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Numerical Modelling of a Diaphragm wall Process in Karolinka Dam

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Abstract

This study focuses on the possibility of numerical modelling of the most important sealing technology, diaphragm walls as the most major popular reliable option when it comes to engineering construction rehabilitation. It is included how to carry out, interaction with adjacent soil, safety factor evaluation associated with the state of the dam body and foundation; before, during, and after reconstruction, changing of pore water pressure with the time, settlement of dam, cement shrinkage, and sensitivity analysis. This modelling was conducted with the finite element method based on software Plaxis 3D. Diaphragm wall has been used in Karolinka dam for reducing seepage through its body. The results are concluded that the highest value of the displacement during the reconstruction process is the horizontal displacement due to water load and pore water pressure variations with the time. Safety factor is highly influenced by the variation of water level in the reservoir, elasticity modulus, and cohesion of the soils.

Keywords: Karolinka dam; Diaphragm wall; Finite Element Method; Displacement analysis; Safety factor; Sensitivity analysis.

Abbreviations3D: Three Dimensional; FEM: Finite Element Method; MC: Mohr-Coulomb; WL: Water level; AES: Average Element Size; OAT: One-At-A-Time Method; FCFD: Fully coupled flow-deformation calculation type in Plaxis; SF: Safety Factor; TBD: Czech Consulting Company for Dam Safety.

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1. Introduction

The diaphragm wall technology has been used as one of the most important technologies for permeability reduction, filling and strengthening–stabilizing purpose of the soil and rock. It is the most popular, economic, quick and efficient method of ground improvement over the world. The diaphragm wall has been developed in the concept of design, equipment and material to be very suitable solution for many of the engineering problems. Diaphragm walls are often the best choice when the dam suffers big damage. According to [1], It is used in the earthen dam over the last 40 years, and suited for clay-rich environments. Much research has been carried out on the behaviour of diaphragm wall induced in soil. Reference [2] presented 3D numerical model of mechanical response of ground, horizontal normal stress, shear stress, and ground displacement during construction of diaphragm wall. Reference [3] studied the effect of the weight of the machine on Karolinka dam displacement during construction diaphragm wall in its core. Reference [4] studied the effect of soil parameters, wall diaphragm parameters and its depth on the maximum wall deflection by using FEM. In my research, I modelled the processes of diaphragm wall construction in the core of Karolinka dam, in addition to studying cement shrinkage, and the effects of this technology on the dam displacement by Plaxis 3D.

2. Case study

Karolinka earth-fill dam is located in Vsetín district on the northern slopes of the Javorník Mountains. The construction of Karolinka dam was completed in 1984 with the objective of Stanovnice flood control, generate hydroelectric power and services water supply. It consistes of vertical clay gravelly core surrounded on both sides by filters of gravel extracted from the valley of the Stanovnice water stream. The face zones are formed by gravelly sand from the Novy Hrozenkov and the upstream face is reinforced with macadam filled with bitumen. The height of the dam is 39.1meters, the length of the dam is 392 meters, the downstream slope is 1: 2.2- 2.4, and the upstream slope is 1:3.3 with reservoir volume of 7.521 million cubic meters and basin area of 23.1 square kilometers [3].

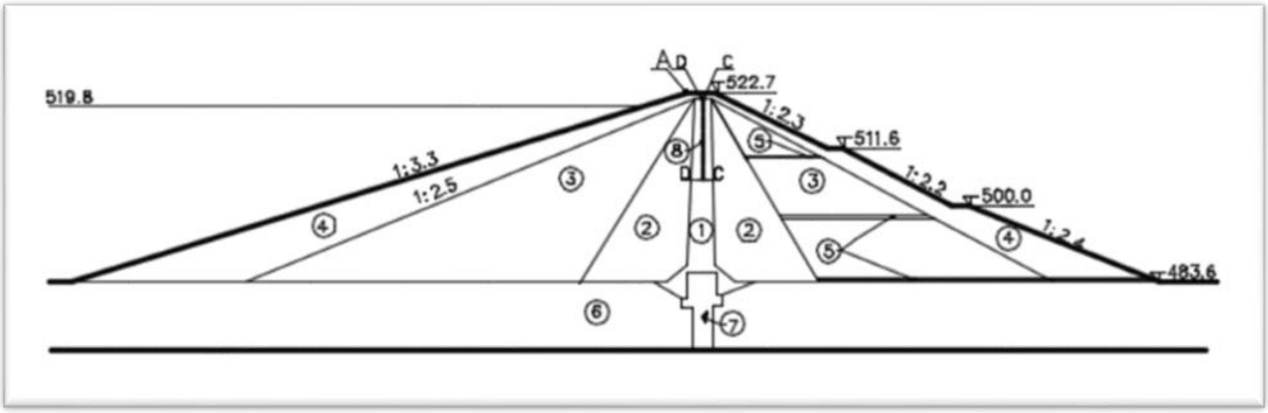

Figure 1: The Cross Section of the Karolinka dam

Legend

1.Core clay gravelly, 2. Zone 2B Gravel with fine –grained soil, 3. Zone 2A Gravel with loam, 4. Zone 3 Gravel with fine-grained soil, 5. Gravel drain, 6. Gravel with loam, 7. Curtain grouting, 8. Diaphragm wall.

2.1. Assumptions of material

- Homogeneous: The properties are not function of position.
- Continuum: There are no holes or voids.
- Isotropic and hydraulic conductivity are considered for each material.
- Elastic-Perfectly Plastic behaviour for the dam and subsoil
- The strains are small.
- Mixture grouting is incompressible.
- Flow in the soil is ideal.

2.2. Constitutive model

The constitutive model used in this study is linear-elastic perfectly plastic with MC failure criterion. MC model involves five input parameters, those are elastic modulus E, poisson ratio ν for soil elasticity, and the friction angle Φ, the cohesion C for soil plasticity, also the angle of dilatancy ψ. It is a first-order to provide with a reliable result of soil behaviour. The material behaves elastically until all the shear strength have been mobilized. When reaching the yield criterion, all load increments will lead to plastic strains [5]. MC failure criterion can be written as the equation for the line that represents the failure envelope [6]:

$$\tau = \sigma' \tan \Phi' + \acute{c} \quad (1)$$

Where τ is shear stress, σ' is effective normal stress, Φ' is effective angle of internal friction and $\acute{C}$ is effective cohesion.

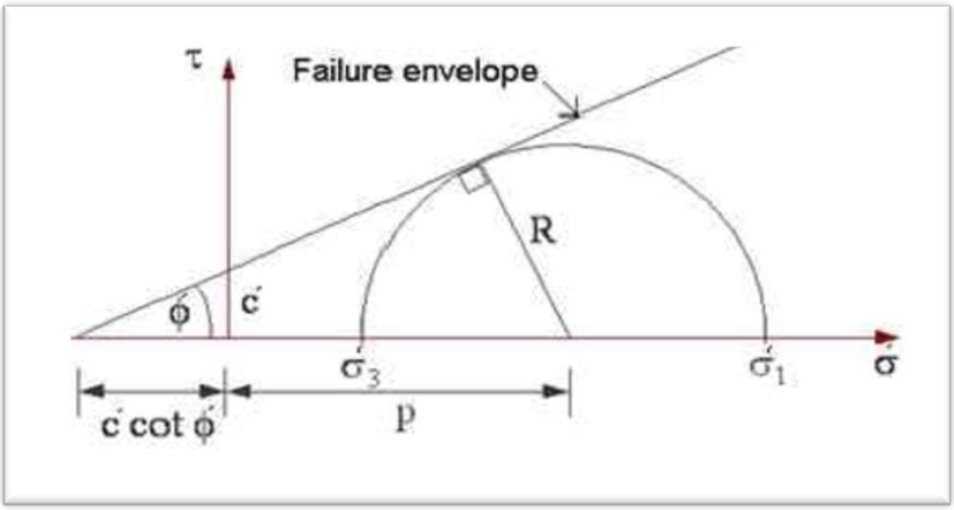

Figure 2: Mohr diagram and failure envelope

MC model is a reliable model, and its parameters are well known, so it can be obtained from different soil tests. For current study method (B) was considered for undrained calculation. It enables us to perform the undrained calculations considering effective stiffness parameters and undrained shear strength. Also, mode (drained) was chosen to analyse the coarse-grained materials. Due to sensitivity analysis, some of parameters are assumed according to the specifications of the materials in the dam. The materials parameters used in modelling are shown in Table 1.

Table 1: Material properties

Parameters	Core	Zone 2b	Zone 2a	Zone 3	Sub Soil	Jet pile	Mixture	Curtain	Drain	Bentonite
Hydraulic conductivity	0.086	0.864	0.864	4.320	4.320	$0.864.10^{-3}$	$0.864.10^{-4}$	/	86.4	$0.864.10^{-5}$
Unsaturated Unit weight	19	19	19	19	19	12.5	12.5	25	20	10.5
Saturated Unit weight [kN/m^3]	21	21	21	21	21	12.5	12.5	25	21	10.5
Young's modulus	20.10^3	70.10^3	70.10^3	70.10^3	70.10^3	25.10^3	500	40.10^6	100.10^3	400
Poisson's ratio [-]	0.3	0.2	0.2	0.2	0.2	0.25	0.4	0.1	0.15	0.4
Cohesion	21	1	1	1	1	200	18	/	1	16
Frictio angle	/	33	33	33	33	/	/	/	37	/

2.3. Basic equations

2.3.1. Static equilibrium of continuum

The equation (2) expresses the static equilibrium of continuum [5]:

$$L^T\sigma + b = 0 \quad (2)$$

Where L^T is the transpose of differential operator, σ is stress vector, and b is body force vector.

2.3.2. Stress-Strain equation

The relation between strain and displacement can be formatted as [7]:

$$\varepsilon_{tot} = L\,u \quad (3)$$

$$\varepsilon_{tot} = \varepsilon_p + \varepsilon_e \quad (4)$$

The general relation between ε and σ can be formatted as [7]:

$$\sigma = D^e\,\varepsilon_e \quad (5)$$

Where u is displacement vector, ε is strain vector, D^e is material stiffness matrix.and ε_p, ε_e plastic and elastic strain respectively.

2.3.3. Safety factor equation

SF is calculated by using Phi-c reduction theory, where specific soil parameters are gradually reduced to failure. The parameters C and tan Φ are decreased gradually until a clear failure and SF is calculated by the Equation (6) [5]:

$$SF = \frac{tan\,\Phi}{tan\,\Phi_{red}} = \frac{C}{C_{red}} \qquad (6)$$

2.3.4. Seepage equation

The mathematical problem solution of seepage comes from equations as follows:

I. Steady state flow analysis:

$$\frac{\partial}{\partial x}\left(k_x\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right) = 0 \qquad (7)$$

II. Transient seepage analysis

$$\frac{\partial}{\partial x}\left(k_x\,\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right) = m\frac{\partial h}{\partial t} \qquad (8)$$

Where k_x , k_y and k_z are coefficient of permeability of soil in x, y, z directions respectively, and m water storage.

2.4. Mesh Generation and Boundary conditions

Setting up the boundary conditions in the model is a major step because the result is dependent on the chosen boundary conditions in the model. In this modelling, 10-node tetrahedral elements for soil elements were used (Figure 3). The sufficient, and well- refined mesh generation of Plaxis 3D. The top (Z_{max}) boundaries set to free and the bottom (Z_{min}) is set to fixed, whereas the right (X_{max}), left (X_{min}), and boundaries: ($Y_{(min,\,max)}$) are set to normally fixed as well. In the ground water flow boundary set boundaries: ($Y_{(min,\,max)}$), and (Z_{min}) to closed. The remaining boundaries are open.

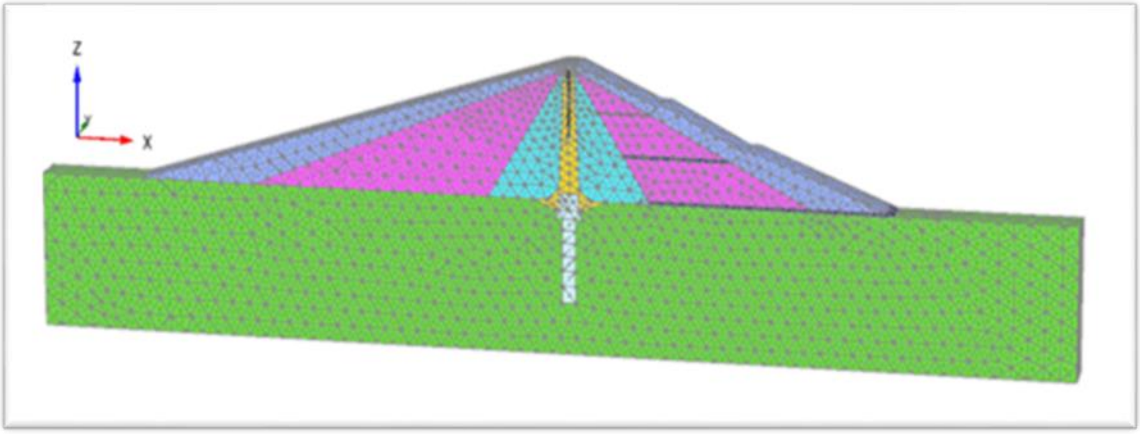

Figure 3: Boundary condition of case study

2.5. Initial conditions

The initial conditions in general comprise the initial groundwater conditions, the initial geometry configuration and the initial effective stress state.

2.5.1. Initial displacements

The hydrodynamic analyses of dams assume at time t = 0, the dam is in the state of static equilibrium and the initial displacements equal zero.

2.5.2. Initial ground water surface

The initial piezometric head in the domain (steady state flow) is equal to specified piezometric head.

$$h_{p,0} = H_0 \qquad (9)$$

Where $h_{p,0}$ is initial piezometric head in the domain (steady state flow), and H_0 is specified piezometric head.

2.5.3. Initial stresses

The initial stress field is influenced by the material weight and the history of its formation. The initial stress field is generated in Plaxis by using the given (default) K_0' value in the sub-soil. This stress state is usually characterized by an initial vertical effective stress and the initial horizontal effective stress, and they are related to the coefficient of lateral earth pressure K_0' as follows:

$$\sigma'_v = \gamma . d \qquad (10)$$

$$\sigma'_h = \sigma'_v . K'_0 \qquad (11)$$

Where σ_v' is vertical effective stress, σ_h' is horizontal effective stress, K_0' is coefficient of lateral earth pressure

[5].

2.6. Interface elements

The interaction between the structural element and the soil is simulated by applying interface element. It is used to reduce the friction between the studied structure and the adjacent soil. It is composed of pairs of nodes one belongs to the structure and second belongs to the surrounding soil. The value of interface element(R_{inter}) ranges between 0.01 and 1.The values in between mean, the contact between structure and soil is not rigid and the structural element and surrounding soil can slip between each other. The interface elements in our case study are presented between the wall and the core with the value of 0.8 depending on some recommendations[8] [9].

2.7. The cement shrinkage

The shrinkage expresses a gradual change in volume of element in all directions during its hardening process due to water loss. The shrinkage as the cause of cracking in the element, which decreases an element's ability, leads to water penetration problems, and effect on its strength and durability . Fly ash typically is used as cementing materials, but it has an obvious influence on the shrinkage as well. Shrinkage increases with increasing in fly ash content.The autogenous shrinkage caused by chemical process of cement hydration. It increases mainly during the first days of hydration (0.4 cm3/100 gr cement) [10]. In Plaxis, shrinkage is modelled by applying a contract surface to the affected area (wall) in hardened state after calculating the value of the shrinkage, based on the typical mix proportions of the wall, the ratio and the mass of cement in mixture too.

2.8. Sensitivity analysis

The sensitivity analysis aims to show the influence of the change in the value of each input parameter on the values of output parameters, to define the most important parameters which have a significant effect on the output ones, thus they should be taken into consideration when it comes to the dam’s safety. The method used in this study is (OAT) method where all the parameters, except selected input parameter were kept constant [11]. Meshing also affects the output parameter. Depending on (AES) of the generated mesh, the effect of its value on the most significant output parameter SF, from the beginning of reconstructions till the end, was studied with five different sizes of meshes.

2.9. Numerical solution in Plaxis 3D

Creating the model in the program Plaxis can be summarized in four phases (Figure. 4).

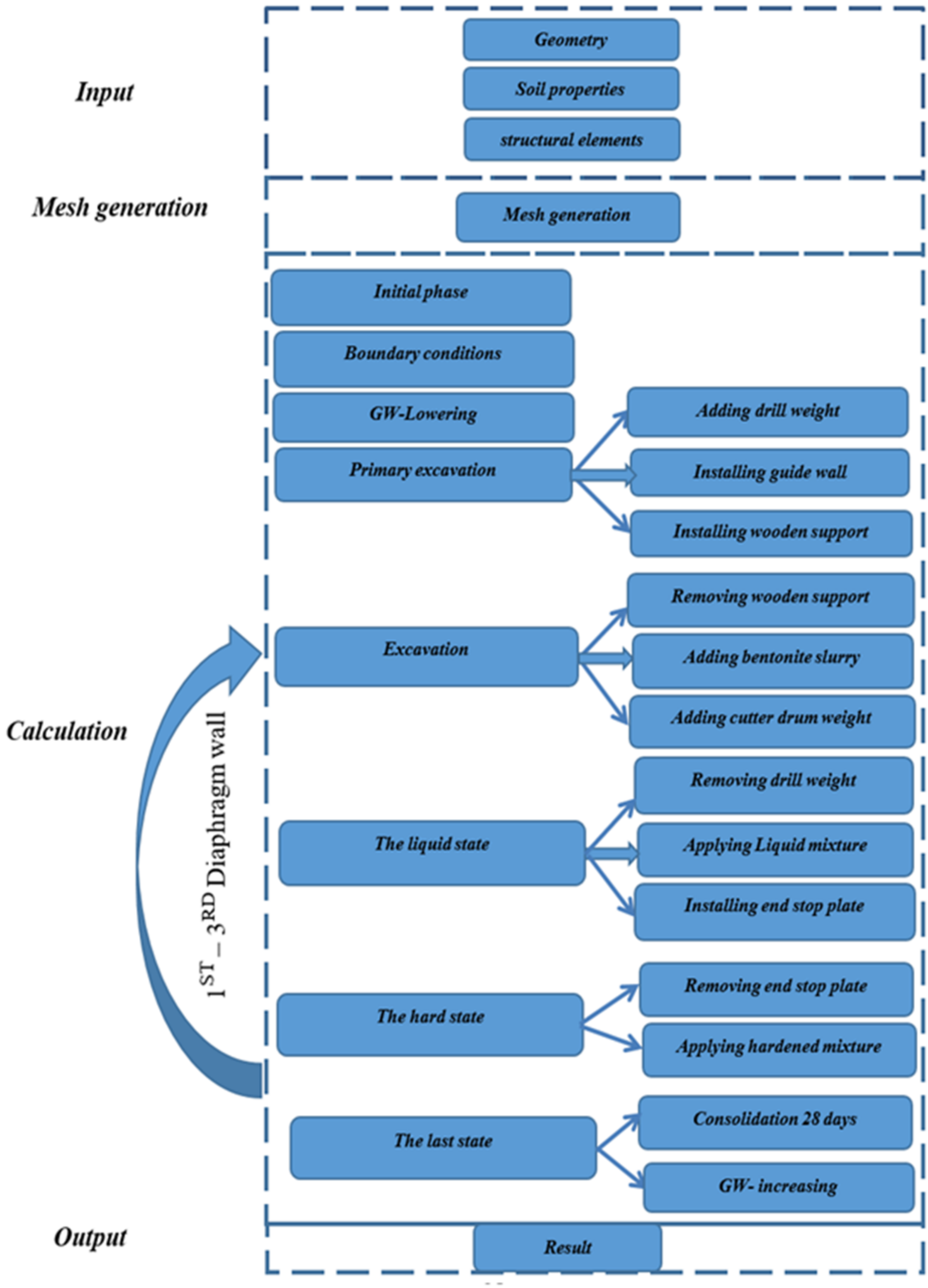

Figure 4: The calculation steps in Plaxis

2.10. Modelling procedure

Figure 5, shows that the construction steps can be summed up as following:

1. Decreasing WL by ten meters in ten days.

2. Preliminary excavation to (1.5 m) with adding weight of drill, and installing the guide wall.

3. Installing the support elements.

4. Removing the supports and adding weight of cutter drum which digs down to tip elevation, with bentonite slurry.

5. Installing end stop plate, and casting the liquid mixture while removing the bentonite slurry.

6. Curing liquid mixture in the wall number 1 by applying a hardened mixture in shrinkage state.

7. Appling the same modelling procedures to construct wall No. 3 then No 2.

8. Increasing WL by ten meters in fifteen days.

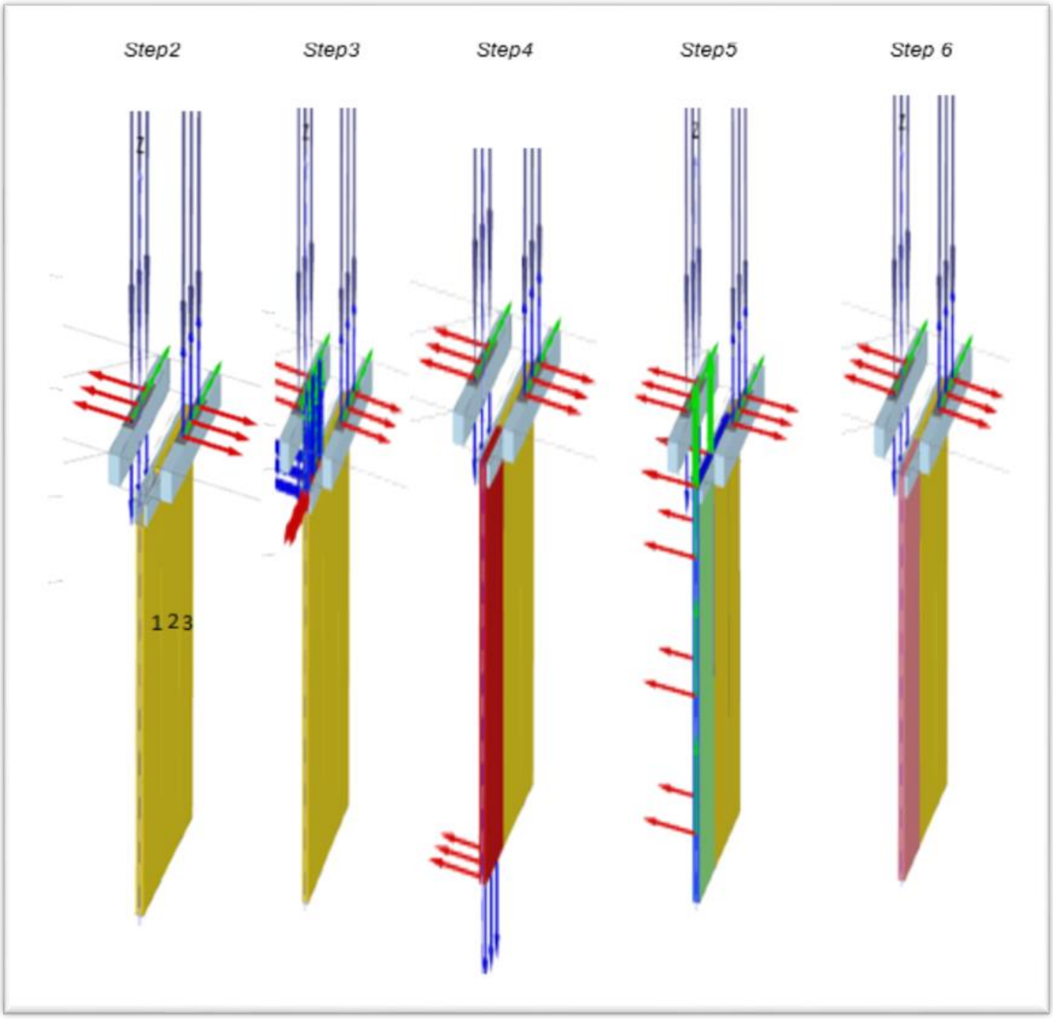

Figure 5: Diaphragm wall construction sequence

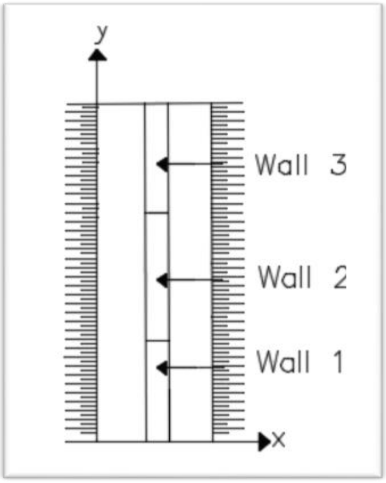

Figure 6: Top view of the dam crest

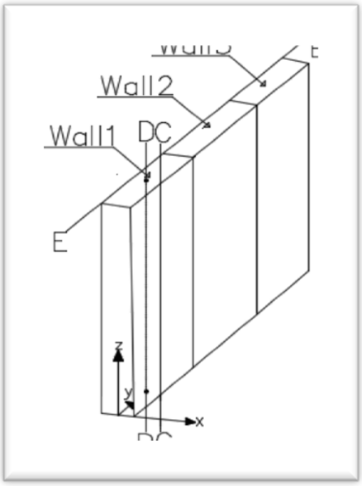

Figure 7: Cross-Section lines

3. Results and discussion

3.1. The total displacement

The horizontal displacement at the crest dam is expressed in the Figures 8, 9. It is clear that the maximum value reached (32mm) during decrease WL in reservoir, and (23.5 mm) during increase WL. This result was concluded depending on FCFD analysis which analyses the development of deformation and pore water pressure as a result of time-dependent hydraulic boundary condition. A number of researchers have investigated the mechanism of soil movements during changing WL (drawdown- filling). Their studies addressed the settlements due to WL variations. They studied the relationship between the displacement and (charge-discharge) rate (m/day). The real data of field studies have indicated that the upper side of the dam core (Point A) is primarily affected by variation in WL in reservoir [12,13,14].

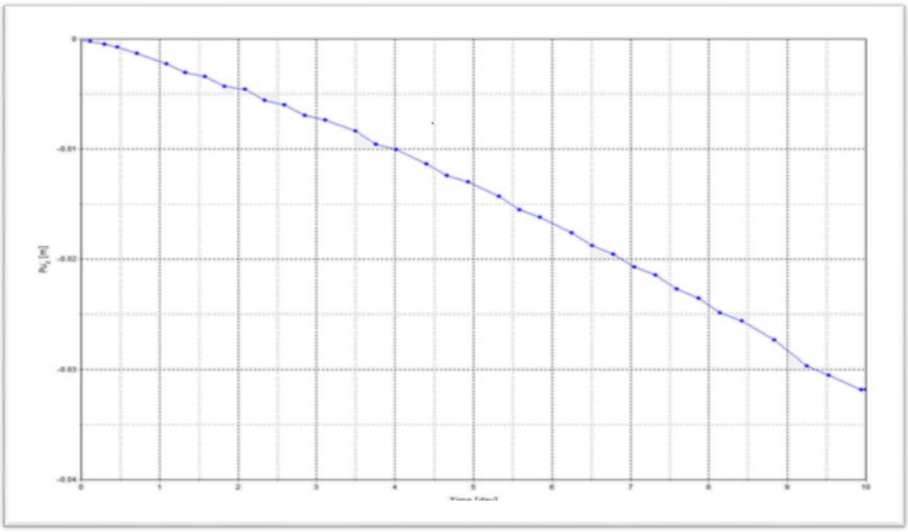

Figure 8: Horizontal displacement-time (decrease WL) history at point A (-2.5, 0, 39)

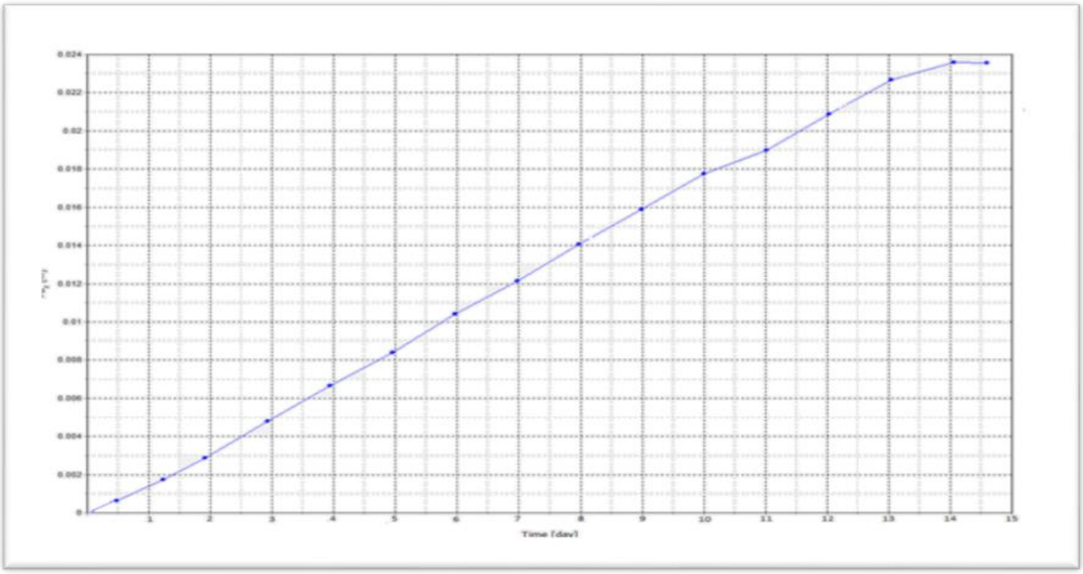

Figure 9: Horizontal displacement-time (increase WL) history at point A (-2.5, 0, 39)

Figure 10, shows the vertical displacement distribution with depth at line cross section C-C Figure (7). The maximum value of the displacement occurred almost in the upper one-third of the wall height and the maximum value of vertical displacement about 0.2% of the wall thickness, so it is relatively small. Many researchers have studied the soil movement during and after construction diaphragm wall, and the results are in good agreement with the current results[15,16,17] .

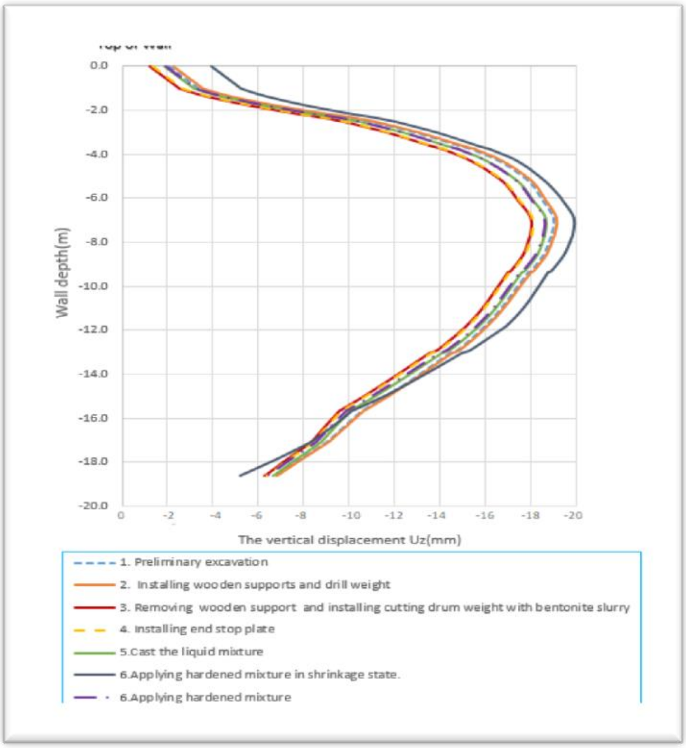

Figure 10: The vertical displacement along the line cross section C-C (construction wall 1)

3.2. Safety factor

Figures 11 and 12, depict that the most critical surface in the initial state is deep with a large radius. Also it is less deep with smaller radius in the last state. It is found to be near the upper part of the core and berm before reconstructions so any remedial steps applied to lower the seepage at the clay will have essential improvement in FS. The value of SF increases in this analysis, it goes from 1.48 to 1.56. When WL does not enter into the failure surface, the stability of slop increases. So SF of dam can be increased by preventing the water from penetrating the slopes by means of drainage techniques. Figure 13, shows SF for studied situations The sudden drop of SF value is normal in c/phi reduction. During the incremental reduction of C and/or Phi an excessive displacement occurs and results in a lower value than that in the previous increment or step. Plaxis will continue to adjust the incremental change in C and/or Phi as if it is looking for the minimum SF. The outcome of SF showed that with variation of WL, SF is fluctuated and governed by water load, pore water pressure changes, and free surface of water position into the dam. As a result, diaphragm wall is an effective technology to improve dam stability[18,19].

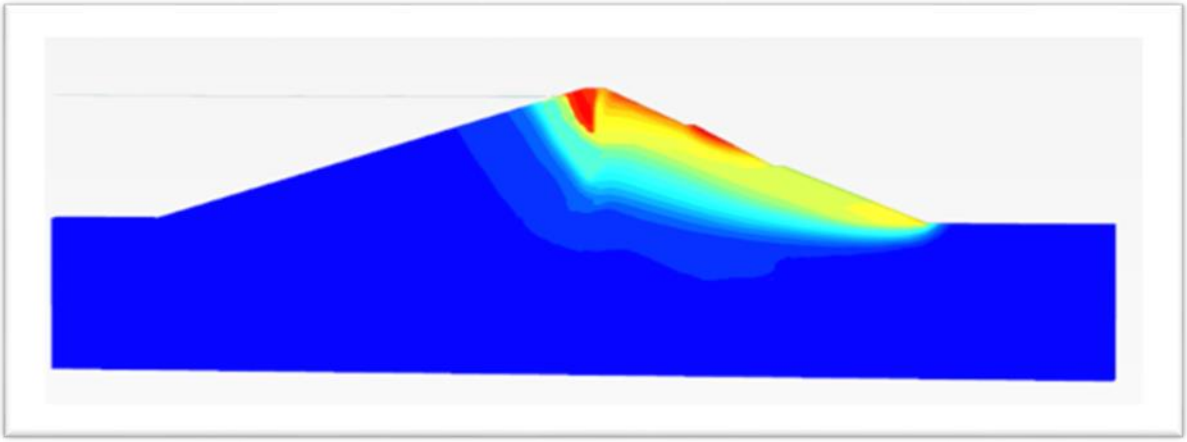

Figure 11: Slip surface at failure (Initial state), FS =1.48

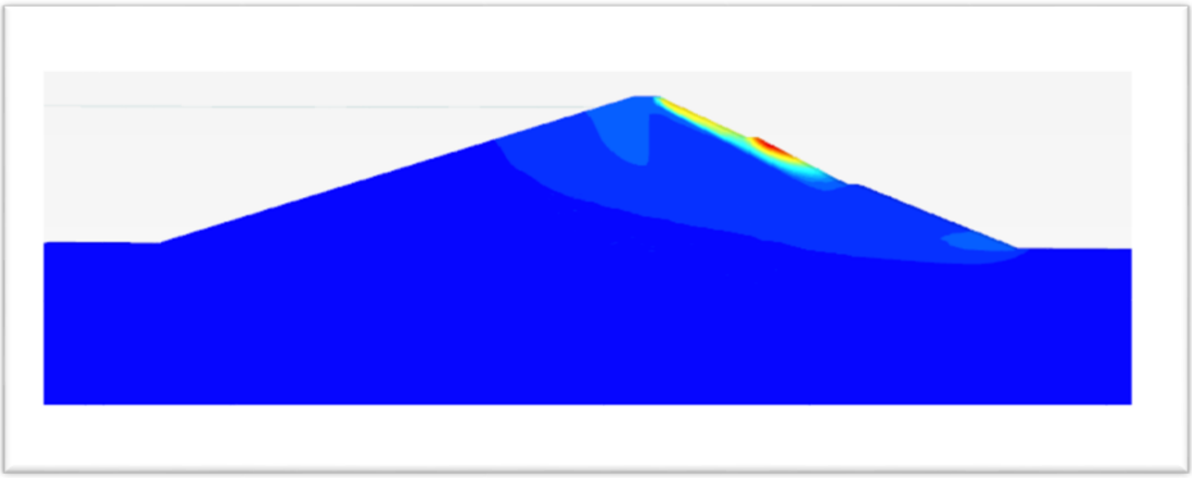

Figure 12: Slip surface at failure (Last state), FS =1.56

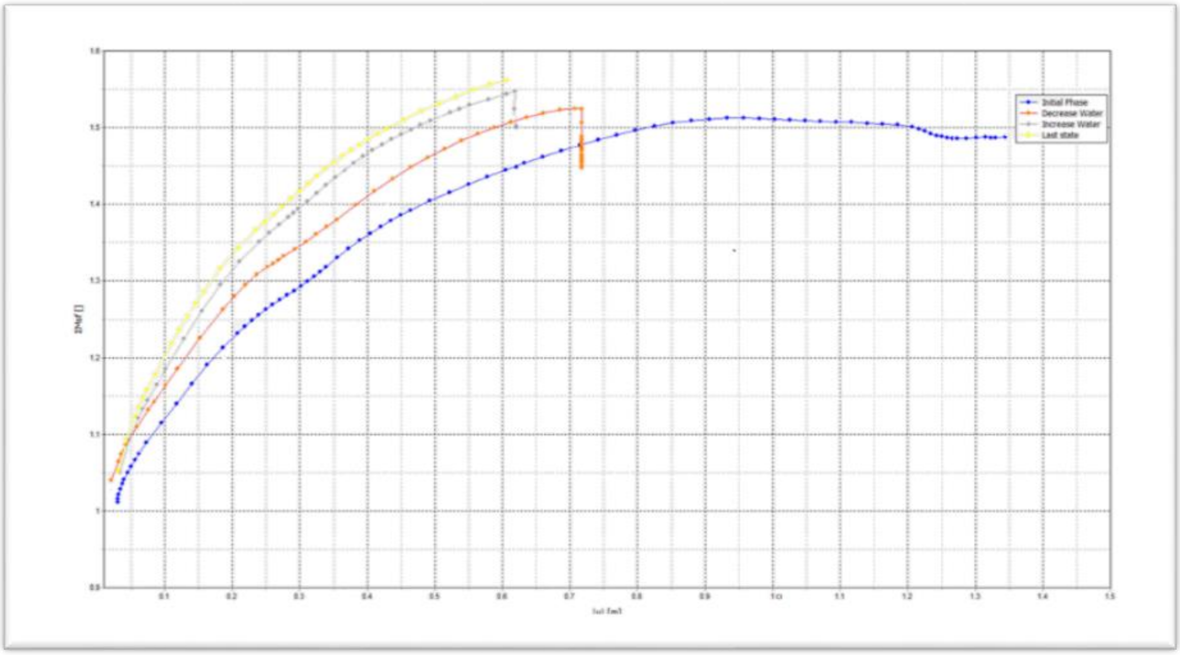

Figure 13: Evaluation of safety factor

Initial state Decrease WL Increase WL Last stat

3.3. Sensitivity analysis

3.3.1. Effect of elasticity modulus and cohesion on SF

To study the effect of soil elasticity modulus and cohesion on the value of SF, each of cohesion and elasticity modulus of all layers of the dam materials are changed with the same ratio, paying attention to keep these changes of these values in the allowable range for each soil material. In the first analysis the initial value was divided by 1.4, and in other analysis it was multiplied by 1.28, 1.56 and 1.85. Figure 14, shows the obtained values of these analyses. SF increases gradually with increasing both the elasticity modulus and cohesion. On the other hand, the cohesion has a bigger effect on SF than elasticity modulus. And these results are in acceptable harmony with [20,21,22] , taking into account the significant differences in the parameters, material properties of the studied dam, and its shape as well. They observed the effect of elasticity modulus variability on earth dam stability using finite element method. As they mentioned, the increase in elasticity modulus value corresponds to the increase of SF.The appropriate determination of both cohesion and elasticity modulus have a significant role on determination of SF.

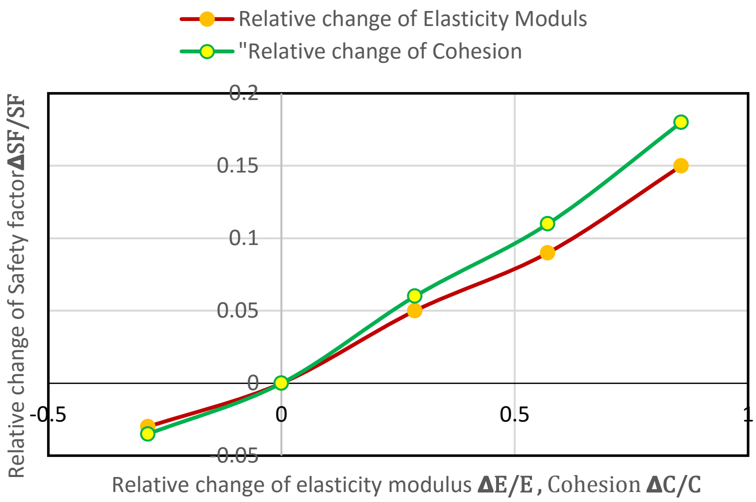

Figure 14: Sensitivity analysis results

Table 2: Relative change of SF

Rate of cohesion, elasticity modulus change	ΔSF/SF	
	Cohesion	Elasticity modulus
The initial state divided by 1.4	-0.04	-0.03
The initial state	0	0
1.28 times of the initial state	0.06	0.05
1.56 times of the initial state	0.11	0.09
1.85 times of the initial state	0.18	0.15

3.3.2. Effect of mesh size on SF

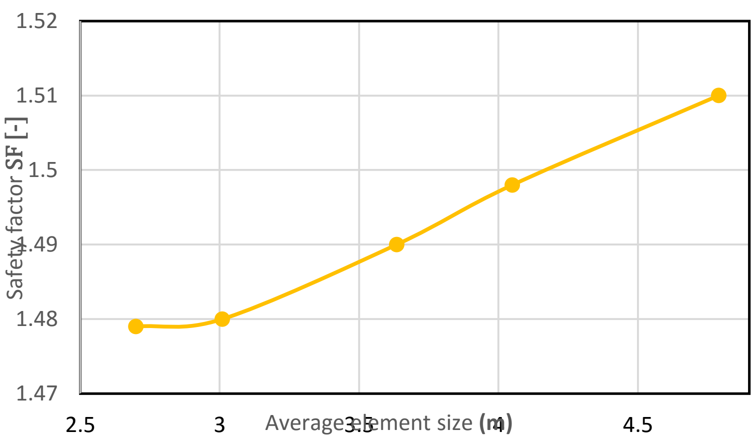

Figure 15: Influence of mesh size on SF

The effect of the element size was studied using five different sizes of meshes (very fine, fine, medium, coarse and very coarse). Figure (15), shows the influence of the element size on SF. It is clear that the very coarse mesh yields a higher FS compared to the other three mesh sizes. As for the finer division, the variation of SF almost vanishes and this matches the source data of [23,24], who presented that with more division, SF no longer will be affected. Thus, when we refine more, there will be no further effects on the value of SF.

4. Conclusion

In this study, a numerical investigation is conducted using Plaxis 3D software which is based on the finite element method, and the results are compared to the measured data performed by TBD company. The main findings in this study can be summarized as follows:

1. The prediction of this study for the vertical displacement at crest dam (diaphragm wall installing) is (8.2mm), which is comparable to measured value (12.2 mm) in the field measurement of displacement.

2. The horizontal displacement at the point A (-2.5,0,39) during decreasing WL reaches its height value (32 mm), and during increasing WL is (23.5 mm), due to the influence of water load and pore water pressure variations with the time.

3. The value of SF before reconstruction stages is (1.48), which is compared to the calculated value depended on: 1- the shape of failure surface, 2- the data taken from measuring well, 3- Bishop method, equals (1.498) [25].

4. The most critical surface in both cases (initial state, last state) is near the upper part of the core and berm so any remedial step is applied to lower the seepage at the clay will have essential improvement in SF.

5. According to the result of sensitivity analysis, it is clear that SF increases gradually with increasing both the elasticity modulus and cohesion. On the other hand, the fine mesh with more refinement, will not have any effect on the value of SF.

6. It is very important to choose the appropriate period for decreasing and increasing WL in the reservoir. In uncontrolled drawdown, water load disappears so, there is no supporting pressure to dam stability. Also, the generated tensile-downward forces lead to a decrease in shear strength of the upstream slope. On the other hand, the unplanned filling the reservoir creates excess pore pressure which may put the dam at risk in some critical conditions. As for the case studied and depending on some recommendations [26], WL was decreased by one meter per day.

7. It is noted that the variation of WL (decrease- increase) affects SF because of water movement in the soil pores, thus reducing the effective stress, soil strength and stability.

8. The process of diaphragm wall in the case study was modelled by using Plaxis 3D, and the measured and numerical results seem to be close.

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