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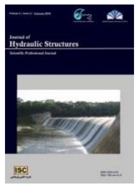

Examining the influence of soil parameters on earth dam slope stability in ABAQUS software

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Abstract

The stability of soil slopes and determination of stability safety factors have always been the subject of study for engineers and researchers. The factor safety of slopes can be determined by using the methods of limit equilibrium method (LEM), strength reduction method (SRM), and limit analysis. The equilibrium method determines the slope safety factor based on the equilibrium of the inter-slice force and without the analysis of tension and strain. In the strength reduction method, based on the tension-strain analysis, the strength of various points of the slope is reduced until it reaches the critical state, and by connecting all of the critical points, the critical rupture level will be obtained. Finite element software and finite difference software determine the safety factors in soil slopes by using the concepts of the strength reduction method. In this study, the safety factors of soil slopes are determined by using ABAQUS software and by using the concept of strength reduction method. Like other types of software, there is no option in ABAQUS for the determination of safety factors and it should be obtained by defining the concepts of strength reduction.

Keywords: Factor of Safety, Slope stability, ABAQUS, Sensitive analysis.

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1. Introduction

If the stability of earth dam slopes, and artificial slopes in the environment are not calculated precisely, they could pose a danger. Due to the great importance of soil slope stability, researchers have carefully considered it in their studies. Their analyses have been either two-dimensional and under the condition of plane strain [1-4] or three-dimensional [5-7].

There are various methods to investigate the soil slope stability and determine the stability safety factor, such as the limit equilibrium method, shear strength reduction, and limit analysis [8, 9]. The limit equilibrium method is used widely by engineers and researchers to determine the safety factor. This method does not conduct the stress-strain analysis, but it can determine the

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slope safety factor. In this equilibrium method, the safety factor is analyzed by checking the equilibrium of inter-slice force and moment [10]. The strength reduction method, S.R.M., was first used by Zienkiewicz et al. (1975) to determine the safety factor in soil slopes [11, 12]. The Finite Element Method, F.E.M., is a logical nonlinear constitutive model for the soil clusters can be implemented into the calculation by depicting plastic points. Over the past years, many researchers have used the strength reduction method (S.R.M.). One of the advantages of the S.R.M. is the determination of the critical rupture level by using shear strain [13].

Different types of software are used for determining the safety factor. Each one of them calculates the safety factor based on one of the mentioned methods. Zettler et al. used FLAC software to determine the safety factor in soil slope [14]. Also, Dawson & Roth used FLAC software to analyze soil slopes [15]. Also, Faws et al. used Plaxis software to investigate the soil slopes and determine their safety factor [16].

Other researchers investigate slope stability with artificial intelligent methods. Wang et al. (2020) developed a multivariate adaptive regression spline-based probabilistic stability analysis attitude for dam slope stability evaluation considering the variations in soil specifications. This method approximates the underlying functional relationship between the variable soil parameters and the factor of safety, accelerating the calculation of the safety factor values [17]. Siacara et al. (2020) solved simultaneously limit equilibrium analysis with seepage calculation to evaluate the safety of an earth dam in long term and during the rapid drop-down [18]. Guo and Dias (2020) bring a Kriging-based probabilistic analysis of a dam [19].

Just as mentioned, different methods and types of software are used to investigate the soil slope and their safety factor, but the ABAQUS software is not yet used to determine their safety factor.

In the course of the present investigation, it is tried to use this software to analyze the soil slope safety factor and investigate the influence of different factors such as material cohesion, angle of internal friction, slope angle, and slope height on safety factor changes.

2. Materials and methods

To analyze and determine the safety factor of soil slopes, soil slope with height, different slope angles, and properties of various materials are defined as presented in table 1. In all analyses, wet unit weight and saturated unit weight of all materials are considered 18 and 20 kN per cubic meter, respectively.

Table 1. Various analyses and their parameters

Material friction angle changes (degree)	**Material cohesion changes (KPa)**	**Slope angle changes (degree)**	**Slope height changes (meter)**
15-25-35	5-15-25-35	15-30-45-60-70	15-20-30

To calculate the safety factor in ABAQUS finite element software, the method of material shear strength reduction is adopted. The finite element method was used for geotechnical problems for the first time in 1966 [20]. Based on the strength reduction method, the soil shear strength is reduced until the slope reaches its unstable state [21]. In the finite element method, this situation is called lack of equilibrium. In the strength reduction method, the behavior of materials is considered elastoplastic. And the soil shear strength parameters are reduced gradually until the durability of slope equilibrium reaches its highest level [22].

The method adopted in the present survey is the method used by Xu et al. (2009) to apply the strength reduction method in ABAQUS. In this method, soil strength parameters are used by the linear changes, corresponding to the strength weight [21].

In this method, the Mohr-Coulomb material shear strength is reduced corresponding to the F_{trial} factor called the safety factor. The shear strength continues until it fails [21]. The definitions of parameters are as follows:

$$\frac{\tau}{F_{trial}} = \frac{C^{`}}{F_{trial}} + \frac{\tan\varphi^{`}}{F_{trial}} \tag{1}$$

Where Ø and c are actual internal friction angle and cohesion of the soil, respectively. Equation 1 reformulate as below:

$$\frac{\tau}{F_{trial}} = C^{*} + \tan\varphi^{*} \tag{2}$$

in which c* and ϕ* are:

$$C^{*} = \frac{C^{`}}{F_{trial}} \tag{3}$$

$$\varphi^{*} = \arctan(\frac{\tan\varphi^{`}}{F_{trial}}) \tag{4}$$

Initially, the full loading condition imposed on the slope with the real shear strength parameters, and the domain of the plastic points will be determined. If this slope is stable, the safety factor is higher than one. Then calculation with greater F can be performed. The smallest amount of F in which a slope is stable is the safety factor [23].

For Mohr-Coulomb material, the steps to search for the value of F_{trial} safety factor at the time of failure are as follows [24]:

1. The finite elements model creates the model by defining the slope geometry and the properties of used materials, and the maximum displacement of the slope is calculated and recorded by the finite element method.
2. The value of F_{trial} and material properties parameters are calculated as described above. New strength values are applied in the model, and the model will be reanalyzed, and the maximum deformation is recorded.
3. The second step is continued systematically by increasing F_{trial} until the finite element model diverges. In other words, this is continued by strength reduction until the slope slips. When the slope slips, the critical value of F_{trial} is the slope safety factor. In the states in which the slope is unstable in primary conditions, the F_{trial} values are increased in the first and second steps until the model converges. Figure 1 shows a sample of completed steps to reach the slip moment and the calculation of the safety factor.

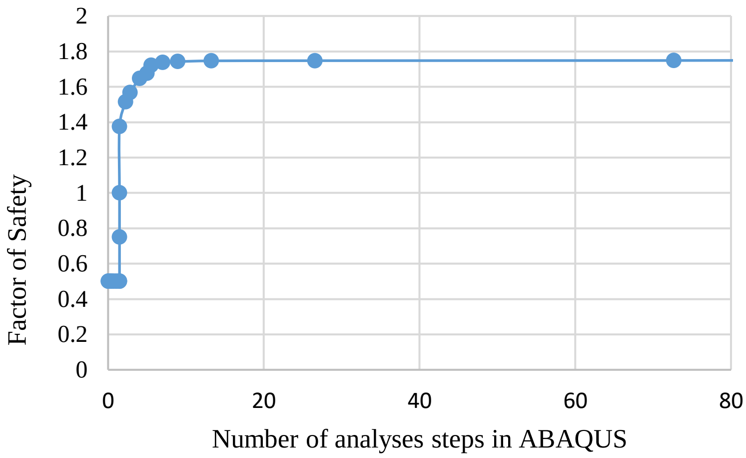

Figure 1. Analysis steps performed in ABAQUS to calculate factor of safety

To analyze further states of the slope with various heights and properties presented in table 1, about 180 different analyses are conducted. The concept of meshing is in a way that more delicate meshing does not impose any significant accuracy in the results. Figure 2 shows a sample of the meshing.

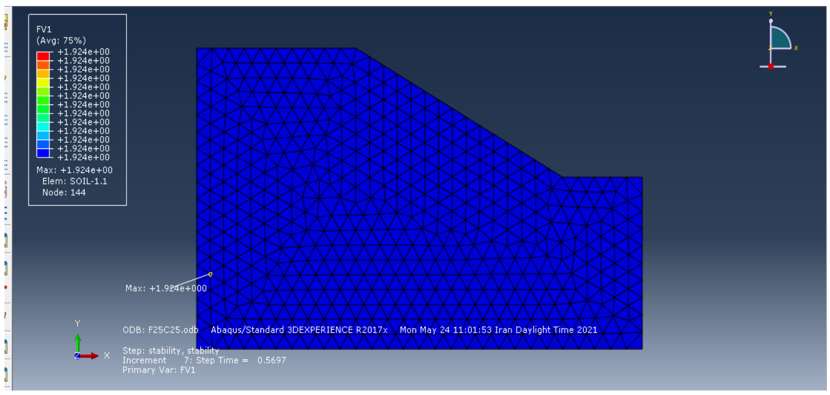

Figure 2. Model mesh in ABAQUS

3. Primary verification of results

Since the strength reduction method for the calculation of safety factors is used innovatively in ABAQUS, to check the preciseness of the results, it is required to compare the results of the analysis of the safety factor of a particular slope in ABAQUS with the results of other software that have a specific method for the calculation of safety factor. FLAC uses the finite difference method for calculating safety factors. In the other hand, Plaxis use strength reduction method for calculating safety factor. SLOPE/W uses the limit equilibrium method for calculating safety factors by the method of Morgenstern-Price in this research. Boundary condition in all software is the same as statical analyses. Lateral displacement in vertical boundary adjusted to be zero. But the vertical and horizontal movement of the lower boundary is equal to zero. The slope with a height of 15 meters, the slope angle of 30, the cohesion of 25 kPa, and friction slope of 15, which its material dry unit weight is 18 kN/m^3, have resulted as in Table 2. Results of several modeling in the software are shown in Figure 3.

Table 2. Comparison of factor of safety results in different software

Software	ABAQUS	FLAC	PLAXIS	SLOP/W
Factor of Safety	1.37	1.36	1.37	1.35

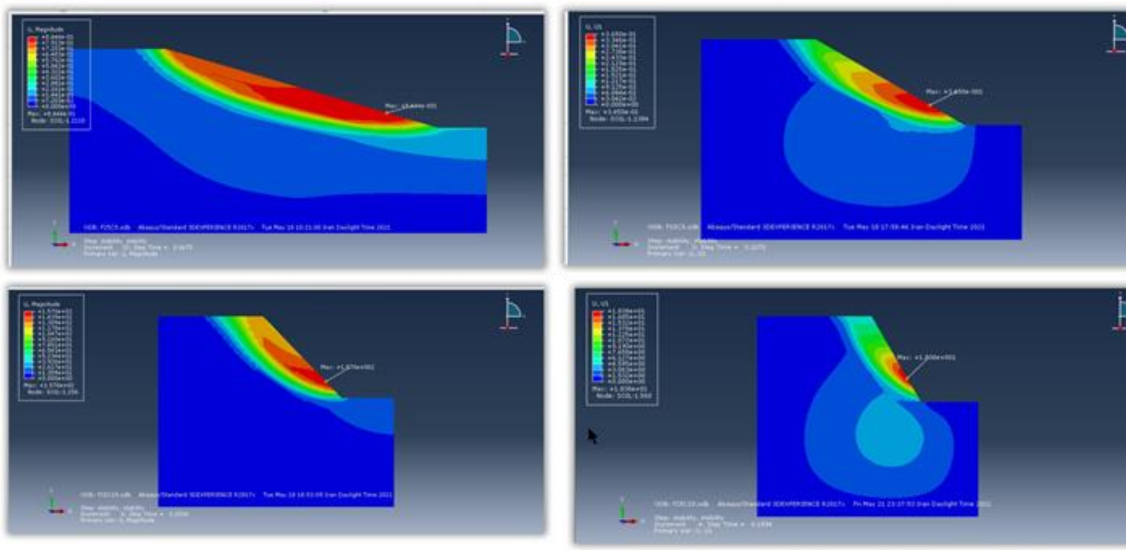

Figure 3. A number of analyzes performed in ABAQUS

4. Discussion and analysis of results

In this section of the study, the influence of different parameters on soil slope safety factor is studied.

4.1. The influence of slope height on the stability

Slope height can affect the safety factor change. However, this change is variable according to the strength parameter changes. Figure 4 illustrates the impression of slope height change with the slope angle of 30°, friction angle of material is equall to 25°, and cohesion change from 5 kPa to 35 kPa.

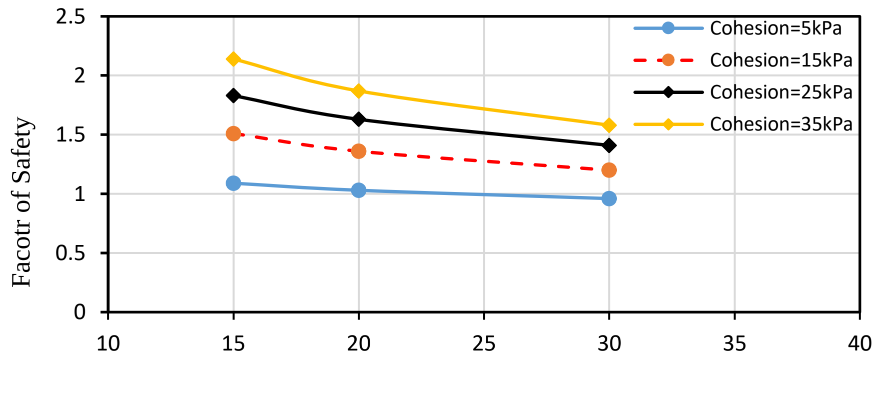

Figure 4. The influence of height changes on slope stability in different cohesion and friction angle of 25 degrees and slope angle of 30 degrees

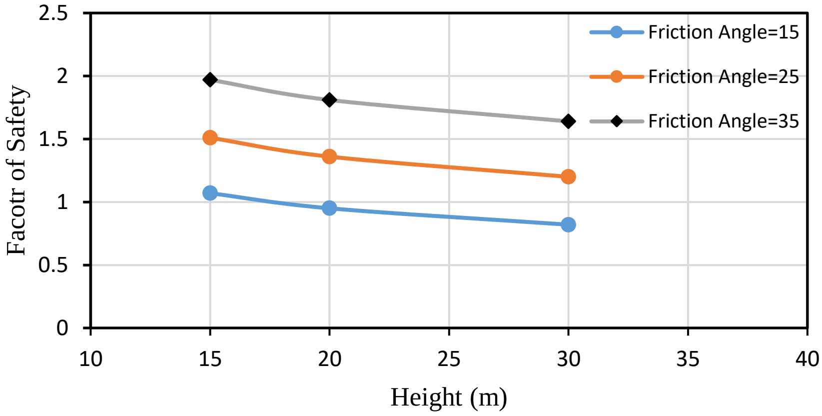

Figure 5. The influence of height changes on slope stability at different friction angles and cohesion of 15 kPa and slope angle of 30 degrees.

As observed in figure 4, when the slope height is 15 meters, the change of cohesion from 5 kPa to 35 kPa will increase the safety by 96% whereas, when the slope height is 30 meters, the cohesion increases from 5 kPa to 35 kPa and the safety factor increases by 64%. These changes are effective to a lesser extent in figure 4 in such a way that if the slope height is 15 and friction angle increases from 15° to 35°, the safety factor will increase by 85% and when the slope height is 30 meters, the safety factor will increase by 99%.

Also, as figure 4 represents, when the cohesion is low, the slope height change will not dramatically affect the safety factor. For example, if the slope height changes from 15 meters to meters, the safety factor will decrease from 1.19 to 0.96.

4.2. The influence of slope angle on stability

Slope angle is another parameter affecting the soil slope stability drastically. An avoidable fact is that by increasing the slope angle, the safety factor decreases [24, 25]. This is shown in figure 6. As the figure presents, the change of slope angle does not affect the safety factor.

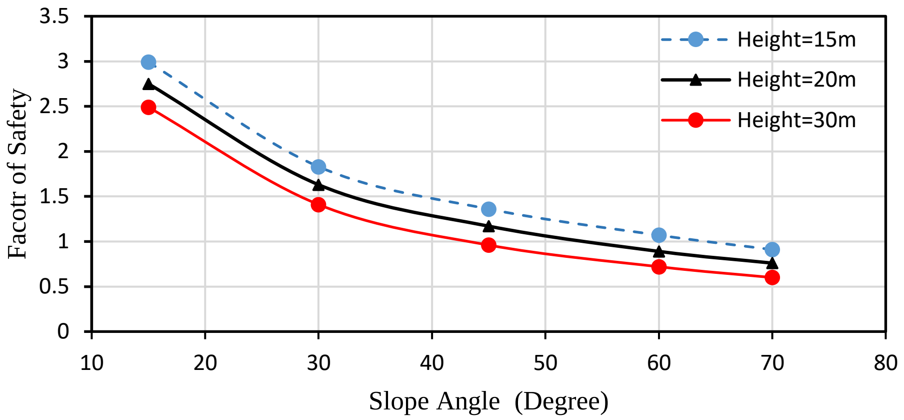

Figure 6. The effect of slope angle on slope stability at various heights and cohesion of 25 kPa and friction angle of 30 degrees

For instance, in the soil slope with a height of 15 meters, the cohesion of 25 kPa, and friction angle of 25° when the slope angle is 15°, the safety factor is 2.99, but when the slope angle increases to 30°, the safety factor decreases to 1.83, Contrary to the common expectation, when the slope angle is less than 45° the change of slope angle will affect the safety factor more than the time when the slope angle is more than 45°. When the slope angle is less than 45°, for increment in slope angle by each degree, the safety factor decrease 7.7 by 4%, but in still, the slopes with a slope angle of more than $45^{\circ} - 70^{\circ}$ for increment in slope angle by each degree, the safety factor decreases by 1.95%.

4.3. The effect of internal friction angle on stability

In the parametric study, by changing properties of the materials safety factor of a slope will change. The effect of material friction angle on slope stability is analyzed in figure 7.

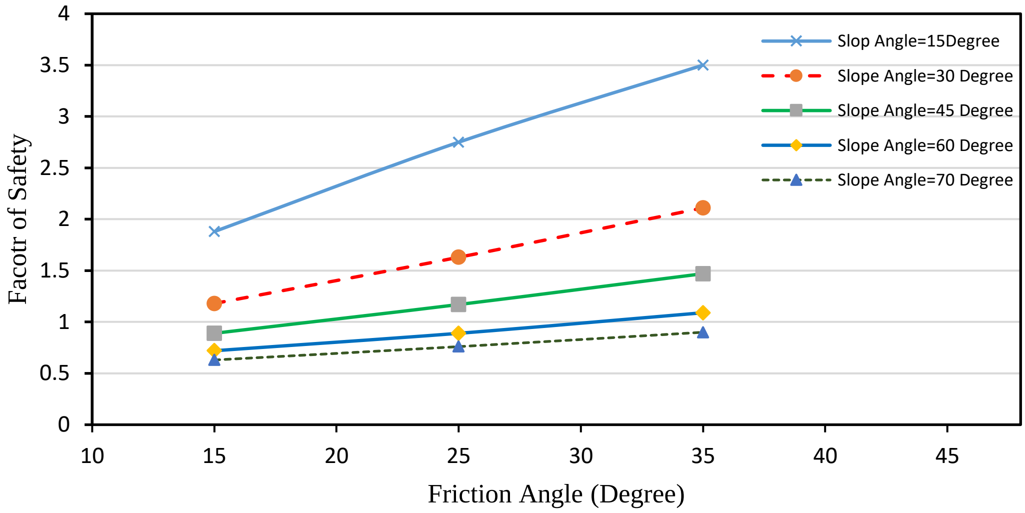

Figure 7. The effect of Ø on slope stability in different slopes (c= 25 kPa and Ø=30 degrees)

As figure 7 illustrates, the material friction angle drastically affects the slope stability, but the most important point of the diagram is the affect of material friction angle in the slopes that have an angle less than 45° on the safety factor. When the slope angle is 15° and the material friction angle is also 15°, the safety factor will be 1.88, but when the friction angle increases to 35°, the safety factor increases to 3.5. Also, in this diagram, it is evident that the safety factor is changed more effectively by slope angle in the granular materials that have more friction angle rather than the fine-grained materials. For instance, the change of slope angle from 15° to 70° in granular materials with a friction angle of 35° will reduce the safety factor from 3.5 to 0.9, but in the case of fine-grained materials with a friction angle of 15° these changes occur in the domain of 1.8 to 0.63.

4.4. The effect of cohesion on stability

Cohesion is another characteristic of the materials that affect the safety factor. In this research, commonly, the domain of material cohesion is considered from 5 to 35 kPa. The effect of cohesion on slope stability is analyzed in figure 8.

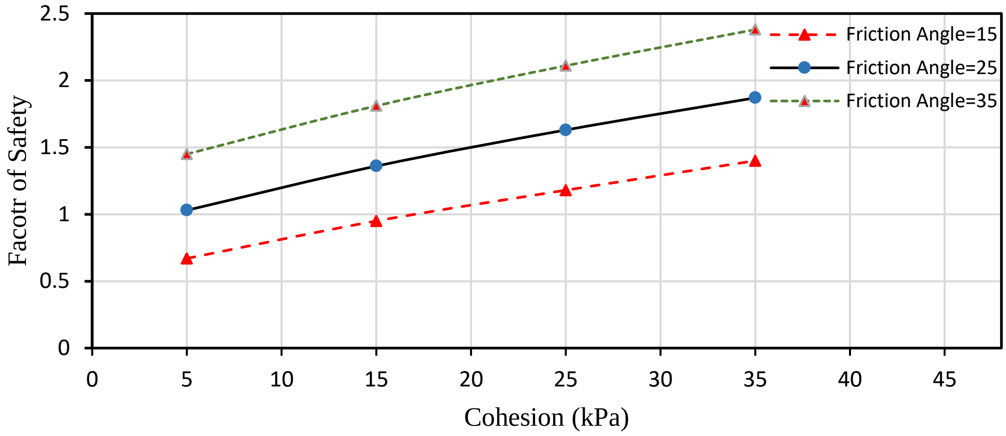

Figure 8. The effect of cohesion on the slope stability at different friction angles

As shown in the figure, by increasing the material cohesion from 5 to 35 kPa, the safety factor increases approximately by 60%.

5. Sensitivity Analysis

In the previous section, the impressions of changing slopes and material properties on the safety factors were investigated. In this basic fundamental analysis, the calculations of a 20 meter slope, 40° of steepness, material friction angle of 25° and cohesion of 20 kPa were considered as the base slope. The results of this analysis are shown in figure 8. The influence of all mentioned parameters is analyzed up to 80% more and less than the base numbers. For example, as it was mentioned noted, the base value of the cohesion impression is considered 36 kPa, and in figure 8, the cohesion influence is shown up to 80% more than the base value (20 kPa) and 80% less than the base value (4 kPa).

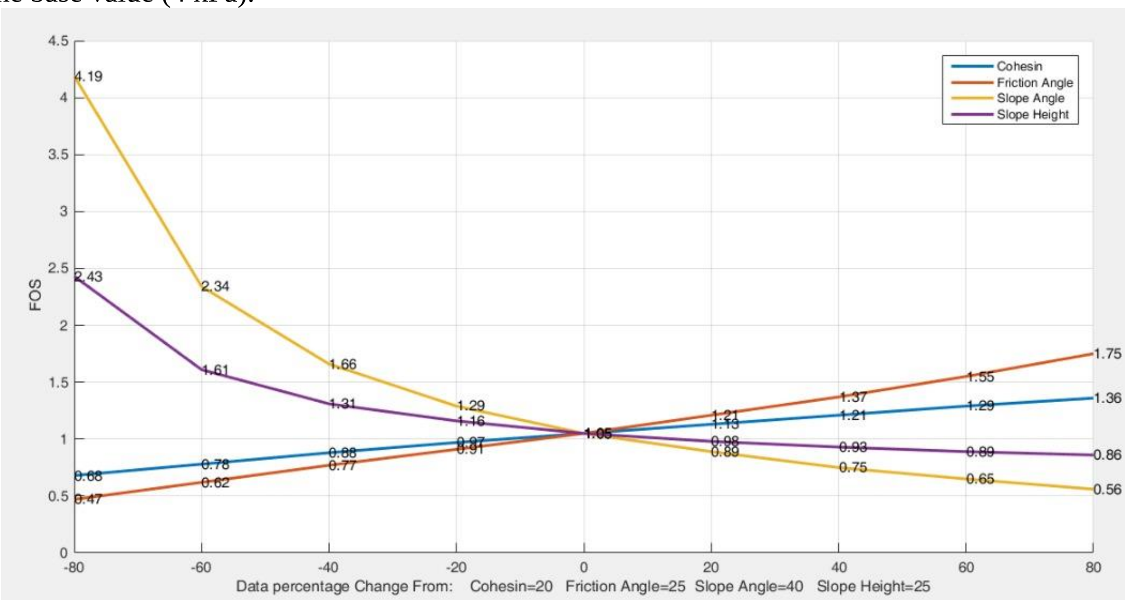

Figure 9. Sensitivity analysis of the effect of slope angle, slope height, soil cohesion, soil friction angle on stability.

In the center of the horizontal axis of figure 9, when the value is zero, then C=20 kPa, Ø=25°, slope angle is 40°, and slope height is equal to 25m. By moving toward positive numbers till 80%, these parameters increase. As illustrates in this figure, among the four mentioned parameters, slope angle change and its reduction from the base number (40°) have the most impression on the safety factor. After slope angle, slope height produces the most significant impact on the safety factor.

Among the friction angle and cohesion, the influence of Ø change on the safety factor is greater than the effect of cohesion on the safety factor in such a way that the increment of friction angle by 60% results in the increment of safety factor by 55%, but the increment of cohesion by 60% results in the increment of safety factor by 29%.

6. Conclusion

in the present work, the safety factors of soil slopes are determined by using ABAQUS software and by using the concept of strength reduction method. ABAQUS is a powerful finite element platform that is rarely used for safety factor determination. By using the method presented in this study, the safety factor in soil slopes can be calculated by this software.

Just as observed, different factors such as slope angle, slope height, material cohesion, and material friction angle, drastically affect the value of the safety factor. Also, in the cases of cohesion and friction angle, the changes of friction angle affect the safety factor changes more than cohesion changes. In addition, slope angle and its changes affect the safety factor changes more than other factors. When slope angle changes by 15 to 40 degrees, this impression is produced more than in other conditions. Slope height is also an essential factor affecting the safety factor, and when the slope height changes by 5 to 15 meters, the changes of slope height affect the safety factor more significantly.

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