



EARTH DAM FAILURE DUE TO LIQUEFACTION CAUSED BY EARTHQUAKES

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Abstract:

We are researching causes and criteria for the liquefaction dam failure by analyzing the safety of the dam under static and dynamic loads against shear failure using the finite element technique, which is used to simulate stability assessment for selected earth dams under different loading conditions. Earth dams, when subjected to seismic activity, face a heightened risk of collapse, leading to dire consequences such as human casualties and substantial economic losses. The extent of seismic vulnerability and the potential complications arising from a dam failure hinge on the specific reactions exhibited during earthquakes. Weak soil and the liquefaction of loose sands contribute to seismic responses like slope failure, piping, displacement, and settlement. Various factors contribute to the potential failure of earth dams under seismic stress. These include seepage through the dam body, hydraulic challenges, structural instability, and liquefaction failures induced by earthquakes. The interplay of these elements underscores the complexity and multifaceted nature of the risks associated with seismic events and their impact on the stability of earth dams. The objective of this study is to find a way to design of earth-fill dams. The finite element method constitutes a numerical approach employed for solving problems related to fluid flow. It relies on a grid pattern, which need not be strictly rectangular, to discretize the flow region into distinct elements, generating N equations with N unknowns. Each element is assigned specific material properties, such as permeability, and boundary conditions, such as heads and flow rates, are established. Compared to the finite difference method, the finite element method offers several advantages, particularly when tackling intricate seepage problems. Its ability to handle more complex scenarios makes it a preferred choice, as it allows for a more nuanced and adaptable representation of the flow dynamics within the given domain. The Lower San Fernando Dam exhibits vulnerability to dynamic loads, with respective F.O.S. values of 0.264 and 0.183 for upstream and downstream directions. The liquefaction area for this dam covers 1350 m², constituting 40.67% of its entire foundation area. In comparison, the Tapar Dam in India faces the risk of slope failure under dynamic loads, featuring F.O.S. values of 0.5 and 0.109 for upstream and downstream directions. Its liquefaction area spans 457 m², representing 52.33% of the dam's overall foundation area. The Fatehgadh Dam in India is deemed unsafe due to slope failure under dynamic loads, with F.O.S. values of 0.313 and 0.548 for the river slopes upstream and downstream. The liquefaction area for Fatehgadh Dam is measured at 333.5 m², encompassing 78.75% of the dam's foundation area. The findings indicate that liquefaction failure is attributed to a minimum liquefaction zone area of 32.96%. A seismic stress-induced safe design standard for storage earth dams is established, with a comprehensive assessment incorporating safety specifications aligned with global norms, regulations, and codes. This examination specifically delves into the dam safety requirements under dynamic loads.

Keywords: Seismic analysis, Earth dams, Liquefaction, Slope instability, Factor of safety, GeoStudio.

I. INTRODUCTION

Dams are built for a variety of objectives, such as irrigation, flood control, and the generation of hydroelectric power. The two primary varieties of storage dams are concrete rigid dams and embankment dams. The two main types of embankment dams, based on the materials used in construction, are earth-fill dams and rock-fill dams. Over 85% of all built dams are embankment dams



[1]. A few factors that affect the type of earth dam chosen include geography, foundation conditions, environmental effects, construction facilities, and socioeconomic research. The type of earth dam chosen depends on several factors, including terrain, foundation conditions, environmental effects, construction facilities, and socioeconomic research. QUAKE/W and SIGMA/W are often utilized in many civil engineering applications. These programs were used in this research to analyze and study the results [2].

In this work, analyses of five earthfill dams that have already collapsed due to liquefaction have been compiled under the influence of earthquakes. These dams are: the Fernando Dam (California) Taper Dam (India), Saluda Dam (Columbia), Fatehghadh Dam (India), and Chang Dam (India). The study aims to find a critical ratio of the volume of liquefied soil from the data of the studied dams to be a guiding value for design engineers that are taken into account when designing earth dams to avoid the occurrence of the phenomenon of liquefaction under the influence of earthquakes.

1. PREVIOUS WORK

According to Singh et al. (2005) [3], Tapar dams were badly impacted, particularly along the upstream parts, although Chang Dam experienced significant slumping. First, the potential for liquefaction of these dams' foundation conditions was determined. According to the meager subsurface information available from inspections carried out before the earthquake, the layers beneath these dams' downstream sections were not saturated, which prevented the Bhuj Earthquake from inducing liquefaction. An earthquake of magnitude of 7.6 (Mw 7.6) occurred on January 26, 2001. The epicenter of the main shock of the event was located near Bachau at latitude 23.368N and longitude 70.348E with a focal depth of about 23.6 km. The event, commonly referred to as the Bhuj Earthquake, was among the most disastrous earthquakes that have affected India. In this work, the liquefaction failure zone was determined by using the finite element method.

According to S. Mahmood et al. (2022) [4], the Makhoul Dam, a massive zonal dam that is now being built on the Tigris River in northern Iraq, was numerically modeled using finite element methods to examine seepage, slope stability, and liquefaction. Due to high pore water pressure, piping, and soil liquefaction, earthquake shakings impose extra hysteric and short-term pressures that may cause dam failure. As a result of applying an earthquake shaking to the dam, the dynamic stability of the dam and soil liquefaction was also assessed. Because the calculated value of the safety factor was more than the permitted amount, the dam was safe from internal erosion and slope failure under static conditions. Su et al. (2022) [6] utilized the Monte Carlo method, the dynamical stability of the earth-rock dam was examined while taking into account the spatial variability of the soil beneath the dam and the coupling effect of the seepage field, stress field, and other hazards. Engineering of early warning measures is suggested by the revelation of the impact of numerous disaster on the stability of the dam. This study achieves the dynamic risk assessment of the dam slope stability under multiple hazards, avoids the restriction of evaluating the dam slope stability with a single safety factor, and provides a reference for risk analysis and emergency management of reservoir dams under the action of multiple hazards.

W. Aziz et al. (2023) [7] studied the effects of top width, shape, and side slopes on upstream and downstream slope stability under various conditions. The safety of an earth dam's side slopes was evaluated using the Slide 6.0 software, and the results were validated. The findings showed that, particularly under steady state and fast drawdown situations, the factor of safety was decreased by increasing the side slopes of the core. The safety factor in the steady state condition decreased along with widening the top.

In the study of Abbas et al. (2021) [8], the seepage during the Al-Wand dam was examined using the Seep/w software, which was used in conjunction with the Geo-studio modeling. Following confirmation that the dam was safe from seepage failure, the analysis was transferred to the QUAKE/W, which is used for liquefaction modeling of earthquakes and dynamic loading and calculates the movement and increasing pressures of pore water that result from seismic vibration or rapid shock loads. The program was used to examine how the earthquake affected the pressure in the

pore water, effective stresses, and displacements. The earthquake's considerable impact on these parameters is also unclear.

The findings of study by Marchamalo-Sacristán, et al. support the use of MT-InSAR monitoring of embankment dams at all stages of their lifecycles, including mature dams like the Bennar Dam [8]. However, geodetic, hydraulic, and geotechnical monitoring should be included as required by dam safety requirements. It has been shown that MT-InSAR is a reliable and economical system for monitoring deformations in embankment dams. Dam deformation's temporal evolution was identified both geographically and temporally. Results support the consolidation of the dam predicted by a theoretical model.

Smail (2022) [10] examined the Souk Tlata earth dam's ability to withstand earthquakes. It is equivalent to a preliminary analysis of the behavior of the dam under quake loading with a dominating frequency that is near the fundamental frequency of the dam. Using Plaxis-2D, a finite element model of the dam was created using plane-strain finite elements. To conduct dynamic analysis, a real earthquake motion was used that corresponds to the primary shock that occurred on May 21, 2003, in Algeria. The findings demonstrate that seismic loading with peak acceleration exceeding 0.10g causes significant settlement at the dam's crest and significant displacement in the upper half of the riprap on the upstream side.

II. MATERIALS AND METHODS

a. Slope Stability of Earth Dam Approach

III. Where, $C \cdot L$ = cohesive strength per meter length of the strip, $W_n \tan \phi$ = frictional strength per meter length of the strip. According to the trapezoidal formula or precisely to a plan meter, the area of each strip that is one meter long determines how much it weighs. The W_n and W_t of each strip can be graphically determined by drawing the triangle of force for each strip as shown in (Fig. 1). The critical circle is located as normal, and the safety factor is discovered for each of the other slip circles. It should be carefully observed that the tangential weights of the first few strips near the slope's toe will resist the propensity to slide; therefore, these weights must be taken with their proper sign [14]. There are other methods used to determine the factor of safety of slopes. They are Ordinary, Bishop's, Janbu, and Morgenstern. Price methods according to

Hence, the strength or shear resistance of the soil determines how stable the slopes of earthen buildings are.

3.4. Earthquake-induced Liquefaction

During cyclic loading, loose cohesion less soils tend to compress if the soil is moist and generally unable to drain during shaking. This can cause normal stress to be transferred from the soil skeleton to the pore water. The soil's effective confining stress decreases as a result, and the loss of strength and stiffness causes the soil deposit to deform [22]. Liquefaction is the loss of strength and stiffness brought on by rising pore pressure, and it can have disastrous results. Although the liquefaction phenomena are qualitatively described in the previous definition, the precise circumstances in which it occurs are not known. This is mostly because failure mechanisms vary based on the pre-earthquake circumstances. Flow liquefaction and cyclic mobility are the two basic phenomenon groups that makeup liquefaction. When

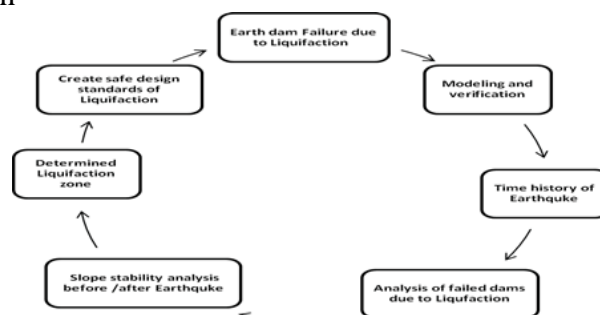


Fig. (1). A methodological flow chart.

Problem Statement

For the dam's stress analysis and slope stability simulation, finite element modeling is used. The GeoStudio programmer GEO-Slope (2018) is utilized for the analyses. Limit equilibrium slope stability evaluations of the downstream and upstream slopes of the dam before and after the earthquake, effect employs all the results of both seepage and stress analyses. The analysis findings are put to use to create safe design standards for massive dams subject to seismic load effects and liquefaction failure dams. Fig. (3) presents a methodological flow chart. This diagram was made to illustrate the basic steps and general objectives of the work to perform an analysis of the stability of earthen dams against earthquakes.

Material Properties of Dams

In this part, the cross-section of the dams under study is presented, as well as the tables of the material properties of the constituent layers of those dams. Table 2 presents a group of dams that are studied in the research are presented, as well as the earthquake forces affecting each dam and the model properties. Bilate Dam Fig. (4) and Table 3 show the material properties of the Bilate dam. Dam examined the estimated flow slope stability factor of the Bilate dam at overall stability both before and after earthquake loading using the GeoStudio computer programmer. Southern National and Oromia are the regions where the Bilate dam is situated. The dam's reservoir has a 52 million m³ capacity and is filled with rock and earth to a height of 42.5 m [23].

IV. METHODOLOGY

Fig. (5) and Table 4 show the cross-section of the San Fernando dam. The eroding embankment as well as the strong chance of the dam collapsing put the 80,000 or so residents in the area below in danger. San Fernando Dam was the second significant dam to crumble. The San Fernando earthquake, which occurred in Southern California in 1971, was a large quake. The 6.6 Richter magnitude earthquake struck on February 9 around 6:00 a.m. The top and upstream slopes of the Lower San Fernando Dam were significantly altered by the San Fernando earthquake in 1971. This dam is located in Southern California [22].

Table 1. Description of a group of collapsed dams as a result of earthquakes.

Dam	Country	H (m)	Acc. of Earthquake	Location of Liquefaction Failure	Mesh of Model		
					Area	Node	Elements
Lower San Fernando	California	22	0.6g	Foundation and dam body	1m*1m	4097	3945
Chang	India	15.5	0.5g	Dam body	1m*1m	1286	1201
Tapar	India	13.5	0.41g	Dam body	1m*1m	2501	2355
Fatehgadh	India	11.6	0.3g	Dam body	1m*1m	949	861
Saluda	Columbia	11.5	0.4g	Foundation and dam body	4m*4m	7573	7357
Saddle	Ethiopia	65	0.318g	Foundation and dam body	1m*1m	18046	17771

Table 2. Material properties of bilate dam [23].

Material	E	Y	C	Φ	G	V	R
Core	17500	19	18.8	26	11000	0.4	0.1
Semi impervious layer	20000	19	15	26	11000	0.4	0.1
Filter	25000	22	0	38	15400	0.3	0.1
Rock fill	62000	22	0	38	28600	0.25	0.2
Clay blanket	17500	19	18	26	11000	0.4	0.2

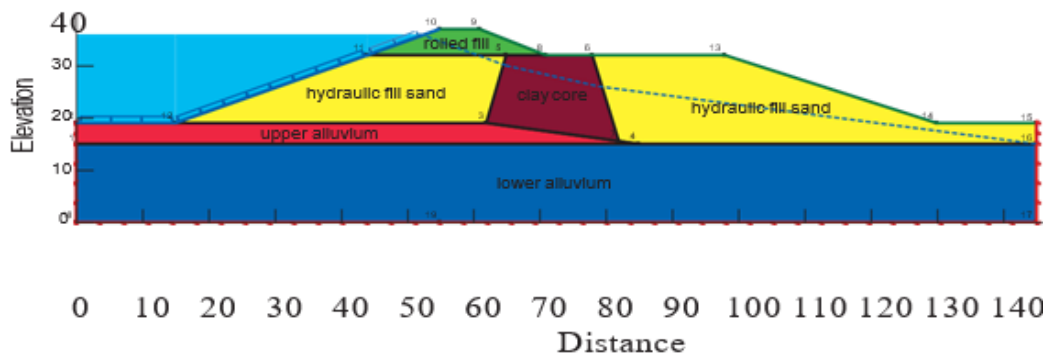


Fig. (2). Cross-section of the San Fernando dam.

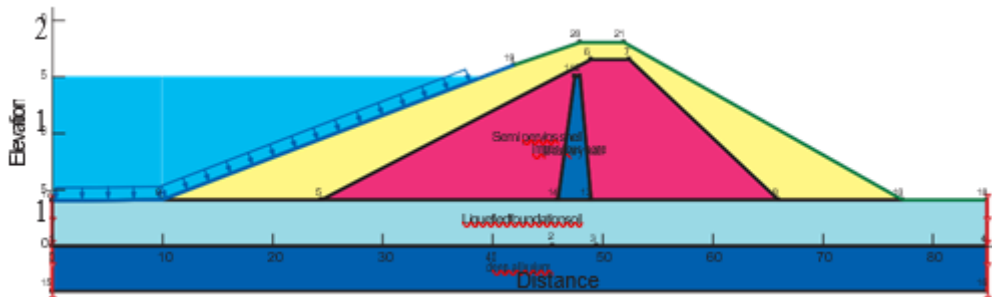


Fig. (3). Cross section of Chang dam.

Table 3. Material properties of San Fernando dam [24, 25].

Material	E	Y	C	Φ	G	V	R
Clay core	17500	19	40	8	8077	0.2	0.1
Rolled fill	66670	22	5	38	30770	0.2	0.1
Hydraulic fill sand	17500	19	5	27	8077	0.2	0.1
Upper Alluvium	17500	19	0	37	8077	0.2	0.1
Lower Alluvium	50000	22	30	40	23077	0.2	0.1

Table 4. Material properties of Chang dam, [3, 26].

Type of Material	E	Y	C	Φ	G	V	R
Semi-precious shell	17500	18	9	30	10000	0.2	0.1
Impervious core	17500	20	65	0	12000	0.2	0.2
Masonry wall	60000	22	80	0	30000	0.3	0.1
Liquefied foundation soil	12000	18	0	10	7000	0.2	0.1
Deep alluvium	20000	20	0	41	17500	0.35	0.2

Chang Dam

The 1959-built Chang Dam is a multiple-zone earthen dam with a 15.5 m maximum section height and a crest length of 370 m. Fig. (6) and Table 5 show the cross-section of Chang Dam and the material properties of the dam. The bedrock on which the dam is constructed is a thin layer of sandstone. The initial design did not consider or take into account the sensitivity of the foundation soil to liquefaction and estimate that the alluvial soils beneath the dam were probably wet when the Bhuj Earthquake occurred, even though the reservoir behind Chang Dam was essentially vacant [3, 26].

Tapar Dam

The earthen dam with many zones, the Tapar Dam, was built in 1976. An extended crest of 1350 meters and a maximum section height of 13.5 meters. In the 1990s, it was raised by another 2.5 m, directly beneath the dam are alluvial sediments that descend more than 30 meters. The Bhuj Earthquake occurred in India on January 26, 2001, with a maximum acceleration of 0.41g [3]. The Tapar Reservoir was largely empty, but the alluvium beneath the upstream face of the dam was moist. Several areas were affected by the upstream toe's liquefaction of the upstream slope to slide laterally and translational [26, 3]. The dam's cross-section shows all of its parts as shown in Fig. (7). Table 6 displays the material characteristics of the dam's parts. Swedish method, developed by Swedish Engineers in 1922, is a well-known approach for examining the stability of slopes and is consequently more frequently utilized. This approach assumes that the curved slip surface is an arc of a circle with a certain center. There will be several of these probable slip rings, each with its center. Picking up the critical slip circle with the lowest soil shear resistance, or the most dangerous critical slip circle, is important. Trial and error are used to determine the circle's center [14].

a. Boundary Conditions for Modeling

The statement of the issue and the boundary conditions for a conventional earth dam are schematically represented in Fig. (2). The following is a succinct summary of these boundary conditions:

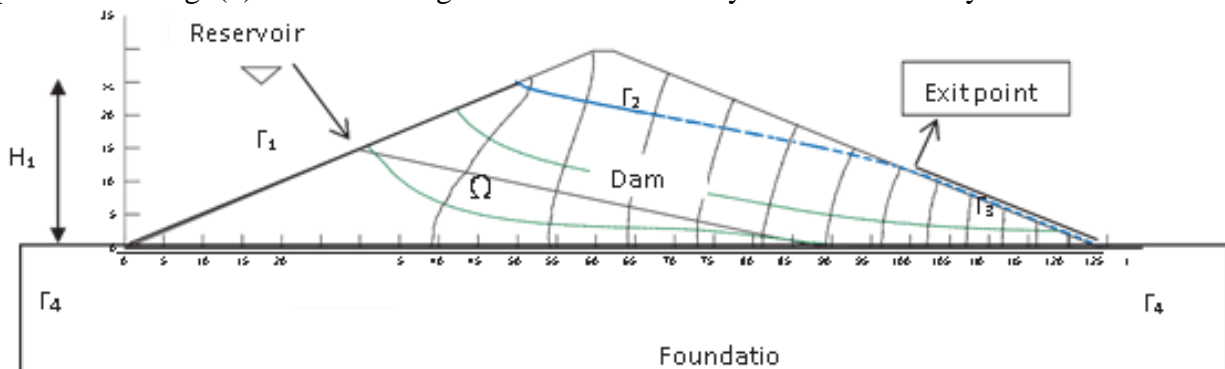


Fig. (4). Boundary conditions and the problem statement (displayed in GeoStudio)

Liquefaction Failure Modeling
Lower San Fernando (California)

The results of the on-site study revealed that the slide was caused by a hydraulic sand fill zone liquefied located close to the foundation of the upstream shell. shows the Horizontal maximum credible earthquake San Fernando Earthquake in 1918 and its maximum acceleration is 0.6 g.

Figures depict the F.S. for the dam slopes both before and following the earthquake (18–21). The safety factor (F.O.S) values before the earthquake, as depicted in the figures, were between 1.449 and 1.629, satisfying the minimal F.S. requirements [25, 27]. The safety factor (F.O.S) readings under static load are an indication of the dam's stability. The safety factor (F.O.S) values following an earthquake varied from

0.264 to 0.183, falling short of the basic limits set by [25, 27]. presents the zone where the initial stress ratio is above or on the collapse surface, as indicated by the yellow shading. This is marked as a zone of liquefaction in QUAKE/W. Fig.

illustrates the area of liquefaction, which has a value of 40.70%.

i. Chang Dam (India)

After the earthquake, the F.S. for the dam slopes is shown in Figs. (23 and 24). The safety factor (F.O.S.) values after the earthquake are 0.105 and 0.243, as can be seen in the supplied figures, and they satisfy the minimal F.O.S. criteria [25, 27]. This is marked as a zone of liquefaction in QUAKE/W. Fig. (25), where the value is 52.20%, depicts the area of liquefaction.

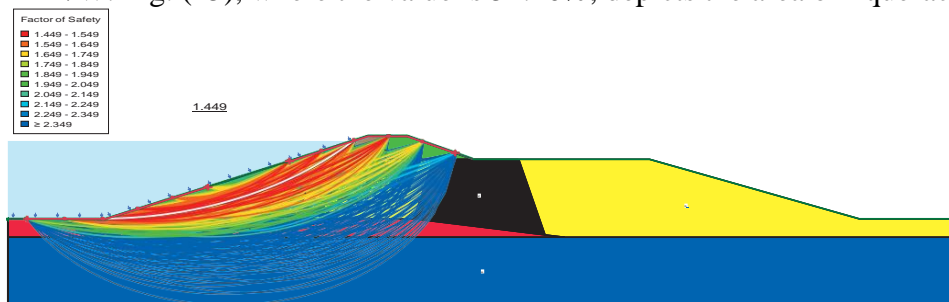


Fig. (5). F.S. of the upstream slope before the earthquake.

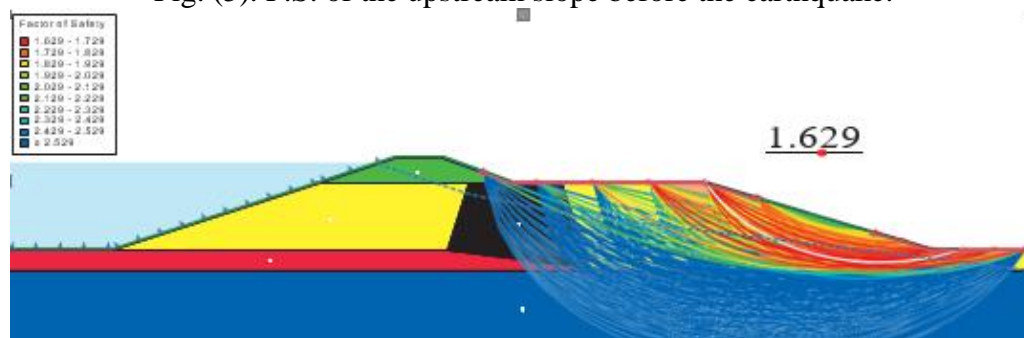


Fig. (6). F.S. of the downstream slope before the earthquake.

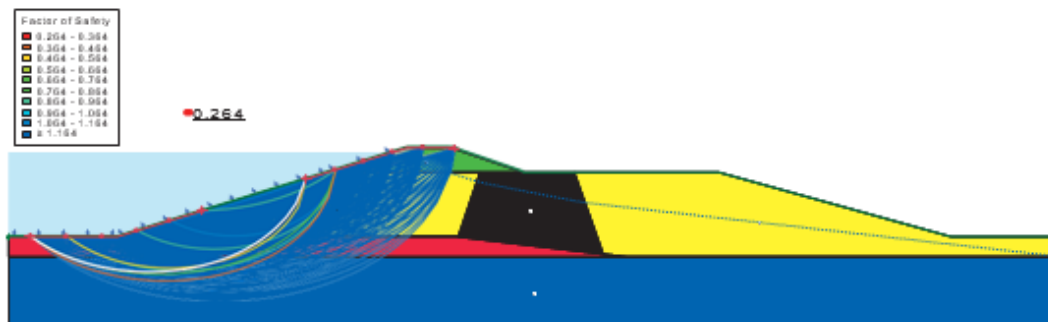


Fig. (7). F.S. of the upstream slope of the earthquake.

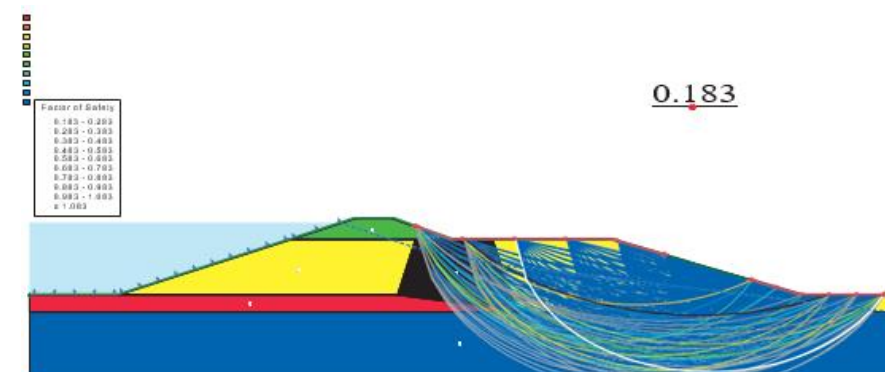


Fig. (8). F.S. of the downstream slope of the earthquake.

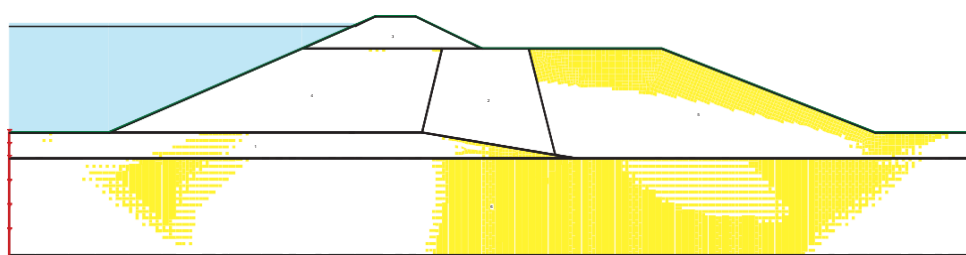


Fig. (9). F.S. of the upstream slope of the earthquake.

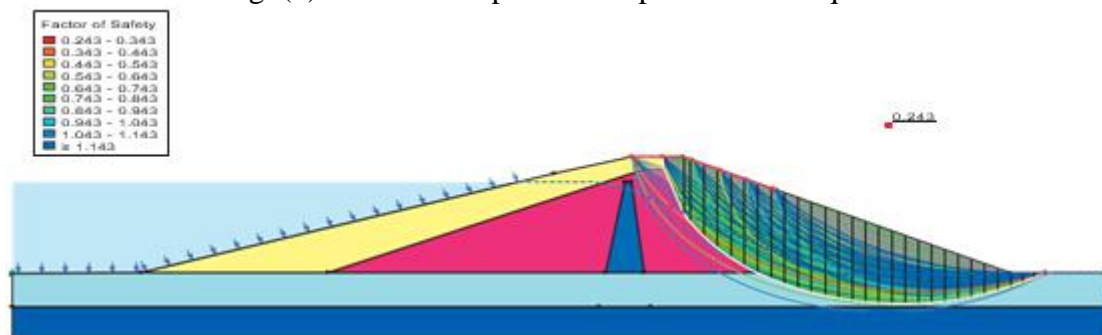


Fig. (10). F.S. of the downstream slope of the earthquake.

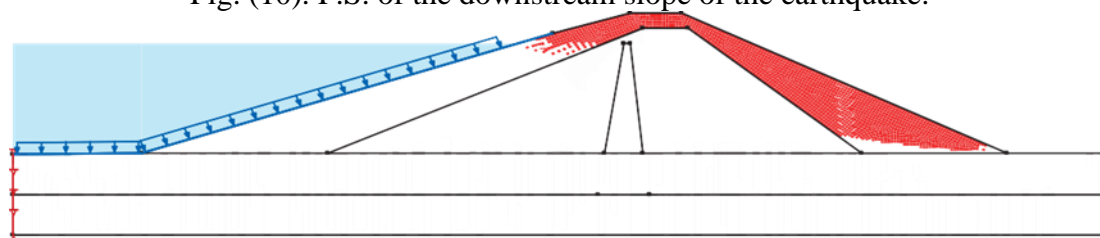


Fig. (11). Liquefaction areas the earthquake.

safety factor (F.O.S) [25, 27, 29].

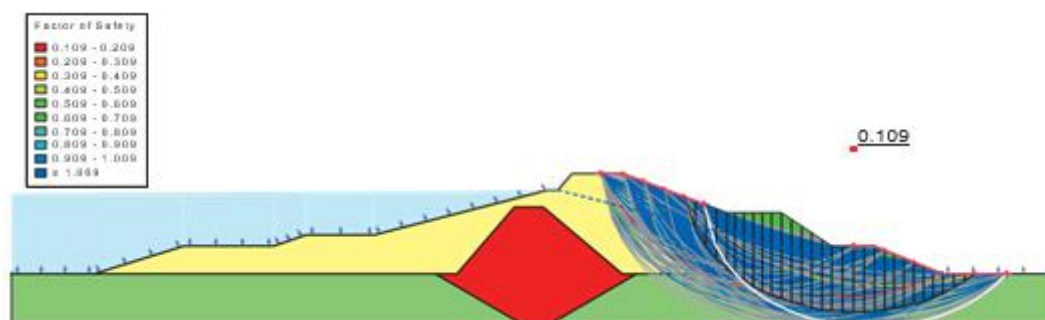


Fig. (12). F.S. of the downstream slope of the earthquake.

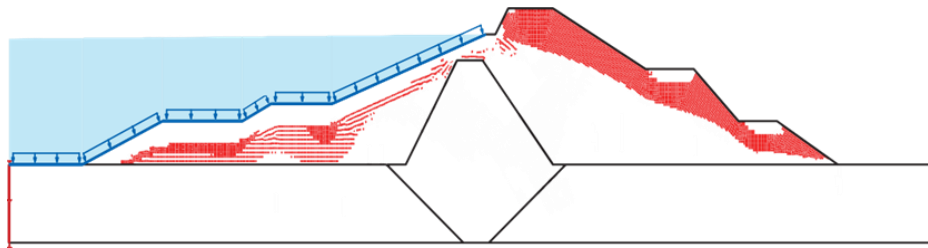


Fig. (13). Liquefaction areas of the earthquake.

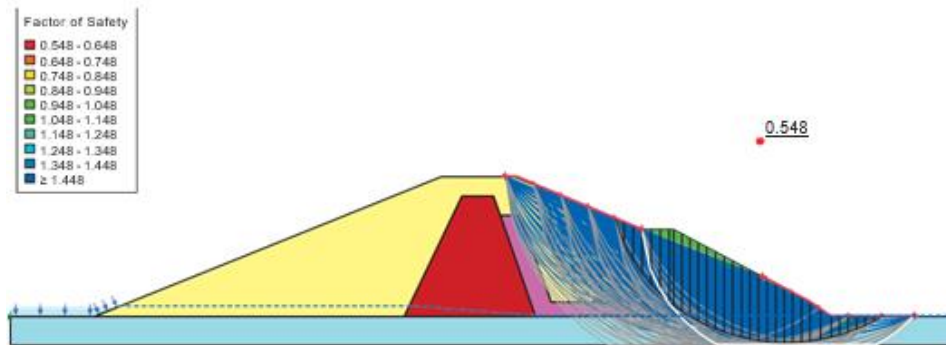


Fig. (14). Liquefaction areas of the earthquake.

Tapar Dam (India)

After an earthquake, the dam slopes' F.S. is shown in Fig. (26); the factor of safety (F.S.) values after the earthquake were 0.109, which is below the minimal F.S. levels specified by [25, 28, 29]. In Fig. (24), the region where the stress ratios are initially above or on the collapse surface is colored red. This area is marked as a liquefied zone in QUAKE/W. Fig. (27), where the value is 52.33%, depicts the region of liquefaction.

Fatehgadh Dam (India)

F.S. for the dam slopes following an earthquake is shown in Fig. (28). The safety factor (F.O.S) values after the earthquake, as shown in the supplied figure, are 0.548, which does not meet the minimal F.S. criteria [25, 27]. The zone where the stress ratios are initially above or on the collapse surface is shown in Fig. (29) as a yellow-shaded area. This is marked as a zone of liquefaction in QUAKE/W. The liquefaction area is shown in Fig. (29), where the value is 78.75%.

Saluda dam (Columbia)

F.S. for the dam slopes following the earthquake is shown in Fig. (30). The safety factor (F.O.S) value after the earthquake, as shown in the presented figure, is 0.102,

V. RESULTS AND DISCUSSION

The Ethiopian Bilate values of 1.54 and 1.483 for upstream and downstream, respectively. F.O.S values of 0.854 and 1.079 for the upstream and downstream due to slope collapse under dynamic loads. The Bilate Dam in Ethiopia has a liquefaction area of 737.2 m², this amount equals 78.67% of the Bilate

Dam's entire foundation area.

Lower San Fernando dam is dangerous under dynamic loads, and the F.O.S. values for the upstream and downstream directions are 0.264 and 0.183, respectively. 1350 m² is the Lower San Fernando Dam's liquefaction area. 40.67% of the Lower San Fernando Dam's overall foundation area is represented in Fig. (31).

Tapar (India) dam is hazardous due to slope failure under dynamic loads, and the F.O.S. values for the upstream and downstream directions are 0.5 and 0.109, respectively. Tapar Dam in India has a

liquefaction area of 457 m². This amount equals 52.33 percent of the Tapar (India) dam's entire foundation area. The slope failure under dynamic loads and the F.O.S. values of 0.313 and 0.548 for the slopes of the river upstream and downstream of Fatehgadh dam (India), respectively, lead to the conclusion that it is unsafe. The size of the liquefaction area is 333.5 m² of the Fatehgadh dam. The foundation area of the Fatehgadh (India) dam as a whole is represented by that figure at 78.75%.

Saluda Dam in Columbia is an unsafe slope failure under dynamic loads, and the F.O.S. values for the upstream and downstream directions are 0.102 and 0.101. Saluda Dam in Columbia has a 32095 m² liquefaction area. This value represents 32.96% of the Saluda Dam's total foundation area (Columbia). All results and discussions are presented in Table 10, Figs. (31 and 32) which show the minimum liquefaction zone area is 32.96% of the total area. The minimum percentage value of liquefaction 32.96% can be relied upon in predicting dams that may be exposed to liquefaction due to strong earthquakes affecting them.

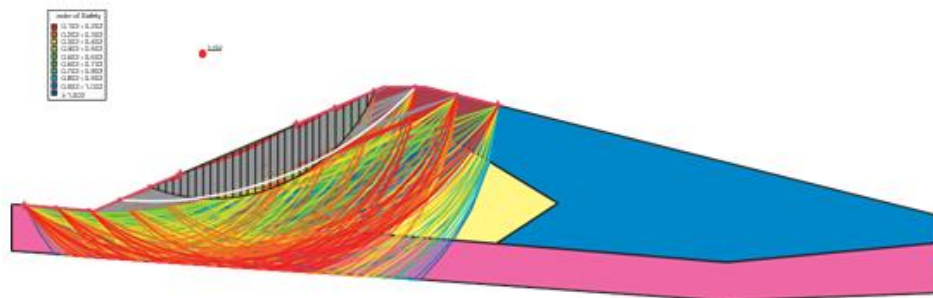


Fig. (14). F.S. of the upstream slope of the earthquake.

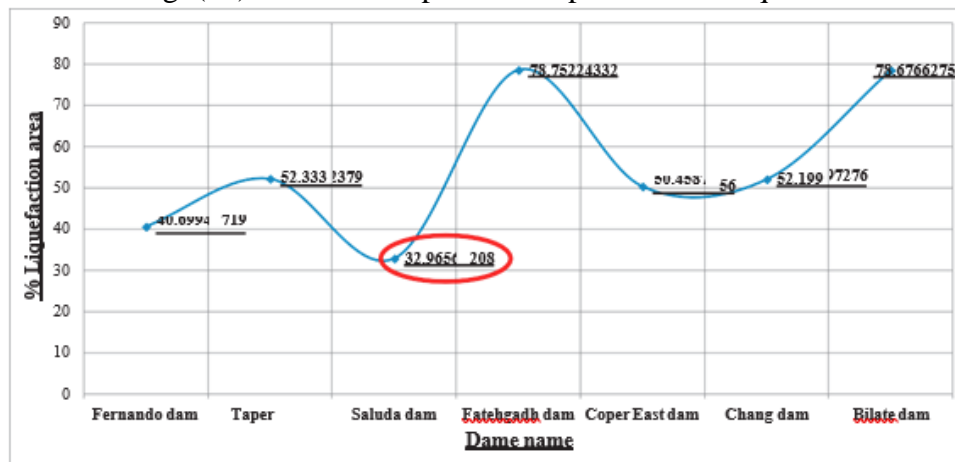


Fig. (15). Liquefied area % for all cases of study.

When the soil's steady-state strength is exceeded by the static shear forces in a deposit of liquefiable soil, flow liquefaction may result. Both during and after an earthquake, it can result in severe flow slide failure. Only loose soil has the potential for flow liquefaction. Cyclic mobility can occur when the static shear stress is less than the steady-state (residual) shear strength and the cyclic shear stress is high enough to suddenly surpass the steady-state strength. At the end of a strong and/or long-lasting earthquake, the deformations caused by cyclic mobility start gradually but grow significantly. Both loose and dense soils are capable of cyclic mobility, but as density rises, deformation dramatically declines. In the contractive zone, an undrained stress channel frequently moves to the left as the inclination of contraction raises the pore pressure and lowers p' . In an earthquake, the q/p' stress ratio and the contours of the initial static stresses' q/pL stress ratios are shown in the figure. The high q/pL ratios near the hydraulic fill's center are an important item to note. The initial q/pL points are thus above the collapse surface in a certain area. With only slight shaking, the soil strength in this zone could be quickly reduced to steady-state strength.

Table 5. Liquefied area % for cases of study.

Dam	Height of Dam	amax	Total Area	Liquefied Area	% (Liquefied Area/Total area)
Fernando dam	22	0.6g	3317	1350	40.67%
Taper dam	15.5	0.41g	873.25	457	52.33%
Saluda dam	116	0.6g	97359	32095	32.96%
Fatehgadh dam	11.6	0.3g	423.48	333.5	78.75%
Chang dam	15.5	0.5g	220.23	114.96	52.20%
Bilate dam	42.5	0.24g	937	737.2	78.67%

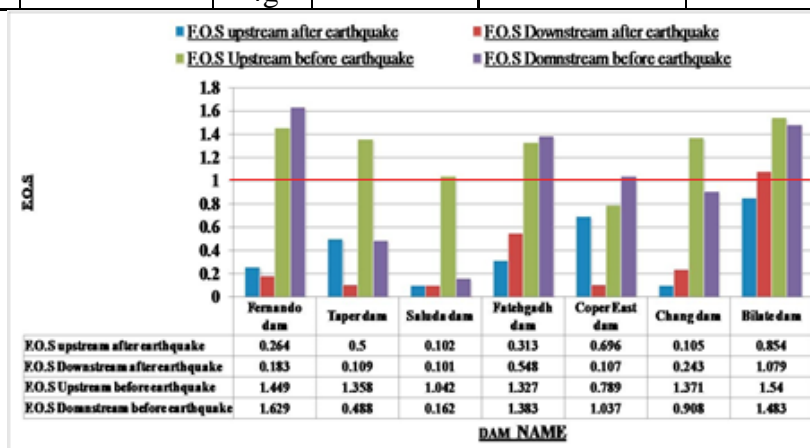


Fig. (16). values of factor of safety before and after the earthquake for all cases of study.

VI. CONCLUSION AND RECOMMENDATIONS

For earthen dams that are going to be built in seismically active areas, a dynamic stability analysis needs to be done. Three different operational load circumstances were utilized to test the dam embankment's upstream and downstream slopes. The case studies provided are excellent illustrations of the various phases of liquefaction analysis in earth-filled embankments. All dams collapse in seismic conditions and with a safety factor of less than 1.0 due to the liquefaction that earthquakes cause. The Ethiopian Bilate Dam is safe against slope failure under static loads; the Bilate Dam is unsafe after earthquake loads and a liquefaction area of 737.2 m². This amount equals 78.67% of the Bilate dam's foundation area. The Lower San Fernando Dam is unsafe under dynamic loads, and the F.O.S. values for the upstream and downstream directions are 0.264 and 0.183, respectively. The Lower San Fernando dam's liquefaction area is 1350 m². This amount equals 40.67% of the Bilate dam's foundation area. Tapar (India) dam is unsafe due to slope failure under dynamic loads, and the F.O.S. values for the upstream and downstream directions are 0.5 and 0.109, respectively. Tapar Dam in India has a liquefaction area of 457 m². This amount equals 52.33% of the Tapar (India) dam's foundation area.

Fatehgadh dam (India), the slope failure under dynamic loads and the F.O.S. values of 0.313 and 0.548 for the slopes of the river upstream and downstream, lead to the conclusion that it is dangerous. 333.5 m² is the size of the liquefaction area of the Fatehgadh dam in India. The foundation area of the Fatehgadh (India) dam as a whole is represented by that figure at 78.75%.



Saluda Dam in Columbia is an unsafe slope failure under dynamic loads, and the F.O.S. values for the upstream and downstream directions are 0.102 and 0.101. Saluda Dam in Columbia has a 32095 m² liquefaction area. This value represents 32.96% of the Saluda Dam's total foundation area (Columbia). the minimum liquefaction zone area is 32.96%. As a result, software creation is crucial for Earth Dam security. It appears that the straightforward and reasonably priced technology can quickly analyze the seismic safety of similarly constructed earth dams without taking earthquake loading into account.

LIST OF ABBREVIATIONS

MST = Ministry of Science and Technology FERC = Federal Energy Regulatory Commission
CRR = Cyclic Resistance Ratio
CSR = The Critical Stress Ratio
AAPD = The Average Absolute Percentage Difference
AME = The Absolute mean Error
EERI = Earthquake Engineering Research Institute

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