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SAFETY MANAGEMENT OF EARTH STRUCTURES IN TERMS OF SEEPAGE CONTROL

- Ph.D. Thesis-

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ABSTRACT

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Field of Specialization:
Hydrotechnical Engineering

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1 INTRODUCTION

1.1 General remarks

The development of seepage through the body and foundation of a dam provides basic information on the behavior of the structure and the possibilities of its safe operation. In the operation phase, the seepage through the body and foundation of the dam assumed by the project serves as a comparison with the measured values. Hydrodynamic effects of flowing water may frequently destroy the filtration stability of the body or subsoil of the dam and thus endanger the safety of the hydraulic structure and its operation. Piping, as a source of failures, accounts for about 30% of the reported cases. After excluding overtopping, it is the biggest contributor. Piping, a concentrated leakage with a progressive character, usually develops along a predetermined path. The currently most frequently used numerical method for the solution of seepage flow – the finite element method – is applied in the thesis.

The seepage through the case study dam is modeled as a steady-state flow with a free surface water table. Although the Initiation of internal erosion along a typically horizontal flow path is admittedly difficult to assess, seepage analyses may provide useful information in terms of the potential gradients along the seepage path. With SEEP/W, piezometric heads or gradients can be received from every node or factor in the finite aspect mesh, which permits an analyst to view the estimated gradients at some point of the embankment or basis being modeled. Due to difficulties associated with performing a positive cutoff requirement, different strategies of seepage control were used in conjunction with cutoffs. As an alternative, impermeable blankets can be positioned upstream of dams to extend the path in the flow direction of seepage. This has the impact of decreasing hydraulic gradients and the volume of seepage at the downstream component of the dam. This lengthening of the seepage path lowers the hydraulic gradient and, thus, reduces seepage flows. The thesis will treat, successively, the numerical model, the calibration of the model, the actual differences between steady-state and transient approaches, and the engineering techniques to provide the required safety. The case study will be Chamerga Dam, under construction in Kurdistan. Special foundation conditions associated with high permeability and non-homogeneities may induce large gradients, and a detailed analysis is required to state the final safety of the dam.

1.2 Objectives of the thesis

The thesis aim was to underline the influence of the dam components on seepage control and their effects on reducing the likelihood of slope stability loss under drawdown conditions. The objectives are summarized as:

- To study the effect of the earth dam impervious core, central or sloping, on the seepage flow before and after the drawdown conditions.
- To study the effect of pore water pressure development in filling stage conditions.
- To study the effect of pore water pressure dissipation in drawdown conditions.
- To study the factor of safety with seepage analysis only and with couple analysis
- To study the influence of the internal water flow on the earth dams' deformation field and volume change.

1.3 Outline of Thesis

This thesis is divided into seven chapters.

Chapter one presents the general remarks concerning the thesis subject, the objectives of the thesis, the actual stage of the problem based on literature review, an outline of the thesis.

The background of type, basic requirement, Characterizations, Cross Section, and material of earth-fill dam. This chapter also presents the advantages and disadvantages of Central Impervious Core and Sloping Impervious Core for earth dam.

Chapter two presents the earth dams, types of earth dams, advantages and disadvantages of the earth fill embankments, basic requirements, zoning, material properties, filter design, and characterization of earth dams.

Chapter three represents the static analysis of embankment dams and the type of these analyses and describes the seepage and stability analyses using the finite element method (FEM). This chapter presents the background theory and equations used for the seepage analysis through the dam and seepage control in embankment and foundation of earth dam and the equations of the stability analysis of the dam. It also describes the method used to estimate the factor of safety against sliding.

Chapter four presents the background and importance of internal erosion to dam safety and description of the path failure, which are phases of internal erosion, mechanics of erosion, continuation and filter action, progression, and breach. The second part of this chapter represented the case history of failures and incidents for concentrated leak erosion, backward erosion, global backward erosion, contact erosion, and suffusion.

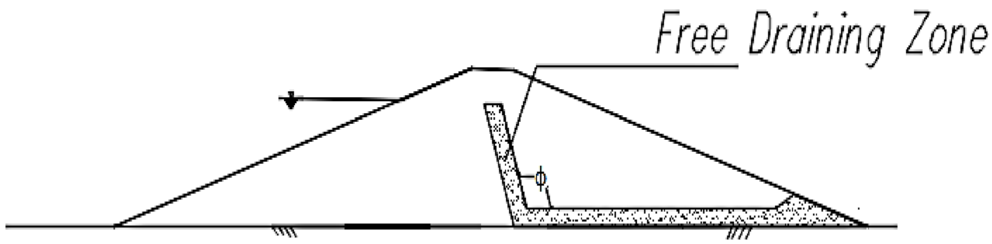
Chapters five and six include the main contribution of the author. The case study is dedicated to the Chamerga earth fall dam under construction in Iraq. Several alternatives concerning the imperviousness of the dam body and its foundation are proposed. By numerical simulation, their effect is analyzed using GeoStudio software. The comparison is made under different situation steady-state analysis and transient analysis "filling stage and drawdown condition" in terms of total hydraulic head, pore-water pressure, and exit gradient; also represented the factor of safety on the upstream face in seepage analysis only and a coupled analyses which mean The incremental change in pore-water pressures from the seepage solutions are used at each load step in the stress-deformation calculation to determine the change in effective stresses. in a couple of analyses.

The results and explanation are presented in **chapter six.** The seepage analysis is done in steady-state, and trainset analysis theory includes the estimation of the water flux, the exit gradient, and the influence of the upstream filter on protecting the upstream slope against erosion. Coupled Stress-Pore Pressure Analysis In this analysis, the seepage analysis is solved independently of the volume change (Ali A. Aldulaimi, 2021). A stability analysis is also conducted, including a deformation analysis and the calculation of the upstream factor of safety against sliding.

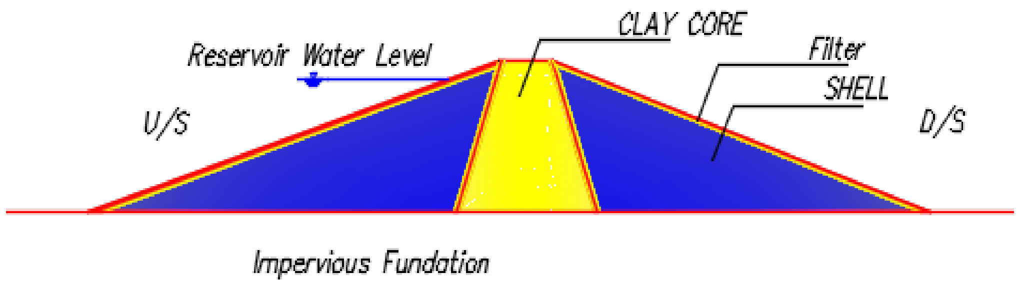
Chapter seven is the final chapter of the thesis and includes the conclusions and recommendations for further research on this topic. The references are presented at the end of the dissertation.

2 EARTH FILL DAMS

This chapter presents successively the advantages and disadvantages of an earth-fill dam and the types of earth-fill dams - homogeneous earth-fill dams, central impervious core earth-fill dams, sloping impervious core earth-fill dams. The feathers and the shortcomings of each dam type are underlined in this chapter.



Homogeneous Earth-fill Dams.



Central Impervious Core Earth-fill Dams.

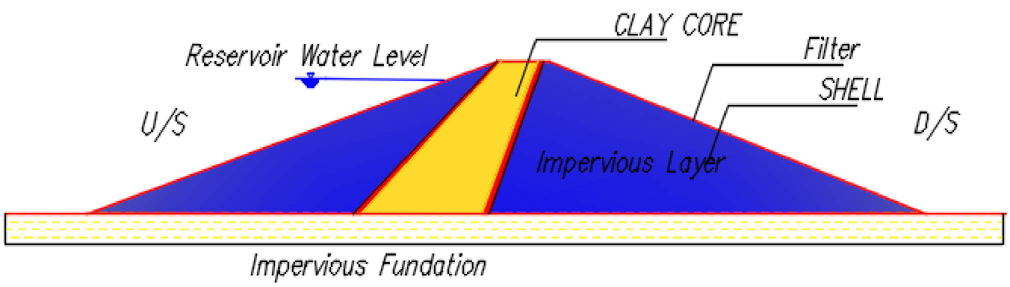


Figure 2-1. Schematic of earth-fill dam type sloping impervious core.

3 STATIC ANALYSIS OF EMBANKMENT DAMS

3.1 Seepage Analysis

Seepage analysis is a necessary issue of geotechnical engineering. In general, linear issues such as the prediction of settlements and deformations, the calculation of glide portions due to regular and transient seepage are all enormously amenable to solution by finite elements. The use of finite factor analysis of slope balance and seepage has won popularity in recent years due to its functionality to cope with complex problems

3.2 Seepage Control in Embankments

All earth and rockfill dams are a challenge to seepage via the embankment, foundation, and abutments. Seepage manipulation is integral to forestall immoderate uplift pressures, instability of the downstream slope, piping via the embankment and/or foundation, and fabric erosion through migration into open joints in the basis and abutments. The cause of the project, i.e., long-term storage, flood control, etc., may additionally impose obstacles on the allowable volume of seepage (U.S Army Corps Engineers, 1993). Three techniques for seepage control in embankments are:

- Flat slopes without drains.
- Embankment zonation.
- Vertical (or inclined) and horizontal drains.

3.3 Seepage Control in Earth Foundations

All dams on earth's foundations are subject to under seepage. Seepage control in earth foundations is necessary to prevent excessive uplift pressures and piping through the foundation.

3.4 Stability Analysis

Structural analyses serve two purposes for the design of earth dams: first, ensure that the dam will be stable during construction, during normal operating conditions, and during possible earthquake loading conditions; and second, to ensure that the deformations during construction, normal operation, or earthquakes will not be excessive (Ali A. Aldulaimi, 2021). These functions are carefully interrelated because instability is inevitably manifested in the shape of large deformations. The stability must be examined under (i) Normal Operation - Steady Seepage and (ii) Rapid Drawdown—Upstream Slope.

3.5 Couple and Consolidation analyses

3.5.1 Fully coupled Stress-Seepage analysis

Analysis that couples the seepage phenomenon and ground stress analysis can be classified in various ways, depending on the coupling. The simplest way is to obtain the pore water pressure distribution by conducting seepage analysis in advance and reflecting it in the total stress/effective stress relationship equation conducted in the following step. Such analysis is called sequential analysis (Martinez, 2018)

3.5.2 Consolidation

The consolidation analysis starts with the assumption that steady-state pore water pressure can be maintained and is used to see excess pore water pressure changes (Martinez, 2018). In other terms, this analysis simulates how excess pore water pressure changes with the changes in load/boundary conditions.

Fully coupled Stress-Seepage analysis does not follow the assumption that steady-state pore water pressure is preserved. Therefore, it is suitable for simulating the transient seepage phenomenon, stress analysis, and stability in the unusual condition in a fully coupled form. Unlike the consolidation analysis, it is possible to define the changes in seepage boundary conditions with time, boundary flow rate, etc. In other terms, for Fully coupled Stress-Seepage analysis, it is possible to use all the transient seepage boundary conditions, structural load, and boundary conditions (Martinez, 2018).

4 INTERNAL EROSION

Internal erosion happens when the soil particles within an embankment dam or its foundation are carried downstream by seepage flow (Ramos-Rivera, 2016)

4.1 Importance of Internal Erosion to Dam Safety

Internal erosion is an essential safety issue for large and small dams, dikes, and levees, as shown by the statistics of historic failures and incidents (Ramos-Rivera, 2016). The statistics of embankment dam incidents show that internal erosion is a major cause of incidents and failure for older dams to a lesser degree. Incidents include new or increased seepage and leakage, sinkholes, and accelerating settlements of the dam.

4.2 Description of path failure

Failures and incidents by internal erosion of embankment dams and their foundations are divided into three general failure modes, as follows:

- Internal erosion through the embankment includes conduits associated with outlet works, spillway walls, or a concrete gravity structure supporting the embankment.
- Internal erosion through the foundation (Fell & Fry, 2007).

- Internal erosion of the embankment within or at the foundation. Including:

a. seepage across the embankment eroding material into the foundation,

b. seepage into the foundation at the embankment contact erodes the embankment material.

There are four phases of the internal erosion process: Initiation of erosion, the continuation of erosion, progression to form a pipe or occasionally cause surface instability (sloughing), and Initiation of a breach.

The first condition for internal erosion to occur is particle detachment. Water seeping through the dam or flowing in cracks must provide enough energy to detach particles from the soil structure.

Four mechanisms occur in the erosion initiation: 1) **Concentrated leaks**, 2) **Backward erosion**, 3) **Contact erosion**, 4**) Suffusion**.

Erosion, once initiated, will continue unless the eroding forces are reduced or the passage of the eroded particles is impeded in some way. Progression is the phase of internal erosion where:

a. For concentrated leak erosion, the erosion in the crack or concentrated leak leads to the development of a pipe.

b. For backward erosion, the erosion process extends upstream from the point of Initiation. A network of small erosion channels forms beneath the soil or embankment, providing the roof to the erosion pipes.

c. For contact erosion, the erosion of the finer soil into the coarser soil continues. This may lead to the development of a pipe in the finer soil.

d. For suffusion, some of the finer fraction is eroded, leaving the coarse matrix of the soil. No pipe is formed, but the permeability of the soil may be increased significantly.

Breach formation happens when the entire process of internal erosion has concluded, detection and intervention have failed. The dam may be breached by one of the five mechanisms listed below, while the internal erosion process will stabilize.

5 CASE STUDY

5.1 Chamrga Dam

The Chamrga Dam is an earth dam located in the north of Iraq on the seasonal river Chamrga, with a total length of 257m with a maximum storage of 1,620,000 m^3 and about 17.5-meter height with the crest elevation at 658 m.a.s.l level. The crest width is 6 m, and there are slopes of 2% to both upstream and downstream directions. The crest of the dam is designed to carry normal car vehicle traffic. The upstream face of the dam has a slope of 1:2.5, as shown in figure 5.1. The upper downstream slope of the dam has 1:2 with a 4-meter berm. While in the lower part, the downstream slope will be flattened to 1:2.5. The foundation soil of the dam site, in general, comprises of Upper Bakhtiari formation. It consists of sand and gravel with some fines (Ali A. Aldulaimi, 2021). A cofferdam with a crest elevation at 648 m asl will be performed upstream of the concrete plinth. The crest width is 4m. The upstream and downstream face slopes are 1:2.75. The cofferdam body will be constructed from clayey silt soil during the dam erection.

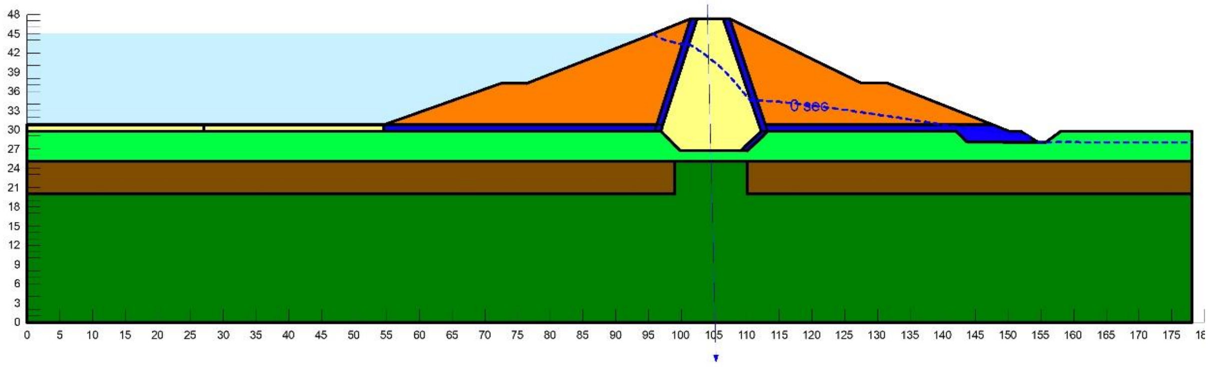


Figure 5-1. Chamrga dam actual design (Ali A. Aldulaimi, 2021).

The properties of the material used in the construction of the dam can be summarized in Table 5.1.

Table 5.1 *Material Properties of Chamrga dam*

Ref. No.	Material	Color code	k (m/s)	γ (kN/m^3)	c (kPa)	Ø (°)
1	Dam body fill		2. exp-05	19	15	38
2	Drainage layer		5. exp-04	17	0	33
4	Sediment		1. exp-04	21	5	39
5	Claystone layer		1. exp-06	23	20	40
6	Conglomerates		5. exp-05	21	5	40
7	Clay blanket		1. exp-07	16	20	20

5.2 Simulation and modeling

The numerical analysis in this thesis has been made based on models and simulations carried out in the computer software named GeoStudio. GeoStudio has widely used computer software for geotechnical and earth science problem modeling. SEEP/W, SIGMA/W, and SLOPE/W, which are tools within GeoStudio, were used to analyze the given construction design of the dam embankment in this research (Ali A. Aldulaimi, 2021).

5.3 Dam model and material parameters.

The Auto CAD drawing of the Chamrga dam was translated into GeoStudio. Regions were created, and material layers were assigned to each region according to the embankment design. At the beginning of the modeling process, simple or estimated material parameters were used as input data. This was according to directions from GeoStudio instructions (GEO-SLOPE, 2012) . and the purpose was to verify that the models worked properly. When the models were verified to similar studies, the accurate material parameters were substituted to refine the analysis. Material parameters used in the simulations will be presented in the SEEP/W, SIGMA/W, and SLOPE/W sections (Ali A. Aldulaimi, 2021).

5.4 Simulated scenarios

Three scenarios have been suggested in this research; these scenarios are illustrated in the flowing:

- Scenario 1

In this scenario, the current situation represented the original cross-section without additions with a clay core. A clay blanket for 55 m extend in the upstream reservoir has been used, as shown in figure 5.1. Max water level upstream (h=15.5m) at elevation 655.5 MASL and downstream (h=0) at elevation 640.00 MASL, the nodes at the bottom and lateral of the dam foundation for each model are considered with the zero-flux condition (Ali A. Aldulaimi, 2021).

- Scenario 2

In this scenario, to achieve an efficient cutoff, its position must be replaced upstream of the cofferdam. The claystone layer up to 5 m thick is continuous from left to right abutments. The new cutoff will be bentonite concrete and extended into the foundation up to the claystone layer. The core material will extend only 2.5 m meter depths to not interfere with the groundwater and the upstream clay blanket connected to the water tightening system of the dam (clay core), as shown in figure 5.2.

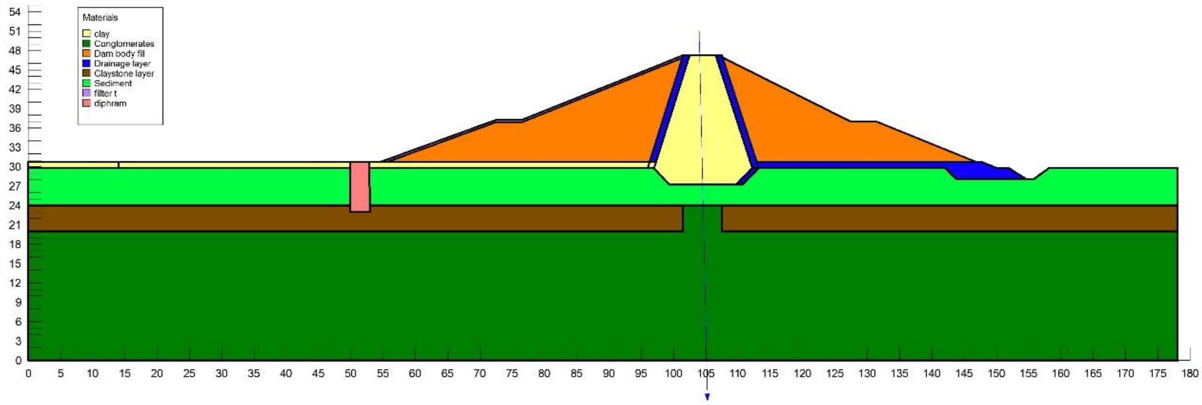


Figure 5-2. Scenario 2, (Ali A. Aldulaimi, 2021).

- Scenario 3

We suggest applying an inclined core and the upstream clay blanket connected to the water tightening system of the dam (clay core) extend in the upstream reservoir, as shown in figure5.3. Every scenario was simulated and analyzed for different operating conditions. The Normal filling stage and drawdown (Ali A. Aldulaimi, 2021).

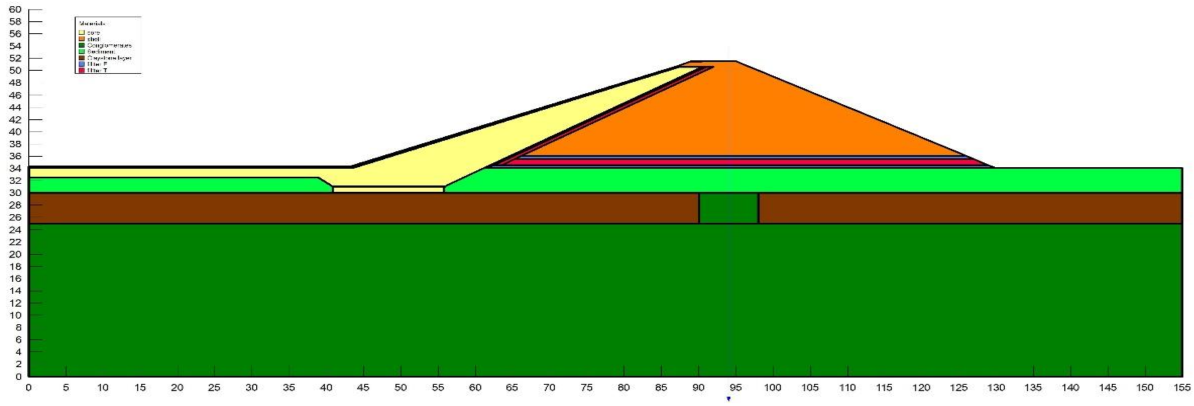


Figure 5-3. Scenario 3, (Ali A. Aldulaimi, 2021).

5.5 Seepage analyses

- Purpose

Simulations in SEEP/W were conducted to locate the phreatic surface, determine the pore water distribution and penetration, and obtain the velocity

and the direction of the seepage in the dam scenarios during (normal, filling stage, and drawdown) conditions. As seepage control is crucial for stable and safe embankment, the seepage analysis can provide information and data for further stability analysis in SLOPE/W (GEO-SLOPE, 2012).

- Input data and boundary conditions

Seepage calculations were based on saturated/unsaturated and steady/unsteady soil seepage equations with the fixed grid finite element method. The mesh properties were set to 2640 nodes and 2536 elements with an approximate global element size of 2 meters. The initial boundary condition for the seepage analysis in the state of steady is the water level in the upstream slope is about 45m. The boundary condition on the downstream slope face is not indicated, as the pressure of pore water depends on the location of the surface's phreatic; thus, the boundary condition on the downstream slope surface is a potential seepage surface. The conditions of boundary for transient analysis of seepage are water level vs. time variables.

A. Steady-state and transient analysis

Steady-state seepage analyses were conducted for scenarios 1, 2, and 3. The simulation began with a steady-state analysis at normal conditions to obtain a defined steady-state seepage process through the embankment. It continued with a transient analysis at filling and drawdown conditions to obtain knowledge about how the seepage process migrates with time.

B. The transient analysis simulates the seepage.

We analyzed scenarios 1,2, and 3 under two conditions.

1- Filling stage conditions over nine days (9 days).

2- Drawdown stage condition over one day (1 day).

5.6 Stress-strain analyses

- Purpose

Simulations in SIGMA/W are performed to analyze the resulting stresses and deformation in the dam scenarios under (filling and drawdown) conditions.

- Input data and boundary conditions

The load and deformation in the dam embankment were simulated using the linear elastic and nonlinear elastic hyperbolic material models.

The boundary conditions were specified with a zero-value x-displacement along the left and right boundary edges and a zero-value x/y-displacement along the base boundary edge. They applied hydrostatic pressures as a stress boundary condition (GEO-SLOPE International, 2009.).

5.7 Stability analyses

- Purpose

Simulations in SLOPE/W were carried out to find potential slip surfaces and the minimum safety factor for the dam scenarios during normal, filling, and drawdown conditions.

- Input data

The Mohr-Coulomb model was applied to all the material layers in the dam. The Mohr-Coulomb model makes use of seven main material parameters. The Poisson's ratio for the different materials has assumed the same values as in the chamrga dam project. Morgenstern-Price data from the simulation in SEEP/W is used as a parent analysis. The used material parameters in the simulated dam model are presented in table 5.1.

6 RESULTS AND ANALYSIS

The results from the simulations are presented divided into the different simulations that have been conducted. The results are presented in the same order as conducted, starting with the seepage analysis in SEEP/W. The seepage analysis was conducted to provide data to the load, deformation and Coupled analysis done in SIGMA/W, and also the analysis is done in SLOPE/W since it is using data from SIGMA/W. The results that SIGMA/W and SLOPE/W are using from SEEP/W are pore water pressure, seepage velocity, volumetric water content, etc. (Ali A. Aldulaimi, 2021).

6.1 Seepage analysis

6.1.1 Steady-state Analysis

The water flux, seepage velocity, and exit gradient results for three scenarios are presented in Figures 6.1 and 6.2. In these figures, the computed contour map of PORE WATER PRESSURE "PWP" distribution and the flow line through Chamrga Dam at the initial steady-state seepage shows that the total head on the right is larger than the total head on the left. The total head deference creates a water flow from the right to the left.

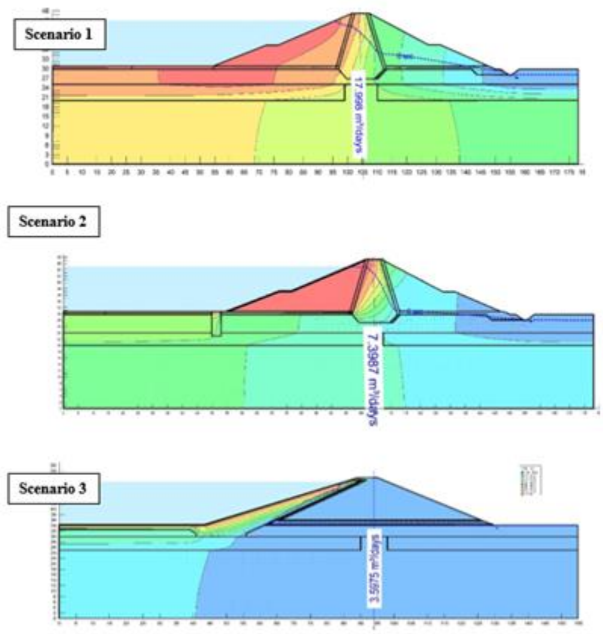


Figure 6-1. Total hydraulic head in the dam (Ali A. Aldulaimi, 2021).

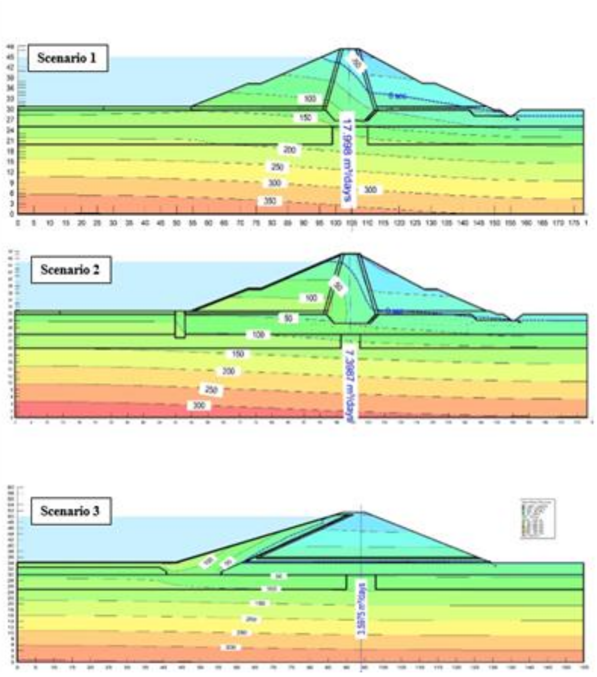


Figure 6-2. scenarios 1,2,3: Pore-water pressure in the dam (Ali A. Aldulaimi, 2021).

The phreatic surface is shown as the thick blue line, the iso-line where the pore-water pressure is zero. The pore-water pressure is negative above the phreatic surface and positive below it. The results from simulations for three scenarios under steady-state are summarized in table 6.1.

Table 6.1 *seepage analysis steady-state*

No.	Scenarios	Operation condition	Max. seepage Velocity Vmax [m/s]	Tot. flux at center Q [m3/s]	Exit gradient Toe downstream
1	Actual cross section	Normal W. L	3.85 x 10-4	2.08 x 10-4	0.84
2	Diaphragm + blanket	Normal W. L	4.3 x 10-5	8.56 x 10-5	0.81
3	inclined core	Normal W. L	2.65 x 10-5	4.15 x 10-5	0.005

6.1.2. Transient analysis

A. Filling stage in 9 days

During reservoir filling, the PWP in the upstream shell and the core increases with the increasing water level, as shown in figure 6.3, but there is almost no change in the downstream shell. Because the conductivities of the core are about four orders of magnitude lower than that of the shell, the phreatic line exits the back of the core at a very low level and shows little change with the increasing water level.

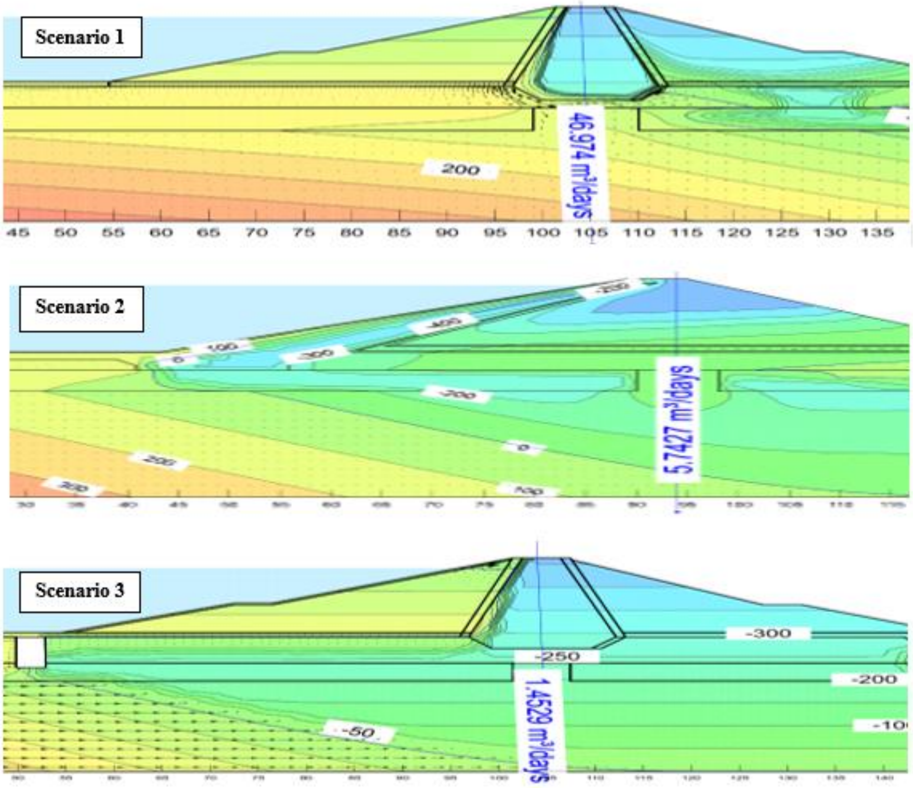


Figure 6-1. PWP developed in the dam's core on scenarios 1,2, and 3 for 9 days (Ali A. Aldulaimi, 2021).

The distributions of the pore-water pressure in the dam in three scenarios 1, 2, and 3 are almost identical when the reservoir water level rises to the normal water level.

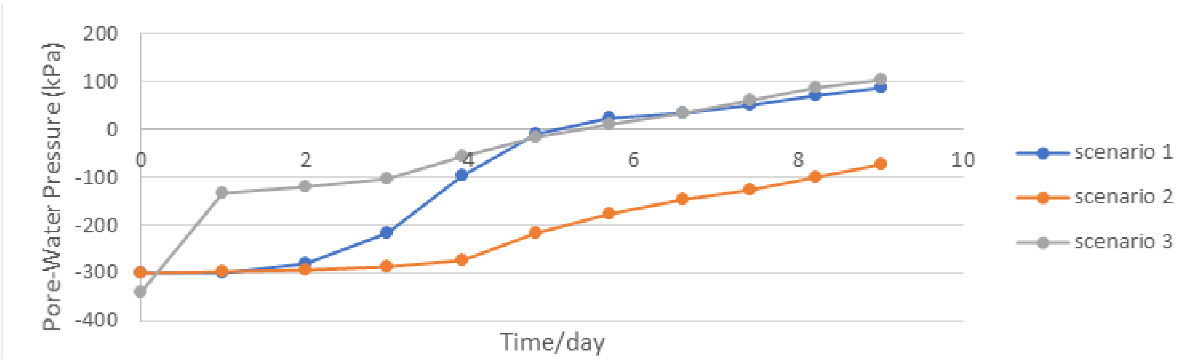


Figure 6-2. Variance of PWP development in the core of the dam.

It can be concluded that the construction and filling processes have little effect on the final distribution of pore-water pressure in the dam. as shown in figure 6.4 (Ali A. Aldulaimi, 2021).

B. Drawdown in 1 day.

The exact mechanism of this condition is as follows: It is assumed that the reservoir has been filled with water at a high level for a sufficiently long time so that the fill material of the dam is fully saturated and steady seepage established. If the reservoir is drawdown rapidly at this stage, the flow direction is reversed, causing instability in the upstream slope of the earth dam. The most critical condition of sudden drawdown means that while the water pressure acting on the upstream slope at the "full reservoir condition is removed," there is no appreciable change in the water content of the saturated soil within the dam because of the low permeability (Ali A. Aldulaimi, 2021). During rapid drawdown, PWP in the dam's body seems not to change very much at all drawdown levels. Even when the water is almost empty, PWP in the dam's body is still high because the phreatic line does not drop. The lag of the phreatic line depends on four factors: permeability coefficient of the dam fills, drawdown rate, active pore volume, and upstream slope gradient (Abadjiev, 1994) .

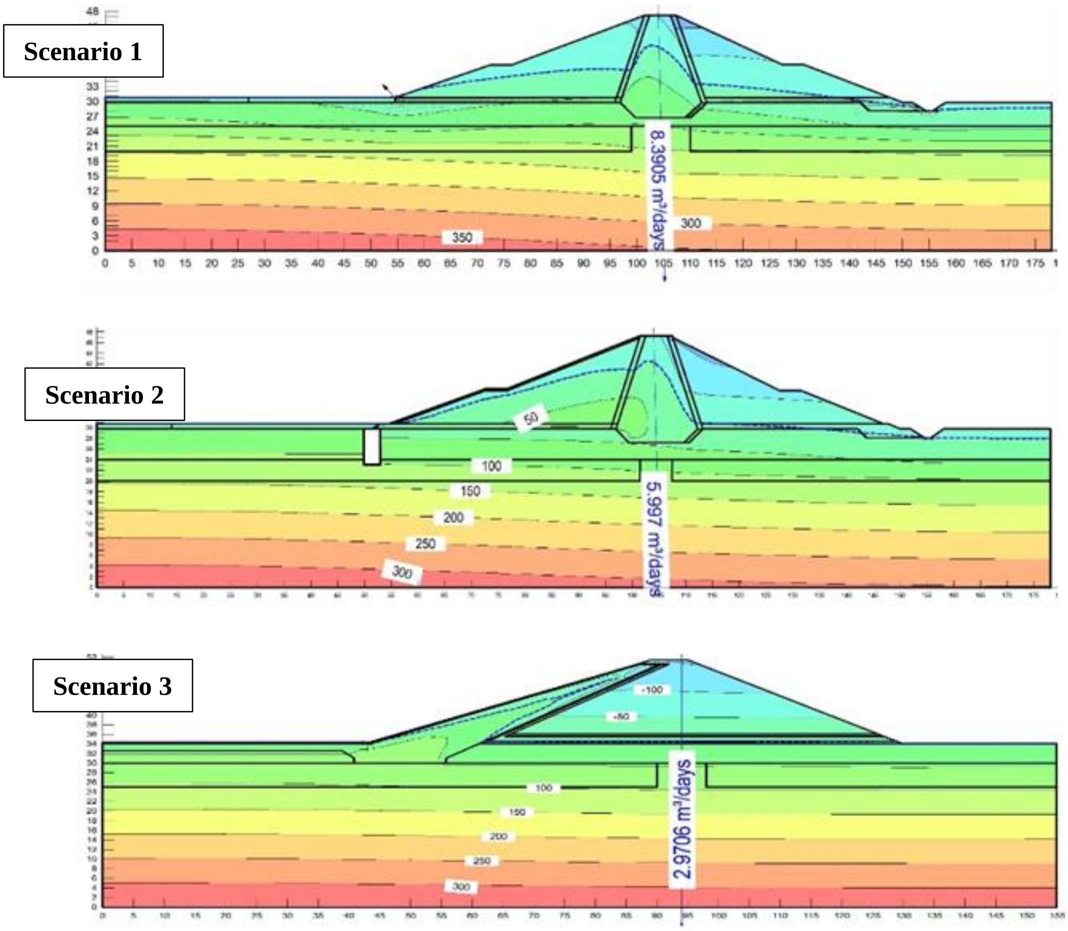


Figure 6-3. Scenarios of PWP distribution in the body at the end of a day of drawdown (Ali A. Aldulaimi, 2021).

Before rapid drawdown, the PWPs are high at the toe of the upstream slope and decrease with elevation until they are below the value of zero for those points that exist above the piezometric line. After drawdown, the PWPs are very low at the toe of the embankment and then increase as the Initiation of pore water dissipation from the dam and then decrease as the elevation increases, as presented in Figure 6.5., 6.6.

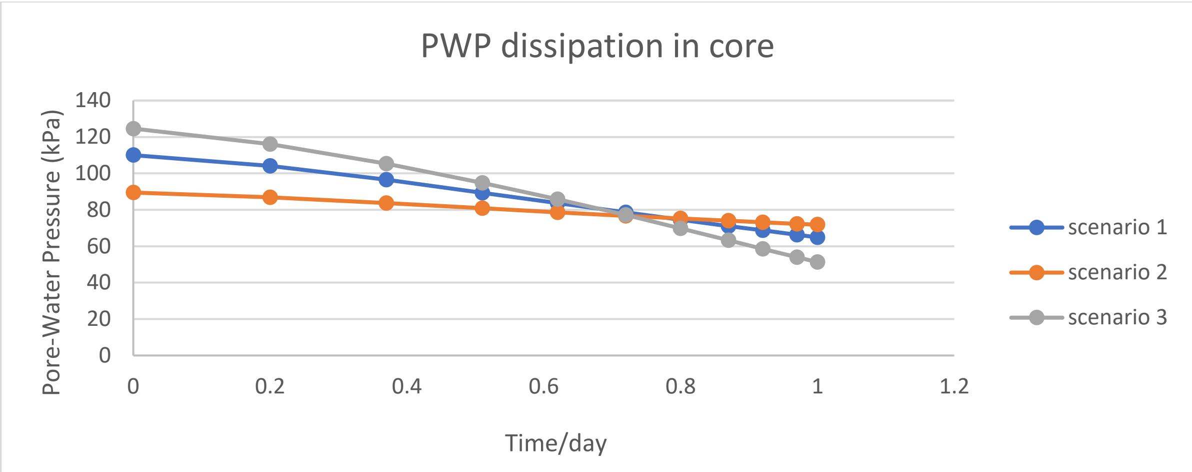


Figure 6-4. A variance of PWP Dissipation in the core of the dam.

The results from simulations in SEEP/W transient analysis during the drawdown in 1 day are summarized in table 6.2 (Ali A. Aldulaimi, 2021).

Table 6.2 Drawdown 1 day for three scenarios

No.	Scenario	Operation condition	Max. seepage Velocity Vmax [m/s]	Tot. flux at center Q [m3/s]	Exit gradient Toe upstream at the end of 1 day.
1	Actual cross section	Drawdown /1day	2.93×10^{-4}	9.7 x 10-5	1.9
2	Diaphragm + blanket	Drawdown /1day	1.47×10^{-4}	6.93 x 10-5	10.38
3	inclined core	Drawdown /1day	3×10^{-4}	8.88 x 10-5	0.005

6.2 Coupled Stress-Pore Pressure Analysis

In this analysis, the seepage analysis is solved independently of the volume change analysis. The incremental change in pore-water pressures from the seepage solutions are used at each load step in the stress-deformation calculation to determine the change in effective stresses. in a couple of analyses, we look for a change in total stress as well as changes in PWP, seep/w analysis doesn't consider a change in total stress. The result from the load and deformation analysis that has been conducted for scenarios 1,2,3 the three scenarios has been simulated during drawdown conditions in 1 day. As shown in the figures, the total stress distribution, the shear stress, and the total displacement in the dam as shown in figure 6.7 (Ali A. Aldulaimi, 2021).

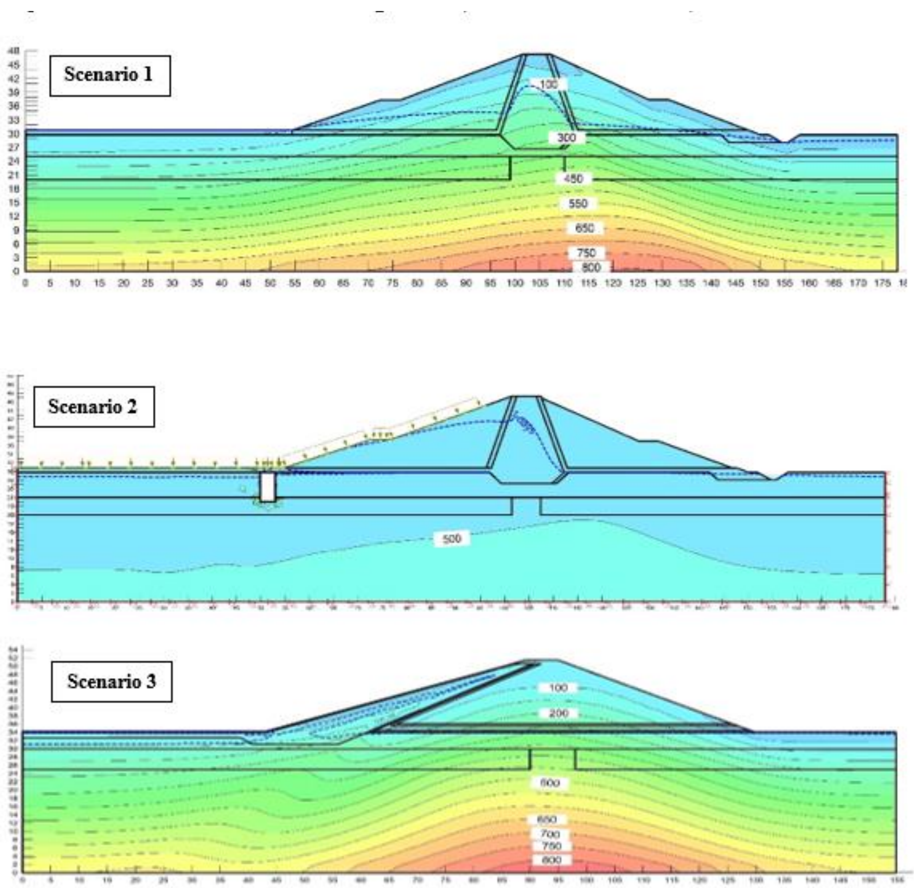


Figure 6-5. Scenarios of Coupled Stress-Pore Pressure.

The total stress is the lowest on top of the dam (zero), then it increases in the middle of the dam and when the dam elevation decreases. Figure 6.8 shows the movement of the soil particles and the deformed shape after the reservoir is suddenly drawdown in 1 day., the seepage force causes the movement of the soil particles in the direction of flow towards the reservoir. This causes a settlement at the dam crest and a swelling of the soil on the upstream face. The highest displacement value is concentrated near the water level after the drawdown, while it decreases gradually toward the foundation surface on both the upstream and the downstream sides.

The magnitude of the soil movement reaches the maximum level as soon as the drawdown process is completed (Ali A. Aldulaimi, 2021).

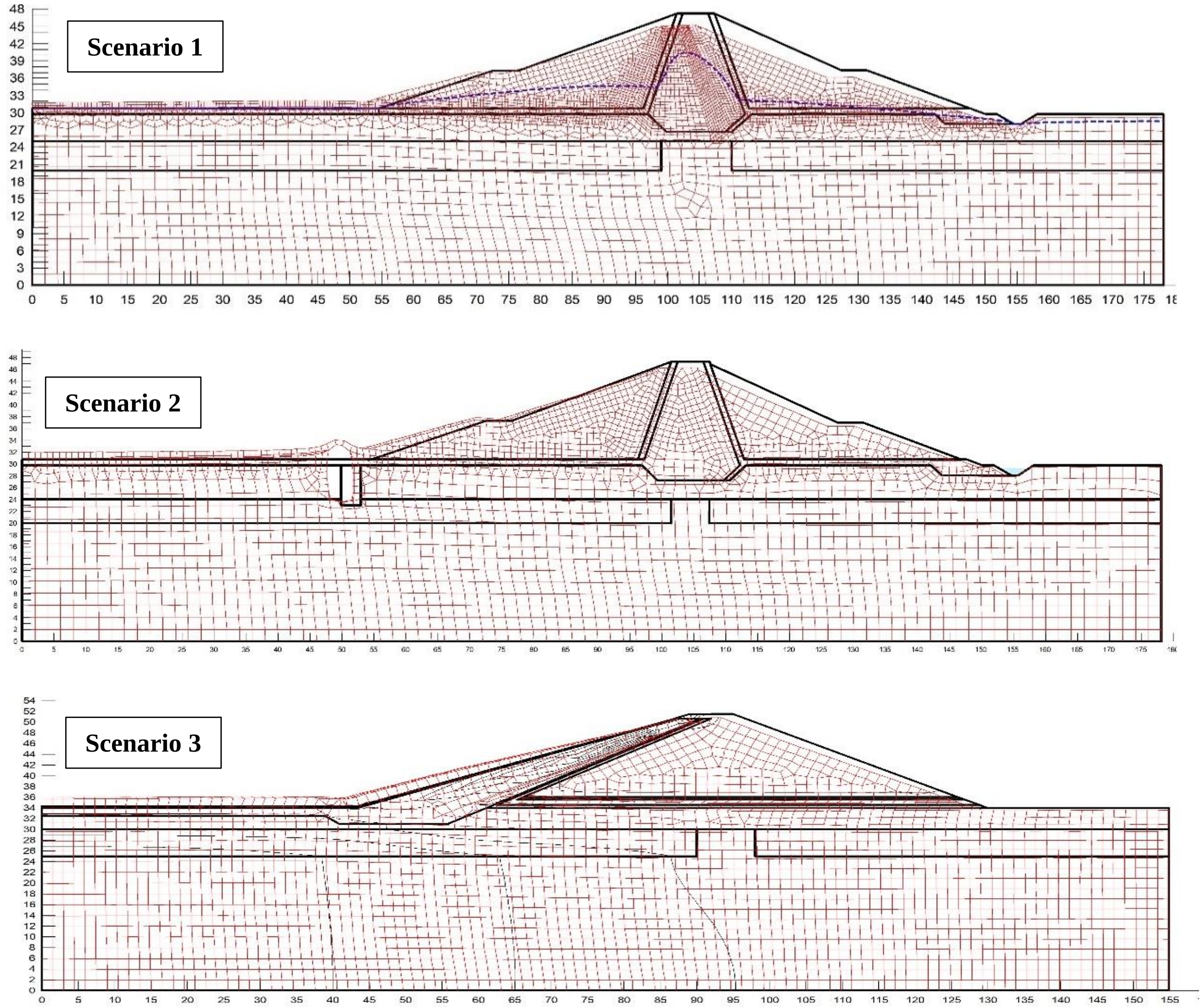


Figure 6-6. Deformed shape after the reservoir at sudden drawdown during 1 day.

- *Summary*

The results of simulations in SIGMA/W are summarized in table 6.3.

Table 6.3 *.max shear stress, max total stress, and displacement of scenarios*

No.	Scenario	Operation condition	Max. shear Stress [kPa]	Max. Total stress [kPa]	Max. Total displ. [m]
1	Actual cross section	Drawdown /1day	51.21	810.95	0.485
2	Diaphragm + blanket	Drawdown /1day	2.6	5.4	0.6114
3	inclined core	Drawdown /1day	60.26	837.57	0.474

From the coupled analysis obtained, the PWP is less than in seep/w analysis as shown in fig; because of removing the weight of water and doing a couple of analyses, there is the tendency for a slight amount of rebound of the soil. This tendency for the rebound influences PWP response, and the result is slightly lower in PWP, as shown in figure 6.9.

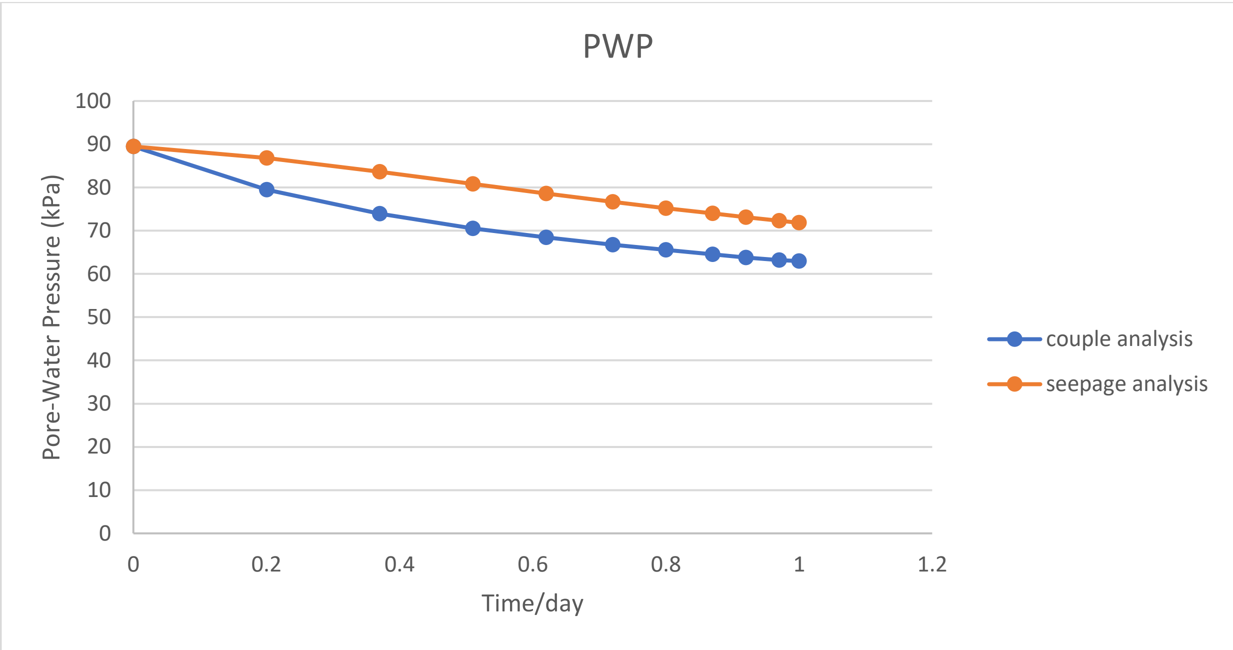


Figure 6-7. Variance of PWP in couple and seepage analysis.

6.3 Stability Analysis

The limit equilibrium (slice technique) analysis of slope stability depending on FEM is used to assess upstream dam slope stability. Results can be obtained from the application of (Morgenstern-price) techniques.

6.4 Factor of Safety

The safety factor gradually decreases as water in the reservoir decreases until all the water in the reservoir is drawn down; then, the factor of safety increases as the pore water dissipation from the dam, as presented in Fig. 22. The minimum factor of safety during slow drawdown falls above the value of (1.0), which means the slope will be in a safe condition when the water drawdown from the reservoir in (1 day) (Ali A. Aldulaimi, 2021).

A. **Scenario1**: calculating the factor of safety by using Morgenstern-price techniques from couple analysis and seep analysis only. Figs. 6.10-6.12 present the Factor of Safety for different time intervals.

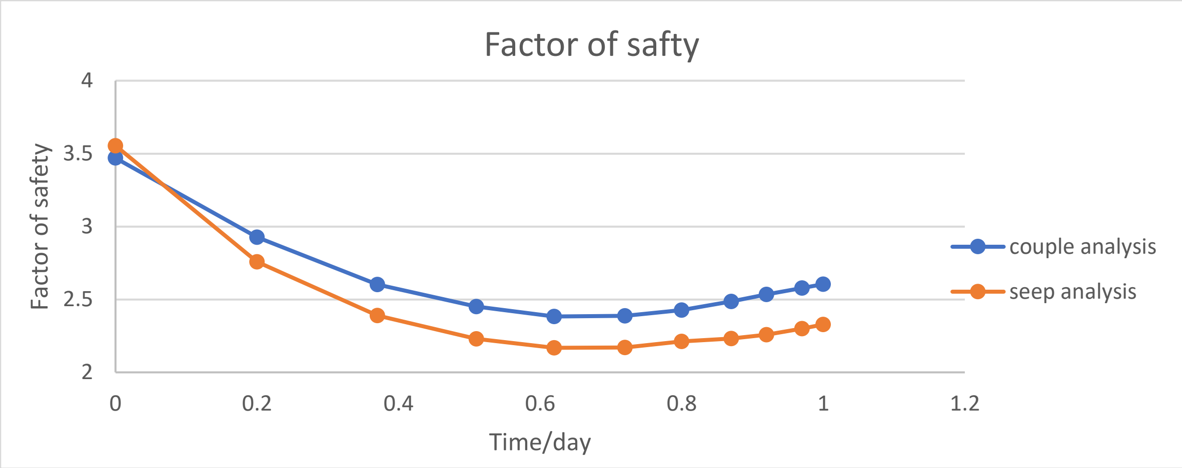


Figure 6-8. The factor of safety variance for couple and seepage analysis in scenario 1.

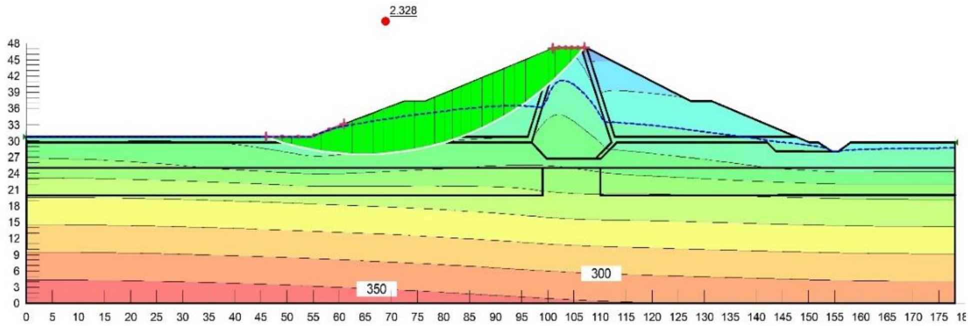


Figure 6-9. Slip surface and factor of safety for seepage analysis at scenario 1.

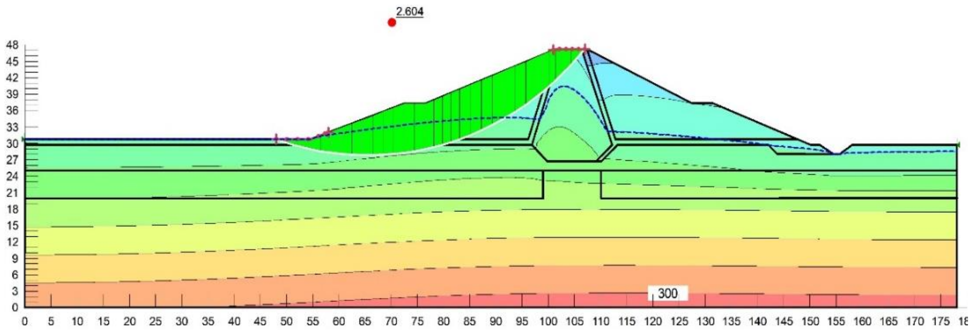


Figure 6-10. Slip surface and factor of safety for couple analysis at scenario 1 (Ali A. Aldulaimi, 2021).

B. **Scenario 2**: calculating the factor of safety by using Morgenstern-price techniques from couple analysis and seep analysis. Figs. 6.13-6.15 present the Factor of Safety for different time intervals.

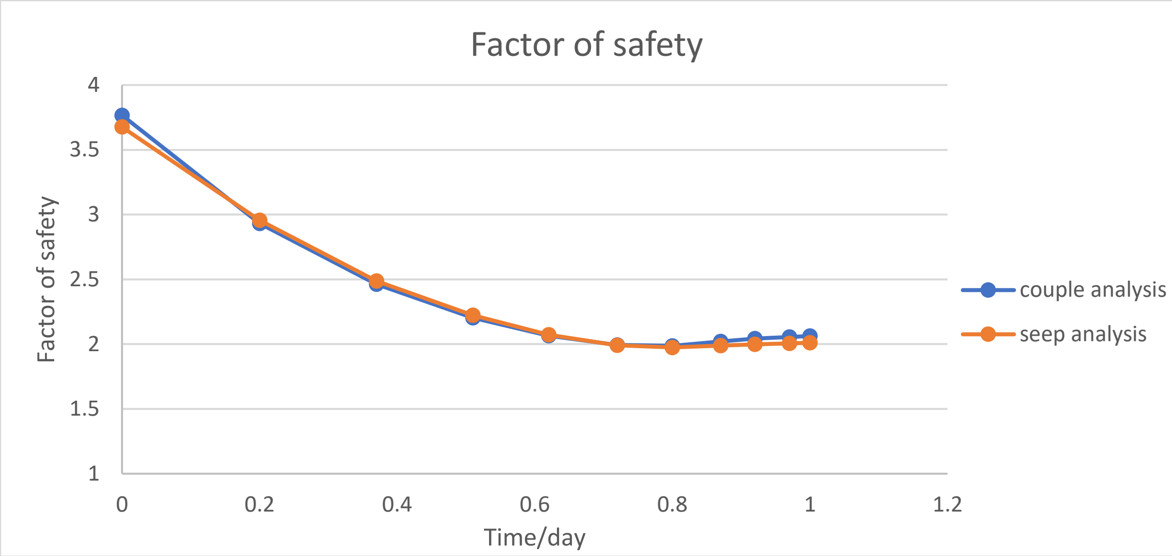


Figure 6-11. The factor of safety for two analysis scenario2.

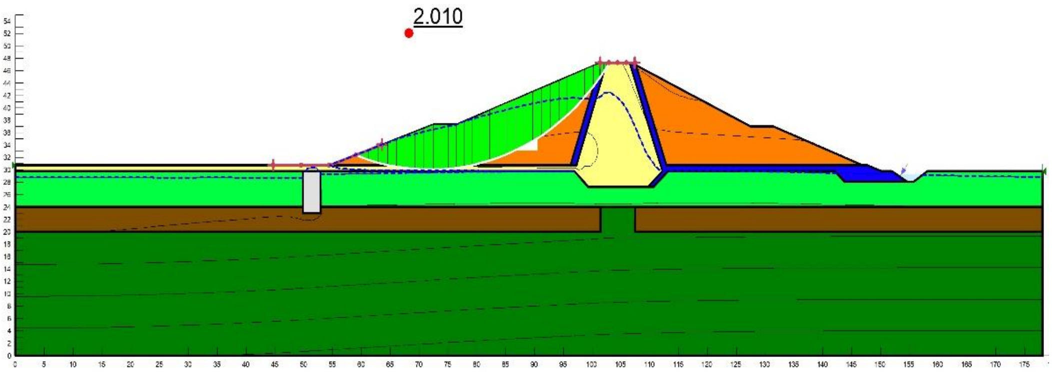


Figure 6-12. Slip surface and factor of safety for seepage analysis at scenario 2.

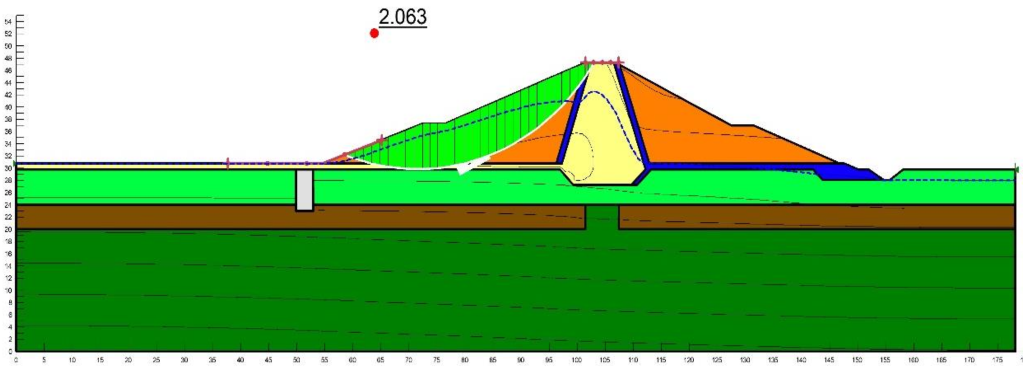


Figure 6-13. Slip surface and factor of safety for couple analysis at scenario 2 (Ali A. Aldulaimi, 2021).

C. **Scenario 3**: calculating the factor of safety by using Morgenstern-price techniques from couple analysis and seep analysis. Figs. 6.16-6.18 present the Factor of Safety for different time intervals.

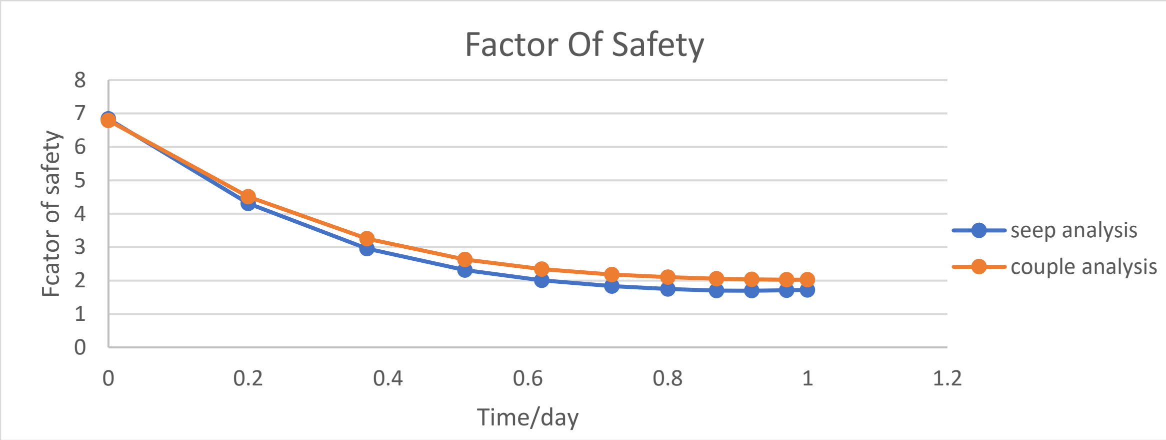


Figure 6-14. The factor of safety for two analysis scenarios 3.

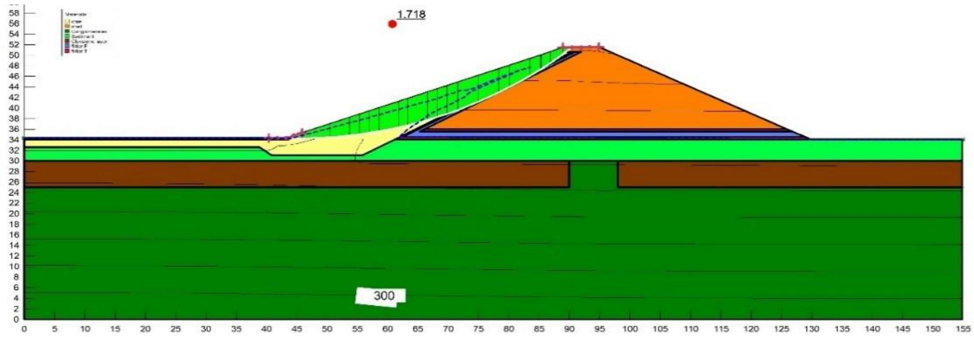


Figure 6-15. Slip surface and factor of safety for seepage analysis at scenario 3 (Ali A. Aldulaimi, 2021).

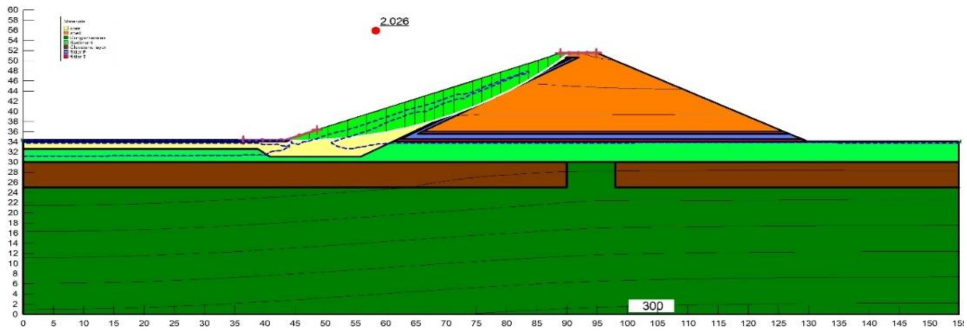


Figure 6-16. Slip surface and factor of safety for couple analysis at scenario 3 (Ali A. Aldulaimi, 2021).

The factor of safety results by using Morgenstern-price techniques for three scenarios regarding seepage analysis only and couple analysis. As shown in table 4. and figure 6.19.

Table 4 Factor of Safety for three scenarios

Scenarios	Operation condition	F.S. from seep analysis only	F.S. from couple analysis
Scenario 1	Drawdown 1 day	2.286	2.594
Scenario 2	Drawdown 1 day	2.073	2.244
Scenario 3	Drawdown 1 day	2.109	2.24

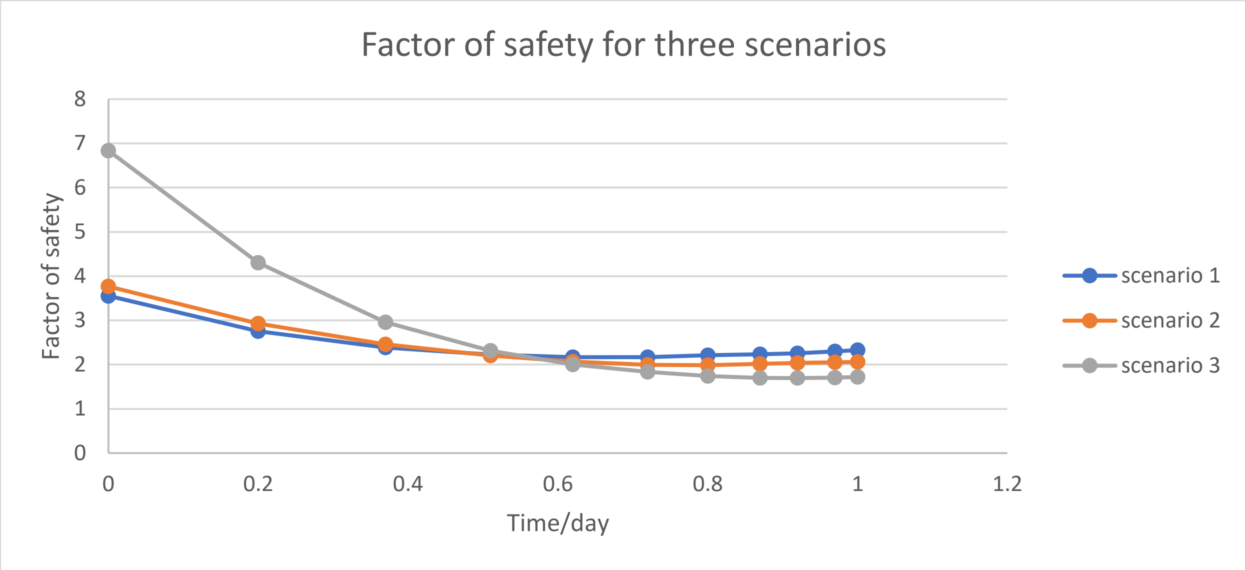


Figure 6-17.The factor of safety for three scenarios.

7 CONCLUSION AND RECOMMENDATIONS

1. From the seepage analysis under steady-state conditions, scenario 3 (inclined core) is the optimum scenario results obtain the total flux 2.65x10-5 m/s, the seepage velocity 4.15x10-5 m3/s and exit gradient in the toe of downstream 0.005 (Ali A. Aldulaimi, 2021).
2. During the filling stage at nine days, the PWP develops in the dam's core is rapid in scenario three from -350kpa to +100.
3. During the drawdown, in 1 day, the dissipation of PWP in the core of the dam in scenario 3 (inclined core) is the optimum that ranges from 125 kpa to 50 kpa
4. During Coupled Stress-Pore Pressure Analysis obtained the maximum shear stress 60.26 kpa, maximum total stress 837.57 kpa, and the X.Y. total displacement of 0.474 is in scenario 3 (inclined core)
5. In couple, the analysis considers the change in total stress as well as the change in PWP.
6. The factor of safety against sliding of the dam slope during rapid drawdown decreases within the start of rapid drawdown of water then starts to increase. This is due to the dissipation of excess PWP with time, increasing the effective stresses in the soil andncreasing its shear strength (Ali A. Aldulaimi, 2021).

7. When the reservoir rapidly drawdown the pore, water pressures in the dam are reduced in two ways: there is an immediate elastic effect by removing the water head from the reservoir and slow dissipation of PWP from the dam body by drainage.
8. During the drawdown, the minimum factor of safety falls above the value of (1.0) for three scenarios which means the upstream slope will be in a safe condition during the rapid drawdown sequences.
9. During the slow drawdown, the factor of safety gradually decreases as water in the reservoir decrease until all the water in the reservoir is drawn down; then, the factor of safety increase as the pore water dissipation from the embankment.
10. For all scenarios obtained factor of safety from two analyses 1,) seepage analysis only and 2) couple analysis that's FS. in couple analysis little be larger than from seepage analysis.
11. Internal erosion initiates when the hydraulic forces exceed the ability of the materials in the dam and foundation to resist them (Ali A. Aldulaimi, 2021).
12. Internal erosion may be arrested in zoned dams if any filters are effective. Inhomogeneous dams, there are no zones; consequently, if erosion initiates, it cannot be arrested
13. The ability of a dam to resist erosive forces is not constant over time. This is because cracking from a settlement, or hydraulic fracture, or zones of low stress, may create sites where erosion can initiate even at water levels previously experienced

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