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# Numerical finite element modeling for earth-dam grouting and curtains wall design by Plaxis software

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**ABSTRACT**

The presented study provide the numerical view and finite element (FEM) based modeling for earth-dam sealing curtains wall in earth-dam by using grout injection procedure. In this regard the plaxis software was used to estimate the variations and provide the simulation which is implemented in geometrical modeling, boundary conditions, assign materials properties, behavioral model, mechanical modeling and seepage analysis. Modeling conduced for two case groups related to before and after curtains wall design. According to the results of seepage analysis, it has been determined that when the sealing curtain is not applied, deformations due to stress, strain and pressure of the perforated water cause changes in the dam area and its expansion in sediments. On the other hand, the expansion of strain in the core range reflects the phenomenon of plastic behavior of the core and downstream, which is the result of in-situ stress and water pore-pressure in it.

## 1. Introduction

The use of injections and curtains wall implementation in earth-dam construction is well known and has a long history (Golze, 1997). Generally the grout injection operation in earth-dams mainly conduced in three stages concluded (Jansen, 2011): (1) In the first phase work is carried out along with exploratory boreholes and core drilling in order to determine the degree of permeability and permeability of the foundation and the sides of the proposed dam site in alluvial fields as well as in rocky soils. Limited amounts of mortar are usually applied in order to obtain basic information about how the soil can be injected. The results of these experiments are used in studies and analyzes related to determining the definitive location of the dam so that it is as low as possible in the designated area of the earth permeability, or it is easier to penetrate it and after filling The lake should sit as small as possible; (2) The second stage of injection is the injection of mortar in order to create a sealing curtain under the sides of the dam. The purpose of doing this is to make the ground impermeable and to strengthen the bearing capacity of the earth is not very desirable. Injection mortar is also selected for the same purpose, which can be defined as cement slurry, possibly coarse as a filter, and a certain percentage of bentonite, which causes the mortar to stagnate from the time it, is made until the mortar sets. Be. This mortar fills the permeable pores and prevents water from passing through. In cases where due to the fineness of the soil while permeability, the injection of mortar is not easily possible with the addition of additives such as sodium silicate or hydrocarbon additives and cement mortar becomes more fluid and permeable. Injection for

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sealing under the dam and its flanks continues between the natural impermeable layers below the dam to the highest water level of the lake until saturation; (3) The third stage of injection in dam construction projects is to fill the gaps of concreted blocks. This is especially important for dams that are built in rock formations. Rock mass injection is often used for dams or tunnels and sometimes mines and other underground structures to reduce or cut off water flow and strengthen formations or both (Ewert and Phillips, 2012).

Geological aspect of dams' site for successful grout injection is necessary, so, the injections procedures must be capable to act in different rock mass and geological environments (Jansen, 2011). In this regards, the grouting can be classified as follow:

*Curtain grouting*: This type of injection is used to seal the joints and cracks of the rock to a certain depth, which reduces the permeability in the rock mass. The purpose of this injection in dam construction operations is to create a relatively impenetrable wall under the core of the dam and in a section of it (Ewert and Phillips, 2012).

*Consoling grouting*: The purpose of reinforcement injection is to improve and uniformize the deformation properties of the rocks that are under the foundation and have been weakened by the explosions that have been done for the purpose of excavation. Reinforcement injection at a depth of 6 m to 9 m above the ground, in three dimensions and usually based on a square pattern that the distance between the boreholes varies from 1 to 5 meters, is done. This injection is usually done before the injection operation to create a sealing curtain; in this way, the rock mass is integrated and its resistance to the injection of the sealing curtain is ensured. This type of injection is performed especially under the core of earth dams in order to create an injection coating layer to prevent the leaching of fine-grained material through the foundation, reduce sub-core leakage and increase the foundation consolidation (Ewert and Phillips, 2012).

*Contact grouting*: Contact injection is the process of filling the gap between the structure and its foundation. The purpose of this type of injection is to remove the distance between the concrete structure and the surrounding stones, so that the two can act as a building unit. In contact injection, only joints are considered that are in the thickness of the stone between 0.5 m to 1 m and are drilled in square meshes with equal distances of 1.5 m to 3 m (Ewert and Phillips, 2012).

The second aspect of grouting is injectability and rock body deformability which is directly affected on the penetration of grout and provide more effective diameters (Fell et al., 2017). As such aspect the grouting can be categorized as:

*Displacement grouting*: This type of injection causes disintegration or deformation of the rock mass or earth material. In this type of injection, the injected material causes the earth materials to move and without penetrating into them, it settles in the place as an independent and separate mass, thus causing the surrounding materials to compact (Ewert and Phillips, 2012).

*Penetration grouting*: This injection does not cause deformation or deformation of the rock or soil mass and only fills the joints, cracks and cavities. This type of injection prevents high pressure. If the ground is the site of saturated injection, the injection material replaces them by expelling water from the empty spaces. Penetration injection may be in both intrusive and exudative modes. In interventional penetration injection, the injection material enters the joint system and fills the gaps and discontinuities of the rock mass without any destructive effect on the rock mass and fills them. Infiltration of seepage is mostly seen in soil and discontinuous materials in which the injection material from the injection site, as a seepage operation, penetrates into the empty spaces of the soil and settles between the solid parts of the soil. The penetration depth of the injected materials and the way of seepage depend on the porosity coefficient, the degree of saturation and the soil permeability coefficient (Ewert and Phillips, 2012).

Finally, the third aspect of successful grouting is related to site condition (known as geomechanical) and operational aspects. In order to perform the injection operation correctly, it is necessary to identify the geology of the site, especially the discontinuities. Studying the characteristics and geological conditions of a region can be effective in identifying and introducing the discontinuity system governing the region. Understanding the system of joints and pores and the physical properties of the rock are the main subject of injection. The most important geological parameters in the injection design are as follows (Ewert and Phillips, 2012):

*Joint spacing*: The distance between the joints can vary from distance to close to each other. In joints with long distances, injection is easier; in contrast, in joints that are close or compressed, problems such as leakage and borehole occur.

*Join opening*: The greater the opening of the joints, the greater the possibility of injection material flowing in them, and therefore the easier the injection operation. The best results are obtained when the joints have an opening of 0.5-6 mm. Joints wider than this range allows the slurry to pass easily, so the movement and penetration of the slurry beyond the required radius must be considered. In this case, the injection should be done in several stages at regular intervals so that the slurry has a chance to harden. In joints with openings less than 0.5 mm, the penetration of the slurry is reduced and therefore the empty spaces in the rock are not filled well. Under these conditions, this penetration restriction can be removed by using chemical compounds.

*Join persistence*: The continuity of the joints affects the penetration radius of the slurry. If the joints lack continuity and extent, it means that more boreholes must be drilled. If the joints are expanded, the grout will cover a sufficient distance.

*Join orientation*: The direction of the joints affects the orientation of the injection boreholes. The slurry will cover a sufficient distance. If the slope of the joints is between 0 and 60 degrees, vertical boreholes get the most intersection with the joints, such conditions are easier to drill and more injection material penetrates into the joints. If the slope of the joints is more than 60 degrees, they need to drill inclined boreholes and as a result, the cost of operation increases.

*Site uniformity*: The uniformity of discontinuity systems means that all boreholes have the same distance and orientation. However, if the site is not uniform and includes dykes and deformations, the distance and direction of the boreholes will vary.

*Rock health*: The act of injecting slurry in rocks that have higher health is more desirable than in the case where the stone has many weaknesses. In rocks that have high health, there is no possibility of falling into the borehole during drilling and no changes occur in the borehole during injection and use of packer and it can be done by ascending or lower-up injection method, which is faster and more cost-effective. It is economical, used. If the stone is in poor health, problems such as drilling and packing will occur during drilling and injection. In such a case, only the injection should be done in stages and in smaller sections and in a descending or up-down manner which slows down injection operations and increases costs.

*Rock strength*: It is easier to inject dense, well-controlled stones than it is to inject weak, broken, and loose stones. Because injection in weak rocks causes the borehole to collapse and the stone blocks to move. In such cases, necessary precautions are needed to prevent the rocks from moving, and it is necessary to inject deeper, which requires drilling deeper boreholes.

*Stress field in rock*: If the rocks in a site have tectonic stresses, or the area is a valley with steep walls, the movement of the block should be considered and controlled during injection. If the rocks that are exposed to the injection are not affected by the stresses in the ground, the injection is followed with greater operational speed. While the rocks of an area react under the influence of the action of different stresses, they become weak and ruptured during the injection operation, the injection operation is slow.

*Piping potential*: In areas where there is a possibility of piping, slurry injection is problematic. This phenomenon is seen in areas where soft materials are present between the joints. They may move due to erosion or dissolution of the material inside or the joint wall. In this case, the injection is done with more intensity to minimize the piping potential of the site.

*Chemical attaches*: The presence of coal or carbonate or other chemicals that can cause severe leakage indicates the importance of large-scale injection. In these cases, two injections should be performed on the accurate and effective injection. In this case, the choice of injection material and its chemical composition should be appropriate to the chemical composition and mineralogy of the host rock.

*Karst and other cavities*: The presence of karst and other cavities such as old mines and canals, etc. cause a large amount of injection material to be wasted into the cavities and cause problems and slowness of injection operations. In such cases, fillers such as sand should be used.

## 2. Grouting and injection operation

Different materials types are used for injection which depends on the purpose of the grouting and the characteristics of the rock or soil being injected. These materials include plastic mortars, cement suspensions or other compounds and additives in water, solutions and chemicals, hot bitumen or bitumen emulsions. The suspension is injected into seamless, fissured rocks and in granular environments with high porosity and large cavities. Mortars made of fine and coarse sand, cement and plasticizers are used to close large cracks and cavities; also, chemical solutions where suspensions cannot penetrate or are used for special purposes such as water control (Fell et al., 2017). The following is the most important group of injection slurries:

*Non-cement grout*: Although cement slurries have been used for a long time, they are not always the best method and are not suitable for all occasions. These non-cement grouts are especially suitable for water control and structural injection. To control water, especially when the movement of water is complex, the required slurry must have the ability to gel quickly and withstand water corrosion. Structural injections also require high strength, which has more properties than non-cement slurries than cement slurries (Ewert and Hungsberg, 2017).

*Slurry solutions*: For chemical injection, various materials are used, including sodium silicate. The choice of injection material depends on the purpose of the injection and the characteristics of the rock or soil being injected. Ideal chemicals for injection grout should have the following conditions (Milanović, 2018):

- Dissolve in powder form in water and form a stable gel,
- If stored in storage, do not lose its properties and sensitivity,
- Non-toxic, corrosive, explosive or dangerous,
- The solution should have a low viscosity and remain stable at normal temperatures,
- The solution and the catalyst and its activating agent should be obtained cheaply,
- Should not be sensitive to groundwater quality and be stable at pH greater than 7.

Chemical slurries have been used with two different effects. The first effect is to cut off the flow of water in the soil, rock or to resist dilution and rapid setting. Another effect is that it is used in large areas to increase resistance. The hardening times of chemical injection solutions can be in the range of instantaneous to several hours, which is much shorter than cement slurries. The properties of this type of slurry vary greatly according to the percentage of contents and their type. Since there are no solid particles with these slurries, the width and width of the joints do not have much effect on their penetration strength and can penetrate inside very narrow cracks of 0.2-0.1 mm (Ewert and Hungsberg, 2017).

*Cement suspensions*: Cement suspensions are used in conventional injections, especially for stone injection. Materials required for suspension include cement, bentonite, clay, sand and filler, sodium silicate, additives for stability and water. Cement suspensions are the best choice for stone injection due to their availability, cheapness and sufficient resistance to water pressure after setting. Sometimes instead of using different types of cement, pozzolans and volcanic ash are used. The suspension mass, which is injected under pressure, flows like a viscous liquid in the cavities and fissures until the larger elements of this mass are blocked in the fissures. The velocity of the suspension flow in cavities and cracks under injection pressure varies from point to point and depends on the pressure gradient, the ratio of water in the suspension, its viscosity, the dimensions, the roughness and the degree of roughness of the cracks and cavities (Ewert and Hungsberg, 2017).

*Cement slurries*: The concentration of the initial slurry is selected according to the engineering characteristics of the joints and openings, the results of permeability tests (Logan), experimental injection and past experiences. Weaver (1991) believes that the thickest slurry that can penetrate into the joints should always be used. However, proponents of the use of dilute slurry believe that its flow causes it to enter narrow joints. Lombardi (1996) believes that the ability of the slurry to penetrate into the joints depends on the size of the cement grains and has nothing to do with the amount of water. In the United States, primary injection mortars with a volume ratio of cement and water of 10.1 have been used in the past to inject stone foundations of dams (Weaver, 1991). The superiority of using concentrated slurries is recommended for the following reasons (Ewert and Phillips, 2012):

- More stability and reduction of slurry irrigation,
- Reduction of slurry shrinkage during setting in the joint and as a result, reduction of empty space and more connection with the stone,
- Reducing the separation of water from the slurry in narrow joints that cause the slurry to stop,
- Increase slurry density and thus increase durability and resistance to water erosion,
- Increases the durability of the grout and reduces the permeability and porosity,
- Limiting the movement distance of the slurry,
- Predictability of injection operations,
- Reducing the risk of injecting stones.

## 3. Stability of cement slurries

The stability of the injection slurry is one of the important factors in injection operations. Slurries that do not have the necessary stability are flooded during flow in the joints, which causes the joint to be blocked and reduces the penetration radius of the slurry, which results in incomplete filling of the joints. Lombardi (1996) compared concentrated and dilute slurries and as a result considered concentrated slurries more stable. Cement to water (C/W) percentage greater than 2 is not sufficiently stable unless 4% bentonite is added.

*Slope effect radius*: In the injection operation, it is necessary to determine the penetration radius of the slurry at the desired location. Increasing the impact radius of the slurry increases the distance between the boreholes, reduces the drilling area and thus reduces the cost, but it should be borne in mind that a large impact radius does not waste the slurry. The radius of action of the slurry depends on factors such as injection pressure, slurry pumping speed, setting time, viscosity, adhesion and joint opening. One of the most important factors in increasing the radius of effect of the slurry is to increase the pressure, but its preconditions are that the pressure prevails over the flow limit and the pores of the joints are open for the entry of solid particles in the slurry. Slurries made of high Blaine cement have high viscosity and viscosity and therefore their range of motion and radius of impact are reduced, so lubricant should be added to them (Ewert and Hungsberg, 2017).

*Slurry resistance*: The strength of the injected grout can be increased due to the hydrochemical reaction due to the setting of the cement as well as due to the water coming out of the grout and creating adhesion resistance. In areas where reduced deformability of the injection site is desired, high-strength mixtures are required. In such cases, the injection slurry must have a high modulus of deformability, which is synonymous with high strength. Slurry resistance should be determined in the laboratory and on samples prepared for 7, 28, 56, 90 days. The strength of the slurry tested depends on the composition of the slurry, the diameter of the sample and the intensity of the applied pressure. Slurry strength in stone depends on the composition of the slurry, time, amount of cement and the width of the cracks (Milanović, 2018).

*Permissible temperatures in the slurry*: The chemical reactions of cement setting are affected by temperature. High temperatures accelerate the setting, but low temperatures can slow or even stop the reactions. The optimum high temperature of the slurry is about 80 $^{o}$F/27 $^{o}$C and the lower limit is 40 $^{o}$F /5 $^{o}$C (Milanović, 2018).

*Cement slurry injection operation*: The joint stones of a dam site are usually injected with grout that is in areas with a permeability of more than one log (Milanović, 2018). Injection slurries in jointed stones must meet the following conditions (Ewert and Phillips, 2012):

- The components of the slurry are small enough to penetrate into the small joints,
- The injection material in the cracks should have sufficient resistance so that it does not erode due to hydrostatic pressure and does not leave the environment,

- The injected mass should reduce the permeability sufficiently.

When the inlet flow rate to the borehole is low, the mixing ratio of the injection slurry should be kept constant until the saturation stage. When the inlet flow to the borehole is high, and the so-called borehole is not pressurized, the slurry concentration should increase. In the first 15 minutes of injection, control of slurry uptake determines the concentration for subsequent injection slurries. The gradual reduction and the amount of borehole slurry in 15 consecutive minutes can indicate that the injection process is correct. If this corrosion remains constant, we should use thicker slurries. If the borehole corrosion increases suddenly, it could be due to its leakage to the ground or fracture, in which case we must increase the concentration and decrease the pressure to prevent leakage (Fell et al., 2017).

## 4. Material and Methods

The grouting is the one of the most important stage in curtains wall design in earth dams or embankments which is required to appropriate understanding about the geological condition, rock mass geo-mechanical characteristics, discontinuity network and grout properties (Jansen, 2011). When a dam sealing curtain is designed or implemented, recursive analysis is used to evaluate its performance in terms of changes in the geotechnical environment that affect the geomechanical and geological properties of the dam site and bed (Fell et al., 2017). The purpose of applying this approach is to provide a logical answer to what is the performance of the dam and the sealing curtain after the dewatering operation and during the conditions of the steady flow of the dam. For this purpose, static (or dynamic) analysis methods are generally used. In geotechnical engineering, the approaches proposed for recursive evaluation are generally considered to be effective for long-term states and structural analyzes which because it determines the changes of the dam in relation to long-term conditions and after dewatering (Brinkgreve et al., 2011). As some deformations (due to in situ stress field) are within the dam, they change with the implementation of the sealing curtain and take on a new nature. Such behavior refers to the plastic strain of the environment, which is caused by the water factor, which appears as surface flow (water behind the dam) and water pore-pressure. By performing recursive analysis, it is possible to estimate the stress-strain conditions, which are aimed at knowing the behavior of the dam in different construction and operation conditions, and to analyze the amount of deformations before and after the formation of the sealing curtain in the dam. Also, by using these results, the performance of the sealing curtain (injection grout) can be examined (Ewert and Hungsberg, 2017).

One of the most widely used approaches today used by geological and geotechnical engineers to evaluate sealing curtains is the use of numerical methods and computer simulations. In this study, these approaches are considered for behavioral analysis of the barrier (Zhang et al., 2020). In this regard, the following objectives are considered for seepage analysis (Ewert and Phillips, 2012):

- Evaluation of total and partial deformations before and after the implementation of the sealing curtain,
- Changes of in-situ stress and strain field and stress-strain relationship for the dam area in the critical section of the dam before and after the construction of the sealing curtain,
- Changes in porous water pressure at the moment of dewatering and long-term analysis of the dam to assess the seepage status,
- Calculation of hydraulic gradients in the dam core and flow focal points,
- Changes in the hydraulic head and water flow under and the dam core before and after the construction of the sealing curtain.

In the other hand, investigation of the success in grouting operation is evaluate with different procedures like analytical/experimental methods, numerical modeling and ground instrumentations (Brinkgreve et al., 2011) which is widely used by various researchers. The presented study used the numerical procedure for investigate the grouting success in curtains wall design in earth dam as well as other approaches.

Numerical approaches include various methods such as finite element method (FEM), discrete element method (DEM), boundary element method (BEM), etc. Among these, the FEM has a good efficiency in soil and alluvium studies due to its algorithmic assumptions that are used for analysis in continuous environments. Considering the soils behavior as elastic-linear plastics and the validity of the Mohr-Coulomb failure criterion, the mechanical behavior of soils against the applied forces and local stresses at different sites can be determined by numerical methods such as FEM analyzed (Brinkgreve et al., 2011).

Plaxis software is two-dimensional analysis software has been introduced and developed to analyze stability, deformation, subsidence, compaction, consolidation and leakage under static and dynamic conditions in the field of geotechnics. This capability makes this FEM software easy to use in the analysis of various environments where the deformation effects of that environment are considered. In finite element numerical analysis, the analysis is based on the implementation of networking called nodes, where spatial displacement, stress concentration on these nodes and networks are continuously evaluated. The expression of theoretical foundations based on the FEM method and Plaxis software is out of the question; but the main advantages of this software, including its high capability in numerical analysis and providing graphical and accurate answers, is one of the most important approaches in its use (Brinkgreve et al., 2011).

In this study, Plaxis software has been used to evaluate the design characteristics of the dam and perform back analysis to investigate the amount of permeability and deformations due to the stress-strain field distribution in the dam bed at its critical point. For this purpose, two simulation groups have been used to identify the geotechnical conditions created in the dam area due to the implementation of the sealing curtain and the functional success rate of the sealing curtain implemented in the dam. Each of the simulation groups has been considered for seepage analysis mentioned in the previous section. The results of the deformations that occurred before and after the implementation of the sealing curtain have been evaluated in interpreting the results of seepage changes and evaluating the pore water pressure conditions created in the area of the dam axis, core and body. Each group of simulations can be divided into three stages of modeling as follows:

- Geometrical modeling and presentation of model boundary conditions,
- Assign properties and provide model behavioral model,
- Mechanical modeling and seepage analysis.

In the geometric modeling, using the design data for the critical section of the dam (main profile), the geometric properties of the dam and the alluvial bed, which have been estimated by conducting engineering geological experiments and surveys, are entered into the model by observing the scale. For this purpose, by determining the appropriate scale in the evaluations, the amount of analysis nodes is determined. Then, considering the boundary conditions, these properties are defined to the model. After constructing the geometric model in the first stage, using the results of laboratory and in-situ geotechnical tests are assigned to the model and the Mohr-Coulomb failure criterion behavioral model. At this stage, the model is ready to perform the analysis operation and as the analysis type (long-term), the water pore-pressure in the initial and final level are entered in each simulations' group. In the final stage, the model under deformation cycles (300 cycles) is solved by considering the intermediate changes in the first stage and eliminating the intermediate changes in the other stage. The simulation results are evaluated for the analysis of the performance of the sealing curtain and the results are interpreted.

In the geometrical modeling stage, after implementing the dam geometry and the main bedding status, Boundary conditions occur in the form of closing infinite boundaries in order not to prevent the reflection or refraction of the deformation and the stress field in the environment. Figs. 1 and 2 shows the geometric models prepared for both simulation groups with defined boundary conditions for these groups. As can be seen, the boundaries of the model are closed in one or both directions depending on the position.

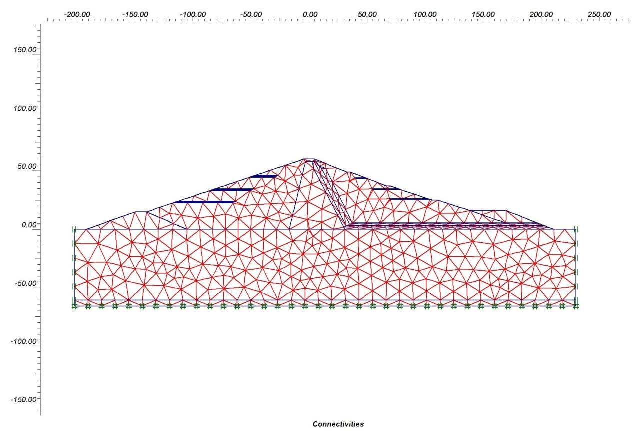


**Figure 1.** Geometrical model for earth-dam before conducting sealing curtains

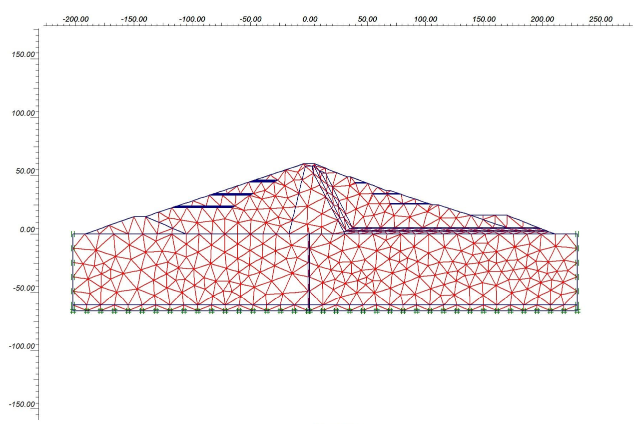


**Figure 2.** Geometrical model for earth-dam after conducting sealing curtains

After the step, the geotechnical properties of the materials have been estimated from laboratory and field test; the model is assigned to geo-materials. Table 1 is presents the input parameters of Plaxis software for assigning mass properties. As can be seen in this table, the main mass characteristics are adopted by elasto-plastic behavioral model. Elasto-plastic behavioral model are the most important behavioral models in soil and rock environment that are accepted by worldwide. This table should be defined individually for each of the materials in the geometric model. The behavioral model used in this study is the Mohr-Coulomb criterion. This behavioral model based on failure envelope under normal and shear stresses in the form of plane and space (Brinkgreve et al., 2011). Figs. 3 and 4 are presented the materials and behavioral properties implementations. After defining the materials properties and behavioral models for dam, the model is prepared to evaluation under the in-situ stress field and water conditions. As further stated, according to the seepage analysis performed, the water situation for a stable and long-term state in the dam is presented.

**Table 1.** Input data for modeling in Plaxis

| # | Unit | Sediment | body | Core | filter | drain | Seal |
|---|---|---|---|---|---|---|---|
| $\gamma_{unsat}$ | $kN/m^2$ | 20.4 | 20.4 | 20.6 | 20.0 | 20.0 | 23.0 |
| $\gamma_{sat}$ | $kN/m^2$ | 21.0 | 21.0 | 21.0 | 20.7 | 20.7 | 23.7 |
| $E_{ref}$ | $kN/m^3$ | 23000 | 18500 | 18500 | 30000 | 30000 | 35226 |
| $\upsilon$ | - | 0.3 | 0.3 | 0.3 | 0.25 | 0.25 | 0.35 |
| $C_{ref}$ | $kN/m^3$ | 25 | 27 | 27 | 0.01 | 0.01 | 13 |
| $\phi$ | degree | 28 | 22 | 30 | 38 | 38 | 30 |
| $\psi$ | degree | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| k | m/dey | 8.64 | $8.6\times10^{-5}$ | $8.6\times10^{-5}$ | 8.64 | 8.64 | $8.6\times10^{-4}$ |

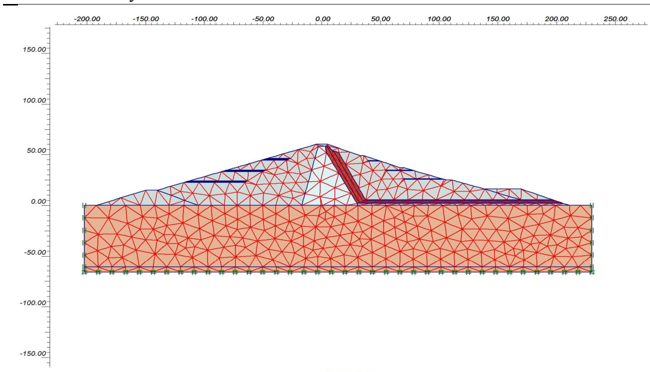


**Figure 3.** Materials and behavioral properties implementations for earth-dam before conducting sealing curtains

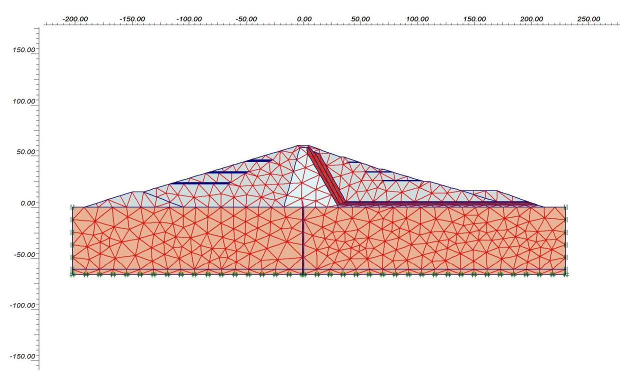


**Figure 4.** Materials and behavioral properties implementations for earth-dam after conducting sealing curtains

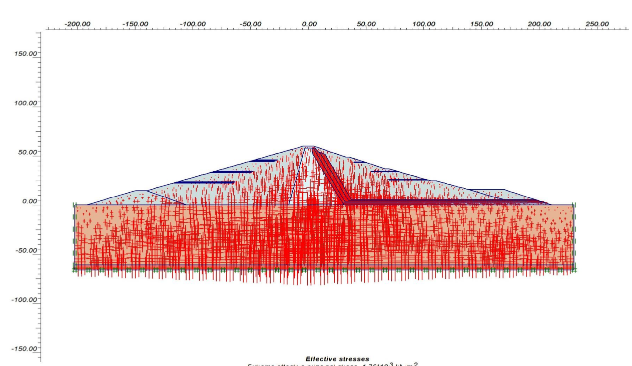


**Figure 5.** In-situ stress condition for earth-dam before conducting sealing curtains

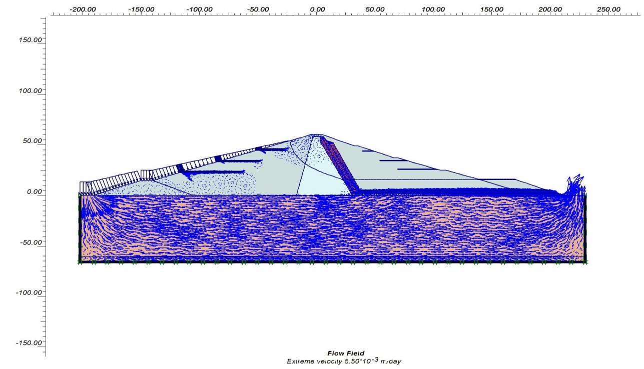


**Figure 6.** Pore-pressure condition for earth-dam before conducting sealing curtains

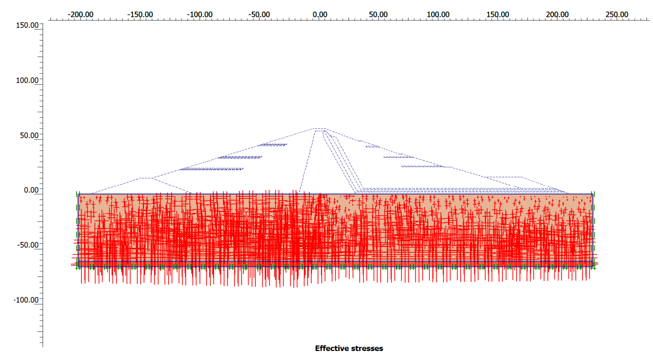


**Figure 7.** In-situ stress condition for earth-dam after conducting sealing curtains

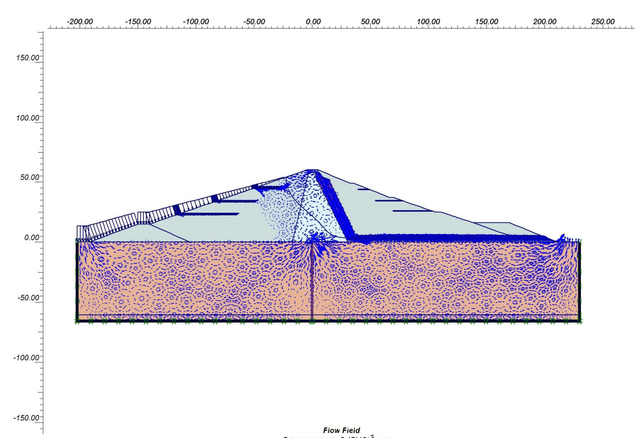


**Figure 8.** Pore-pressure condition for earth-dam after conducting sealing curtains

Therefore, the in-situ stress field characteristics must be defined statically and the water pore-pressure in a stable state. Figs. 5 to 8 provide elements of in-situ stress and stable flow in the dam for initial conditions. As can be seen, the changes of stress and water pressure elements according to the laws of stress in the soil have been done in a deep distribution, which indicates the accurate and appropriate implementation of the model along with environmental conditions and Hoek's law.

## 5. Results and Discussions

For assessment of modeling success in sealing curtain design, the mechanical model was calculated after the geometrical and geo-materials implementations. After that the model runs for both before and after status of conducting sealing curtain in earth-dam. The following results obtained from these stages named mechanical modeling.

### 5.1. Mechanical model for before the implementation of the sealing curtain

In the mechanical modeling stage, the model is finalized and ready for analysis. For this purpose, the model is solved (calculated) under specific plastic behavior during specific cycles and the output of the analysis is examined and interpreted. In mechanical modeling, the deformations created in the dam and the environment from the initial conditions to the conditions after the dam is dewatered and the construction of the sealing curtain are calculated and the amount of changes and displacements in the analysis nodes is estimated. . This information is used to evaluate the seepage from the dam body and bed during the stages before and after the construction of the sealing curtain and during the dam dewatering (long-term analysis). Figs. 9 to 13 present the results of solving the mechanical model for simulation before the implementation of the sealing curtain.

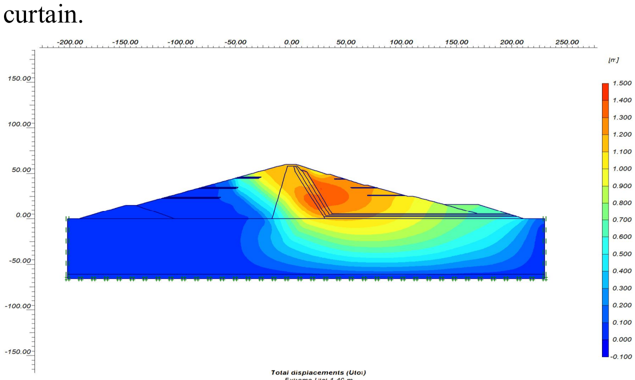


**Figure 9.** Total displacement estimated for earth-dam before conducting sealing curtains

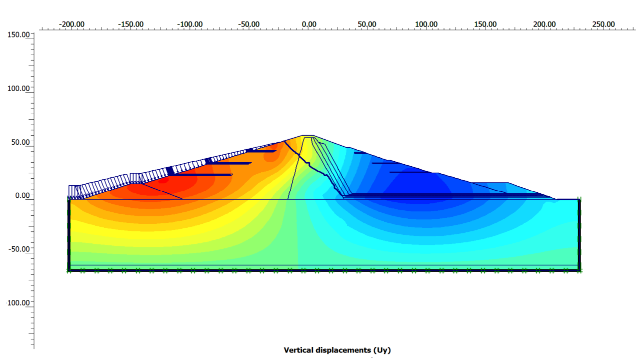


**Figure 10.** Vertical up-lift estimated for earth-dam before conducting sealing curtains

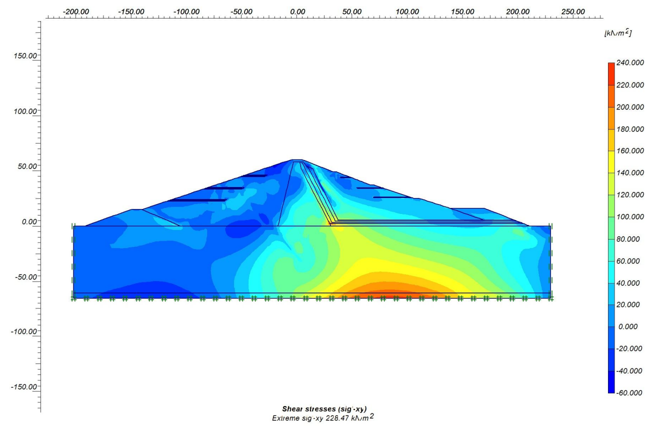


**Figure 11.** Mean shear stress estimated for earth-dam before conducting sealing curtains

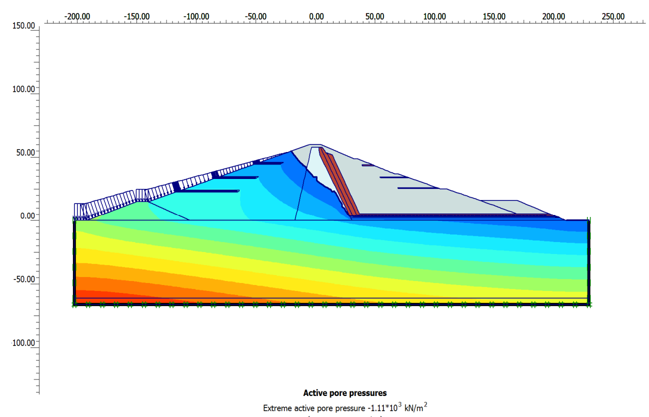


**Figure 12.** Active pore-pressure estimated for earth-dam before conducting sealing curtains

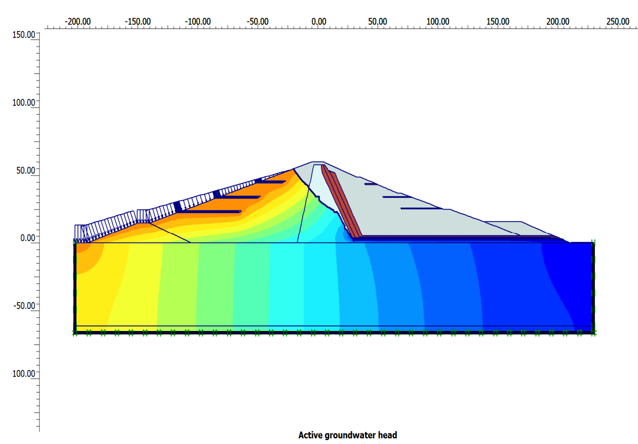


**Figure 13.** Active groundwater head estimated for earth-dam before conducting sealing curtains

### 5.2. Mechanical model for after the implementation of the sealing curtain

This step is the same as the step before applying the sealing curtain. But the main difference in this part is the implementation of the sealing curtain. The presence of sealing curtain causes a decrease in pore water pressure and flow in sediments and its transfer to the dam areas, especially the dam core, which can be traced in the results presented during field operations and instrumentation and designed by geotechnical engineers. The core of the dam is considered. In such circumstances, it is very important to evaluate the seepage in the body and bed of the dam and especially its core. Deformations due to dam dewatering operations (long-term analysis) will cause further expansion of plastic areas and concentration of stress in the dam body. Figs. 14 to 18 present the results of solving the mechanical model for simulation after the implementation of the sealing curtain.

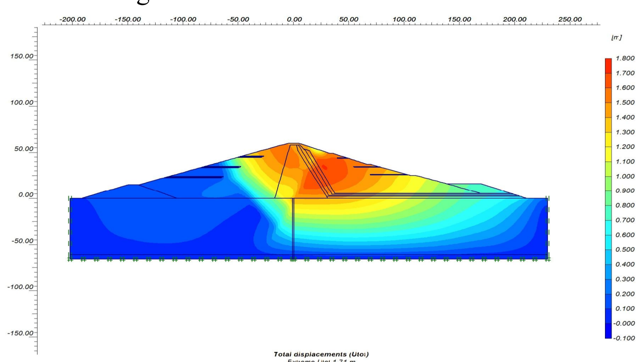


**Figure 14.** Total displacement estimated for earth-dam after conducting sealing curtains

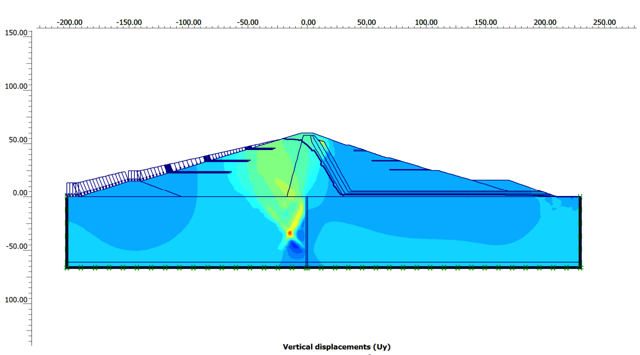


**Figure 15.** Vertical up-lift estimated for earth-dam after conducting sealing curtains

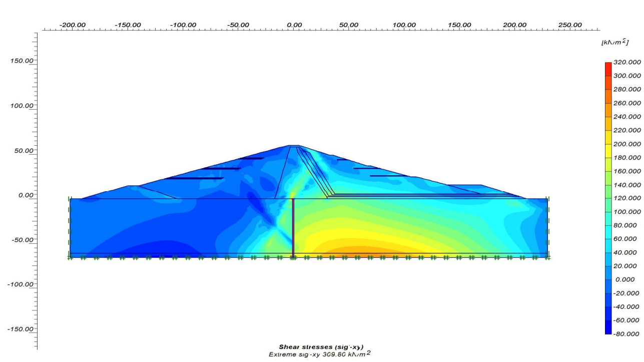


**Figure 16.** Mean shear stress estimated for earth-dam after conducting sealing curtains

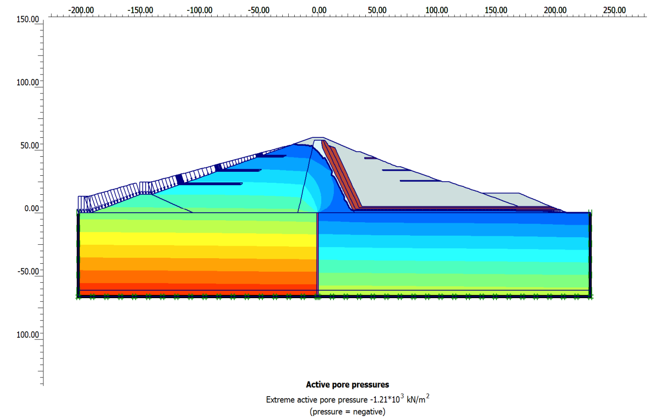


**Figure 17.** Active pore-pressure estimated for earth-dam after conducting sealing curtains

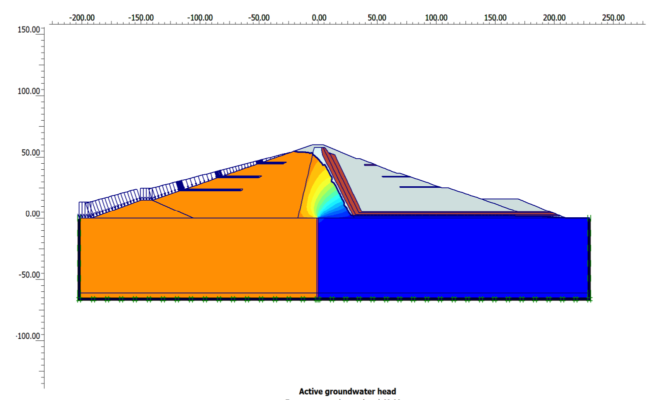


**Figure 18.** Active groundwater head estimated for earth-dam after conducting sealing curtains

In seepage analysis in the dam site, it is necessary to present the flow status in the dam area and the distribution of both potential and flow lines. As is well known, flow lines and potential are perpendicular to each other. Estimating the condition of potential lines in the dam body when the sealing curtain is applied can be very effective in estimating the location of flow lines. This issue also has an effect on estimating the flow status in the body and bed of the dam. Fig. 19 shows the condition of the estimated potential lines for the final area of the dam after the construction of the sealing curtain, and Fig. 20 shows the distribution and movement (flow) status in the dam site. As can be seen in these figures, the presence of a sealing curtain causes the parallel potential lines to act parallel to the sealing curtain and direct the flow to the dam core and downstream of the dam. This issue is also observable in field conditions and is considered in dam stability designs. It also focuses on the current flow in the dam core and downstream of the fuselage. This issue also justifies the position of the potential lines and the performance of the flow lines in the modeling and shows the efficiency of the analysis. If we rearrange the results of this flow distribution situation in the dam body with the shear stress state (which are directly related to each other), the final in situ stress distribution state after changing the flow state in the dam site. As shown in these figures, the process of sealing the curtain has caused the shear stress in situ in the bed area to be reduced and its main focus is upstream and the core of the dam. Also, the effect of outflow from downstream has caused overpressure of pore water in the downstream part of the dam and this in turn has increased the shear stress in this area. The change of flow in the area of the sealing curtain has caused a decrease in shear stress to be observed and estimated in the upstream part of the dam and the reservoir section of the sealing curtain. This also emphasizes the proper functioning of the sealing curtain. On the other hand, the upstream flow in the dam area causes expansion in the soil and requires proper consolidation operations in the dam bed or improvement in the area of the galleries that can significantly reduce this water pressure in the side and foundation of the earth-dam.

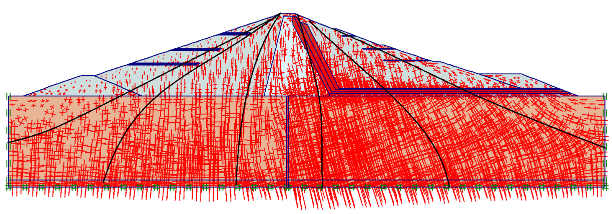

**Figure 19.** The potential lines status in earth-dam after conducting sealing curtains

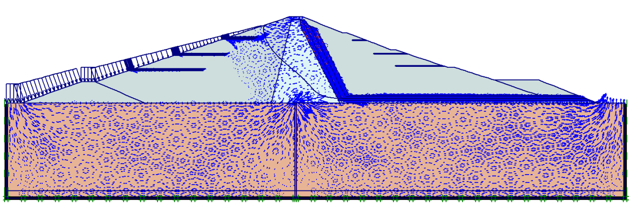

**Figure 20.** The flow status in earth-dam after conducting sealing curtains

## 6. Conclusion

Considering the results of performing FEM numerical analyzes by Plaxis software, the following can be mentioned:

- Modeling shows that the vertical stresses and the main stresses have decreased to the maximum in the area of the core and shell connection and have obvious changes.
- Paying attention to the width of the foundation as well as the proximity of the properties of the materials to each other, the use of homogeneous earth dam has shown good performance, which has increased the strains in the dam body by implementing a sealing curtain.
- In general, the results confirm the appropriate behavior of the dam structure against different loading conditions, displacement, stresses, and water pore-pressures are acceptable, and seepage analysis performed by Plaxis software indicates a continuous flow continuity and distribution of flow lines and potentials rationally.
- Effective stress analysis has shown that the process of bottom-up sealing curtain implementation in the design of the dam has been successfully implemented and its performance has been confirmed by reducing the deep stress and directing the flow to the dam area. This indicates a decrease in sediment permeability by the sealing membrane.
- According to the results of seepage analysis, it has been determined that when the sealing curtain is not applied, deformations due to stress, strain and pressure of the perforated water cause changes in the dam area and its expansion in sediments. On the other hand, the expansion of strain in the core range reflects the phenomenon of plastic behavior of the core and downstream, which is the result of in-situ stress and water pore-pressure in it.
- The presence of the sealing curtain has caused the lines of parallel potential and the flow of current perpendicular to the sealing curtain to act and direct the current to the core of the dam. It also focuses on the current flow in the dam core and downstream of the fuselage. This issue also justifies the placement of potential lines in modeling and shows the efficiency of analysis.

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