SAFETY FACTORS FOR THE SEISMIC DESIGN OF CONCRETE GRAVITY DAMS

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ABSTRACT *Earthquake safety of concrete gravity dams has been widely studied in recent years. However, due to the uncertainties of seismic ground motion and its interaction with the reservoir and the dam structures, further research continues in several directions. In this paper, design safety factors have been evaluated in terms of the basic design parameters on the basis of a pseudo-static analysis. At the design stage, it is particularly important to decide on the seismic parameters for the maximum credible earthquake. Ground motion may also alter the uplift pressure through changes in ground seepage and cracks in the concrete body of the dam. Thus, variations of the safety factors with the effective seismic acceleration and the reduction coefficient for the uplift pressure carry great importance in choosing suitable dimensions for the dam. It is expected that this analysis will facilitate to obtain an appropriate initial design, which may than be examined in detail with more advanced techniques.*

INTRODUCTION

Rapid developments in computer technology enabled the application of advanced structural analysis techniques in the earthquake safety of concrete dams in the last few decades. However, many uncertainties remain in predicting the behavior of dams during heavy earthquakes. Amongst these are the crack formation and propagation processes in the concrete body of the dams, the nonlinear behavior 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 used together with statistical methods in the studies of stability analysis for the safety evaluation of dams, [Hall (1998), Tinawi et. al. (2000), Leclerc et.al. (2007)]. Another issue is the most appropriate definition of the seismic input which may have many uncertainties, but its affect is very significant in the seismic design and seismic safety evaluation of the dams. Progress has been made in defining maximum credible earthquake (MCE), maximum design earthquake (MDE) and safety evaluation earthquake (SEE). With more seismic records available, understanding the effects of the very short duration peak ground acceleration (PGA) which may be 0.5g-1.0g or even higher in heavy earthquakes and the sustained effective seismic acceleration (which about 0.5-0.67 PGA)have improved. A very important indirect result of the seismic activity is the affect on the uplift forces due to increasing pressure acting through the cracks in the concrete body or under the foundations resulting from increased seepage. This must be taken into account in the stability analysis for the seismic design as it may have very significant effect for the safety of the dam.

In this paper, it is intended to present a preliminary approach based on a simplified pseudo-static stability analysis to obtain safe design conditions depending on the most important design parameters to obtain a feasible initial design which may be examined later in more detail using further analysis.

THEORY FOR DESIGN CRITERIA

A simplified model is adopted in order to obtain manageable results with sufficient accuracy. The upstream surface of the dam is assumed vertical and the effect of the silt layer near the ground is omitted. In Figure-1, dam cross-section with static and pseudo-static loads is shown. With the dam height *H*, base width *b* and the crest width *c*, and taking the water height *h*, the loads per unit width of the dam body, assuming $\frac{c}{b} << 1$: and $h \approx H$, are given by:

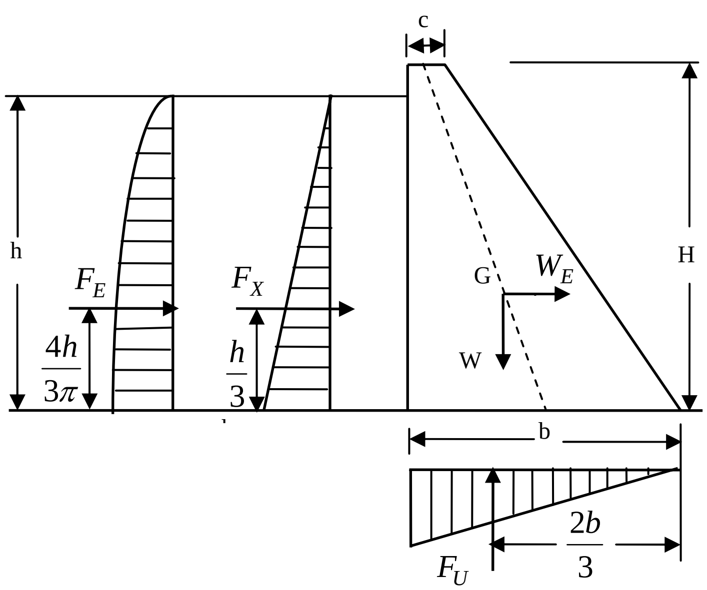

Figure-1. Static and pseudo-static loads on a gravity dam

Horizontal hydrostatic force : $F_X = \frac{1}{2}\gamma_W h^2$

Horizontal seismic hydrodynamic force : $F_E = 0.555\alpha\gamma_W h^2$

Vertical uplift force,(including approximate seismic pressure) : $F_U = \frac{1}{2} m\gamma_W hb(1+\alpha)$

Weight of the concrete dam body : $W = \frac{1}{2}\gamma_C bh$

Seismic load on dam body $:W_E = \frac{1}{2}\alpha\gamma_C bh$

where γ_w and γ_c are the specific gravities of water and concrete respectively, m is the reduction coefficient for the uplift pressure ($0 \le m \le 1$), $\alpha = \frac{a}{g}$ the coefficient for the effective seismic acceleration, *a* being the seismic acceleration.

For static stability, overturning moments about the downstream tip of the base must be less than the resisting moment,

$$W.\frac{2b}{3} \ge F_X.\frac{h}{3} + F_E.\frac{4h}{3\pi} + F_U.\frac{2b}{3} + W_E.\frac{h}{3} \tag{1}$$

with necessary substitutions, this becomes

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

which gives

$$\frac{b}{h} \ge \frac{1}{\sqrt{2}}\left[\frac{(1+1.41\alpha)}{(1+\frac{\alpha}{2})\frac{\gamma_C}{\gamma_W} - (1+\alpha)m}\right]^{\frac{1}{2}} \tag{3}$$

From this inequality, base/height ratio of the dam is selected with same safety margine as

$$\frac{b}{h} = \left[\frac{(1+1.41\alpha)}{(1+\frac{\alpha}{2})\frac{\gamma_C}{\gamma_W} - (1+\alpha)m}\right]^{\frac{1}{2}} \tag{4}$$

From Equation 4, variation of $\frac{b}{h}$ with m and α is shown in Figure-2 where $\frac{b}{h}$ increases with increasing m and with increasing α, ($\frac{\gamma_C}{\gamma_W} = 2.5$ is used).

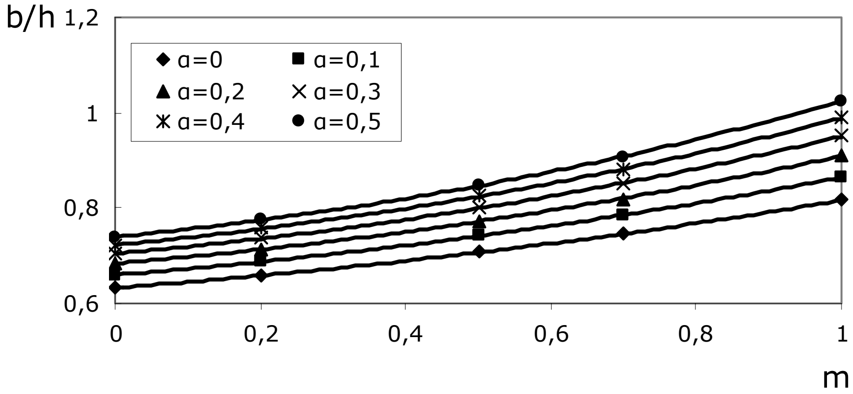

Figure-2. Variation of dam base width to dam height ratio with m and α

The safety factor against overturning including seismic effects is given by

$$\varepsilon_d = \frac{W.\frac{2b}{3}}{F_X.\frac{h}{3} + F_U.\frac{2b}{3} + F_E.\frac{4h}{3\pi} + W_E.\frac{h}{3}} \tag{5}$$

which after substitutions, becomes

$$\varepsilon_d = \frac{2.\frac{\gamma_C}{\gamma_W}(\frac{b}{h})^2}{(1+1.41\alpha) + \left[2m(1+\alpha) + \alpha.\frac{\gamma_C}{\gamma_W}\right]\left(\frac{b}{h}\right)^2} \tag{6}$$

If it is assumed that $\frac{b}{h}$ is chosen in accordance with Equation 4, ε_d as a function of m and α is shown graphically in Figure-3 (where $\frac{\gamma_C}{\gamma_W} = 2.5$ is used).

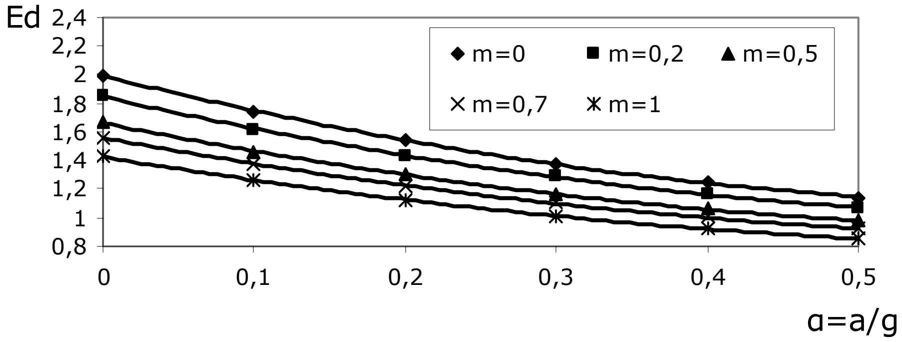

Figure-3. Variation of safety factor against overturning with effective seismic acceleration coefficient and reduction coefficient on uplift pressure

Assuming the friction coefficient on the base is k, the safety factor against sliding on the base is given by

$$\varepsilon_k = \frac{(W - F_U)k}{F_X + F_E + W_E} \tag{7}$$

and after necessary substitutions, this becomes

$$\varepsilon_k = \frac{\left[\frac{\gamma_C}{\gamma_W} - m(1+\alpha)\right] k.\frac{b}{h}}{(1+1.11\alpha) + \frac{\gamma_C}{\gamma_W}.\alpha.\frac{b}{h}} \tag{8}$$

The variation of ε_k with m and α is shown in Figure-4, where $\frac{b}{h}$ is chosen according to Equation 4 and $\frac{\gamma_C}{\gamma_W} = 2.5$, $k = 1.0$ is used.

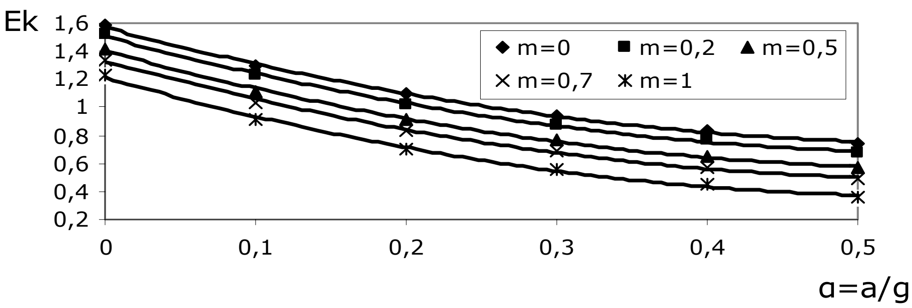

Figure-4. Variation of safety factor against sliding with effective seismic acceleration coefficient and reduction coefficient on uplift pressure

CONCLUSIONS

Stability analysis for a concrete gravity dam on the basis of a pseudo-static approach including seismic loads gives the safety factors against sliding and overturning. The basic parameters included in the analysis are the dam base width to dam height ratio (*b/h)*, effective seismic acceleration coefficient (α), reduction coefficient on the uplift pressure (*m*) and the base friction coefficient (*k*). It is assumed that for a given constant value of the base friction coefficient ($k = 1.0$), both safety factors decrease as the coefficient of seismic acceleration increases and the same occurs as the reduction coefficient on the uplift pressure increases. For a range of values of the pressure reduction coefficient around $m = 0 - 0.3$ and the seismic acceleration coefficient $\alpha = 0 - 0.2$, both safety factors ε_k and ε_d are greater than unity, where the critical one being ε_k. The upper value $\alpha = 0.2$ for the seismic acceleration coefficient would correspond to a value of the peak ground acceleration (PGA) of around 0.4g which may be applicable for areas at the border of moderate to high seismic activity. For very heavy earthquakes, PGA has been measured up to or exceeding 1.0g. In that case, the effective acceleration coefficient would be around $\alpha = 0.5$ and the need for improvements in the safety factors (especially for ε_k) become very clear, possibly by taking measures to increase the base friction and the base width.

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