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Effects of the vertical component of ground motion on the seismic performance of Bhakra Gravity Dam

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Abstract. In this paper, the earthquake component effects on the seismic performance of Bhakra Gravity Dam in India are investigated. For the purpose, Bhakra Dam is modeled two-dimensionally considering dam-reservoir-foundation interaction. In the finite element modeling, dam and foundation are represented by PLANE182 elements in ANSYS with different material properties, and fluid is considered with FLUID29 elements. This type of element provides translation and pressure degrees of freedom. Linear time history analyses on the dam are performed by considering components of the 1991 Uttarkashi and 1999 Chamoli (NW Himalaya) Earthquakes in India. During the analyses firstly the horizontal component of earthquakes are applied to system and results are obtained, and then both of horizontal and vertical components are applied to the systems together. In the analyses, element matrices are computed using the Gauss numerical integration technique. The Newmark method is used in the solution of the equation of motions. Also, Rayleigh damping is considered. The seismic performance of Bhakra Dam is examined and presented by dynamic characteristics, displacements, principal stresses, and demand-capacity ratios. The results showed that the vertical components of the earthquake significantly affect the response of the dam. The results show that the vertical component with the horizontal component cause biggest tensile stresses compared to only the horizontal component for both earthquakes. However, displacement response is changed depending on the ground motion. As a conclusion of this study it can be said that the vertical component changes the structural response of the dam on both of the good and bad behaviors.

Keywords: Bhakra Gravity Dam; demand-capacity curve; finite element modeling; seismic performance; vertical component

1. Introduction

Dams retain huge amount of water within their reservoirs which are generally used to provide electricity, usage water, and fresh water. Hence, they have to be built against loads especially earthquakes. During an earthquake, large displacements and stresses may occur on the body of dams. Also, reservoir water behaves dynamically instead of acting hydrostatic pressure. Due to earthquakes, earth sliding may occur and fragile and damages may be on the slopes of dams and thus overflow may exist on the crest of dam which causes economical and life losses. From the past to present, many studies have been prepared to investigate the response of dams. However, the studies have to be separate due to different behaviors of dams such as concrete and earth dams.

Earth dams are classified as earth fill and rock fill dams, and concrete dams are classified as gravity, arch or roller compacted concrete dams. All of these dams behave separately and the researchers investigated specifically all these types of dams. The main references of these studies are presented by Lotfi *et al.* (1987), Gazetas (1987), Chopra (1988) and El-Aidi and Hall (1989). This study reflects the dynamics of a gravity dam by the different views of angle. Thus, the introduction and the literature review are prioritized.

Gravity dams are designed in such a way that its own weight resists the external forces. Also they can be easily constructed on site if the foundation is strong enough to bear dam's huge weight. Hence, they are preferred to design and construct. Geometrical design of such kind of dams depends on the ratio of base width to height. If suitable conditions are available, gravity dams will be constructed up to great heights such as Grand Dixence Dam in Switzerland (284 m) and Bhakra dam in India (226 m) (USDIBR 1976). The main load sources of gravity dams are listed as hydrostatic, uplift pressure, silt, ice wave pressures and pressure due to earthquakes (USACE 1995, USACE 2003). The earthquakes due unknown time, energy and intensity may cause many effects on the gravity dams. Hence, researchers are deeply investigated to earthquake response of gravity dams. These studies contain linear and nonlinear dynamic response of gravity dams, damage mechanism, experimental and numerical investigation of reservoir-dam interaction, seismic fracture analysis, effect of reservoir geometry, stochastic seismic response, shaking table tests (Bhattacharjee and Leger 1992, Valliappan *et al.* 1996, Proulx and Paultre 1997, Ghaemian and Ghobarah

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1999, Guanglun *et al*. 2000, Tekie and Ellingwood 2003, Calayır and Karaton 2005, Lotfi 2005, Millan *et al*. 2007, Arabshahi and Lotfi 2008, Phansri *et al*. 2010, Valamanesh *et al.* 2011, Bilici and Bayraktar 2012, Ardebili *et al*. 2013, Wang *et al*. 2014, Altunışık and Sesli 2014). In addition some recent studies related to gravity dams are summarized below.

Akpinar *et al*. (2014) examined the principal stresses and effective damping on a gravity dam after finite element analyses by inducing ground motion in lateral direction. Comparisons of the stress results obtained using frequency and time domain methods revealed that the dam height and elastic modulus ratio of foundation rock to concrete are significant parameters that may influence earthquake induced stresses. In the study a new effective damping prediction equation was proposed in order to estimate earthquake stresses accurately with the approximate time domain approach. Zeidan (2015) studied the effect of foundation flexibility on dam-reservoir-foundation interaction. In the study, a 110 m high dam has been modeled considering dam-reservoir-foundation interaction and has been investigated utilizing seismic analysis using FEM via ANSYS code. The analyses are performed under El-Centro N-S record of Imperial Valley earthquake in upstream-downstream direction. The effect of foundation flexibility has been obtained by considering various dam-foundation rock interaction ratios i.e., the ratios of the modulus of elasticity of foundation to the modulus of elasticity of dam. Results show that both foundation mass and flexibility have an outstanding impact on the behavior of dams. Mohsin *et al.* (2015) investigated optimum design of low concrete gravity dam on random soil subjected to earthquake excitation. For the purpose 2D finite element model of Al-Teeb Gravity Dam considering dam-reservoir-foundation interaction is constituted in ANSYS software to find the optimum design based on the principle of fluid-structure and soil-structure interactions. Earthquake records are transformed as time–history forces and applied in lateral direction. As a conclusion it is highlighted that the finite element method simulated by ANSYS is efficient with the optimization process. Alembagheri (2016) studied the earthquake damage estimation of concrete gravity dams using linear analysis and empirical failure criteria. For the purpose, a new methodology considering static pushover analysis is developed to estimate the level of damage from linear time history analyses. A damage index is defined depending on tensile cracking of concrete material. Three different gravity dams are analyzed for twelve scales of ground motions. In the analyses longitudinal records of the earthquakes are applied to dams and based on the obtained results, a damage index is introduced and calibrated to help in quantitative assessment of the damage state. Bernier *et al.* (2016) presented a case study related to seismic fragility of concrete gravity dams with spatial variations of the angle of friction. In the content of the study, Outardes-3 Dam located in northeastern Quebec is modeled and analyzed, including spatial variations of the angle of friction and offering insights regarding the significance of modeling parameters, importance of spatial variation, and overall vulnerability of the dam to two failure modes. Varughese and Nikithan (2016) performed static, modal and transient analyses of Koyna dam-reservoir-foundation system using finite element method to investigate seismic behavior of concrete gravity dams. For performing transient analysis, using earthquake time history records are applied to dam in upstream-downstream direction. Ziaolhagh *et al.* (2016) investigated the dynamic characteristics of a flexible gravity dam- compressible rectangular reservoir system. In the study finite element model of the system is constituted using classical 8-node elements and new 21-node elements separately. In the study it is concluded that the high-order elements treat more precisely than the eight-node elements. Sevim (2018) studied geometrical dimension effects on the seismic response of gravity dams. This paper presents the parametric study related to different base width/dam height (L/H) ratios. In the study, a concrete gravity dam with the height of 200 m is selected and finite element models of the dam are constituted including five different L/H ratios of 0.25, 0.5, 0.75, 1.00 and 1.25. It is concluded from the study that the L/H ratios considerably affect the seismic response of gravity dams. Sevim and Toy (2020) presented a study related to structural response of concrete gravity dams under blast loads. For the purpose Sariyar Concrete Gravity Dam in Turkey is selected for numerical application with its 85 m reservoir height (H), 255 m reservoir length (3H), 72 m bottom width and 7 m of top width. In the study firstly a hydrostatic analysis is done and then the blast loads are considered with full reservoir. It is highlighted from the study that blasting analysis model has more effective than the only hydrostatic analysis model.

Literature review shows that many studies are required to understand seismic response of gravity dams. Most of analyses of gravity dams take into account only the horizontal component, whereas the dynamic response of a gravity dam to the vertical component of the earthquake motions may be similar in amplitude to that induced by the horizontal ground motions and should be considered in the analysis (Chakrabarti and Chopra 1972). In this study, earthquake component effects on the seismic performance of Bhakra Gravity Dam in India are studied. For the purpose, Bhakra dam is modeled two-dimensionally considering dam-reservoir-foundation interaction. In the finite element modeling, dam and foundation are represented by PLANE182 elements in ANSYS with different material properties, and fluid is considered with FLUID29 elements. This type of element provide translation and pressure degrees of freedom. Linear time history analyses of the dam are performed by applying components of the 1991 Uttarkashi and 1999 Chamoli (NW Himalaya) Earthquakes in India. During the analyses firstly the horizontal component of earthquakes are applied to the system and results are obtained, and then both of horizontal and vertical components are applied to the systems together. Seismic performance of Bhakra dam is examined by dynamic characteristics, displacements, principal stresses, and demand-capacity ratios.

2. Theory and formulation

2.1 Earthquake forces

An earthquake produces waves which are capable of

shaking the Earth upon which the dam is resting, in every possible direction. The effect of an earthquake is, therefore, equivalent to imparting an acceleration to the foundations of the dam in the direction in which the wave is travelling at the moment. Earthquake wave may move in any direction, and for design purposes, it has to be resolved in vertical and horizontal components. Hence, two accelerations, i.e., one horizontal acceleration (a_h) and one vertical acceleration (a_v) are induced by an earthquake. Horizontal acceleration (a_h) may cause the hydrodynamic pressures, i.e., horizontal inertia forces. A vertical acceleration (a_v) may either act downward or upward. When it is acting in the upward direction, and then the foundation of the dam will be lifted upward and becomes closer to the body of the dam. Thus the effective weight of the dam will increase and hence, the stress developed will increase. When the vertical acceleration is acting downward, the foundation shall try to move downward away from the dam body, thus reducing the effective weight and stability of the dam. Hence, this the worst case for designs (Ali *et al.* 2012).

2.2 Dam-reservoir-foundation interaction

Reservoirs considerably affect the dynamic response of the dam during earthquakes. Hence, the reservoir effects have to be considered in the analyses. In this study the modeling and analysis of dynamic dam-reservoir-foundation interaction during earthquakes have gone through the direct method. The discretized structural dynamic equation including the dam-and-foundation system subjected to ground motion can be formulated using finite element approach where the soil and structure are included within the same model and analyzed in a single step in Eq. (1) (Khosravi *et al*. 2012, Mohsin *et al.* 2015, Varughese and Nikithan 2016, Khiav 2017).

$$M_s\ddot{x}_e + C_s\dot{x}_e + k_s x_e = -M_s\ddot{x}_g \quad (1)$$

where M_s, C_s, and k_s are the structural mass, damping and stiffness matrices, respectively, x_e, $\dot{x}_e$, $and\ \ddot{x}_e$ are the nodal displacement, velocity and acceleration vectors, respectively, and $\ddot{x}_g$ is the ground acceleration vector. The reservoir produces hydrodynamic effects during earthquakes termed as Qp_e. Here, the discretized wave equation of reservoir is given by Eq. (2) as

$$M_f\ddot{p}_e + C_f\dot{p}_e + k_f p_e + p_w Q^T(\ddot{x}_e + \dot{x}_e) = 0 \quad (2)$$

where M_f, C_f, and k_f are the fluid (reservoir water) mass, damping and stiffness matrices, respectively, p_e is the nodal pressure and, $p_w Q^T$ is referred to as the coupling matrix. Dynamic equilibrium equation of the coupled system is obtained from Eqs. (1) and (2) as given in Eq. (3)

$$M_c\ddot{x}_c + C_c\dot{x}_c + k_c x_c = F(t) \quad (3)$$

where M_c, C_c, and k_c are the coupled mass, damping and stiffness matrices, respectively and $F(t)$ is the dynamic load vector (Dungar 1978, Wilson and Khalvati 1983, Sevim 2011, ANSYS 2017).

2.3 Demand capacity curve

In present days, the optimum gains are aimed to build dams as more economically, more usefully and more safely. Many dam safety evaluations currently utilize a linear elastic model for mass concrete with criteria on an allowable maximum tensile stress (Chopra 1988, Lee and Fenves 1998). A linear earthquake analysis of a concrete dam subjected to strong ground motion gives peak tensile stresses greater than the dynamic tensile strength of concrete, so that nonlinear procedures are required to assess the seismic safety of concrete dams in earthquake-prone areas. However, it is generally known that nonlinear time history analysis of dam-reservoir-foundation systems demands too much memory and time on the computers. It is also possible to use linear procedures for qualitative estimating of the damage level of concrete dams subjected to earthquakes (Ghanaat 2002).

The seismic performance of concrete dams is evaluated in accordance with displacements, stresses, demand-capacity ratios (DCRs) and the cumulative inelastic duration. DCR for dams is defined as the ratio of the calculated maximum principal stresses to the tensile strength of the concrete. The dam response to the maximum design earthquake (MDE) is considered to be within the linear elastic range of behavior with little or no possibility of damage if computed DCR values are less than or equal to 1. The dam is considered to exhibit nonlinear response in the form of opening and closing of contraction joints and cracking of the horizontal joints (lift lines) or concrete if the estimated DCR values exceed 1. The levels of nonlinear response or opening and cracking of joints or concrete for arch and gravity dams are considered acceptable if the DCR value < 2 and the cumulative inelastic duration falls below the performance curves given in Fig. 1. The maximum permitted DCR for linear analysis of dams is 2 (Ghanaat 2002). A demand-capacity ratio of 2 allows stresses up to twice the static tensile strength of the concrete or to the level of the dynamic apparent tensile strength, as long as the overstressed region is less than 15 percent of the gravity dam surface area. The cumulative duration beyond a certain level of DCR is obtained by multiplying number of stress values exceeding that level by the time-step of the time history analysis. The cumulative inelastic duration in Fig. 1 refers to the total duration of all stress excursions beyond a certain level of DCR (Ghanaat 2002).

3. Numerical example

3.1 Description of Bhakra Gravity Dam and its finite element modeling

This study addresses the seismic performance of Bhakra Gravity Dam subjected to earthquake directions. Here, Bhakra Gravity Dam is selected for the numerical example. The construction of the dam was finished in 1963 after detailed plans and some years' works. The dam was the highest gravity dam when it was constructed with its 226 m height. The dam has 9.14 m and 190.5 m widths at crest and base, respectively. Some photos and 2D geometry of the dam are given in Fig. 2 (Url-1). The dam is situated in the state of Himachal on the Satluj River in India. Satluj is a river coming from Himalayas. It is a perennial river but

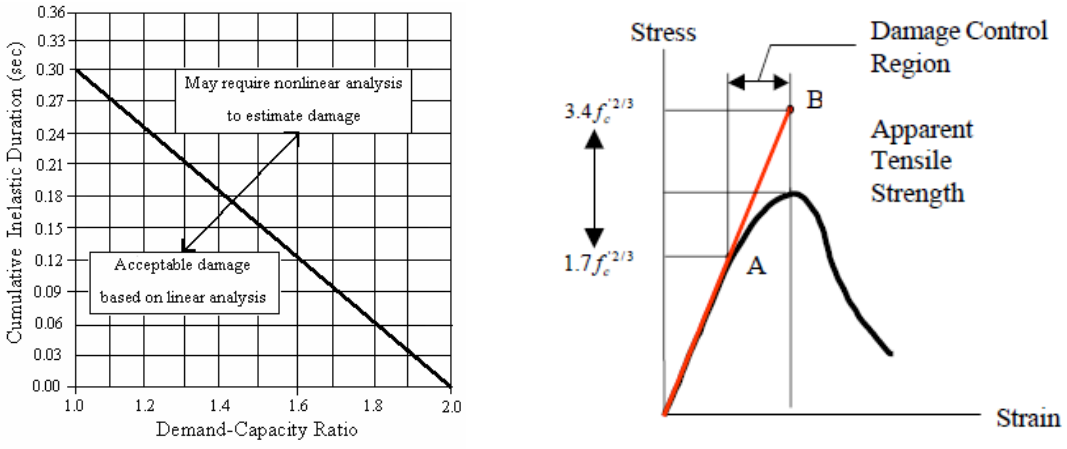


Fig. 1 Performance curve for linear elastic analysis of gravity dams (Ghanaat 2002)



Fig. 2 Some photos and 2D geometry of Bhakra Gravity Dam (Url-1)

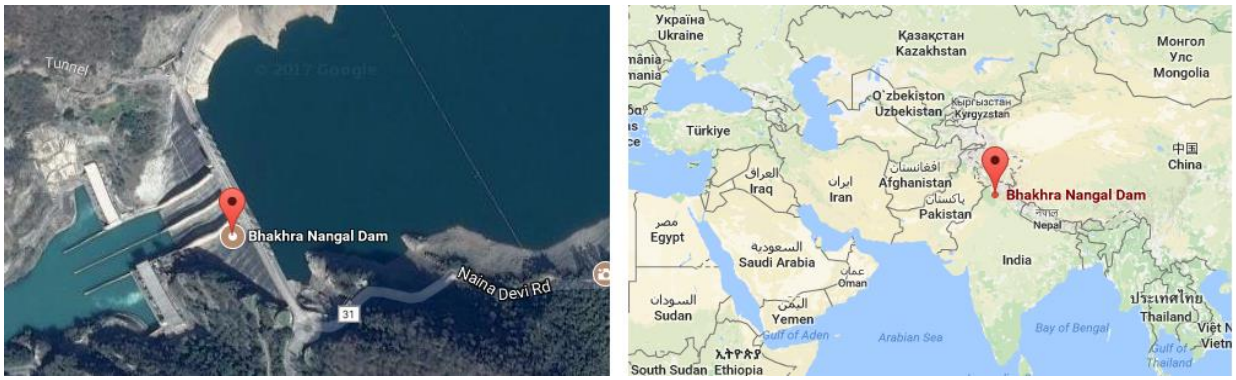


Fig. 3 Location of Bhakra Gravity Dam

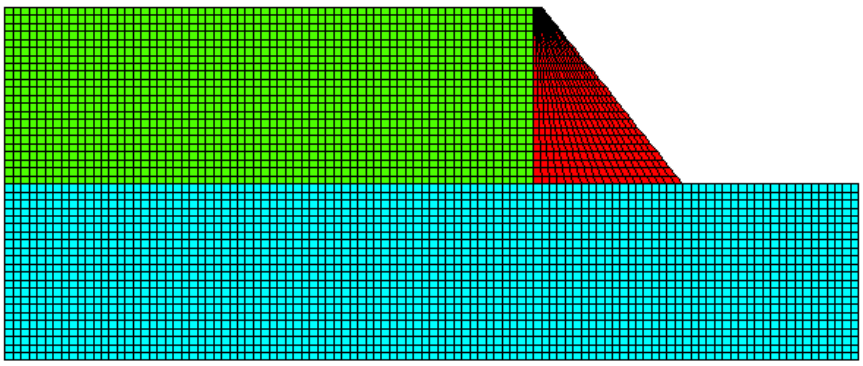


Fig. 4 2D Finite element modeling of Bhakra dam

Table 1 Material properties of Bhakra dam-reservoir-foundation system

System	Element type	Material Properties		
		Elasticity Modulus (MPa)	Poisson ratio	Mass density (kg/m^3)
Dam	PLANE182	25000	0.2	2500
Reservoir	FLUID29	2070	-	1000
Foundation	PLANE182	50000	0.3	-

Table 2 Dynamic characteristics of Bhakra dam

Modes	Full reservoir		
	Frequencies (Hz)	Periods (s)	Mode shapes
1	0.965	1.036	Lateral
2	1.574	0.635	Lateral
3	2.310	0.433	Vertical
4	2.912	0.343	Lateral
5	3.237	0.309	Vertical
6	3.322	0.301	Lateral
7	3.565	0.281	Vertical
8	3.802	0.263	Lateral
9	4.036	0.248	Lateral
10	4.328	0.231	Vertical

carries enormous water during floods and rains (Fig. 3).

Finite element model of Bhakra dam is constituted two-dimensionally by ANSYS (2019) software considering dam-reservoir-foundation (full reservoir) interaction effects (Fig. 4). The model includes geometrical dimensions given in Fig. 2. Dam body is represented using PLANE182 elements which are used for 2-D modeling of solid structures. The elements have four nodes and has two degrees of freedom at each node such as X and Y translations. The element has the capabilities of plasticity, stress stiffening, large deflection, and large strain ANSYS (2019). In the modeling, reservoir is extended to 3 dam heights through upstream direction. Such a modeling neglects the effects on deflections, stresses, and natural frequencies of the dam (USACE 2003, Sevim 2011, Sevim *et al*. 2011a, b, Sevim *et al.* 2012). Reservoir is represented using FLUID29 elements which are used for both modeling fluid domain and fluid-structure interaction. The element has four nodes with three degrees of freedom per node: translations in the nodal x and y directions and pressure. The translations, however, are applicable only at nodes that are on the interface. Foundation is modeled using PLANE182 elements and extended as dam height through vertical and downstream directions. Also the foundation is modeled on upstream direction under the reservoir. Boundary conditions for the foundation are fixed under and near sides of the foundations. The foundation model should be preferred as massless in which only the effects of foundation flexibility are considered. The size of the foundation model should be determined based on the modulus ratio of the foundation to the concrete, E_f/E_c. If $E_f/E_c \geq 1$, the foundation model should be extended one dam height in the upstream, downstream, and downward directions to neglect the effects of the dam body. Thus, these assumptions are generally use

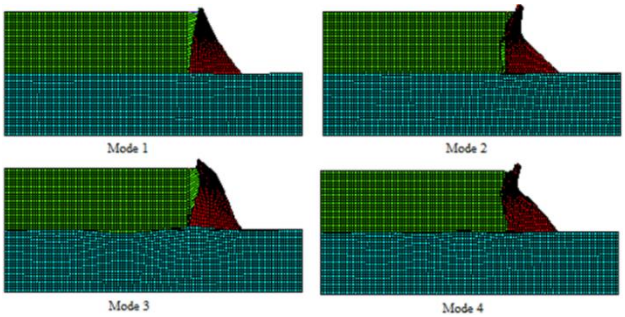


Fig. 5 First four mode shapes of Bhakra dam for empty reservoir

to model and evaluate the gravity dam. Material properties assumed in the modeling are given in Table 1 (USACE 2003, Sevim 2018). A mesh study is done to decide optimum mesh size. According to this investigations, 4376 nodes and 418 PLANE182 elements for the dam body, 2354 PLANE182 elements for the dam foundation and 1452 FLUID29 elements for the dam reservoir are used during the finite element modeling (Fig. 4).

3.2 Modal analysis of Bhakra dam

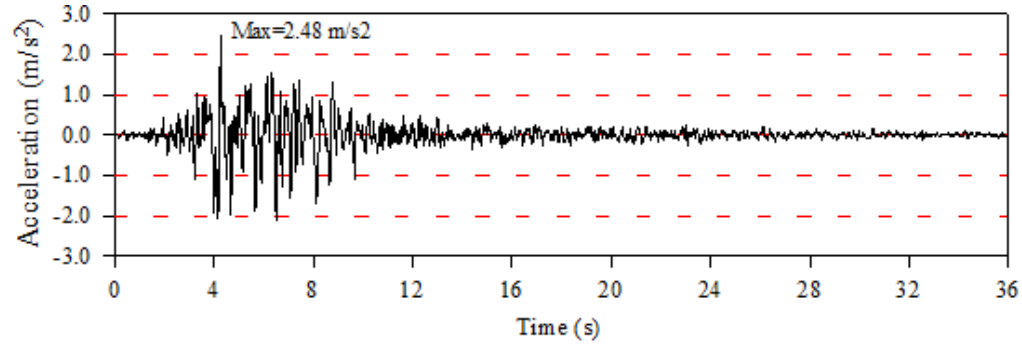
Modal response shows the mode shapes and natural frequencies during an earthquake. In this part of the study, modal analysis of Bhakra dam is performed and the first four mode shapes are illustrated in Fig. 5. As can be seen in Fig. 5, the mode shapes are lateral and vertical bending modes. Also, the first ten modes and natural frequencies which are used to calculate Rayleigh damping coefficients are listed in Table 2.

3.3 Seismic performance of Bhakra Gravity Dam

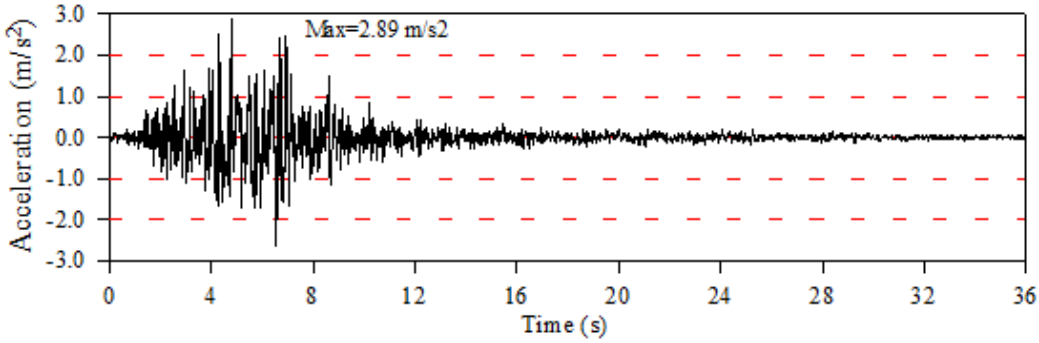
In this part of the study, seismic performance of Bhakra dam is investigated under lateral and vertical earthquake forces. For the purpose, Uttarkashi and Chamoli (NW Himalaya) Earthquakes which occurred in India are selected which provide to discuss near fault effects. Uttarkashi Earthquake occurred in 1991 under 10 km depth from the hypocenter with 7.0 magnitude, and Chamoli Earthquake occurred in 1999 under 15 km depth from the hypocenter with 6.6 magnitude (Url-2). As components of the earthquakes, N85E (H) and UP (V) components obtained in Bhatwari station for Uttarkashi Earthquake, and N70W (H) and UP (V) components obtained in Gopeshwar station for Chamoli Earthquake are preferred. Acceleration time histories and spectral accelerations obtained for 5% damping are plotted in Figs. 6 and 7, respectively for Uttarkashi and Chamoli Earthquakes (Url-2).

In the study, it is aimed to see the effects of vertical earthquake loads on the seismic performance of the dam. Hence, firstly horizontal acceleration components are applied o the dam in the horizontal direction and linear time history analyses are performed. Then the analyses are repeated for both horizontal and vertical directions together.

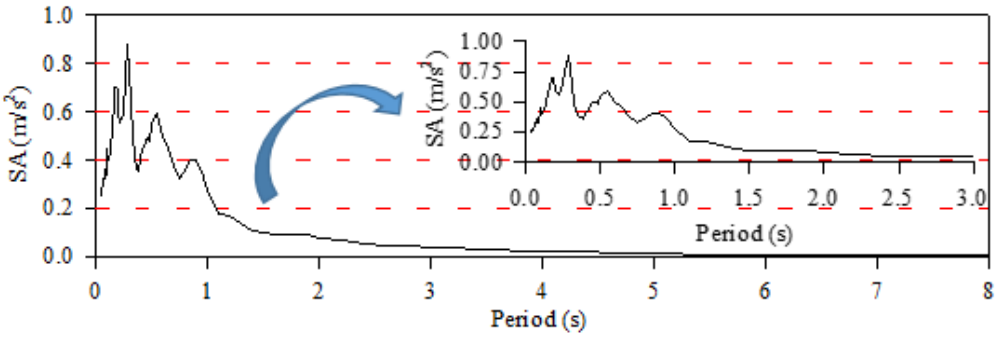
Element matrices are computed using the Gauss numerical integration technique (Bathe 1996). The



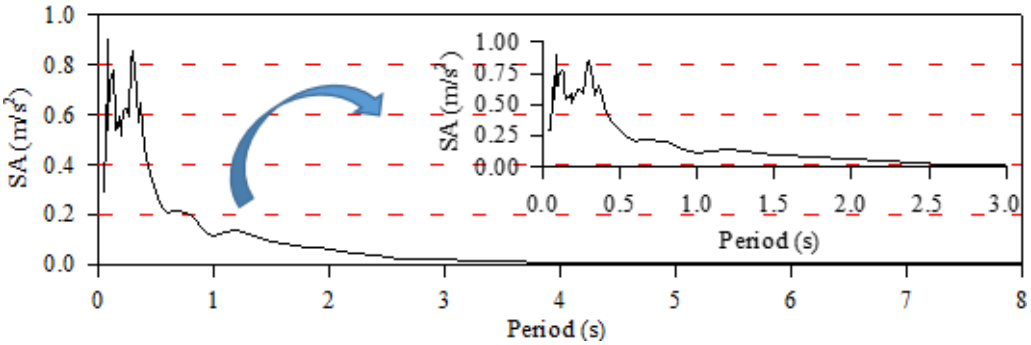
(a) The time-histories of ground motion acceleration component of N85E (H)



(b) The time-histories of ground motion acceleration component of UP (V)



(c) Spectral acceleration of ground motion component of N85E (H)



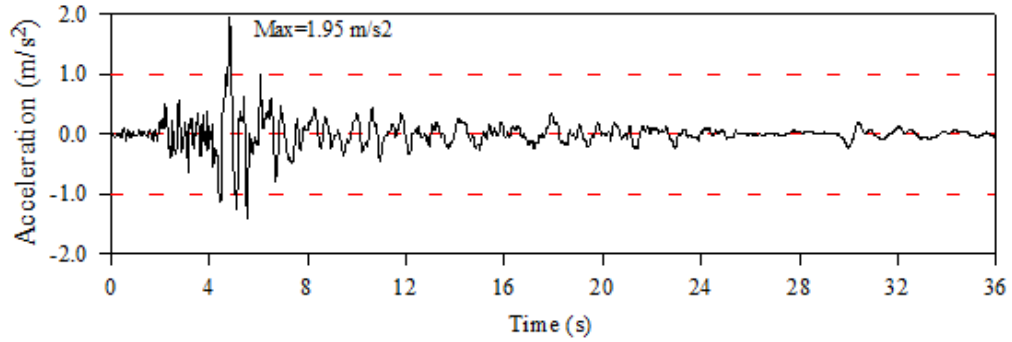
(d) Spectral acceleration of ground motion component of UP (V)

Fig. 6 The time-histories of ground motion acceleration and spectral acceleration of ground motion components subjected to the 1991 Uttarkashi Earthquake

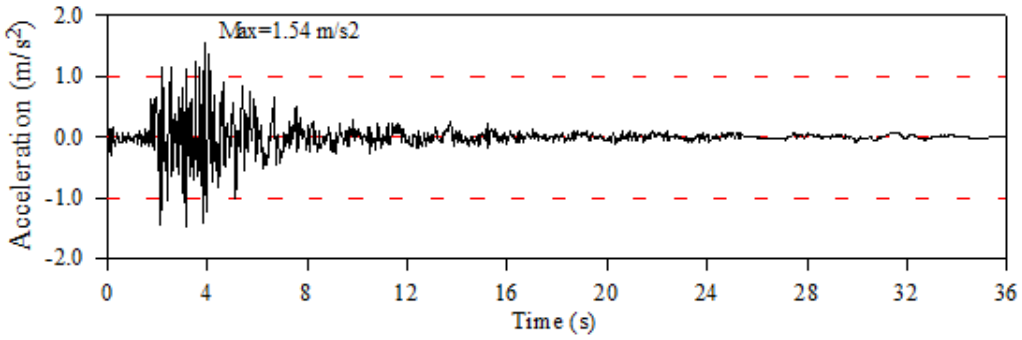
Newmark method is used in the solution of the equation of motions. Damping matrices of the systems are considered by Rayleigh damping which is represented related to mass and stiffness matrices. Rayleigh damping constants are calculated within a frequency range 0.97-4.33 Hz assuming 5% damping ratios. Because of too much memory needed for the analyses, the first 18 seconds of the ground motions (See Figs. 6 and 7), which are the most effective durations, are taken into account in computations.

3.3.1 Analysis results of the 1991 Uttarkashi earthquake

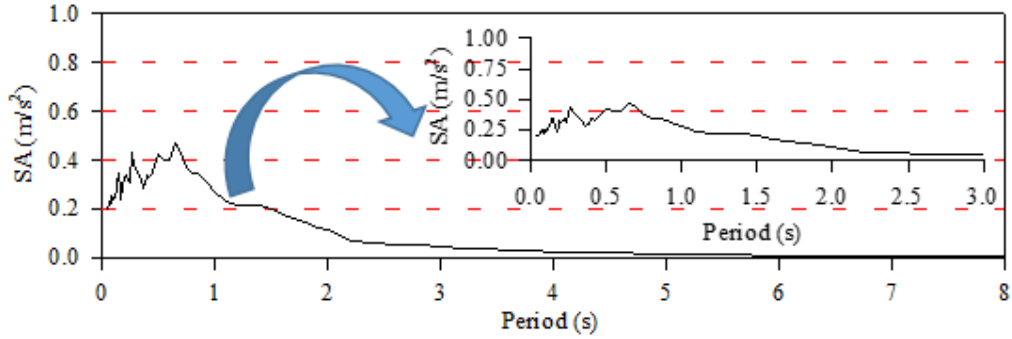
The time histories of lateral displacements at the crest point on the downstream side of the dam are presented in



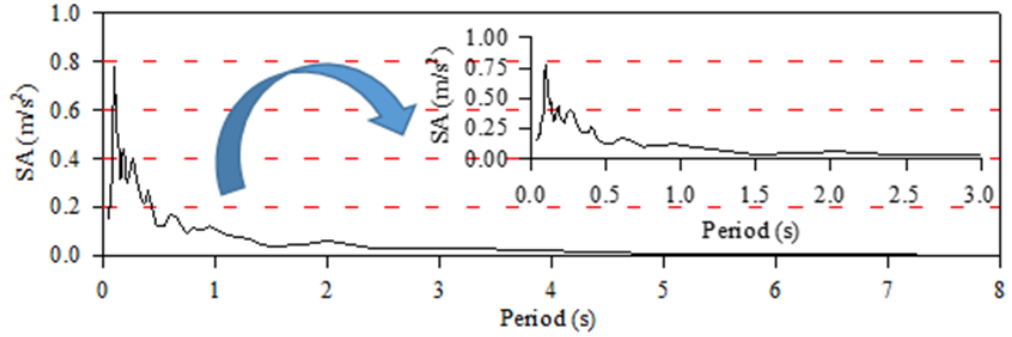
(a) The time-histories of ground motion acceleration component of N70W (H)



(b) The time-histories of ground motion acceleration component of UP (V)



(c) Spectral acceleration of ground motion component of N70W (H)



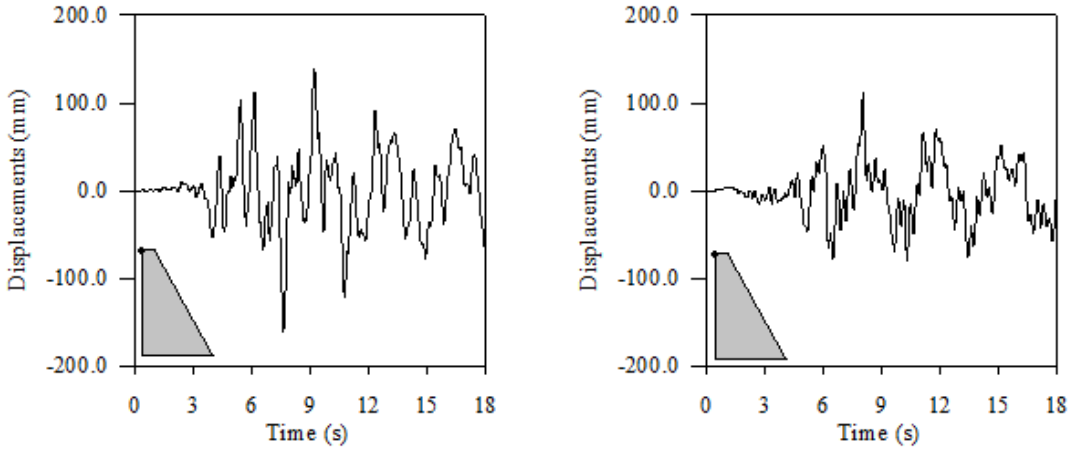
(d) Spectral acceleration of ground motion component of UP (V)

Fig. 7 The time-histories of ground motion acceleration and spectral acceleration of ground motion components subjected to the 1999 Chamoli Earthquake

Figs. 8(a) and (b) for the horizontal (N85S) and horizontal (N85E)-vertical (UP) components of the 1991 Uttarkashi Earthquake. As seen in Fig. 8, only the horizontal (H) component causes the biggest displacement compared to its horizontal and vertical (H-V) components together.

However, the frequency of displacements are significantly changed as a result of applying horizontal and vertical components together compared to the only horizontal component results. On the other hand maximum displacements are obtained as 160 m and 117 mm for H and H-V components, respectively.

The maximum lateral displacements of the dam through I-I section where the biggest values occurred are given in



(a) H component (b) H-V components

Fig. 8 The time-histories of the lateral displacements for (a) horizontal (N85S) (H) (b) horizontal (N85E)-vertical (UP) (H-V) components of the 1991 Uttarkashi Earthquake

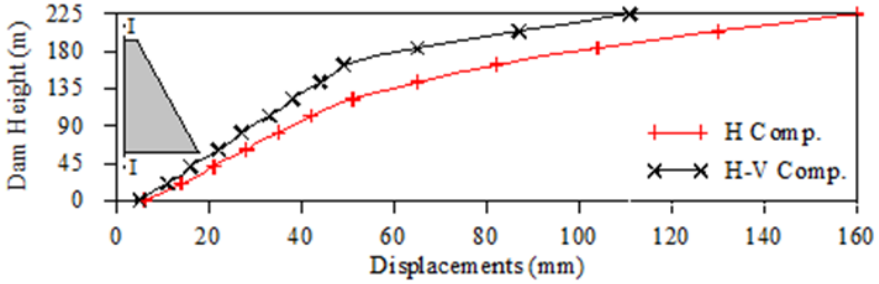
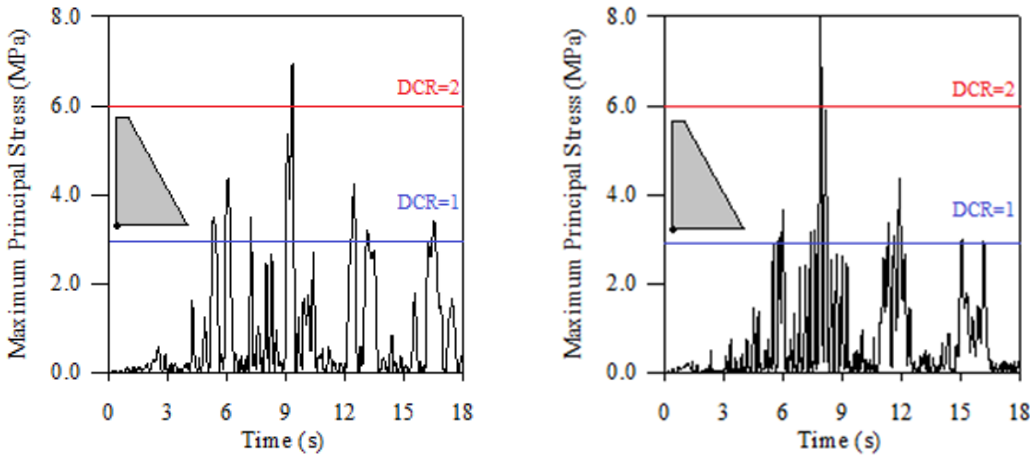


Fig. 9 The maximum lateral displacements of the dam through I-I section



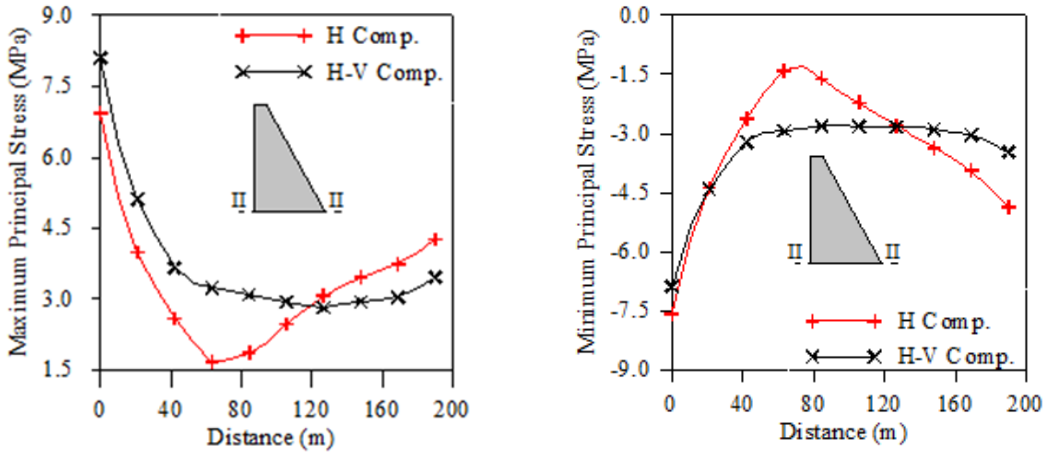
(a) H component (b) H-V components

Fig. 10 The time-histories of the maximum stresses for (a) horizontal (N85S) (H) (b) horizontal (N85E)-vertical (UP) (H-V) components of the 1991 Uttarkashi Earthquake

Fig. 9 considering both H and H-V components. The displacements obtained from H component are nearly 25% higher than those from H-V components.

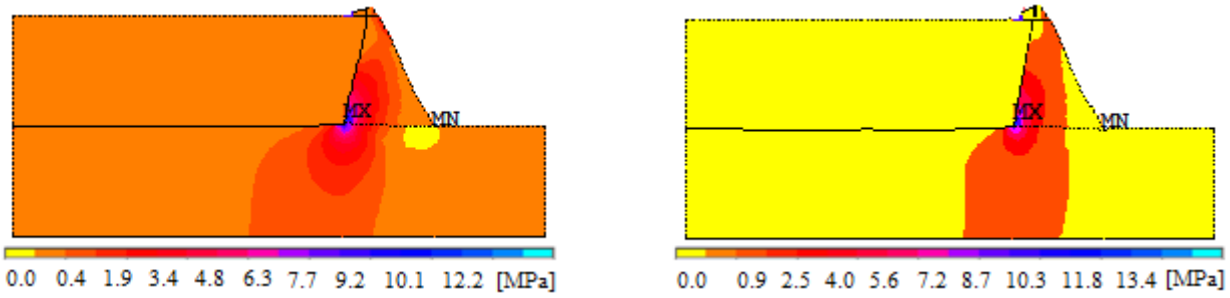
The time histories of the maximum principal stresses at the base point on the downstream side of the dam are presented in Figs. 10(a) and (b) for the horizontal (N85S) and horizontal (N85E)-vertical (UP) components of the 1991 Uttarkashi Earthquake. As seen in Fig. 10, H-V components causes the biggest stress compared to its horizontal H components. Also, the frequency of the stresses are significantly changed as a result of applying horizontal and vertical components together compared to the only horizontal component results.

The maximum and minimum principal stresses of the dam through II-II section where the biggest values are obtained are given in Figs. 11(a) and (b) considering both H and H-V components. It can be seen in Fig. 11 that H-V components cause the biggest stress value, but due to



(a) Maximum stresses (b) Minimum stresses

Fig. 11 Variation of the maximum and minimum principal stresses on the dam along to II-II section



(a) H component (b) H-V components

Fig. 12 Maximum principal stress contours for (a) horizontal (N85S) (H) (b) horizontal (N85E)-vertical (UP) (H-V) components of the 1991 Uttarkashi Earthquake

effects of the vertical component stresses obtained from H-V components are decreased and lower than those of H component through the upstream face of the dam, especially after 120 m.

The maximum principal stress contours through the lateral direction at which the maximum stresses occur are shown in Figs. 12(a) and (b) for horizontal (N85S) and horizontal (N85E)-vertical (UP) components of the 1991 Uttarkashi Earthquake. It can be seen that the maximum stresses occur at the base point on the upstream face of the dam. The maximum principal (tensile) stresses obtained for the H-V component are larger than those for only the H component. It is possible that the limited tensile capacity of the dam concrete may result in local damage to the base of Bhakra for both H and H-V components.

In this study, the tensile strength of concrete material is selected as 3 MPa. It is seen from Fig. 10 that some principal stresses are over DCR=1 for both H and H-V components. This means that the principal stresses obtained from analysis of Bhakra dam are more than the tensile strength of the dam concrete. Performance curves for the most representative point of Bhakra dam obtained from both H and H-V components are presented in Fig. 13. The results for Bhakra Dam show that the demand-capacity ratios for both H and H-V components are exceed 2 and the cumulative inelastic duration is substantially greater than the acceptable level. However, it is seen from Fig. 13 that H

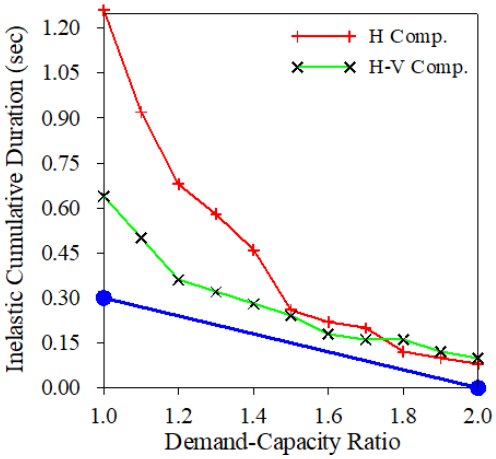
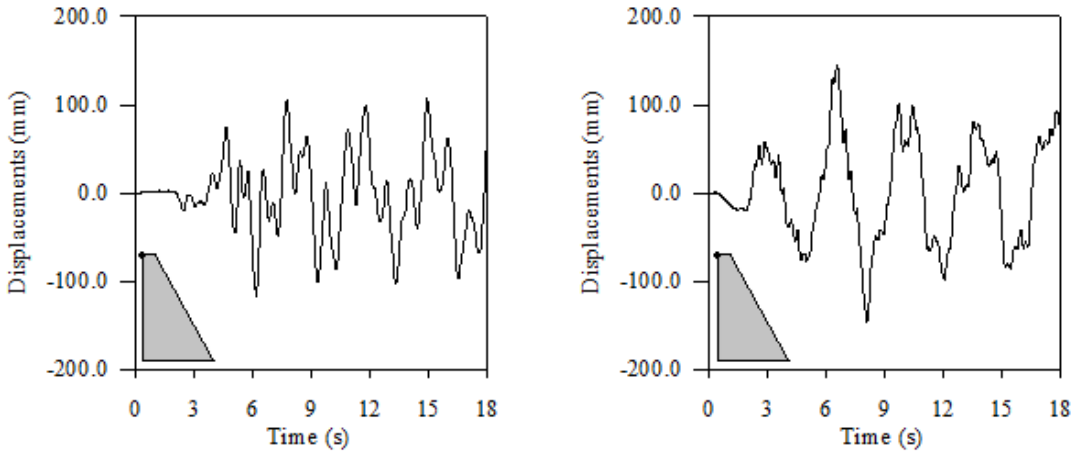


Fig. 13 Performance curves for the most representative point of Bhakra Dam subjected to H and H-V components

component has more effects on the performance curve of the dam than H-V components. It is thought that the selected records may cause damage on the dam body. Therefore, nonlinear analysis of the Bhakra Dam-reservoir-foundation system under the 1991 Uttarkashi Earthquake records would require for more accurate estimate of the damage. On the other hand, vertical component provides good response to the dam compared the only horizontal component. Although H-V components cause the biggest tensile stresses



(a) H component (b) H-V components

Fig. 14 The time-histories of lateral displacements for (a) horizontal (N75W) (H) (b) horizontal (N75W)-vertical (UP) (H-V) components of the 1999 Chamoli Earthquake

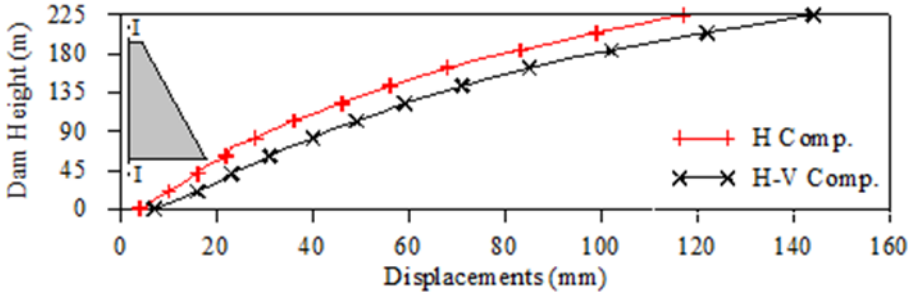
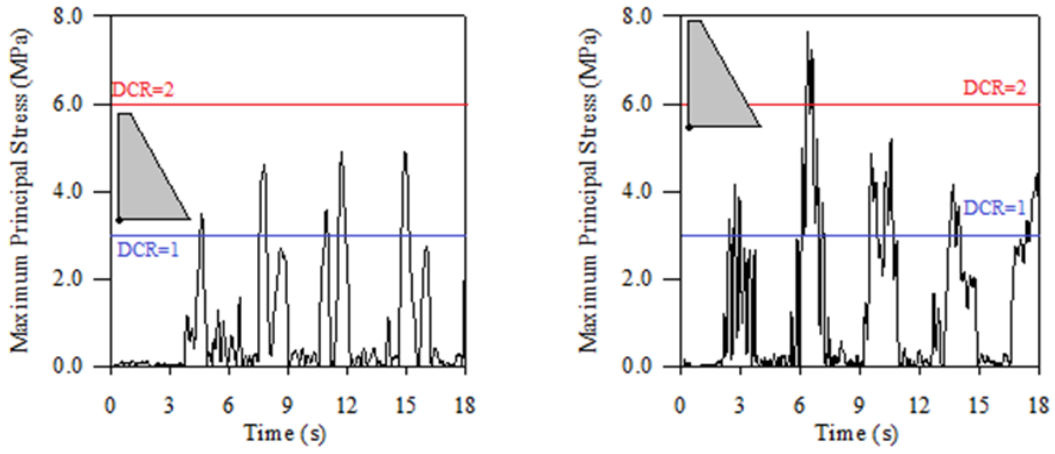


Fig. 15 The maximum lateral displacements of the dam through I-I section



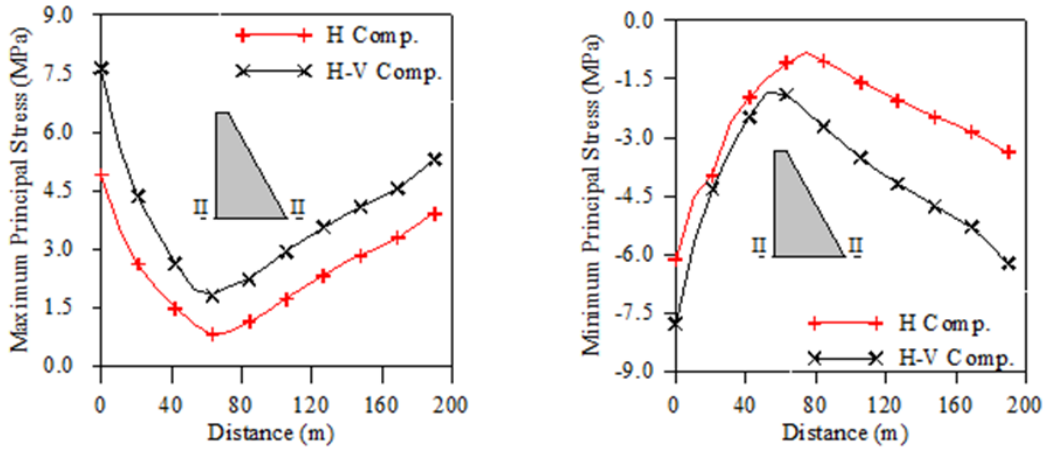
(a) H component (b) H-V components

Fig. 16 The time-histories of maximum stresses for (a) horizontal (N75W) (H) (b) horizontal (N75W)-vertical (UP) (H-V) components of the 1999 Chamoli Earthquake

compared to H component (see Figs. 10 and 11(a)), H component has larger fatigue effects on the dam over a longer duration when examining Fig. 13.

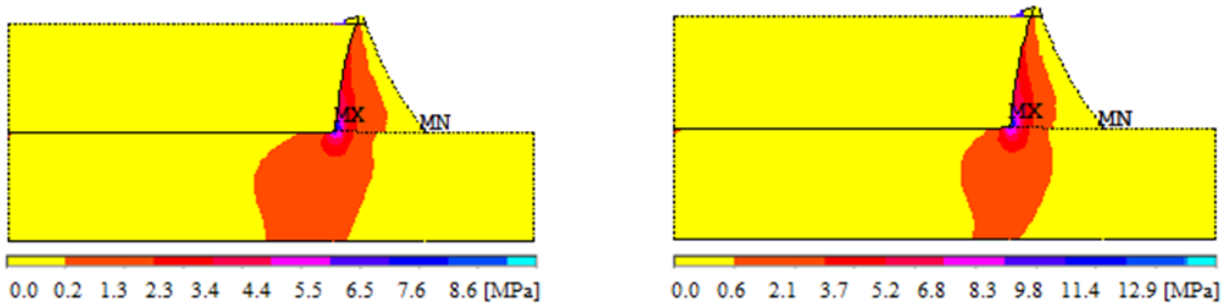
3.3.2 Analysis results of the 1999 Chamoli earthquake

The time histories of lateral displacements at the crest point on the downstream side of the dam are presented in Figs. 14(a) and (b) for the horizontal (N75W) and horizontal (N75W)-vertical (UP) components of the 1999 Chamoli Earthquake. As seen in Fig. 14, H-V components causes the biggest displacement compared to its H component. Also, the frequencies of displacements are significantly changed as a result of applying horizontal and vertical components together compared to the only horizontal component results. On the other hand, the maximum displacements are obtained as 118 m and 148 mm for the H and H-V components, respectively.



(a) Maximum stresses (b) Minimum stresses

Fig. 17 Variation of the maximum and minimum principal stresses on the dam along to II-II section



(a) H component (b) H-V components

Fig. 18 Maximum principal stress contours for (a) horizontal (N75W) (H) (b) horizontal (N75W)-vertical (UP) (H-V) components of the 1999 Chamoli Earthquake

The maximum lateral displacements of the dam through I-I section where the biggest values is given are shown in Fig. 15 considering both H and H-V components. The displacements obtained from H-V components are nearly 20% higher than those from only the H component.

The time histories of the maximum principal stresses at the base point on the downstream side of the dam are presented in Figs. 16(a) and (b) for the horizontal (N75W) and horizontal (N75W)-vertical (UP) components of 1999 Chamoli Earthquake. As seen in Fig. 16, H-V components causes the biggest stress compared to its horizontal H components. Also, the frequencies of stresses are significantly changed as a result of applying the horizontal and vertical components together compared to the only horizontal component results.

The maximum and minimum principal stresses of the dam through II-II section where the biggest values are obtained are given in Figs. 17(a) and (b) considering both H and H-V components. It can be seen in Fig. 17 that H-V components cause the biggest stress value along to the section. On the other hand, the stresses decrease through to the middle of the section and then they increase again for both H and H-V components.

The maximum principal stress contours through the lateral direction at the instant at which the maximum stresses occur are shown in Figs. 18(a) and (b) for the horizontal (N75W) and horizontal (N75W)-vertical (UP)

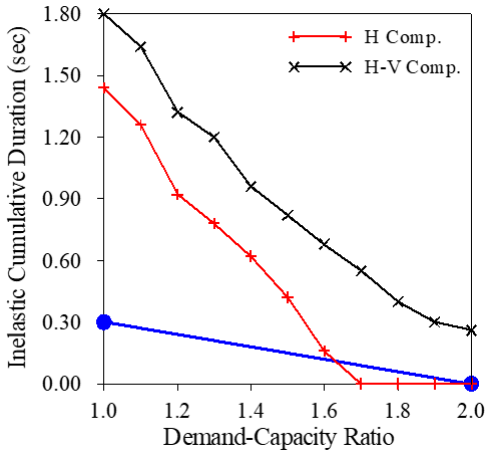


Fig. 19 Performance curves for the most representative point of Bhakra Dam subjected to H and H-V components

components of the 1999 Chamoli Earthquake. It can be seen that the maximum stresses occur at the base point on the downstream face of the dam. The maximum principal (tensile) stresses obtained for the H-V component are larger than those for the H component only. It is possible that the limited tensile capacity of the dam concrete may result in local damage to the base of Bhakra for both H and H-V components.

In this study, the tensile strength of concrete material is

selected as 3 MPa. It is seen from Fig. 16 that some principal stresses are over DCR=1 for both H and H-V components. This means that the principal stresses obtained from the analysis on Bhakra Dam are more than the tensile strength of the dam concrete. The performance curves for the most representative point of Bhakra Dam obtained from both H and H-V components are presented in Fig. 19. The results for Bhakra Dam show that the demand-capacity ratios for both H and H-V components are exceed 2 and the cumulative inelastic duration is substantially greater than the acceptable level. In addition, it is seen from Fig. 19 that H-V components have more effects on the performance curve of the dam than the H component only. It is thought that the selected records may cause damage on the dam body. Therefore, nonlinear analysis of the Bhakra Dam-reservoir-foundation system under the 1999 Chamoli Earthquake records would require for more accurate estimate of the damage. Because H-V components cause biggest tensile stresses compared to H component (see Figs. 16 and 17(a)), H-V components have greater fatigue effects on the dam over a longer duration when examining Fig. 19.

4. Conclusions

This study has addressed the effects of the vertical component of ground motion on the seismic performance of Bhakra Gravity Dam in India. For the purpose, Bhakra dam is modeled two-dimensionally considering dam-reservoir-foundation interaction using ANSYS finite element software. Linear time history analyses of the dam are performed by conducting components of the 1991 Uttarkashi and 1999 Chamoli (NW Himalaya) Earthquakes in India. During the analyses firstly the horizontal components of the earthquakes are applied to the system and results are obtained, and then both of horizontal and vertical components are applied to the systems together. The following conclusions obtained from the study are specified.

- The displacements obtained from H component are nearly 25% higher than those from H-V components under the 1991 Uttarkashi ground motion. On the other hand, the displacements obtained from H-V components are nearly 20% higher than those from H component under the 1999 Chamoli ground motion. Also, the frequencies of displacements are significantly changed as a result of applying horizontal and vertical components together compared to the only horizontal component results for both Uttarkashi and Chamoli ground motions.
- H-V components cause the biggest stress compared to its horizontal H components for both Uttarkashi and Chamoli ground motions. Also, the frequencies of stresses are significantly changed as a result of applying horizontal and vertical components together compared to the only horizontal component results.
- According to the 1991 Uttarkashi and 1999 Chamoli ground motions, it is possible to claim that the limited tensile capacity of the dam concrete may result in local damage to the base of Bhakra dam for both H and H-V components.
- H-V components cause the biggest tensile stresses compared to H component for both earthquakes. However, H component has greater fatigue effects on the dam over a longer duration subjected to the 1991 Uttarkashi ground motion. On the contrary, H-V components have greater fatigue effects on the dam over a longer duration subjected to the 1999 Chamoli ground motion. However, the demand-capacity curve shows that the response of the dam should be investigated nonlinearly for both Uttarkashi and Chamoli ground motions.

The results show that the vertical component changes the structural response of the dam both of good and bad behaviors. Hence, the results obtained in this study demonstrate the necessity of using vertical components of earthquakes. More analyses are required to see the effects of vertical components. However, they induce dynamic responses in gravity dams, and hence should be considered an integral part of the seismic assessment of these structures.

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