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RESEARCH PAPER

Seepage and Stability Analysis of the Eyvashan Earth Dam under Drawdown Conditions

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ABSTRACT: The rapid drawdown condition to control floods and irrigation is one of the things that may occur over the lifetime of the dam. Also, the stability of the dam at the rapid drawdown will be more important due to the faster reduction of the water level of the dam reservoir than the pore water pressure. In this study, the finite element method and GeoStudio software used to study the seepage from the body earth dam. Also, the complete elastic-plastic model of Mohr-Coulomb is considered in the analysis. In this study, the stability analysis of the Eyvshvan earth dam after rapid drawdown due water to release of the dam reservoir to downstream agricultural lands during drought crisis, is investigated. For the validation, first, the results of the pore water pressure instrument were compared with the results of numerical analysis. The results of multivariate regression analysis (coefficient of determination) showed very good agreement (R^2=0.98). The results showed that the phreatic line remains after 29 days from the start of the rapid drawdown of the reservoir, while half of the volume of the drained reservoir remains at 1842 masl (1/3 of the crest). The analysis of dam stability during rapid drawdown using both Morgenstern-Price and Bishop Methods showed that the most critical situation would occur after 42 days of discharge with a factor of safety (FoS) of 1.71, with no stability hazard and the upstream slope would be safe.

Keywords: Eyvashan Earth Dam, Factor of Safety, Geostudio, Pore Water Pressure, Rapid Drawdown.

1. Introduction

After the dam reservoir is filled (impounding) and the water penetrates the body of the dam, any rapid and slow drawdown in the reservoir may cause damage and cracks in the upstream slope of the dam. In this case, the drop in reservoir water's height is faster than the depletion of the pore water pressure body or foundation of the dam. The rapid drawdown of the reservoir water reduces the resistive force against the propulsion force. Because, firstly, the pressure on the upstream as a superconductor; secondly, the saturation line in the dam body is placed above the reservoir's surface, and the drainage cannot decompress the pore water pressure with the speed at which the reservoir water level decreases. Zedan et al. (2018) studied the

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behavior of the Khasa-Chai Dam using Geo-Slope software to find the factor of safety of the upstream slip surface during the drawdown conditions. The results of their studies showed that the water flux decreases fast relating to reservoir slow drawdown as the water in the rapid drawdown.

Sica et al. (2019) studied the rapid drawdown of Campolattaro Dam placed in a highly seismic area of Southern Italy, using FLAC2D software. Their studies showed that a seismic previously experienced by the dam further contribute to decreasing dam stability during the rapid drawdown especially during the first stages of reservoir reduction. Also, the faster the drawdown, the smaller the dam safety factor against stability (FOS) with more prominent effects of the initial (pre-drawdown) soil conditions. When the phreatic line (free surface) falls slowly or remains almost at the same position, it is considered as ”rapid” drawdown. The lag of the phreatic line or the rate of drawdown depends on four factors: permeability coefficient of the dam, rapid drawdown rate, pore active volume, and upstream slope. The exit gradient and the rate of flow at the downstream face decrease with time as the water in the reservoir drawdown which means the factor of safety against boiling increases with time (Abadjiev, 1994).

Nian et al. (2011) investigated the slope stability of homogeneous dams under rapid drawdown. In addition to the saturated and unsaturated analyzes, they also examined the stability of the upstream slope of the dam during the rapid drawdown. Lane and Griffiths (2000) produced operating charts for structure safety using FEM to provide a direct method to assess slope stability of the partial and complete submerged soil under the different rates of reservoir drawdown.

Numerous studies have reported the effects drawdown of dam slope stability using limit analyses, numerical analyses, and laboratory tests (Yan et al., 2010; Wang et al., 2012; Viratjandr and Michalowski, 2006; Gao et al., 2014; Alonso et al., 2016). All embankment dams are subject to some seepage passing through, under, and around them. If uncontrolled, seepage may be detrimental to the stability of the structure as a result of excess pore water pressures, or by internal erosion (Fattah et al., 2017).

López-Acosta et al. (2014) utilized the SEEP/W program, based on FEM, to study the influence of filter in the reduction of the soil erosion problems under drawdown conditions. Three filter types were analyzed at a drawdown rate of 1 m/day. The results showed better efficiency in reducing the pore water pressure when using two horizontal filters at the toes of the upstream and downstream slope. Zomorodian and Abodollahzadeh (2010) investigated the influence of horizontal drains on the upstream slope of rockfill dams in the condition of rapid drawdown using limit equilibrium and finite element methods. The development of pore water pressure, outpouring rate of flow, and factor of safety was inspected. The amount of water leakage and seepage in the dam was investigated by using the SEEP/W software and the static slope stability analysis by using the SLOPE/W software.

Zhang and Luo (2017) developed a simplified method to analyze the stability of a strain-softening slope for determining the subsidiary shear deformation under rapid drawdown. This method was based on a new algorithm and was verified to be effective in the stability evolutionary analysis of the strain-softening slopes caused by the dropping of the water level. The results showed that the behavior of the strain-softening and the initial level of water have a significant effect on the critical slip surface and the slope stability under the drawdown event.

The behavior of progressive failure is important to prevent the overestimation of the slope factor of safety. Stark and Jafari (2018) recently utilized the finite element method to investigate the reasons that caused the upstream slope failure of the San Luis Dam under a drawdown event. Alonso and Pinyol (2016) calculated the distributions of the pore water pressure under rapid drawdown conditions using different approaches. They analyzed two real cases to study the effect of rapid drawdown. The first case study involved the Glen Shira Dam in Scotland. A similar analysis was performed for the upstream slope of the Glen Shira Dam, Scotland, and numerical results were compared with field measurements during a controlled drawdown. A key aspect of the case was the correct characterization of permeability of a representative soil profile. This case allows the validation of the computational results through comparison with field measurements. The upstream slope was covered by a rockfill filter for increasing the stability of the slope. A thin wall of reinforced concrete also used in the dam center. Another modeled case was the slope failure of the Canelles Reservoir in Spain after a reservoir drawdown event. The rainfall effect was also simulated in the model. The results showed that coupled flow deformation analysis is necessary for saturated and unsaturated soils to measure the distribution of the pore water pressure within the slope. Salmasi et al. (2015) used numerical simulation and GeoStudio software to measure the effect of relief wells on reducing the load on a homogeneous dam.

Bahrami et al. (2018) analyzed the static and quasi-static stability of the Narmab Dam and sensitivity analysis with GeoStudio Slope/w software. They found that according to static and quasi-static conditions, Narmab Dam is stable in all loading stages (end of construction, first impounding, and steady-state seepage). For static conditions of the end of construction, the sensitivity of adhesion is greater than the angle of the internal friction, but in other conditions, the sensitivity of the friction angle has more effects.

Boroomand and Mohammadi (2019) investigated the Alborz Dam seepage considering the uncertainty in soil hydraulic parameters. Their results showed that uncertainty in the hydraulic parameters of the Alborz Dam is notable, and the risk is important in this dam. It was also found that the quantity of seepage increases considerably when the dam is without clay core, therefore, the core is necessary to decrease the amount of seepage through the earth dam. Siacara et al. (2020) studied the reliability analysis of the rapid drawdown of an earth dam using a direct coupling.

In this paper, the rapid drawdown condition is investigated by instrument results and the finite element method for the Eyvashan earth dam. Changes in pore water pressure and stability during the rapid drawdown of the reservoir will be also studied.

2. Methodology

2.1. Eyvashan Earth Dam- Case Study

Eyvashan earth dam has 1.5 km distance from the upstream of the village of Eyvashan and about 57 km from Khorramabad in the coordinates of 48°49'2" and 33°28'31" degrees north, located on the Horod River. The area of the Horod river drainage basin up to the dam axis is 120 km^2. The dam is a rockfill earth dam type. The dam was designed with a maximum height of 68 m and a crest length of 650 m and a normal water level of 1864 masl (meters above sea level). It has a storage capacity of 52 million m^3. The upstream slope is 1 v: 2.5 h and the downstream local slopes are 1 v: 1.85 h and 1 v: 2.0 h. The area of the lake at a normal level is 2.3 km^2. Figure 1, presents the Eyvashan earth dam.

The construction site of the Eyvashan earth dam from the geological viewpoint of the rock bed includes conglomerate rocks that have outcrops in the boundaries of these rocks but deposited on the conglomerate rock in the bottom of the valley of alluvial sedimentary deposits. In terms of lithology, the conglomerate of the dam axis and the lake is composed of limestone, sandstone, slate, metamorphic rocks and igneous rocky parts with a silty-sandy and sometimes silt-clay matrix.

2.2. Instrumentation Sections of Eyvashan Earth Dam

The instrumentation of the Eyvashan earth dam in 4 sections with numbers 228-228, 229-229, 230-230 and 231-231 is considered in 0 + 249, 0 + 356, 0 + 477 and 0 + 546, respectively. In the present study, the characterization of the instrument installed in the section 229 of Eyvashan earth dam is investigated. In Figure 2, the position of the cross-sections and the section of the instrumentation 229 of the dam are shown. The highest level of instrumentation is related to the 229-229 cross-section with 7 levels and the least number of instrumentation levels related to the 231-231 section with 5 levels. The electrical piezometer embankment (EPE) on the maximum cross-section of the Eyvashan earth dam is shown in Figure 2.

2.3. Governing Equation for Seepage Analysis

The long-time steady-state and the transient analysis of the seepage are conducted by using numerical models. The numerical model of Seep/W is applied in which an instrument is using the finite element method to simulate the water flowing through porous media (Seep/W). Seep/W is used to simulate the groundwater movement in both the steady or transient states. The software is based on the flow of water in saturated and unsaturated soils and is based on Darcy's law, which may be expressed as a Eq. (1):

$$q=k.i \tag{1}$$

in which q: is the specific discharge, k: is the hydraulic conductivity, and i: is the gradient of the total hydraulic head.

The hydraulic conductivity in Eq. (1) is maintained at a constant value in the fully saturated soil, while it is modeled as various values for the unsaturated soil changing with the water content of the soil. The basis of the seepage equations is that the difference between the inflow and outflow values is equal to the water volume changes over time. Thus, the main equation governing seepage problems is expressed as follows:

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial H}{\partial y}\right)+Q=\frac{\partial \theta}{\partial t} \tag{2}$$

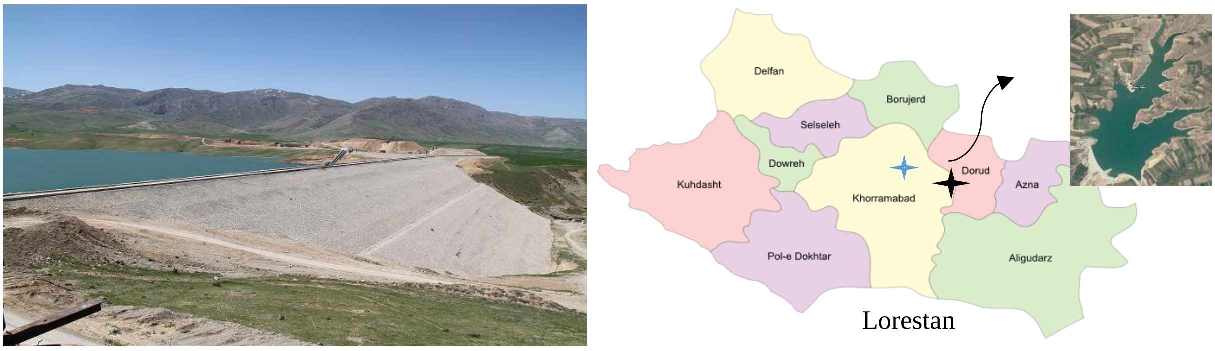


Fig. 1. Eyvashan earth dam

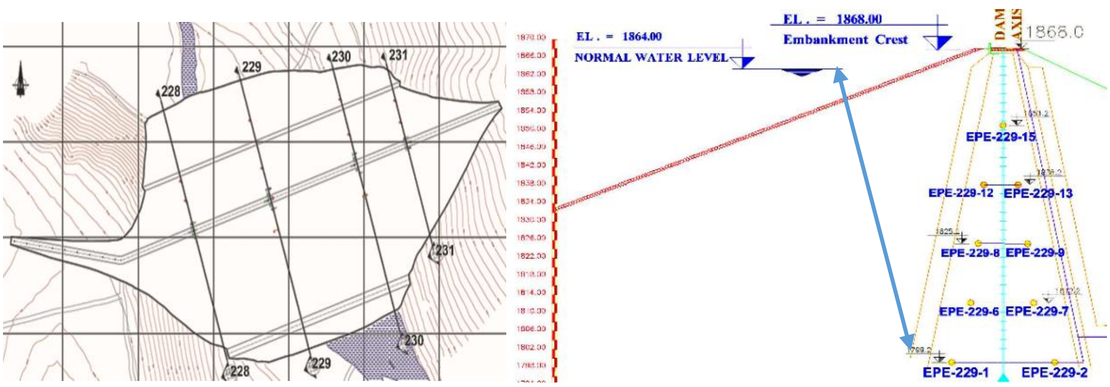


Fig. 2. Position of the instrument on the plan and maximum cross-section of the Eyvashan earth dam

in which ∂H: is the total head, k_x: is the permeability coefficient in x-direction, k_y: is the permeability coefficient in y-direction, Q: is the leakage from boundary, $\partial\theta$: is the water content, and t: is the time.

If the steady-state of the outflow and inlet is constant at the equilibrium state, the main equation will be transformed into Eq. (3):

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial H}{\partial y}\right)+Q=0 \qquad (3)$$

Mainly, this equation equates the water flux flowing through a two-dimensional elemental volume in x and y-directions plus the applied boundary flux to the volumetric water content with consideration to the time. The change in the volumetric water content is related to the changes in the stress state variables: $(\sigma - ua)$ and $(ua - uw)$, which σ: is the total stress, ua: is the pore air pressure, and uw: is the pore water pressure. It is assumed in Seep/W that the total stress in the soil is constant, which means there is no change in the variable of $(\sigma - ua)$. Also, the program assumes no change in the pore air pressure (ua). Therefore, the change in the volumetric water content of soil depends only on the change in the pore water pressure (uw). Changes in the volume of water by Eq. (4) are related to changes in the pore water pressure.

$$\partial\theta = mw.\gamma w.\partial(H-y) \qquad (4)$$

in which mw: is the storage curve slope, γw: is the unite weight of water, H: is the total hydraulic head, and y: is the elevation.

By substituting Eq. (4) into Eq. (2), the general governing differential equation may be stated as (Seep/W):

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial H}{\partial y}\right)+Q= mw.\gamma w.\partial(H-y) \qquad (5)$$

2.4. Governing Equation for Slope Stability Analysis

This section discusses the underlying theory used in the analysis of the stability of slopes in this research. The critical surface of failure may lie between the topsoil and a cylindrical surface in a finite slope. The shear strength on the critical surface consists of two components, soil cohesion, and frictional resistance. Slope/W uses the theory of finite equilibrium forces and torques to calculate the fracture stability coefficient. For the analysis based on effective stress, the shear strength is determined by Eq. (6):

$$\tau = c` + (\sigma_n - u).\tan\varphi` \qquad (6)$$

in which τ: is the shear strength, $c`$: is the effective cohesion, $\sigma_n$: is the total normal stress, $u$: is the pore water pressure and $\varphi`$: is the effective internal friction angle. Stability analysis includes landslide crossing the soil mass and segmentation with slices vertical. The slip surface may be circular, composite, or a straight line.

2.5. Monitoring of Electrical Piezometer Embankment (EPE)

In summer 2017, to prevent drying up of the river and occurrence of the environmental disasters, the provision of the environmental rights of the river, as well as to compensate for the shortage of water from Beiranshahr to the Pol-e Dokhtar city about 9.2 liters per second of water were released from the Eyvashan earth dam in 58 days. The Kashkan River forms an important part of the riverside stream of Karkheh River and includes about one-third of Lorestan province. The unprecedented drop in the Kashkan River discharge in this season is due to the absolute performance of the climatic factors, as well as the unprecedented planting of hydrophilic species, especially rice, which plumbs the water of the Kashkan River. Eyvashan earth dam has target lands with a network area of 2500 ha, and because its network has not been completed, there is the possibility of releasing water downstream and compensating for a shortage of 46 million m^3. Therefore, the results of the piezometers installed in the core of the Eyvashan earth dam in the conditions of rapid drawdown reservoirs were investigated within 58 days. The illustrated results in Figure 3 shows that volume of the reservoir at the level of 1864 masl is equivalent to 52 million m^3 and will decrease to 6 million m^3 after the rapid drawdown of the reservoir at the level of 1814 masl (dead volume). On the 1806 masl, two piezometers are located on the up and down core axis. At the beginning of the rapid drawdown in the reservoir, and the level of 1864 masl, the highest pore water pressure in the piezometer 229-1 (reservoir side) was 505 kPa and in the last reading after 58 days at the level of 1814 masl, it was reduced to 214 kPa. In the 229-2 piezometer, a uniform process and very small changes in pore water pressure are observed (127 to 70 kPa).

At the level of 1812 masl, two piezometers are located on the up and down Ax-core. Figure 4 shows that at the ow sbeginning of the rapid drawdown in the reservoir and at the level of 1864 masl, the maximum pore water pressure in the piezometers 229-6 (side of the reservoir) was 360 kPa, and at the last reading at the level of 1814 masl, it was reduced to 106 kPa. In piezometers 229-7, the results are mild and the pore water pressure has dropped from 79 to14 kPa.

At the level of 1825 masl, two piezometers are located on the up and down Ax-core. According to Figure 5 at the beginning of the rapid drawdown in the reservoir and at the level of 1864 masl, the maximum pore water pressure in the piezometers 229-8 (side of the reservoir) was 270 kPa, and at the last reading at the level of 1814 masl, it was reduced to 14 kPa. In piezometers 229-9, the results are mild and the pore water pressure has dropped from 43 to 3 kPa.

At the level of 1838 masl, two piezometers are located on the up and down Ax-core. IT can be seen if Figure 6 that at the beginning of the rapid drawdown in the reservoir and at the level of 1864 masl, the maximum pore water pressure in the piezometers 229-12 (side of the reservoir) was 149 kPa, and at the last reading at the level of 1814 masl, it was reduced to -242 kPa. The pore water pressure was read at the 229-13 piezometer and before the rapid drawdown of the reservoir -118, which decreased to -291 after 58 days.

At the level of 1851 masl, one piezometer was installed on the clay core ax. Figure 7 shows that the pore water pressure dropped to 59 kPa before the rapid drawdown in the reservoir and at the end of the 58 days, the drainage of the reservoir decreased to -375 kPa.

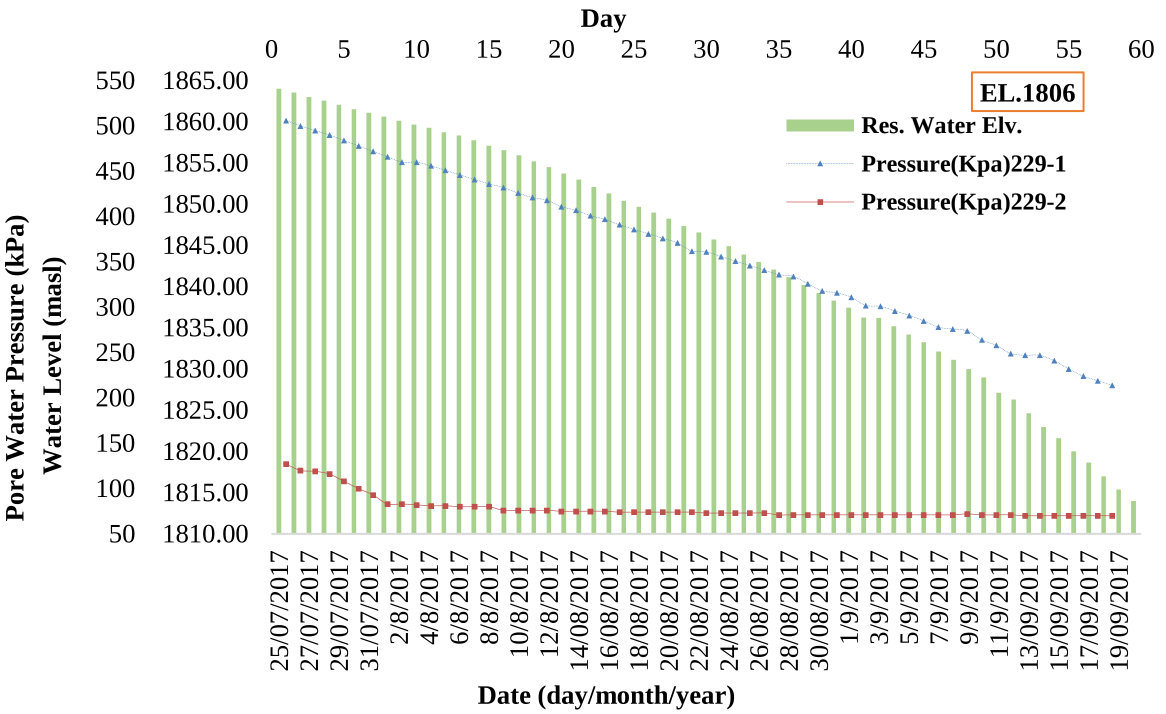


Fig. 3. Pore water pressure in the core of Eyvashan earth dam during rapid drawdown (EL.1806 masl)

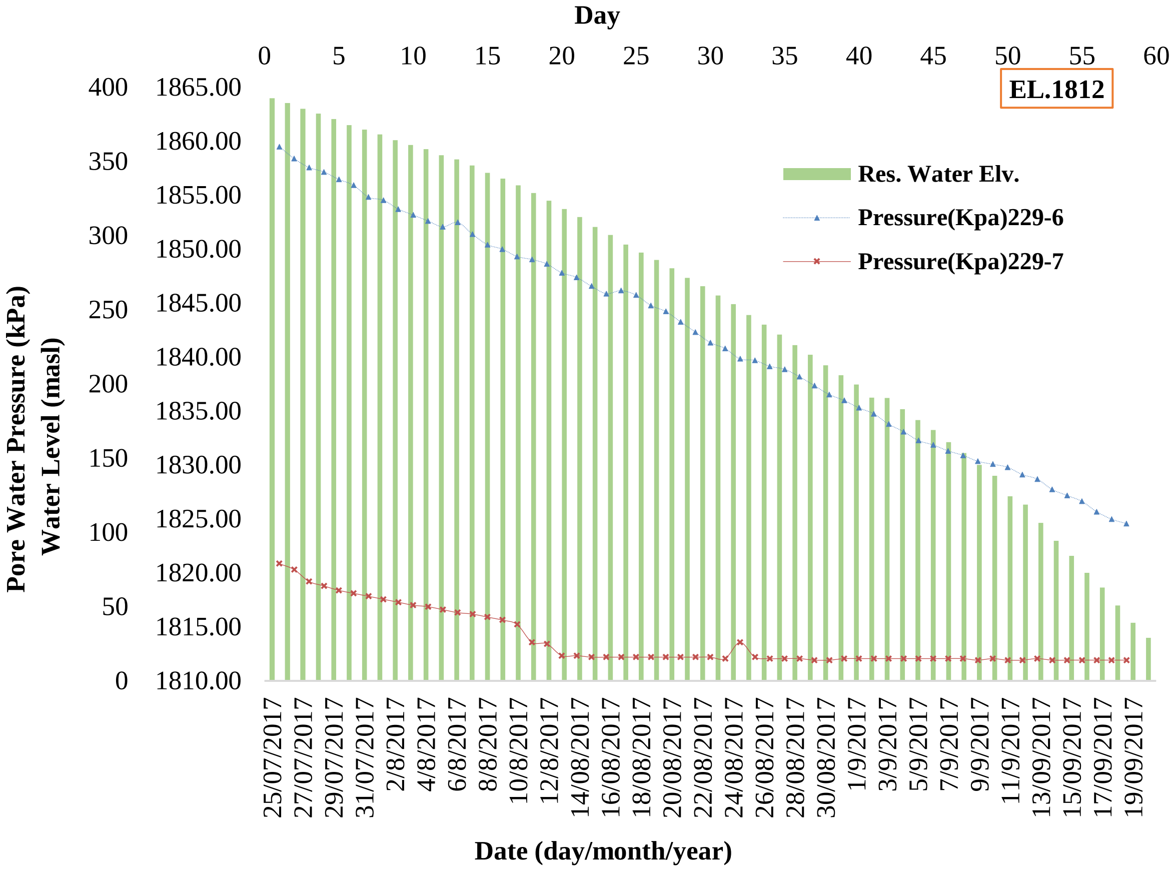


Fig. 4. Pore water pressure in the core of Eyvashan earth dam during rapid drawdown (EL.1812 masl)

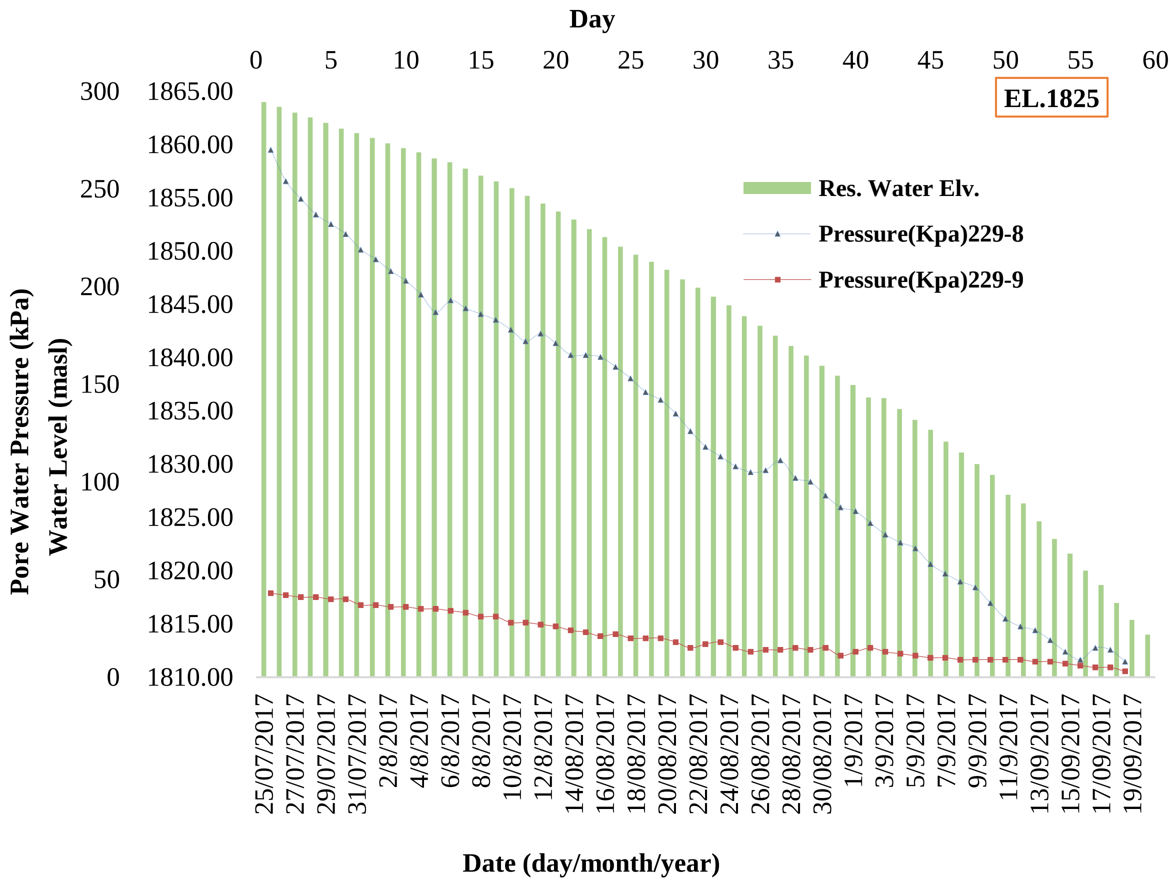


Fig. 5. Pore water pressure in the core of Eyvashan earth dam during rapid drawdown (EL.1825 masl)

Fig. 6. Pore water pressure in the core of Eyvashan earth dam during rapid drawdown (EL.1838 masl)

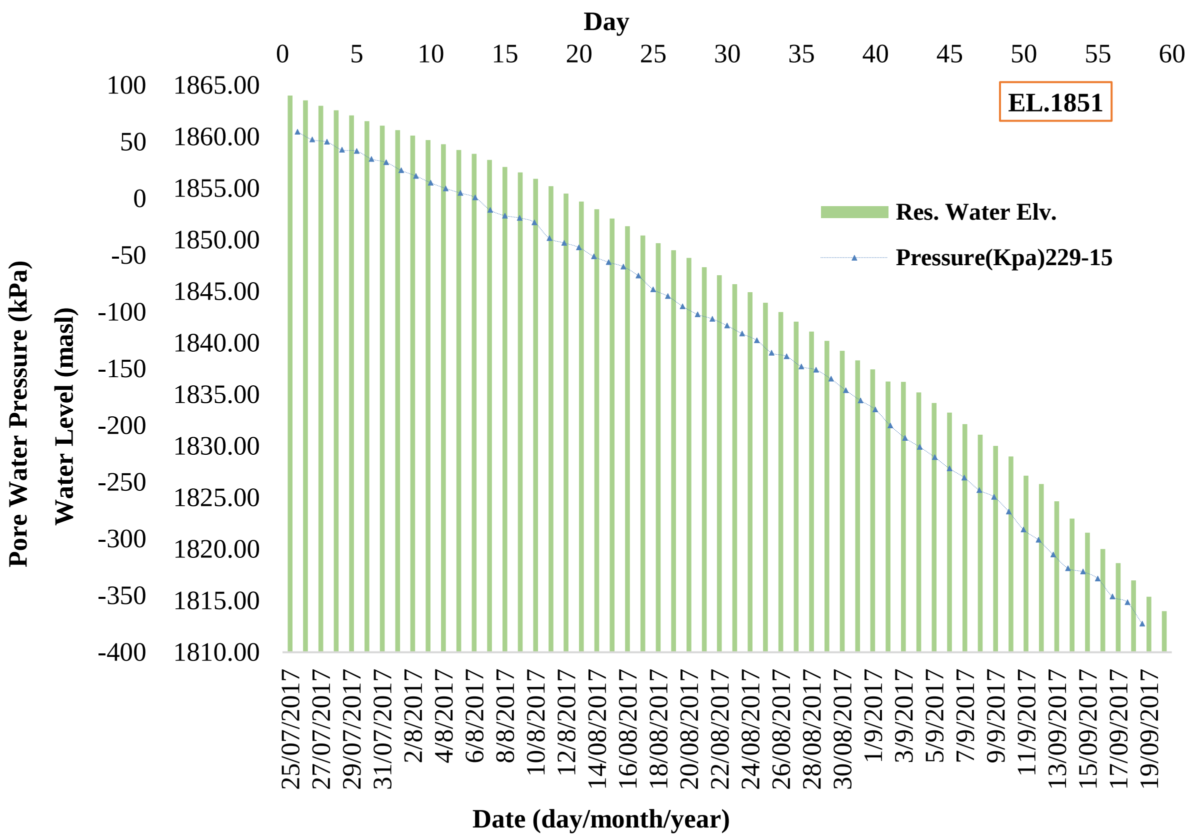


Fig. 7. Pore water pressure in the core of Eyvashan earth dam during rapid drawdown (EL.1851 masl)

3. Modeling and Analysis

To verify the data obtained from instrumentation readings, the pore water pressure on the Eyvashan earth dam was modeled using the GeoStudio software. Then the results of the numerical analysis were compared with the results of the observation. The behavior of the material of the dam body and the core in the analysis and the complete elastic-plastic model of Mohr-Coulomb were considered. The Mohr-Coulomb model is one of the simplest soil behavioral models. Since most soil parameters such as dough and elastic soil are present in this model, it is appropriate to model most soil behavioral conditions. In FEM based analysis, the selection of the proper shape of the element, element number, element size, etc. is crucial to minimize their effect in the calculation of the numerical results. Consequently, the mixed element (triangle and quadrilateral) have been considered. The number of elements and nods used in the main model was 2670 and 3105, respectively. Tables 1 and 2 show the parameters of the Mohr-Coulomb elasto-plastic model for various zones of the dam. For the drawdown analysis, the boundary condition is specified as a hydrostatic pressure for the dam reservoir. The hydrostatic pressure (water level) is 64 m on the upstream side and zero on the downstream side (dry). The displacement in the x-direction is specified as a fixed boundary condition on the left and the right of the ends of the foundation. Fixed x and y displacement condition is also specified at the bottom of the dam model. In the transient analysis, the boundary conditions for seepage vary in value over time (Figure 8). The rapid drawdown of the upstream water is simulated by lowering the water level from 64 m to 14 m in 58 days. Process and solution algorithm is described in Figure 9.

In this study, two steady and transient modes of modeling have been used. Before the rapid drawdown of the reservoir, a steady-state is used for modeling. The transient seepage analysis includes determining pore-water pressures during the drawdown and stability analysis of the upstream dam slope. For the analysis, each material was assumed to be homogeneous and isotropic. The steady-state results for the Eyvashan earth dam are shown in Figure 10a. The low permeability of both the core and the complete cut-off wall reduces the magnitude and velocity of the seepage, which keeps the total head and the phreatic level at the upstream at a constant value. Inside the core, the total head is suddenly reduced to a very low value, and the phreatic line drops. During the drawdown event, water occupying the soil voids begins to flow out of the dam.

For rapid drawdown modeling, transient analysis is used. The modeling was done in 58 days to match the actual results. Figure 10b shows the arrows indicating the flow direction for the case where the reservoir level has dropped to half of its initial level in fourteen days. The results showed that a substantial volume of water will seep out the dam starting from the core and the cut-off wall faces because of the low permeability of the core and the cut-off wall. The results of the numerical analysis of the Eyvashan earth dam indicate that the stagnant water level which has fallen without the water in the body, has the opportunity to evacuate. In this case, the hydrostatic pressure on the outer surface of the upstream slope is eliminated, while the overpressure of the pore water pressure remaining in the body remains.

Drawdown ratio is the most important factor affecting rapid drawdown. The drawdown ratio is shown as L/H, (L: reservoir water drop due to rapid drawdown, H: the normal water level) (Griffiths and Lane, 2000) (see Figure 11).

The drawdown rate is also the drainage drop of the reservoir water relative to the time indicated by R (cm or m/day) (Berilgen, 2007). United States Bureau of Reclamation (USBR) (1987) has proposed a critical drawdown rate of 0.5 ft (15 cm) per day. In the transient analysis, the reservoir water level changes with time. Therefore, the head of water (H) specified at the upstream of the dam is dependent on time. The total head of water versus time illustrated in Figure 12, shows the initial and final values of the head. Moreover, the head versus time function shows the total head when the earth dam is under steady-state seepage, without any reduction in reservoir water level with time. Thus a constant total head of 138 m has been applied at time equals to zero. Moreover, to simulate a rapid drawdown condition, for loss of 50 m head in the reservoir over 58 days with a final head of 88 m, boundary condition has been applied in such a way that the reduction in reservoir water and pore-water pressures in the dam at a different time during the rapid drawdown process was modeled.

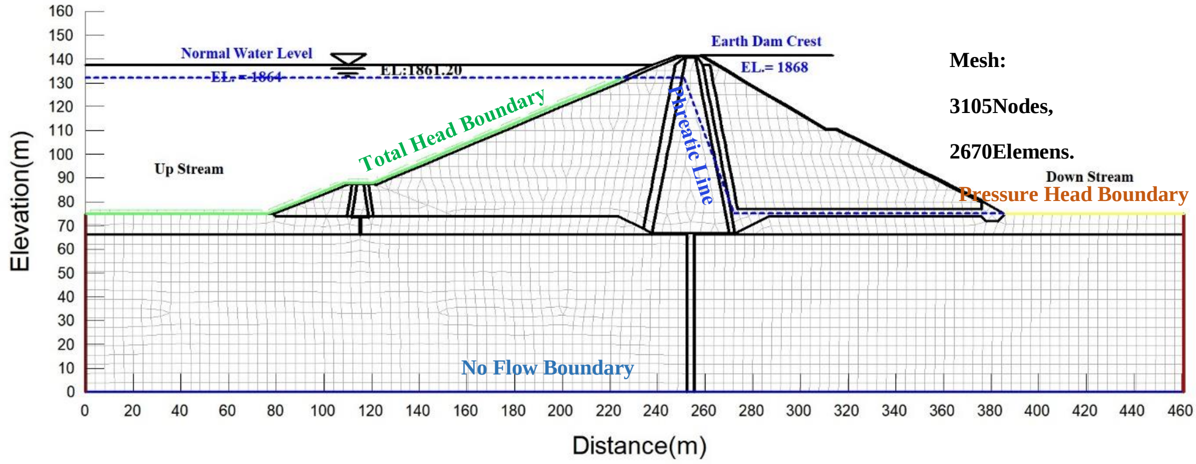


Fig. 8. Boundary conditions for the seepage analysis and the finite element mesh (Eyvashan earth dam)

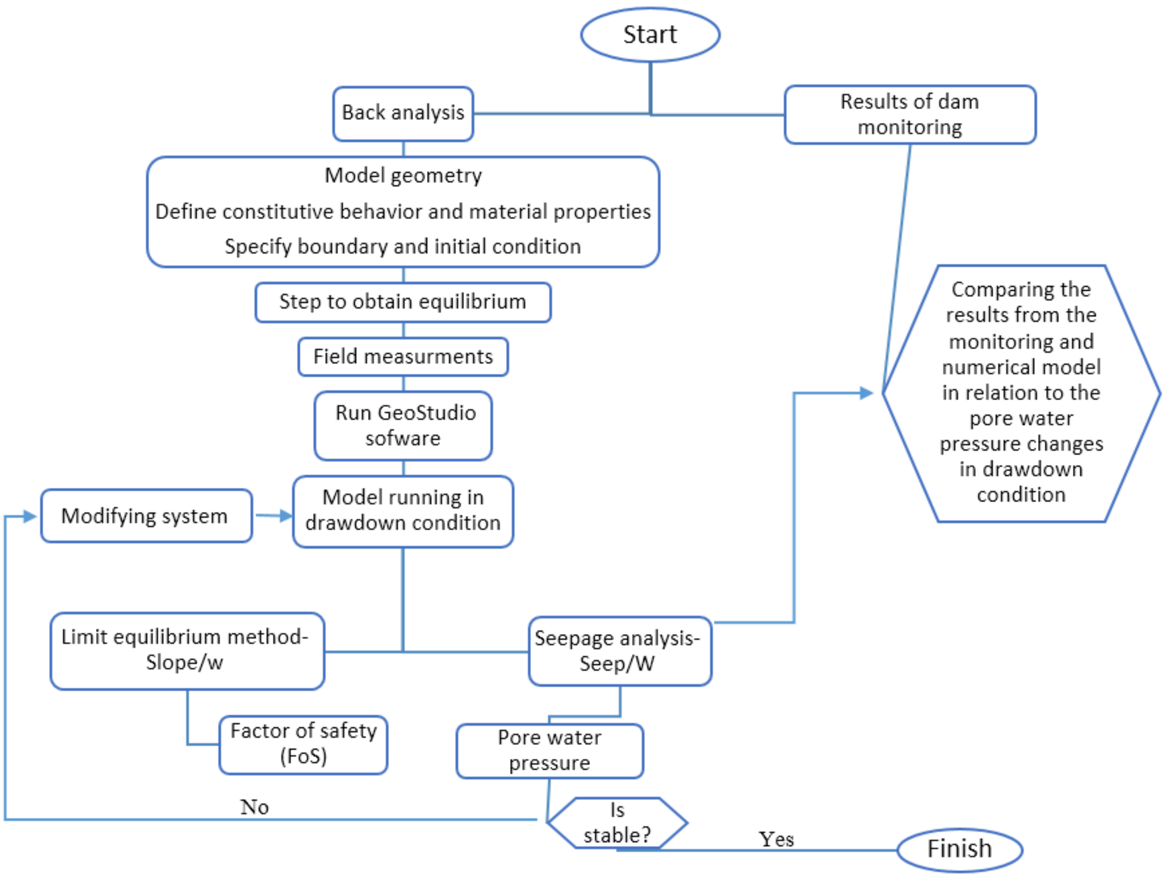
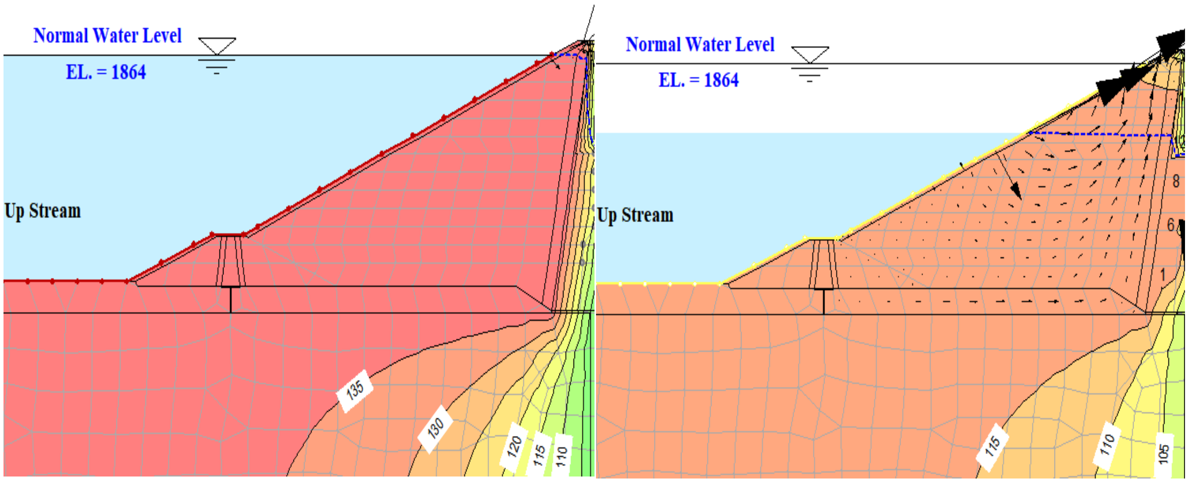


Fig. 9. Back analysis method and solution algorithm

Table 1. Initial amounts of material parameters in the body of the dam

Material	Mohr-Coulomb	Type material	Young's modulus E (MPa)	γ_{dry} (kN/m^3)	γ_{wet} (kN/m^3)	γ_{sat} (kN/m^3)	c, c′ (kPa)	
Core	Elasto-Plastic	Undrained	35	17	20	21	63	11
		Drained					28	24
Shell	Elasto-Plastic	Drained	70	22.5	23.8	24.5	-	-
Filter	Elasto-Plastic	Drained	45	19	21	22	-	-
Drain	Elasto-Plastic	Drained	55	20.5	22	23	-	-
Alluvium	Elasto-Plastic	Drained	500	21.5	-	23.2	-	-
Foundation	Elasto-Plastic	Drained	5000	25	-	25.5	-	-
Cut-off wall	Elasto-Plastic	Drained	2500	24	-	24	-	-



(a) (b)

Fig. 10. Total head contours (m) and flow directions of the water flux: a) Before the drawdown event; and b) after the reservoir is dropped to half in 42-day (GeoStudio)

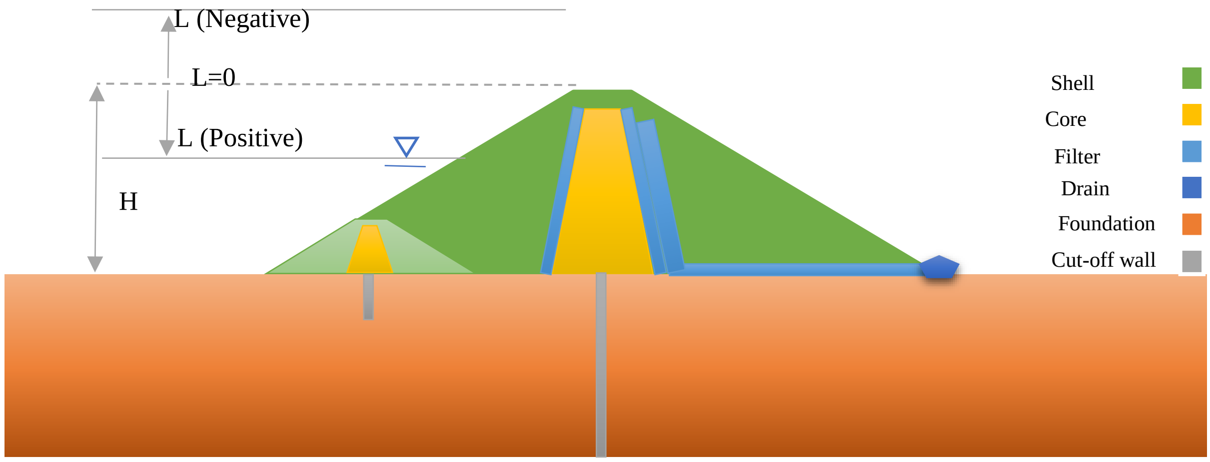


Fig. 11. Drawdown ratio (Eyvashan earth dam)

Table 2. Permeability of various materials of Eyvashan earth dam

Materials	k_x (m/sec)	k_y/k_x
Core	2.5×10^{-2}	0.2
Shell	1×10^{-3}	1
Filter	1×10^{-4}	0.5
Drain	2×10^{-2}	1
Alluvial	5×10^{-3}	1
Foundation	1×10^{-9}	1
Cut-off wall	1×10^{-7}	1

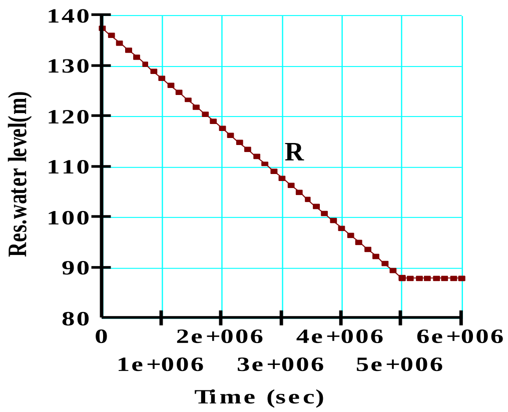


Fig. 12. Drawdown rate (head versus time), GeoStudio

4. Results and Discussion

4.1. Seepage Analysis

When the phreatic line (free surface) falls rapidly, almost in the same position, it is considered as rapid drawdown. The lag of the phreatic line or the rate of drawdown depends on four factors: drawdown rate, the permeability coefficient of the dam, pore water pressure, and upstream slope gradient. In cases where the reservoir water of the dam needs to fall quickly due to special conditions and on the other hand, the material on the slope of the dam is impermeable, the phreatic line does not fall so much and it causes instability. (Abadjiev, 1994). When the reservoir dam is rapid drawdown, pore water pressures in the dam core and body are reduced in two ways. There is an immediate elastic effect due to the removal of the total or partial water load and there is a slower dissipation of pore pressure due to drainage. It is assumed in this phenomenon that the reservoir has been maintained at a high level for a sufficiently long time so that the fill material of the dam is fully saturated and steady seepage established. In drawdown condition, the direction of flow is reversed, causing instability in the upstream slope of the embankment. The "instantaneous" drawdown is a hypothetical condition that is assumed and pore pressures along the sliding surface are determined by inspection of "instantaneous" pore water pressure at different points in the finite element mesh. The most critical condition of rapid drawdown means that while the water pressure on the upstream slope at the "full reservoir" condition is removed, there is no tangible change in the water content of the saturated soil within the dam (see Figure 13). This figure presents the water flux flowing out of the upstream face after the drawdown conditions, as a function of time during and after the drawdown event. The seepage now starts to exit the dam immediately after the drawdown starts for all the drawdown periods. Also, the seepage period is further prolonged and lasts for more than 58 days.

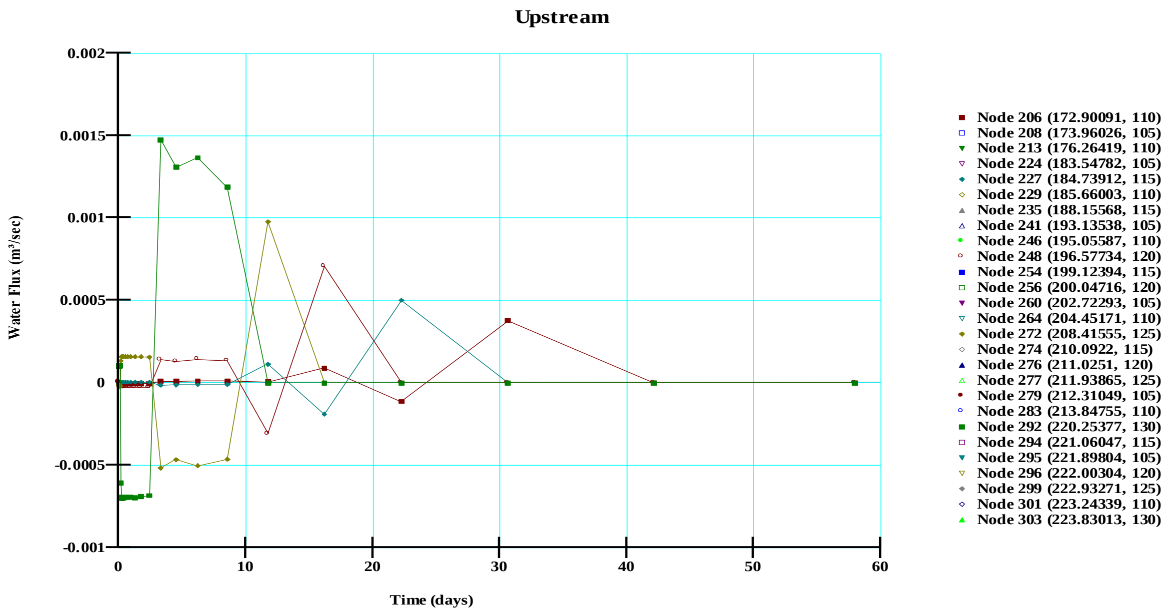


Fig. 13. The behavior of the water flux flowing out of the upstream face after the drawdown conditions

Figure 14 shows variations in pore water pressure during the rapid drawdown of the reservoir. In the conditions of the rapid drawdown of the reservoir of the Eyvashan earth dam and according to the modeling results performed based on the reality, the water level has decreased by 50 meters in 58 days (5011200 sec). The results show that the phreatic line remains constant after 29 days from the start of the rapid drawdown of the reservoir, while half of the volume of the drained reservoir remains at 1842 masl ($\frac{1}{3}$ of the crest dam). Throughout the time of the rapid drawdown of the reservoir, the pore water pressure has decreased. To accurately compare the results of numerical analysis with the actual results, the sections were precisely modeled on the actual position in the geostationary software. The results of the numerical analysis of the pore water pressure during the rapid drawdown of the reservoir based on time and at different levels are shown in Figure 15.

In addition, the results show that the water pressure graphs on the upstream of the core axis have been reduced more rapidly and steeper than the downstream sections. In Figure 16, variations in pore water pressure are shown in relation to the core height during the rapid drawdown at different sections of the dam core.

It is clear that at higher levels of the core, the pore water pressure drop is higher. In the upstream sections, the core has a higher drop than the downstream side, which is adjacent to the horizontal drain. To evaluate and compare the performance of the instrumentation and the GeoStudio model, multivariate regression used from the criterion of the coefficient of explanation (Eq. (7)).

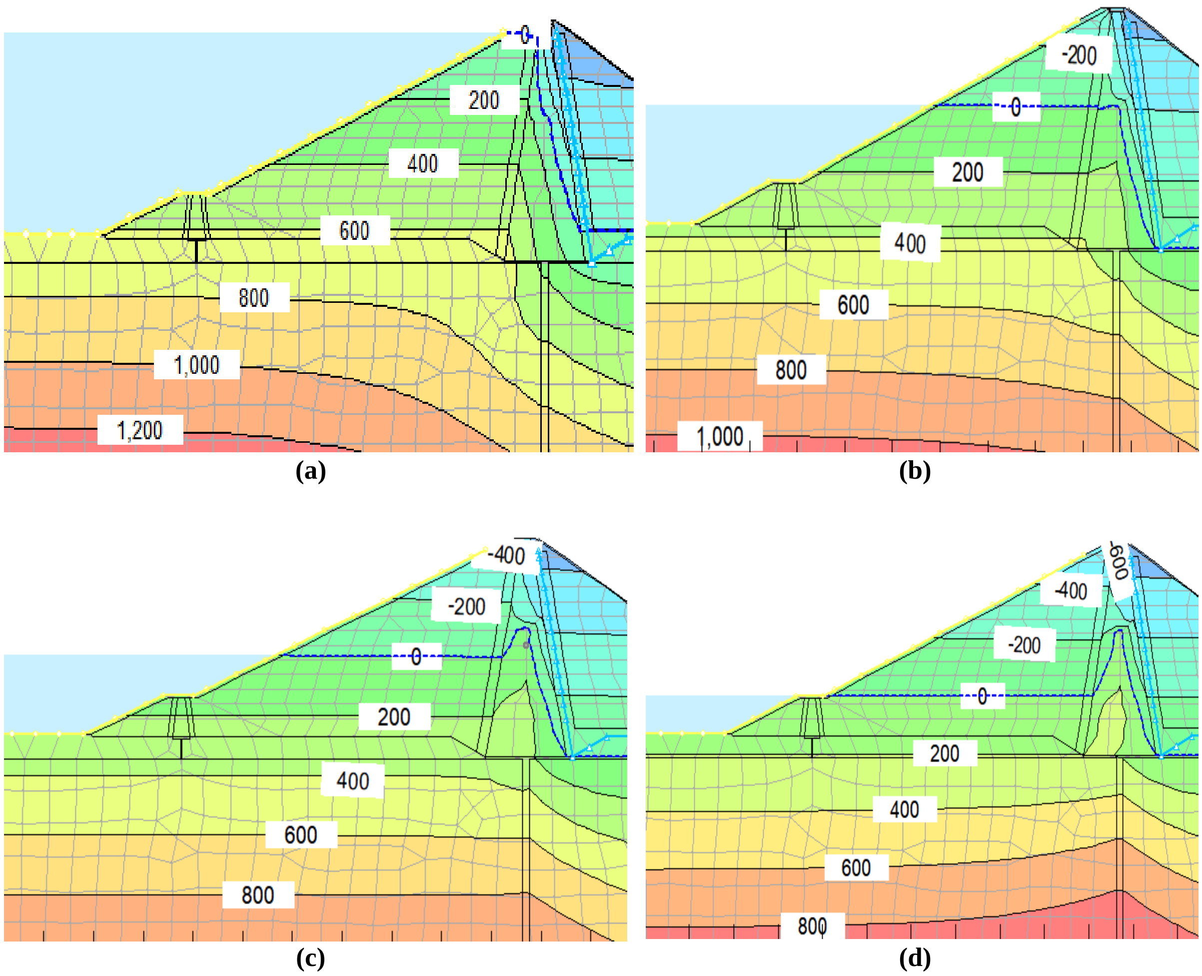


Fig. 14. Pore water pressure contours during drawdown (GeoStudio): a) Start drawdown; b) After 30 days; c) After 42 days; and d) After 58 days

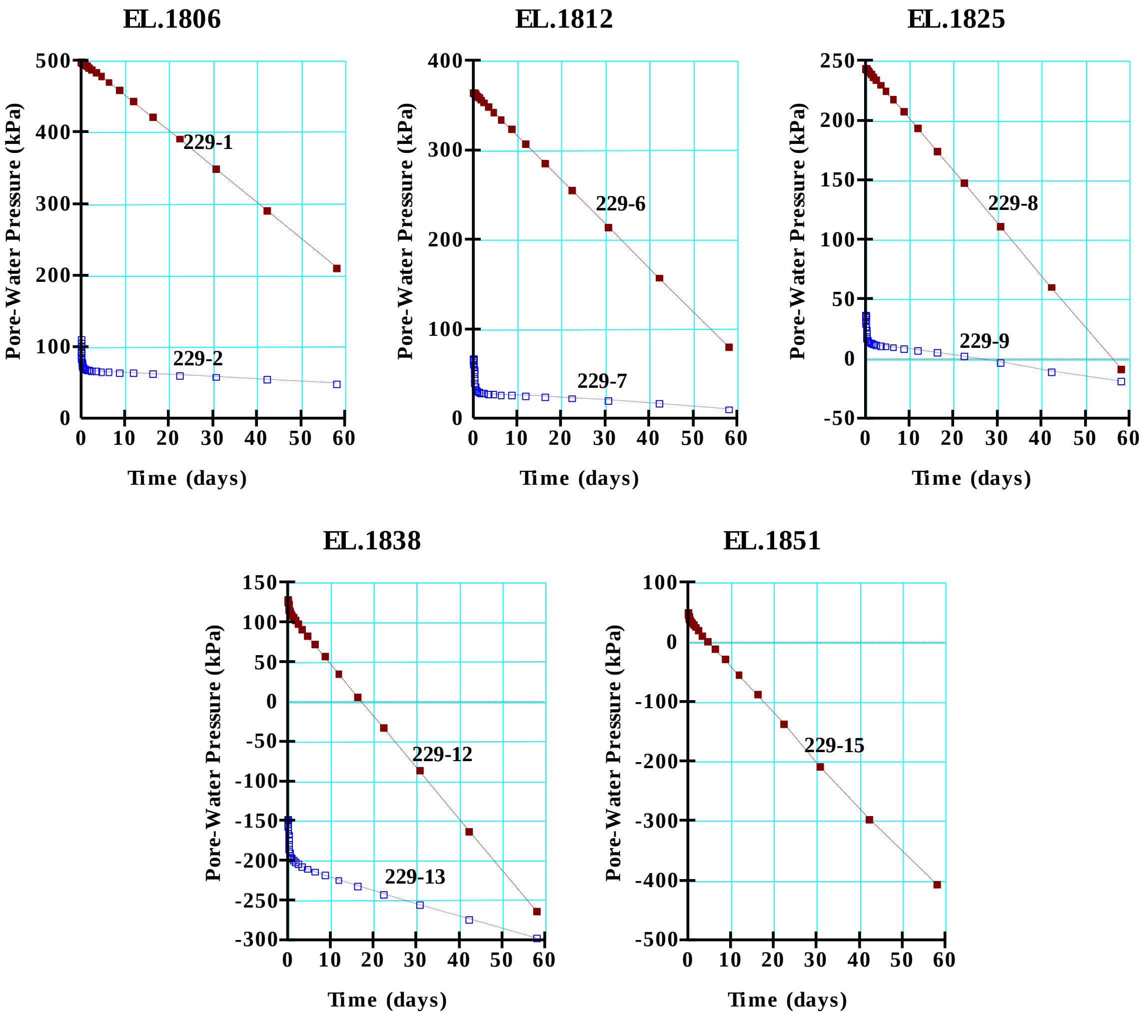


Fig. 15. Pore water pressure in the core of Eyvashan earth dam during rapid drawdown (GeoStudio)

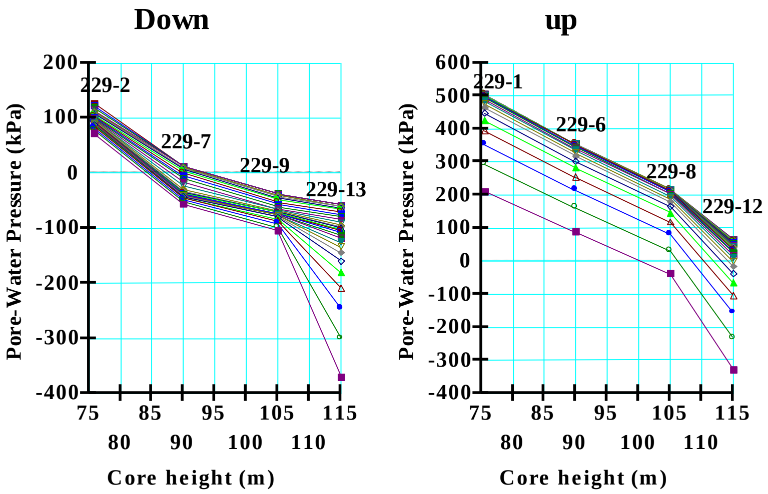
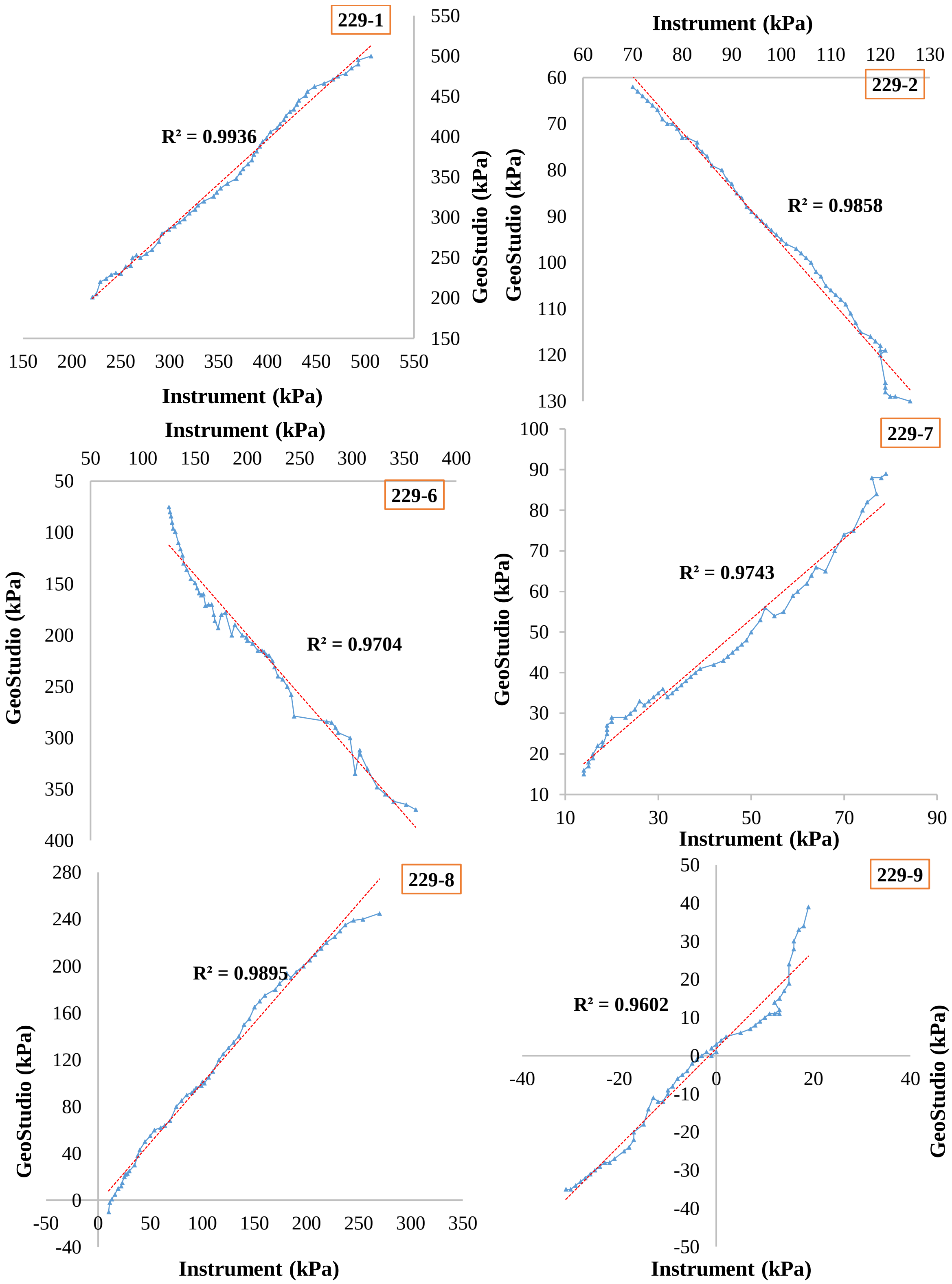


Fig. 16. Variations in pore water pressure relative to the core height during rapid drawdown

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(Pi - Oi)^2}{\sum_{i=1}^{n}(Pi - Oave)^2} \qquad (7)$$

in which n: is the number of samples, O_i and P_i : are respectively the observed values and the predicted values, and O_{ave}: is the mean of observational values.

The explanatory factor shows that the regression line between the predicted and measured values is close to the regression line with a slope of one. In the calculations, the closer R^2 to 1, the more efficient the model is. Indeed, if the value of R^2 is equivalent to 1, it shows a perfect fit, indicating a complete fit between the observational and predicted data. By applying Eq. (7) on the observed and predicted data, the coefficient of explanation for GeoStudio software was about 0.98 which showed the correspondence of the results of pore water pressure for Instrumentation and predicted values (see Figure 17).



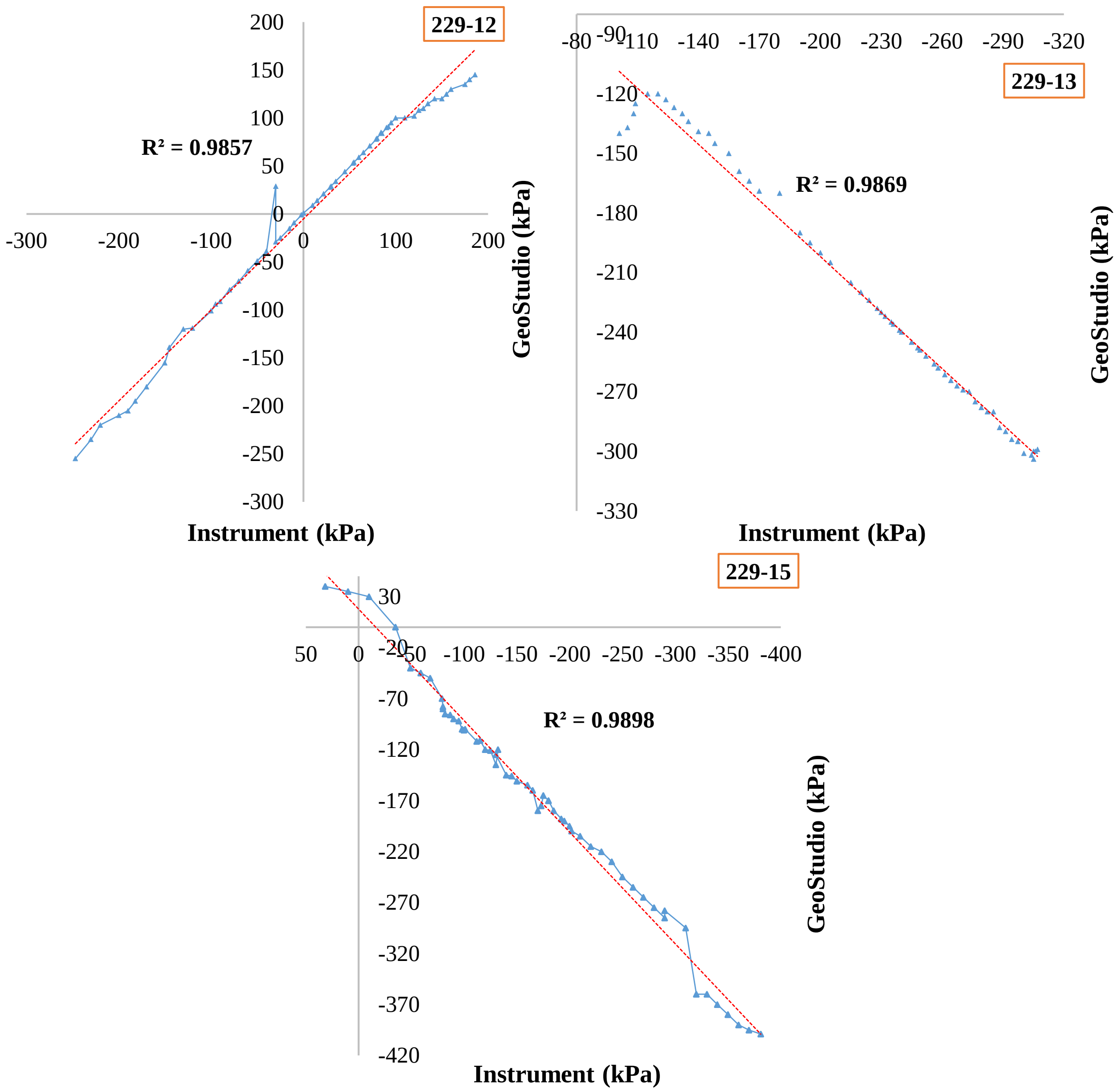
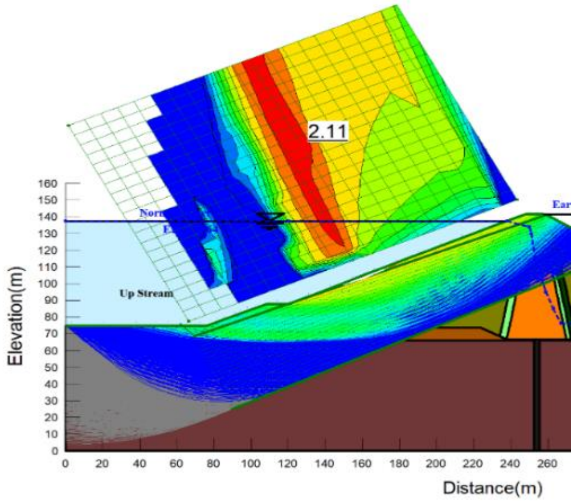


Fig. 17. Distribution diagram for the observed and predicted values (GeoStudio)

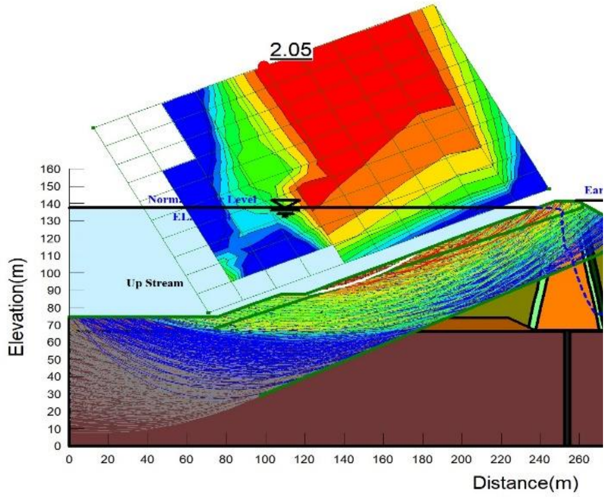
4.2. Slope Stability Analysis

The precise method of reservoir drawdown analysis is to use the transient analysis results. In this method, unlike the steady-state method, the exact amount of pore water in the drainage reservoir is used. With this method, the factor of safety can be obtained at different times of drainage of the reservoir. In the Eyvashan earth dam model, the reservoir dam has fallen from 64 to 14 m in 5011200 sec. In this type of analysis, the phreatic line decreases with time, which reduces pore water pressure over time and thus changes the amount of factor of safety. The factor of safety results has been computed using Morgenstern-Price and Bishop's usual methods as shown in Figure 18 for different conditions of water level (rapid drawdown). The minimum factor of safety in the Morgenstern-Price and Bishop methods for upstream slip surface at steady state was found to be 2.11 and 2.05, respectively.

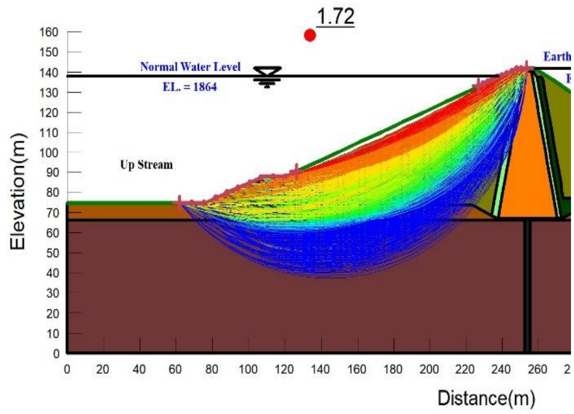
The factor of safety gradually decreases as water in the reservoir decrease to 42 days of drawdown (water reservoir level 1830 masl) that a minimum factor of safety during drawdown falls above the value of (1.72 for both methods Morgenstern-Price and Bishop). Then, the factor of safety increases until the last day of rapid drawdown (58 days). So that at the time of full discharge, the factor of safety will be 2.01 for the Morgenstern-Price method and 2 for the Bishop method. Therefore, according to the results of the stability of the upstream slope of the dam in a rapid drawdown mode (within 58 days), the dam will not have a problem in terms of stability in conditions drawdown. Figure 19 represents the factor of safety for different time intervals.



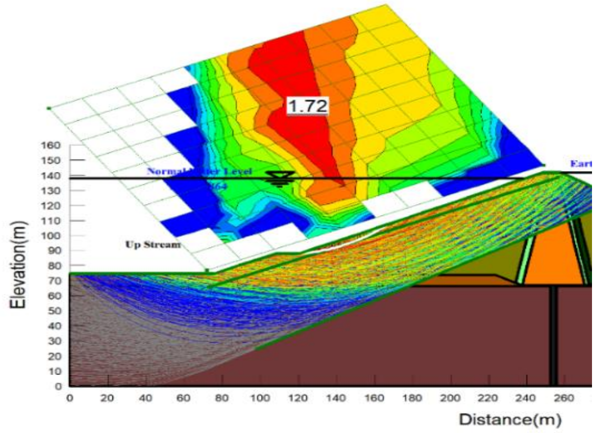
(a1)



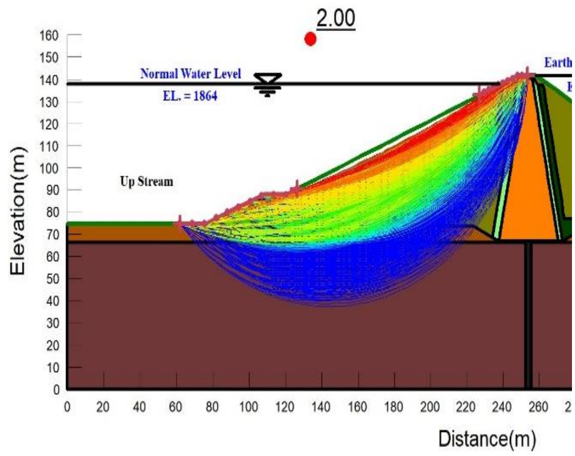
(a2)



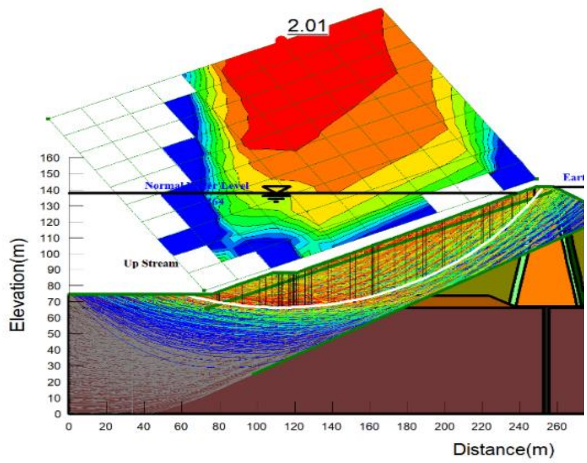
(b1)



(b2)



(c1)



(c2)

Fig. 18. Critical slope surface and factor of safety after rapid drawdown: a) Before drawdown; b) After 42 day; c) After 58 day (1: Morgenstern-Price; and 2: Bishop)

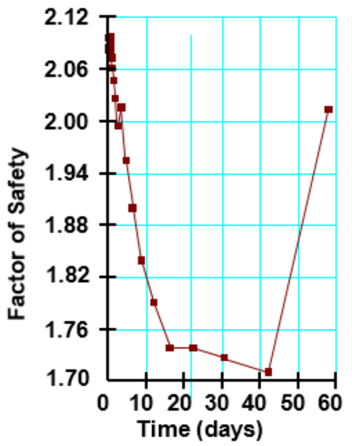


Fig. 19. Factor of safety results by using different methods for Eyvashan earth dam

As with the instantaneous drawdown analysis, the factor of safety decreases when the reservoir is drawdown. However, the Factor of Safety (FS) for the slow drawdown analysis does not drop below 1.72. According to Figure 19, FS is reduced until the dam reservoir drop is continued. But after the end of the rapid drawdown, it gradually increases and it reaches an amount of constant after a relatively long period. The reason for this is that after the end of the rapid drawdown, it takes a while before the phreatic line reaches its lowest level and the amount of pore water pressure is also fixed and in the analysis steady-state of the transient state analysis mode, the safety factor will remain constant.

5. Conclusions

In the conditions of the rapid drawdown of the reservoir of the Eyvashan earth dam and according to the modeling performed based on reality, the water level has decreased by 50 m in 58 days (5011200 sec). The results showed that the phreatic line remains constant after 29 days from the start of the rapid drawdown of the reservoir, while half of the drained reservoir volume remains at 1842 masl ($\frac{1}{3}$ of the crest). Throughout the time of the rapid drawdown of the reservoir, the pore water pressure has decreased. To accurately compare the results of numerical analysis with the actual results, the sections were precisely modeled on the actual position in the geostationary software. To evaluate and compare the performance of the instrumentation and the GeoStudio model, multivariate regression was used and the criterion of the coefficient of explanation. By applying R^2 on the observed and predicted data, the coefficient of explanation for GeoStudio software was about 0.98, which showed the correspondence of the results of pore water pressure for instrumentation and predicted values. The minimum factor of safety in the Morgenstern-Price and Bishop methods for upstream slope surface at steady state was found to be 2.11 and 2.05, respectively. The factor of safety gradually decreases as water in the reservoir decrease to 42 days of drawdown (water reservoir level 1830 masl) that a minimum factor of safety during drawdown falls above the value of 1.72 (for both Morgenstern-Price and Bishop methods). Then, the factor of safety increases until the last day of rapid drawdown (58 days) so that at the time of full discharge, the factor of safety will be 2.01 for the Morgenstern-Price method and 2 for Bishop Method. Therefore, based on the results of the stability of the upstream slope of the dam in a rapid drawdown mode (within 58 days), the dam will not have a problem in terms of stability in conditions drawdown.

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