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Seismic Analysis of Earthen Dams Subjected to Spectrum Compatible and Conditional Mean Spectrum Time Histories

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ABSTRACT

The present work attempts to study the seismic behaviour of two earthen dams, *viz.* Chang and Kaswati dam, located in Gujarat, India for different sets of time histories. Each set comprises eight earthquake time histories, where one time history set is compatible to Indian Standard IS-1893(1)-2016, Type –II spectrum (SC) and another time history set is compatible to Conditional Mean Spectrum (CMS) as per the recent state-of-art related to selection of time histories for dynamic analysis. Numerical simulation has been carried out in Geo studio (2012) software which uses the finite element method for analyzing the earthen dams and includes SEEP/W, SLOPE/W and QUAKE/W analysis for estimating seepage, slope stability and dynamic response, respectively. Steady-state method is used to determine the seepage through the dam body in seepage analysis and Morgenstern-Price method is used to determine the factor of safety in stability analysis. The failure phenomenon in the earthen dam after the application of earthquake load is studied, in which the dam material follows Mohr-Coulomb failure criterion. The reservoir level has been considered as one of the parameters for the numerical study. It is observed that the water level in the upstream has a significant effect on relative horizontal displacement as well as relative vertical displacement of the dam crest, amplification of ground motion at the dam crest and post-factor of safety of the dam for the considered sets of earthquake time histories. Moreover, it is also concluded that the selection of time histories is a very important step for seismic analysis of dams.

KEYWORDS: Earthen dam, Conditional mean spectrum, Spectrum compatible time histories, Soil amplification.

INTRODUCTION

Earthen dams are the most common type of dam because of easy availability of construction material and low construction cost. A number of earthen dams exist all over India for irrigation, hydroelectric power generation, flood mitigation and drinking purpose. The failure of an earthen dam during a strong earthquake can cause a disaster and hence loss of life and properties. Therefore, proper designing of earthquake-resistant dams is very important. Moreover, it is also important to analyse the earthen dam for earthquake load so as to ensure the level of safety.

Though failure of a dam occurs occasionally, several studies have been conducted in India and abroad to

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know the reasons of failure. Singh et al. (2005) analyzed the seismic behaviour of six earthen dams (i.e, Chang, Shivlakha, Suvi, Tapar, Fatehgadh and Kaswati dams) in Gujarat by using the acceleration time history of 2001 Bhuj earthquake and observed that out of the six dams, Chang dam suffered from severe slumping, whereas Shivlakha, Suvi and Tapar dams were severely affected, especially over the upstream section. Shatnawi (2012) studied the reduction in the storage capacity of Alghadeer Alabyadh dam in Jordan along with the nature of the bottom sediments, using GIS techniques. Tatewar et al. (2012) studied the stability analysis of Bhimdi earthen dam located in Amravati area of Maharashtra state and concluded that the berm width is directly affecting the stability of the dam. Charatpangoon et al. (2014) conducted seismic analysis of Fujinuma dam by considering the input motion of 2011 Tohoku earthquake ($M_w = 9$) and concluded that it is very important not only to design an earthquake-resistant dam, but the maintenance of existing dams needs to be carried out for seismic safety. Baghlani et al. (2014) proposed a procedure using genetic programming in conjunction with metaheuristics to find the optimal shape of a dam and for case study, they presented the optimization of Bluestone dam. Further, Asif Raja et al. (2014) studied the stability and seismic behaviour of Nara earthen dam and observed that the soil behaves linearly during static analysis, but after seismic analysis, due to the effect of non-linearity, soil stresses and displacements change from the linear elastic to the nonlinear elastic model. Aliberti et al. (2016) carried out a study on the seismic performance of the San Pietro dam by using different methods, such as pseudo-static, simplified displacement and dynamic 2D finite difference methods and observed that the analysis leads to an expected permanent displacement at the crest of the dam which was smaller than the service free board of the dam. Pavan et al. (2016) studied the seepage analysis of Ramanahalli earthen dam and found out the amount of flow passing through the section of embankment earthen dam using finite element software SEEP/W. Also, they studied the seismic behaviour of this earthen dam by using finite element software QUAKE/W. Castelli et al. (2016) considered the input motion of 1990 St. Lucia earthquake to analyze the dynamic response of the Lentini earthen dam and compared the results of free field 1D Plaxis simulation with those obtained by the EERA and MARTA codes. They concluded that all the codes used are quite in good agreement to each other. Arshad et al. (2017) determined the quantity of seepage passing through the Hub dam at different water levels (i.e., minimum, normal and maximum water levels), as well as the slope stability of Hub dam by different methods (i.e., Jambu, Bishop, ordinary slice and Morgenstern price methods) by considering different loading conditions (i.e., end of construction, steady-state seepage and rapid draw down). It was observed that the quantity of seepage is increasing as the water level increases. Olukanni et al. (2018) studied the application of a genetic algorithm in simulating the process of a multi-purpose reservoir with specific emphasis on Jenna hydropower dam, Nigeria. Recently, Pelecanos et al. (2018) studied the effect of dam-reservoir interaction on the nonlinear seismic response of earth dams and concluded that although hydrodynamic pressure has an insignificant effect on the dam crest accelerations, stress and strain development within the dam body can be significantly underestimated if dam-reservoir interaction is ignored.

The aim of the present study is to study seepage behaviour, variation of stresses, modal analysis and seismic response of Chang dam and Kaswati dam by changing various reservoir levels for the selected sixteen input motions, in addition to the variation of post-factor of safety of the selected earthen dams for the considered reservoir levels by using a commercially available finite element-based software; namely, Geo studio (2012).

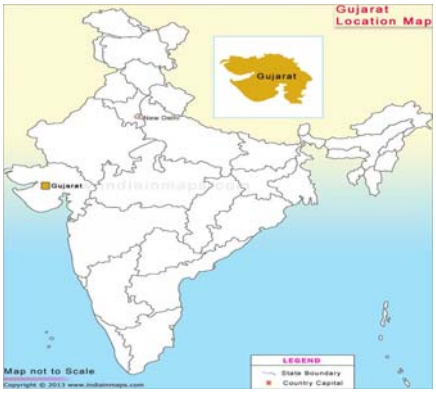
DAM DESCRIPTION AND SELECTION OF TIME HISTORIES

In the present work, Chang and Kaswati dams have been selected as representative earthen dams for post-earthquake analysis, as both of them are situated in

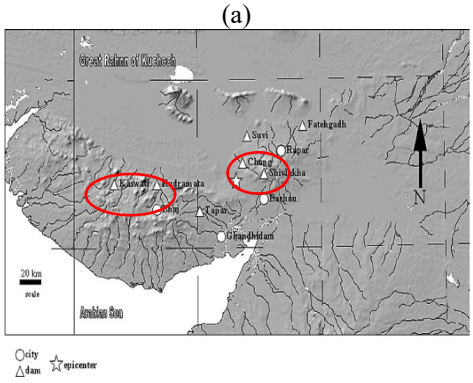
Gujarat (zone V) which is seismically active as per the seismic zoning map of IS 1893(1):2016. Both dams are multi-zone earthen dams to provide irrigation and drinking water in the state of Gujarat. Fig. 1 shows the location of the present study.

Chang Dam

Chang dam is a multi-zone earth dam constructed in 1959, in the state of Gujarat, India. It has a length of 80 m, a height of 19.5 m and a crest width of 6m, as shown in Fig. 2 (a). The dam was founded on sand and silt mixtures over shallow sandstone bedrock. During the 2001 Bhuj earthquake, the reservoir was nearly empty; however, researchers showed the presence of liquefaction (sand boils) attributed to the saturated foundation soil condition. Therefore, it is important to study the seismic analysis of the Chang dam for different levels of reservoir condition.



(a)

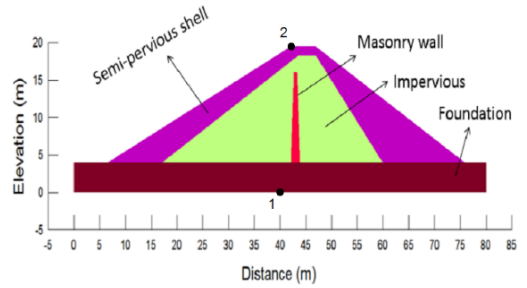


(b)

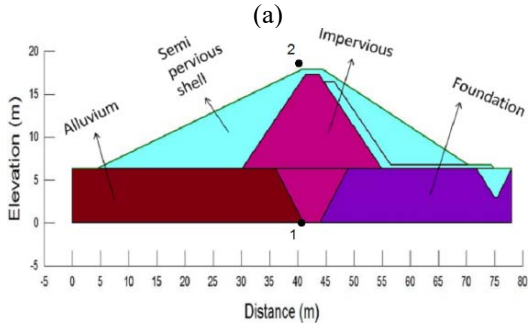
Figure (1): (a) Map of India and (b) Location of the present study

Kaswati Dam

Similar to Chang dam, Kaswati dam is also a multi-zone earth dam, constructed in 1973, with a length of 78 m, a height of 18 m and a crest width of 4 m, as shown in Fig. 2 (b). The dam was founded on loose to medium dense silt sand mixtures. There was limited experimental data of the site. Similar to Chang dam, the reservoir behind Kaswati dam was nearly empty at the time of Bhuj earthquake, but the alluvium soil underneath the dam was in a saturated state. As reported by Singh et al. (2005), the EERI reconnaissance team had reported liquefaction of foundation soils in the upstream side. The downstream slope, on the other hand, remained largely unaffected.



(a)



(b)

Figure (2): Geometric model of (a) Chang dam and (b) Kaswati Dam

Though the selected dams had formerly different geometric properties, from comparison point of view, the same material properties have been considered from the literature (Singh et al., 2005) for both dams, as shown in Table 1. In case of dynamic properties of soil, generic curves; i.e., modulus reduction and damping

ratio curves proposed by Seed and Idriss (1970) have been used, as shown in Fig. 3.

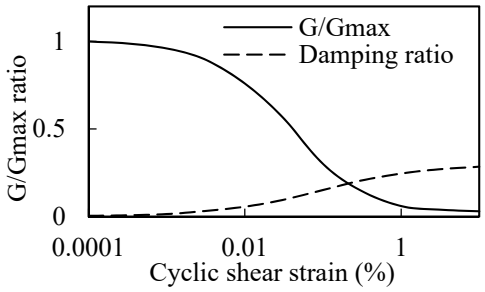


Figure (3): Modulus and damping ratio curves (Seed and Idriss, 1970)

In this study, the dams have been considered as a 2D plane strain model, in which meshing has been carried out by considering 3- m element size of triangular and quadratic elements. It is found that the total numbers of nodes and elements are 357 and 106 for Chang dam and 430 and 135 for Kaswati dam, respectively. In this study, the dam has been modelled both in Geo studio and ABAQUS software. In Geo studio, SEEP/W, SLOPE/W and QUAKE/W have been used for estimating seepage, slope stability and dynamic response, respectively. The ABAQUS code has been used to determine the mode shapes and natural frequencies of both dams in order to study the seismic response. The boundary conditions were restrained in the horizontal and vertical directions at the bottom of the model. For both edges, the boundary conditions were fixed only in the lateral direction and were free in the vertical direction. The behaviour of the dam materials is described using the Mohr-Coulomb soil model. The dam's body was classified into three portions: upper, middle and bottom, where the modulus of elasticity (E) is assumed to be constant in the respective portions of the dam. The reservoir pressure on the upstream face was applied as static pressure acting on the upstream slope in a direction perpendicular to the upstream face and the interaction between the reservoir and dam body was neglected. To acquire the initial stress condition, static and seepage analyses were conducted in advance.

Time History Selection

Dynamic analysis is recommended for embankments located over active fault zone, the failure of which may lead to high levels of risk. Dynamic analysis essentially involves the estimation of the deformation behaviour of an earthen dam or an embankment using the finite element method or finite difference method. The results of such analyses are sensitive to the input seismologic parameters. In dynamic analysis, the choice of suitable earthquake record is an important issue. The recorded time histories can be used directly or after making them compatible with the design code spectra. However, the process of making recorded time histories compatible to target spectra can lead to distortions in frequency content. In contrast to this, Adhikary et al. (2014) justified the use of spectrum-compatible (SC) time histories, despite frequency content distortion. Baker (2011) proposed a tool for ground-motion selection known as conditional mean spectrum (CMS). He showed that the commonly used method of selecting time histories that match the target spectrum is an unsuitable target, as it conservatively implies large spectral values at all periods within a single ground motion. An alternative method, termed as conditional mean spectrum method, in which the spectrum is formed by concentrating the spectral value at period of interest, was proposed by him.

In the present study, two sets of strong ground motion data have been selected, each having eight numbers of earthquake records. In the first set, the earthquake records have been made compatible to IS 1893(1):2016 response spectra of medium soil (Type-II). For this spectrum compatibility, the recorded time histories were first scaled to target peak ground acceleration (i.e., 0.36 g) in the time domain and then made compatible with the required target spectra (i.e., 1893-I: 2016 response spectra of medium soil), using wavelet-based spectral matching procedure (Mukherjee and Gupta, 2002). The IS 1893 response spectra of medium soil (Zone V) and their compatible time histories are shown in Fig. 4. In the second set, the recorded time histories compatible to Conditional Mean

Spectrum (CMS) have been selected using the methodology proposed by Baker (2011). In this case, by performing modal analysis, the fundamental time period of Chang dam and Kaswati dam has been obtained as 1.58 s and 1.47 s, respectively. Further, the CMS has been obtained for the spectral values of 0.3 g and 0.32 g at 1.58 s and 1.47 s period of interest, respectively. As the difference between obtained spectral value of both dams is very little (i.e., 0.02 g), CMS obtained for both the dams is more or less the same, as can be observed in Fig. 3. Hence, the time histories matched to CMS of both dams are the same and have been obtained from PEER (Pacific Earthquake Engineering Research Center) ground motion database (shown in Fig. 5).

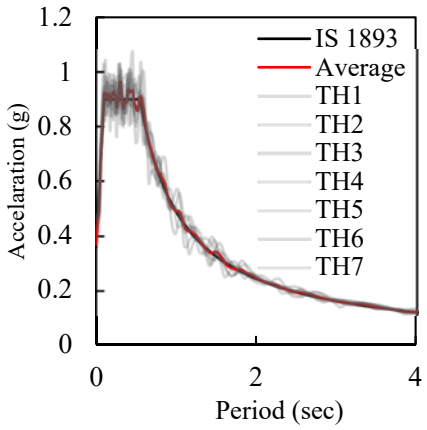


Figure (4): Target IS 1893 Type-II spectra along with compatible spectra of time histories

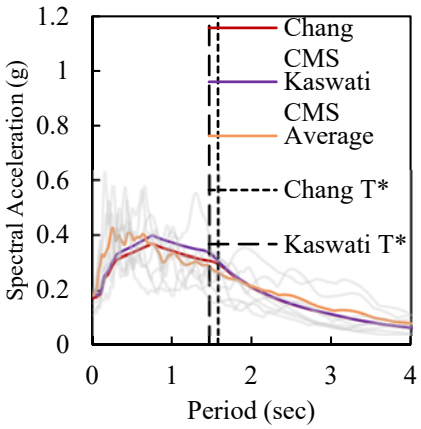


Figure (5): CMS for Chang dam and Kaswati dam along with spectra of time histories matched to CMS

Table 1. Material properties of Chang and Kaswati dams (Singh et al., 2005)

Material Name	Unit weight (kN/m^3)	Cohesion (kPa)	Poisson's ratio	Phi (degree)
Semi-pervious shell	18	9	0.35	30
Impervious core	20	65	0.35	0
Masonry wall	22	80	0.4	0
Alluvium	18	0	0.35	0
Foundation	18	0	0.35	0

RESULTS AND DISCUSSION

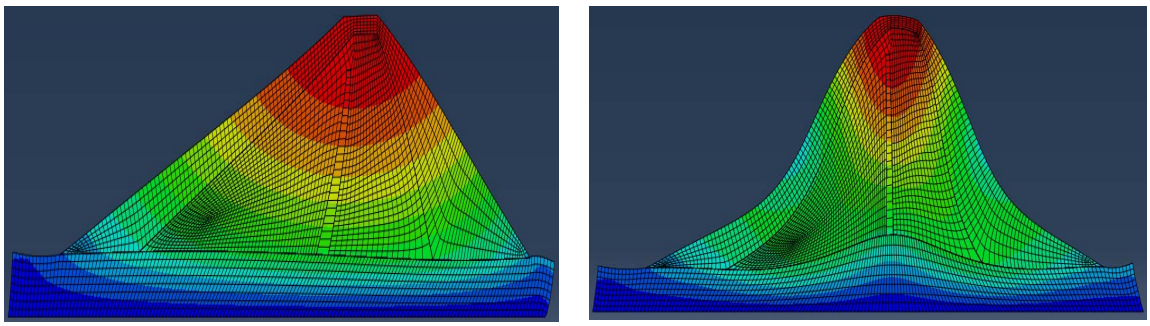
Modal Analysis

Modal analysis has been conducted for Chang and Kaswati dams to determine the natural frequencies and their corresponding mode shapes. Before the performance of dynamic analysis, free vibration analysis is very important, since it depicts the natural frequencies of the structure. If the earthquake record has a predominant frequency in that range, there may be an occurrence of resonance which may lead to great structural damage (Chakraborty et al., 2019). In this study, modal analysis has been performed by using ABAQUS software, version 2017. The results of modal analysis of Chang dam and Kaswati dam are shown in Fig. 6 and Fig. 7, respectively. The natural frequencies

of the first two modes of Chang dam are 0.63 Hz and 0.97 Hz, respectively. Similarly, the natural frequencies of the first two modes of Kaswati dam are 0.68 Hz and 0.98 Hz, respectively. From the modal analysis results, it has been observed that the first mode is in horizontal direction, whereas the second mode is in vertical direction. Both models of the dams were considered to be in empty reservoir state for modal analysis.

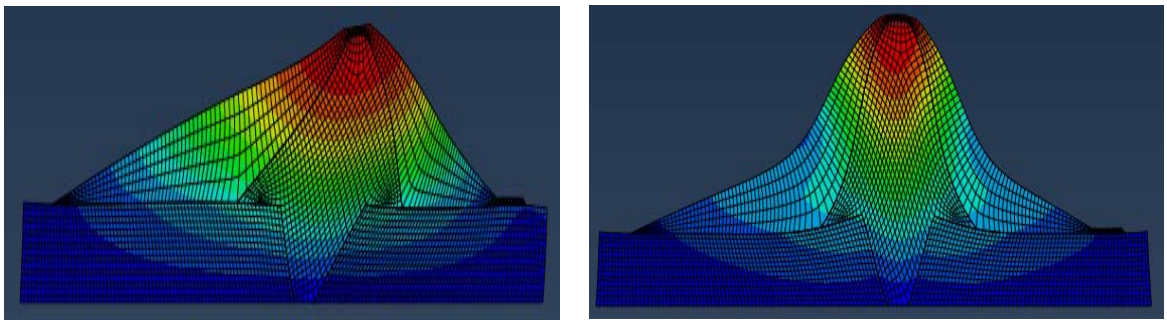
Seepage Analysis

The seepage analysis of Chang dam and Kaswati dam has been carried out by using SEEP/W program of Geo studio software. The method and the soil model used in this case study are shown in Table 2 and seepage analysis has been carried out by considering different heights of water level (i.e., 5 m, 10 m and 15 m for Chang dam and 7 m, 12 m and 17 m for Kaswati dam, respectively). The pore water pressure contours are shown in Figs. 8 and 9 for Chang dam and Kaswati dam, respectively. Results of seepage analysis in terms of seepage and seepage velocity are shown in Table 3 and Table 4 for Chang dam and Kaswati dam, respectively. From seepage results, it is observed that the contours of pore water pressure increase as the water level increases. It is observed that both seepage and seepage velocity are increasing with the increase of reservoir level, as expected.



(a) (b)

Figure (6): Natural frequency for Chang dam. (a)1st mode:0.63 Hz (horizontal direction) and (b)2nd mode: 0.97 Hz (vertical direction)



(a) (b)

Figure (7): Natural frequency for Kaswati dam. (a)1st mode:0.68 Hz (horizontal direction) and (b) 2nd mode: 0.98 Hz (vertical direction)

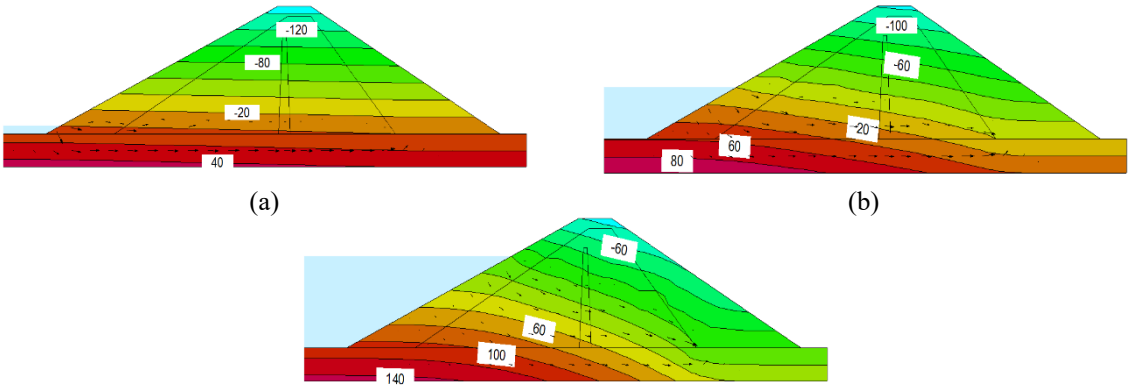


Figure (8): Contours of pore water pressure of Chang dam at (a) 5 m, (b) 10 m and (c) 15 m water level

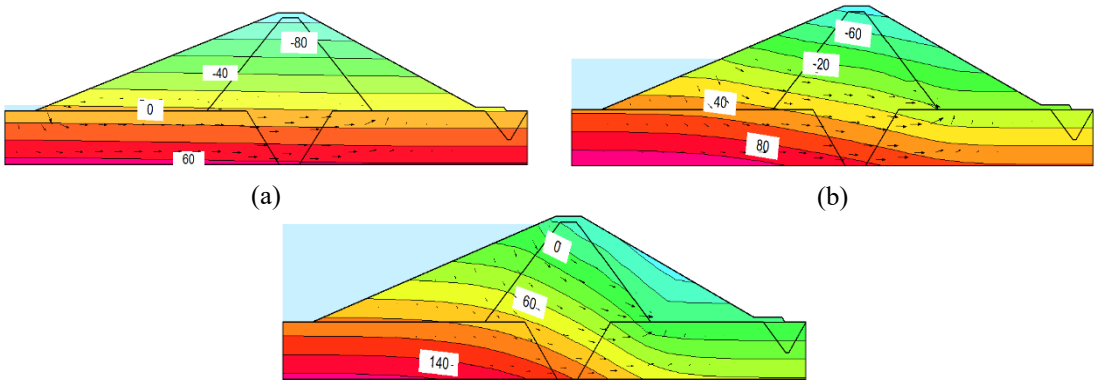


Figure (9): Contours of pore water pressure of Kaswati dam at (a) 7 m, (b)12 m and (c)17 m water level

Table 2. Description of SEEP/W analysis

Soil model	Analysis method	Boundary conditions
Saturated/unsaturated for impervious, semi-pervious and masonry wall Saturated only for foundation	Steady-state method	Reservoir pressure on U/S, seepage face and zero pressure on D/S.

Table 3. Computed parameters of Chang dam for different water levels

Parameters	At 5 m water level	At 10 m water level	At 15 m water level
Seepage (m^3/sec)	8.719×10^{-7}	9.84×10^{-6}	3.025×10^{-5}
Seepage velocity (m/sec)	4.22×10^{-7}	4.66×10^{-6}	6.922×10^{-6}

Table 4. Computed parameters of Kaswati dam for different water levels

Parameters	At 7 m water level	At 12 m water level	At 17 m water level
Seepage (m^3/sec)	9.088×10^{-7}	1.369×10^{-5}	4.926×10^{-5}
Seepage velocity (m/sec)	3.164×10^{-7}	4.813×10^{-6}	9.295×10^{-6}

Dynamic Analysis

Dynamic analysis of Chang dam and Kaswati dam has been carried out by considering QUAKE/W program of Geo studio software. Equivalent linear dynamic method of analysis has been used along with equivalent linear soil model. Figs. 10 and 11 show the relative displacement time histories (*viz.* horizontal and vertical) for Chang dam, obtained at different reservoir levels (RL) for bracketed duration of the typical time histories considered. It has been observed that for Chang dam, the variation between relative horizontal displacement time history obtained at crest for 5 m, 10 m and 15 m reservoir levels is very little as compared to the variation of relative vertical displacement time history for both sets of time histories considered. Similar observations are obtained for Kaswati dam, as shown in Figs. 12 and 13. However, in the case of Kaswati dam, the response for 7 m and 12 m reservoir levels has an insignificant difference. Moreover, the relative vertical displacement obtained at 17 m RL increases drastically as compared to the response at 7 m and 12 m. Further, the peak relative displacement of each set of time histories for all the considered reservoir levels is plotted in Fig. 14 and Fig. 15 for Chang dam and Kaswati dam, respectively. It has been observed that there is an increase of relative horizontal and relative vertical displacements at the crests of the dams as the reservoir level increases. Also, it is interesting to note that the peaks of relative displacement for SC time histories are close to each other, whereas in the case of CMS time histories, the peak displacements fluctuate for both relative horizontal and relative vertical displacements. In addition, the response as obtained from SC time histories is higher as compared to that obtained from CMS time histories. Further, the amplification ratio has been evaluated by taking the ratio of spectral acceleration response at the crest of the dam (point 2, as shown in Fig. 2 a, b) to the input acceleration response (point 1 as shown in Fig. 2 a, b). Figs. 16 and 17 show the average amplification ratio for SC and CMS set of time histories for Chang dam and Kaswati dam, respectively. It has been observed that for lower period (i.e., upto 1 sec), the amplification ratio decreases as the reservoir level increases, whereas for longer period (greater than 1 sec), the amplification ratio increases with the increase in the reservoir level. Interestingly, for Kaswati dam, the amplification ratios for 7 m and 12 m RL coincide for both sets of time histories.

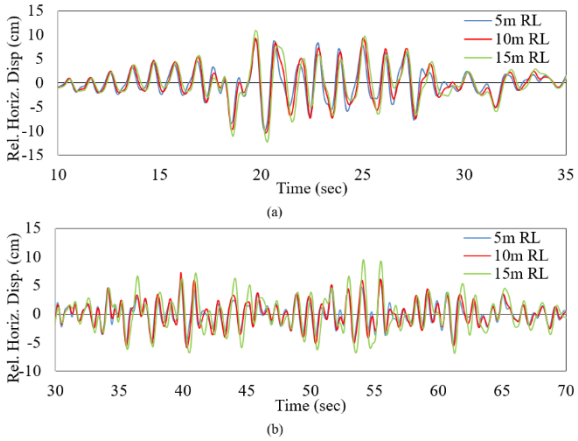


Figure (10): Relative horizontal displacement at the crest of Chang dam for different reservoir levels subjected to (a) SC time history (TH-5) and (b) CMS matched time history (TH-14)

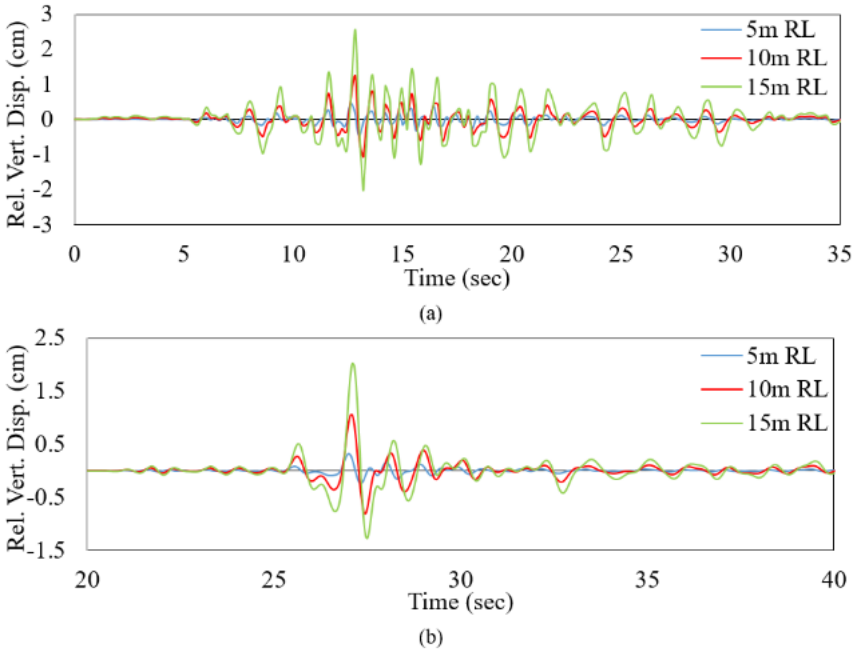


Figure (11): Relative vertical displacement at the crest of Chang dam for different reservoir levels subjected to (a) SC time history (TH-7) and (b) CMS matched time history (TH-10)

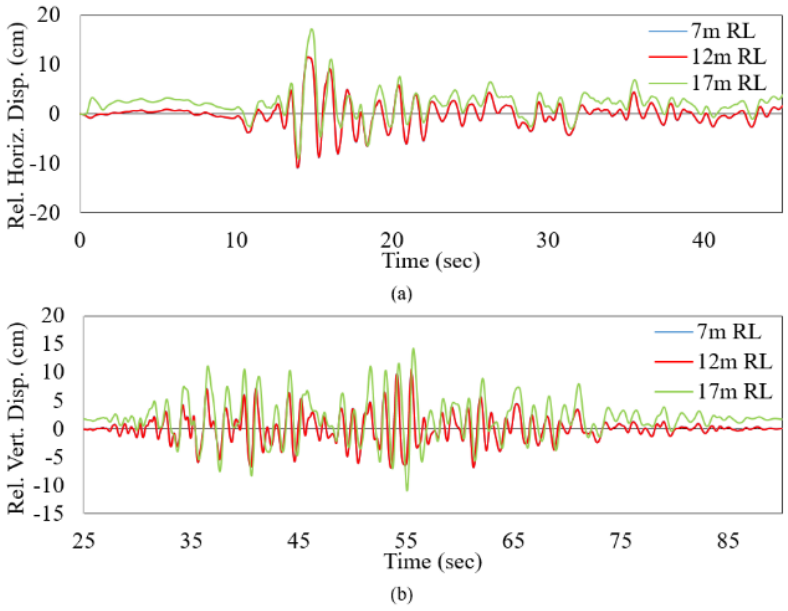


Figure (12): Relative horizontal displacement at the crest of Kaswati dam for different reservoir levels subjected to (a) SC time history (TH-4) and (b) CMS matched time history (TH-14)

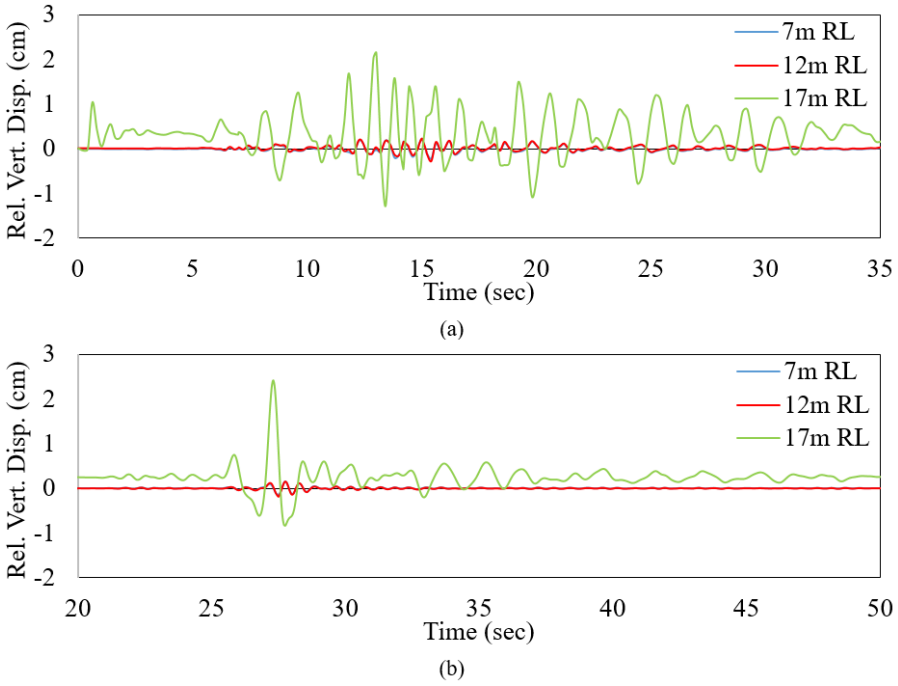


Figure (13): Relative vertical displacement at the crest of Kaswati dam for different reservoir levels subjected to (a) SC time history (TH-7) and (b) CMS matched time history (TH-10)

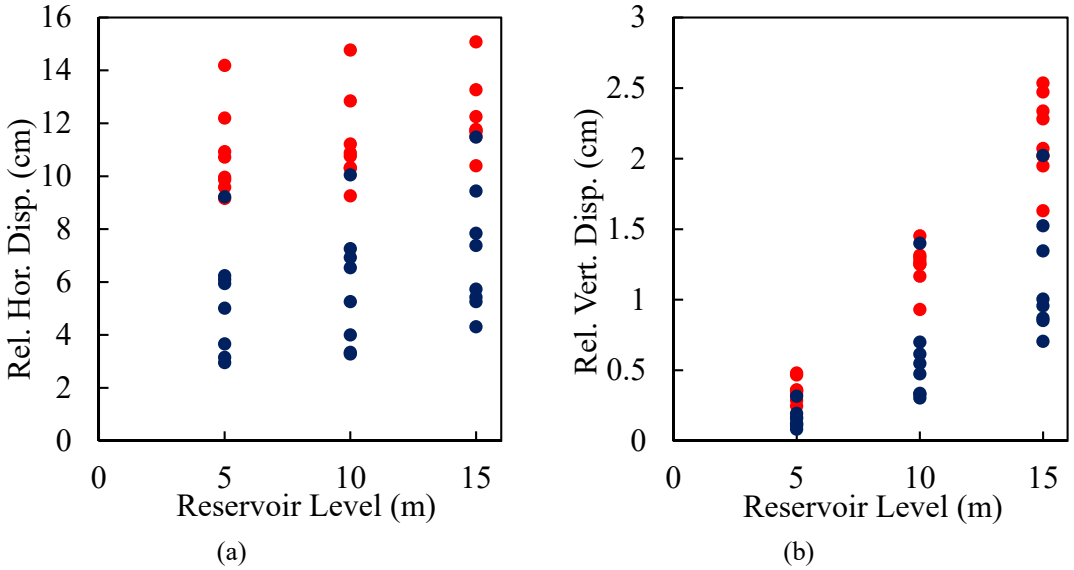
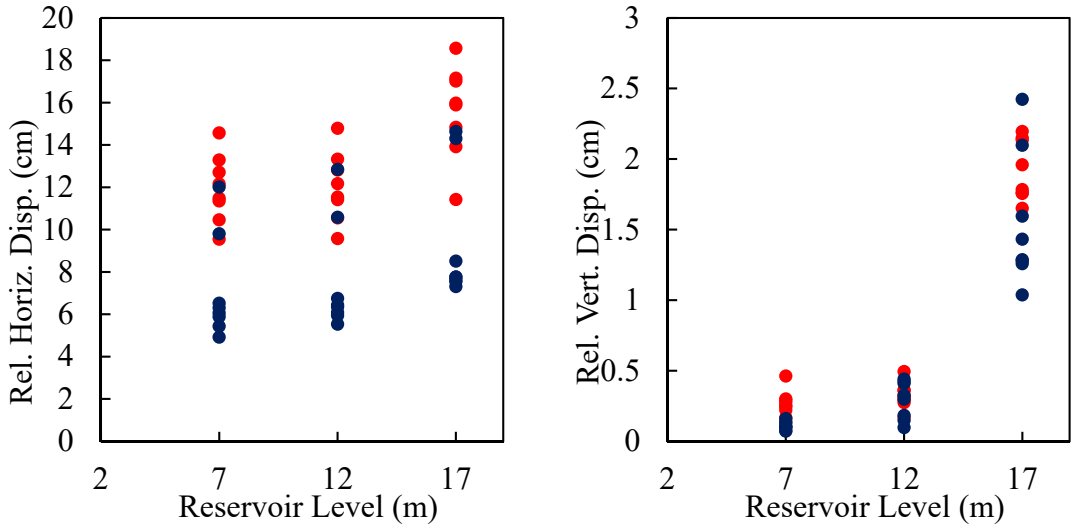
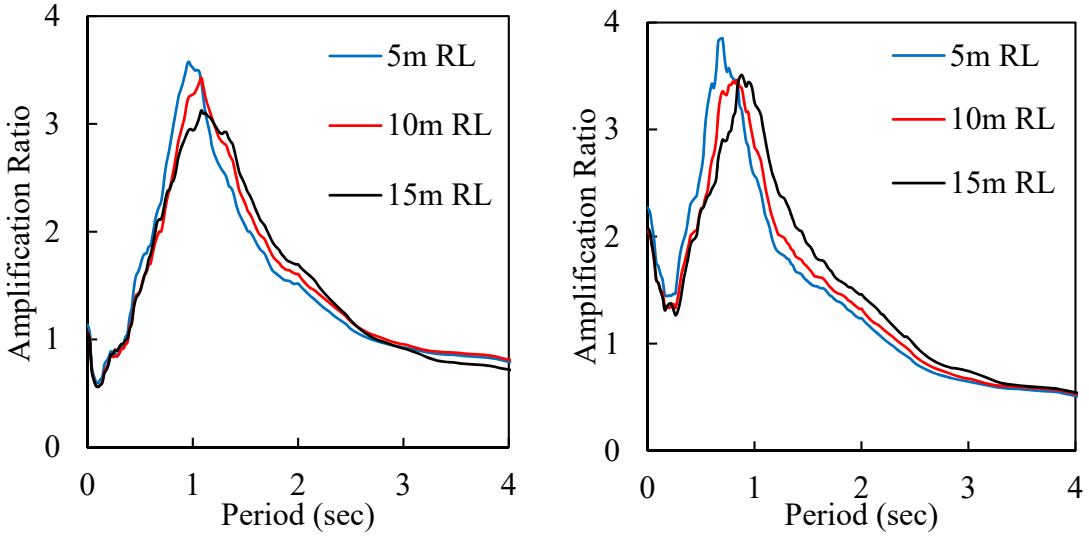


Figure (14): Peak relative (a) horizontal and (b) vertical displacement, at crest for various reservoir levels of Chang dam (red dots represent the peak relative displacement of eight considered SC time histories, whereas blue dots represent the peak relative displacement for eight CMS time histories)



(a) (b)

Figure (15): Peak relative (a) horizontal and (b) vertical displacement, at crest for various reservoir levels of Kaswati dam (red dots represent the peak relative displacement of eight considered SC time histories, whereas blue dots represent the peak relative displacement for eight CMS time histories)



(a) (b)

Figure (16): Average amplification ratio of Chang dam for (a) SC set of time histories (b) CMS set of time histories

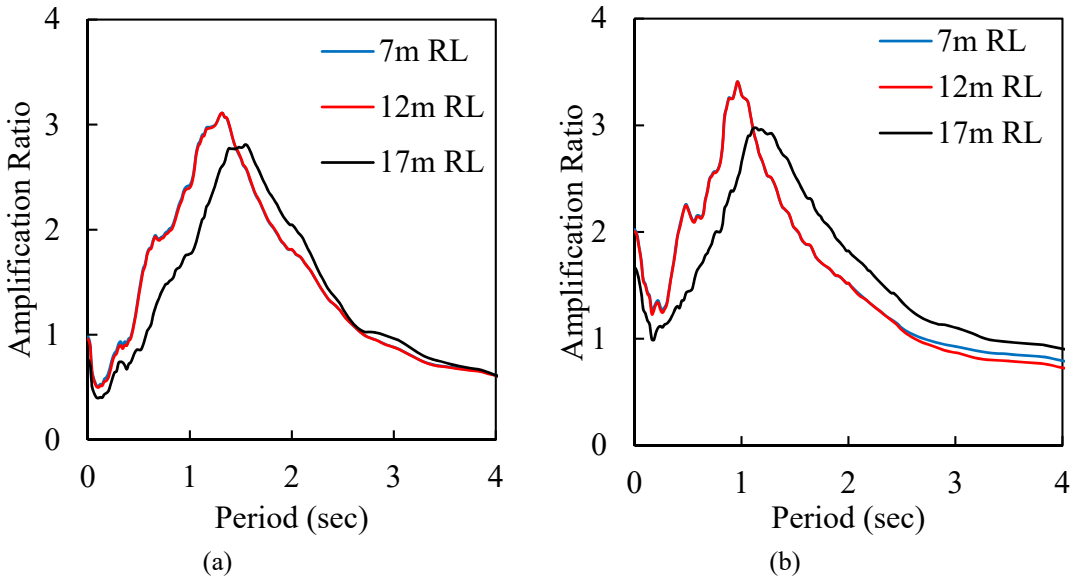


Figure (17): Average amplification ratio of Kaswati dam for (a) SC set of time histories (b) CMS set of time histories

Post-factor of Safety Analysis

Post-factor of safety has been computed after applying the earthquake on the upstream side of the dam by using SLOPE/W program of Geo studio software. Table 5 shows the analysis method, soil model and parent analysis used in the post-factor of safety analysis. Because of the presence of saturated alluvium in the foundation, it is observed that there is a generation of excess pore water pressure which causes liquefaction in the foundation. Since the slip surface is passing through the liquefaction zone, the factor of safety is less than unity. Results of post-factor of safety analysis are shown in Figs. 18 and 19 for Chang dam and Kaswati dam, respectively. From these figures, it is observed that the post-factor of safety is less than unity and is increasing with the increase in the reservoir level.

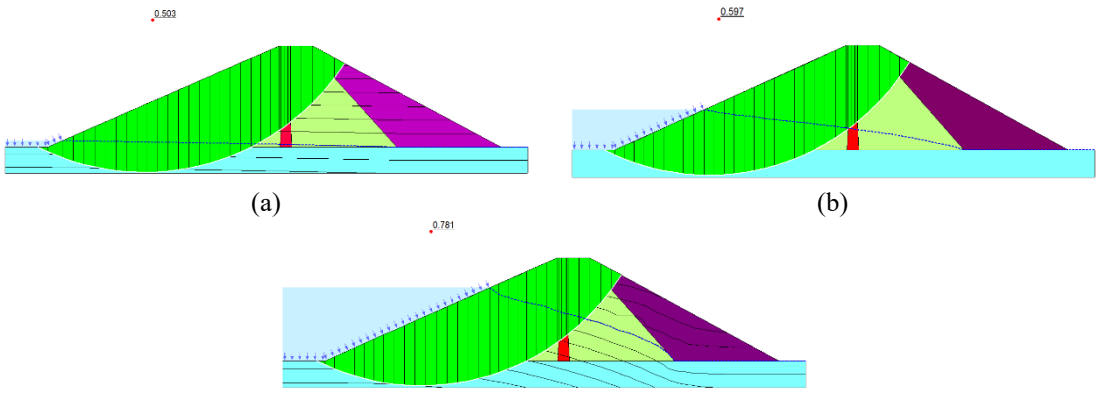


Figure (18): Post-factor of safety and slip surface of Chang dam at 5 m, 10 m and 15 m water levels

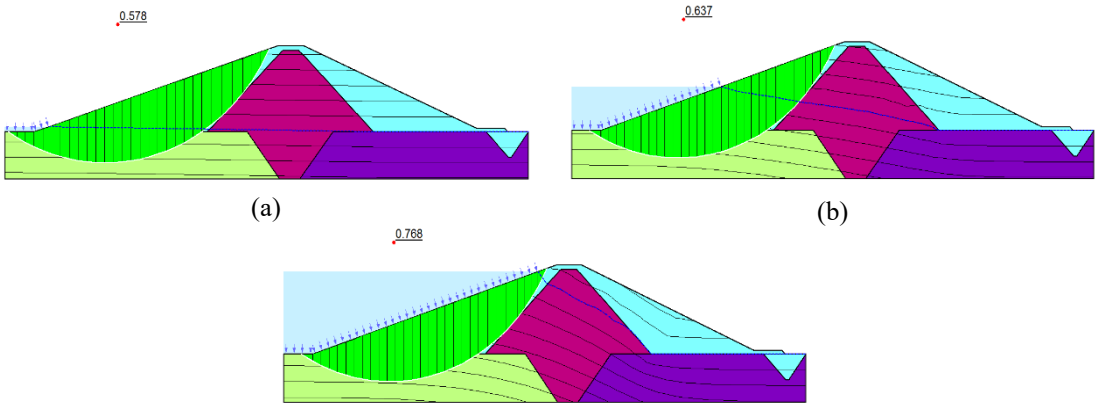


Figure (19): Post-factor of safety and slip surface of Kaswati dam at 7 m water level

Table 5. Description of post-factor of safety analysis

Soil model	Analysis method	Parent analysis
Mohr-Coloumb	Morgenstern-Price method	Dynamic analysis

DISCUSSION AND CONCLUSIONS

The present study investigates the seismic behaviour of two earthen dams, *viz*. Chang dam and Kaswati dam located in a seismically active region (zone factor of 0.36 g) of Gujarat, India, subjected to two sets of time histories. The first set of time histories is comprised of eight earthquake motions made compatible to Indian Standard IS-1893(1)-2016, Type-II, medium soil spectrum, while another set of eight time histories is selected, which were matched to the Conditional Mean Spectrum (CMS), where conditioning is carried out for the fundamental period of the earthen dams. The results show that the reservoir level has a significant effect on both seepage and seepage velocity with a linear relationship. For the different reservoir levels considered, it is observed that the relative horizontal displacement of the crest is insignificant as compared to the relative vertical displacement. This shows that for the dynamic analysis of earthen dams, the vertical response should also be studied and vertical ground acceleration time history should not be neglected. For the different sets of time histories considered, it is observed that the peak relative horizontal and vertical displacements of the crest are less for the CMS time histories as compared to the SC time histories, which indicates that CMS is a better representation of the earthquake scenario. The results also show that the dam crest may be subjected to amplification of time histories and in case of resonance, the response of the dam may be alarming. In addition, the generation of pore water pressure and the chance of liquefaction due to a saturated foundation condition should be investigated and not neglected.

ABBREVIATIONS

SLOPE/W: is a leading slope stability software for soil and rock slopes. It can effectively analyze both simple and complex problems for a variety of slip

surface shapes, pore-water pressure conditions, soil properties and loading conditions.

SEEP/W: is a powerful finite element software product for modeling groundwater flow in porous media. It can model simple saturated steady-state problems or sophisticated saturated / unsaturated transient analyses with atmospheric coupling at the ground surface.

QUAKE/W: is a powerful finite element software product for modeling earthquake liquefaction and dynamic loading. QUAKE/W determines the motion and excess pore-water pressures that arise due to earthquake shaking, blasts or sudden impact loads.

EERA: Equivalent -Linear earthquake analysis code of California.

MARTA: Metropolitan Atlanta Rapid Transit Authorities.

ABAQUS: A software that uses finite element and computer-aided engineering.

EERI: Earthquake Engineering Research Institute.

CMS: Consitional Mean Spectrum.

SC: Spectrum Compatible.

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