University of Baghdad
College of Engineering
JOURNAL OF ENGINEERING

Journal of Engineering

journal homepage: www.jcoeng.edu.iq

Volume 31 Number 12 December 2025

Effect of Repeated Earthquakes on Al-Adhaim Earth Dam Factor of Safety and Seismic Improvement Using Stone Columns

Abdulsalam Mahdi Mirza[1], **Zuhair Kadhim Jahanger**[1,*], **Basim Sh. Abed**[2]

[1]Department of Water Resources Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq
[2]Al-Hadi University, Baghdad, Iraq

ABSTRACT

Earth dams in regions with moderate to high seismic activity are crucial for protecting downstream communities. Iraq and its neighboring areas have seen recurrent seismic activity, notably the 2017 Halabja Earthquake, which potentially compromised the integrity of the existing earth dam. The Darbandikhan Dam, affected by an earthquake, has inadequacies in its crest and downstream slope, presenting a greater danger of significant earthquake-induced damage compared to cyclic shocks. Consequently, evaluating the dam's safety is essential for safeguarding downstream residents and identifying optimal ways to avert slope stability failure amid recurrent seismic activity. Iraq's seismicity map is being updated to reflect earthquake magnitude, highlighting the need for immediate action. Stone columns are a ground improvement technique that utilizes compacted stone columns to enhance soil strength by increasing shear strength and reducing excess pore water pressure in non-cohesive soils. The behavior of prop stone columns on slopes under static and dynamic loads has not been extensively investigated. This study examines the influence of stone columns on the stability of the downstream slope of the Al-Adhaim Earth Dam in Diyala Governorate, Iraq, under static and dynamic loads induced by four earthquakes with a peak ground acceleration of 0.2 g for durations of 15 and 30 seconds, using Geo Studio software for various scenarios. The findings indicated that the stone column resulted in a very slight improvement in the safety factor of the downstream slope under static load conditions. The presence of the stone column significantly improved the safety factor during all seismic occurrences relative to its absence.

Keywords: Earth dam, Slope stability, Earthquake, Stone column, Repeated.

1. INTRODUCTION

Earth dams, often referred to as embankment or fill-type dams, are simple structures made of earth and rock-fill materials. These prevent slippage and overturning due to their weight. In limited clay materials, these can have a zonal core with three vertical zones. Earth dams are used for irrigation, potable water systems, and flood protection. Their widespread

*Corresponding author
Peer review under the responsibility of University of Baghdad.
https://doi.org/10.31026/j.eng.2025.12.06

Article received: 15/05/2025
Article revised: 03/10/2025
Article accepted: 10/10/2025
Article published: 01/12/2025

adoption due to local soils, robust mechanisms, and engineering capabilities has made them a popular choice **(Titova et al., 2017)**. When energy is suddenly released from the crust and upper mantle, it causes seismic events like earthquakes, which cause the Earth to vibrate and quiver. The term "seismic activity" describes the historical pattern of earthquakes in terms of their frequency, kind, and magnitude. Dam responses are determined by the magnitude of seismic shocks. An earthquake may jeopardize the integrity of the dam or result in the destruction or deformation of other structures, such as a bridge. When soil becomes too saturated or too partly saturated to resist the applied force from earthquake shaking, the normal material begins to behave more like a liquid, a process known as soil liquefaction **(Taher and Jahanger, 2024)**. The dam's structure or other essential parts could fail as a result of this **(Taher and Jahanger, 2023)**.

Damage to fundamental strength and instability of embankments can result from strong ground shaking. In the opinion of many dam experts, embankment dams are suitable when properly compacted according to specifications. It is a mistake, however, to think that embankment dams are impervious to damage and collapse, especially in the presence of near-source impacts, even when compacted correctly **(Gordan et al., 2022)**. Earth dams dynamically evaluated in the context of seismic forces, such as catastrophic earthquakes, are an important issue. During seismic occurrences, it is crucial to reduce damage and ensure that structures remain intact. Seismic activity in Iraq was high enough to cause embankment dams, villages, and fissures to move, which might lead to their eventual or immediate collapse. Dam instability and internal erosion caused by vertical and horizontal fissures might cause the dam to crumble. After earthquakes, both the general public and dam engineers express concerns about the safety of dams, highlighting the need for effective mitigation techniques. **(Yousif et al., 2019)**. Therefore, it is critical to investigate how severe earthquakes affect earthen dam stability over time and to develop treatments that lessen the likelihood of earthquakes damaging these structures. A multitude of studies have used many methodologies, including digital elevation model (DEM), finite element model (FEM), and experimental techniques. **(Alzamily and Abed, 2022a)** to identify various ways to ignore engineering issues. In both static and dynamic loading **(Bayati and Bagheripour, 2019)**. Finite element methods are extensively used for the numerical resolution of structural, hydrodynamic, and multiphysics challenges. The approaches are widely used since engineers and scientists can mathematically model and numerically resolve very complicated issues. Engineering analyses are conducted to evaluate designs, whereas analyses in many scientific disciplines are primarily undertaken to gain insight into and ideally anticipate natural processes. The ability to forecast a design's performance and the occurrence of natural phenomena is very valuable. It enables the enhancement of safety and cost-effectiveness in designs, while insights into nature's predictions may aid in catastrophe prevention. Consequently, the use of the finite element approach significantly enhances human existence **(Bathe, 2007)**. The GEO-Studio subprograms (Seep/w, Slope/w, and Quake/w) utilized in this study a finite element programs employed to investigate the variations in seepage field, stress field, displacement field, and stability coefficient of the slope under diverse rainfall conditions, focusing on seepage mechanics, and to elucidate the alterations in unsaturated soil and the impact of earthquakes on earthdams **(Tan et al., 2023)**.

(Gelgalu and Zewdie, 2023) have analyzed the seismic impact on Gidabo Dam located in Southern Ethiopia, using GeoStudio software subprograms (Seep/w, Slope/w, and Quake/w). In this study, two earthquakes were used, one with a peak ground acceleration

(PGA) of 0.15 g and the other with a PGA of 0.3 g. The study was based on the initial steady-state analysis from Seep/w. Slope/w was used to do the slope stability analysis without considering seismic stresses, yielding a factor of safety greater than one, which indicates that the dam is safe against sliding. Static analysis indicates that the dam is stable against sliding, exhibiting factors of safety of 1.537 downstream and 1.499 upstream. Slope/w Quake/w were used to calculate the safety factor after an earthquake. The dynamic analysis shows that the safety factor for the upstream slope was 1.104, whereas for the downstream slope it was 0.806 under PGA of 0.3 g. The factor of safety for the upstream slope was 1.115, whereas for the downstream slope it was 0.824 under PGA of 0.15 g.

(Lu et al., 2025) have used geosynthetic reinforcements to improve the stability of the earth dam. The study was conducted using GeoStudio software subprograms (Seep/w, Slope/w, and Quake/w). Seismic investigation that included ground shaking with a peak acceleration of 0.1 g revealed substantial displacements (0.984 m) and a decreased factor of safety (1.279) upstream slope, both of which were getting close to the permitted level. There was liquefaction zones found, especially in the shell, suggesting a significant susceptibility to seismically induced loss of shear strength. The factor of safety was raised to 1.503 by using geosynthetic reinforcements in optimal geometries (horizontal layers, 4 m vertical spacing, and 20 m length) to mitigate these concerns. The safety of earthen dams in earthquake-prone areas may be improved with the help of these findings, which show how well geosynthetics to reduce soil liquefaction and increase seismic resistance.

(Aude et al., 2022) have analyzed the stability of the Al-Adhaim earth dam with geotextile reinforcement. Geo-Studio subprograms (Seep/w, Slope/w, and Quake/w) are used in this study to evaluate the performance of geotextile reinforcement on Al-Adhaim earth dam. After the application of seismic shaking to the structure, the dynamic stability of the dam and the liquefaction of the soil were evaluated. According to the analytical results, the dam proved stable under static settings. Additionally, the dynamic condition results showed that an earthquake with PGA of 0.38 g and a period of 10 seconds caused the dam to move vertically by 0.12 m and reduced the factor of safety to 1.01. In order to lessen the effects of soil liquefaction found in the dam's shell, geotextile strengthening was suggested. With a factor of safety of 1.946, which means that the reinforcement improved the dam's stability.

(Abbas and Al-hadidi, 2021) have analyzed the effect of the Halabja earthquake on Al-Wand Earth Dam using (Seep/w, Slope/w, and Quake/w). The results show that the factor of safety under static load for upstream is 3.119, and for the downstream is 3.072. The safety factor after the Halabja earthquake in the dam's upstream and downstream sections is 2.979 and 2.972, respectively, reflecting a decrease of about 4.5% and 3.3% in the upstream and downstream portions, respectively.

Stone columns are a prevalent ground improvement method for enhancing weak soil conditions. They diminish total and differential settlements, expedite consolidation, enhance bearing capacity and slope stability, and mitigate liquefaction risk **(Pal and Deb, 2018)**. The enhancement is achieved by using gravel or crushed stone, which has superior stiffness, strength, and permeability compared to the naturally weak soil. Furthermore, column construction alters the characteristics of the adjacent soil. **(Black et al., 2011; Al-Khalidi et al., 2024)**.

There are a lot of ways to prevent a soil slope from collapsing. Stone columns are an easy and inexpensive option for this purpose. Their superior strength causes them to obstruct the slippery surfaces. They reduce part of the pore pressure that builds up in the soil surrounding the stone columns because of their higher porosity **(Castro and Sagaseta,**

2012). It is essential to consider the slope's response to dynamic stressors, such as seismic activity, while assessing its stability. Improving slope failure-prone regions or averting likely collapse are two ways to reduce the factors that cause slope movement and increase soil resistance to slides **(Jawad, 2011)**. There are some studies that have addressed the effect of stone columns on the stability of earthen slopes. (**Goswami and Deka, 2023)** studied the effect of the effect of Installation of Stone Columns on the Stability of Soil Slopes using the PLAXIS 2d program. The study investigated the impact of stone column number, length, and diameter on soil slope factor of safety using artificial neural networks. The results show that the stability of soil slopes is significantly enhanced by the use of stone columns, with increased column numbers, lengths, and diameters resulting in increased stability.

(Vekli and Çadır, 2022) Have studied the stability of the stone column slopes under different earthquake loads using the PLAXIS 2d program. The study aimed to improve safety factors for slopes with varying angles, soil cohesiveness, and earthquake magnitudes. The stone column technique was used to enhance slopes with similar characteristics. Different internal friction angles and s/D ratios were used. The study found that slope models without considering earthquake forces and using stone columns had higher safety values of 1.01 to 1.34 times compared to those without. Additionally, safety ratings of slope models with stone columns increased by 1.02 to 1.80 times in response to seismic forces.

(Dar and Shah, 2021) studied the stability of embankment supported with stone columns. This research evaluates the performance of ordinary stone columns (OSC) and geosynthetic-encased stone columns (GESC) in supporting embankments using a three-dimensional finite element software (PLAXIS3D). A parametric examination was performed to evaluate the impact of many parameters, including the spacing-to-diameter ratio (S/D), encasement stiffness, soil cohesion, stone column friction angle, and embankment friction angle, on the factor of safety against deep-seated collapse. Comprehensive slope stability assessment and formulation of simplified factor of safety evaluation models for stone Column-reinforced embankments. Results indicate that encasing stone columns improves the stability of embankments. Reducing the column spacing (S/D) improves stability. An increase in the stiffness of geotextile encasement, the friction angle of the stone column, and the friction angle of the embankment enhances the performance of embankments.

(Çadır et al., 2021) have investigated the influence of a stone column on a soil slope under the effect of earthquakes using (PLAXIS3D). This investigation revealed that the Slopes enhanced with stone columns exhibited a greater factor of safety in comparison to slopes devoid of stone columns, both under seismic forces and in their absence. About seismic force. In the research, the safety factor of the slopes enhanced with stone columns under the influence of seismic forces rose by up to 1.24 times compared to slopes without stone columns.

It is worth noting that the Al Adhiam earth dam is designed to withstand earthquakes of 0.25 g (maximum credible earthquake) (**Binnie and Partners, 1989**). However, this would not have been credited to repeated earthquakes during long-term periods. Therefore, this would have a significant risk to the overall stability of the Al-Adhaim Earth dam that earthquakes could have caused, and threatening impacts on the Al-Adhaim Earth dam downstream slope and environment. This research mainly aims to numerically simulate the behavior of Al-Adhiam Earth dam under more than one earthquake and calculate the safety factor at the downstream slope with and without the presence of stone columns under static and dynamic loading.

2. DESCRIPTION OF STUDY AREA

A tributary of the Tigris River, Al-Adhaim was the site of the construction of the Al-Adhaim Dam. In addition to reducing the impact of floods in Baghdad, it is an important source of agricultural water for the Dhulwaiya agricultural project, the Kirkuk irrigation project phase 3, and the surrounding areas. Operating at an altitude of 131.5 meters above sea level (m.a.m.s.l.), the reservoir began operations in 1999 with a capacity of 16 × 10^8 km^3. There are 120 km^2 of surface area in the reservoir. At a height of 143 meters above sea level, the storage capacity is 38 × 10^8 km^3. With a design discharge of 1,150 m^3/s at a crest height of 131.5 m.a.m.s.l., the ungated spillway was constructed to handle a flood wave that is expected to reach 12,700 m^3/s at flood level **(Hussain et al., 2022)**. **Fig. 1** shows the location of the Al-Adhaim earth dam in the seismic hazard map of Iraq.

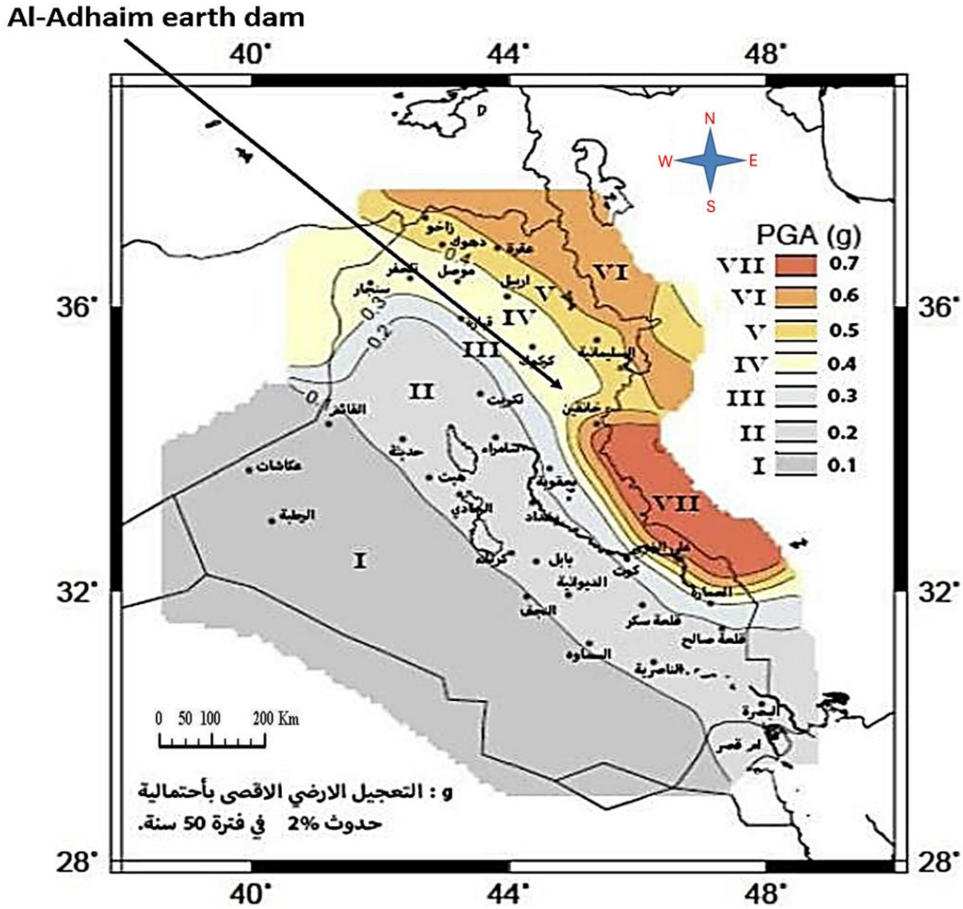


Figure 1. Seismic hazard map of Iraq after the Iraqi seismicity code 2017. **(Ministry of Construction, Housing, Municipalities, and Public Works, 2017)**.

The embankment had a slope of 2.5H:1V upstream and 2H:1V downstream. Between an elevation of 94 m.a.s.l., it featured a downstream berm, and between 100 and 115 m.a.s.l., it included additional berms. Chimney filters linked to blanket filters were installed in the area to assist with the drainage of seepage water. While the downstream slopes were protected by coarse gravel and a filter layer, the upstream slopes were reinforced by precast concrete blocks on a gravel filter layer, fine gravel, a fine filter layer T, and an even finer filter layer F. Here are the material properties of the Al-Adhaim earth dam, as listed in **Table 1**. The cross-section for the dam is also shown on **Fig. 2**.

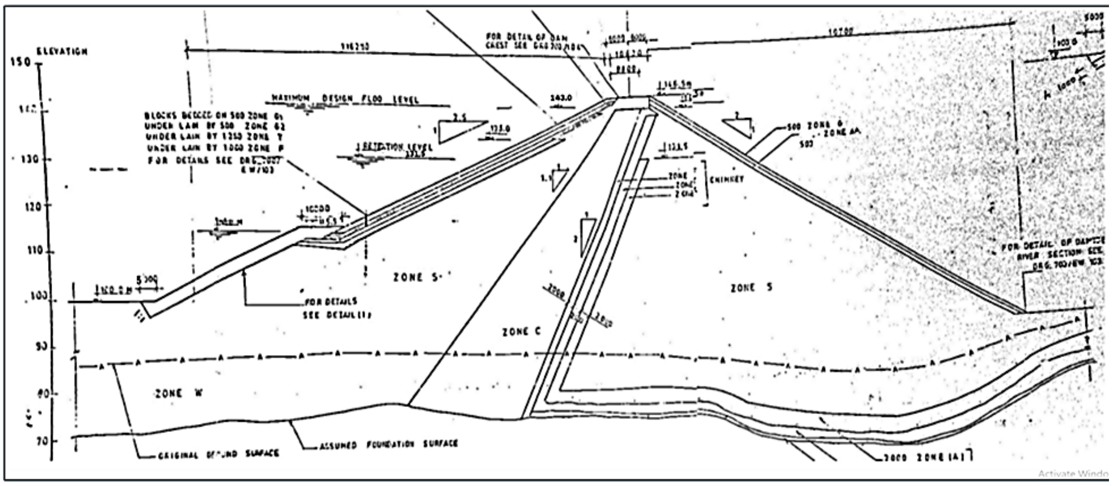


Figure 2. Cross-section of Al-Adhaim earth dam **(State Commission of Dams and Reservoir, Ministry of Water Resources, 1995).**

Table 1. Material properties of the Al-Adhaim earth dam **(Hassan et al., 2024)**.

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

Due to the unavailability of data for Al-Adhaim Dam from the State Commission of Dams and Reservoirs, Ministry of Water Resources, the attributes of the gravel filter, finer filter, and riprap protection were compared to those employed in the filters of Hamrin Dam and Makhoul Dam, as illustrated in **Table 2.**

Table 2. Material properties.

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. METHODOLOGY

Full-scale earth dams are more appropriately analyzed by finite element models FEM. This study used GeoStudio software to construct a two-dimensional solid geometry of the AL-Adhaim Earth Dam. The GEOSTUDIO software is capable of conducting a variety of analyses, such as dynamic analysis, slope stability, seepage, and stress-strain. SEEP/W, SLOPE/W, and QUAKE-W are GEOSTUDIO subprograms that are capable of simulating the movement and pore-water pressure distribution within permeable materials, stability of earth dams' slopes, and analyzing the effect of dynamic stresses on earth dams. The seep/w subprogram is used first to simulate the effect of upstream water level on the Al-Adhiam earth dam and to validate the Al-Adhiam earth dam. Secondly, the quake/w subprogram is used to simulate the effect of earthquakes on Al-Adhiam earth dam (the pore water pressure condition is already obtained from seep/w). Finally, the Slope/w sub program has been used in this study to calculate the factor of safety under static and dynamic loads (the dynamic stress is taken from quake/w). The equivalent linear model is utilized in this study. The dynamic analysis's boundary conditions are all vertically fixed displacements, except the nodes' left and right vertical boundary conditions, which allow horizontal movement. A fluid pressure boundary is a high-pressure barrier that defines the elevation of the upstream water surface. **Tables 1** and **2** above illustrate the input materials used in the numerical modeling required for the examination of both static and dynamic analysis at AL-Adhaim Earth Dam. The following subsection includes a description of the subprogram used in this study:

3.1 Seep/w

Many software programs have been extensively utilized, making it easier to carry out intricate computations and simulations by providing appropriate inputs and data. As a result, the analysis is more thorough, and mistakes are lower than with field observations. Engineers utilize the SEEP/W program, which is part of the Geo-Studio software and includes many programs, to examine and assess seepage problems in dams. The numerical finite element approach is its mainstay **(Jassam and Abdulrazzaq, 2019; Alzamily and Abed, 2022b)**.

3.1.1 Seepage Equation

The partial differential equation (PDE) governing the SEEP/W system is as follows **(Al-Nedawi and Al-Hadidi, 2020)**:

$$\frac{\partial}{\partial x}\left(kx\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(kx\frac{\partial H}{\partial y}\right)+Q=\frac{\partial \theta}{\partial t} \quad (1)$$

H represents the hydraulic head, Q denotes the applied boundary flux, t signifies the time domain, θ indicates the volumetric water content, and Kx and Ky refer to the hydraulic conductivity in the x and y directions, respectively. Eq. (1) is a temporal variable that differentiates inflow and outflow of a volume based on changes in volumetric water content. In an improbable scenario, the left side of the equation becomes zero when the deluge volume matches the out-transition volume, achieving a steady state **(Al-Nedawi and Al-Hadidi, 2020).**

$$\frac{\partial}{\partial x}\left(kx\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(kx\frac{\partial H}{\partial y}\right)+Q=0 \quad (2)$$

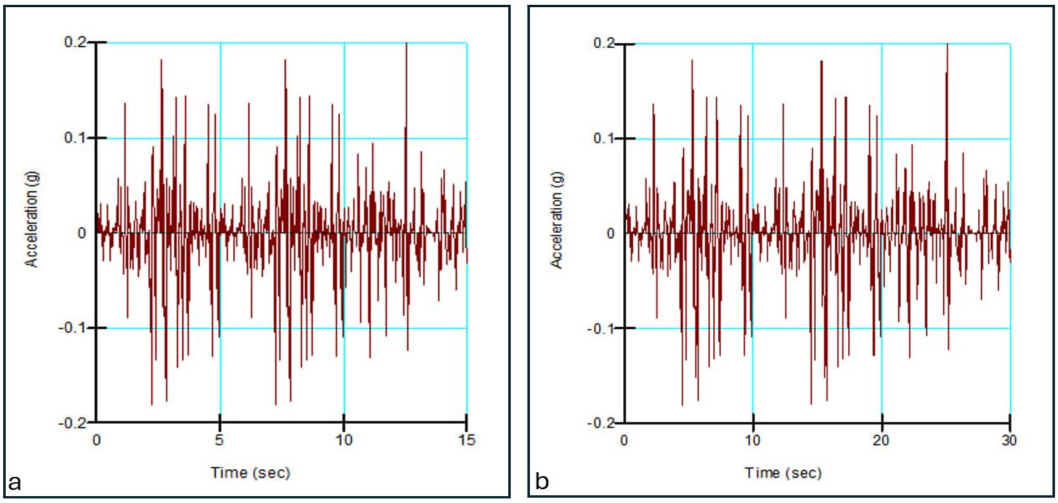
3.2 Slope/w

The SLOPE/W program is used for evaluating the slope factor of safety, owing to its intuitive interface that makes it accessible for both seasoned and rookie users. The program has sophisticated analytical capabilities that can address intricate soil and rock slope stability issues. It can do both two-dimensional and three-dimensional analyses. SLOPE/W offers a range of material models for simulating different soil types, including linear and nonlinear Mohr-Coulomb, Bishop, and Hoek-Brown models. Plus, SLOPE/W solves for both the force and momentum components of the safety factor, so you can get the basic slip surface area at various altitudes and calculate the safety factor **(Idrus et al., 2023)**.

3.3 Quake/w

The Quake/w finite element software is useful for studying the impact of earthquakes on embankments and natural slopes. At regular intervals, it determines the static and dynamic ground stresses that occur during an earthquake. In the event of an earthquake, slope/w may use these stresses to determine the lasting deformation by analyzing stability fluctuations. **(Moayed and Ramzanpour, 2008)**.

The 2017 Halabja earthquake had a PGA of 0.1 g **(Ismael and Ahmed, 2023)**, resulting in significant damage to the Darbandikhan Dam, including the formation of longitudinal fractures on the downstream slope and the crystal. The chosen peak ground acceleration for assessing its effect on the Al-Adhaim Earth Dam is 0.2 g, with durations of 15 and 30 seconds. The dam area, illustrated in **Fig. 1**, is located in zone IV, which has a peak ground acceleration probability of 0.4 g over fifty years, resulting in a considerably greater seismic influence on slope stability compared to the 0.2 g average employed in this study scenario for 15 s and 30 s. **Fig. 3** shows the record of the earthquake at 0.2 g for the duration of a) 15 s and b) 30 s used in this study.



a)15 s b) 30 s

Figure 3. Record of the earthquake at 0.2 g for duration for a)15 s and b) 30 s (Quake/w).

4. STONE COLUMN

Various measures may be used to avert slope failure. Employing stone columns for this objective is a straightforward and cost-effective approach. Their enhanced strength enables them to improve stability along potential failure planes. They decrease the pore pressure in the soil around the stone columns to a certain degree due to their increased porosity. Slope stability assessments must include the slope's reaction to dynamic pressures, including seismic events. Mitigating the causes that trigger slope movement and enhancing the sliding resistance of soils may be accomplished by upgrading regions susceptible to slope failure or averting potential slope collapse **(Vekli and Çadır, 2022).** The stone column approach was used for enhancement. When positioned on the sliding surface and at the slope's base, enhancement measures such as gravel-filled ditches and stone columns may augment the average friction **(Baez and Martin, 1995)**. **Table 3** illustrates the details of the stone columns used in this study, in accordance with the relevant literature and best practices for this earth dam.

Table 3. Material properties of the used stone column in this study **(Murugesan and Rajagopal, 2006).**

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

The diameter of the stone column analyzed in this research, concerning its effect on the stability of the downstream slope of Al-Adhaim, is 50 cm, with a length-to-diameter ratio (L/D) of 16 and a spacing of 17.5 m downstream. The position of the stone column is shown in **Fig. 4.**

The sites were selected based on the development of excess pore water pressure and the maximum shear stresses induced by seismic sliding forces in these areas. By improving soil stiffness, which reduces shear strain under cyclic loading, and by promoting drainage, which prevents the accumulation of excessive pore water pressure, stone columns can mitigate the onset of liquefaction.

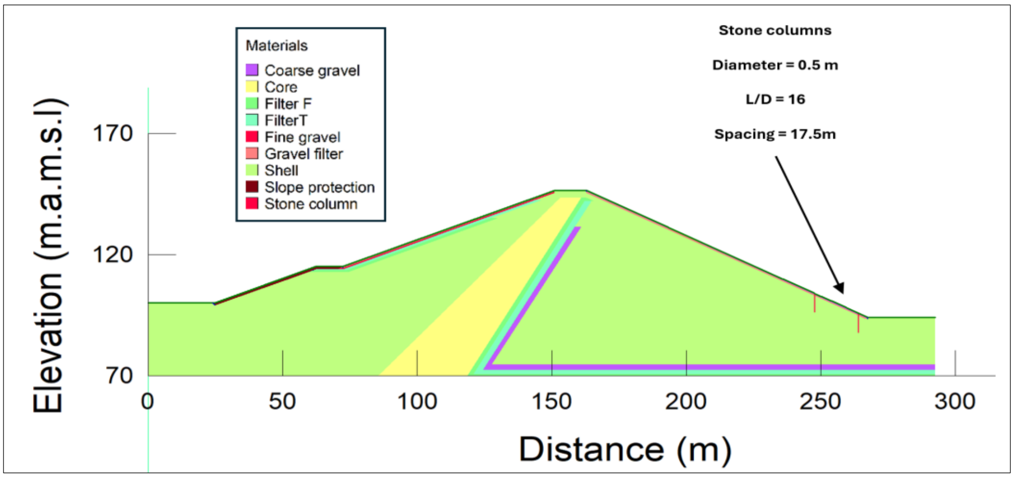


Figure 4. Location of stone columns.

Concerns of slope stability, particularly landslip reduction and stabilization, may be successfully addressed using stone columns. The study considers two scenarios involving the placement of stone columns under static and dynamic stresses to calculate the safety factor for the downstream slope:

- Case 1: one stone column at the downstream slope
- Case 2: two stone columns at the downstream slope

5. RESULTS AND DISCUSSION

This section presents the results obtained from the use of Geo Studio software (Seep/w, Slope/w, Quake/w). This includes the validation results and factors of safety for the downstream slope under static and dynamic loads for cases 1 and 2.

5.1 Validation Result

For statistically confirming the agreement between the Seep/w program's results and the field measurements, which evaluated similar shapes under the same hydraulic conditions. A comparison was conducted between the piezometer reading obtained in the field at 115.98 m.a.m.s.l. and those computed using the numerical model. The numerical model's findings closely align with field measurements **(State Commission of Dams and Reservoir, Ministry of Water Resources, 2021)**, with a maximum percentage difference of 6.8%. **Table 4** and **Fig. 5** present the pressure head calculated from the numerical model alongside the pressure head obtained from field measurements Al-Adhiam earth dam.

Table 4. Field piezometer readings and model

Water Table (m.a.m.s.l)	91.67	86.11	92.13	89.3	91.92
Field reading (m)	2.23	7.25	1.55	4.16	2.03
Calculated (m)	2.14	7.61	1.68	4.5	1.89
Percentage different %	4.8	4.9	4.7	4.5	6.8

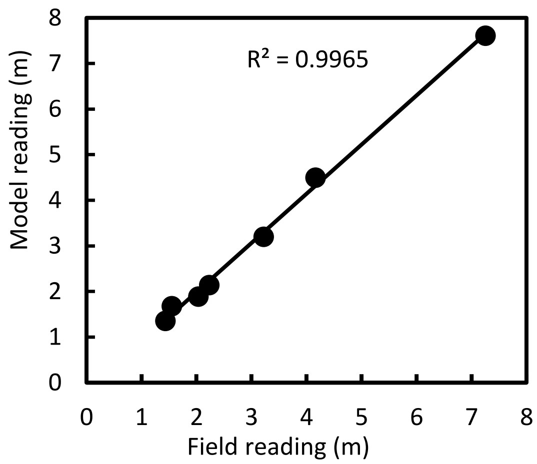


Figure 5. Calculated and Field reading

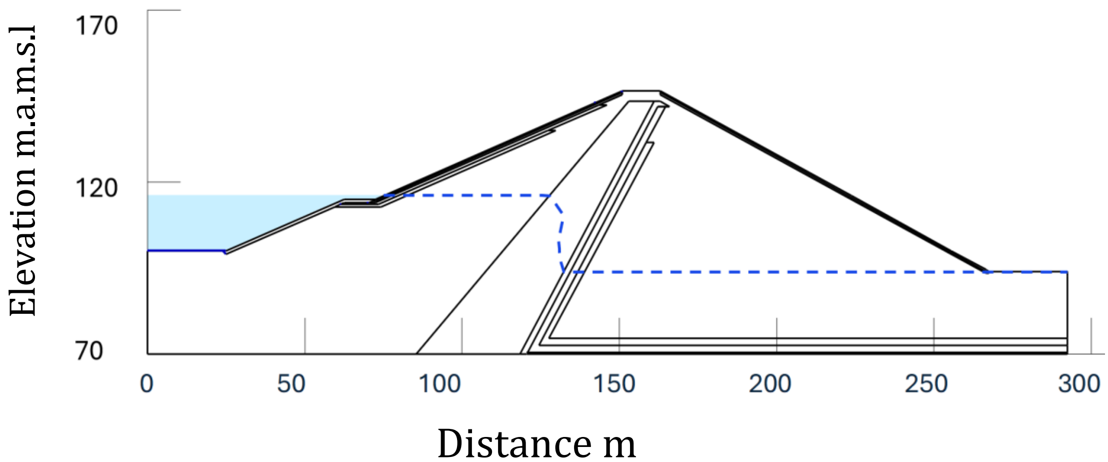
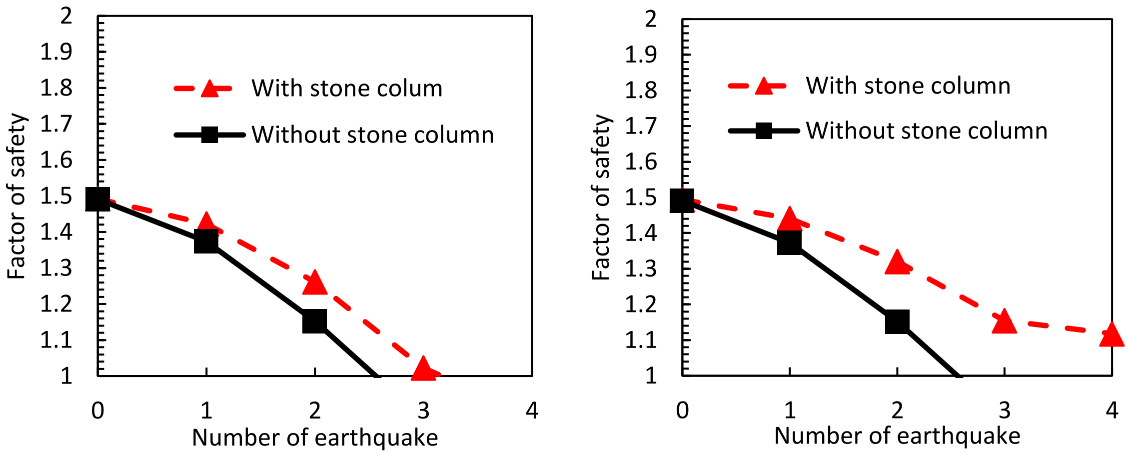


Figure 6. The Phreatic line after comparing the validation using Seep/w.

5.2 Factor of Safety

Slope stability is a critical component in geotechnical engineering. The use of finite element analysis for slope stability has been more popular in recent years, owing to its capacity to address complicated issues **(Zheng et al., 2006)**. The examination of slope stability in earth dams is crucial for determining the structural integrity of these dams. The stability of an earth dam is contingent upon its geometry, components, material qualities, and the forces exerted against it. The safety of earth dams has garnered heightened attention in geotechnical engineering due to their prevalence as the most common dam type globally. Their failure can result in significant social and economic repercussions, underscoring the importance of slope stability analysis **(Ma et al., 2021)**. According to **(Gelgalu and Zewdie, 2023).** A soil slope is classified as unstable when the factor of safety is less than one. The stability of the downstream slope of Al-Adhiam earth dam exposed to more than one earthquake was analyzed using (SEEP/W, SLOPE/W, and QUAKE/W) programs. **Figs. 7 and 8** show that the presence of the stone column led to a very slight increase in the safety factor under static load by 0.67% in case 1 and by 0.20% in case 2. **Fig. 7a**) case 1, when a stone column is present during an earthquake, the safety factor is larger than when it is not. However, at the 1nd earthquake, the presence of the stone column improved the factor of safety by 3.56%. After the 2nd, the stone column's existence enhanced the safety factor by 9.46%. However, after the 3rd and 4th earthquakes, the factor of safety increased by 16% and 5.81% with a stone column (case 1) at the downstream slope. However, the downstream slope failed after the 3rd earthquake and 4th earthquake in case 1, with and without a stone column. **Fig. 7 b**) case 2 shows that the factor of safety in all earthquakes is higher compared to the case of a one-stone column (case 1), which means that increasing the number of stone columns in the downstream slope has increased the factor of safety. However, after the 1st and 2nd, the stone columns improved the factor of safety by 4.95% and 14.67%, respectively. However, the stone columns improved the factor of safety by 31.1 % after the 3rd earthquake and by 32.78% after the 4th earthquake.



a) Case 1 (one SC at D/S) b) Case 2 (two SC at D/S)

Figure 7. Factor of safety at downstream slope depending on repeated earthquake with and without stone column under PGA of 0.2 g with duration of 15 s at normal water level 131.5 m.a.m.s.l (a) One SC (b) Two SC.

Fig. 8 shows that increasing the earthquake time to 30 seconds resulted in a slight change in the safety factor in all earthquakes compared to 15 seconds for cases 1,2. A stone column enhances the safety factor due to its high shear strength parameter and stress redistribution. During earthquakes, stress accumulates on the sliding surface, oriented away from the failure surface due to the column's elevated stiffness. The column lowers excess pore pressure and enhances effective stress due to its high permeability, improving slope stability.

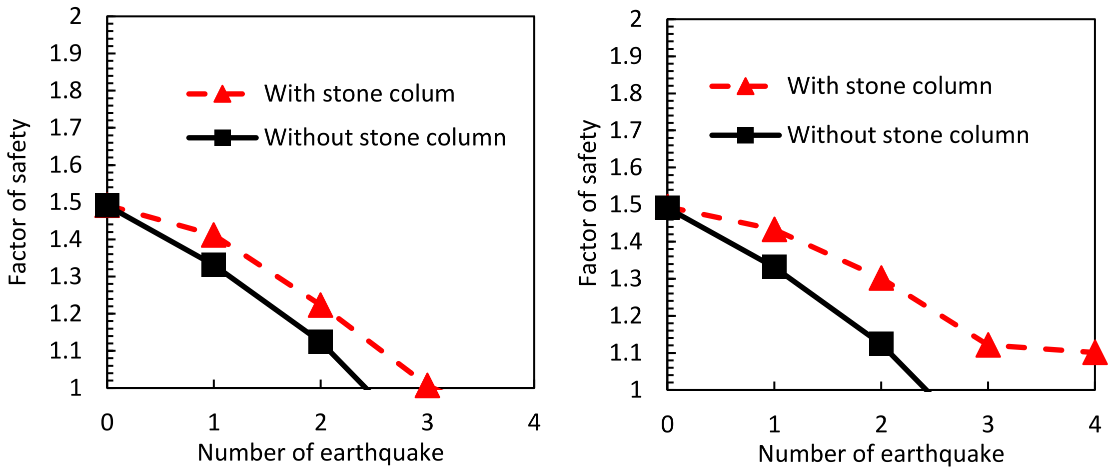


Figure 8. Factor of safety at the downstream slope depending on repeated earthquakes with and without a stone column under PGA of 0.2 g with a duration of 30 s at normal water level 131.5 (m.a.m.s.l) (a) One SC (b) Two SC.

6. CONCLUSIONS

This research examines the stone column approach for enhancing soil strength, which entails positioning the stone column on the failure surface to augment shear resistance and mitigate excess pore pressures induced by earthquakes. The paper addresses the computation of the safety factor fr the downstream slope, including both the presence and absence of the stone column, as well as the effects of static and seismic load.

- The validation included comparing the piezometer readings of the model with those from the field, revealing a maximum percentage discrepancy of 6.8% between the readings.
- The results showed that the stone column slightly increased the safety factor in static load.
- The downstream slope failed after the third earthquake at times 15 seconds and 30 seconds with a maximum ground acceleration of 0.2 g.
- The higher shear coefficients, permeability, and stiffness of the stone column distribute stresses at the failure surface. In Case 1, the presence of the stone column significantly enhanced the safety factor throughout all earthquakes, although it fell after the third earthquake. In Case 2, which had an increased number of stone columns, the safety factor improved throughout all earthquakes relative to Case 1.
- Increasing the earthquake time to 30 seconds resulted in a slight change in the safety factor.

NOMENCLATURE

Symbol	Description	Symbol	Description
g	Standard gravitational acceleration, m/s^2	Q	Applied boundary flux, m^3/s
H	Hydraulic head, m	t	Time, s
K_x	Hydraulic conductivity in X direction, m/s	θ	Volumetric water content
K_y	Hydraulic conductivity in Y direction, m/s		

Credit Authorship Contribution Statement

Abdulsalam Mahdi Mirza: Writing – review & editing, Writing – original draft, Validation, Software, Methodology. Zuhair Kadhim Jahanger: The corresponding author and owner of the project idea, Writing–original draft, Writing – review & editing, Validation, Methodology. Basim Sh. Abed: Writing & review.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

Abbas, I.H. and Al-hadidi, M.T., 2021. Effect of Halabjah earthquake on Al-Wand earth dam: numerical analysis. In *E3S Web of Conferences*, Vol. 318, P. 01016. EDP Sciences. https://doi.org/10.1051/e3sconf/202131801016

Al-Khalidi, E.E., Ahmed, M.D., Sheikha, A.A., and Jahanger, Z.K., 2024, January. Effect of length to length-to-diameter ratio on column bearing capacity stabilized with sodium silicate. In *AIP Conference Proceedings,* 2864(1). AIP Publishing. https://doi.org/10.1063/5.0186299.

Al-Nedawi, N.M. and Al-Hadidi, M.T., 2020. Seepage and slope stability analysis for Hemrin earth dam in Iraq using Geo-Studio software. *Solid State Technology*, *63*(3), pp. 3434-3448.

Alzamily, Z.N., and Abed, B.S., 2022a. Comparison of seepage trough zoned earth dam using improved light-textured soils. *Journal of Engineering*, *28*(3), pp. 32-45. https://doi.org/10.31026/j.eng.2022.03.03.

Alzamily, Z.N., and Abed, B.S., 2022b. Experimental and theoretical investigations of seepage reduction through zoned earth dam material with special core. *Materials Today: Proceedings*, *61*, pp. 998-1005. http://dx.doi.org/10.1016/j.matpr.2021.10.283

Aude, S.A., Mahmood, N.S., Sulaiman, S.O., Abdullah, H.H., and Al Ansari, N., 2022. Slope stability and soil liquefaction analysis of earth dams with a proposed method of geotextile reinforcement. *GEOMATE Journal*, *22*(94), pp. 102-112. http://dx.doi.org/10.21660/2022.94.j2241.

Baez, J.I., Martin, G., 1995. Permeability and shear wave velocity of vibro-replacement stone columns. In *Soil Improvement for Earthquake Hazard Mitigation*, pp. 66-81.

Bathe, K.J., 2007. Finite element method. *Wiley encyclopedia of computer science and engineering*, pp. 1-12. https://doi.org/10.1002/9780470050118.ecse159.

Bayati, H., and Bagheripour, M.H., 2019. Shaking table study on liquefaction behaviour of different saturated sands reinforced by stone columns. *Marine Georesources & Geotechnology*, *37*(7), pp. 801-815. https://doi.org/10.1080/1064119X.2018.1492051.

Binnie and Partners, 1989. Main Adhaim Dam: Phase IV Report. State Commission on Dams, Ministry of Agriculture and Irrigation, Republic of Iraq.

Black, J.A., Sivakumar, V. and Bell, A., 2011. The settlement performance of stone column foundations. *Géotechnique*, *61*(11), pp. 909-922. http://dx.doi.org/10.1680/geot.9.P.014.

Castro, J., Sagaseta, C., 2012. Pore pressure during stone column installation. *Proceedings of the Institution of Civil Engineers-Ground Improvement*, *165*(2), pp. 97-109. https://doi.org/10.1680/grim.9.00015.

Çadır, C.C., Vekli, M. and Şahinkaya, F., 2021. Numerical analysis of a finite slope improved with stone columns under the effect of earthquake force. *Natural Hazards*, *106*(1), pp. 173-211.

Dar, L.A. and Shah, M.Y., 2021. Deep-seated slope stability analysis and development of simplistic FOS evaluation models for stone column-supported embankments. *Transportation Infrastructure Geotechnology*, *8*(2), pp. 203-227.

Gelgalu, G. and Zewdie, M., 2023. Seismic Analysis of Embankment Dam: the Case of Gidabo Dam, Southern Ethiopia. *Southern Ethiopia*. http://dx.doi.org/10.2139/ssrn.4674530.

Gordan, B., Raja, M.A., Armaghani, D.J., and Adnan, A., 2022. Review on dynamic behaviour of earth dam and embankment during an earthquake. *Geotechnical and Geological Engineering*, *40*(1), pp. 3-33. https://doi.org/10.1007/s10706-021-01919-4.

Goswami, A., Deka, S., 2023, October. Study of the Effect of Installation of Stone Columns on the Stability of Soil Slopes using Finite Element Method. In *IOP Conference Series: Materials Science and Engineering*, Vol. 1282, No. 1, P. 012020. IOP Publishing. https://doi.org/10.1088/1757-899x/1282/1/012020.

Hassan, W.H., Atshan, T.T., and Thiab, R.F., 2024. Effect of drainpipes on seepage and slope stability through a zoned earth dam. *Open Engineering*, *14*(1), P. 20240040.

Hussain, H.H., Al Obaidy, A.I., Hommadi, A.H., Al Hudaib, H.T., Al Masoodi, A.T., Saeed, F.H., and Al Saeedi, N.N., 2022. Modifying the spillway of Adhaim Dam, reducing flood impact, and saving water. *Journal of Water Management Modeling*, 30(C485). https://doi.org/10.14796/jwmm.c485.

Idrus, J., Hamzah, N., Ramli, R., Md Nujid, M., and Sadikon, S.F., 2023. Enhancing Slope Stability with Different Slope Stabilization Measures: A Case Study using SLOPE/W Software. Jurnal Kejuruteraan, 35(6), pp. 1427 -1434.

Ismael, M.A., Ahmed, B.A., 2023. Numerical simulation of pile group response in slope layered soil under the effect of seismic loading. *Journal of Engineering*, *29*(12), pp. 173-186. https://doi.org/10.31026/j.eng.2023.12.11.

Jassam, M.G., Abdulrazzaq, S.S., 2019. Theoretical analysis of seepage through homogeneous and non-homogeneous saturated-unsaturated soil. *Journal of Engineering*, *25*(5), pp. 52-67. https://doi.org/10.31026/j.eng.2019.05.04.

Jawad, A.S., 2011. Reliability analysis of the seismic stability of embankments reinforced with stone columns. *Journal of Engineering*, *17*(04), pp. 829-845. http://dx.doi.org/10.31026/j.eng.2011.04.14.

Lu, C.W., Ahmad, S., Mohammad, Z., Lee, W.L., Wen, H.C., and Lin, Y.F., 2025. Enhanced stability and liquefaction resistance of earth dams with a proposed method of geosynthetic Reinforcements. *Advances in Civil Engineering*, *2025*(1), P. 2827855. http://dx.doi.org/10.21660/2022.94.j2241.

Ma, Z., Liao, H., Dang, F., and Cheng, Y., 2021. Seismic slope stability and failure process analysis using explicit finite element method. *Bulletin of Engineering Geology and the Environment*, *80*, pp. 1287-1301. https://doi.org/10.1007/s10064-020-01989-3.

Ministry of Water Resources, Iraq–Based on State commissions of dams and Reservoirs, 1995, unpublished report for adhaim dam project.

Ministry of Water Resources, Iraq–Based on State commissions of dams and Reservoirs, 2021, unpublished report.

Ministry of Construction, Housing, Municipalities, and Public Work, 2017, Earthquake-Resistant Buildings Blog.

Moayed, R.Z. and Ramzanpour, M.F., 2008. Seismic behavior of zoned core embankment dam. *Electronic Journal of Geotechnical Engineering*, *4*, pp. 1-15.

Murugesan, S., and Rajagopal, K., 2006. Geosynthetic-encased stone columns: Numerical evaluation. *Geotextiles and Geomembranes*, *24*(6), pp. 349-358. https://doi.org/10.1016/j.geotexmem.2006.05.001.

Pal, S., and Deb, K., 2018. Effect of stiffness of stone column on drainage capacity during soil liquefaction. *International Journal of Geomechanics*, *18*(3), P. 04018003. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001108.

Taher, H.K., and Jahanger, Z.K., 2024, January. Liquefaction potential effect in Makhool Earth dam under seismic impact. In *AIP Conference Proceedings,* 2864(1). AIP Publishing.

Taher, H.K., and Jahanger, Z.K., 2023, July. Seismic impact on Makhool Earthdam in flood and drought seasons. In *AIP Conference Proceedings,* 2787(1). AIP Publishing. https://doi.org/10.1063/5.0148009.

Tan, Y.L., Cao, J.J., Xiang, W.X., Xu, W.Z., Tian, J.W. and Gou, Y., 2023. Slope stability analysis of saturated–unsaturated based on the GEO-studio: a case study of Xinchang slope in Lanping County, Yunnan Province, China. *Environmental Earth Sciences*, *82*(13), P. 322. https://doi.org/10.1007/s12665-023-11006-x.

Titova, T.S., Longobardi, A., Akhtyamov, R.G. and Nasyrova, E.S., 2017. Lifetime of earth dams. *Magazine of Civil Engineering*, 1, 69, pp. 34-43. http://dx.doi.org/10.18720/MCE.69.3.

Vekli, M., and Çadır, C.C., 2022. Stability analysis of stone column slopes under different earthquake loads. *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi*, *27*(2), pp. 749-764. https://doi.org/10.17482/uumfd.1064770.

Yousif, O.S., Zaidn, K., Alshkane, Y., Khani, A., and Hama, S., 2019, May. Performance of Darbandikhan Dam during a major earthquake on November 12, 2017. In *Proceedings of the EWG2019, 3rd Meeting of Dams and Earthquakes, An International Symposium, Lisbon, Portugal*, pp. 6-8.

Zheng, H., Tham, L.G. and Liu, D., 2006. On two definitions of the factor of safety commonly used in the finite element slope stability analysis. Computers and Geotechnics, 33(3), pp. 188-195. https://doi.org/10.1016/j.compgeo.2006.03.007.

تأثير الزلازل المتكررة على معامل أمان سد العظيم الترابي والتحسين الزلزالي باستخدام الأعمدة الحجرية

عبد السلام مهدي مرزا[1]، زهير كاظم جهان كير[1,*]، باسم شبع عبد[2]

[1]قسم هندسة الموارد المائية, كلية الهندسة, جامعة بغداد, بغداد, العراق

[2]جامعة الهادي، بغداد، العراق

الخلاصة

السدود الترابية في المناطق ذات النشاط الزلزالي المتوسط إلى المرتفع ضرورية لحماية المجتمعات الواقعة أسفل النهر. ربما يكون زلزال حلبجة في العراق عام 2017 قد أضر بسلامة هيكل السد. شهد العراق والمناطق المجاورة له نشاطًا زلزاليًا متكررًا، ولا سيما زلزال حلبجة عام 2017، الذي قد يكون أضر بسلامة السد الترابي الحالي. يعاني سد دربنديخان، الذي تأثر بالزلزال، من مشاكل في قمته ومنحدره السفلي، مما يشكل خطراً أكبر من حيث الأضرار الجسيمة الناجمة عن الزلازل مقارنة بالهزات الدورية. وبالتالي، فإن تقييم سلامة السد أمر ضروري لحماية سكان المناطق السفلية وتحديد الطرق المثلى لتجنب انهيار استقرار المنحدر وسط النشاط الزلزالي المتكرر. الأعمدة الحجرية هي تقنية لتحسين التربة تستخدم أعمدة حجرية مضغوطة لزيادة قوة التربة من خلال تعزيز قوة القص وتقليل ضغط الماء الزائد في المسام في التربة غير المتماسكة. لم يتم التحقيق على نطاق واسع في سلوك أعمدة الدعامة الحجرية على المنحدرات تحت الأحمال الساكنة والديناميكية. يتضمن الهدف دراسة تأثير الأعمدة الحجرية على استقرار المنحدر السفلي لسد العظيم الترابي في محافظة ديالى، العراق، تحت تأثير أحمال ساكنة وديناميكية ناجمة عن أربعة زلازل بلغت ذروة تسارعها الأرضي 0.2 جي، لفترات زمنية تتراوح بين 15 و30 ثانية، باستخدام برنامج جيو ستوديو لسيناريوهات مختلفة. أشارت النتائج إلى أن العمود الحجري أدى إلى تحسن طفيف في عامل الأمان للمنحدر السفلي تحت تأثير الأحمال الساكنة. وقد أدى وجود العمود الحجري إلى تحسن ملحوظ في عامل الأمان خلال جميع الهزات الأرضية مقارنةً بغيابه.

الكلمات المفتاحية: سد ترابي، استقرار المنحدر، زلزال، عمود حجري، تكرار.