

SLOPE STABILITY AND SOIL LIQUEFACTION ANALYSIS OF EARTH DAMS WITH A PROPOSED METHOD OF GEOTEXTILE REINFORCEMENT

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ABSTRACT: Dam projects require comprehensive studies and a careful implementation process; thus, the causes of the possible failure, during the construction or operation of dams, should be thoroughly investigated. Specifically, geotechnical analysis of seepage, static stability, and seismic stability is essential to be evaluated. Earthquakes shaking imposes additional hysteric and short-term loads in the two directions that may cause serious problems and may lead to dam failure due to settlement, piping, high pore water pressure, and soil liquefaction. In this study, Geo-Studio 2018 software was utilized to evaluate the slope stability and the seepage analysis of Al-Adhaim Dam in Iraq. The dynamic stability of the dam and the soil liquefaction were also evaluated as a result of applying earthquake shaking to the dam. The results obtained from the analysis indicated that the dam was stable in the static condition. Furthermore, the results of the dynamic condition indicated that an earthquake, with an acceleration value of 0.38g and 10 seconds period, caused a vertical displacement of the dam of 0.12 m and reduced the factor of safety to 1.01 which was less than the allowable value. Therefore, geotextile reinforcement was suggested to reduce the effect of the soil liquefaction that was observed in the front shell of the dam. As discussed herein, the reinforcement increased the dam stability as the factor of safety of the dam increased to 1.946 which was within the allowable values.

Keywords: *Earth dams, Earthquake, Geo-Studio, Slope Stability, Liquefaction*

1. INTRODUCTION

The static design method is one of the oldest methods that has been used in geotechnical engineering. The slope stability theory, according to a sliding mass divided into slices, was first applied at the beginning of the Twentieth Century for safety factor calculations and the method was then developed by Fellenius, Janbu, and Bishop. With the aid of advanced software and finite elements methods, new methods such as Morgenstern-Price and Spencer have been devolved by using iterative procedures [1, 2]. The purpose of slope stability studies is to calculate the slope factor of safety. The stability of the slope is determined by comparing the calculated values of the safety factor to the correspondent values from the relevant codes [3–5]. Because possible failure of dams may cause great human and economic losses, it is essential to study the dynamic analysis and slope stability of the dams due to the seismic loads which depend on the static analysis of the dam before the earthquake shaking [6–8]. Earthquakes cause a serious threat to the stability of the dams as the statistics indicated that complete or partial failure of earth dams due to earthquakes is caused by 1) dam settlement which

leads to transfer cracks; 2) internal erosion and piping inside the dam that may lead to dam failure when filter systems are not well designed, and 3) the rise of pore water pressure that may lead to soil liquefaction which represents the greatest danger on the dam stability [9–11]. The possibility of the occurrence of the aforementioned problems depends on many factors such as the intensity of the earthquake, the construction materials of the foundations, the topographic conditions of the dam site, dam type, water level of the dam reservoir, and the freeboard [12–14]. Therefore, it is necessary to study the specific conditions for the dam site and the seismic conditions of the site. Sawada et al. [15] discussed the behavior of small earthen dams under seismic loads. The upstream and downstream sides of an earth dam were stabilized with a polypropylene geotextile. The results showed that the effective stress of the materials on the upstream side significantly increased, despite the observed deformations of these materials being greater than that of the downstream materials. Furthermore, a large difference in the phase of the measured acceleration was observed between the upstream slope and downstream slopes. The purpose of the dynamic design of dams is to calculate the values of

dynamic safety factors and pore water pressure development during earthquake shaking and to compare these values with the allowable values. The shape of the circular slip surface from the dynamic design is similar to that of the static design. However, the vertical and horizontal forces values, which result from the earthquake acceleration and excess pore water pressure, are added to the equation that calculates the static factor of safety to calculate the dynamic factor of safety. The dynamic analysis depends on the static stresses of the dam at the time of the earthquake occurrence [16–20].

Soil liquefaction is defined as the phenomenon that highly reduces soil shear strength and causes large deformations when the pore water pressure increases due to cyclic loading. Saturated sand, silty sand, gravelly sand are the most vulnerable soils to liquefaction. The permeability of gravel is high enough to dissipate excess pore water pressure unless gravel presents within a fine-grained soil that prevents the dissipation. Many methods have been developed to evaluate the liquefaction potential of different types of soils based on plasticity, grain size distribution, and actual moisture in the field [21–24].

This study consists of evaluating the current condition of the dam and its stability during earthquakes events, proposing a solution for the possible liquefaction, and discussing the effects of this solution on the dam stability. Geotextile reinforcement is an economical, easy, and frequently used method for earthworks and road projects. The cost of this method was not calculated in this research because it depends on many other factors, but in general, the use of geotextile for earthwork applications is cost-effective compared to the total cost of the project. The GeoStudio Model, for studying the equilibrium of slopes (GeoSlope), determines the shearing forces affecting the slopes of the dam, calculates the shear strength and pore water pressure values during periodic loading during the earthquake. It also determines the areas of soil liquefaction within the slope.

The main objective of this research is to conduct analysis and modeling for an earth dam under operation (Al-Adhaim Dam) by using Geo-Studio 2018. The dam area is seismically active as many lights and moderate earthquakes have recently hit the area. These recent earthquakes may indicate a possible occurrence of a major earthquake within the dam area. Therefore, the resistance of the dam to earthquakes should be evaluated to avoid the possible causes of failure. Seepage and pore water pressure in the dam and the foundations were calculated by using SEEP/W software. The obtained values were then used to calculate the factor of safety of the static condition by using Slope/W to evaluate the dam before the earthquake. A dynamic study was performed by using

Quake/W to evaluate the dynamic factor of safety and the vulnerable liquefaction zones caused by an earthquake. Geotextile reinforcement was proposed to keep the dam safe during earthquakes.

2. MATERIALS AND METHODS

For an adequate study of the stability of dams, the study should be comprehensive that include all the different conditions of operation. Therefore, the current study includes the following conditions:

- 1- Study of the static stability and seepage at the maximum storage and steady-state seepage.
- 2- Study of the stability during rapid drawdown. Water level increases the stability of the front face of the dam when the storage is maximum with the steady-state flow. In case the drawdown of the reservoir is higher than the water dissipation from the dam, the excess pore water pressure inside the dam will increase and cause soil liquefaction. Similar behavior will occur during earthquakes.
- 3- Dynamic stability during earthquakes.
- 4- Suggest solutions to prevent dam failure.

2.1 Numerical Model

Many numerical models have been developed to analyze the stability and seepage of dams such as Geo-Studio, Plaxis, and FLAC. Geo-Studio includes a package of software to analyze many aspects of dams under different loading conditions. In this study, the stability was analyzed by using SLOPE/W based on the Morgenstern-Price method at different loading conditions. The static analysis was with a steady-state of seepage and with transient seepage during the rapid drawdown. QUAKE/W was used to evaluate the safety factor as an earthquake shaking was applied, based on the initial static condition.

2.2 Study Area and Data Collected

Al-Adhaim Dam was used as a case study which is located on the Al-Adhaim River 133 km northeast of Baghdad within Diyala Province in Iraq. It is located within the coordinates $34^{\circ} 33' 54''$ N and $44^{\circ} 30' 56''$ E as shown in Fig.1. Al-Adhaim dam is a multi-purpose earth dam as it is used to control the flooding of the Al-Adhaim River, provide the quantities of water needed to irrigate the cultivated areas in the Al-Adhaim Basin, as well as be used in generating electricity. Its storage capacity is about 1.5 billion cubic meters. The dam consists of shells constructed of sand-gravel soils, 8 m inclined clay core, and two layers of filters, as presented in Fig.2. The main properties of the earth fill materials are presented in Table 1. The maximum storage level is 131.5 m [25–28].

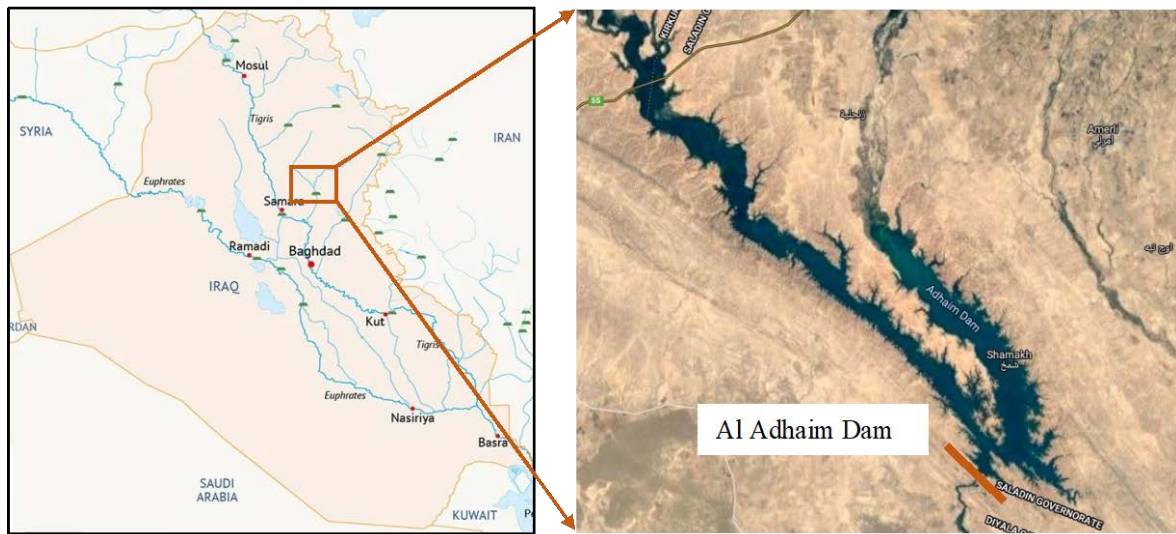


Fig.1 The location of the study area in Diyala Province in Iraq

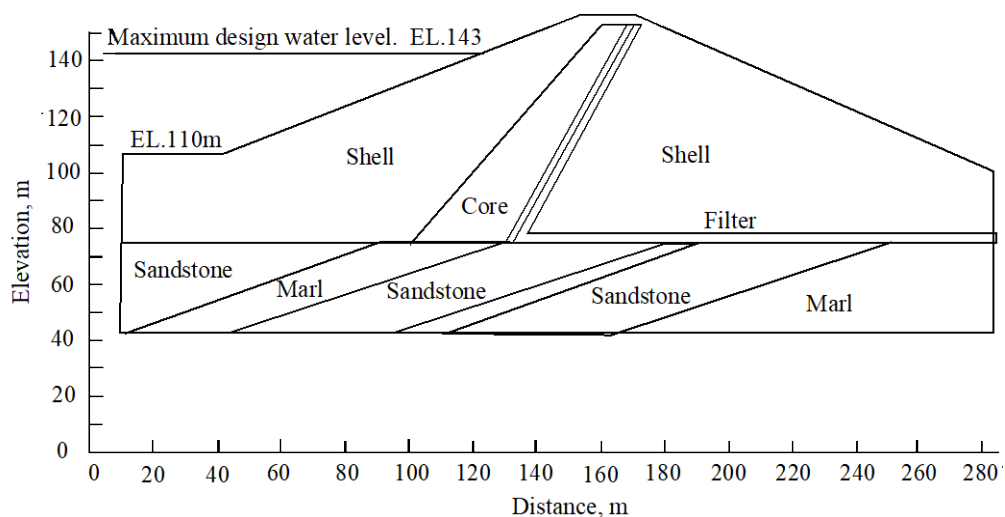


Fig.2 The cross-section of Al-Adhaim Dam

3. RESULTS AND DISCUSSION

3.1 Static Analysis of the Dam Before Earthquake Shaking

The static analysis of the dam before the occurrence of the earthquake shaking is summarized in the following steps:

1- Seepage Study: Seepage through the dam and the foundations may cause piping, increase pore water pressure, and reduce soil shear strength. These changes may cause serious problems to the stability

of the dam. SEEP/W was used to study the seepage at the maximum storage with the steady-state flow to determine the seepage line and pore water pressure inside the dam, as shown in Fig.3.

2- Slope Stability Study: SLOPE/W was used to calculate the static factor of safety for the front and backside of the dam based on the values of pore water pressure that were obtained from the analysis with SEEP/W. The calculated values of the factor of safety were 1.882 for the front face and 1.849 for the back face, as shown in Fig.4 and Fig.5, respectively.

Table 1. The properties of Al-Adhaim Dam soils (After [25])

Material zone	Modulus of Elasticity [MN/m^2]	Permeability [m/sec]	Poisson's Ratio	Unit Weight [kN/m^3]	Cohesion [kN/m^2]	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

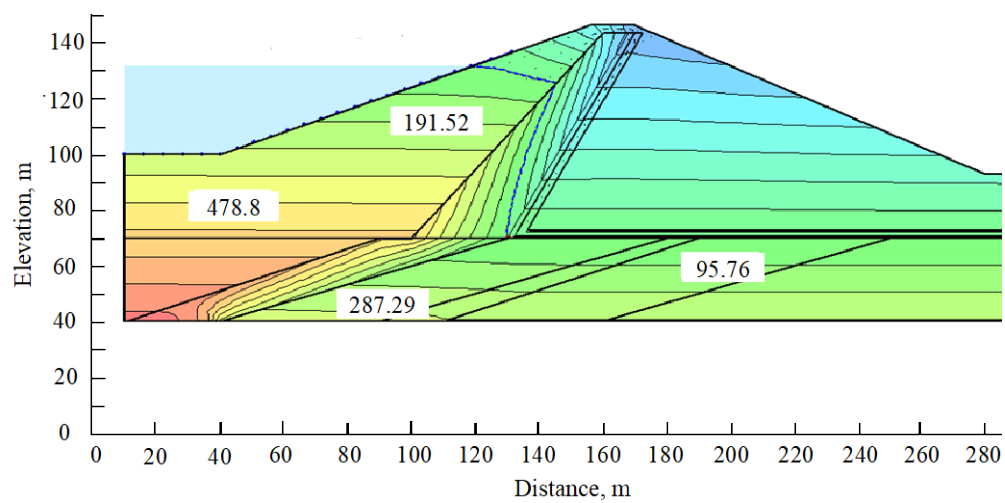


Fig.3 Analysis of seepage by using SEEP/W

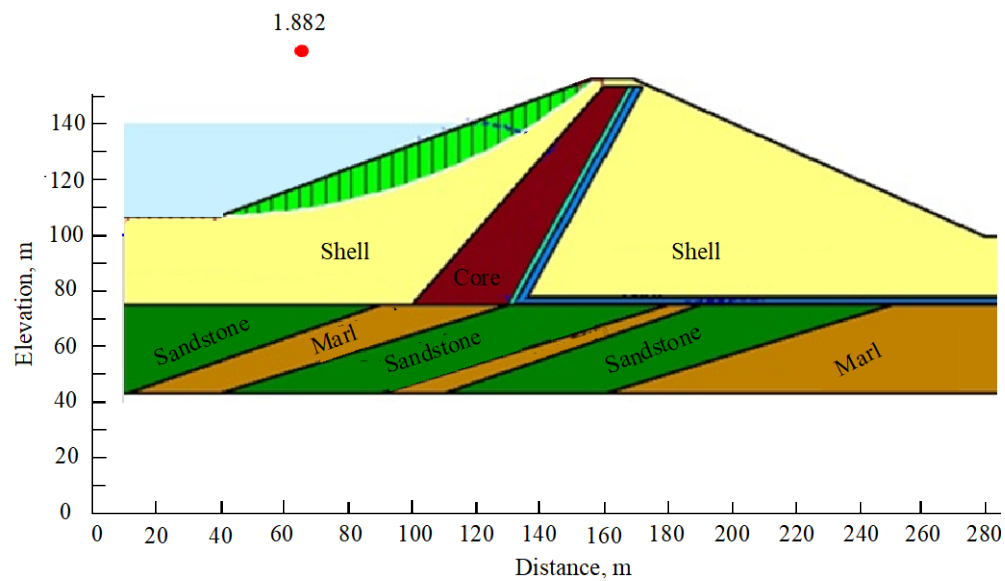


Fig.4 Slope stability analysis for the front face of the dam

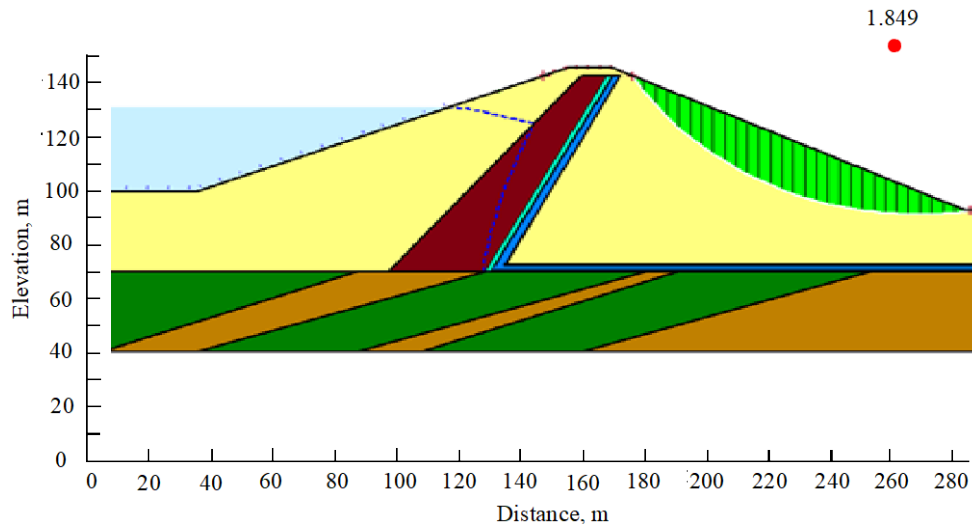


Fig.5 Slope stability analysis of the dam back face

3- Study of Seepage and Stability as a Result of Rapid Drawdown: Earthquakes cause cyclic motion of the water in the dam reservoir. When the storage water level increases during the earthquake, water will flow toward the back face of the dam. However, when the water level suddenly decreases in a short time, the flow will be reversed towards the front

face which highly decreases the factor of safety. Therefore, seepage was analyzed due to the change in the water level within 10 seconds period by using SEEP/W for the transient condition. The variation of the safety factor caused by the rapid drawdown is as presented in Fig.6. The value of the factor of safety obtained from the analysis was 1.834.

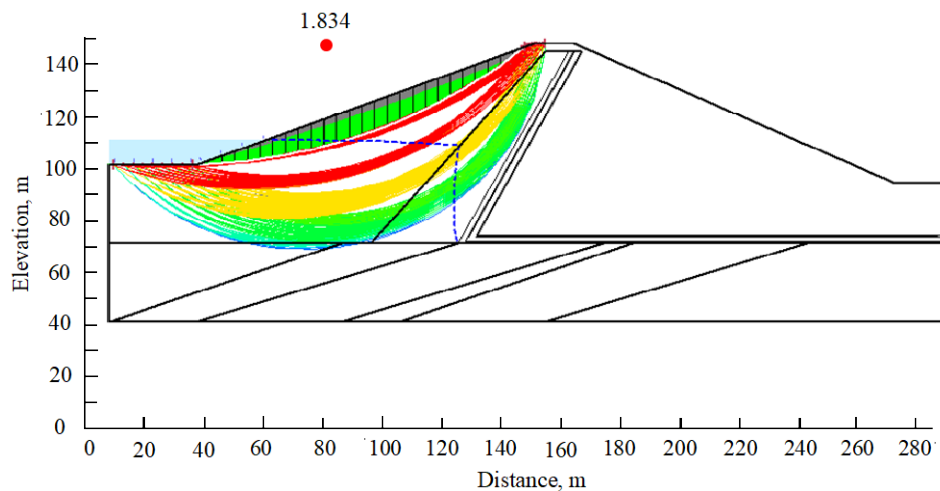


Fig.6 The variation of the factor of safety as a result of the rapid drawdown

3.2 The Static Analysis of the Initial Stresses

The static analysis was performed before the earthquake to evaluate the initial stresses and pore water pressure. Fig.7 shows the total stress at the maximum storage, and the value of the factor of safety for the front face based on the static stresses is shown in Fig.8. The results obtained from slope stability analysis at the static condition for Al-Adhaim Dam are presented in Table 2. The results were compared with the allowable values, as presented in the design guidelines of USACE 2003

[29]. It can be seen that the dam is stable under the different loading conditions.

3.3 The Dynamic Analysis of the Dam

The dynamic analysis of the dam was performed by using Queke/W as the stresses were evaluated during the earthquake based on the static analysis as an initial state. The dam was placed under the vertical and horizontal components of the ground motion with peak ground acceleration (a_{max}) of 0.38g and a period (T) of 15 seconds, as shown in Fig.9. The ground motion parameters were obtained

from the available data of the seismic activity of the dam area.

The total and effective stresses were determined from Queke/W. As shown in Fig.10, the value of the perpendicular displacement that resulted from the earthquake shaking, was 0.21 m at the top of the dam. The relative displacement of the dam during the earthquake shaking was as high as 0.4 m at 9 seconds, as shown in Fig.11. Slope/w was then used to determine the dynamic factor of safety. As shown

in Fig.12, the minimum value of the dynamic factor of safety was 1.01 at T of 10 seconds. The values of the safety factor at any time during the shaking are presented in Fig.13. The minimum safety factor value by, using the dynamic analysis, was 1.2. The variation of the factor of safety, for the critical slip surface of the front face, with the values of the acceleration are shown in Fig.14. The safety factor was less than the allowable value (1.2) when the value of acceleration was 0.12 g.

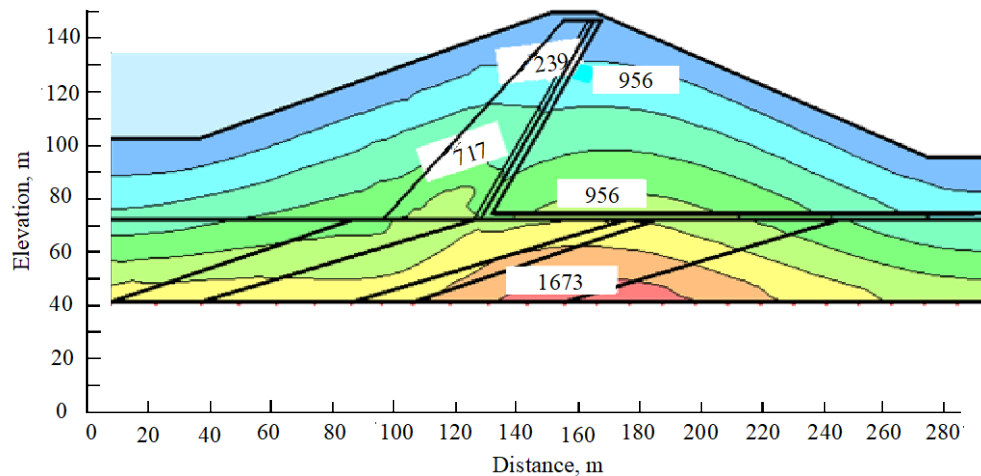


Fig.7 Initial stresses at the maximum storage

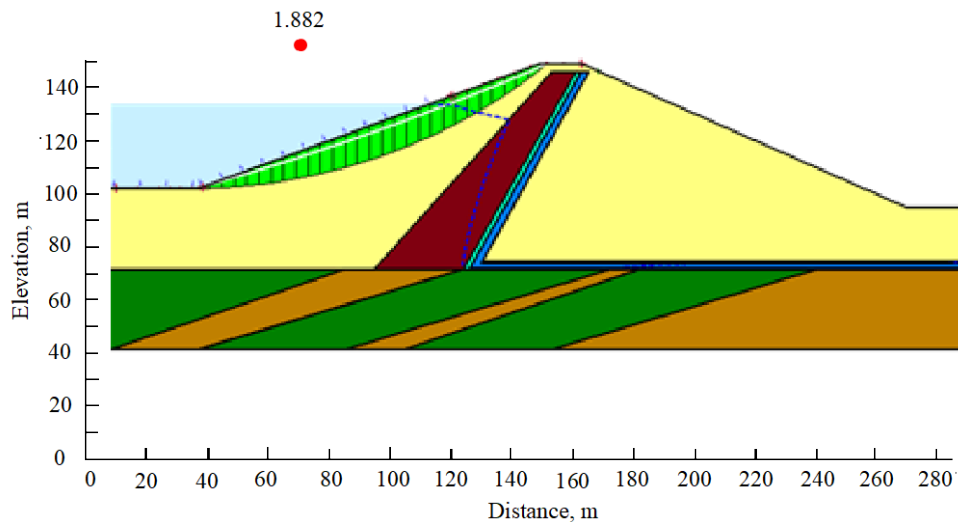


Fig.8 The factor of safety for the front face as evaluated from the static stresses

Table 2. The results obtained from the static stability analysis

Static loading	The factor of safety for the front face	The factor of safety for the back face	USACE 2003 Limits	Dam evaluation
Maximum storage	1.882	1.848	1.5	Stable
No storage	1.881	1.850	1.5	Stable
Rapid drawdown	1.834	-	1.2	Stable

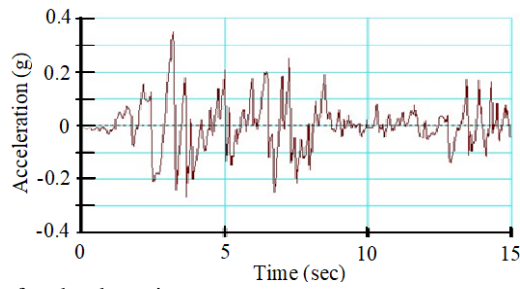


Fig.9 Peak ground acceleration for the dam site

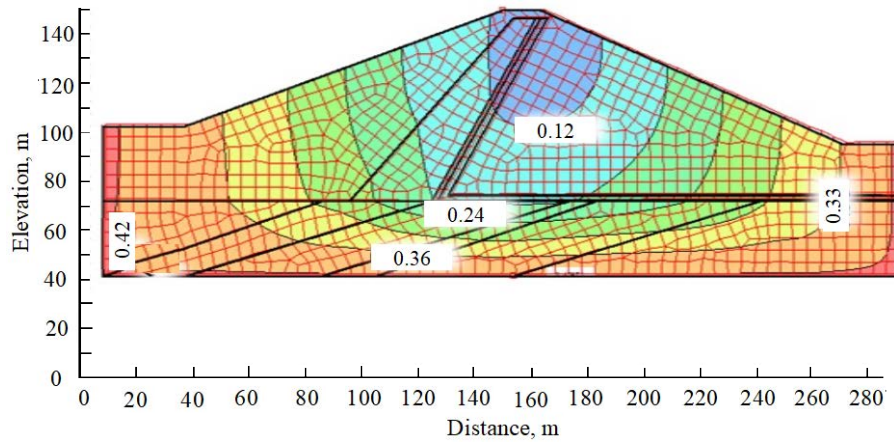


Fig.10 Displacement values and shapes after the earthquake shaking

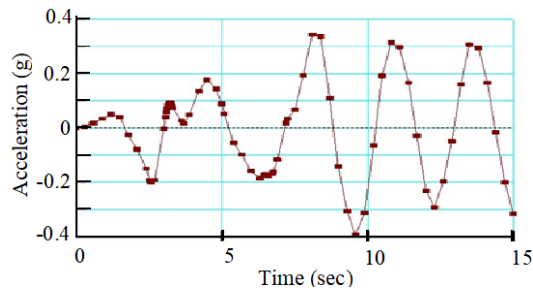


Fig.11 Relative displacement during the earthquake

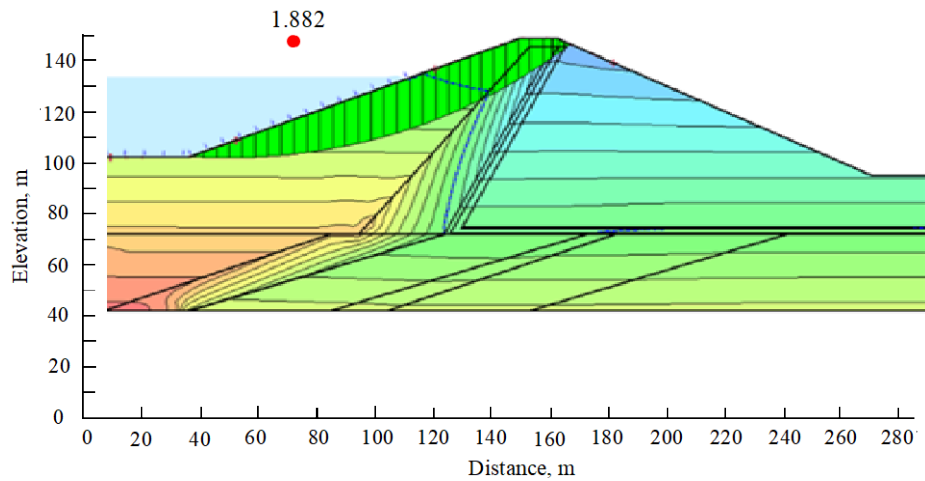


Fig.12 Minimum factor of safety during the earthquake at the maximum storage of the reservoir

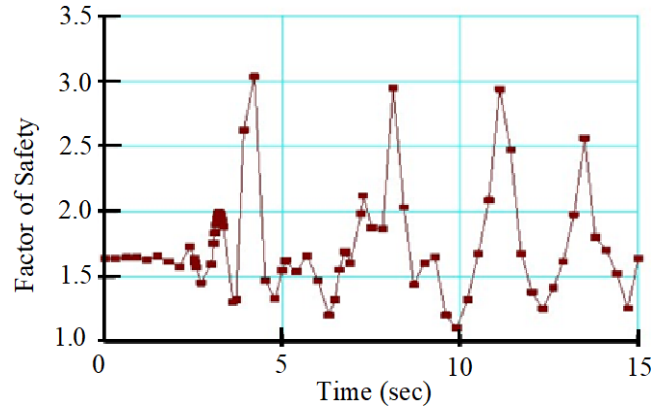


Fig.13 The variation in the factor of safety of the front face of the dam during the earthquake shaking

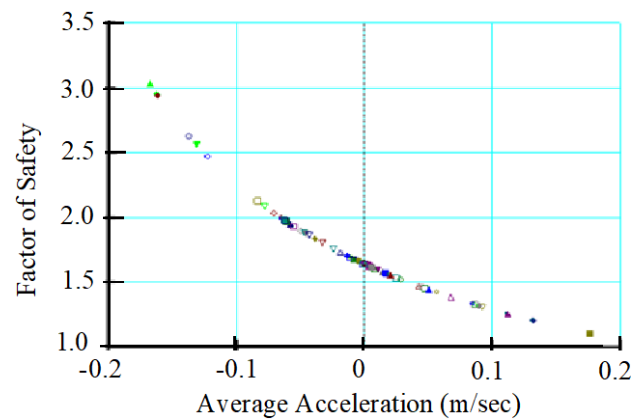


Fig.14 The variation of the values of the factor of safety with the average acceleration

3.4 Soil Liquefaction

As shown in Fig.15, liquefaction was observed in the front shell due to the earthquake shaking. It can be seen that earthquake-triggered liquefaction was developed within the upstream slope as the soil lost its shear strength. Specifically, the liquefaction zone was observed in the lower part of the slope and near the face of the slope as the soil within this zone is likely to be fully saturated and can densify during the shaking. The zone is at unacceptable risk of flow failure.

3.4 Geotextile Reinforcement

Geotextile reinforcement was suggested to support the liquefiable soil on the front face of the dam, as presented in Fig.16. The suggested geotextile reinforcement is to be placed in horizontal layers according to the following specifications:

- 1- The vertical spacing between the layers is 5 m.
- 2- The length of the geotextile layers is 20 m.
- 3- The geotextile layers extend from the face of the front shell of the dam.
- 4- The geotextile layers were placed within the zone

that is vulnerable to liquefaction, as presented in the aforementioned analysis.

Geotextile installation is an easy process when the appropriate tools are available. The geotextile layer is added within the embankment fillings at the front and back of the dam. The dam embankment layer should be leveled properly, all the protruding objects must be removed from the face of the layer and the geotextile layer is laid according to engineering drawings. The process of stretching the geotextile layer must be done tightly to keep it level and flat. The ends of adjacent layers shall be overlapped at the same site and fixed at the overlap sites and the edges using staples, soil, or other suitable materials. The next layer of earth embankment dictates is placed directly on the geotextile layer, with a thickness ranging from 100 mm to 300 mm or more, according to the required engineering specifications and soil type, and the soil is compacted until the required density of the soil is reached. The strength values of the utilized geotextile material areas are listed in Table 3.

The value of the factor of safety increased to 1.946 after using the geotextile reinforcement. Fig.17 shows the shape of the critical circle. The values of the factor of safety during the earthquake shaking, after using the reinforcement, are presented in

Fig.18. The geotextile increased the stability of the slope during the earthquake shaking as the value of

the factor of safety increased to a maximum value of 1.966 at T of 6 seconds.

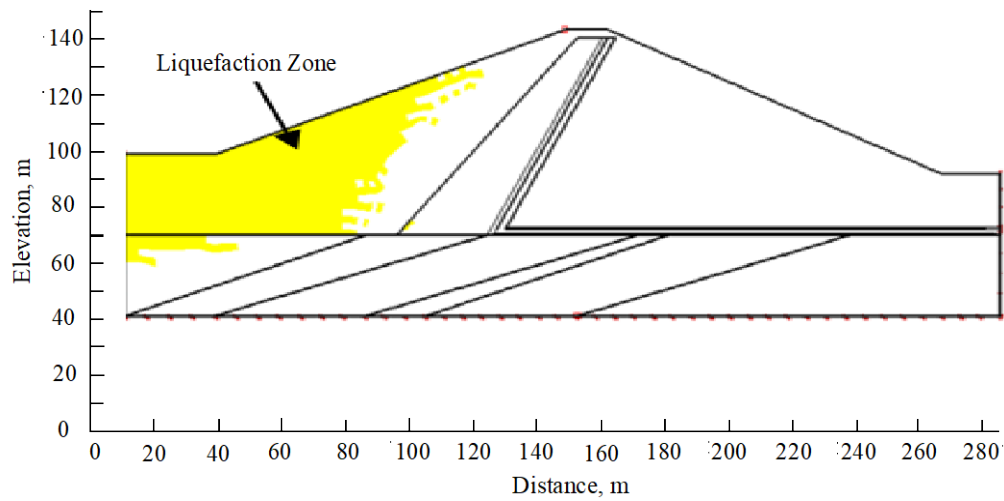


Fig.15. Liquefiable zones of the dam

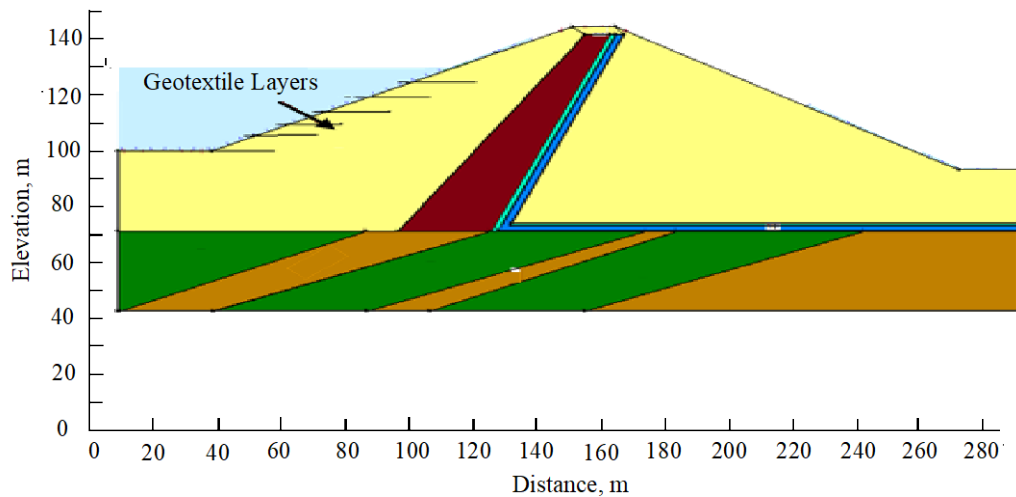


Figure 16. Geotextile reinforcement of the liquefiable zone.

Table 3. The strength Geotextile material (after [30])

Degree of Geotextile Survivability	Grab Strength ¹ [lb]	Burst Strength ² [psi]	Puncture Strength ³ [lb]	Trap Tear ⁴ [lb]
Very high	270	430	110	75
High	180	290	75	50
Moderate	130	210	40	40
Low	90	145	30	30

Note: The values are for minimum average roll (any roll must meet or exceed the minimum values as listed in this table). These values are usually 20 % lower than typical values given by manufacturers. ¹ ASTM D 4632, ² ASTM D 3786, ³ ASTM D 4833, ⁴ASTM D 4533.

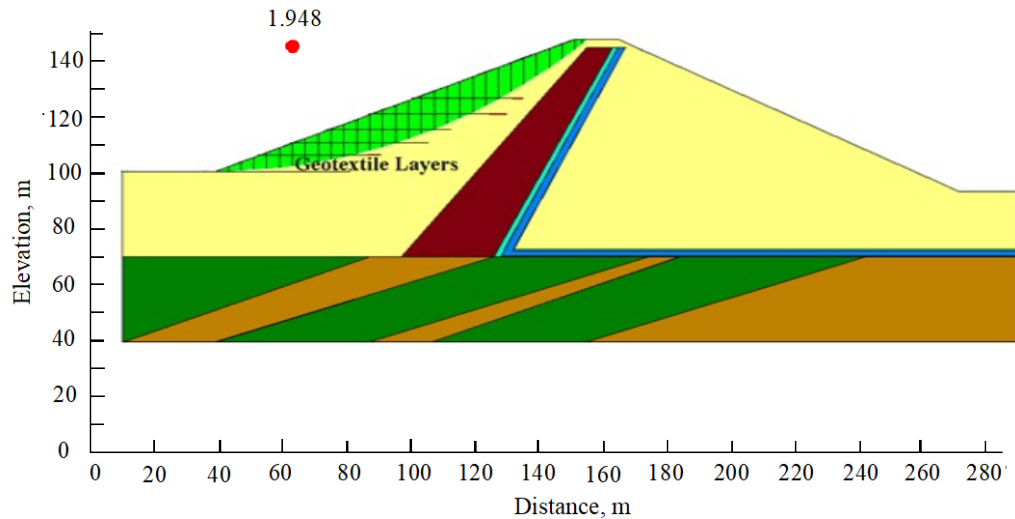


Fig.17 The factor of safety value after using the geotextile reinforcement

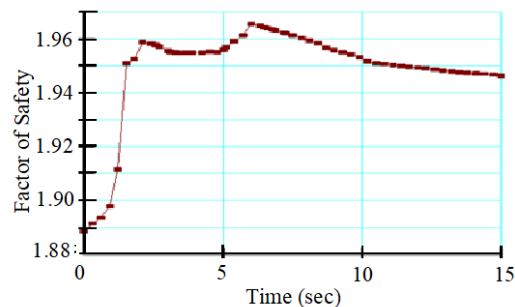


Fig.18 The variation of the factor of safety values during the earthquake shaking after using the geotextile reinforcement

4. CONCLUSION

The static and dynamic stability of Al-Adhaim Dam was evaluated by using SLOPE/W and SEEPE/W. The values of seepage, pore water pressure, and factor of safety were determined for the static condition. The dynamic stability was also evaluated during the earthquake shaking by using QUAKE/W. The following conclusions can be drawn from the analysis:

- The values of seepage and pore water pressure were within the allowable limits before applying the earthquake shaking.
- For the static condition, the values of the factor of safety for the front face, the back face, and the front face during the rapid drawdown were 1.882, 1.848, and 1.834, respectively. These values were less than the allowable values that are presented by the design guidelines of USACE 2003.
- Applying ground shaking to the dam produced a vertical displacement of 0.12 m and a relative

displacement of 0.4 m after 9 seconds of the earthquake shaking.

- The minimum value of the dynamic safety factor was 1.01 at T of 10 seconds which was less than the allowable value (1.2) for the dynamic stability.
- The relationship between the factor of safety and the acceleration showed that the factor of safety decreased to less than the allowable value at a ground acceleration value of 0.12g.
- The liquefaction analysis indicated that the front shell of the dam is liquefiable.
- Using geotextile reinforcement within the front shell of the dam increased the factor of safety to 1.946 which was within the allowable values.

5. ACKNOWLEDGMENTS

The authors acknowledge the financial support provided by the Lulea University of Technology (LTU), Sweden. The authors also acknowledge providing the data of the Al-Adhaim by the Ministry of Water Resources (MOWR), Iraq.

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