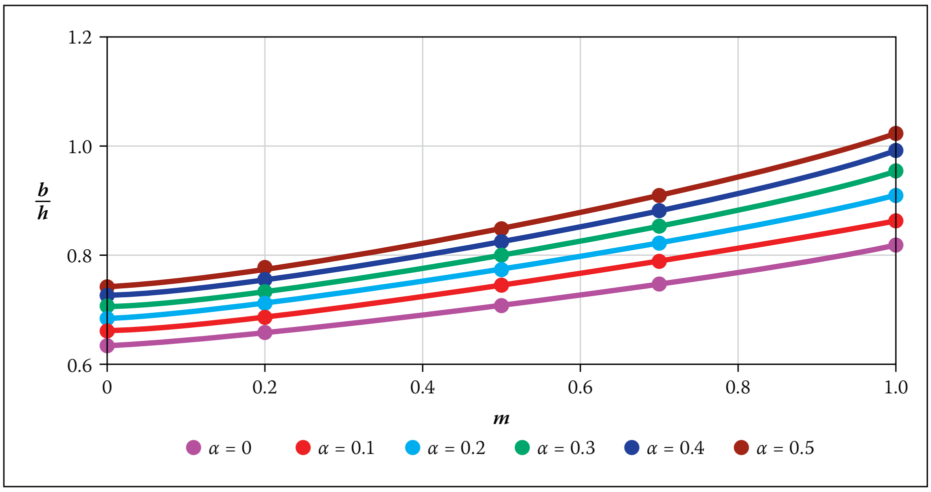

Figure 2 Relationship between the b/h ratio and m and α (Opan & Temiz 2007)

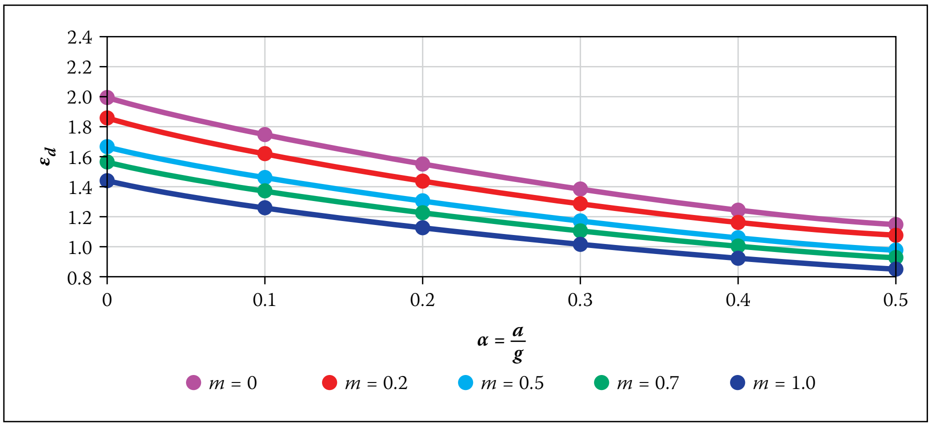

Figure 3 Changes of ε_d related to m and α (Opan & Temiz 2007)

where a is the reduction factor (a is between 0.543 and 0.555) for the earthquake force (Westergaard 1933).

Vertical pore water pressure force is:

$$F_U = \frac{1}{2}m\gamma_W hb(1+\alpha) \qquad (3)$$

The weight of the concrete dam wall is simplified by assuming that the cross-section of the wall is a triangle with base b and height h. In other words $H = h$. The weight of the concrete gravity dam is:

$$W = \frac{1}{2}\gamma_C bh \qquad (4)$$

Earthquake force due to concrete gravity dam weight is:

$$W_E = \frac{1}{2}\alpha\gamma_C bh \qquad (5)$$

where γ_w and γ_c are the specific weights of concrete and water respectively and m is the pressure reduction factor for the water pressure force ($0 \leq m \leq 1$). The ratio α is the earthquake acceleration divided by gravitational acceleration.

PSEUDO ANALYSIS

Pseudo analysis for dams is based on dam stability. The stability of a CGD is provided by its moments. If the moment that attempts to tip the dam at the toe point is lower than the resisting moment, the dam remains stable. This is demonstrated in Equation 6:

$$W\cdot\frac{2b}{3} \geq F_X\cdot\frac{h}{3} + F_E\cdot\frac{4h}{3\pi} + F_U\cdot\frac{2b}{3} + W_E\cdot\frac{h}{3} \qquad (6)$$

With the substitution of Equations 1 to 5, this is equivalent to:

$$\left[(2+\alpha)\frac{\gamma_C}{\gamma_W} - 2m(1+\alpha)\right]\frac{b^2}{h^2} \geq (1+1.41\alpha) \qquad (7)$$

After simplification, it becomes:

$$\frac{b}{h} \geq \left[\frac{(1+1.41\alpha)}{(2+\alpha)\frac{\gamma_C}{\gamma_W} - 2(1+\alpha)m}\right]^{\frac{1}{2}} \qquad (8)$$

Equation 8 provides a relationship between the b/h ratio, and m and α are obtained. This relationship is shown in Figure 2 where $\frac{\gamma_C}{\gamma_W}$ is 2.5.

The overturning safety factor is attained from the ratio of resist moment to subvert moment. According to this definition, the overturning safety factor is obtained below:

$$\varepsilon_d = \frac{W\cdot\frac{2b}{3}}{F_X\cdot\frac{h}{3} + F_U\cdot\frac{2b}{3} + F_E\cdot\frac{4h}{3\pi} + W_E\cdot\frac{h}{3}} \qquad (9)$$

After substitution and rearrangement, it becomes:

$$\varepsilon_d = \frac{2\cdot\frac{\gamma_C}{\gamma_W}\left(\frac{b}{h}\right)^2}{(1+1.41\alpha) + \left[2m(1+\alpha) + \alpha\cdot\frac{\gamma_C}{\gamma_W}\right]\left(\frac{b}{h}\right)^2} \qquad (10)$$

where $\frac{\gamma_C}{\gamma_W}$ is accepted as 2.5. The ratio b/h is found versus m and α, changes of ε_d connected with m and α are obtained, and ε_d decreases with increasing values of m and α.

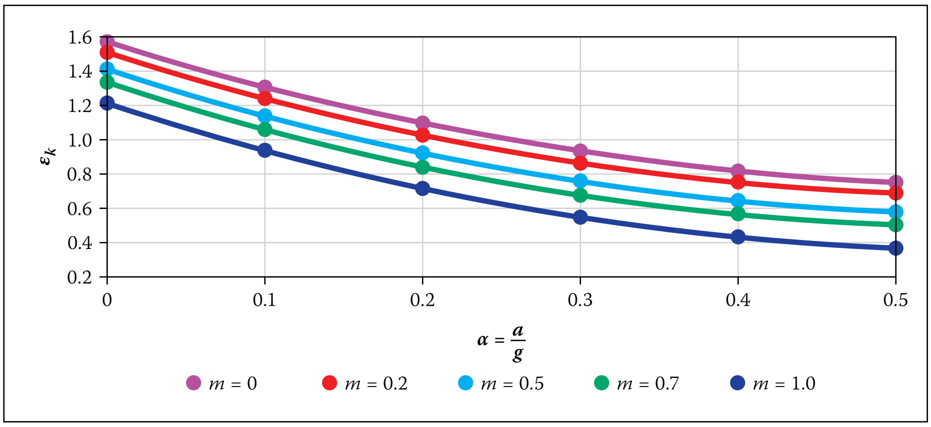

Figure 4 Changes of ε_k related to m and α (Opan & Temiz 2007)

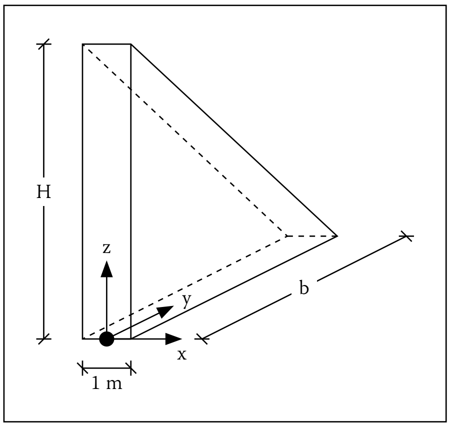

Figure 5 Principal axes of dam

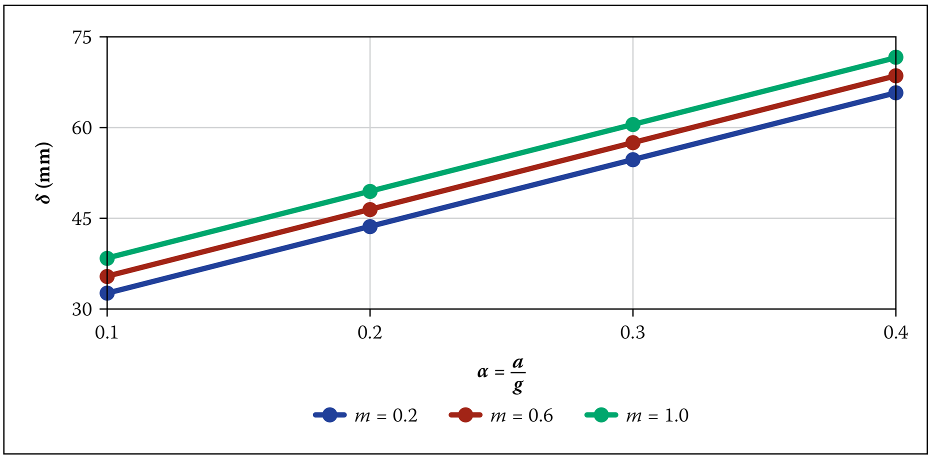

Figure 7 Changes of deflection related to m and α on y-direction at topping point for b/H = 0.6

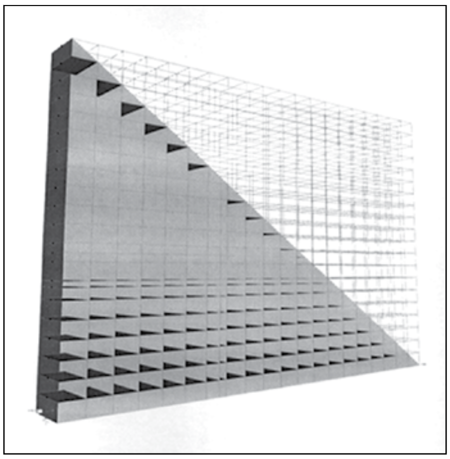

Figure 6 View of the meshes on the shells

The sliding safety factor is attained from a ratio of resist force to sliding force. According to this definition, the sliding safety factor is obtained as follows:

$$\varepsilon_k = \frac{(W - F_U)k}{F_X + F_E + W_E} \tag{11}$$

With the rearrangement of this equation, Equation 12 is formed:

$$\varepsilon_k = \frac{\left[\frac{\gamma_C}{\gamma_W} - m(1 + \alpha)\right] \mathrm{k} \cdot \frac{b}{h}}{(1 + 1.11\alpha) + \frac{\gamma_C}{\gamma_W} \cdot \alpha \cdot \frac{b}{h}} \tag{12}$$

where $\frac{\gamma_C}{\gamma_W} = 2.5$ and $k = 1.0$ are accepted, and b/h is obtained versus m and α in Equation 8.

Changes of ε_d and ε_k related to m and α are calculated as shown in Figures 3 and 4, where it can be seen that ε_d and ε_k decrease with increasing values of m and α.

STRUCTURAL ANALYSIS USING *SAP2000*

A CGD is modelled by using the shells of the finite element in the *SAP2000* program. The principal axis of the dam in this program is shown in Figure 5. Shells are separated into 0.50 × 0.50 meshes, as shown in Figure 6. Small dimensions are chosen for these meshes

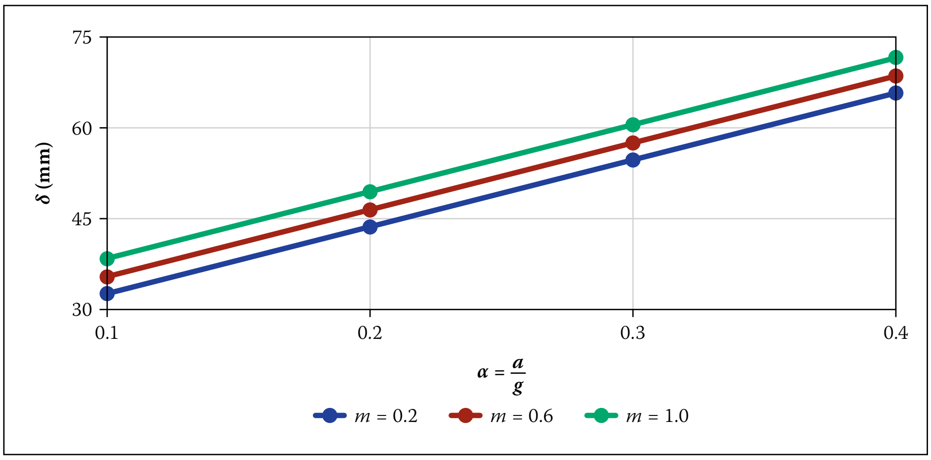

Figure 8 Changes of deflection related to m and α on y-direction at topping point for b/H = 0.8

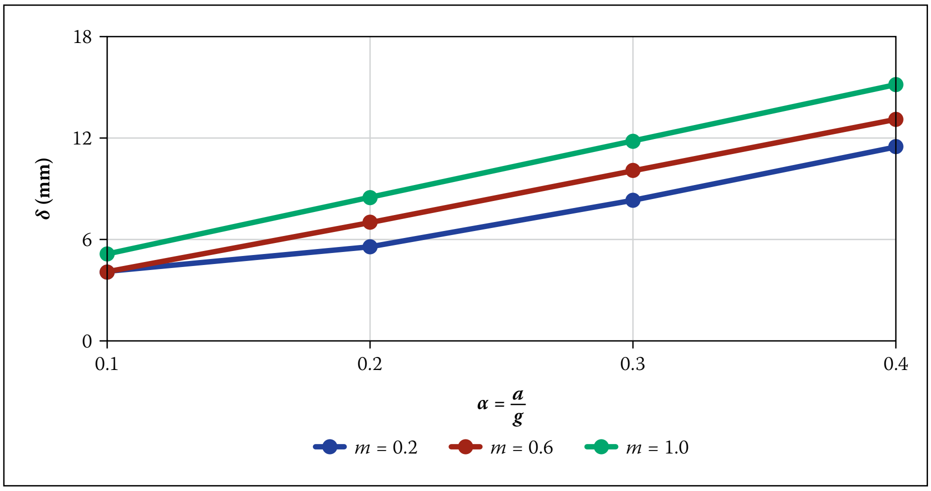

Figure 9 Changes of deflection related to m and α on y-direction at topping point for b/H = 1.0

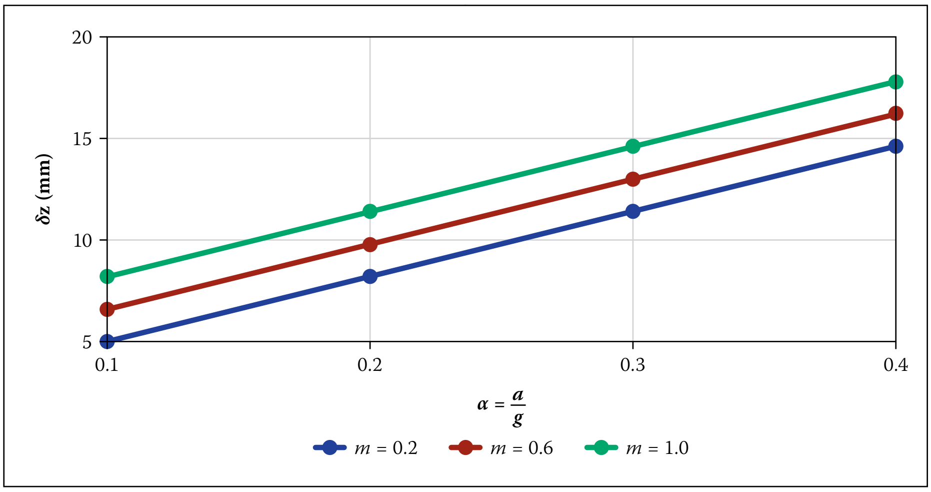

Figure 10 Changes of deflection related to *m* and *a* on y-direction at toe point for *b/H* = 0.6

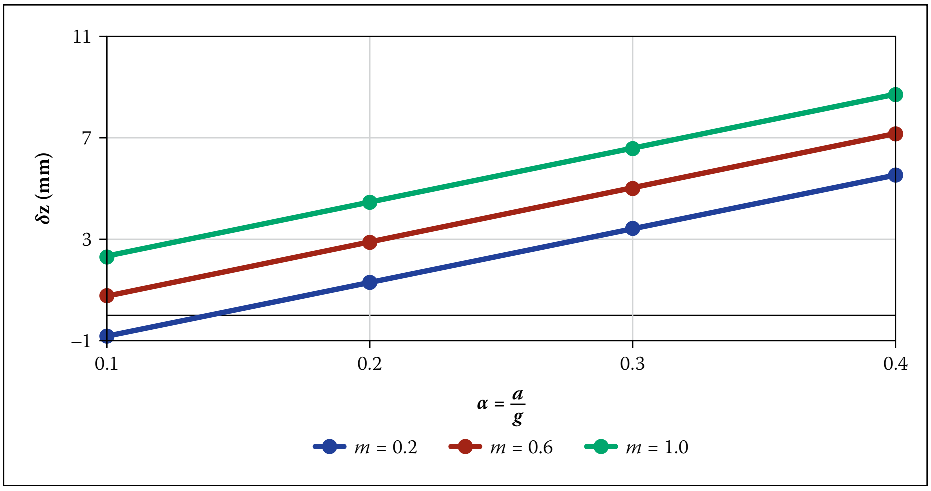

Figure 11 Changes of deflection related to *m* and *a* on y-direction at toe point for *b/H* = 0.8

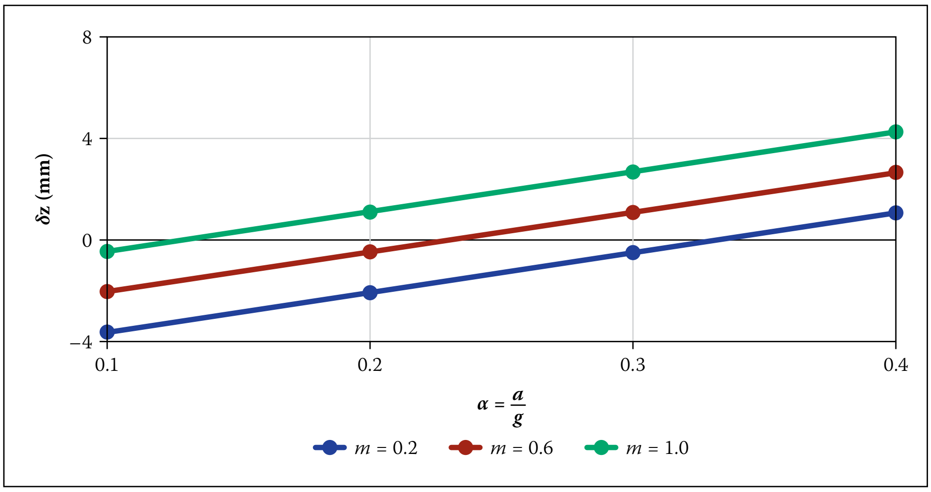

Figure 12 Changes of deflection related to *m* and *a* on y-direction at toe point for *b/H* = 1.0

to achieve results closer to reality. Deflection values for topping and points are attained by establishing models in different mesh dimensions. Mesh dimension is defined by considering computing time and the fact that there are no changes in deflection. The foundation soil of the dam was modelled via the spring element. The density of the soil was accepted as being sand-loose and sand-medium, and the modulus of sub-grade reaction was chosen as $k_s = 2\,500\ t/m^3$. The stiffness of the spring element was determined by using the modulus of the sub-grade reaction and foundation effective area. Analyses were performed at *h = 10 m, H = 10 m, m = 0.2, 0.6* and*1.0,* and at *b/h* ratios *0.6, 0.8* and *1.0.* Note that the analysis was simplified by assuming a wall height *H* to be the same as the water depth *h*. Deflection values at every direction are read from the topping point and toe point, as shown in Figure 1. Deflection vectors of these points are obtained as follows:

$$\delta = \sqrt{\delta_x^2 + \delta_y^2 + \delta_z^2} \qquad (13)$$

where δ is the deflection vector.

RESULTS

The effects of safety factors on the deflections in a concrete gravity dam during an earthquake were determined in this study. A concrete gravity dam with a base width *b* and height *H* was specified, using pseudo analysis for the *b/H* ratios and earthquake acceleration values between 0.1 g and 0.4 g. Values for specified parameters were obtained from the structural analysis program *SAP2000*. Graphs were plotted for the selected dam from the results of the *b/H* ratio and earthquake acceleration, and the deflection and safety factors were evaluated. $\frac{\gamma_C}{\gamma_W} = 2.5$ and $k = 1.0$ were accepted in the pseudo analysis.

In Figure 2 it can be seen that the *b/h* ratio increased with an increase in *m* and *α*. In Figures 3 and 4 the safety factors decreased with increasing *m* and *α*. Deflection of the topping point related to *m* and *α* at *b/H = 0.6, 0.8* and *1.0* are shown in Figures 7, 8 and 9 respectively. It can therefore be said that deflection increased with increasing *m* and *α*. Deflection of the toe point related to *m* and *α* at *b/H = 0.6, 0.8* and *1.0* are shown in Figures 10, 11 and 12 respectively. Deflections increased with increasing in and, and deflections decreased with an increase in the *b/H* ratio.

CONCLUSIONS

In this study, tipping and sliding safety factors of a dam during an earthquake, and deflections at toe and topping points, were determined. Pseudo analysis was performed to define safety factors. Changes to these safety factors versus *m* and *α* were investigated, and it was seen that safety factors decreased with increasing *m* and *α*. *SAP2000* was used to determine deflections at the toe and topping points. According to the changes in these deflections versus *m* and *α* it can be said that deflection increased with increasing *m* and *α*. In addition, safety factors increased with increasing *b/H*, while deflection decreased with increasing *b/H*. Further research should cover analysis and studies regarding crack formation and dispersion in a concrete gravity dam during an earthquake.

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