Finite element analysis of a zoned earth dam under earthquake excitation

Areej A Jawad1, Waqed H Hassan2 and Mohammed Y Fattah3

1 Graduate student, Civil Engineering Department, University of Kerbala, Karbala, Iraq. Email: areegealaa885@gmail.com
2 Professor, Civil Engineering Department, University of Kerbala, Karbala, Iraq. E-mail: Waqed2005@gmail.com
3 Professor, Civil Engineering Department, University of Technology, Baghdad, Iraq.

Abstract: This paper presents a finite element analysis of a zoned earth dam under the effects of earthquake conditions. GeoStudio software, and in particular the sub-programs SEEP/W and QUAKE/W were used, and the earthquake used in the analysis was an Iraqi earthquake that occurred in Ali Al-Garbi, within the Missan governorate. The Haditha dam section data was used for the hypothetical dam construction. The total length of length of this dam is 9,064 metres, which includes 8,875 metres of earth fill, and the maximum height of the dam is 57 m. The shell is constructed from a mix of sand and gravel, with an average particle diameter ranging from 0.24 to 16.7 mm. Three different properties were used to represent the core material, and each of these properties was analysed under three different heads of water on the upstream side. The results showed that high water levels at the upstream side of the dam heavily influenced the analysis results. The water flux, water conductivity, and peak displacement all increased with the increase in the water level upstream of the dam. For a water level equal to 152 m, the maximum values of water flux, water conductivity, and maximum displacement were $3.951 \times 10^{-3}$ m$^2$/sec, $6.654 \times 10^{-3}$, and 2.03 m, respectively, while where the water level was 143 m, these values were equal to $2.023 \times 10^{-3}$ m$^2$/sec, $3.995 \times 10^{-3}$, and 1.85 m, respectively. Further analysis showed that the water flux, water conductivity, and peak displacement increased with increases in the void ratio and degree of saturation of the clay core material, moving from $2.023 \times 10^{-3}$ to $3.951 \times 10^{-3}$ m$^2$/sec for water flux, from $3.995 \times 10^{-3}$ to $6.654 \times 10^{-3}$ for water conductivity, and from 1.85 to 2.03 m for peak displacement.

Keywords: Earth dam, earthquake, finite elements, clay core.
1. Introduction
Dams are large hydraulic infrastructures constructed across rivers to create reservoirs on the upstream side to meet various functional needs such as storing and diverting water for irrigation or water supply, flood control, and fishing; another major use of dams is to generate hydro-electrical power [1, 2, 3, 4, and 5]. About eighty-five percent of all dams in the world are embankment dams due to the widespread applicability of this method. These are constructed from raw soil and subsurface materials [6, 7, 8, and 9], and can thus be classified into two types, earth dams and rock-fill dams. Earth dams are seriously affected by earthquakes, defined as any dynamic forces operating within the earth, with following failure types emerging: instability, internal cracking, settlement damage to associated structures, and differential movements. The responses of embankment dams to earthquakes are affected by water-dam interaction, dam-foundation interaction, and sediment at the bottom of a reservoir [10, 11, 12, 13, 14, and 15].

Previous studies have presented several different methods of analysing the earthquake responses of dams. [16] and [17] suggested a pseudo-static method of analysis to calculate the minimum seismic load that could cause instability of the dam slope, while [18] used a pseudo-static slope to analyse earth dams, discovering that sliding occurred when the acceleration exceeded the strength of the material. [19] also used this method on the La Villita dam to investigate observed response asymmetry, with two points on the two edges of the dam crest monitored (one inside and one outside the sliding mass) and their responses compared; this showed that the point inside the sliding mass presented an asymmetric acceleration response [20 and 21]. [22] performed a dynamic analysis of the effects of the San Fernando earthquake in 1971 on the San Fernando dam, based on 0.55 g of maximum acceleration over a 15 sec period. The stability of the dam was assessed by investigating the potential for liquefaction and strain within several potential failure areas, and the results showed that after 10 s of movement starting, peak acceleration occurred. [23] then used a simple sliding block model to investigate the observed acceleration asymmetry, concluding that this was the result of a localised slip failure. The shear beam method was then extended to consider the effects of canyon geometry and inhomogeneous dam materials by multiple researchers [24, 25, 26, 27, 28, and 29]. [30] used the two-dimensional analysis Geo-Slope program to study the dynamic behaviour of a zoned core in the Mamloo earth-fill dam. The results of this study showed that the maximum horizontal acceleration at the zoned core dam crest reached 0.0206 g while that in the simple core reached 0.0207 g. [31] performed dynamic analysis of the Khassa dams using the two-dimensional finite element analysis program GeoStudio with sub-programs SEEP/W and QUAKE/W. The researchers selected different amplitudes of acceleration of the El-Centro earthquake with a period of 10 sec, and the results showed that the largest horizontal displacement occurred at the base of the dam at a time of 60 sec. The results also showed that the horizontal displacement increased with depth of the point from the crest.

The objectives of this study are to model the behaviours of an earth dam using the finite element method for three levels of water head at the upstream side to study the effect of degree of compaction of the core material on the dynamic response of the dam.

2. Description of the Modelled Dam
Haditha Dam is an earth fill dam with three components, the foundation, shell, and core, as shown in Figure 1. The dam was constructed in 1977 and began operation in 1988. Haditha dam is located in a narrow part of the Euphrates River, a few kilometres upstream from Haditha, at 34° 120' latitude and 42° 210’ longitude. Figure 2 is an aerial photo of the location of Haditha dam. The total length of the dam is 9,064 metres, which includes 8,875 metres of earth fill. The earth fill segment is divided into 3,310 metres on the right bank, 4,985 metres on the left bank, and another 580 metres in the river channel. The maximum height of the dam is 57 m, and the dam crest level is fixed at 154.00 m above sea level, with a width of 20 m [32, 33, 34, and 35]. About 30 million m³ of materials were required to construct the Haditha dam. The shell was constructed from a mix of sand and gravel with an average particle diameter range of 0.24 to 16.7 mm, while the core
was constructed from the clay materials known as “mealy dolomite” or “powder dolomite”. The source of the dolomite utilised in construction was the Euphrates Formation, which is one of the dominant formations at the site and which outcrops at both the right and left bank of the river. This formation varies in thickness between 13 – 26 m [36]. Stability analysis of the dam showed that the design parameters provided good slope stability under the dynamic effects of earthquakes and occurrence of excess pore water pressure.

Figure 1: Haditha dam: typical cross-section.

Figure 2: Aerial photo of Haditha dam location

3. Analysis of the Dam
The analysis was divided into two stages. In the first stage, the program SEEP/W was used, and in the second stage, QUAKE/W was applied.
4. Seepage analysis
The sub-program SEEP/W was used to analyse the seepage through and under the dam. The upstream boundary nodes were designated as head boundaries, with a total head equal to the water level in the reservoir, while the downstream boundary nodes were designated with a total head equal to 110 m. The bottom nodes along the foundation were designated as zero discharge (no flow).

5. Dynamic analysis
The dynamic analysis was conducted in the sub-program QUAKE/W once the seepage analysis was complete, as the dynamic analysis required the results obtained from SEEP/W. In the dynamic analysis, the boundary conditions along the horizontal base of the foundation were assumed to be restrained in the vertical direction and free in the horizontal direction, while the side of the dam was fixed in Y-direction, as illustrated in Figure 3. A linear elastic model was used in the analysis and the damping ratio was assumed to be 0.02, based on the results in [37]. The core zone was a clay soil, as obtained from the southern part of Baghdad city. The collected soil was tested in the laboratory under three different degrees of compaction, and the responses of the properties of the core material were analysed under three different heads of water at the upstream side. The shell and foundation zone properties used were obtained from previous studies [36]. The model involved several parameters as shown in Table 1. The finite element mesh used for the analysis is shown in Figure 4, and this included quads and triangular elements [38-41]. The dam was subjected to disturbance based on the Iraqi earthquake in Ali Al-Garbi within the Missan governorate; the acceleration-time history of this earthquake is shown in Figure 5. This earthquake was selected due to the existence of reliable data which have been filtered; it is thus conventionally used in dynamic analyses.

Figure 3: Haditha dam model with Y-fixed boundary condition.
Figure 4: Typical finite element mesh.

Table 1: The input parameters of the core material.

| material condition       | Core                          | Shell              |
|--------------------------|-------------------------------|--------------------|
|                          | Compacted at the dry side    |                    |
| Dry unit weight (kN/m³)  | 17.3                          | 17.45              |
| of water content         | 17.05                         |                    |
| Degree of saturation (%) | 0.76                          | 0.74               |
| Void ratio               | 0.59                          | 0.51               |
| Permeability (m/sec)     | 5.21*10⁻⁷                     | 4.43*10⁻⁷          |
| Coefficient of           | 0.0274                        | 0.0211             |
| compressibility (m²/kN)  | 0.0211                        | 0.021              |
|                          | 0.63                          |                    |

Figure 5: The acceleration-time history record for Iraqi earthquake at Ali Al-Garbi with 0.1 g amplitude.

6. Results and Discussion
The time of the analysis runs carried out in SEEP/W and QUAKE/W was 60 sec, with an interval time of 0.02 sec. The results of the analysis were classified into three categories depending on the level of water at the upstream side of the dam:
At each level of water, three different properties of the core materials were examined. The soil of the core was compacted at three different water contents, resulting in three degrees of saturation, and the previous analyses were repeated for each material type in the core as explained in Table 1. The analysis results obtained from SEEP/W and QUAKE/W showed that water flux ranged from $2.023 \times 10^{-3}$ to $3.951 \times 10^{-3}$ m$^3$/sec; the hydraulic gradient ranged from 0 to 0.785; the hydraulic conductivity ranged from $3.995 \times 10^{-3}$ to $6.654 \times 10^{-3}$; while the peak displacement varied from 1.852 to 2.120 m. Figures 7 to 10 show typical curves to illustrate maximum total stress, mean total stress, x-total stress, and y-total stress for nodes (1), (2), and (3), as explained in Figure 3.

**Figure 6:** Maximum total stress vs. time.

**Figure 7:** Mean total stress vs. time.
As shown, the maximum total stress ranged from 3.75 kPa for node (1) to 54.2 kPa for node (3), while the mean total stress ranged between 1.05 kPa and 22.11 kPa. However, the X-total stress was equal to 49.7 kPa and Y-total stress reached 36 kPa. All these figures reflected dry conditions in the core material, which allowed higher results to be obtained, as soil in dry condition has high value of dry unit weight, and low values of degree of saturation and void ratio.

The main parameters within the finite element analysis were hydraulic flux, hydraulic conductivity, hydraulic gradient, and peak displacement. All of these values increased with an increase in void ratio and degree of saturation. Variations in these properties were also obtained from changes when preparing core materials under different degrees of compactions and optimum water content. Figures 10 to 13 illustrate these relationships, while Figure 14 shows the contours of the total head equal to 143 m passing through the dam.
Figure (10): (a) Hydraulic flux vs. void ratio, (b) Hydraulic flux vs. degree of saturation.
Figure (11): (a) Hydraulic conductivity vs. void ratio, (b) Hydraulic conductivity vs. degree of saturation.
Figure 12: (a) Hydraulic gradient vs. void ratio, (b) Hydraulic gradient vs. degree of saturation.

Figure 13: (a) Peak displacement vs. void ratio, (b) peak displacement vs. degree of saturation.
7. Conclusions

Based on seepage and quake analysis carried out on the hypothetical dam using the finite element method, the following conclusions emerged:

1. Any increase in water level at the upstream side of the dam has a significant effect on the qualities under analysis, with the water flux, water conductivity, and peak displacement all increasing with increasing the water level upstream of the dam. The maximum values were $3.951 \times 10^{-3}$ $m^2/sec$ for water flux, $6.654 \times 10^{-3}$ for water conductivity, and 2.03 m displacement, all at a water level equal to 152 m, while at a water level of 143 m these values equalled $2.023 \times 10^{-3}$ $m^2/sec$, $3.995 \times 10^{-3}$, and 1.85 m respectively.

2. The maximum stress of 45.2 kPa was generated in the lowest point, at the foundation of the dam, while the lowest stress of 3.75 kPa was obtained at the highest point of the dam.

3. The results show that the water flux, water conductivity, and peak displacement all also increase with increases in the void ratio and degree of saturation of the clay core material, ranging from $2.023 \times 10^{-3}$ to $3.951 \times 10^{-3}$ $m^2/sec$ for water flux, from $3.995 \times 10^{-3}$ to $6.654 \times 10^{-3}$ for water conductivity, and from 1.85 to 2.03 m for peak displacement.

8. References

[1] Athania S. S., Shivamantha, C. H, Solankia and G. R. Dodagoudar, (2015) “Seepage and Stability Analyses of Earth Dam Using Finite Element Method”, International conference on water resources, coastal and ocean engineering, pp. 876 – 883.

[2] Hassan, W.H., 2019. Application of a genetic algorithm for the optimization of a location and inclination angle of a cut-off wall for anisotropic foundations under hydraulic structures. Geotechnical and Geological Engineering, 37(2), pp.883-895.

[3] Hassan, W.H., 2020. Climate change impact on groundwater recharge of Umm er Radhuma unconfined aquifer Western Desert, Iraq. International Journal of Hydrology Science and Technology, 10(4), pp.392-412.
[4] Hassan, W.H., Attea, Z.H. and Mohammed, S.S., 2020. Optimum layout design of sewer networks by hybrid genetic algorithm. Journal of Applied Water Engineering and Research, 8(2) pp.1-17.

[5] Hassan, W.H. and Hashim, F.S., 2020. The effect of climate change on the maximum temperature in Southwest Iraq using HadCM3 and CanESM2 modelling. SN Applied Sciences, 2(9), pp.1-11.

[6] Venuja T., Kurukulasuriya C., (2020), “Seepage in Iranamadu Dam and Its Influence on the Stability”, ICSBE 2018, LNCE 44, pp. 325–338, 2020.

[7] Hassan, W.H., Jassem, M.H. and Mohammed, S.S., 2018. A GA-HP model for the optimal design of sewer networks. Water resources management, 32(3), pp.865-879.

[8] Hassan, W.H., 2017. Application of a genetic algorithm for the optimization of a cutoff wall under hydraulic structures. Journal of Applied Water Engineering and Research, 5(1), pp.22-30.

[9] Hassan, W.H., Nile, B.K., Al-Masody, B.A., 2017. Climate change effect on storm drainage networks by storm water management model. Environmental Engineering Research, 22(4), pp.393-400.

[10] Zhao, C., Valliappan, S. and Wang, Y. C. [1992] “A numerical model for wave scattering problems in infinite media due to P and SV wave incidences,” International Journal for Numerical Methods in Engineering 33, pp. 1661–1682.

[11] Khalaf, R.M. and Hassan, W.H., 2013. Evaluation of irrigation water quality index IWQI for Al-Dammam confined aquifer in the west and southwest of Karbala city, Iraq. International Journal of Civil Engineering IJCE, 23, pp.21-34.

[12] Kais Jalal, H. and Hassan, W.H., 2020. Three-dimensional numerical simulation of local scour around circular bridge pier using Flow-3D software. MS&E, 745(1), p.012150.

[13] Majeed, S.A.A.D., Mohammed, O.I. and Hassan, W.H.,2016. Determining Irrigation Water Quality Index for Evaluation Groundwater Quality of Green-Belt Zone, Karbala, Iraq. 4th. International Congress on Civil Engineering, Architecture and Urban Development

[14] Mohammed, S.R., Nile, B.K. and Hassan, W.H., 2020, January. Modelling Stilling Basins for Sewage Networks. In IOP Conference Series: Materials Science and Engineering (Vol. 671, No. 1, p. 012111). IOP Publishing.

[15] Mohsen, K.A., Nile, B.K. and Hassan, W.H., 2020, January. Experimental work on improving the efficiency of storm networks using a new galley design filter bucket. In IOP Conference Series: Materials Science and Engineering (Vol. 671, No. 1, p. 012094). IOP Publishing.

[16] Terzaghi, K. (1950). “Mechanisms of landslides, Engineering Geology” (Berkey) Volume, Geological Society of America.

[17] Sarma, S. K., 1979. “Response and Stability of Earth Dams during Strong Earthquakes”, Miscellaneous Paper GL-79-13, Department of the Army, Waterways Experiment Station, Vicksburg, MS.

[18] Gazetas, G. and Uddin, N. (1994), “Permanent deformation on pre-existing sliding surfaces in dams”. Journal of Geotechnical Engineering, 120, No. 11, 2041-2061.

[19] Uddin, N. (1997), “A single-step procedure for estimating seismically-induced displacements in earth structures”. Computers and Structures, 64, No. 5/6, 1175-1182
[20] Seed, H. B., Wong, R. T., Idriss, I. M. and Tokimatsu, K. (1986). “Moduli and damping factors for dynamic analyses of cohesionless soils”. Journal of Geotechnical Engineering, 112, No. 11, 1016-1032.

[21] Elgamal, A.-W. M., Scott, R. F., Succarieh, M. F., and Yan, L. [1990], “La Villita Dam response during five earthquakes including permanent deformation”, J. of Geotech. Engrg., ASCE, 116(10), 1443-1462.

[22] Dakoulas, P. and Gazetas, G. (1987), “Vibration Characteristics of Dams in Narrow Canyons”, Journal of Geotechnical Engineering, ASCE, Vol. 113, No 8, pp. 899-904.

[23] Abdel-Ghaffar, A. M. & Koh, A. S. (1981), “Longitudinal vibration of non-homogeneous earth dams”. Earthquake Engineering and Structural Dynamics, 9, No. 3, 279-305.

[24] Gazetas, G. (1982), “Shear vibrations of vertically inhomogeneous dams”. International Journal for Numerical and Analytical Methods in Geomechanics, 6, No. 1, 219-241.

[25] Nile, B.K., Hassan, W.H. and Esmaeel, B.A., 2018. An evaluation of flood mitigation using a storm water management model [SWMM] in a residential area in Kerbala, Iraq. MS&E, 433(1), p.012001.

[26] Nile, B.K., Hassan, W.H. and Alshama, G.A., 2019. Analysis of the effect of climate change on rainfall intensity and expected flooding by using ANN and SWMM programs . ARPN Journal of Engineering and Applied Sciences,14(5).

[27] Hassan, W.H. and Nile, B.K., 2020. Climate Change and Predicting Future Temperature in Iraq Using CanESM2 and HadCM3 Modeling. Modeling Earth Systems and Environment.

[28] Fattah, M.Y., Hassan, W.H. and Rasheed, S.E., 2018. Behavior of flexible buried pipes under geocell reinforced subbase subjected to repeated loading. International Journal of Geotechnical Earthquake Engineering (IJGEE), 9(1), pp.22-41.

[29] Fattah, M. Y., Hassan, W. H., & Rasheed, S. E. (2018). Effect of geocell reinforcement above buried pipes on surface settlement. International Review of Civil Engineering, 9(2), 86–90.

[30] Moayed R. Z., and Ramzanpour M. F. (2008), “Seismic Behavior of Zoned Core Embankment Dam”, EJGE journal Vol.13 band A, pp.1-15

[31] Fattah M. Y., Alwash H. H., and Hadi S. A., (2017), “Earthfill Dams Response to Earthquake Excitation -Khassa Chai Dam as a Case Study”, Al-Nahrain Journal for Engineering Sciences (NJES) Vol.20 No.2, 2017 pp.405-418 Special Issue - Proceedings of the 4th Eng. Conf. (21April 2016, Al-Nahrain Univ., Baghdad, IRAQ)

[32] Adamo N., Sissakian V.K, Al-Ansari N., Elagely M., Knutsson S., and. Laue J., (2018), “Comparative Study of Mosul and Haditha Dams in Iraq: Different Construction Materials Contribute to Different designs”, Journal of Earth Sciences and Geotechnical Engineering, vol. 8, no. 2, 2018, 71-89 ISSN: 1792-9040 (print version), 1792-9660 (online) Scienpress Ltd, 2018.

[33] Al-Mussawi, W.H., 2008. Kriging of Groundwater Level-A Case Study of Dibdiba Aquifer in Area of Karbala-Najaf. journal of kerbala university, 6(1), pp.170-182.

[34] Al-Mussawi, W.H., 2009. Numerical Analysis of Velocity Profile and Separation Zone in Open Channel Junctions. Al-Qadisiyah Journal for Engineering Sciences, 2(2), pp.262-274.

[35] Al-Mussawi, W.H., Al-Shammary, M.H. and Alwan, H.H., 2009. Three-dimensional numerical investigation of flow at 90 open channel junctions. Journal of Kerbala University, 7(4), pp.260-272.
[36] Yacoob T.1985, “Dolomite as Core Materials for Dams”. 15th ICOLD Congress Proceeding Q 55, R 33 Lausanne 1985
[37] Hadi S. A., (2010), “Effect of Earthquake on Earthfill Dams (Khassa Chai Dam as Case Study)”, A Thesis Submitted to the Building and Construction Engineering Department of the University of Technology in Partial Fulfilment of the Requirements for the Degree of Master of Science in Building and Construction Engineering /Water Resources Engineering.
[38] Al-Mussawi, W.H., 2014. Assessment of groundwater quality in Umm Er Radhuma aquifer (Iraqi Western Desert) by integration between irrigation water quality index and GIS. Journal of University of Babylon, 22(1), pp.201-217.
[39] AL-Musawi, W.H., Shukur, A.H.K. and Al-Delewy, A.A., 2006. Optimum design of control devices for safe seepage under hydraulic structures. Journal of Engineering and Sustainable Development, 10(1), pp.66-87.
[40] Khalaf, R.M. and Hassan, W.H., 2016. Estimation the hydrogeological characteristics of Al-Dammam confined aquifer in the west and southwest of Karbala city, Iraq. Journal of kerbala university, 14(2), pp.24-35.
[41] Almohammed, W.H., Fattah, M.Y. and Rasheed, S.E., 2018. Numerical Analysis of the Effect of Geocell Reinforcement above Buried Pipes on Surface Settlement and Vertical Pressure. International Journal of Geotechnical and Geological Engineering, 12(3), pp.256-262.