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Static And Seismic Stability Analysis of Small Hydraulic Structure Under Seepage Load: A Case Study of Rawanduz Dam

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ABSTRACT

The analysis of the reservoir-dam-foundation coupled system is much more complicated than that of the structure alone because of the difference between the characteristics of the foundation and concrete dam. The small hydraulic structure may be built in seismically active regions, where ground movement would impose earth pressures. The safety of these structures should be investigated quite critically by logical and precise methods. Rawanduz dam subjected to EL-Centro earthquake-S00E component excitation was chosen as a typical case of study. The static and dynamic stability of the Rawanduz dam had been analyzed and evaluated. A 2-D Finite Element model employed using ANSYS software to simulated dam response. The water was modeled as an additive mass according to the theory of Westergaard on the back of the dam while leaving the rest of the reservoir inactive. The dam body is presumed homogeneous, elastic, and isotropic properties for mass material. The soil was assumed to be flexible and analyzed as a nonlinear material. When assessing the stability of the structure under the influence of the seepage loads, the structure was founded safe because the exit gradient value was equal to (0.25), which was less than the critical value of the exit gradient (1/6). Results showed that the principal stresses at the heel and toe of the dam were founded important to study the stability. The static and dynamic analysis findings indicate that the stress values are very low, hence satisfy the normal criteria for protection factors relating to the tensile and compressive strength of the concrete.

1. Introduction

Basically, the design of the systems of small hydraulic structures (such as wires and small concrete dams) depends on the specifications and functions of concrete dams such as supplying the water, flood control, also generate electric power.

The hydraulic structure might be built in seismically active zones, where ground shaking could put them under a lot of pressure. However small hydraulicstructure s canfail when exposed to the impact of large loads such as seismic load.

Failures of the small hydraulic structures under static and earthquake loads could cause loss of quantities of water, lives, and substantial financial.

For example, the Baozhusi Dam, located in China, suffered structural damage that led to cracks inside the dam body due to the earthquake that struck the city in 2008 [1].

Due to the noticeable increase in the number of earthquakes in world, the stability of small hydraulic structures has emerged as a major research area. Hamdi and Al-Shadeedi [2] was studied the stability of the hydraulic structure under the influence of the seismic load. The Performance of the dam has been modeled and investigated by an analytically method and FEM by using ANSYS software package to assure the safe performance of the dam. Results show that

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the structure was safe in terms of compression and tensile stresses.

Sarker [3] studied the dynamic response of concrete dam including the interaction between reservoir, dam, and foundation. In this study, the analysis was performed by the software ANSYS through modeling the Koyna dam. The results showed that the tensile strength of the dam is less than the tension stress of the dam, and this leads to the failure of the concrete dam.

Khan and Sharma [4] studied the stability of a structure with the intersecting galleries unplugged. They presented the stress analysis of the maximum overflow block of a 13m high concrete gravity dam, which has an intersection of cut–off wall gallery and access gallery. In their study, the dam block had been numerically modeled using FLAC 3D in three dimensions along with foundation rock and the intersection of two galleries. The minimum factor of safety of the dam block with respect to compression was found to be 1.56, for extreme loading conditions and galleries unplugged. The structure was found to be stable with minimal tension of the order of 0.2 MPa along the floor and roof of the access gallery. Numerical model analyses were found effective in studying the behavior of structures with complex configurations.

This research focuses on developing a model FE for a small hydraulic structure with interaction with soil and an added mass method using Westergaard theory. The main purpose of the research is to assess the stability of a hydraulic structure under the influence of static and dynamic load. Rawanduz Dam in the Governorate of Erbil has been selected a case of study in this research. In order to assess the stability of the hydraulic structure, the linear time-history analysis was used as the input ground motion.

2. Case of study

The Rawanduz Dam which is situated in a seismically active area of northern Iraq was chosen as a case study. Rawanduz Dam was far about 40 Km from the city of Rawanduz Located within the governorate of Erbil. The dam entered service in 2015.

Rawanduz dam placed on limestone foundation. It aims to collect water to power the turbine. The length of the dam was 68m while its height was 15m. Figure (1) shows the Rawanduze dam cross-section (all dimensions in meter).

Tables (1) and (2) show the property of concrete and foundation, respectively.

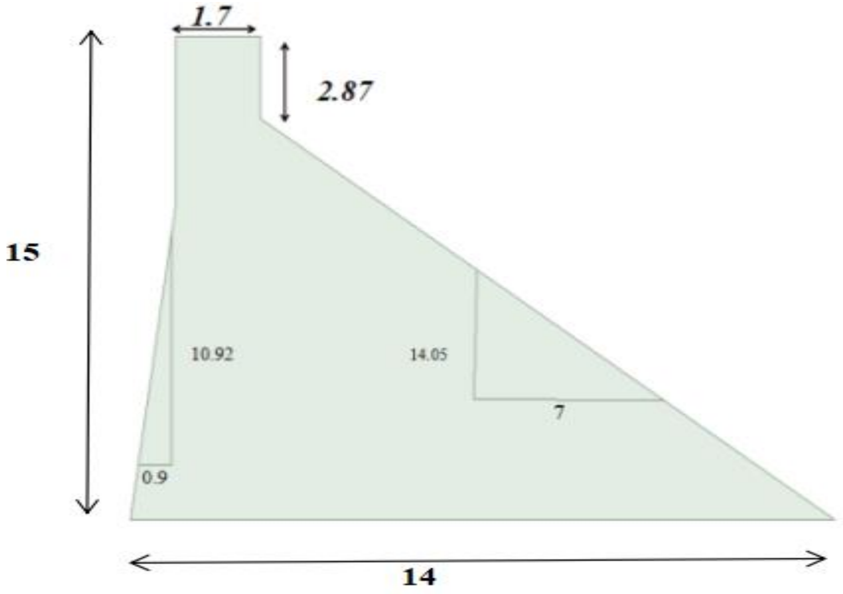

Figure 1. Rawanduz dam cross section

Table 1: Concrete properties [5]

Parameter	Value	Unit
Density	2400	Kg/m^3
Elastic modules	25000	Mpa
Poisson’s ration	0.2	
Compressive strength	25	Mpa
Tensile strength	2.74	Mpa

Table 2: Foundation (lime stone) properties [5]

Parameter	Value	Unit
Poisson’s ration	0.29	-
Internal friction	0.77	-
Cohesion	9	Mpa
Permeability coefficient	1	Cm/sec

3. Methodology of the study

To meet the study objective, the methodology adopted in this study could be divided into two parts; theoretical work, and data analysis. These will be achieved according to the following flow chart:

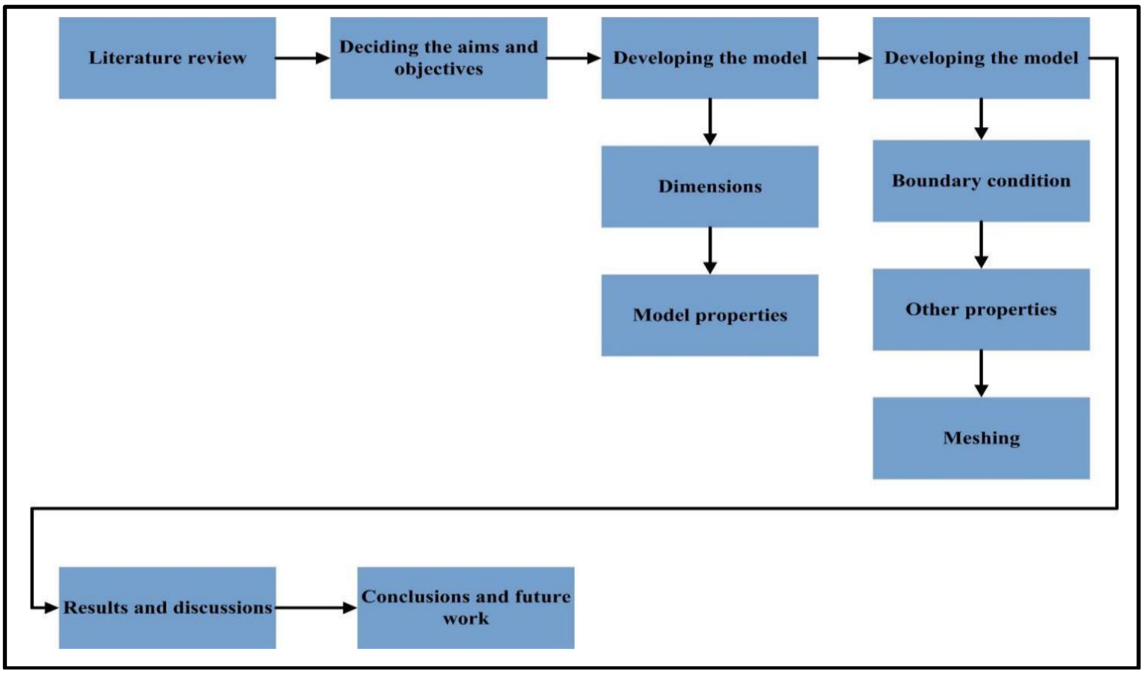

Figure 2. Research methodology scheme

4. Modelling of the problem

4.1 Hydrodynamic pressure modeling

The hydrodynamic pressure has been modeled according to Westergaard's theory [6]. Westergaard's theory assumes that the pressure of the water does not change during an earthquake, as if it was an added mass on the back of a dam. The added mass was expressed as the following:

$$\frac{7}{8} p_w \sqrt{h_w (h_w - y)} \tag{1}$$

where P_w is the density of water ,h_w is the reservoir height, y is the vertical position and $(h_w\text{-}y)$ is the depth of water from the top surface.

4.2 Soil modeling

In order to express the nonlinear behavior of the soil with the structure, the analysis depend on Drucker-Brucker modeling (DP) [7]. However, forms of linear plastic flow potential and (DP) selected to model the soil. The DP nonlinear yield criteria form was:

$$f(\sigma,\sigma_y) = \sigma_e + \alpha\frac{1}{3}\,\mathrm{tr}\,(\sigma) - \sigma_y = 0 \qquad (2)$$

where: σ_y = uniaxial yield stress, α = pressure sensitivity, σ_e = is the equivalent stress and rely depend on C and ϕ for soil. The plastic flow potential form is:

$$Q(\sigma,\sigma_y) = \sigma_e + \bar{\alpha}\frac{1}{3}\,\mathrm{tr}\,(\sigma) - \sigma_y = 0 \qquad (3)$$

where: $\overline{\alpha}$ is the flow potential pressure sensitivity.

4.3 Soil - Structure modeling

The seismic safety assessment of the concrete gravity dam is performed by means of a 2-D Finite Element model utilizing the ANSYS program. The elements that have been considered to discretize the problem are: 1) A four–nodes element of PLANE 42 (structural 2D solids) shown in Figure (3) was used to discretize both dam body and foundation. The foundation and dam elements are in a state of plane–strain. This effect is included only if KEYOPT (3) =2.

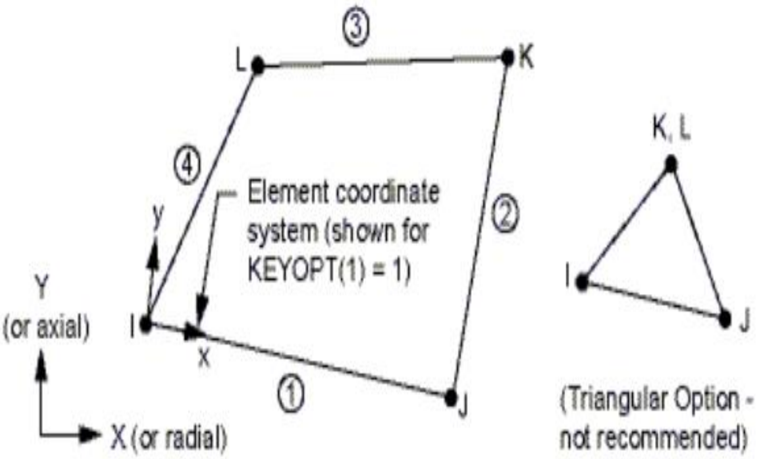

Figure 3. PLANE42 element geometry [8]

2) As well, the interface of soil-structure interaction issue is represented numerically through the linking equation [9]:

$$M\ddot{U} + C\dot{U} + KU = -MI\ddot{u}_g \qquad (4)$$

where $U, \dot{U}, \ddot{U}$: represent the system of relative displacements, velocity, and acceleration vectors with respect to the base, respectively. I: Influence vector, $\ddot{u}_g$ indicates solicitation direction, M, C, K: System mass, damping and stiffness matrix respectively. $\ddot{u}_g$: Horizontal component of ground acceleration.

Also, the interface of the soil–structure interaction problem that is expressed numerically by coupling equation (4) which could be discretized via issuing a NUMMRGE order to all nodes and elements on touch surfaces or by using CONTA172 and TARGE 169 elements with a SURF in between them. CONTA172 represents interaction and sliding between two-dimensional "target" surfaces (TARGE169) and a deformable surface described by this function. This element was distributed at the surface of an element with midsize nodes. Also, the geometric characteristics of this element are similar to the properties of the solid element which it is linked; Figure (4).

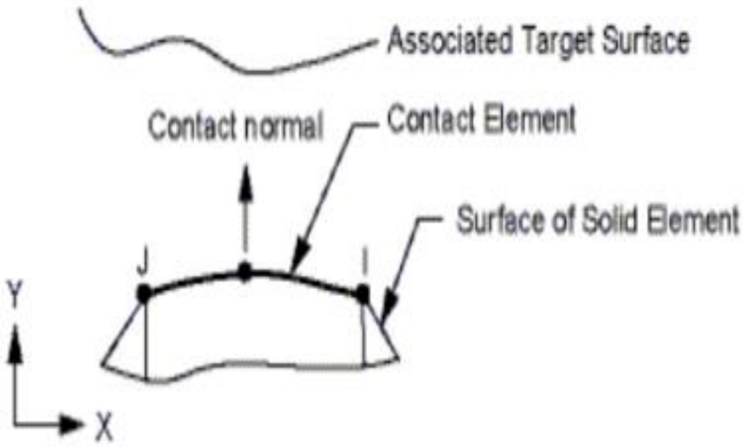

Figure 4. CONTA172 element geometry [8]

Connect happens when the surface of the element enters one of the target segment elements (TARGE169) on a definite target surface. Coulomb and shear stress friction is permitted. TARGE169, Figure (5), represents 2D surfaces that are associated with contact elements. Contact elements themselves, denoted by TARGE169, overlap rigid elements defining border of deformable-body also presumably in contact with the target surface. This touching surface is discretized by a collection of target segment elements (TARGE169) and linked to the associated contact surface by a mutual real constant set.

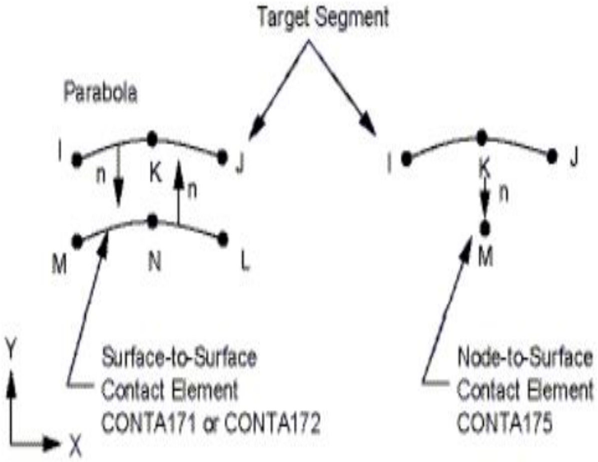

Figure 5. TARGE169 Element Geometry [8]

4.4 Coupled Reservoir-Dam-Foundation system and mesh generation

As mentioned earlier, the water pressure was governed by equation (1), dam and foundation linked by equation (4). The numerical FE model was conducted using an ANSYS with the amount of 8514 elements and 9100 nodes. The foundation region is assumed to be constrained in both directions vertical and horizontal. The side of the water reservoir is restricted by hydrostatic the water pressure. Figure (6) show mesh generation and boundary condition of dam model.

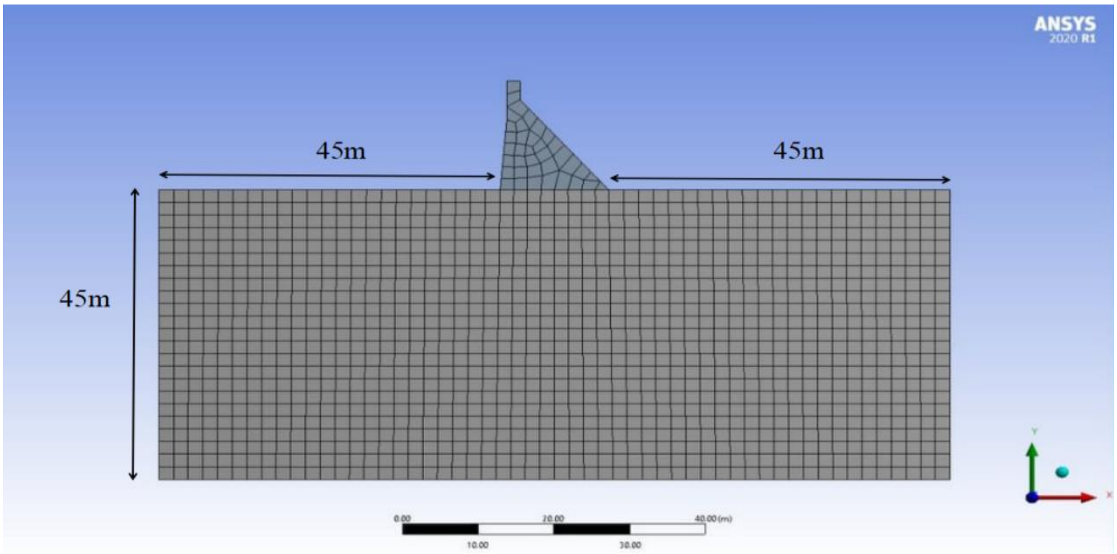

Figure 6. The meshing of the dam model and boundary condition

5. Seismic ground motion

To investigate the seismic response of the Rawanduz dam, the time -history of the EL-Centro earthquake was used in the analysis.EL-Centro earthquake has the highest acceleration equal 0.25g. Figure (7) shows time history of El-centro earthquake [10].

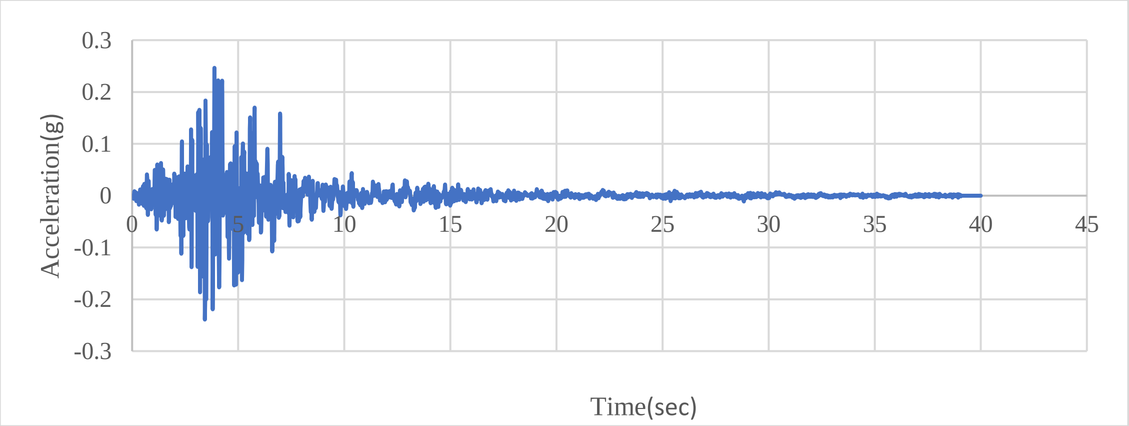

Figure 7. Time history for EL - Centro earthquakes

6. Seepage analysis

The most important phenomenon to consider when constructing and building dams was water seepage under the body of the dam, since concrete dam is greatly influenced by the mechanics of foundation behavior. As a result, it could have a significant impact on dam displacements and stresses. Seepage quantity, uplift strain, and exit gradient are all essential quantities while researching this phenomenon [11]. FLUENT program, which is a part of the ANSYS, contains a broad range of applications and is commonly used by engineers to research and analyze seepage issues in dams. Figures (8) and (9) shows equipotential lines and flow lines respectively.

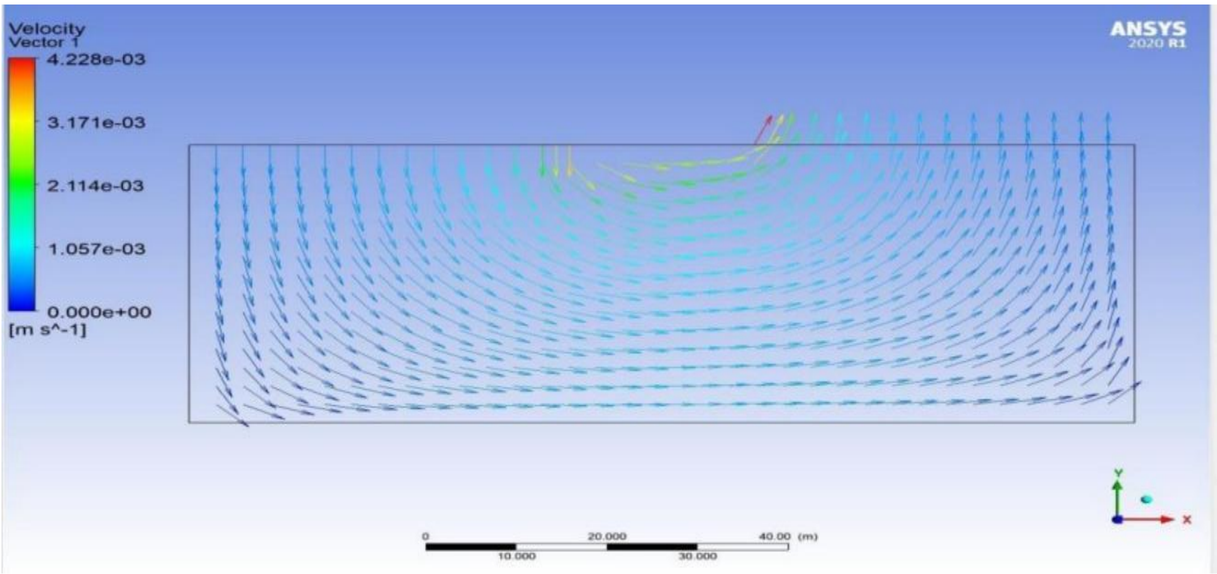

Figure 8. Flow lines

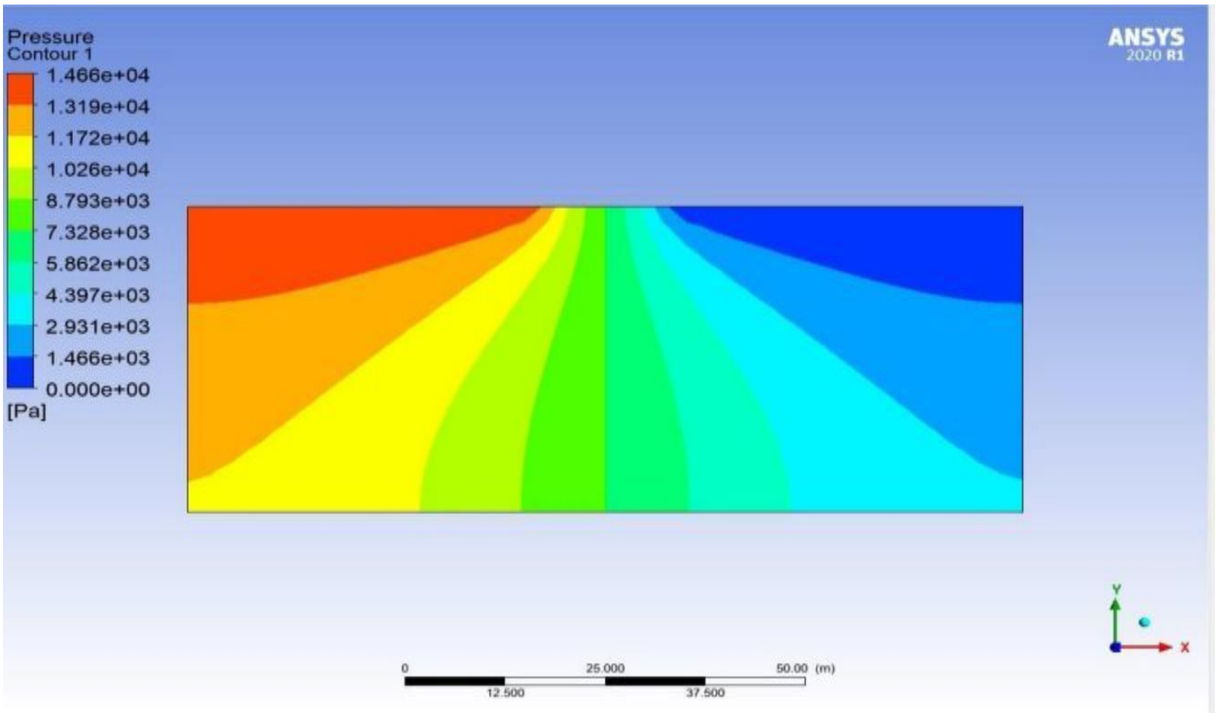

Figure 9. Equipotential lines

The maximum seepage flow was (4.22×10^{-3} m/s) at the exit point downstream of the concrete dam. The maximum water pressure was (1.4 Mpa) at the heel of the dam. The researcher determined the excite gradient and its value was equal to (0.1), which is less than the safe value of the exit gradient, which is equal to (1/6) [12]. Therefore, the structure is safe from the impact of the seepage loads.

7. Verification of the local stability

The principal stresses are of interest when evaluating dam stability. The local stability is guaranteed if the evaluated maximum compressive and tensile stresses do not exceed the corresponding strengths.

Two of the most critical parts of the construction are the heel and the toe of the dam. Therefore, the principal stresses at these areas are important to study [13].

7.1 Static analysis

The static load acting on the dam section are self-weight of the dam, the hydrostatic pressure from reservoir water and seepage loads under the dam.

Based on the static analysis, there are a tensile stress at the heel. These tensile stresses if they exceed the permissible limit, can lead to cracks between the dam and the foundation and thus lead to an overturning of the dam [14].

The maximum compression stress was 0.02 MPa, Figure (10). This value does not surpass the permissible selected concrete compressive strength (25MPa). The maximum tensile stress value (0.05 MPa) was at the dam heel, Figure (11). The positive numbers signify tensile stresses, whereas negative numbers represent compressive stresses.

The static analysis findings indicate that the stress values are very low and satisfy the normal criteria for protection factors relating to the tensile and compressive strength of the concrete content.

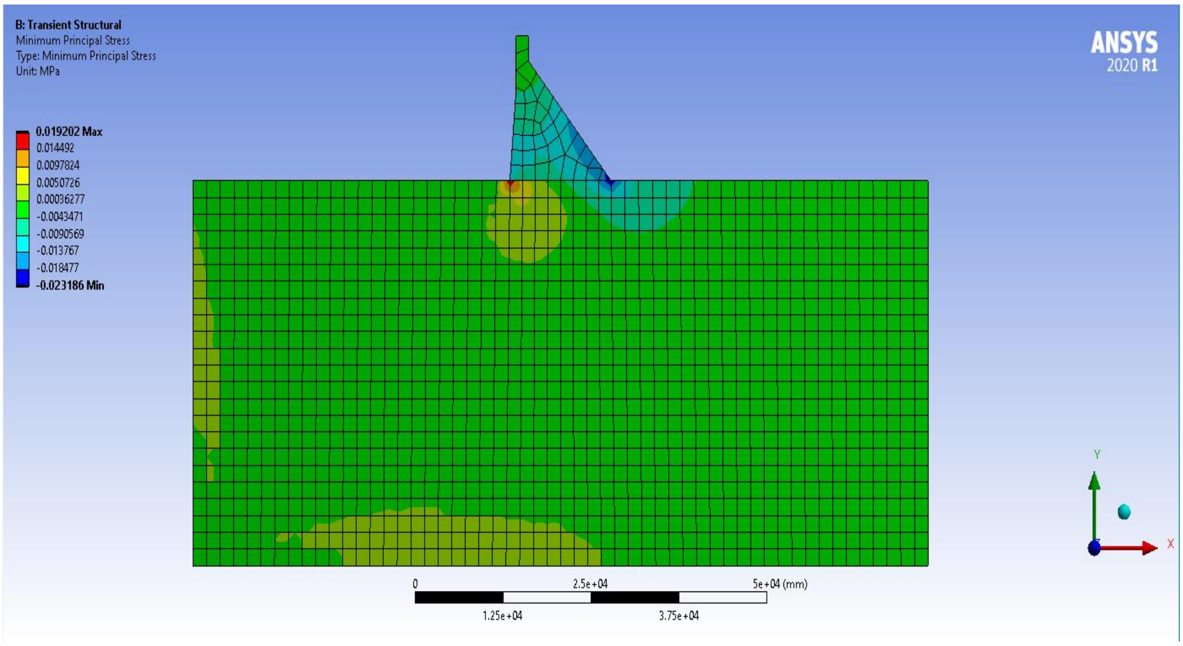

Figure 10. Minimum principal stresses

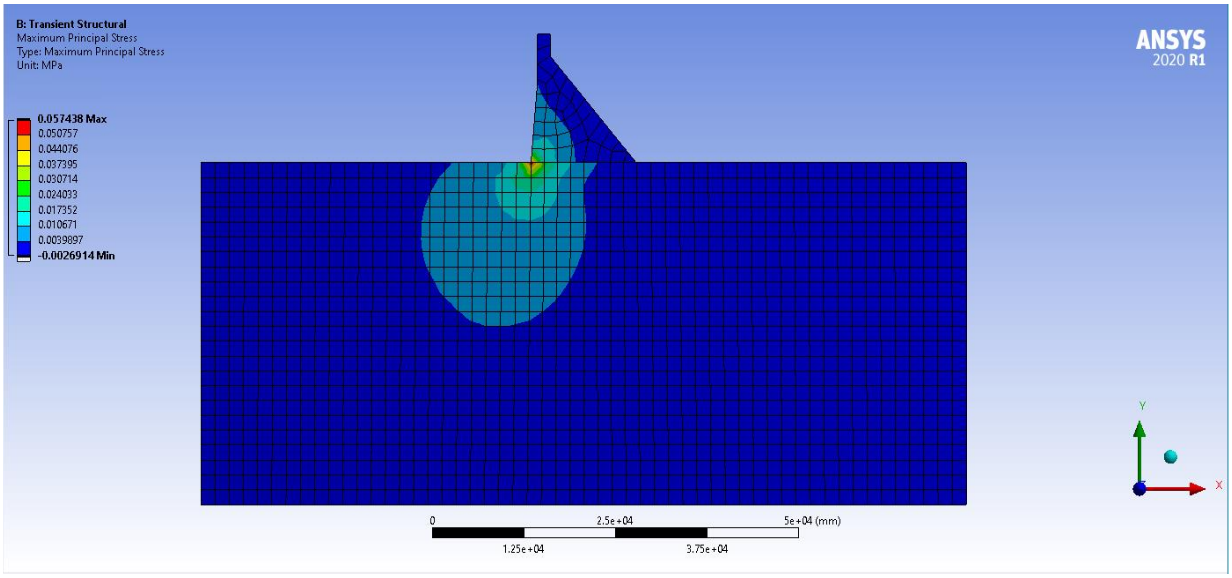

Figure 11. Maximum principal stresses

7.2 Dynamic analysis

We adopted in the stability analysis of Rawanduz dam under the influence of dynamic loads on the time - history of Elcentro earthquake which has the peak acceleration was (0.25 g). 9.8 seconds after the earthquake, when the reservoir was full, the researcher noticed that the highest tensile stress was on upstream side near the hell, while the highest compressive stress was in the direction of the Downstream near the toe, where [15] noted similar founding. Figures (12) and (13) show maximum and minimum principal stress, respectively.

The maximum compression stress (0.24295 Mpa) does not surpass the chosen concrete's permissible compressive strength (25MPa). The maximum tensile stress value (0.40709Mpa) was found at the dam heel; this value is appropriate since it is less than 2.74MPa.

The dynamic analysis findings also indicate that the stress values are very low and satisfy the normal criteria for protection factors relating to the tensile and compressive strength of the concrete content.

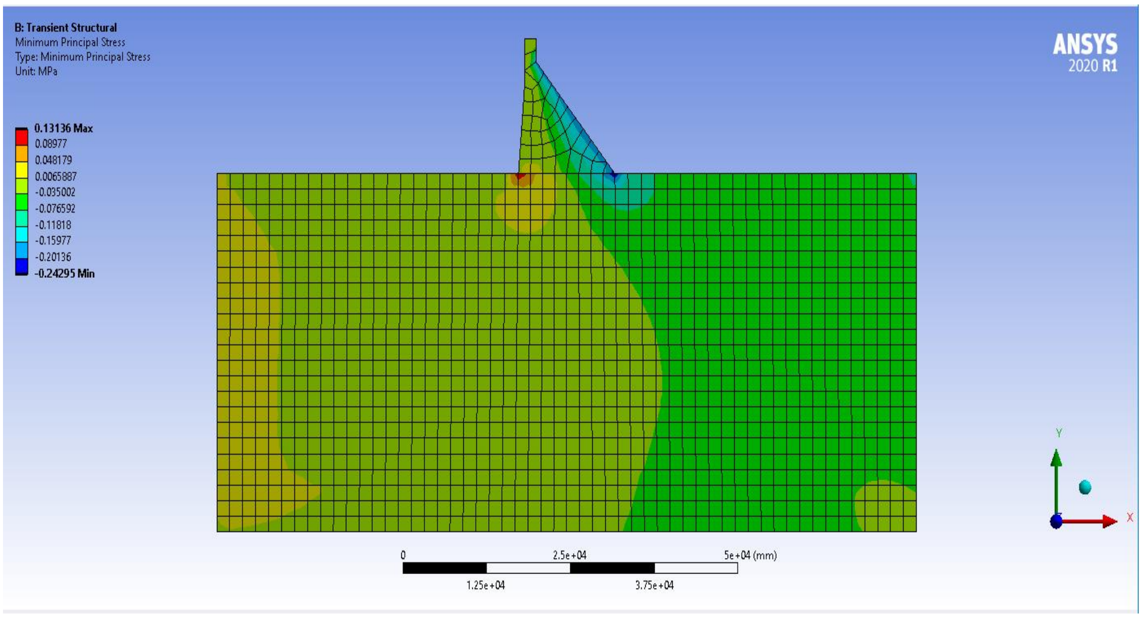

Figure 12. Minimum principal stresses

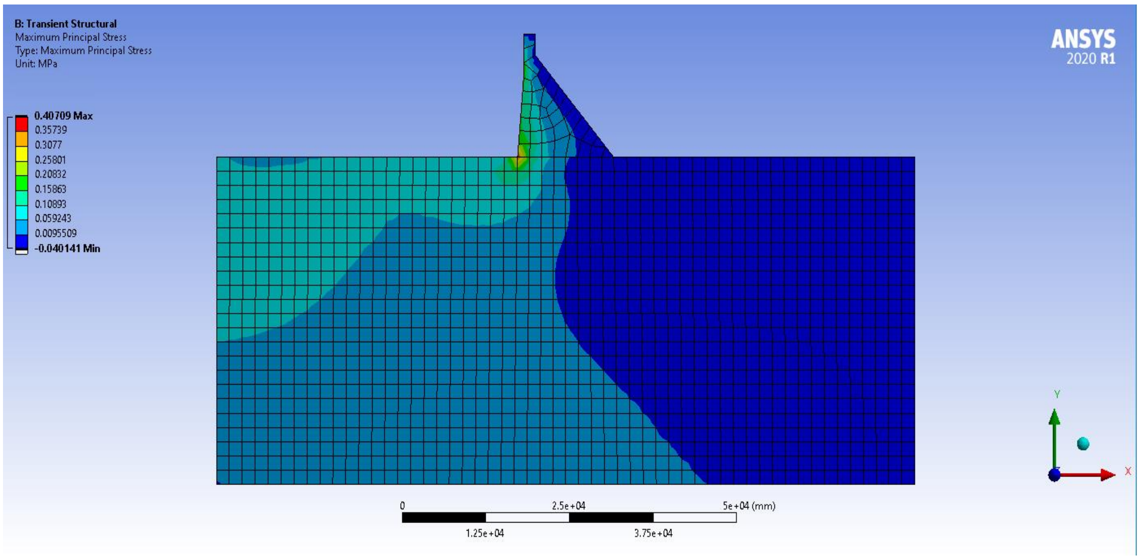

Figure 13. Maximum principal stresses

Figure (14) shows maximum deformation of the dam. The maximum deformation (0.4775mm) observed at the dam crest on upstream edge, where dam was free in this location and become more sensitive.

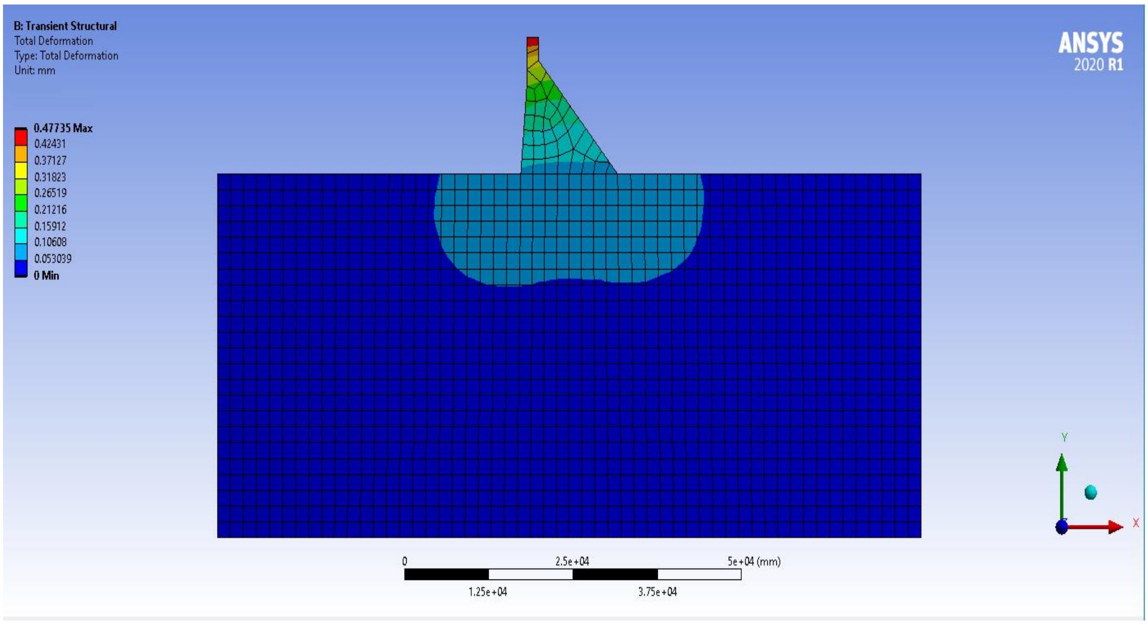

Figure 14. Maximum deformation

Figure (15) shows the Time history for crest horizontal displacement of the dam. When the earthquake struck the dam, the horizontal displacement of dam's crest began to increase until it reached highest value at the second 9.8s and began to fade until the end of the earthquake.

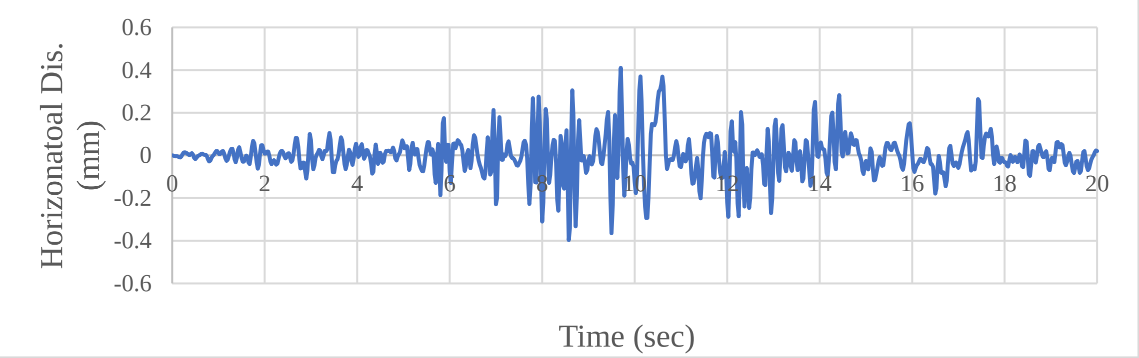

Figure 15. Time history for crest horizontal displacement of Rawanduz dam

5. Conclusion

1. The structure was safe from the impact of the seepage loads because the exit gradient value was equal to (0.25), which was less than the safe value of the exit gradient, which is equal to (1/6).
2. Results show that the principal stresses at the heel and toe of the dam are critical points to study the stability of the concrete dam.
3. The static and dynamic analysis findings indicate that the stress levels were very minimal and satisfy the normal criteria for the protection factors relating to the tensile and compressive strength of concrete content.
4. The maximum deformation (0.4775mm) observed at the dam crest on upstream edge.

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