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Effect of Static Seismic Loading and Uplift Parameters on the Stability of a Concrete Gravity Dam

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***Abstract*—A concrete gravity dam is a major hydraulic structure which resists all external forces by its weight. Consideration of earthquake force is a major concern for the construction of major structures like dams. The main objective of this study is to obtain the design base width of a dam for different seismic conditions by varying the earthquake coefficients in both vertical and horizontal directions. This has been done by equating the different factors of safety for a dam with their limiting conditions under both tail water and no tail water condition. The shape of the Mettur dam in India is considered for the study. In the study the base width was calculated using Newton Raphson method in C++ and their variation plotted. A study on the variation of uplift pressure with change in the position of drainage gallery and the total uplift force and moments were obtained. A comparison was done in the design base width obtained for a particular case of earthquake without drainage gallery to the design base width obtained with gallery in different locations for that earthquake condition. From the study, the optimum location of the drainage gallery was found to be lying within the range of 0.25-0.5 times the base width from the heel of the dam. The position of drainage gallery was changed for different values of uplift ratio and then plotted.**

Keywords—Base Width, Horizontal Earthquake Coefficient, Tail Water, Uplift, Vertical Earthquake Coefficient.

I. Introduction

A dam is a major hydraulic structure which restricts the flow of water or underground streams thereby creating reservoirs. The water stored by reservoirs can be used for different purposes like irrigation, hydropower, human consumption, industrial use, aquaculture, and navigability. The retained water from the dam can also be evenly distributed between locations. Depending on the location where the dam is constructed the earthquake forces acting on the dam in that zone are assessed using IS-1893, Part I, 2002. Also various soil characteristics, ground water level, provision of drainage galleries, there is a variation in the uplift.

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Since the consequences of a large dam failure can be disastrous, consideration of seismic stability of a dam has been given great importance. Many researches have been conducted in this field and several sites have been studied because of the risk posed to the population downstream of the dam lest any failure should occur as the seismic design concepts in use at the time most existing dams were built were inadequate.

Ali et al. (2012) did a comparative study in the design and analysis of concrete gravity dam by using ANSYS where vertical, principal and shear stresses were obtained using earthquake intensities in the range of $0.1g$-$0.3g$ in an increment of $0.05g$. Using ANSYS displacements were determined at global coordinates and stresses at x and y axes were calculated and principal stress evaluated.

Arun and Raghuraman (2016) made a study on the response of gravity dam under different earthquake accelerations using ANSYS. Koyna Dam, situated in Maharashtra was studied. The study involved the finite element modelling of gravity dam subjected to earthquake acceleration having maximum amplitude of $0.5g$ in software ANSYS 12.0 so as to find out the type of failure, the dam was likely to suffer. The actual section of the Koyna Dam was safe in compression but failure occurred due to tension at the downstream side where change of slope occurs and hence the dam was remodeled and the modified section was analyzed for different stresses.

Chawla et al. (1990) did an analytical solution based on seepage theory to determine the average uplift pressure across a dam section having a system of equally spaced drains of uniform diameter. The optimal location of the drains for the minimum uplift was also obtained for the values of the ratio of radius of drain, r, and dam base width, l, i.e. r/l equal to 0.0003, 0.001, and 0.005 and the values of the ratio distance between the drains, n, and dam base width, i.e.n/l equal to 0.05, 0.075, 0.1, and 0.2.

El-Razek and Elela (2001) did a practical study on the optimum location of the drainage gallery underneath a gravity dam. The optimum position of the drainage gallery was experimentally obtained to be $0.5B$ from the heel where B is the base width of the dam. Uday and Hasan (2016), studied the optimum location of drainage gallery under gravity dam using a computer program package “SLIDE V.5.005” and found the optimum location to be $0.167B$ from the heel of the dam of base width, B.

II. Model of the dam

For the analysis purpose, in the present study, the shape of the Mettur dam is taken into consideration. Mettur dam, situated over the River Kaveri is one of the oldest concrete gravity dam in India. It is located in the Salem district of Tamil Nadu. For the given height of a dam, say 50m, the variation of base width of the dam with respect to the variation of seismic coefficients are observed. Also drainage galleries are introduced at distances ranging from 0.1-0.9*B*, where *B* is the base width of the dam. Figure 1 represents the model of the dam taken and Fig. 2 is the model of the dam with drainage gallery.

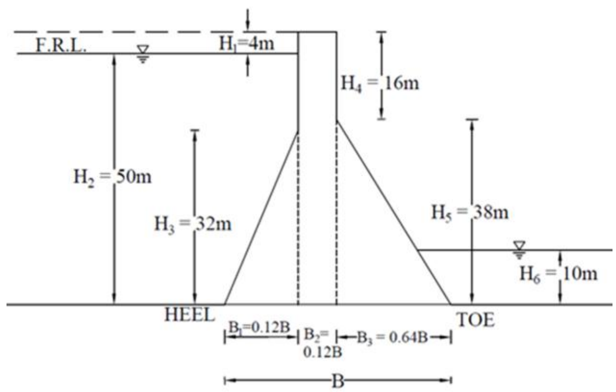

Figure 1. Model of dam

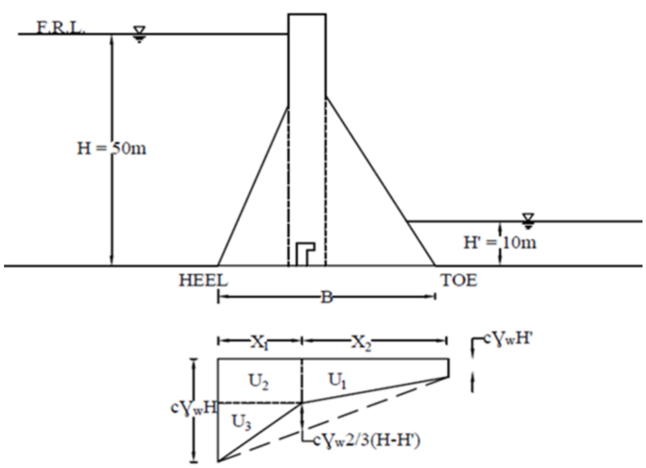

Figure 2. Model of the dam with drainage gallery

III. Methodology

A. Earthquake forces used

A constant height of dam of 50m is considered for the analysis with a freeboard of 4.0m and a tail water level of 10.0m. The coefficient of friction is taken as 0.75 and shearstrength of concrete is taken as 1400 N/mm^2. It is user defined and these may vary as per convenience. Uplift coefficient is arbitrarily taken as 2/3. The base of the dam is divided into three sections which are in proportion to *B*.The forces considered are the weight of the dam, that gives the resisting moment and water pressure, uplift of water, hydrodynamic pressure and earthquake pressure which contributes to the overturning pressure in the dam.

According to Zangler, total hydrodynamic pressure,

$$P_e = 0.726\, p_{ey} H \qquad (1)$$

Where, H is the height of the full reservoir level

p_{ey} is the hydrodynamic force given as

$$p_{ey} = C_m \alpha_h \gamma_w H \qquad (2)$$

$$C_m = 0.735\, \Theta/90^{\circ} \qquad (3)$$

where Θ = Inclination of upstream face with horizontal, γ_w = Unit weight of water, α_h = Horizontal earthquake acceleration.

The moment, $$M_e = 0.412\, P_e H \qquad (4)$$

The net vertical and horizontal forces are calculated and hence the resisting moments, M_R, and the total overturning moments, M_O, are computed. Equating the factor of safety against overturning = 1.5, sliding = 1, shear friction factor = 4, and accepting the values of α_v and α_h from the user, equations are obtained in terms of the variable *B*, i.e. the base width of the dam. These equations are solved by Newton Raphson method in C++ to arrive at a particular value of base width, *B*. Earthquake coefficients within the range of α_h = 0.0-0.10g and α_v = 0.0-0.10g are chosen with an increment of 0.01g. IS-1893, Part 1, 2002 recommends a value of 0.1g as the maximum earthquake coefficient, however for severe cases a value upto 0.3g may also be considered.

B. Consideration of Uplift Parameters

- At first taking the full reservoir level of water as 50m and tail water of 10m, at different drainage locations X_1/B, equations are obtained by equating the factor of safety for sliding, factor of safety for overturning, factor of safety for shear friction with their respective limiting values, using a fixed value of earthquake coefficient, α_v = 0.03. α_h is varied from 0-0.1g. Hence different values of uplift forces are obtained for each case and these equations are solved by programmes in C++ using Newton Raphson method to get the value of the variable *B*. The effect of uplift is seen and the value of the design base width for a particular case of factor of safety, for α_v = 0.03, obtained for the dam with drainage gallery at different locations is compared to the value of design base width for the same conditions of the dam but without drainage gallery.

- For a given height of dam, H = 50m, uplift forces are calculated. The uplift pressure at drainage gallery is given by U_1 and the total uplift pressure is U. The ratio U_1/U gives the value of relative uplift pressure. These are plotted against the different drainage gallery locations.

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IV. Results and Discussions

The variation of base width for both tail water and no tail water condition are tabulated for different seismic coefficients and are plotted as seen in Fig. 3 - Fig. 8 for factor of safety of sliding, overturning and shear friction. The variation of base width for both drainage gallery and no drainage gallery conditions are also compared. Fig. 9 - Fig. 11 represents the comparison of the dam base width when the drainage gallery is presents within the range of X_1/B = 0.1 - 0.9 to the no drainage gallery condition. Here X_1 is the location of drainage gallery from the heel of dam of base width, *B*. Fig. 12 is the variation of ratio of uplift pressure U_1/U to the different drainage gallery location where U_1 is the uplift at the drainage gallery location and U is the total uplift at the base of the dam.

A. *Effect of Static Seismic Load on the Base Width of the dam*

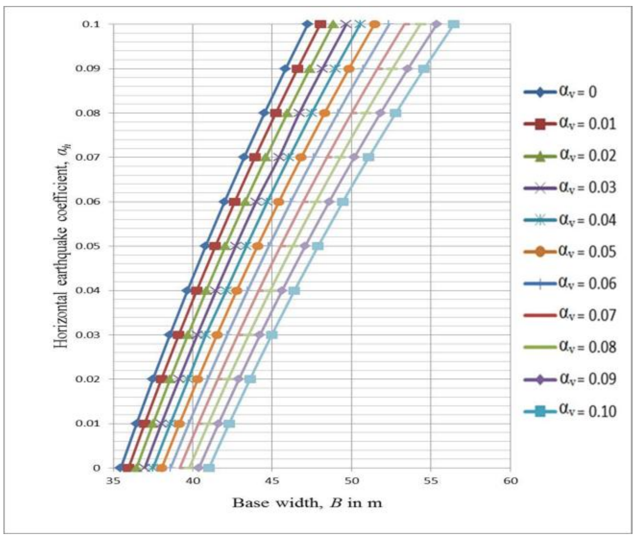

Figure 3. Variation of base width with the effect of α_h, for different values of α_v for sliding effect (For no tail water condition)

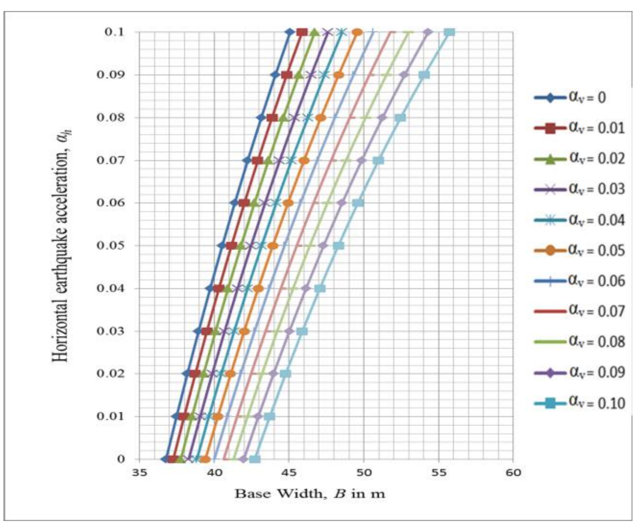

Figure 4. Variation of base width with the effect of α_h, for different values of α_v for overturning effect (For no tail water condition)

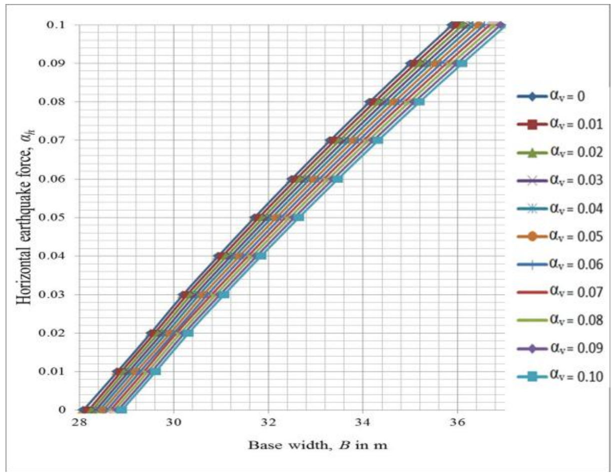

Figure 5. Variation of base width with the effect of α_h, for different values of α_v for shear friction effect (For no tail water condition)

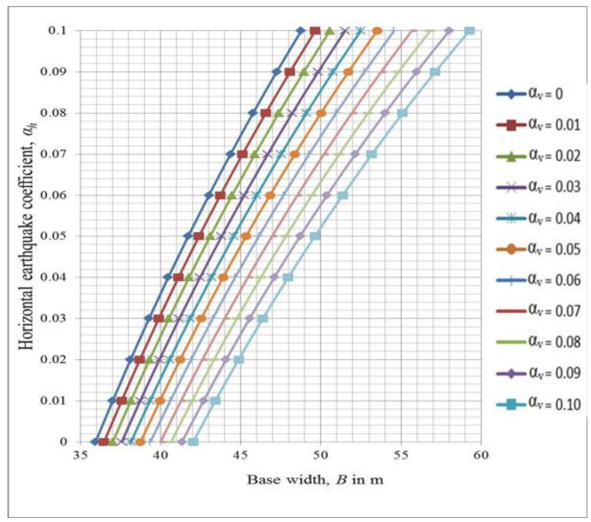

Figure 6.Variation of base width with the effect of α_h, for different values of α_v for sliding (For tail water condition)

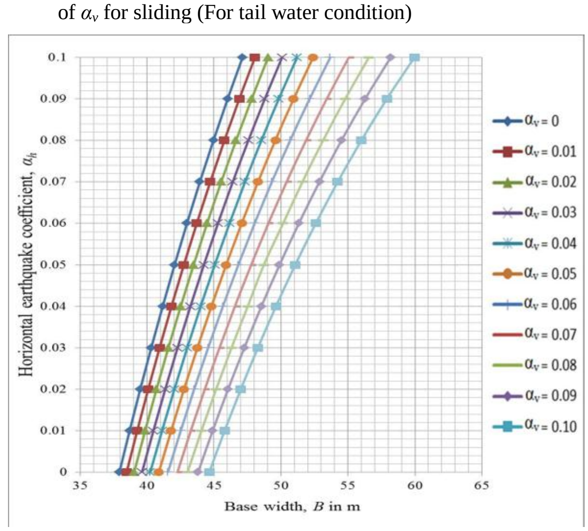

Figure 7. Variation of base width with the effect of α_h, for different values of α_v for overturning (For tail water condition)

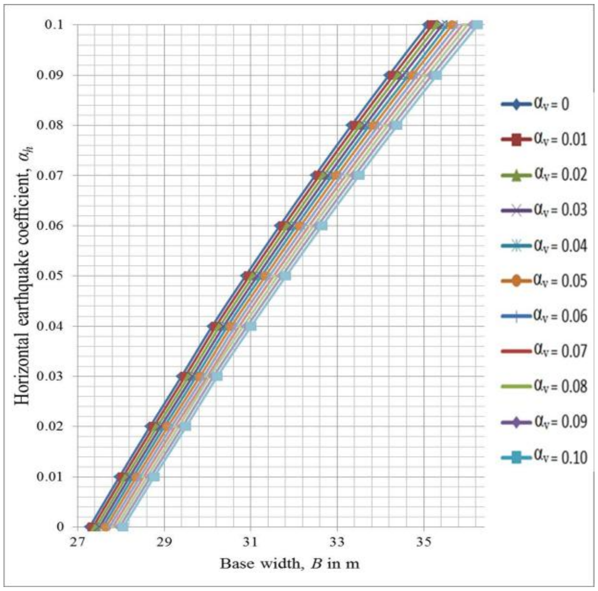

Figure 8. Variation of base width with the efect of α_h, for different values of α_v for shear friction (For tail water condition)

B. ***Effect of drainage gallery on the base width of the dam***

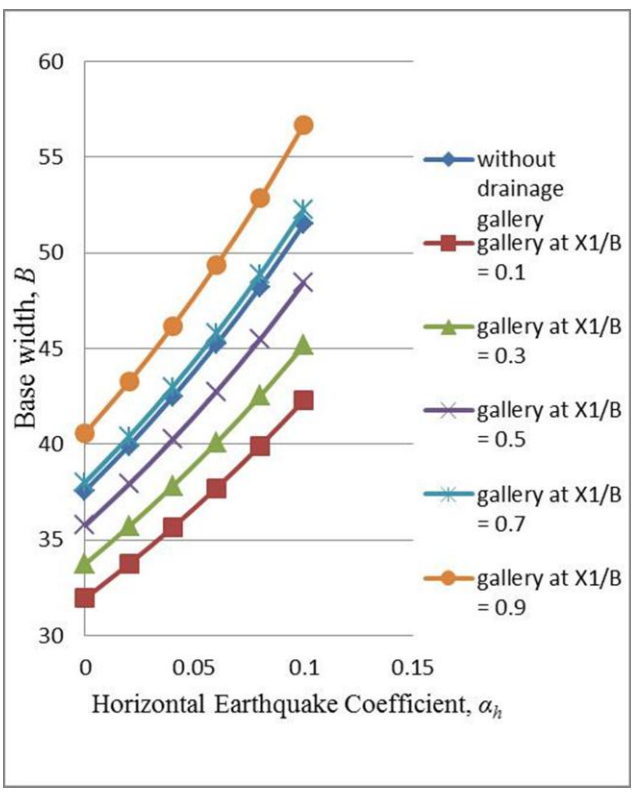

Figure 9. Plot for comparison of base width for different drainage gallery conditions, for factor of safety for sliding

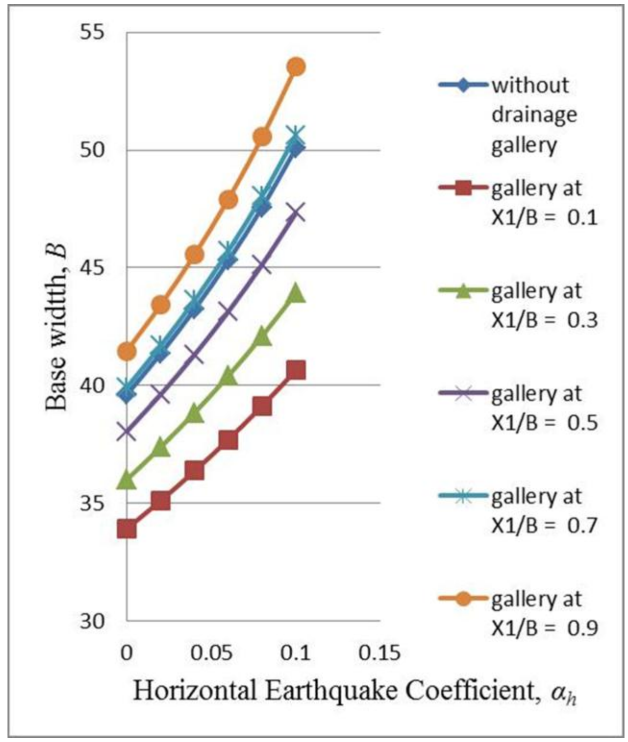

Figure 10. Plot for comparison of base width for different drainage gallery conditions, forfactor of safety for overturning

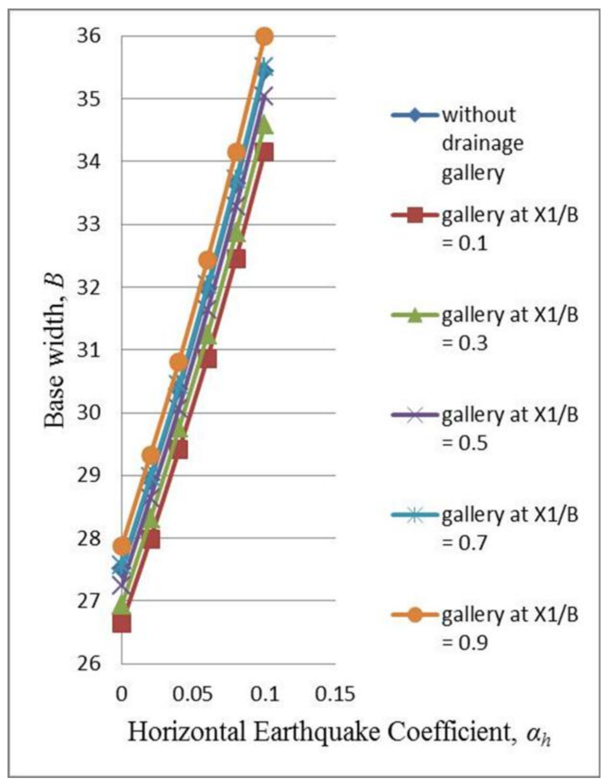

Figure 11. Plot for comparison of base width for different drainage gallery conditions, for factor of safety for shear friction

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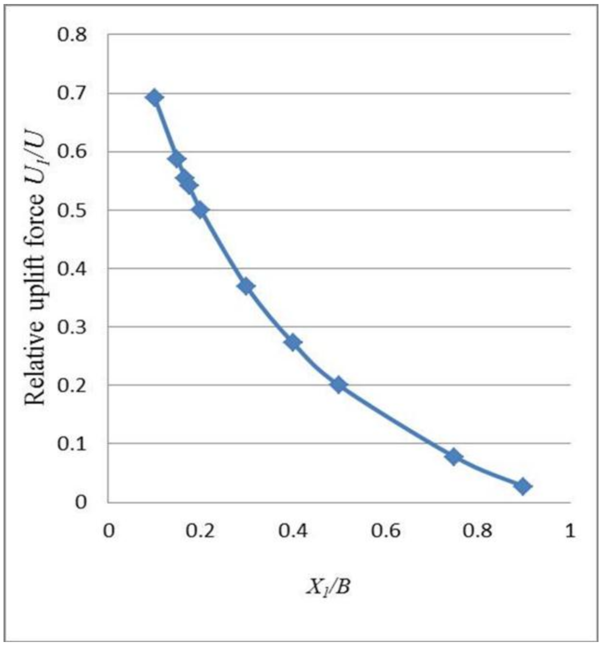

Figure 12. Position of drainage gallery vs relative uplift force

V. Conclusions

The following points may be concluded from this study of stability analysis:

- The variation in base width, B is seen to be almost linear up to a value of α_h = 0.05, after which the value is seen to vary rapidly up to α_h = 0.10.
- For the design purpose the maximum value of B shall be considered amongst all the three factors of safety for a particular case of tail water condition. Amongst all the three factor of safety considered, the base width for shear friction criteria is least, while it is maximum for the sliding criteria only when the αv and $\alpha_h$are less and it gradually increases and becomes maximum in the case of factor of safety for overturning as α_v and α_h increases to 0.1g.
- In the case of factor of safety for shear friction factor such a trend is not followed, because a constant value of shear strength of concrete is considered in this case.
- The value of base width, B, is more in case of reservoir with tail water than in the no tail water condition because of the presence of uplift pressure in the tail water condition which increases the overturning moment.
- The uplift may be reduced by provision of drainage galleries in a dam section. From the study it may be concluded that when the drainage galleries are present till X_1/B = 0.5, the uplift was reduced and hence the value of base width also decreased, beyond which the reduction in uplift was not significant due to the presence of drainage gallery. Hence the location of the drainage gallery may be optimized to be lying within the range of X_1/B = 0.25-0.5 from the practical point of view.

Although this study has been done for the Mettur dam, it can be applied for any gravity dam at different sites by changing the height of the dam, uplift parameters and earthquake coefficients applicable for a given site condition.

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