Seismic Response Study on Kaswati Dam

Barnali Ghosh and S. K. Prasad

1 Introduction

A Mw 7.7 earthquake struck the Kutch region, in the state of Gujarat, India, at 8:46 a.m., on January 26th, 2001. This was among the most harmful earthquakes in the history of India. More than 16,000 human beings were killed and more than 167,000 were injured [1]. There are as many as 170 earth dams in the Kutch region. Among them, seven dams medium in size and 14 dams small in size were severely damaged [3]. Longitudinal cracks, Subsidence of the crest, lateral spreading are a few typical failures suffered. Most of these dams were built in 1950s and 1960s [6] and were not designed as earthquake resistant structures due to the lack of knowledge in seismic design during those days. The seismic behaviour of earth dams under an earthquake requires proper analysis in order to understand the exact cause of failure so that necessary remedial measures and proper rehabilitation can be carried out in future.

Here, stability analysis of Kaswati dam is presented using PLAXIS software (version 8), a finite element package, considering two-dimensional plane-strain idealization to evolve dynamic response of earth dams [8]. PLAXIS was introduced for two-dimensional plane-strain analysis to find out the dynamic behaviour of earthen dams and embankments [9]. Griffith et al. (1988) showed that advanced soil models can be used to showcase the correct predictions for different loading conditions and have successfully used numerical approach of dams and embankments [4]. The analysis using the finite element method allows studying the behaviour of the dam considering changes in stresses, strains, accelerations and displacements at different points in the body of the dam using a real accelerogram.

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2 Project Description

Kaswati Dam, an earth dam, was constructed in 1973. The maximum height of the dam is 8.8 m and the crest length of 1455 m [7]. Similar to other dams in Gujarat, the water level in Kaswati Reservoir was almost near the dead storage level during the Bhuj Earthquake [5] and the soil below that level was completely saturated. The devastating earthquake activated shallow sliding mainly near the toe of the upstream side slope of the dam [2] and liquefaction near the upstream side of the toe of the dam was considered the main culprit for this failure. The EERI reconnaissance team reported that there are developments of cracks in the upstream slope side of the dam and cracks are as deep as 1.5 to 1.7 m [7]. It was also reported that there was a loss of stability near the upper part of the downstream side slope after the earthquake. Even the appearance of the longitudinal cracks on the crest of the dam may also be related to the liquefaction of the foundation soil. However, loss of stability in the upper part of the downstream slope is unlikely because of the liquefaction of foundation soils [5]. The deformed shape of the Kaswati Dam is shown in Fig. 1 with its pre-failure layout and Fig. 2 represents the idealization using PLAXIS [7].

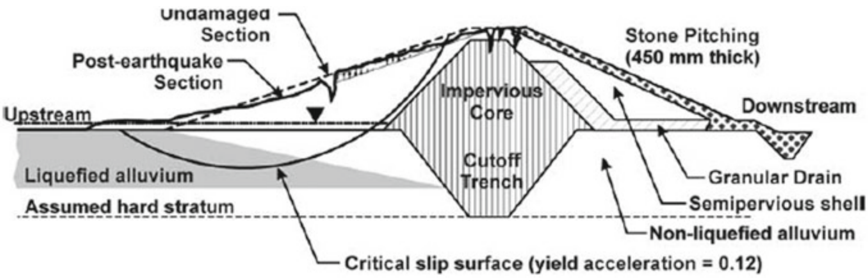

Fig. 1 Cross section of Kaswati Dam (modified from EERI 2001, Singh et al. (2005))

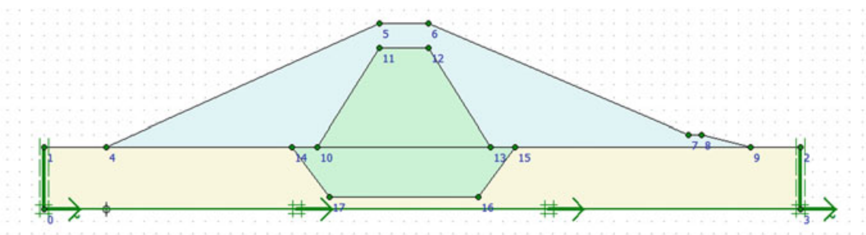

Fig. 2 Pre failure Cross section of Kaswati dam by PLAXIS 2D

Table 1 Soil properties of Kaswati dam

Property	Semi pervious shell	Impervious core	Foundation
γ (kN/m^3)	18	20	18
γ_{sat} (kN/m^3)	20	22	20
K_x (m/day)	1.0 E^{-7}	1.0 E^{-9}	1.0 E^{-6}
K_y (m/day)	1.0 E^{-7}	1.0 E^{-9}	1.0 E^{-6}
υ	0.33	0.33	0.33
E (kN/m^2)	50,000	70,000	60,000
C (kN/m^2)	0	0.2	0
Ø (°)	34	20	20

3 Material Properties of Kaswati Dam

As shown in Fig. 2, Kaswati dam is split into 4 separate layers, each representing individual soil material stretch. The soil stretches of the dam portion are grouped by using Eq. (1) suggested by Sawada and Takahashi. The equation shows the effect of height differential on shear modulus and the shear wave velocity of the zone materials situated at several parts of the dam cross section.

$$V_s = 140Z^{0.34} \tag{1}$$

Here, V_S indicates shear wave velocity and Z is the dam height from the crest. The relationship between shear wave velocity, shear modulus and Modulus of Elasticity (G and E) is shown in Eq. (2).

$$G = \rho \times V_s^{-2}$$

$$G = E/2(1 + \mu) \tag{2}$$

Here, μ is the Poisson's ratio. The soil parameters related to the four zones of soil found using the above two equations and the following results given by [12] are listed in Table 1. These results are used as input parameters in this study.

4 Dam Simulation

The simulation of the dam starts with identifying the clusters (Kaswati Dam consists of 4 clusters) and finding the properties associated to each cluster. Figure 3 shows the section of a generated mesh of the Kaswati dam.

The impact of the input motion on the seismic response of the Kaswati dam is presented below. The nearest station was the IITR station in Ahmedabad with

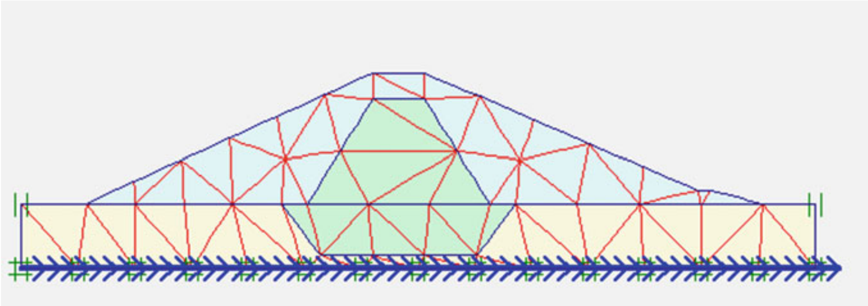

Fig. 3 Section of generated Mesh of Kaswati dam by PLAXIS 2D

a hypocentral distance of 239 km. This accelerogram cannot provide an accurate result as the distance is too large. Hence, the dam was excited with the accelerogram obtained from Strong-Motion Virtual Data Centre (VDC), which was having modified shaking and almost similar effect on dam (Chilie earthquake, 27/02/2010). It was applied for a period of 20 s as shown in Fig. 4.

The numerical analysis with PLAXIS generally involves 3 parts [11]. In the initial phase, plastic analysis is performed by adding different dam materials and applying suitable material properties. The next phase consists of plastic analysis under the self-weight of the dam and the third step includes dynamic analysis under seismic loading. The last and final phase loading is put in the form of an accelerogram file input. The total deflections, displacements in the horizontal direction and vertical

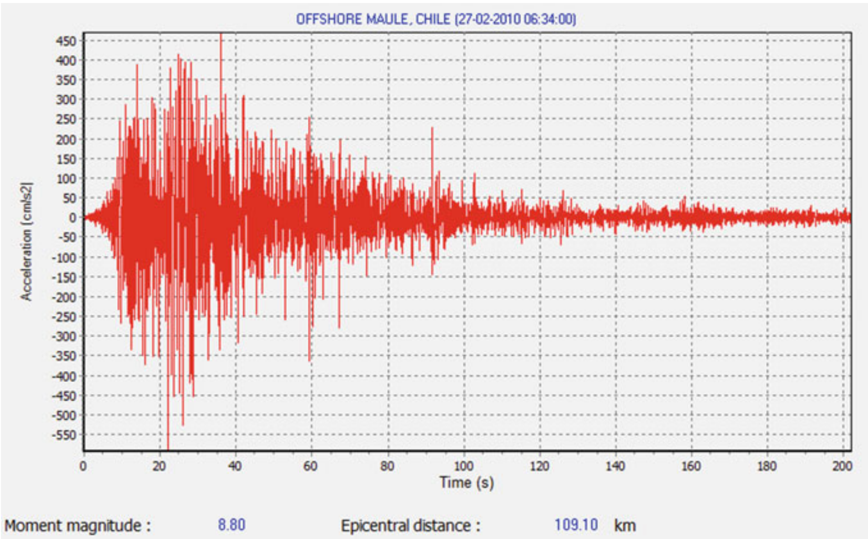

Fig. 4 Acceleration time history used for the analysis

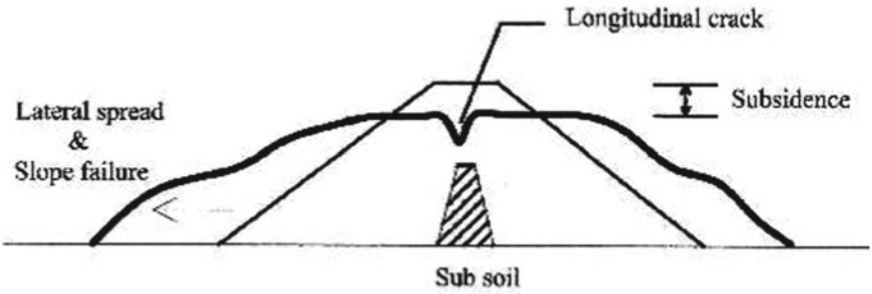

Fig. 5 Typical failures observed in earth dams during Bhuj earthquake (modified from EERI 2001)

direction of the dam are found as the result of the analysis, and diagrams are shown in Figs. 6 and 7.

The total displacements are the complete collected displacements combined from horizontal and vertical displacement components at all the nodes displayed on the geometrical figure. Similarly, the horizontal (x) and vertical (y) displacement components at all the nodes are found at the end of calculation. Figure 6 shows the large lateral displacements (Extreme total displacement is 1.94 m) on both upstream and downstream sides. Sliding of slopes associated with a major drop down in the crest elevation also can be seen. Slope failure also can be observed (Fig. 8).

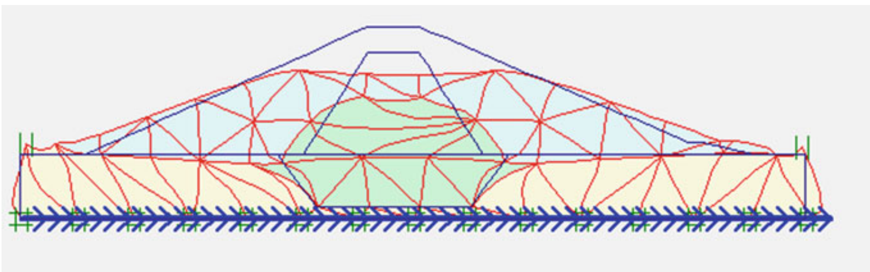

Fig. 6 Deformed mesh of Kaswati Dam (extreme total displacement was 1.94 m, displacement scaled up 2.00 times)

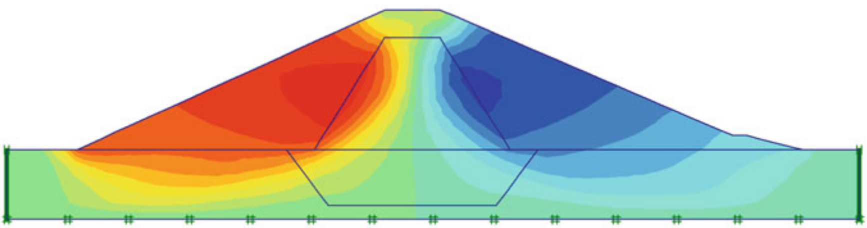

Fig. 7 Distribution of total horizontal displacements (Ux), maximum 1.32 m

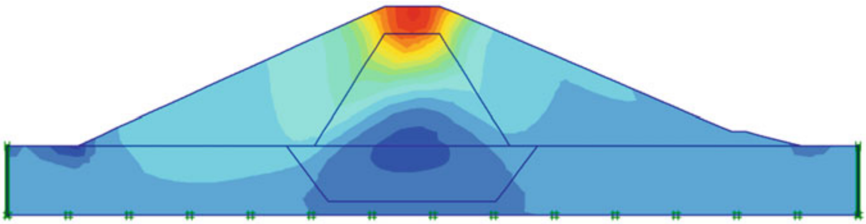

Fig. 8 Distribution of total vertical displacements (Uy), maximum 1.94 mm

5 Time Displacement Analysis

Before starting the calculation in PLAXIS, reference points are chosen on cross section of the dam. These points are chosen at different levels of the dam. Point D is chosen at the centre of the dam, Point A is at the top, points B and C are chosen on upstream and downstream sides of the dam and points E and F are at the base. Horizontal displacement–time curves related to the above mentioned points at different levels of the cross sections are shown for Kaswati Dam. Figure 9 shows the location of nodes for time-displacement curves.

Figure 10 shows time-displacement curve for various points of the dam. From Fig. 10, it is seen that point B and C (red and yellow colour curve) which is at the upstream side and downstream side of the dam shows maximum horizontal displacement followed by the crest and base. Extreme horizontal displacement is noted as 1.22 m. Whereas for the vertical displacement, it is seen that (Fig. 9) maximum vertical displacement has occurred at the crest of the dam, where a major drop in crest elevation is observed (blue colour in the curve). With the increment in time, deformation of the crest increases and ultimately leads to the failure of the dam. Extreme vertical displacement is noted as 1.8 m (Fig. 11).

Figure 12 shows the time acceleration curve at different points of the dam. From the graph, it is seen that maximum acceleration is the inside core of the dam (pink colour in the curve). Time and acceleration show a constant pattern throughout the duration of shaking.

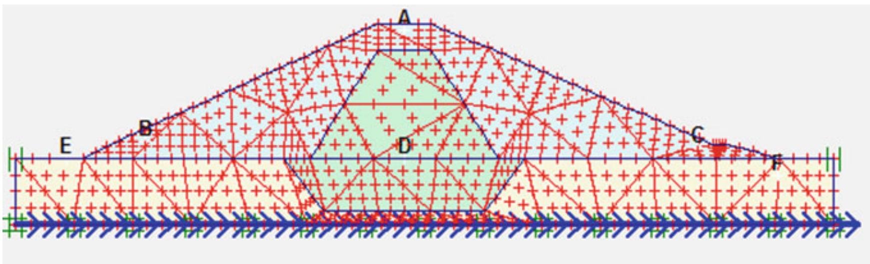

Fig. 9 Location of nodes for time-displacement curves

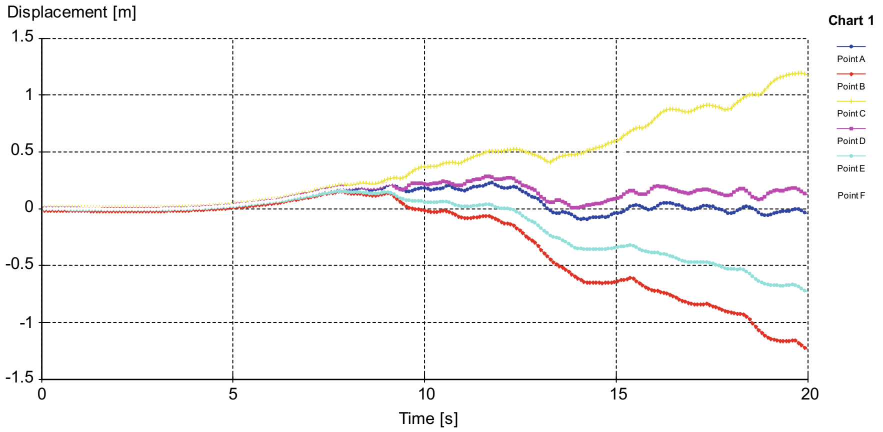

Fig. 10 Time displacement curves for different points (horizontal displacement)

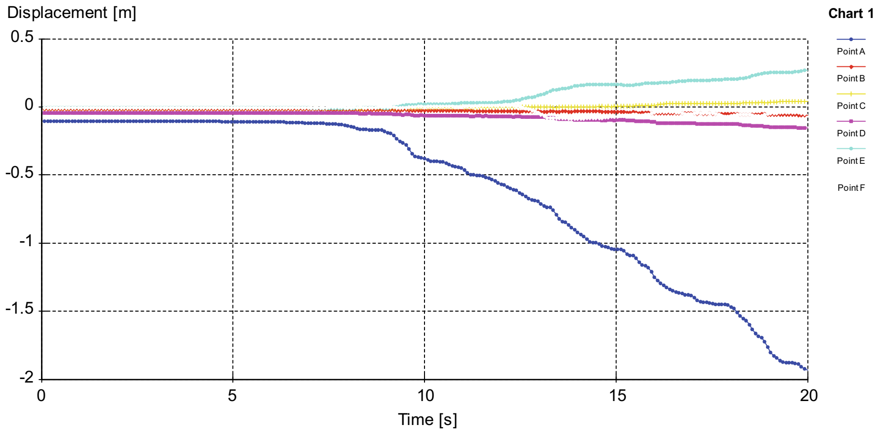

Fig. 11 Time displacement curves for different points (vertical displacement)

6 Stress Analysis

The extreme effective principal stress is -292.42 kN/m^2. Pore water pressure is additionally developed due to seepage of water through the dam. Hence, active pore water pressure includes steady state water pressure, seepage pressure and excess pore water pressure developed during shaking. For this analysis, active pore water pressure was found to be -50 kN/m^2.

During an earthquake, the development of excess pore pressure causes liquefaction resulting in collapse [10]. The downstream slope of the dam did not show any evidence of sand boils, lateral spread, or liquefaction related effects [1], but possible liquefaction is found in the foundation near the upstream toe. In Fig. 13, it is seen

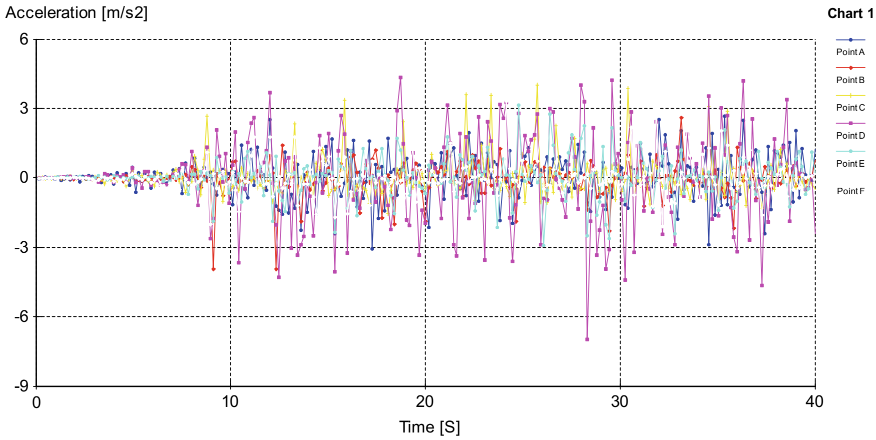

Fig. 12 Time acceleration curves for different points

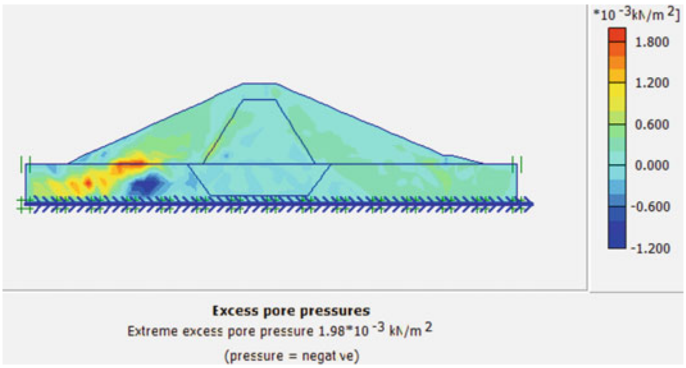

Fig. 13 Excess pore water pressure

that extreme excess pore water pressure was generated near the upstream toe of the dam.

7 Concluding Remarks

The present study focussed on comparing the findings from numerical analysis with those of actual behaviour during the Bhuj earthquake. In the numerical analysis, it was found that the vertical displacement was the maximum at the crest indicating the subsidence. The lateral displacements were maximum at toe and heel, but of opposite natures. The core was subjected to maximum acceleration during shaking indicating the effect of shaking on dis-similar materials. The excess pore water pressure was the maximum near the upstream in foundation soil indicating the possible liquefaction. All these observations matched the actual conditions during the earthquake. Hence, the present study infers that seismic safety analysis of all existing dams in India may result in useful findings and the analysis using finite element approach with 2D plane-strain idealization may be sufficient to gather enough information about the safety of dams. This can be an excellent tool for preparedness for future big earthquakes.

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