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Stability of Al-Adhaim Earth Dam Under Seismic Actions in Iraq

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Abstract. The investigation of earth dams under significant earthquake loads, such as catastrophic earthquakes, is a critical subject in dynamic evaluation. Damage mitigation and structural performance during an earthquake are crucial considerations for an earthen dam. However, Iraq and its neighbors have experienced frequent earthquake activity, including the 2017 Halabja Earthquake, which may have damaged some existing earth dams, posing a higher risk of severe earthquake-induced damage than a cyclic shock. Therefore, assessing the dam's safety is crucial for protecting downstream communities and determining the best strategies to prevent slope stability failure in the face of frequent seismic activity. Nevertheless, the seismicity map of Iraq is being adjusted to reflect the high magnitude of earthquakes, hence; highlighting the need for urgent action to prevent further consequences of seismic activity. Stone columns are a ground improvement technique that utilizes compacted stone columns to improve soil strength by increasing shear strength and reducing excess pore water pressure in non-cohesive soil. It is worth mentioning that prop stone columns on the upstream and downstream slope under the influence of static and dynamic load were not yet well addressed. Thus, the aim includes the study of the impact of stone columns on the stability of the slopes of the Al-Adhaim Earth Dam in Diyala governorate in Iraq, subjected to static and dynamic loads influenced by four earthquakes with a peak ground acceleration of 0.15g for 30 seconds and for different cases, utilizing the Geo Studio program (Seep/w, Slope/w, Quake/w). The results showed that the stone column led to a marginal enhancement in the safety factor of both the upstream and downstream slopes under static load. However, the inclusion of the stone column led to a clear improvement in the safety factor during all earthquakes relative to its exclusion.

Keywords: Al-Adhaim Earth Dam, Seismic, Slope Stability, Stone column, Earthquake, Factor of safety.

1. INTRODUCTION

Recently, Iraq among other neighboring countries faced exceptional earthquake activity and significantly repeated since the beginning of the new century. These earthquakes i.e. Halabja Earthquake causes damage to the existing Darbandekhan earth dam in Iraq. This was hit by the earthquake in 2017 and the dam has been shown different deficiencies in downstream slope and the crest. Therefore, it seems that the first hit of the earthquake points toward more serious consequences than the first hit if the wound is exposed to a cyclic shock of any other earthquake similar to the one in 2017. Therefore, checking out the safety of the existing earth dam is necessary for the safety of our people downstream of the river to determine the best way to prevent the slope stability failure of the existing earth dam in such repeated seismic activity in the region. In addition to the reported increase in the number of earthquakes in Iraq, there are also concerns over the potential of earthquakes whereby the seismicity map of Iraq is being altered to reflect the high magnitude of the quake.

Earth dams are sometimes constructed on a big scale to generate electrical energy, manage flood control, and provide potable water for agricultural purposes, among other uses [1]. The breakdown of earth dams results in significant economic and human losses, hence elevating the need for the design and reinforcement of dams.[2]. An earthquake is a seismic disturbance of the earth's surface caused by the abrupt release of energy in the crust and upper mantle, a natural phenomenon that happens abruptly owing to the fracturing of subterranean rock strata, resulting in movement and vibration of the earth. Earthquakes may be either imperceptibly mild or sufficiently violent to devastate whole towns. Seismic activity refers to the frequency, kind, and magnitude of earthquakes experienced by a location over time, whereas dams respond variably to seismic occurrences according to their intensity. During this event, effective pressure arises between the soil particles beneath the dam and the water, leading to an increase in pore pressure and a transition from a solid state to a liquid state. Liquefaction may result in the collapse of the dam's source or its foundational structures [3-5]. Consequently, it is essential to examine the impact of significant earthquakes on the stability of earthen dams and to identify mitigation strategies to diminish the seismic risk to these structures [6]. For these reasons, studying the long-term impact of strong earthquakes on the stability of earthen dams is important, and finding treatment methods to reduce the risk of earthquakes on earthen dams.

Stone columns, also known as granular piles, are one of the most often utilized methods for improving soil. Stone columns possess several uses for enhancing ground conditions, including treating soft cohesive soils, minimizing the settling of foundations, slope stabilization, and increasing bearing capacity, reduce excess pore water pressure [7-10]. Stone columns may effectively resolve slope stability concerns, including landslip mitigation and stabilization by enhancing the shear resistance of the soil along a possible slide surface and in addition to replacement or displacement of the in-situ soil. Enhanced drainage of pore water pressures may be accomplished by including a more permeable gravel column inside the slope, hence augmenting the strength of the in-situ soils and enhancing stability [11,12].

The collapse of a soil slope may be alleviated by many methods. To achieve this objective, the installation of stone columns is an economical and straightforward procedure. They also alleviate some of the pore pressure generated in the soil around the stone columns due to their increased porosity.[13-15]. In slope stability evaluations, the response of the slope to dynamic loads, such as earthquakes, is essential[16,17]. Mitigating the factors that induce movement on a slope and/or enhancing the soil's resistance to sliding may arise from improving the region susceptible to slope failure or averting potential slope collapse.[18-19]. In this research, the Al-Adhaim earth dam's reaction to seismic activity was investigated. Furthermore, the effect of stone columns on the stability of the slopes of the Al-Adhaim earth dam which is located in Diyala was studied under static load and under the influence of four earthquakes with a peak ground acceleration of 0.15g for a period of 30 seconds using the Geo Studio program (Seep/w,Slope/w,Quake/w).

2. STUDY AREA

Al-Adhaim Earth Dam is located in Diyala governorate in Iraq, 40 km from Al-Adhaim town on the main course of the Al-Adhaim river upstream of the river gauging station of Injana, north of Baghdad City. It is an earthfill embankment dam 3800 m long with a crest of 150 meters above sea level (m.a.s.l) constructed across the Al-Adhaim River at the location of Damir Kapu in Hermine Mountain It was built during the period 1989-2000. The objective of this dam includes flood control of the Al-Adhaim River, water storage for irrigation, 40 MW electrical power generation, development of tourism and green areas, aquatic life, and sediment transport control for turbidity control of the downstream of Tigris River during flood season [State Commission of Dams and Reservoir, Ministry of Water Resources]. Figure 1 shows and seismic hazard map of Iraq after Iraqi seismicity code. The embankment section was designed with an upstream side slope of 2.5H:1V and a downstream side slope of 2H:1V. It included a berm at elevations 100 (m.a.s.l) and 115 (m.a.s.l.), and a downstream berm at elevation 94 (m.a.s.l). The section also included chimney filters connected to blanket filters for drainage of seepage water. The upstream slopes were protected by precast concrete blocks on a gravel filter layer, fine gravel, then fine filter layer T and finer filter layer F while the downstream slopes were protected by coarse gravel and a filter layer. These properties of the dam are tabulated in Table 1. In addition, the original layout of the dam is shown in Figure 2.

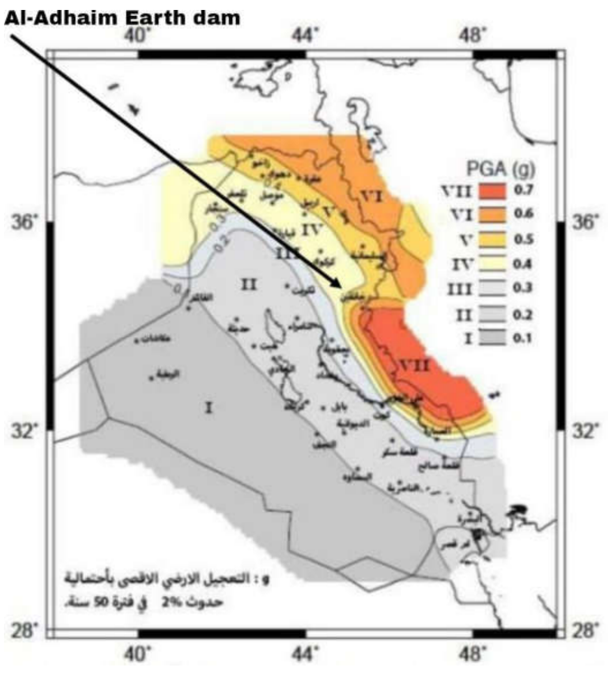


Figure 1: Seismic hazard map of Iraq after Iraqi seismicity code 2017 (Ministry of Construction, Housing, Municipalities, and Public Works).

Table 1**:** Material properties of the Al-Adhaim earth dam [20].

Material Zone	Permeability (m/sec)	Unit Weight (kN/m^3)	Cohesion (kN/m^2)	Friction Angle (degree)
Shell	1.25×10^{-5}	17.658	0	37
Core	2.25×10^{-10}	19.62	60	23
Filter F	1.2×10^{-5}	18.658	0	35
Filter T	1×10^{-4}	18.658	0	35

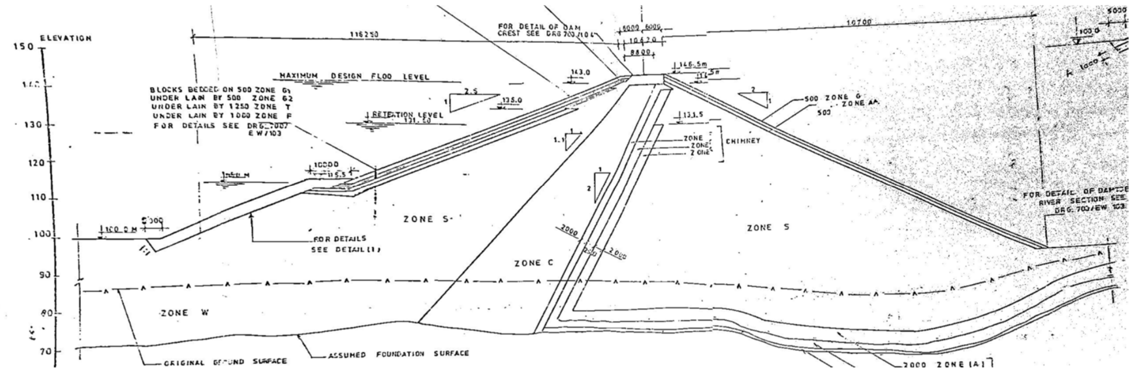


Figure 2: Cross section of Al-Adhaim earth dam [State Commission of Dams and Reservoir, Ministry of Water Resources].

The properties of the gravel filter, fine filter, and riprap protection were correlated to what was used in the filters of Hamrin Dam and Makhoul Dam Table 2, as data were not available for Al-Adhaim dam in State Commission of Dams and Reservoir, Ministry of Water Resources.

Table 2: Material properties [State Commission of Dams and Reservoir, Ministry of Water Resources].

Material zone	Permeability (m/sec)	Unit Weight (kN/m^3)	Cohesion (kN/m^2)	Friction Angle (degree)
Fine gravel	0.000012	16	0	35
Gravel filter	0.00012	20	0	35
Coarse gravel	0.0001	16	0	35
Slope protection	0.0001	19	0	35

3. FINITE ELEMENT METHOD SIMULATION

Several researchers have identified different ways to overlook engineering challenges using numerous techniques i.e. DEM, FEM, and experimental [21,22] under static and dynamic loading [23,24]. Many software programs have been utilized extensively, allowing for the execution of intricate computations and simulations by supplying appropriate inputs and data. As a result, mistakes are less common and the analysis is more thorough than with field observations. The phreatic surface and seepage may be simulated using the finite element software seep/w [22,25]. To confirm that the Seep/w program model is valid, the field piezometer readings must be compared with the piezometer. The readings of the field piezometer reading and simulation model as shown in Table 3 and the seep/w model after the comparison between field and model piezometer reading at upstream water level 115.98 m.a.m.s.l is shown in Figure 3. Because of its user-friendly interface, which makes it suitable for both novice and expert users, the slope/w application is used to assess the slope factor of safety. The software can handle complex soil and rock slope stability problems because of its advanced analytical capabilities. Both 2D and 3D studies may be performed using it. For modeling various soil types, slope/w provides a variety of material models, such as linear and nonlinear Mohr-Coulomb, Bishop, and Hoek-Brown models. [26, 27]. For analyzing seismic effects on embankments and natural slopes, Quake/w is a finite element program. It calculates the dynamic and static ground stresses during an earthquake at predetermined intervals. During the earthquake, slope/w may utilize these stresses to evaluate stability variations and calculate the resulting permanent deformation. [28, 29].

The peak ground acceleration that was chosen to study its effect on the Al-Adhaim Earth Dam is 0.15g with a duration of 30 seconds. However, it is worth noting that the dam area according to Figure 1 is in zone IV of probability's peak ground acceleration of 0.4 g in fifty years which would mean its earthquake effect much higher impact on the slope stability than the average used in this scenario of the study of 0.15g for 30 seconds. Furthermore, the use of 0.15g serves as a preliminary metric for assessing the seismic performance regarding the dam's stability, whereas the likelihood of a 0.4g event happening during a fifty-year span is two percent, indicating its rarity.

Table 3: Comparison of piezometer readings and model Seep/w readings.

Piezometer elevation (m.a.s.l)	**89.44**	**78.86**	**90.56**	**85.16**	**89.89**	**91.03**	**88.78**	**133.55**	**129.93**	**123.9**	**140.57**
Water Table (m.a.s.l)	91.67	86.11	92.13	89.32	91.92	92.46	92	133.55	129.93	123.9	140.57
Field Measured (m)	2.23	7.25	1.55	4.16	2.03	1.43	3.22	Dry	Dry	Dry	Dry
Calculated (m)	2.14	7.61	1.68	4.5	1.89	1.36	3.2	Dry	Dry	Dry	Dry
Percentage Different %	4.8	4.9	4.7	4.5	6.8	4.8	0.6	Dry	Dry	Dry	Dry
Field measurements are taken from the State Commission of Dams and Reservoir, Ministry of Water Resources at upstream water level 115.98 m.a.m.s.l											

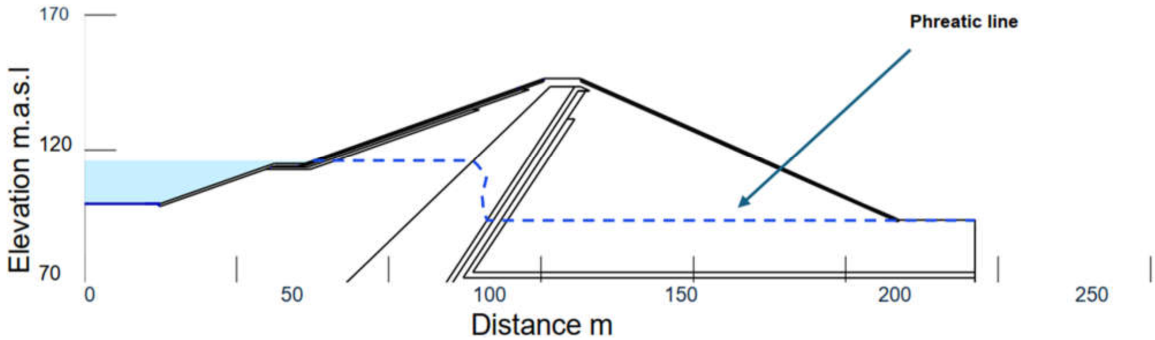


Figure 3: Seep/w model after the comparison between field and model piezometer reading at upstream water level 115.98 m.a.s.l.

4. STONE COLUMN IN SLOPE STABILITY

The behavior of a slope under dynamic loads, such as earthquakes, is crucial for stability assessments of slopes. Enhancing the area susceptible to slope collapse or averting probable slope failure might diminish the causes that induce movement in a slope and/or augment the sliding resistance of the soils. [18,30]. The stone column approach was used as a tool for enhancement. Enhancement techniques, such as stone columns and gravel-filled ditches, may augment the average friction by positioning them on the sliding surface and at the slope's base [31]. Researches indicate that stone columns may endure more shear strength compared to the adjacent soil when subjected to earthquake forces such as shear and compression waves [32,33]. The stone column characteristics chosen in this research are shown in Table 4, following the literature and good practices suitable to the case in this earth dam.

Table 4: Material properties of used stone column in this study [34].

Material	Permeability (m/sec)	Unit Weight (kN/m^3)	Cohesion (kN/m^2)	Friction Angle (degree)
Stone column	0.0138	20	0	42

Therefore, the diameter of the stone column in this study that was chosen to analyze its impact on the stability of the upstream and downstream slope of Al-Adhaim is 50 cm and length to diameter (L/D) = 16 with spacing 17.5 m downstream. The location of the stone column as shown in Figure 4 was chosen after analyzing the effect of the earthquake on the Al-Adhaim earth dam is at the toe of the D/S slope and the U/S slope above the normal water level 131.5m.a.s.l. It is noted that these locations were chosen on the point of generation of excess pore water pressure and where maximum shear stresses are generated due to sliding by the forces of earthquakes in these locations. Factors contributing to slope instability include cyclic stress, particularly from seismic activity, which may induce increased pore water pressures in soils, hence negatively impacting their shear strength. Stone columns may alleviate liquefaction initiation by facilitating drainage (thereby preventing excess pore water pressure accumulation) and by enhancing soil stiffness, which reduces shear strain during cyclic loading. Stone columns may effectively resolve slope stability concerns, including landslip mitigation and stabilization. Therefore, the analysis includes calculating the factor of safety in the upstream and downstream slope with and without the installation of stone columns under the influence of static and dynamic loads for different cases:

Case 1- one stone column at the upstream slope.
Case 2- one stone column at the downstream slope.

Case 3- two stone columns at the downstream slope.
Case 4- one stone column upstream and two stone columns downstream.

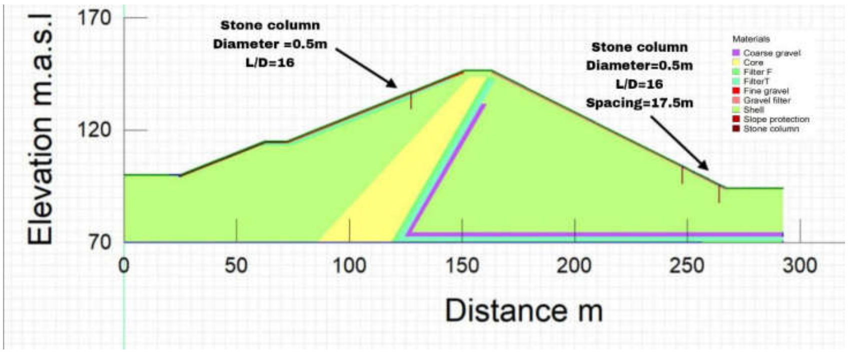


Figure 4: stone columns at Al-Adhaim Earth Dam.

5. RESULT AND DISCUSSION

As can be seen in Figure 5 the factory of safety at the U/S slope fails after the 3th cycle of the earthquake. However, the D/S slope fails after 2nd earthquake ongoing. This triggers the fact of risk possibility in the future in case any two or more earthquakes would occur. Repeated earthquakes lead to the collapse of the overall structure, which means that future precautions must be taken to avoid the failure of Existing earth dams. The impact of recurrent earthquakes is unequivocal, resulting in the collapse of the upstream and downstream slopes. Figure 6 shows a comparison between the factor of safety in the upstream slope with and without a stone column. In case 1, the factor of safety in all earthquakes is higher in the case of the presence of the stone column compared to its absence, however. The magnitude of the earthquakes diminished the slope's strength, leading to a reduction in the safety factor at the summit until collapse transpired after the fourth earthquake. However, when the stone column is positioned on the upstream slope, it has been shown that the safety factor is increased for all seismic events. Figure 6 cases 2 and 3 shows that the stone column downstream does not affect the safety factor upstream in all earthquakes. Figure 6 Case 4 shows that the existence of a stone column in the upstream and downstream Slopes gave a higher safety factor in the third and fourth earthquakes compared to Case. Figure 7 shows a comparison between the factor of safety in the downstream slope with and without a stone column.

Figure 7 Case 1 shows that the existence of the stone column upstream has no effect on the factor of safety at the downstream slope, however. The downstream slope fails at the third and fourth earthquakes as shown in Figure 7, while in cases 2, 3,4 the downstream slope does not fail. In general, the results showed that the presence of a stone column increases the safety factor in the upstream slope and downstream slope in the case of its presence in the slope. The increase in the safety factor with the presence of a stone column has several reasons, including stress redistribution, however. Under the influence of earthquakes, the stress is concentrated on the sliding surface, and the stress at the sliding surface is directed away from the failure surface due to the high stiffness of the stone column to the more solid soil layers. Also, the stone column reduces excess pore pressure and increases the effective stress due to the high permeability of the stone column, which improves the stability of the slope. One of the reasons for increasing the safety factor with the presence of a stone column is reducing the internal erosion that occurs within the soil, as the stone column works to reduce the width of cracks due to the distribution of stress.

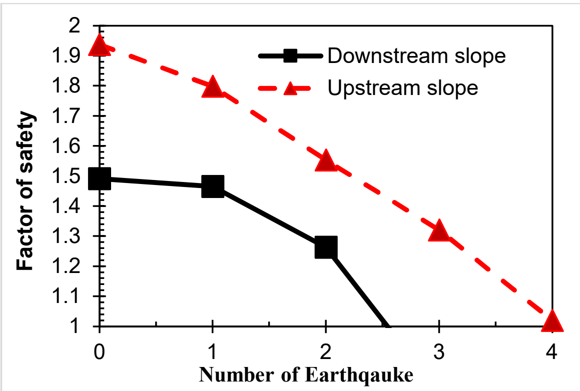
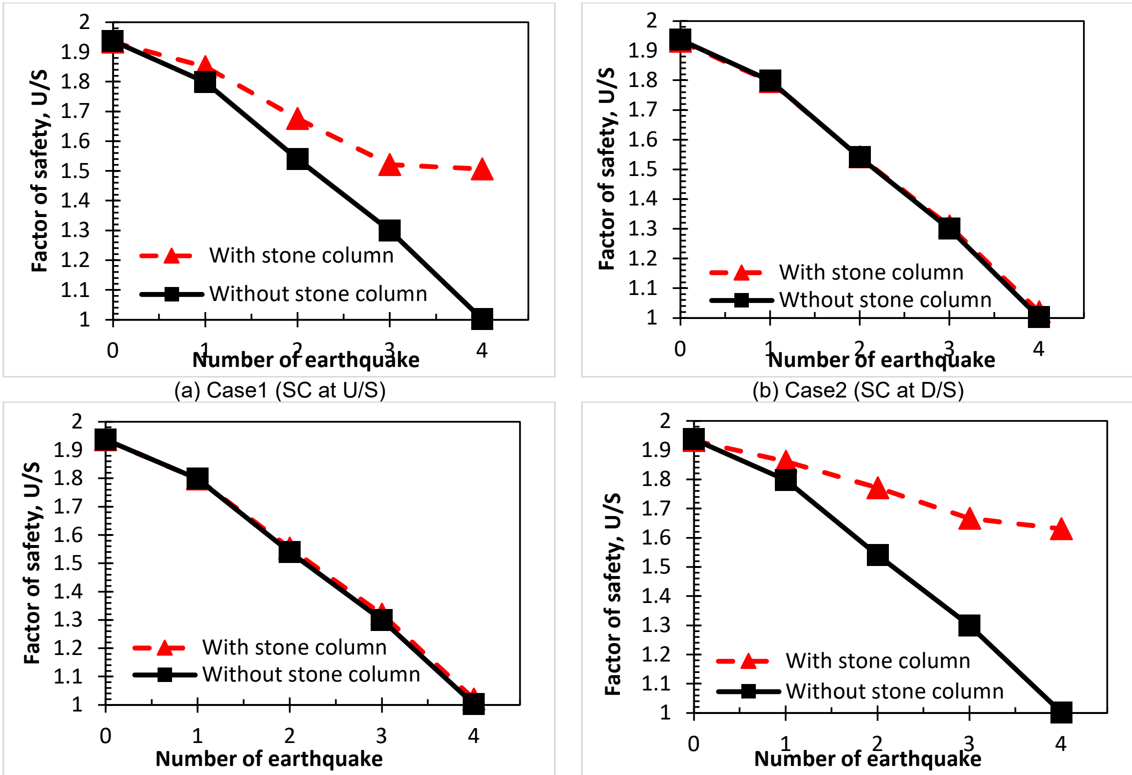


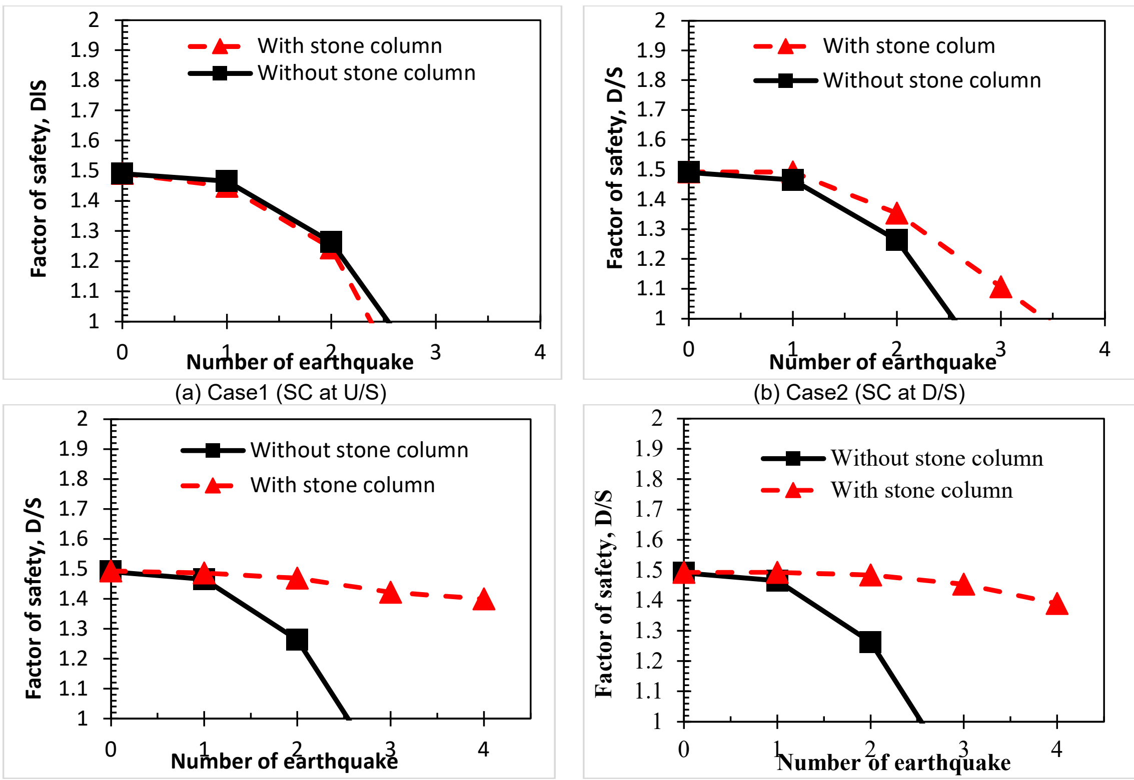
Figure 5: Effect of earthquakes on slope stability of Al-Adhaim earth dam.



(a) Case1 (SC at U/S) (b) Case2 (SC at D/S)

c) Case (3) (Two SC at D/S) d) Case (4) (Two SC at D/S and one at U/S)

Figure 6: Factor of Safety at upstream slope depending on repeated earthquake with and without stone column (a)Upstream (b) Downstream (c)Two downstream (d) Upstream and two Downstream.



(a) Case1 (SC at U/S) (b) Case2 (SC at D/S)

c) Case (3) (Two SC at D/S) d) Case (4) (Two SC at D/S and one at U/S)

Figure 7: Factor of Safety at Downstream slope depending on repeated earthquake with and without stone column (a) Upstream (b) Downstream (c) Two downstream (d) Upstream and two Downstream.

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4. CONCLUSION

Finite element modeling is an essential instrument for evaluating the performance of many systems, such as earth dams. Geo Studio software was used to assess the performance of stone columns on the slope stability of an Al-Adhaim dam, concentrating on the impact of earthquakes on the dam's stability and compare the safety factor in the presence compared to the lack of the stone column.

- The seepage was analyzed using Seep/w to compare the piezometer reading in the simulation with the field readings of the Al-Adhaim earthdam. It was found that the error rate for all readings was less than 10%, i.e. within acceptable percentages.
- The results showed that repeated earthquakes lead to the failure of the downstream and upstream.
- The presence of a stone column in the upstream does not affect the factor of safety in the downstream. Likewise, the presence of a stone column in the downstream does not affect the factor of safety in the upstream.
- Because of the high shear coefficients, high permeability, and high hardness of the stone column, which redistributes stresses in the failure surface, the upstream slope failed in the 4th earthquake without the stone column but did not fail in its presence. As a result, a higher safety factor was assigned to the upstream slope when the stone column was present, however. The downstream slope failed after the 2nd earthquake. In case 2 and after the 3rd earthquake, the downstream slopes collapse. In cases 3 and 4, the downstream slope is stable throughout earthquakes.

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