Numerical analysis of a zoned earth dam considering hydrodynamic force during the earthquake excitation

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Abstract. This paper presents finite element analysis of a zoned earth dam considering hydrodynamic force during the earthquake. Geostudio software using the sub-program SEEP/W and QUAKE/W was used. The earthquake that is used in this analysis are Iraqi earthquake that happened in Ali Al-Garbi within Missan governorate and El-Centro earthquake. Haditha dam section was used for the hypothetical dam. The maximum height of the dam is 57 m. The shell was constructed from the mix of sand-gravel with the average particles diameter range from (0.24 to 16.7 mm). Three different properties were used for core material, each one of these properties was analyzed under three different heads of water in the upstream side. The main parameters that have the influence on the analysis results are; water level in the upstream side of the dam, intensity of the earthquake, properties of the core material, and the value of hydrodynamic force. The hydraulic flux and peak displacement increase with increasing these parameters.

1. Introduction

Earth dams are large hydraulic structures used to reserve semi-fluid or water wastes. Earth dams are classified into small dams that are constructed from one basic material, and large dams that are have high over 15 m and constructed from two or more basic materials [1]. A dam also has many functions, it can be used to store and collect water which can be evenly distributed between locations. It is also considered as the main suppliers of water for drinking, industrial, and agricultural purposes. It also serves as a major flood control system and often supplies water to power plants. Consequently, dams' stability and safety play a vital role, especially at critical times such as flood periods [2].

Many of researchers have studied the seismic attitude of dams using numerical and physical models analyzes. Many of these researches inclusive investigating of the damage of embankment dams without tank in the upstream side. In addition, some researchers have examined the seismic fulfillment of dams of land filling with the tank in the upstream side [3-6]. [7] showed in his results that with decreasing relative soil density the deformation in the body of dam increases. Although the deformation was greater on the upper side of the dam than on the underside, it was found that the slope was nicer on the upper side of the dam in. However, seismic behavior of dams with core sloping regions has only been examined in a few small-scale modeling studies.
Earth-dams are affected by the earthquake, earthquake defines as the dynamic forces that are operating within the earth and cause the following failures; internal cracking, settlement, differential movements, instability and damage to associated structures [8]. When the dams are subjected to an earthquake, the problem of hydrodynamic pressure occurs in the reservoir in the upstream face of the dams. During an earthquake, a dam subjected in to a hydrodynamic pressure, in addition to the hydrostatic pressure on the dam surface. These forces magnitude are mainly influenced by the intensity of earthquake [9].

Calculating hydrodynamic pressure and evaluating intense pressure loads on the dam face is a vital issue in the earthquake resistant design of the dam body.

The magnitude of the surface pressure is defined as the local change in hydrostatic pressure that can be induced by the surface waves attributed to the vertical displacement of the free surface approximately as suggested by [10]:

\[ P_m = \left( S_t C_d \omega_s \lambda \right) / L_d \]  \hspace{1cm} (1)

where:

- \( P_m \) magnitude of surface pressure,
- \( C_d \) coefficient of dissipation,
- \( \omega_s \) dimensionless instantaneous vertical velocity component,
- \( \lambda \) wavelength of the surface waves,
- \( L_d \) dissipation zone length, and
- \( S_t \) Strouhal number produced from equation 2.

\[ S_t = \frac{V_m T}{H} \]  \hspace{1cm} (2)

\[ F_r = \sqrt{gH} \]  \hspace{1cm} (3)

\[ R_e = \frac{\rho V_m H}{\mu} \]  \hspace{1cm} (4)

where:

- \( H \) The reservoir depth (m),
- \( V_m \) The maximum ground velocity (m/sec), and
- \( T \) the oscillation period of the ground motion(sec).

The velocities ground is included in momentum equations to represent the analysis of the earthquake excitation in dam reservoir. The arithmetic field and grid system are supposed to move with the ground. The velocity vector \( V \) is defined with respect to the moving Earth. The terms compressibility was not included in the momentum equations in the analysis because they were found, in preliminary studies, at least six orders of magnitude smaller than other terms in the equations.

The objective of the present study is modeling the behavior of earth dam by the finite element to investigate the hydro-dynamic pressure imposed on the upstream side of the. The effects of hydrodynamic force on the earth dam under three conditions of water level in the reservoir and three various properties of core material are studied.

2. Description of the dam

In this theoretical study, a hypothetical dam is assumed to have the same section of Haditha dam. Haditha dam is an earth fill dam that consists of three components; foundation, shell, and core as explained in Figure 1. The maximum height of the dam is shell was constructed from the mix of sand-gravel with the average particles diameter range from (0.24 to 16.7 mm). 57 m. The dam crest level was fixed at 154.00 m (a.s.l.), and the width of crest was 20 m [11].
When stability analysis of the dam was performed, the design parameters provided good slope stability under the dynamic effects from earthquakes and occurrence of excess pore water pressure. While the core was constructed from clay materials also called “mealy dolomite” or “powder dolomite”. The source of the dolomite utilized in construction was the Euphrates Formation, which is one of the dominant formations at the site and which outcrops mainly at the right and left bank of the river. This formation has varying thickness between (13 – 26 m) [13].

### 3. Analysis of the model

The finite element model of the dam section was developed to analyze the effects of hydrodynamic force behavior of dam reservoirs during two types of earthquakes are Ali Al-Garbi and El-Centro earthquake. The finite element model was developed using the two-dimension program Geostudio. The analysis is divided into two stages, in the first stage the program SEEP/W is utilized, and in the second stage using QUAKE/W is used as presented in the sub-sections below:

#### 3.1. Seepage analysis

The sub-program SEEP/W is used to analyze the seepage through and under the dam. The boundary nodes in the reservoir are designated as head boundaries with total head equals to the water level in the reservoir, and the boundary nodes in the downstream side are designated with total head equal to (110 m). The bottom nodes along the foundation are designated as a zero discharge (no flow).

#### 3.2. Dynamic analysis

After completing the seepage analysis, the dam is analyzed by the program QUAKE/W depending on the results obtained from the program SEEP/W. In dynamic analysis, the boundary conditions along the horizontal base of the foundation are assumed to be restrained in the vertical direction and free in the horizontal direction. While the sides of the dam are fixed in Y-direction as explain in Figure 2. Linear elastic model is used in the analysis. The damping ratio is assumed to be 0.2. The core zone is assumed to be a clay soil obtained from south parts of Baghdad city. The collected soil was tested in the laboratory under three different degree of compactions. Each one of these properties of core material were analyzed under three different heads of water in the upstream side. While the shell and foundation zone properties obtained from previous studies. The model involves the following parameters as an input explained in Table 1. After the geometry model is created and material properties are fully defined to dam’s layers, the model has to be divided into fine elements to build a finite element mesh, these elements are interconnected at specified joints lie on the element boundaries called nodal points. The finite element mesh used for the analysis is shown in Figure 3. The mesh includes Quads and triangular elements. The
value of hydrodynamic pressure obtained under two types of earthquake; El-Centro and Ali Al-Garbi. For El-Centro earthquake, three different amplitudes of acceleration; 0.05, 0.1, and 0.2 g are used for El-Centro earthquake. At each amplitude, three different reservoir depths; 43 m, 47 m, and 52 m are analyzed. Also, in each depth of reservoir, three different properties of the core material. While in Ali Al-Garbi earthquake, only one acceleration amplitude of 0.1 g is used with three different reservoir depths and three different properties of the core material. Table 2 summarizes the value of hydrodynamic pressure obtained from equation (1).

![Figure 2. Dam model with boundary conditions.](image)

### Table 1. The input parameters of the core material.

| material condition               | Core Compacted at the dry side | Core Compacted at optimum water content | Core Compacted at the wet side | Shell |
|----------------------------------|--------------------------------|----------------------------------------|--------------------------------|-------|
| Dry unit weight (kN/m³)          | 17.45                          | 17.3                                   | 17.05                          | 18.5  |
| Degree of saturation (%)         | 0.76                           | 0.74                                   | 0.82                           | 0.77  |
| Void ratio                       | 0.59                           | 0.51                                   | 0.53                           | 0.63  |
| Permeability (m/sec)             | 5.21*10⁻⁷                      | 4.43*10⁻⁷                             | 3.38*10⁻⁷                     | 4.02*10⁻⁴ |
| Coefficient of compressibility (m²/kN) | 0.0274                      | 0.02111                                | 0.0211                        | 0.002 |
Figure 3. Typical finite element mesh.

| Earthquake Type | Earthquake peak acceleration (g) | Reservoir depth H (m) | Period of the ground motion, T (sec) | Hydrodynamic pressure, Pm (kN/m²) |
|-----------------|----------------------------------|-----------------------|------------------------------------|-----------------------------------|
| El-Centro       | 0.05                             | 43                    |                                    | 27.16                             |
|                 |                                  | 47                    |                                    | 22.74                             |
|                 |                                  | 52                    |                                    | 18.58                             |
|                 | 0.1                              | 43                    |                                    | 54.33                             |
|                 |                                  | 47                    |                                    | 45.48                             |
|                 |                                  | 52                    |                                    | 38.33                             |
|                 | 0.2                              | 43                    | 32                                 | 108.66                            |
|                 |                                  | 47                    |                                    | 90.95                             |
|                 |                                  | 52                    |                                    | 70.30                             |
| Ali Al-Garbi    | 0.1                              | 43                    | 60                                 | 191.00                            |
|                 |                                  | 47                    |                                    | 159.87                            |
|                 |                                  | 52                    |                                    | 130.61                            |

4. Results and discussions
The results of analysis have shown that the stability and deformation in dam’s body are affected by the following parameters: oscillation period of the ground motion, reservoir depth, properties of core zone, and the intensity of earthquake. The presentation and discussion these parameters in the following subsections below.

4.1. Effect of pulsating period of the ground motion
The deformation of the dam body increases with time, the maximum displacement increase with increasing the time as shown in displacements – time curve in Figure 4. The reason of that is the value of the hydrodynamic force which increases with increasing the oscillation period of the ground motion
because the relationship between them is direct proportion. Also, a comparison between the El-Centro and Ali Al-Garbi earthquake reveals that the maximum displacements obtained during the influence of Ali Al-Garbi. The reason of that is the oscillation period of the ground motion of Ali Al-Garbi is greater than that of El-Centro earthquake that made the value of hydrodynamic force is greater than that obtained from El-Centro.

The maximum displacements presented in Figure 4 are higher than those obtained without considering hydrodynamic forces, which are 2.093 m, 2.104 m, and 2.504 m for points 1, 2 and 3, respectively.

![Figure 4](image)

**Figure 4.** Horizontal displacement – time curve during 0.2g El-Centro earthquake considering hydrodynamic pressure.

### 4.2. Effect of reservoir depth

The deformation of dam body increases with decreasing the depth of reservoir because of the indirect proportion relationship between the hydrodynamic pressure and reservoir depth. The maximum displacements, hydraulic flux, hydraulic conductivity, and hydraulic gradient decrease with increase reservoir depth due to decrease the value of hydrodynamic force as illustrated in Figures 5 through 8. The reason of that is that these hydrodynamic forces may presents large stresses on the reservoir dam slope, which in turn result in substantial strains due to localized yielding of the soil materials. Also, some significant shear strains develop in the upstream dam slope potentially due to these additional reservoir hydrodynamic pressures and that agree with the results of [14]. In addition, the higher water level in the reservoir adds same type of stability to the dam body which is also realized in slope stability analysis.

![Figure 5](image)

**Figure 5.** Maximum displacements vs. reservoir height for 0.2g El-Centro earthquake considering hydrodynamic pressure.
Figure 6. Hydraulic flux vs. reservoir depth for 0.2g El-Centro earthquake considering hydrodynamic pressure.

Figure 7. Hydraulic conductivity vs. reservoir depth for 0.2g El-Centro earthquake considering hydrodynamic pressure.

Figure 8. Hydraulic gradient vs. reservoir depth for 0.2g El-Centro earthquake considering hydrodynamic pressure.
4.3. Effect of properties of the core zone

The properties of core material have a significant effect on the stability of the dam’s body. The basic properties that have the largest effects on the analysis results are void ratio, dry unit weight, and degree of saturation. As explained in Figures 9 through 16, the maximum displacements, hydraulic flux, hydraulic conductivity, and hydraulic gradient increase with increasing the soil void ratio and degree of saturation.

![Figure 9. Hydraulic flux vs. void ratio for 0.2g El-Centro earthquake pressure.](image)

![Figure 10. Hydraulic flux vs. degree of saturation for 0.2g El-Centro earthquake.](image)

![Figure 11. Hydraulic conductivity vs. void ratio for 0.2g El-Centro earthquake](image)
Figure 12. Hydraulic conductivity vs. degree of saturation for 0.2g El-Centro earthquake

Figure 13. Maximum displacements vs. void ratio for 0.2g El-Centro earthquake.

Figure 14. Maximum displacements vs. degree of saturation for 0.2g El-Centro earthquake.
4.4. Effect of the earthquake peak acceleration

The intensity of the earthquake has the influence on the value of the hydrodynamic force. The value of the hydrodynamic force increases with increasing the earthquake peak acceleration which affects the stability of the dam and leads to increase the maximum displacements, hydraulic flux, hydraulic conductivity, and hydraulic gradient as illustrate in Figures 17 through 19. At El-Centro earthquake, the value hydrodynamic pressure increase from 18.58 kN/m² at 0.05g amplitude of acceleration and 52 m reservoir depth to 108.66 kN/m² at 0.2g amplitude of intensity and 43 m reservoir depth. While in Ali Al-Garbi, the value of hydrodynamic force reaches to 191 kN/m² at reservoir depth equal to 43 m.

Figure 15. Hydraulic gradient vs. void ratio for 0.2g El-Centro earthquake.

Figure 16. Hydraulic gradient vs. degree of saturation for 0.2g El-Centro earthquake
Figure 17. Hydraulic flux vs. hydrodynamic force under various intensities of earthquake.

Figure 18. Hydraulic conductivity vs. hydrodynamic force under various intensities of earthquake.

Figure 19. Maximum displacements vs. hydrodynamic force under various intensities of earthquake.
5. Conclusions
From the analyses of the seepage and earthquake that were carried out on a zoned earth dam using the numerical analysis method, the following conclusions can be presented below:

- Under the earthquake effect, the water level in the upstream side of the dam has a significant effect on the results of analysis. The water flux, water conductivity, and peak displacement increase with increasing the water level in the upstream of the dam.
- The results of the analysis of hydrodynamic force showed that the reservoir depth, core zone properties, pulsating period of earthquake, and the intensity of earthquake are main parameters that affect the stability of the dam. The maximum displacement for the dam crest is higher than that obtained without considering hydrodynamic forces which is 2.51m.
- The peak acceleration of the earthquake has the influence on the value of the hydrodynamic force. The value of the hydrodynamic force increases with increasing the earthquake peak acceleration.
- Finally, the hydrodynamic analysis results show that the hydrodynamic force causes the piping phenomena and leads to hydraulic failure to dam’s body.

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