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Seismic Response Assessment of Al-Adhaim Earth Dam Under Earthquake Loading

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Abstract: This paper investigates the seismic response of the Al-Adhaim earth dam using the finite element GeoStudio program. The analysis focuses on pore water pressure, horizontal and vertical effective stresses, displacements, accelerations, and liquefaction potential under a 30-second earthquake record. Four instrumented points were selected on the body of dam: two at the crest (A and B) and two near the core foundation (C and D). Results show that pore water pressure variations remain within safe limits, crest points exhibit higher dynamic response than deep points, and the foundation demonstrates strong damping capacity. Liquefaction zones are limited to upstream saturated sandy layers, while the clay core remains stable. Overall, the dam demonstrates satisfactory seismic performance for the studied scenario of earthquake.

Keywords: Earth dam; seismic analysis; pore water pressure; liquefaction; effective stress; displacement.

1. Introduction

Earthquakes have a long history of causing devastation throughout human experience [1]. Civil infrastructure encompasses various structures designed to directly protect human populations from environmental disturbances and extremes [2]. However, certain infrastructure elements, which experience these disturbances directly in their appointed function, can themselves become the cause of catastrophic failure [3]. The failure of this infrastructure can result in severe consequences for human civilization and development [4]. Dams exemplify this consideration; they are designed to impound waterways and control floods, but in the event of failure, this stored volume and confining force are released, causing significant destruction [5, 6].

Earthquake occurrences set the stage for failure mechanisms in earth dams by inducing transient amorphous behavior [7]. This dynamic behavior results in degradation of soil and dam properties until failure events extend [8]. Neither design nor analysis practices currently available can confidently eliminate the potential for failure of earth dams when earthquakes occur [9]. Seismic hazard assessments further emphasize these zones, where dam break and failure could result in widespread hazard [10]. The potential for loss of life, disruption of society, and destruction of property are therefore critical considerations for any new dam construction [11]. A scientific analysis of the potential for seismic drag on the universally unfavorable and brittle clay core zone forms the primary motivating force in the present study. Adhaim Dam-a young, incomplete structure in the northeast of Baghdad, can serve as a proper case study for this analysis [12].

Earth dams are complex geotechnical systems whose safety under earthquake loading depends on the combined response of soil layers, pore water, and structural geometry [13]. The studies by [14, 15] investigated pore water pressure generated during Halabja and Kobe earthquakes using experimental model. The results showed that the pore water pressure reduces by (37-88) % when using sheet pile wall under dam. The shape of cross section of dam and intensity of earthquake play a significant influence on stability of dam.

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In this study, Al-Adhaim Dam is taken as a case study. A two-dimensional finite element model was built in GeoStudio to evaluate the dam response under a recorded earthquake, [2]. The analysis considered pore water pressure, effective stresses, displacements, and accelerations in both initial and dynamic states. Two operational upstream water levels were used in the overall research (normal and maximum), while the present article focuses on the results at the normal water level.

2. Study Area and soil properties of earthdam

The Al-Adhaim Dam, which is situated in Iraq's Diyala Province on the Al-Adhaim River 133 kilometers northeast of Baghdad, was used as a case study. Its coordinates are 34°33′54′N and 44°30′56′E. The Al-Adhaim dam is a multipurpose earth dam that may be used to generate power, regulate the Al-Adhaim River's flooding, and provide the water required to irrigate the agricultural lands in the Al-Adhaim Basin. It has over 1.5 billion cubic meters of storage space. As shown in Fig. 1, the dam is made up of two layers of filters, an 8 m inclined clay core, and shells made of sand-gravel soils. Table 1 lists the primary characteristics of the earth fill materials.

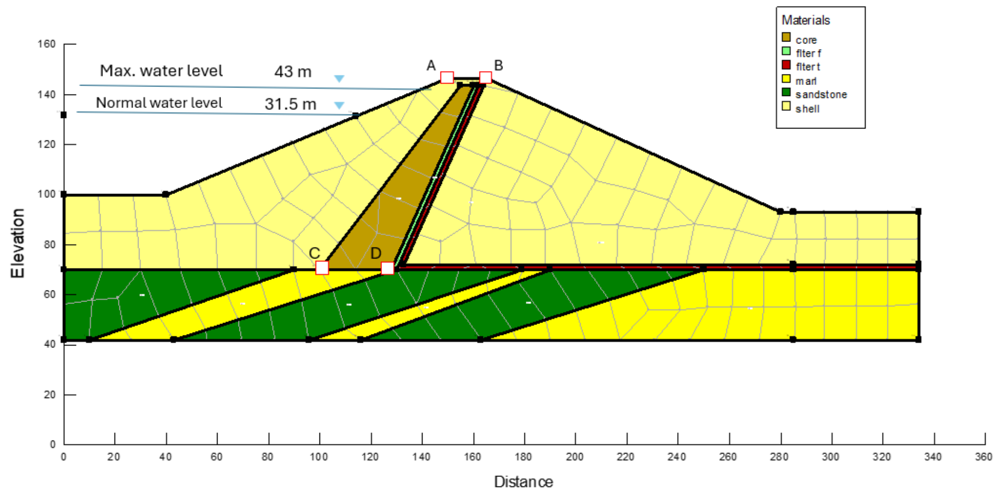

Fig. 1 The selected points and the chosen operational water level upstream of the Al-Adhaim dam (GeoStudio quake\w 2025) by the researcher.

Table 1. The primary characteristics of the earth fill materials [16].

Material zone	Modulus of Elasticity [MN/m²]	Permeability [m/sec]	Poisson's Ratio	Unit Weight [kN/m³]	Cohesion [kN/m²]	The angle of Internal Friction [degrees]
Shell	19	1.25×10^{-5}	0.3	17.658	0	37
Core	30	2.25×10^{-10}	0.45	19.62	60	23
Filter F	19	1.2×10^{-5}	0.3	18.658	0	35
Filter T	19	1×10^{-4}	0.3	18.658	0	35
Foundation on Marl	350	1×10^{-10}	0.35	20.601	600	10
Foundation on Sandstone	300	5.5×10^{-8}	0.35	20.601	0	38

3.Methodology

Figure 1 shows a specific cross-section of the Al-Adhaim Dam that was selected and modeled using GeoStudio. The upstream water level was set to the normal operating level (131.5 m above sea level, with a net water depth of 31.5 m from the storage base). Material properties, stratigraphy, and boundary conditions were adopted from site investigations and design data. Four representative points were monitored: A and B on the crest (upstream and downstream sides of the roadway) and C and D near the core base on the upstream and downstream sides, respectively. The seismic loading was applied for a total duration of 30 seconds with peak ground acceleration (PGA) of 0.10 g, and the response was extracted at selected time stages corresponding to 0 s, 14 s (peak), 24 s, and 30 s.

A popular numerical analysis software package for geotechnical and geo-environmental engineering applications is called GeoStudio. The application mainly uses the finite element technique (FEM) to simulate the coupled response between soil deformation and pore water pressure and to describe soil–structure interaction in seismic analysis. Soil material qualities, constitutive models, hydraulic boundary conditions, initial stress state, saturation level, and the features of the applied seismic loading are the primary elements influencing the accuracy of GeoStudio studies [17].

The Quake/W module of GeoStudio (version GeoStudio Quake/W 2025) was used in this study to simulate the earth dam's seismic activity. The program solves the dynamic equilibrium equations under time-dependent seismic loading by discretizing the dam body and foundation into finite elements. By establishing suitable material parameters and hydraulic circumstances that corresponded to the typical upstream water level, pore water pressure generation and effective stress variation were simulated. Time-history analysis was used to assess the response of pore water pressure, effective stresses, and liquefaction potential at both the dam body and specific monitoring stations when seismic input motion was provided at the model boundaries [17].

The numerical output included contour distributions of pore water pressure and effective stresses, as well as time histories of response quantities at points A, B, C, and D. The main quantities used in the evaluation were: (i) pore water pressure; (ii) vertical and horizontal effective stresses; (iii) vertical and horizontal displacements; and (iv) vertical and horizontal accelerations. In addition, liquefaction zones were identified based on excess pore pressure development and loss of effective stress in saturated granular layers.

4 Results and Discussion

4.1 Pore Water Pressure Response

The pore water pressure distribution at the normal water level, presented in Table 2, was evaluated at the four selected times. At the crest points A and B, the pore water pressure remains negative (approximately -50 kPa initially), reflecting an unsaturated condition in the upper part of the dam body. During shaking, the pressure at point A increases from about −50 kPa to approximately -41 kPa, while at point B it varies slightly between −50.8 kPa and −49 kPa. In all cases, the pore pressure remains negative, indicating that the soil did not reach full saturation and that the effective stress and shear strength in the upper core did not experience a critical reduction.

In contrast, points C and D, located in the saturated zones near the foundation, exhibit high positive pore water pressure. At point C, the pressure increases gradually from 598 kPa to about 602 kPa, while at point D it increases from approximately 406 kPa to about 415 kPa. These small increments (about 4 kPa at C and 9 kPa at D) reflect a limited amount of excess pore pressure due to earthquake loading, which remains within safe limits as shown in Figure 2.

Table 2. Maximum, minimum and variation of pore water pressure at points A, B, C and D.

Point	Max. u (kPa)	Min. u (kPa)	Δu (kPa)	Percentage change
A	-49.5	-41.0	8.5	20.7%
B	-50.8	-49.0	1.8	3.7%
C	598	602	4	0.67%
D	406	415	9	2.2%

*u: pore water pressure.

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The findings in Table 2 show that the location within the dam body has a major impact on variations in pore water pressure. Both crest locations A and B have negative pore water pressures, which indicate unsaturated conditions. Because point A is more exposed to seismic forces, its variation is comparatively higher (20.7%). On the other hand, foundation points C and D exhibit extremely tiny pressure variations (≤ 2.2%) and stay fully saturated, suggesting significant damping capability and steady hydraulic behavior at depth. Overall, the small amount of pressure variation at all locations indicates that there was no development of critical excess pore water pressure during the earthquake.

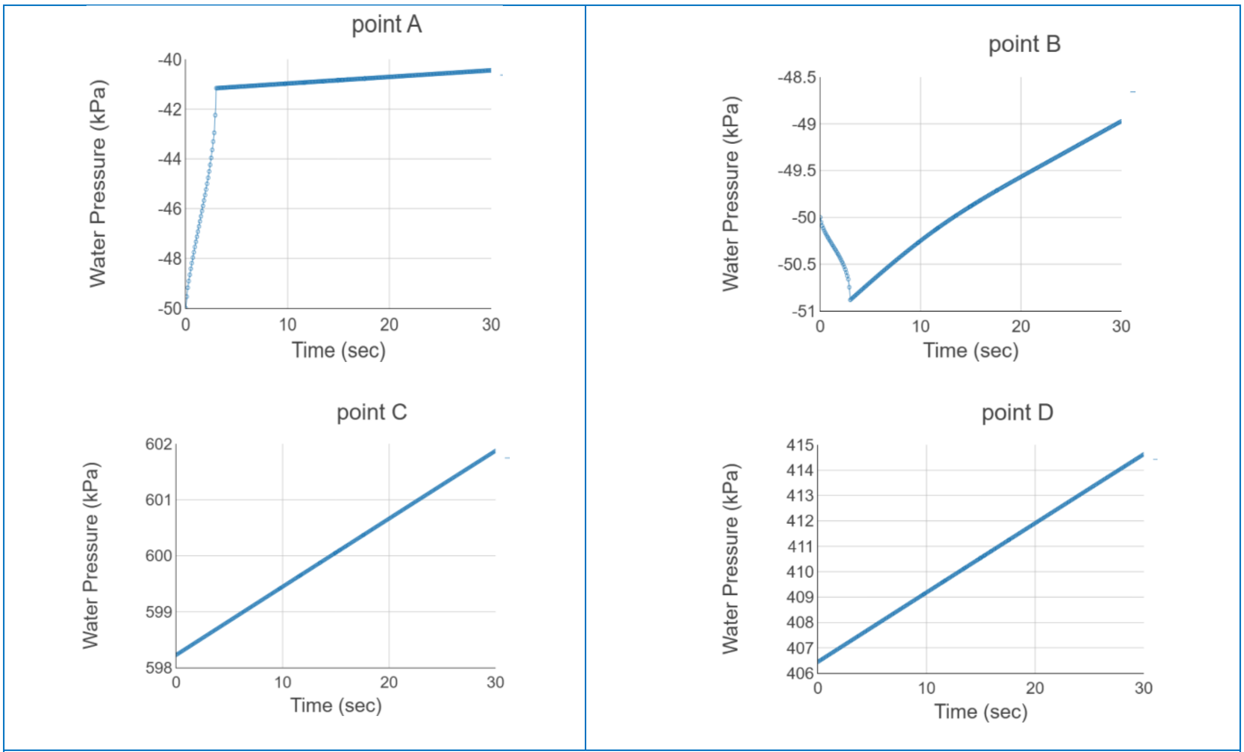

Fig.2 Points A, B, C, and D pore water pressure plot.

4.2 Vertical Effective Stresses

The vertical effective stresses at points A, B, C, and D show clear differences corresponding to their locations as shown in Table 3. At the crest, point A exhibits stresses between 75 kPa and 95 kPa, while point B has smaller values between 10 kPa and 14 kPa. These ranges indicate a flexible response of the surface layers under shaking. At depth, point C near the upstream foundation has stresses between 450 kPa and 600 kPa, whereas point D near the downstream foundation records the highest values between 930 kPa and 1000 kPa. The relatively small percentage change at D (~7%) reflects the high rigidity and stability of the downstream foundation.

Table 3. Maximum, minimum and variation of vertical effective stresses at points A, B, C and D.

Point	Max. σv (kPa)	Min. σv (kPa)	Δσv (kPa)	Percentage change
A	95	75	20	21%
B	14	10	4	30%
C	600	450	150	25%
D	1000	930	70	7%

* σv: vertical effective stresses.

The findings above show that vertical effective stress rises with depth, which is indicative of increased overburden pressure and confinement in the foundation zones. Crest points A and B are more sensitive to seismic loading, as evidenced by their lower stress values and increased relative fluctuation. Points C and D, on the other hand, show high stress levels with little change, especially at point D, indicating stable and well-confined foundation behavior during the earthquake.

4.3 Horizontal Effective Stresses

Horizontal effective stresses reveal that the crest is more sensitive to seismic loading than the deep zones. Point A reaches a maximum of about +65 kPa and a minimum of about −25 kPa before stabilizing around +15 kPa. Point B fluctuates between +35 kPa and −35 kPa and stabilizes close to zero. At depth, point C ranges between 240 kPa and 320 kPa, while point D records the highest stable values between 500 kPa and 600 kPa, reflecting the stiffness of the deep downstream materials as shown in Table 4.

Table 4. Maximum, minimum and variation of horizontal effective stresses at points A, B, C and D.

Point	Max. σh (kPa)	Min.σh (kPa)	Δσh (kPa)	Percentage change
A	+65	−25	90	138%
B	+35	−35	70	200%
C	+320	+240	80	25%
D	+600	+500	100	16.7%

* σh: horizontal effective stresses.

From results above the seismic sensitivity clearly decreases with depth, according to the horizontal effective stress results. Because of their exposure to horizontal ground acceleration and reduced lateral constriction, crest points A and B show greater stress fluctuations and higher percentage variation. On the other hand, strong, well-confined materials and steady horizontal stress conditions during the earthquake are indicated by foundation points C and D, which maintain high stress levels with little relative change, especially at point D.

4.4 Vertical Displacement

Table 5 shows the vertical displacements at the crest (points A and B) are larger than those at depth. Point A exhibits a maximum upward displacement of about +0.020 m and a minimum downward displacement of −0.015 m, while point B reaches +0.030 m and −0.025 m. Deep points C and D show very small vertical movements, in the order of millimeters, confirming the stability of the foundation.

Table 5. Maximum, minimum and variation of vertical displacement at points A, B, C and D.

Point	Max. σh (kPa)	Min.σh (kPa)	Δσh (kPa)	Percentage change
A	+65	−25	90	138%
B	+35	−35	70	200%
C	+320	+240	80	25%
D	+600	+500	100	16.7%

It is evident from the table above Due to direct seismic excitation and reduced confinement, vertical displacements are greatest at crest points A and B. In contrast, foundation points C and D show very little movement, suggesting stable and well-confined behavior at deep.

4.5 Horizontal Displacement

In Table 6 the horizontal displacements are most pronounced at the crest, where point A shows values between −0.015 m and 0.055 m and point B between −0.020 m and 0.050 m. At depth, points C and D undergo smaller horizontal movements (up to about 0.015–0.018 m), indicating the role of the deep soil mass in damping lateral motions and preventing their full transmission to the surface.

Table 6. Maximum, minimum and variation of horizontal displacement at points A, B, C and D.

Point	Max. horizontal disp. (m)	Min. horizontal disp. (m)	Δ horizontal disp. (m)	Percentage change
A	+0.055	−0.015	0.070	127%
B	+0.050	−0.020	0.070	140%
C	+0.015	−0.004	0.019	126%
D	+0.018	−0.005	0.023	128%

from the results above due to direct horizontal seismic loading, horizontal displacements are more noticeable at crest points A and B, whereas foundation points C and D exhibit less movement, indicating stable behavior at depth and efficient damping.

4.6 Vertical Acceleration

Vertical acceleration time histories show that the crest points A and B experience the highest levels of oscillation, with peak values of about +0.15 g and −0.10 to −0.11 g. Deep points C and D exhibit much lower amplitudes, typically below ±0.02 g, demonstrating the effectiveness of the dam body in damping vertical seismic waves as shown in table 7.

Table 7. Maximum, minimum and variation of vertical acceleration at points A, B, C and D.

Point	Max. vertical acc. (g)	Min. vertical acc. (g)	Δ vertical acc. (g)	Percentage change
A	+0.15	−0.10	0.25	167%
B	+0.14	−0.11	0.25	178%
C	+0.010	−0.015	0.025	250%
D	+0.020	−0.020	0.040	200%

Due to direct exposure to seismic motion, vertical acceleration values are maximum at crest points A and B. In contrast, substantially lower accelerations at foundation sites C and D show efficient damping and stable dynamic behavior of the dam body at depth.

4.7 Horizontal Acceleration

Horizontal acceleration is also largest at the crest. Point A records about +0.15 g to −0.12 g, while point B reaches +0.17 g to −0.14 g. Deep points C and D show smaller ranges, between about +0.06 g and −0.09 g at C and +0.08 g to −0.10 g at D. These trends confirm that the crest is the most sensitive region, whereas the foundation provides strong damping and maintains accelerations within safe limits as shown in Table 8.

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Table 8. Maximum, minimum and variation of horizontal acceleration at points A, B, C and D.

Point	Max. horizontal acc. (g)	Min. horizontal acc. (g)	Δ horizontal acc. (g)	Percentage change
A	+0.15	−0.12	0.27	180%
B	+0.17	−0.14	0.31	182%
C	+0.06	−0.09	0.15	250%
D	+0.08	−0.10	0.18	225%

Due to direct exposure to horizontal seismic excitation, horizontal acceleration is most noticeable at crest points A and B. In contrast, foundation points C and D show lower acceleration levels, indicating stable dynamic performance at depth and efficient energy dissipation.

4.8 Liquefaction Potential

In Figure 3 the liquefaction analysis indicates that potential liquefaction zones are concentrated in the upstream soil envelope and some saturated foundation layers, while the clay core and the downstream envelope remain practically stable.

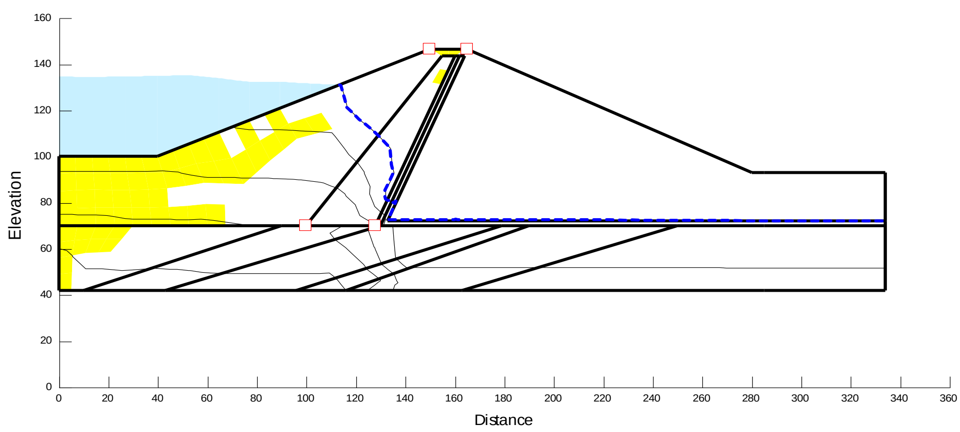

Fig. 3 Liquefaction area in the dam body.

Liquefaction occurs mainly in saturated sandy or silty materials located below the water table, where increased pore pressure during shaking reduces shear strength and effective stress. The limited spatial extent of these zones suggests that the overall structural risk is localized and can be mitigated by improving weak soils and enhancing drainage conditions

5. Conclusions

Based on the finite element analysis of Al-Adhaim Dam under a 30-second earthquake record at the normal water level, the following conclusions can be drawn:

- Pore water pressure variations at both crest and foundation points remain within safe limits, with no indication of hydraulic instability or widespread liquefaction.

- Vertical and horizontal effective stresses at the foundation (points C and D) demonstrate high stiffness and rapid damping, confirming the stability of the deep zones.
- Crest points (A and B) exhibit larger displacements and accelerations than deeper points, which is consistent with theoretical expectations for earth dams subjected to seismic loading.
- Horizontal and vertical accelerations decrease significantly with depth, reflecting the strong damping capacity of the dam body and foundation materials.
- Liquefaction potential is limited to localized upstream saturated sandy or silty layers, while the clay core remains stable. Appropriate soil improvement and drainage measures in the affected zones can further enhance dam safety.
- Overall, the dam shows a satisfactory seismic response for the studied earthquake scenario.

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