

Seismic response of a concrete gravity dam considering hydrodynamic effects

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Abstract

Massive concrete gravity dams supporting huge water reservoir are subjected to hydrodynamic forces resulting from the time-dependent stresses generated at the reservoir water-dam interface. Indian Standard Code (IS 1893-2003) suggests considering hydrodynamic pressure that varies with depth of reservoir and shape of the dam, similar to a pseudo-static analysis. Such an assumption leads to largely conservative analysis and over-safe design. This article reports the response of the Pine Flat Dam under seismic conditions considering hydrodynamic stresses on the upstream face, varying both spatially and temporally. The Kern County seismic ground motion has been chosen for the analysis, for which both S69E and vertical component of accelerations have been considered along with their combined action. GeoStudio 2007 modules of Sigma/W and Quake/W have been used in unison to achieve the modeling. The study illustrates a significant variation in the estimated seismic response when the hydrodynamic forces are included in the design.

Keywords: Concrete gravity dam, Seismic response, Hydrodynamic effect, Geo-Studio 2007.

Introduction

Dams are barriers that impound water or underground streams for various purposes such as hydropower and hydroelectricity, water storage and irrigations, water flow stabilization, flood prevention, land reclamation, navigation, water channel diversion as well as recreation and aquatic beautification. Dams can be natural, anthropogenic, or animal-made. Based upon their construction materials, shape and purpose, dams can be classified structurally as arch dams, gravity dams, arch-gravity dams, barrages, embankment dams, rock-fill dam, concrete faced-rock fill dam, and earth – and-rock fill dams. In terms of usability, they can be categorized as saddle dams, weirs, check dams, dry dams, diversionary dams, underground dams and tailing dams. The importance of these structures convey the idea of the catastrophic disaster which can occur due to its failure, the main causes of which may include inadequate spillway capacity, piping through the embankment, foundation or abutments, spillway design error, geological instability caused by the water level fluctuation in the upstream, poor maintenance, extreme rainfall and seismic shocks and earthquakes. Failure of dams occurs quite rapidly without adequate prior warning with a potential of causing excessive calamity.

During the earthquakes, the additional pressure exerted by the moving water on the upstream face of the dam is termed as hydrodynamic force. A similar situation arises when a wave impacts on the offshore jetties. The hydrodynamic forces are spatially and temporally variable, and in contrary, significantly different to the pseudo-static analysis conventions. According to the Indian Standards (IS 1893-2003), due to horizontal acceleration, instantaneous hydrodynamic pressure is produced on the dam face, opposite to the direction of the earthquake, which results in alternate cycles of compression and tension forces (extreme tension may lead to cavitations). The methodology detailed in the IS code to determine this hydrodynamic force is based on pseudo-static analysis, with no temporal variation of the same. This may lead to significant over-safe design.

Pseudo-static method of analysis has been one of the earliest methods of estimating the hydrodynamic pressure distribution. ‘Added-mass’ effect of an incompressible reservoir fluid (Westergaard, 1933), linear momentum balance principle to investigate earthquake forces (Chwang and Housner, 1978), potential-flow theory (Chwang, 1978, 1979), and the application of Laplace’s equation (Zee and Zee, 2006) are the examples of the applicability of the pseudo-static analysis in such problems. It is worth mentioning that such analyses considers the worst condition of the earthquake force acting through a special location of the structure, and hence, avoids the temporal

effect of the earthquake motions on the developed hydrodynamic pressure and its time-dependent variation on the upstream face of the dam. The pseudo-static analyses reveals that the hydrodynamic pressure distribution is mostly parabolic and the maximum pressure occurs at the base (or near the base) of the dam. However, it is well understandable that the variation of hydrodynamic pressure is time-dependent, which varies during the event of an earthquake. To-and-fro motion of the dam, reservoir and dam-reservoir foundation results in an alternate build-up and release of reservoir water-dam face interaction stresses, which are representations of the hydrodynamic pressures itself. Hence, the hydrodynamic pressure may be significantly different in comparison to that estimated from a worst-case scenario pseudo-static analysis. Both the distribution and magnitude of the forces along the upstream face of the dam are different, and at time might exceed the magnitudes as observed in the pseudo-static analysis. Hence, it is necessary to have a proper dynamic analysis of the dam-reservoir systems to understand the hydrodynamic pressure variation. Limited studies in this respect have been carried out, and hence, this aspect needs further investigation.

Most of the earlier researches have been focused on to determine the hydrodynamic pressure variation on the upstream face of the dam, without delving deeper into finding what would be the consequence of the same on the response of the dam. This paper reports the findings of the dynamic analysis carried out on Pine Flat Dam to determine the effect of hydrodynamic stresses on the response of the dam. Chopra and Gupta (1981) reported the findings of a similar study on behavior of Pine Flat Dam considering the horizontal and vertical components of the Kern County Earthquake (Taft ground motion). The study reported the utilization of the first 20 sec duration of the motion with the PGA as 0.15g for horizontal (S69E) component and 0.083g for the vertical component of the motion. Since the entire duration of the strong motion was 54.14 sec (Fig. 1), the above segment with the corresponding PGA is not believed to provide proper representation of the effect of the earthquake in the generation of the hydrodynamic pressure. Based on the approach by Trifunac and Brady (1975), this article reports a more realistic application of the earthquake strong motions in the determination of effect of hydrodynamic pressure distribution on the response of the dam. Comparative data have also been reported herein to portray the differences in the results of the present study with that of the earlier one by Chopra and Gupta (1981). In order to achieve the dynamic analysis of the concerned dam and determine its response, a geotechnical finite element package, GEOSTUDIO 2007 has been used in the present study.

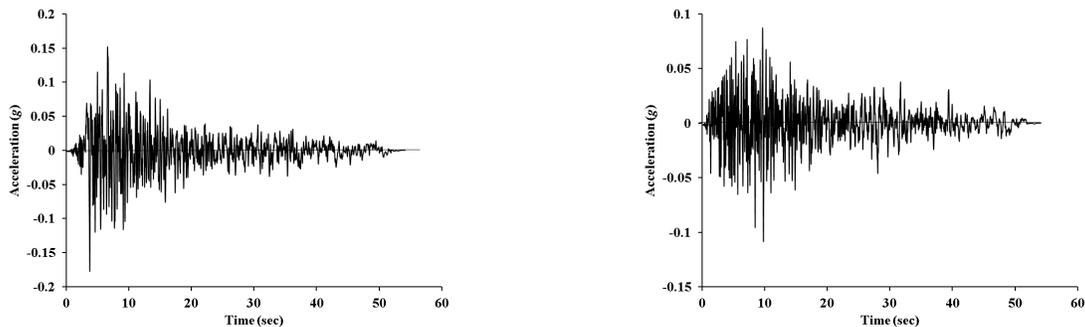


Figure 1. (a) Horizontal S69E and (b) Vertical component of the Kern County ground motion (Taft Lincoln station)

GeoStudio Modeling of Pine Flat Dam

Pine Flat Dam is a concrete gravity dam on the Kings River of central California in United States. The dam is 122 m high supporting the Pine Flat Lake, one of the largest reservoirs in California. The freeboard of reservoir is at level of 116 m. The upstream face of the dam is nearly vertical having a slope 0.05H:1V, while the inclined downstream side has slope of 0.78H:1V. The dam material (i.e. concrete) is a brittle material with no yield point and does not show any plastic deformation. Hence, linear elastic model has been used represent the behavior of unreinforced concrete gravity dam. The model comprises of two parts namely the concrete dam and the foundation rock. The presence of water in the reservoir is simulated through hydrostatic and hydrodynamic stresses. The modeling and subsequent analysis of the dam has been carried out on the basis of the following assumption: (i) Reservoir water is incompressible and inviscid, (ii)

Concrete gravity dam is perfectly rigid, and (iii) Hydrodynamic pressure at the surface of water is zero. The dam has been modeled and analyzed using the FEM package GEOSTUDIO 2007 and its various modules namely SIGMA/W (Load-deformation for hydrostatic stresses) and QUAKE/W (Generation of initial static stress conditions and equivalent linear dynamic analysis for dynamic and hydrodynamic stresses).

Analysis of Pine Flat Dam

The hydrodynamic analysis of the Pine Flat Dam has been carried out under the action of 1952 Kern County strong motion recorded at Taft Lincoln station. For the analysis, the horizontal component of the motion (S69E) and the combined horizontal-vertical motion have been used; the motions were so chosen that a comparative study can be provided with the results reported by Chopra and Gupta (1981). The analysis has been carried out for both empty and full reservoir conditions to comprehend the effect of reservoir water on the seismic response of the dam. The hydrodynamic force have been determined using the methodology provided by Chwang and Housner (1978) and used on the upstream face of the dam (for a full-reservoir condition) in several segments to compromise on the variation of the continuous variation of the hydrodynamic pressure on the dam face. The entire analysis has been carried out in three stages which are described in the subsequent sections.

Stage I: Empty Reservoir Condition

Initial Static Condition under Geostatic Stress: This sub-stage has been modeled using the QUAKE/W 'in-situ stress' module and is used to simulate the development of geostatic stresses in the dam in an empty reservoir condition (hence, just after the construction of the dam). The dam rests on a 30m thick foundation rock. Both the dam and foundation has been considered to be perfectly rigid, and has been represented by a linear elastic model. The unit weight of the dam and foundation has been considered as 25 and 26 kN/m³ respectively, the Young's modulus of the material are 22.5 and 68.94 GPa respectively, while the Poisson's ratio has been considered to be 0.2 and 0.33 respectively. The bottom of the foundation rock has been restrained from both horizontal and vertical movements, while the far-off lateral boundaries have been restricted from only horizontal displacements. Fig.2 depicts the GeoStudio model used.

Dynamic Condition: In order to simulate the dynamic response of the dam after construction, the QUAKE/W 'equivalent linear elastic dynamic' model has been used. Apart from the material parameters defined for the in-situ condition, the Damping ratio for both the material has been chosen to be 0.1, and the shear stiffness (G_{max}) for the dam and foundation has been chosen as 9.33 and 25.92 GPa respectively (Chopra and Gupta, 1981).

Stage II: Full Reservoir Condition

Initial Static Condition under Geostatic Stress: This sub-stage has been modeled as has been mentioned for Stage I.

Hydrostatic Stress Condition: The hydrostatic pressure has been applied on the upstream face of the dam using the 'Load-deformation analysis' unit of the SIGMA/W module. Based on the full reservoir level, the hydrostatic pressure is calculated for a triangular variation towards the base of the reservoir (Hydrostatic pressure, $P=\gamma h$, where γ is the unit weight of water and h is the depth from the reservoir water level), with a zero value at the reservoir water level. The hydrostatic pressure is applied through stress boundary conditions, which require the stress value to be provided either as a constant or temporally varying. Unlike as stated, since the hydrostatic pressure varies continuously along the depth of the dam face below reservoir water level, which is not possible to be applied directly through stress boundary conditions. Hence, the upstream face of the dam has been divided into several segments (each segment being marked by two nodes of the finite element discretization), and the average of the hydrostatic pressures on those particular segments has been applied as the average constant hydrostatic pressure on the corresponding segment. Hence, the continuous hydrostatic pressure is applied as stepped incremental pressure on the segmented upstream face of the dam. The hydrostatic pressure boundary condition is shown in Fig. 3.

Dynamic Condition: This sub-stage has been modeled as has been mentioned for Stage I.

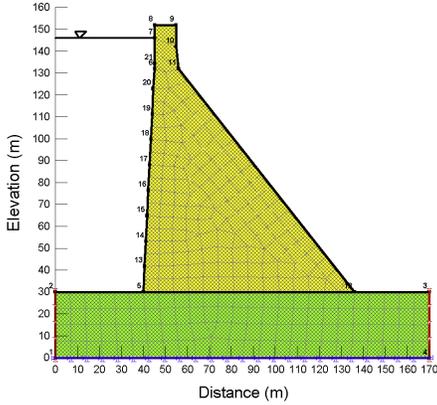


Figure 2 Geostatic stress condition

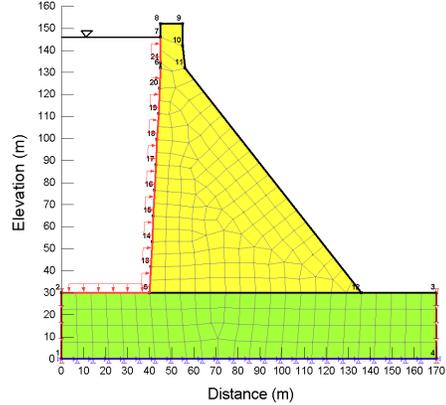


Figure 3 Hydrostatic stress condition

Stage III: Full Reservoir Condition

Hydrodynamic Stress: Hydrodynamic stress, generated due to colliding reservoir water with the dam face, is a coupled phenomenon, and requires a fluid-structure interaction module for its proper modeling and analysis. However, GEOSTUDIO 2007 does not have the same facility and cannot differentiate the reservoir water to be compressible/incompressible or viscid/inviscid. Hence, an uncoupled analysis have been attempted and reported to take into account the hydrodynamic stress analysis. Similar to the hydrostatic stress application, the hydrodynamic stress has also been applied on the segmented upstream face of the dam. Initially, following the Momentum method (Chwang and Housner, 1978) and based on the degree of inclination of the upstream face with the horizontal (θ), the variation of the hydrodynamic pressure coefficient (C_p) with the normalized depth below freeboard (y/h) has been determined (Fig. 4). Based on the peak ground acceleration coefficient of the strong motion (a_0), the hydrodynamic pressure is subsequently calculated as

$$p = C_p \gamma a_0 h \quad (1)$$

The estimated pressure corresponds to a pseudo-static condition, which has been subsequently modified to a temporal scale, $p(t)$. The dam and foundation material have been considered as infinitely rigid (owing to its high modulus of elasticity) and hence, does not affect the propagation of the strong motion (i.e. does not result in significant augmentation or attenuation) through the body of the dam and foundation. Hence, the estimated pseudo-static hydrodynamic pressures are multiplied with the corresponding strong motion temporal acceleration factor ($\alpha(t)$) as obtained from the strong motion data modified for the PGA). The modified hydrodynamic pressure is then algebraically added to the estimated pseudo-static pressure (computed earlier) so as to maintain the latter as the mean of the temporal variation of the hydrodynamic stress. The procedure can be represented as:

$$p(t) = p \pm \alpha(t) \cdot p = p [1 \pm \alpha(t)] \quad (1)$$

Similar to the application of hydrostatic pressure, the temporal hydrodynamic stress as estimated above is applied over different segments on the upstream face of the dam (Fig. 5). Fig. 6 depicts a typical variation of the hydrodynamic stress on one of the segments of the upstream face of the dam.

Results and Discussions

Static Analysis of the Pine Flat Dam

Under both empty and full reservoir conditions, the static analysis of the dam has been carried out to determine the in-situ and geostatic stresses generated in Pine Flat dam due to the material properties and geometry of the structure. The empty reservoir condition simulates the immediate post-construction behavior of the dam; while the full reservoir condition represents the situation when the reservoir has been filled completely up to the desired level (i.e. the hydrostatic pressure of water is active). Fig. 7 shows the distribution of mean total stress on the upstream face of the dam

for the above two conditions. For the empty reservoir condition, the variation is nearly linear since the stresses are affected only by the geometry and weight of the structure. Upon the application of hydrostatic pressure on the upstream face, the crest of the dam suffers a displacement away from the reservoir (~ 20 mm), which results in a significant stress reduction in the upstream face (as evident from Fig. 7) especially near the toe of the dam.

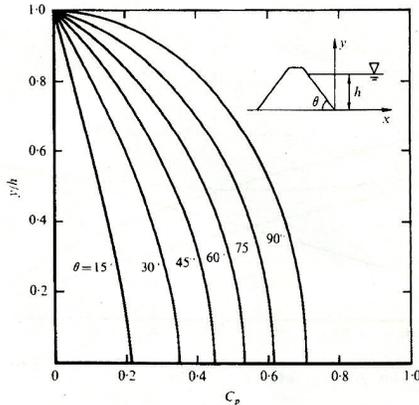


Figure 4 Variation of C_p (Chwang and Housner, 1978)

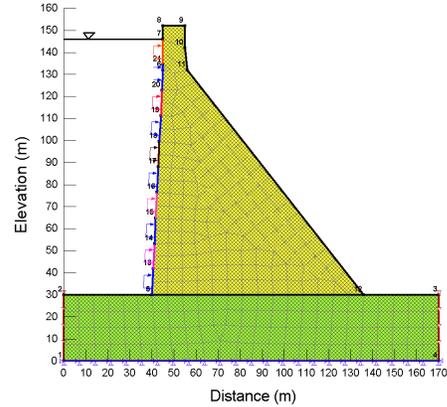


Figure 5 Hydrodynamic stress condition

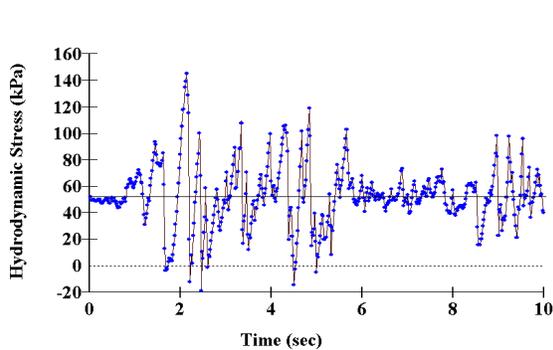


Figure 6 Typical temporal hydrodynamic pressures

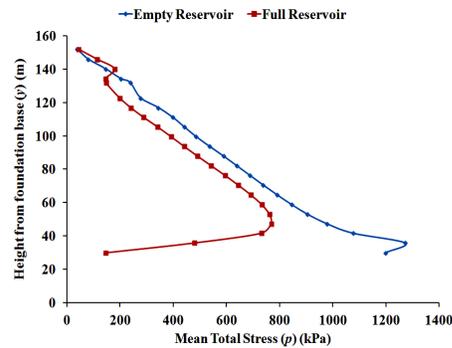


Figure 7 Variation of mean total stress under in upstream dam-face under static conditions

Dynamic Analysis of the Pine Flat Dam: 20 sec Kern County Motions

Pine Flat Dam had been subjected to the Kern County Earthquake in 1952, and hence the same strong motion recorded with the Taft Lincoln Station has been used for the dynamic analysis of the same. In order to validate the present FE model, as used by Chopra and Gupta (1981) in a coupled hydrodynamic analysis, the first 20 sec of the motion (only horizontal and combined components) have been used in the present preliminary study with the corresponding PGAs as mentioned earlier. Fig. 8(a) depicts the variation of mean total stress in the upstream face under empty reservoir condition when only the horizontal S69E component has been used in analysis. It has been observed that although the PGA of the 20sec motion occurs at 6.6 sec, the maximum mean total stress occurs at a time step (6.7 sec) beyond the occurrence of PGA. The stresses at these two time-steps are significantly different from each other and are attributed to the accumulation of stresses during the earthquake motion. The dam also experiences tensile stresses towards the end of the seismic motion as evidenced from the negative stresses experienced. Similar exercise has been carried out considering the full reservoir condition (i.e. in the presence of hydrostatic pressure). As depicted in Fig. 8(b), the outcome has been similar to Fig. 8(a). The attempt has been repeated with the combined use of S69E and the vertical component of the Kern County motion, and the results have been compared with that reported by Chopra and Gupta (1981). Table 1 enlists the comparative for the full reservoir condition which shows a reasonable agreement between the results.

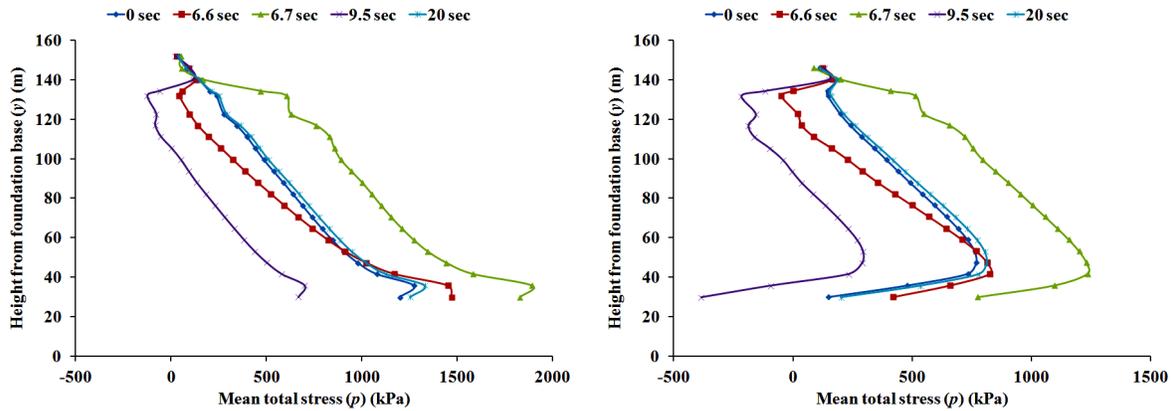


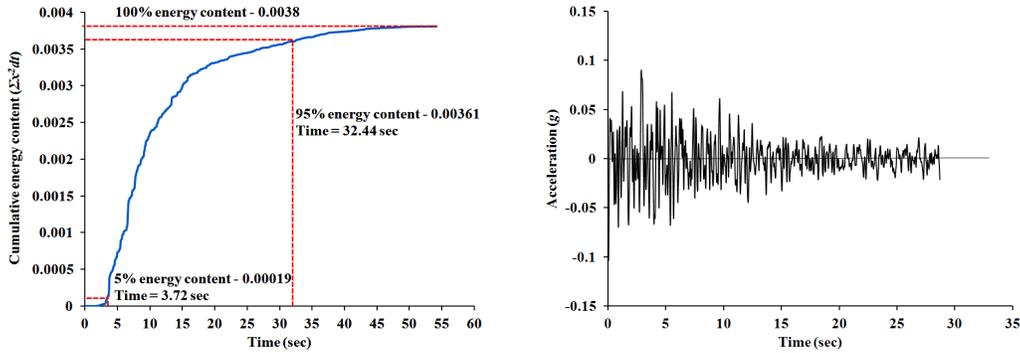
Figure 8 Variation of mean total stress for S69E component with (a) empty and (b) full reservoir conditions

Table 1 Comparative study of mean total stresses under full reservoir condition

Full Reservoir Condition	S69E component		S69E and Vertical components	
	GeoStudio modeling	Chopra and Gupta (1981)	GeoStudio modeling	Chopra and Gupta (1981)
Max. mean total stress on the u/s face (kPa)	1235.38	1055.7	1271.93	1221.3
Max. mean total stress on the d/s face (kPa)	1156.89	1435.2	1178.24	1552.5
Relative crest displacement (mm)	21	35	21	37

Dynamic Analysis of the Pine Flat Dam: Modified Kern County Motions

Chopra and Gupta (1981) considered the first 20 sec motion for the dynamic analysis using PGAs as 0.15g and 0.083g for the horizontal and vertical component respectively. However, this motion includes a rising part of significant time duration (~5 sec) beyond which the prominent intensity of the earthquake is experienced. Moreover, the actual Kern County motion is of significantly higher duration (54.14 sec) having a very long decaying tail as well. Hence, a 20 sec segment of the complete motion [as adopted by Chopra and Gupta (1981)] will not be a precise complete representation of the input motion. In order to assess the complete dynamic response of the dam, it is necessary to use the entire input motion. However, in this consideration, it is not advisable to use the PGA for the estimation of the mean temporal hydrodynamic pressure at a particular point on the upstream face of the dam. The PGA occurs momentarily, while the mean hydrodynamic stress is evaluated for the entire time duration, and is liable to be overestimated if the afore-mentioned procedure is used. In order to tackle such overestimation, the methodology proposed by Trifunac and Brady (1975) has been used. Instead of utilizing the entire strong motion history, the technique suggests to use only the effective duration that accommodates the stationary content of the signal (that part of the signal containing the significant maximum energy of the entire strong motion). This method is well suited for the signals having large anterior transition and posterior decay. The postulate suggests using the central 90% of the motion having the significant energy content. The same has been used to estimate the effective time duration for the Kern County motion components. Fig. 9(a) depicts the determination of the stationary content of the horizontal S69E component, pertaining to time duration of 3.72 sec to 32.44 sec. The root mean square (RMS) acceleration computed for this duration is obtained as 0.034g, and the maximum probable acceleration (MPA) is estimated to be three times the RMS acceleration (= 0.103g). The estimated MPA is considered to be the PGA of the modified motion (of time duration 2.73 sec). Fig. 9(b) shows the modified S69E component of the strong motion, which is further used for the present study. Similar exercise for the vertical component modified the time duration to 31.37 sec, and the MPA is obtained as 0.063g.



**Figure 9 (a) Significant energy content of a strong motion as per Trifunac and Brady (1975)
(b) Stationary content of strong motion signal and estimation of MPA**

The modified Kern County horizontal and vertical components are utilized as the input motions in the GeoStudio FE model and the dynamic response of the dam are inspected. It is observed that the magnitudes of mean total stress for various conditions reduces as compared to the 20sec motion as has been used earlier, the latter exercise yielding more realistic results in terms of reducing the degree of overestimation. Table 2 provides a comparative of the results as reported by Chopra and Gupta (1981) to those obtained in the present study using the 20 sec S69E motion and 28.73 sec of the modified S69E motion. Apart from the maximum mean stresses, the maximum crest displacement is also significantly reduced which definitely leads to a more engineered and economic design of the dam geometry and configuration.

Table 2 Comparative study of mean total stresses for Kern County S69E motion

Full Reservoir Condition	GeoStudio modeling		Chopra and Gupta (1981)
	20 sec S69E	28.73 sec modified S69E	
Max. mean total stress on the u/s face (kPa)	1235.38	1034.57	1055.7
Max. mean total stress on the d/s face (kPa)	1156.89	783.25	1435.2
Relative crest displacement (mm)	21	12	35

Hydrodynamic Analysis of the Pine Flat Dam: Modified Kern County Motions

Using the mean hydrodynamic stress obtained from the stationary content of the Kern County strong motion components, the temporal and spatial variation of the hydrodynamic stresses on the upstream face of the dam is determined. As enlisted in Table 3, the magnitudes of the stresses reveal that in comparison to the results obtained by Chopra and Gupta (1981), utilization of the stationary content of the signal results in the reduced hydrodynamic stresses on the dam face. It is also noticed that the hydrodynamic stresses and the relative crest displacement does not change with the inclusion of the vertical component in the excitation motion. This is attributed to the fact that in the present study, the temporal variation of the applied hydrodynamic stress at specified locations on the upstream dam-face has been determined solely on the basis of horizontal component, and hence the effect of the vertical component is not portrayed in the estimated hydrodynamic stresses. However, it is worth mentioning that a dam of irregular structure shows the non-coincidence of the centre of stiffness and centre of application of vertical seismic force, and hence, the effect of vertical

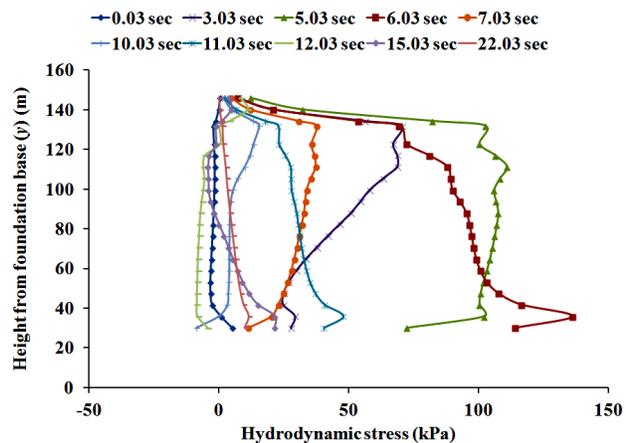


Figure 10 Typical hydrodynamic stress variation

component of the strong motion should also be used for the estimation of the applied hydrodynamic stresses.

Fig. 10 shows a typical variation of the temporal and spatial variation of the hydrodynamic stresses on the upstream face of the dam as obtained from the present study. The figure reveals that hydrodynamic pressure significantly varies with time, as well as along the height of the dam, during the occurrence of an earthquake. Due to the stress accumulations during seismic motions, the maximum hydrodynamic pressure, in most cases, had been observed to occur beyond the PGA time-step. The observed variation is substantially different than that defined by the 'exact theory' or the 'momentum method', as shown in Fig. 4 (Chwang and Housner, 1978). It can be well noted that the maximum hydrodynamic pressure need not always occur near the toe of the dam (which is portrayed by the pseudo-static analysis), rather can occur anywhere along the height of the dam during the occurrence of strong motion.

Table 3 Comparative study of hydrodynamic stresses and relative crest displacement

Full Reservoir Condition	GeoStudio modeling		Chopra and Gupta (1981)	
	S69E (modified)	S69E+ Vertical (modified)	S69E	S69E+ Vertical
Max. mean total stress on u/s face (kPa)	156.8	156.8	483	420.9
Max. mean total stress on d/s face (kPa)	126.9	126.9	317.4	55.2
Relative crest displacement (mm)	2.2	2.2	11	6.6

Conclusions

The article reports the response of a concrete gravity dam subjected to seismic motions considering hydrodynamic effects. Stage-wise analysis has been carried simulating various conditions of geostatic, hydrostatic, seismic and hydrodynamic stress developments. Geostatic stresses, as expected, are found to vary linearly with the depth of the dam, while the presence of hydrostatic stresses lowered the stresses developed at the upstream dam face. In case of seismic motions, the maximum stress accumulated in the dam is observed at a time-step beyond the occurrence of the PGA. Strong motions have been found to generate tensile force in the dam face as well. Hydrodynamic stresses have been applied on the upstream dam face at specified locations and its overall effect on the upstream face of the dam has been investigated. Instead of using the entire strong motion, the stationary content of the strong motion with modified PGA has been applied to have a realistic assessment of the dynamic and hydrodynamic response of the dam. Comparison with the earlier literature shows a significant reduction in the generated stresses. The hydrodynamic stress is found to significant temporal and spatial variation in case of a seismic event, which is substantially different as conventionally treated by the pseudo-static methods, and should be accounted in the design and analysis of such dams.

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