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Stability Control of Narmab Dam and Sensitivity Analysis of Reliability Coefficients

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Abstract

Static and quasi-static stability analysis of embankment dams is of vital importance in different stages of dam's design, construction and operation. The stability can be studied using different techniques which are generally analyzed through Limit Equilibrium Method. Base on this main method, the critical slip surface is selected and the shear strength required to counter the slip at the selected surface is obtained and compared with shear strength of the soil at that surface in order to obtain confidence coefficient. In the present research, the Geo-studio Slope/w software that is a geotechnical software based on finite element method and is widely used in geotechnical field, is employed in order to analyze the stability of the body and foundation of Narmab dam in Golestan province. Narmab dam is a homogeneous embankment dam with a height of 60 m, crest length of 807 m and reservoir volume of 115 million cubic meters. The confidence coefficients provided by the software are compared to the permissible confidence coefficients. Moreover, the sensitivity of the confidence coefficients values to the changes in the effective factors, adhesion and internal friction coefficient, is analyzed. The analyses were performed on 8 values (±5, ±10, ±15, ±20) of c and φ and the obtained values of confidence coefficients were compared. In addition, a comparison was made between different methods of stability analysis. According to the static and quasi-static conditions, Narmab dam is stable in all loading stages (End of Construction, First Impounding and Steady State Seepage and In general, only for the static conditions of the end of construction stage, the sensitivity of adhesion is greater than the angle of internal friction, but, in other conditions and stages, the sensitivity of friction angle has more effects.

Keywords: Stability; Coefficient of Confidence; Finite Element; Sensitivity Analysis; Geo-Studio Slope/W.

1. Introduction

The monitoring of safety and stability of embankment dams during construction, first impounding and operation are of particular importance. This is particularly important due to the damage caused by the slippage of the embankment slopes, because slippage of slope may lead to loss of human life and property or causes irreparable damage to a dam [1]. One of the most important and significant factors in the stability of embankment dams is the shear strength of materials used in the body and foundation of the dam. Shear strength of soils depends on the particle size, aggregation, density, structure, moisture content and drainage conditions during shear and also, loading history for cohesive soils. The shear strength of soil mass is the internal resistance of the surface area of soil, which can be used to deal with a failure or slip along any inner surface. Therefore, considering the importance of embankment slopes, the effect of static forces and earthquakes on their stability is of vital importance.

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From the engineering economics point of view, optimal confidence coefficient and slip surface reduces excavation or embankment volume with a slight change in slope gradient. Various methods have been proposed for investigation of stability of slopes. For example, the seismic slope stability analysis that is classified into: sliding blocks, dynamic analysis and quasi-static methods [2]. The present study is an attempt to investigate the stability of the body and foundation of Narmab dam in the Golestan province in static and quasi-static states and to analyze the sensitivity of the confidence coefficients relative to changes in effective factors. The software used in this research is Geo-Studio. The Seep/w and Slope/w software were used to determine the slope stability base on the coupled water-force analyses.

Narmab dam is a homogeneous embankment dam with a height of 60 m, crest length of 807 m and reservoir volume of 115 million cubic meters. This dam is under construction in order to save the flood regime of Narmab, Chehelchay and Khormalou rivers, for developing of agriculture in this region and supplying of municipal and industrial water. From the regional geological point of view, the project area is located on the border of Gorgan-Dasht and Kopet-Dag- Hezar Masjed zones. The rocks of the dam site are mainly non-homogenous in range of permeable to impermeable rocks. The limestone in the dam axis is made up of volcanic rocks. These rocks are basalt, which are mainly covered with alluvial materials and have considerable weathering [3].

Figure 1. Narmab dam location

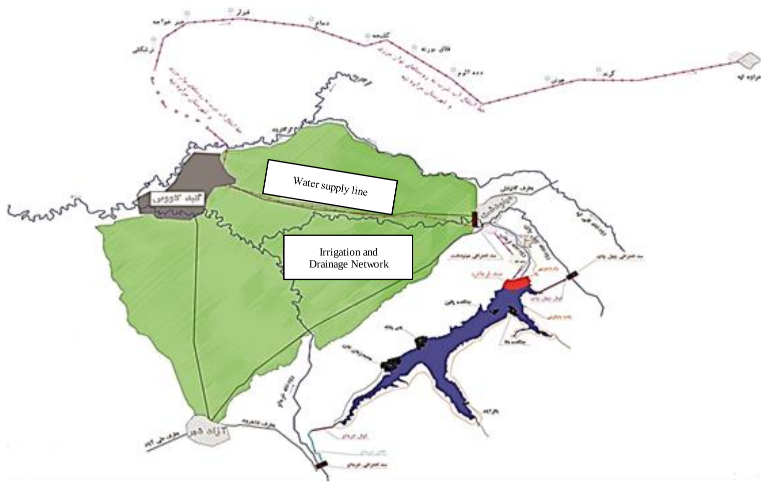


Figure 2. Narmab dam plan [4]

Equilibrium Method is one of the most common methods used to evaluate and analyze the stability of the embankment slopes. In this method, first, a hypothetical sliding mass is considered, then the propulsion and resistance forces are calculated using the limit equilibrium equations. The results are discussed to determine the confidence coefficients of the expected mass against the slip. There are different methods for solving equilibrium equations and calculating stability coefficients. These methods can be categorized into two groups:

a) Mass method: In this method, the whole soil mass located above the slip surface is considered as a single rigid body and the equilibrium force and anchor equations are written for it. This method is used when the whole soil mass is homogeneous, the infinite slope analysis method, the plate-based slip surface, and the Swedish method are derived from the main method.

b) Procedure of slices: In this procedure, the soil mass above the sliding surface is divided into a number of vertical slices, and the equilibrium equations are written for each slice separately in accordance with some simplifying assumptions and force between slices. The solution to these equations can also provide the coefficient of confidence of the total soil mass against slip. This procedure can account for soil heterogeneity and the effects of pore water pressure in calculations. Procedures such as bishop, spencer, morgenstern and price, and some other stability analysis methods employ this procedure to evaluate the stability of slopes.

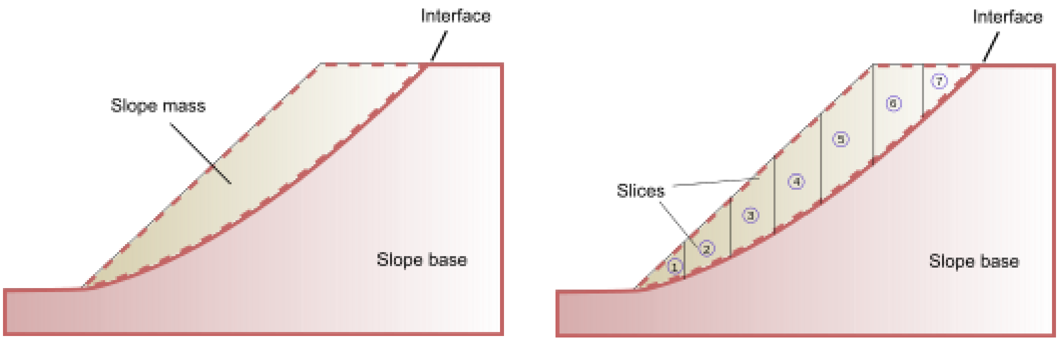


Figure 3. a) Mass method, b) Procedure of slices

Selection of a suitable method for analyzing of the stability for an embankment slope is essentially dependent on the objectives and available tools. The noteworthy point in selection of a proper method for slope stability analysis is that the method should be sufficiently precise. Therefore, the more equations used for the analysis, the more accurate the results will be. In the present study, the Morgenstern-Price method has been used. The failure surface can take different forms and the satisfied equilibrium equations include both force and anchor equations.

The main criterion in the analyses and evaluation of the embankment slopes stability is estimation of the minimum coefficient of confidence and comparison of it with the permitted values [1]. The coefficient of confidence in the analysis of embankment dam stability is the quantity that shows the margin of structure safety against the occurrence of shear failure [5]. The accuracy of the calculated coefficient of confidence for the slope stability is precisely determined by the physical and mechanical properties of the materials. Generally, the physical and mechanical parameters required for the materials used in a dam for the stability analysis are:

φ: Internal Friction coefficient of materials

C : Cohesion

γ : Specific gravity of materials in natural state

γ_{sat} : Specific gravity of materials in saturated state

2. Literature Review

Askaripour and Soltani (2015) investigated the effect of deviations in measured values of shear soil parameters on the stability of embankment dams. In this research, Geo-Studio software was used for the data analysis. The results of this study indicate that the effect of material density changes on the slope stability is not significant, but the smallest changes in the cohesion and the friction angle have a significant effect on the stability of the dam [6].

Taghizadeh and Vafaiean (2015) studied the stability of the embankment slopes by changing the shear parameters of the soil in a hypothetical embankment slope using FLAC software. They concluded that the change in the cohesion parameters and the internal friction angle of the soil has a significant effect on the stability of the embankment slopes [7]. Alonso (1976) performed a Risk Analysis of Slopes and investigated its Application to Slopes in Canadian Sensitive Clays. He concluded that uncertainty in cohesion parameters, pore water pressure and the method used to analyze important uncertainty factors result in slope stability [8].

Kamanbedast and Delvari (2012) studied the analysis of earth dam by the seepage and stability using ANSYS and Geo-Studio software. The results wore compared whit Geo studio Software result. Firstly, dam was studied with using this analysis method, then seepage is predicated the seepage rate in ANSYS. The results show that the seepage analysis is lower than Geo-studio results about 18% percent. Besides, slope stability analyses show that the general results are almost at similar range for both software. But, safety factor values (for two software) had distinctive difference [9].

Hasani et al. (2013) investigated the analysis of earth dam by control of seepage and stability using ANSYS and Geo-Studio software. They concluded that the significant difference of two software is related to safety factor and eventually it can be deducted that ANSYS answer is more acceptable [10].

Arshad et al. (2017) investigated the numerical analysis of seepage and slope stability in an earthen dam by using Geo-Slope software. The simulation results reveal that upstream and downstream side of the dam section has a direct effect on the factor of safety [11].

Devi and Anbalagan (2017) studied the slope stability of earthen dams by using Geo-Studio software. They have concluded that the provision of drain increases the factor of safety on the downstream side and the provision of a drain on downstream side improves the factor of safety (FOS) on the upstream side [12].

Table 1. Specifications of body and foundation of Narmab dam [13]

Materials	Resistance parameters		γ	
Internal friction angle (degree)	Cohesion KN/m^2		Saturation KN/m^2	Wet KN/m^2
38	0	Drain	20.7	20
		Fine grained soil of dam body		
10	120	UU	21	20.6
22	27	CU		
30	13	CD		
		Foundation-Fine grained		
6	145	UU	21	20.8
15	35	CU		
27	20	CD		
		Coarse grain		
38	0	CD	21	20.4
43.18	10810	Basalt [14]	24	24

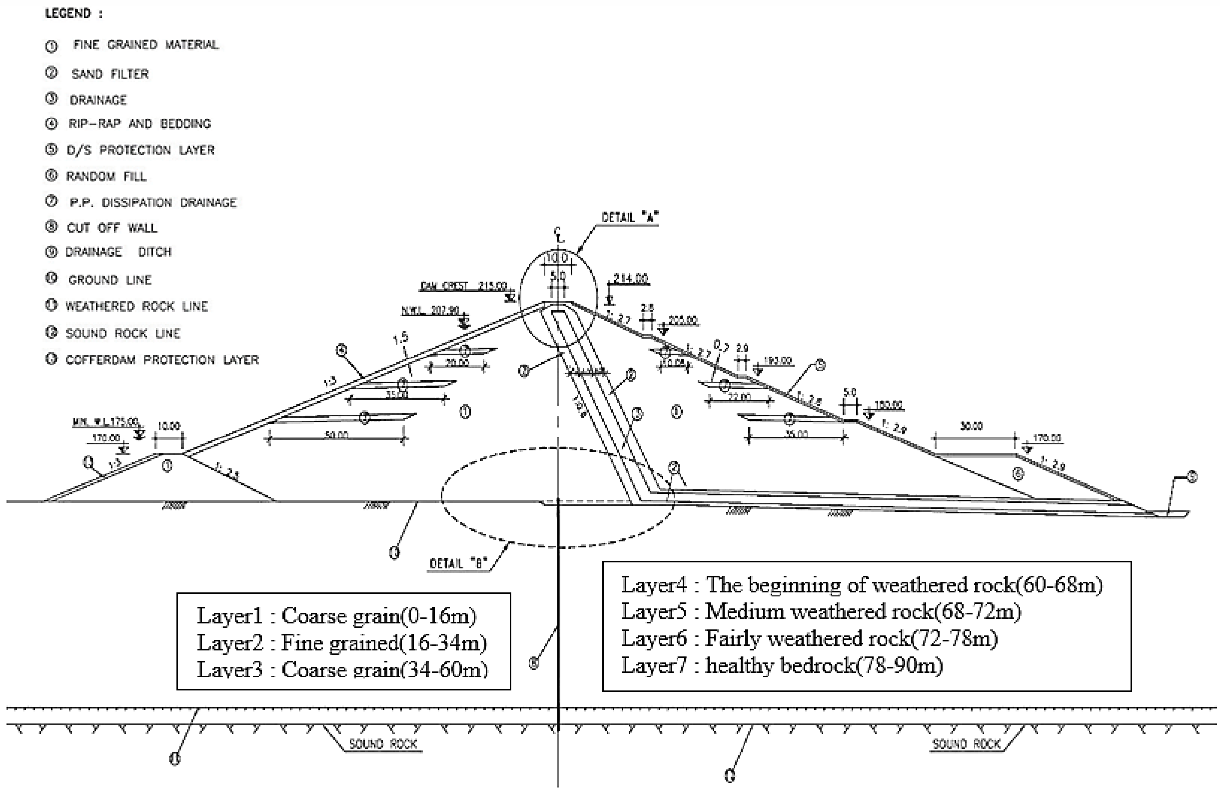


Figure 4. Narmab dam – Typical Section

3. Research Methodology

In the first step, the geometry of the dam is plotted according to the data provided by the regional water company of Golestan province and then, the section is zoned according to the materials (Figure 4).

In the second step, attempts are made to define the properties of materials. In the present study, the Mohre-Columb behavior model is used to define the mechanical properties of materials. In this process, the coefficient of internal friction, cohesion and specific gravity of the materials are determined for individual materials according to the data provided by the experimental tests (Table 1). In this section, we need to define the suction curve for body materials and filters and drains. Suction curves are applied according to the function of moisture content in the material which are measured during the construction of dam. This function is a graph in which the percentage of volumetric moisture content is plotted in accordance with the matric suction. The materials extracted from the dam and numbers volumetric moisture content in terms of matric suction charts, diagrams each barrier materials can be obtained separately (Figure 5).

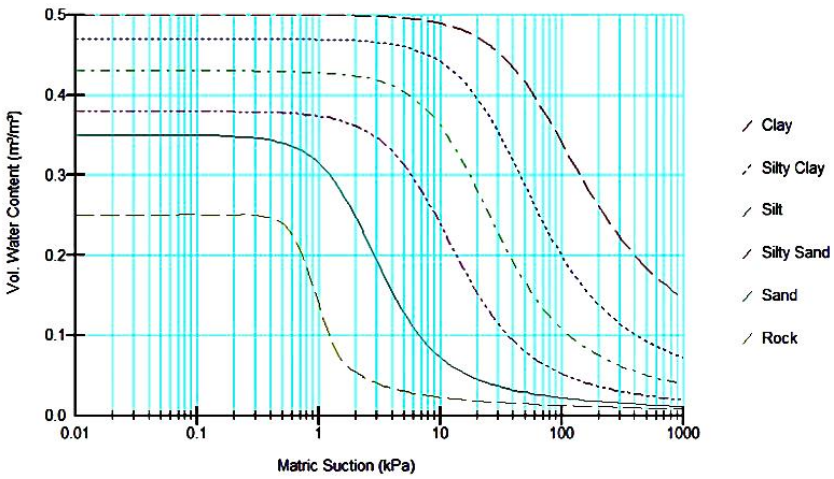


Figure 5. Chart volumetric moisture content in terms of matric suction [15]

Table 2. Saturated volumetric water content and the remaining insulation materials of Narmab dam

Residual moisture content	Materials
0.15	Clay body
0	Sandy filter and Sandy drainage

Saturated volumetric water content	Materials
0.5	Clay body
0.33	Sandy filter
0.33	Sandy drainage

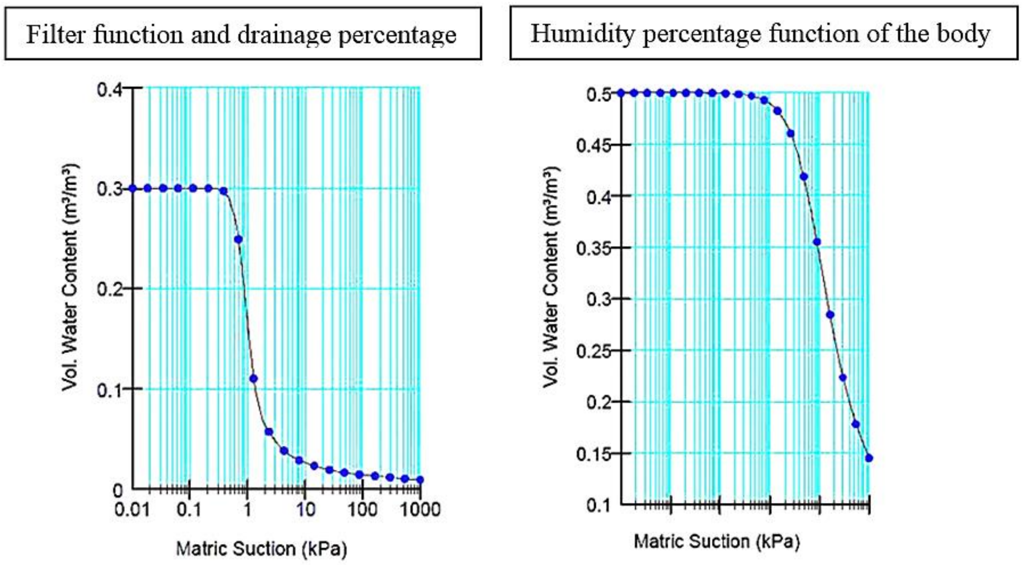


Figure 6. Charts of volumetric moisture content in terms of matric suction insulation materials Narmab dam

The critical loading cases for the evaluation of embankment dam stability can be expressed as follows:

- End of Construction (static and quasi-static)
- First Impounding

- Steady State Seepage (static and quasi-static)

In the third step, depending on the dam mode that is going to be analyzed, some boundary conditions need to be defined. In the end of construction step, the UU condition is dominant for the body material and the fine-grained layer of the foundation, and since the dam is not filled yet, there is no need to define boundary conditions, and we only need to define the pore water pressure coefficient for fine-grained body and foundation materials. Due to the multiplicity of drains and filters in the dam body, we consider the extra pore water pressure coefficient is considered equal to 0.3. In the Initial reservoir filling step, the CU condition dominates over the body material and the fine-grained layer of the foundation, and we have to apply the pressure on the reservoir, which is uniformly applied to the foundation and triangularly applied to the body. In the steady state seepage, the CD condition is dominant over the body material and the fine-grained layer of the foundation, and we first need to perform a seepage analysis in the Seep/w software and then introduce the obtained piezometric line into the Slope/w software. In all the above 3 loading cases, the CD mode is dominant over the coarse-grained materials of the foundation.

In the fourth step, it needs to define the sliding surfaces for the dam body, so that the software can calculate the confidence coefficient according to the most critical slip surface. In the present study, the Entry and Exit and also, Grid and Radius methods are used to define the slip surface in the parallel, so that we can analyze the stability of the body and analyze the sensitivity of the confidence coefficients, and so, the results can be compared by the different stability analysis methods in terms of the changes in the factors that affecting on the Narmab dam stability. In the Entry and Exit method, the beginning and end of the slip surface is introduced to the software, so that the software can choose the most critical slipping surface. In the Grid and Radius method, it needs to define a grid and radius for the dam. The greater radius size and grid lines make the analysis more accurate.

These four steps are identical for both static and quasi-static analyses. In the quasi-static analysis, the slip potential of a soil mass is investigated using different stability analysis methods and the stability confidence coefficient is calculated by applying a horizontal or vertical seismic coefficient (as required). In fact, the seismic effects are statistically introduced into the analysis by applying the forces obtained from multiplying the seismic coefficients by the weight of the slipping mass in horizontal and vertical directions. The horizontal seismic coefficient that leads to displacement of the slipping surface, it is more critical to the stability of the dam, therefore, we disregard the vertical seismic coefficient. The required stability can be obtained if the horizontal seismic coefficient is equal to 0.15 and the confidence coefficient is 1.15, according to Seed and Idriss (1970) research [16].

Table 3. Permeability coefficients and volume variation of body and foundation materials of Narmab dam [13]

Kind of materials	Volumetric change coefficient (1/KPa)	Permeability coefficient (m/s)
body	4×10^{-5}	$\mathbf{1 \times 10^{-7}}$
Filter	2.5×10^{-5}	$\mathbf{1 \times 10^{-2}}$
Drain	2.5×10^{-5}	$\mathbf{1 \times 10^{-1}}$
Grouting wall	-	$\mathbf{1 \times 10^{-8}}$
Layer 1-Foundation: Coarse grain	-	$\mathbf{1 \times 10^{-5}}$
Layer 2-Foundation: Fine grained	6.5×10^{-5}	$\mathbf{1 \times 10^{-8}}$
Layer 3-Foundation: Coarse grain	-	$\mathbf{1 \times 10^{-4}}$
Layer 4-Foundation: Rock with high weathered	-	$\mathbf{1 \times 10^{-5}}$
Layer 5-Foundation: Medium weathered rock	-	$\mathbf{1 \times 10^{-6}}$
Layer 6-Foundation: Fairly weathered rock	-	$\mathbf{1 \times 10^{-7}}$
Layer 7-Foundation: healthy bedrock	-	$\mathbf{1 \times 10^{-9}}$

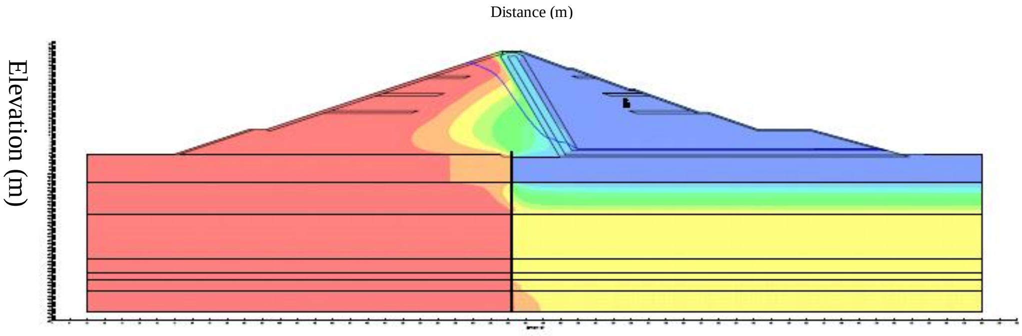


Figure 7. Seepage analysis of Narmab Dam by slope/w

4. Results

According to the analyses which are performed in Slope/w software, the results which are included the safety factor of stability are presented in Tables 4 and 5.

Table 4. Results of different stability modes for static conditions

Analysis mode	Type of analysis	Materials	Shear strength parameters	Allowable Safety Factor [1]	Confidence ratio of the most critical wedge Grid and Radius	Confidence ratio of the most critical wedge Entry and Exit
Finished making	Static	Body Foundation	UU Fine grained UU Coarse grain CD	1.33	1.640	1.811
Initial dehydration	Static	Body Foundation	CU Fine grained CU Coarse grain CD	1.4	2.361	2.356
Persistent Perspiration	Static	Body Foundation	CD Fine grained CD Coarse grain CD	1.5	1.742	2.028

Table 5. Results of different stability modes for static-pseudo condition

Analysis mode	Type of analysis	Materials	Shear strength parameters	Authorized Confidence [16]	Authorized Confidence [17]	Confidence ratio of the most critical wedge Entry and Exit	Confidence ratio of the most critical wedge Grid and Radius
Finished making	Quasi-static	Body Foundation	UU Fine grained UU Coarse grain CD	1.15	1.1	1.119	1.101
Persistent Perspiration	Quasi-static	Body Foundation	CD Fine grained CD Coarse grain CD	1.15	1.1	1.406	1.400

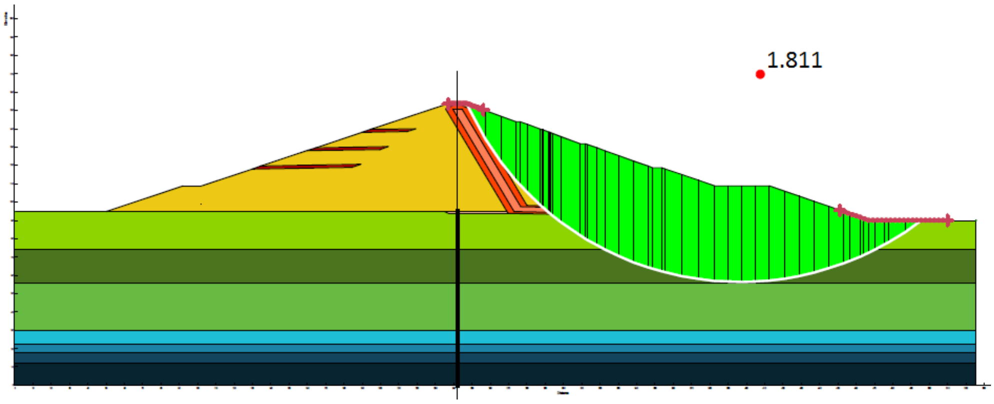


Figure 8. Critical failure slip at the end of construction using the Entry and Exit method

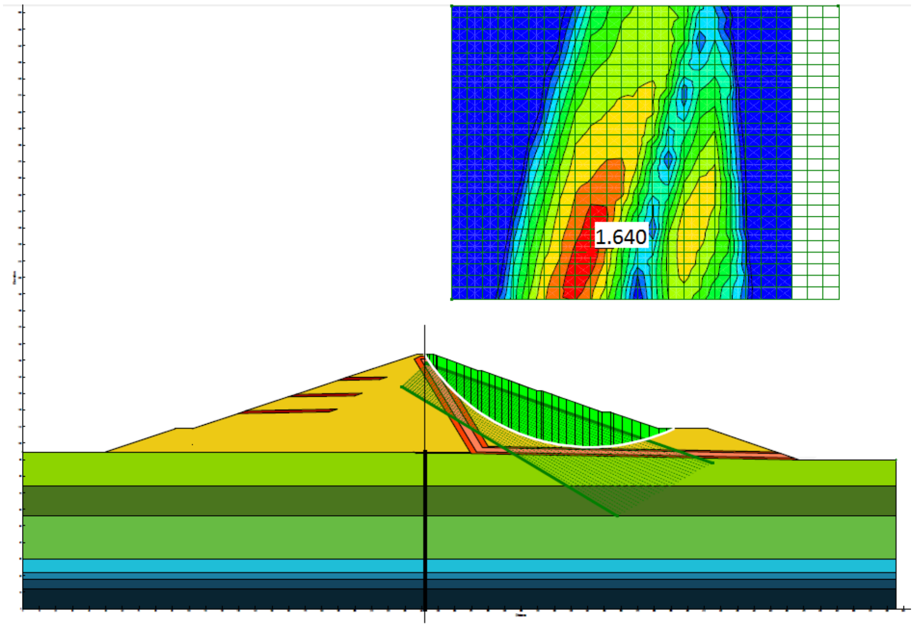


Figure 9. Critical failure surface at the end of construction using the Grid and Radius method

As shown in the Figures 8 and 9, the wedge of potential failure in the Entry and Exit method is larger than Grid and Radius. As a result, the safety factor, which is obtained at the end of construction with the Entry and Exit method, differs about 0.171 in the comparison with other method.

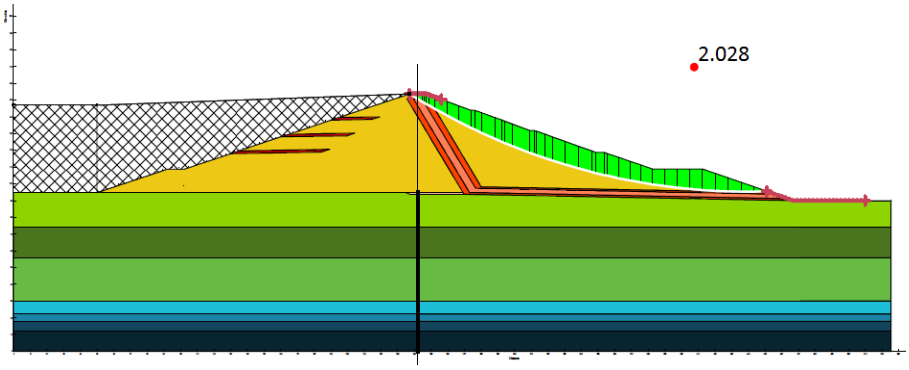


Figure 10. Critical static safety factor for first impounding by Entry and Exit Method

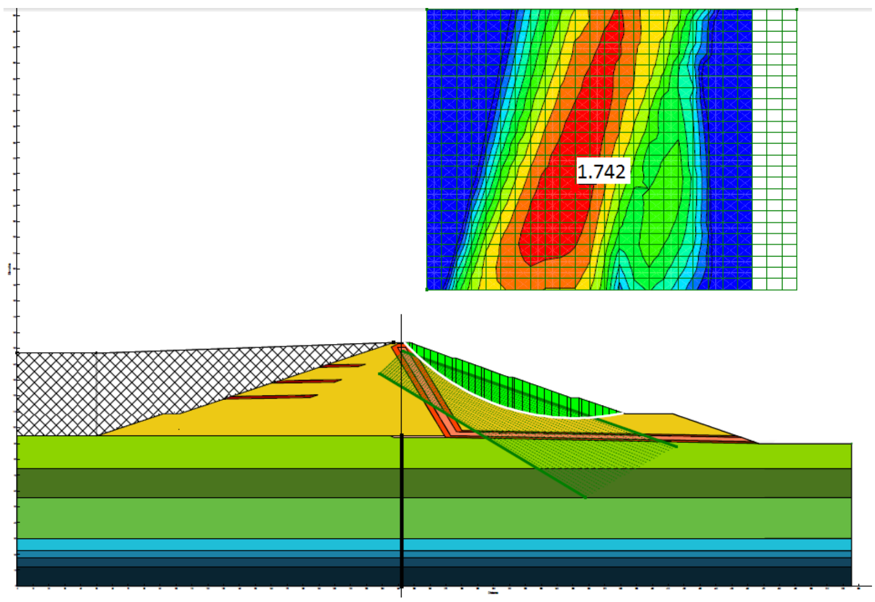


Figure 11. Critical static safety factor for first impounding by Grid and Radius method

According to Figures 10 and 11, we find that: The safety factor which is obtained at the first impounding stage by the Entry and Exit method, is higher than the reliability obtained by the Grid and Radius method. The difference is about 0.286.

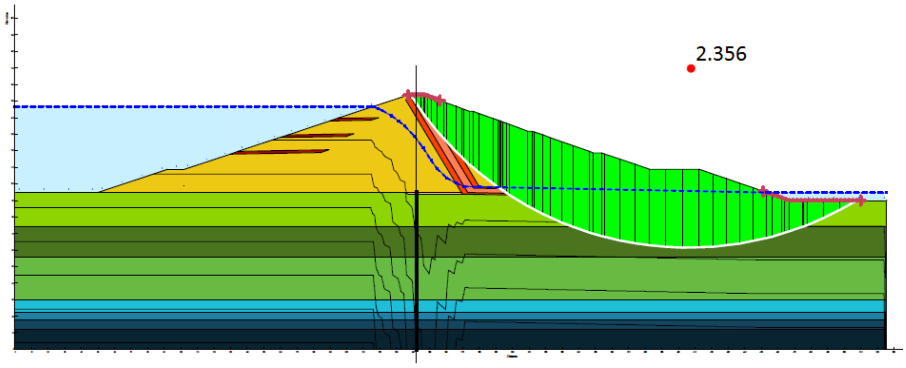


Figure 12. Critical safety factor at the steady state seepage condition using the Entry and Exit method

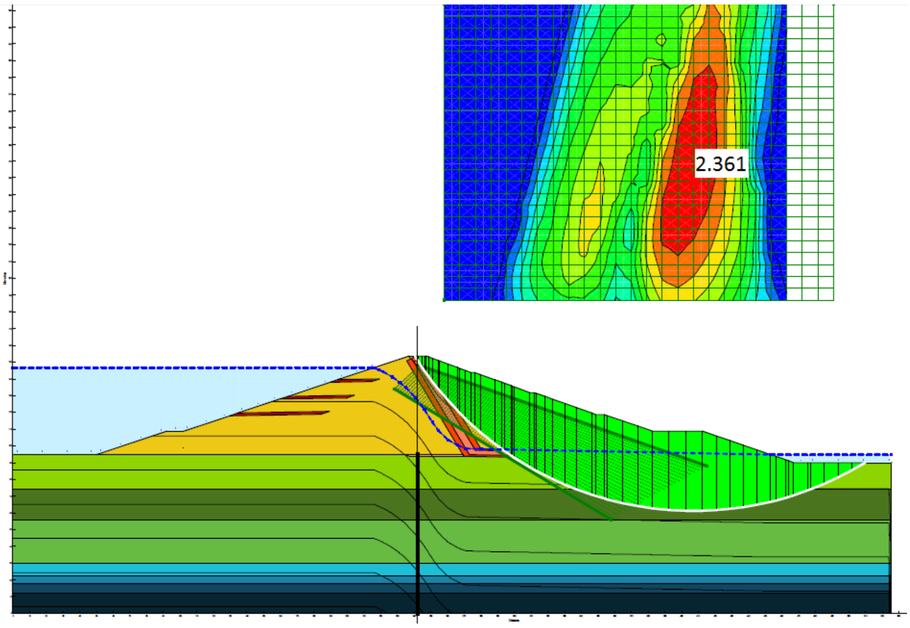
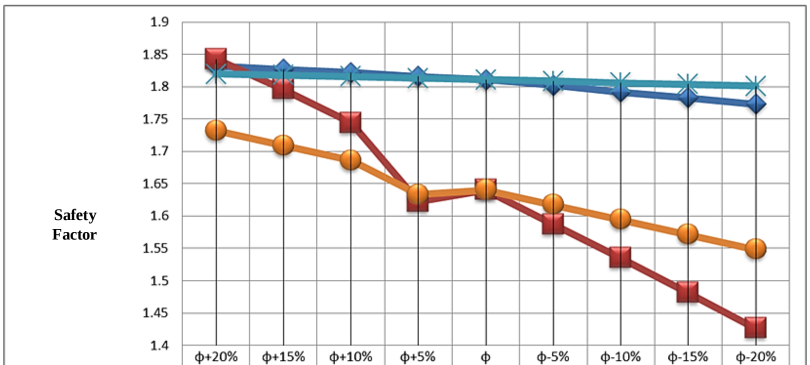


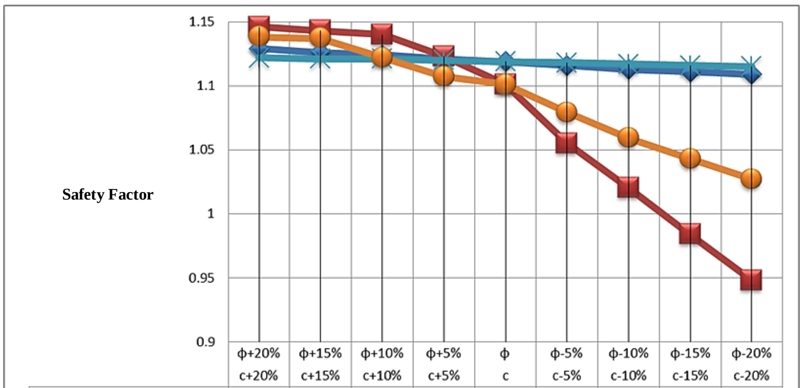
Figure 13. Critical safety factor at the steady state seepage condition using Grid and Radius method

The safety factor, which is obtained for the steady state seepage stage by the Entry and Exit method, differs from the Grid and Radius about 0.005. The difference can be negligible, thus the probable failure surfaces are mentioned by these two methods are approximately the same. We understand this from Figures 13 and 14.



	ϕ+20% c+20%	ϕ+15% c+15%	ϕ+10% c+10%	ϕ+5% c+5%	ϕ c	ϕ-5% c-5%	ϕ-10% c-10%	ϕ-15% c-15%	ϕ-20% c-20%
Entry and Exit(c)	1.832	1.827	1.822	1.816	1.811	1.802	1.792	1.783	1.773
Grid and Radius(c)	1.843	1.796	1.744	1.622	1.64	1.587	1.535	1.481	1.426
Entry and Exit(ϕ)	1.82	1.818	1.816	1.813	1.811	1.809	1.806	1.804	1.801
Grid and Radius(ϕ)	1.732	1.709	1.686	1.633	1.64	1.617	1.594	1.571	1.548

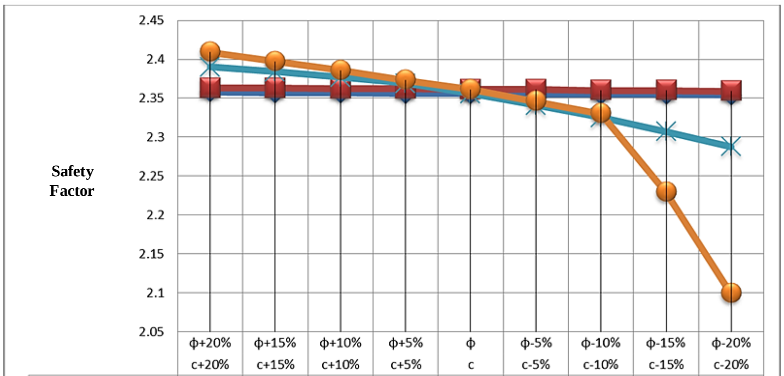
Figure 14. Sensibility on the mechanical parameters of body and foundation materials at the end of construction (Static loading)



	ϕ+20% c+20%	ϕ+15% c+15%	ϕ+10% c+10%	ϕ+5% c+5%	ϕ c	ϕ-5% c-5%	ϕ-10% c-10%	ϕ-15% c-15%	ϕ-20% c-20%
Seismic Entry and Exit(c)	1.129	1.126	1.124	1.121	1.119	1.116	1.113	1.111	1.109
Seismic Grid and Radius(c)	1.146	1.143	1.14	1.123	1.101	1.055	1.02	0.984	0.948
Seismic Entry and Exit(ϕ)	1.122	1.121	1.121	1.12	1.119	1.118	1.117	1.116	1.115
Seismic Grid and Radius(ϕ)	1.138	1.137	1.122	1.107	1.101	1.079	1.059	1.043	1.027

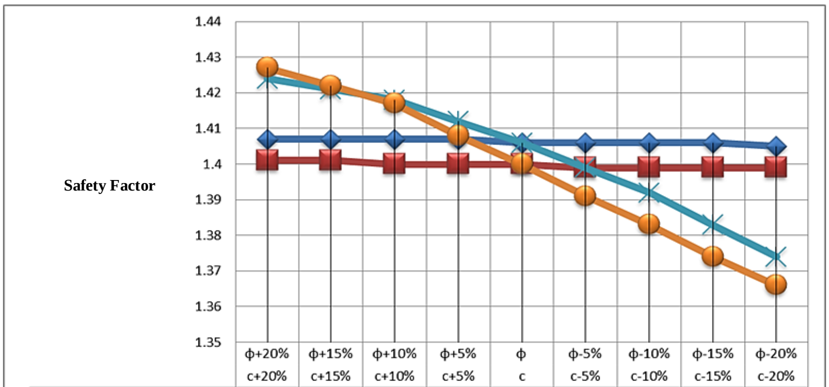
Figure 15. Sensibility on the mechanical parameters of body and foundation materials at the end of construction (quasi-static loading)

According to the results of Figure 14, the Entry and Exit method provides more reliable values in the comparison with the Grid and Radius method. The same result can be concluded from Figure 15 as shown for quasi-static analyses. Also, the sensitivity of the friction angle coefficient on the results is higher than the adhesion for static analyses, but the results of quasi-static analyses show that the cohesion is more effective on the stability's safety factor of the dam.



	ϕ+20% c+20%	ϕ+15% c+15%	ϕ+10% c+10%	ϕ+5% c+5%	ϕ c	ϕ-5% c-5%	ϕ-10% c-10%	ϕ-15% c-15%	ϕ-20% c-20%
Entry and Exit(c)	2.358	2.357	2.357	2.356	2.356	2.355	2.355	2.355	2.354
Grid and Radius(c)	2.363	2.363	2.362	2.362	2.361	2.361	2.36	2.36	2.359
Entry and Exit(ϕ)	2.39	2.384	2.377	2.369	2.356	2.341	2.325	2.307	2.288
Grid and Radius(ϕ)	2.409	2.397	2.386	2.373	2.361	2.346	2.33	2.229	2.099

Figure 16. Sensibility analyses on the mechanical parameters of body and foundation materials at the first impounding (static loading)



	ϕ+20% c+20%	ϕ+15% c+15%	ϕ+10% c+10%	ϕ+5% c+5%	ϕ c	ϕ-5% c-5%	ϕ-10% c-10%	ϕ-15% c-15%	ϕ-20% c-20%
Seismic Entry and Exit(c)	1.407	1.407	1.407	1.407	1.406	1.406	1.406	1.406	1.405
Seismic Grid and Radius(c)	1.401	1.401	1.4	1.4	1.4	1.399	1.399	1.399	1.399
Seismic Entry and Exit(ϕ)	1.424	1.421	1.418	1.412	1.406	1.399	1.392	1.383	1.374
Seismic Grid and Radius(ϕ)	1.427	1.422	1.417	1.408	1.4	1.391	1.383	1.374	1.366

Figure 17. Sensibility analyses on the mechanical parameters of body and foundation materials at the first impounding (pseudo-static loading)

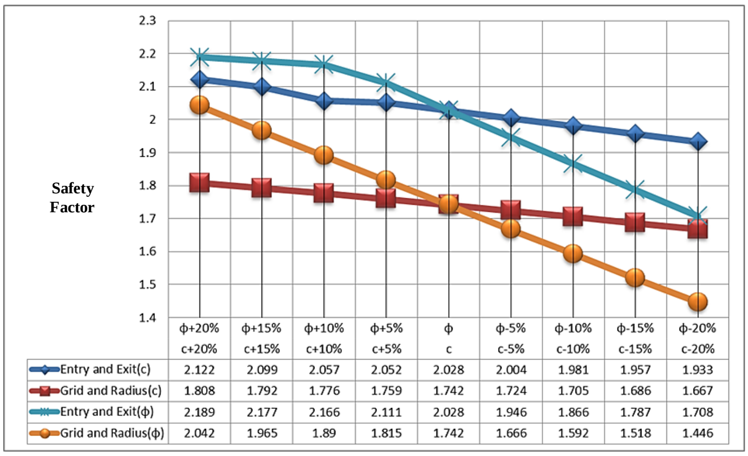


Figure 18. Sensibility analyses on the mechanical parameters of body and foundation materials at the steady stage seepage (static loading)

Figure 16 shows that for all values of c, the Entry and Exit method provides a lower safety factor than the Grid and Radius method, and the same result is obtained by increasing the value of φ and decreasing it to φ-10%. In both methods, the sensitivity of the friction angle is greater than cohesion. In the same comparison for the pseudo-static loading, According to Figure 17, for all c and φ values, except for φ+20%, the Entry and Exit method provides more reliable values than the Grid and Radius method. In both methods, the sensitivity of the friction angle is the most.

It is notable that the same results can be concluded by the sensitivity analysis during the steady state seepage as shown in Figure 18.

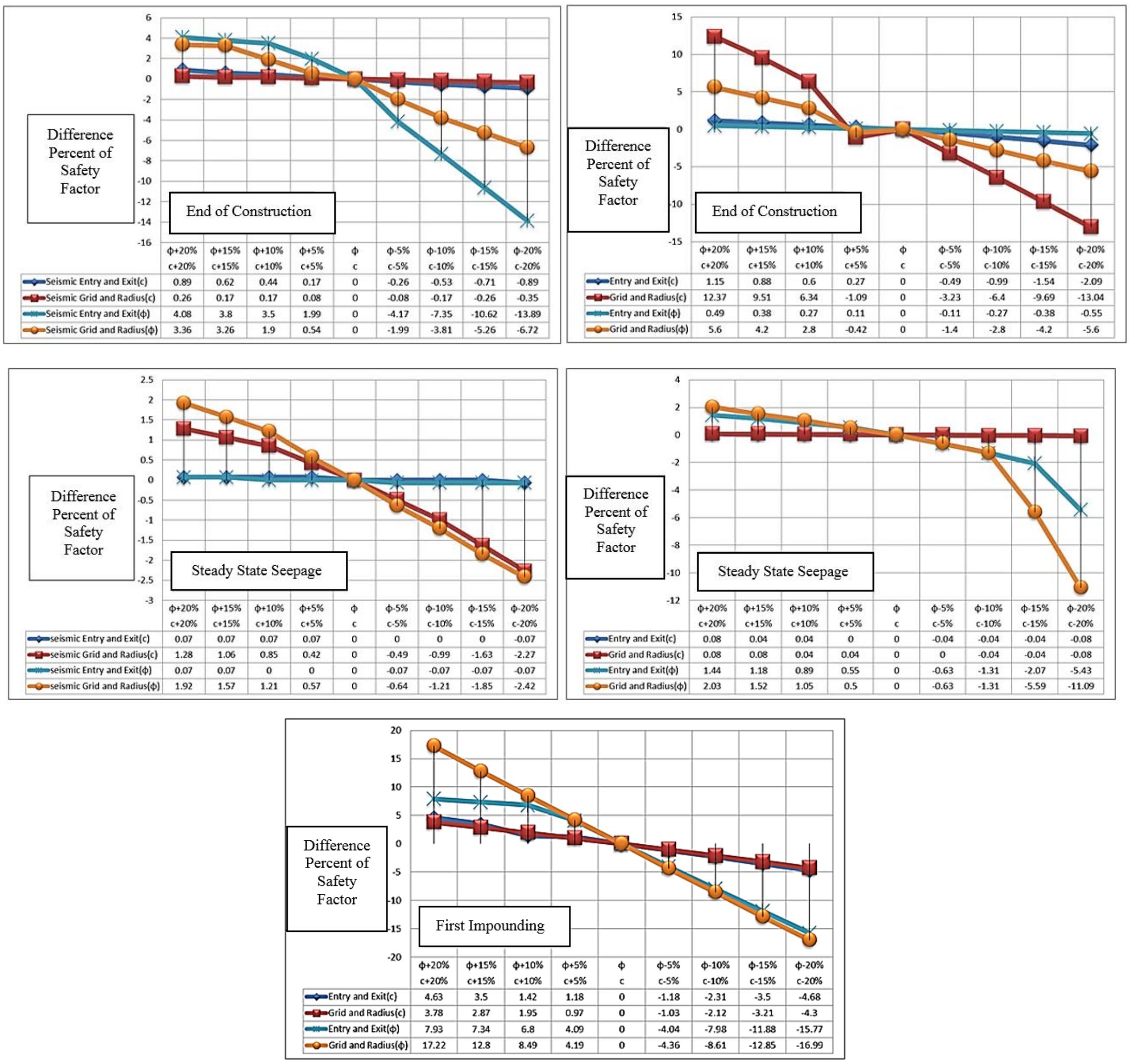


Figure 19. Difference percent of safety factor by changing of the mechanical parameters

Figure 18 shows that the internal friction coefficient has more effects on the dam body stability at the three main loading condition, the end of construction-first impounding and steady state seepage, during the static and quasi-static conditions. The conclusion of results is mentioned in table 6. In this table, the average sensitivity of the coefficients of reliability in static and quasi-static conditions of the different stages are presented.

Table 6. Average Sensitivity values of the confidence coefficients

Analysis Method		Steady State Seepage		First Impounding	End of Construction	
		Quasi-static	Static	Static	Quasi-static	Static
Entry and Exit	c	0.04	0.04	2.80	0.56	1.00
	φ	0.05	1.69	8.23	6.17	0.32
Grid and Radius	c	1.12	0.05	2.53	0.19	7.70
	φ	1.42	2.96	10.69	3.35	3.38

5. Conclusion

GeoStudio software plays an important role in evaluation of the stability of embankment dam or other geotechnical structures. The stability of the homogeneous embankment dam of Narmab was analyzed using the GeoStudio software and the results were compared to the international standards and instructions. In the article, research is made to evaluate the stability of the body and foundation of Narmab dam using the above-mentioned software and determine the sensitivity of the confidence coefficient to the mechanical parameters of the material used in the body and foundation of this dam. The most important findings of the present study are listed as below.

- According to the static and quasi-static conditions, Narmab dam is stable in all loading stages (End of Construction, First Impounding and Steady State Seepage.
- For all three main loading stages of the dam, the coefficients of internal friction and cohesion have a sensitive correlation with the value of the safety factors and also, these correlation is nonlinear. The results is in good agreement by Hasanlou's presentation [18].
- In static conditions and for the end of construction stage, the sensitivity of the confidence coefficient to cohesion is greater than its sensitivity to the angle of internal friction. In these conditions, the average sensitivity of c and φ at the end of construction for the Entry and Exit method is 1% and 0.32%, respectively, for Grid and Radius, 7.7% and 3.38% respectively.
- The sensitivity of the confidence coefficient to variation in the internal friction angle is more significant in the Entry and Exit method while the sensitivity of the confidence coefficient to cohesion changes proved to be more significant in the Grid and Radius method in the quasi-static conditions and for the end of construction stage. The average sensitivity of c and φ at this stage and for the Entry and Exit method is 0.56% and 6.17%, respectively, for the Grid and Radius method, 0.19% and 3.35%, respectively.
- According to conclusion table (Table 6), for both the static and quasi-static conditions, during the steady state seepage stage, the sensitivity of the confidence coefficient to the angle of internal friction is more significant.
- In the static conditions and for the first impounding stage, the sensitivity of the confidence coefficient to the angle of internal friction is more significant than the sensitivity to cohesion. The average sensitivity rate of φ in the Entry and Exit method is 8.23% and the average sensitivity rate of C is about equal to 2.8%. In the same way, the sensitivity of C and φ in the Grid and Radius method are 2.53% and 10.69% respectively.

In general, only for the static conditions of the end of construction stage, the sensitivity of adhesion is greater than the angle of internal friction, but, in other conditions and stages, the sensitivity of friction angle has more effects.

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