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Article

Modeling the impact of soil cohesiveness on embankment stability under rapid drawdown

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Abstract. For embankment slope stability, soil cohesivity is one of the most important shear strength parameters. The effect of cohesiveness on the slope stability of a homogeneous embankment dam under rapid drawdown loading conditions was examined in this study. With the use of numerical modeling in GeoStudio, different situations were explored based on cohesiveness (0 kN/m^2, 5 kN/m^2, 10 kN/m^2, and 15 kN/m^2) under a 1 m per day drawdown rate. The factor of safety value obtained from the long-term steady-state condition under 15 kN/m^2 cohesion was equivalent to a 116.8% increase from the one obtained under 0 kN/m^2 cohesion. The factor of safety values obtained after subjecting the embankment to different soil cohesion levels yielded a p-value of 1.91×10^{-41}, according to the Analysis of Variance. The calculated p-value (alpha value) is less than 0.05, suggesting that the differences between the examined cohesiveness values based on the list of the factor of safety values are statistically significant. The findings derived in this study show that it is significant to capture the effect of material characteristics during the design phase of an embankment dam.
Keywords: embankment, numerical modeling, factor of safety, soil cohesiveness, slope stability.

1. Introduction

Soil cohesiveness is defined as the ability of soil particles to be structured or arranged in a united manner, with close or strong internal connections. Cohesion is the component of a rock's or soil's shear strength that is unaffected by interparticle friction [1]. In general, shear strength under zero normal stress, or the intersection of a material's failure envelope with the shear stress axis in the shear stress-normal stress space, is referred to as cohesion in soil mechanics [2]. On the other hand, drained cohesion is defined as cohesiveness under saturated drained conditions, while apparent cohesion is defined as cohesion under variably saturated conditions [3].

The potential relationship governing the compressive stress (p) as well as the corresponding shear strength (s) in cohesive soils is commonly considered to be described by an empirical equation known as Coulomb's equation as highlighted in Equation 1 [1].

$$s = c + p \tan \varphi \tag{1}$$

Whereby: c is the shear cohesion, φ is the angle of internal friction.

The technique of estimating and assessing how much stress a given slope can handle before failing is known as slope stability [4]. Commercial highways, dams, excavated slopes, and soft rock walks in reservoirs, forests, and parks are examples of common slopes. Slope stability analysis is important for civil and geotechnical engineers planning construction for highways, dams, embankments, and other excavated slopes, because failing to comprehend slope stability can lead to landslides, unwanted movement, and injury to both property and people [5].

Furthermore, in the case of embankment slope stability, a single failure surface can be examined using several approaches that have evolved through time to determine its Factor of Safety (FS) [6]. An engineer must choose the most critical surface, i.e. the one with the lowest FS when analyzing the stability of either man-made or natural slopes [7]. Designers must consider whether the slope should be reinforced to meet the minimum needed FS after selecting this surface [8]. Slope stability concerns have caused projects to be drastically altered in the past, with the decision-making process being both a technical and a financial issue [9].

Prior to the development of computational tools, determining the critical failure surface was a difficult task that necessitated several, time-consuming manual analyses. Nonetheless, technological improvements have made it possible to carry out a variety of examinations [10]. As a result, after numerous rounds, the critical failure surface and its FS can be easily determined. The Mohr-Coulomb criterion is commonly used to incorporate the material(s)' cohesion and friction.

Clay, silty clay, sandy clay, clay loam, and, in rare circumstances, silty clay loam and sandy clay loam are examples of cohesive soils. Noncohesive soils include clean sand and gravel. If the silt is nonplastic, sand and gravel containing silt may be noncohesive, necessitating the measurement of the Atterberg limits. Cohesive behavior would be observed in sand and gravel with clay or plastic silt. In geotechnical engineering, numerical modeling is commonly used to study the responses of infrastructures in civil engineering [11]. To cope with various geotechnical difficulties, a variety of handmade or commercialized numerical codes are available.

The impact of soil cohesiveness on embankment stability under coupled fast drawdown analysis is examined in the present study. In GeoStudio software, the topic is investigated using the finite element method.

2. Materials and Methods

2.1 General description of the numerical simulation

Under the steady-state condition and rapid drawdown rate, finite element method analyses were used to explore the effect of cohesion on slope stability (1 m per day). Different cases were considered, as determined by soil cohesion (0 kN/m^2, 5 kN/m^2, 10 kN/m^2, and 15 kN/m^2). The GeoStudio software suite was used to perform the numerical modeling (GeoStudio 2018 R2 v9.1.1.16749). The GeoStudio's SEEP/W and SLOPE/W sub-units were primarily employed for seepage and slope stability analyses, respectively.

2.2 Embankment geometry

In all of the cases studied, the embankment geometry was kept constant while the material cohesiveness was changed to investigate its influence on the embankment stability. As illustrated in Figure 1, the embankment is roughly 68 meters wide at the base and 8 meters wide at the top, with a height of 11 meters. The reservoir's highest water level is 9 meters.

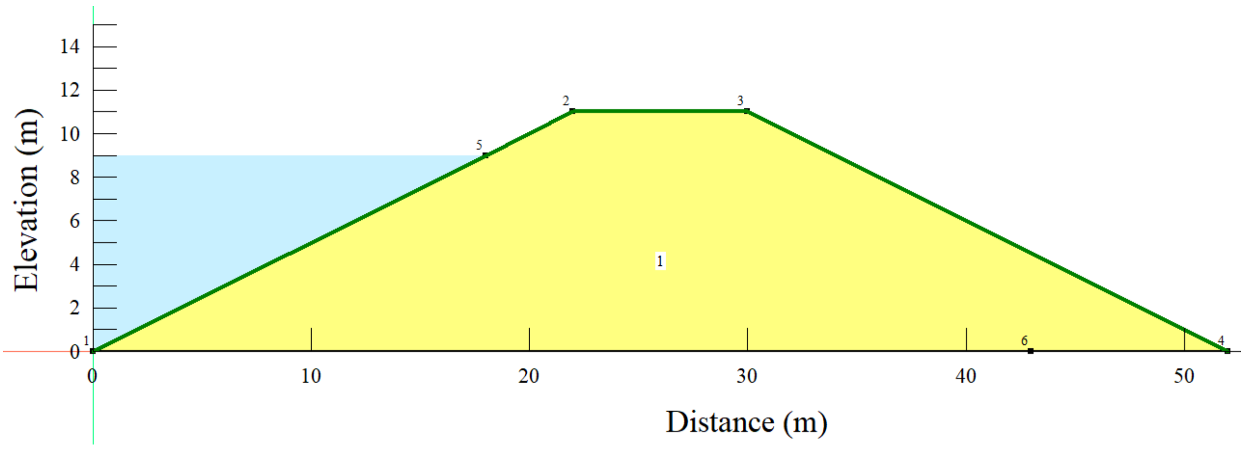

Figure 1 – Geometry of the study embankment

2.3 Soil material characteristics

To avoid any fluctuation and capture the influence of variations in the soil cohesion, the soil material parameters for the embankment were kept constant for all of the models analyzed. The soil material parameters utilized in the seepage and slope stability analyses are summarized in Table 1. The major soil parameters in the model were saturated water content, coefficient of compressibility, conductivity, residual water content, soil unit weight, cohesion, and internal friction angle.

Table 1 – Soil material properties

Soil material properties	Symbol	Unit	Value
Saturated water content	θ_s	%	43
Coefficient of volume compressibility	M_v	m^2/kN	2×10^{-4}
Saturated conductivity	K_{sat}	m/s	1×10^{-6}
Residual water content	θ_r	%	5.5
Soil unit weight	γ	kN/m^3	20
Cohesion	c'	kN/m^2	0, 5, 10, 15
Internal friction angle	$\emptyset'$	degrees	27

2.4 Statistical analysis

To test if the differences between sets of data were statistically significant, a single-factor Analysis of Variance (ANOVA) was utilized. This method examines the amounts of variance within each group using samples from each group. The significance level was calculated using the combination of alpha (0.05) and p-value to be more specific.

3. Results and Discussion

The model embankment was initially put through a series of long-term steady-state investigations with varying cohesion levels. Figure 2 shows that as the soil cohesiveness increased, the long-term steady-state factor of safety values increased as well. The factor of safety value obtained from the 5 kN/m^2 cohesiveness was equivalent to a 52.6 % increase over that obtained from the 0 kN/m^2 cohesion.

Meanwhile, the 10 kN/m^2 cohesiveness factor of safety value was equivalent to a 22.2 % increase over the 5 kN/m^2 cohesion. In addition, the factor of safety value obtained from the 15 kN/m^2 cohesiveness was roughly 16.2 % higher than that obtained from the 10 kN/m^2 cohesion. The results also show that as the soil cohesiveness in the embankment increases, the disparity in terms of factor of safety values between cohesion values under long-term steady-state conditions decreases.

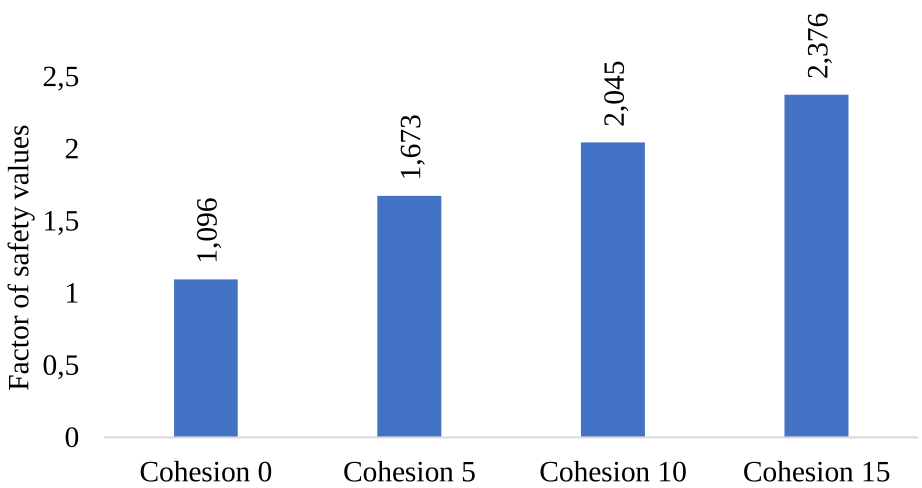

Figure 2 – Factor of safety values from long-term steady-state conditions

When the embankment was subjected to 0 kN/m^2 cohesion and a 1 m per day drawdown rate, Figure 3 shows the trend of the factor of safety values. The minimum factor of safety (attained on the eighth day of drawdown) was roughly 0.749, as shown in Figure 3. The factor of safety value obtained is 31.66 % lower than that obtained using the long-term steady-state condition and 0 kN/m^2 cohesion. Furthermore, the minimum factor of safety value is less than one, indicating that the embankment has failed.

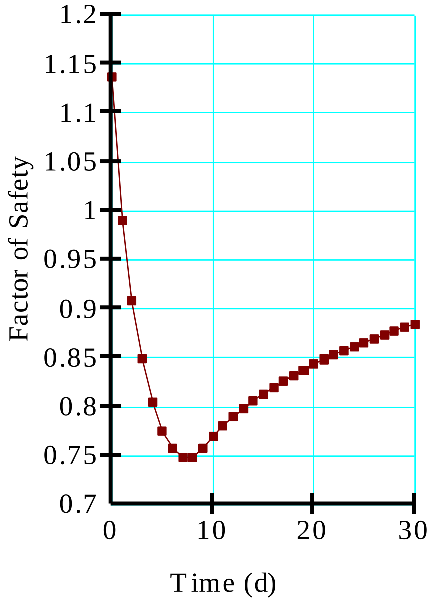

Figure 3 – Graph of the factor of safety values from 0 kN/m^2 cohesion material

Figure 4 depicts the factor of safety values obtained from a 1 m per day drawdown rate and a 5 kN/m^2 cohesiveness. In contrast to the minimal factor of safety value obtained from the 0 kN/m^2 cohesion, Figure 4 shows that the 5 kN/m^2 cohesion generated a minimum factor of safety greater than 1 (1.058), which can be regarded as safer. The factor of safety is 36.76 % lower than calculated using the long-term steady-state condition and 5 kN/m^2 cohesion.

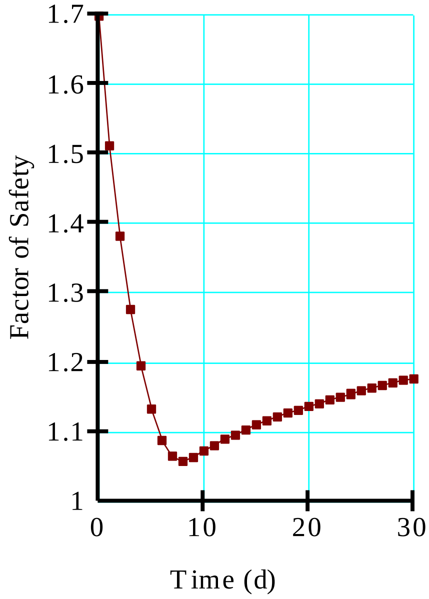

Figure 4 – Graph of the factor of safety values from 5 kN/m^2 cohesion material

The factor of safety values from the 1 m per drawdown rate and 10 kN/m^2 soil cohesiveness are summarized in Figure 5. It was discovered that a minimal factor of safety value of about 1.293 was obtained. The factor of safety value obtained is 36.77 % lower than that obtained using the long-term steady-state condition and 10 kN/m^2 cohesion.

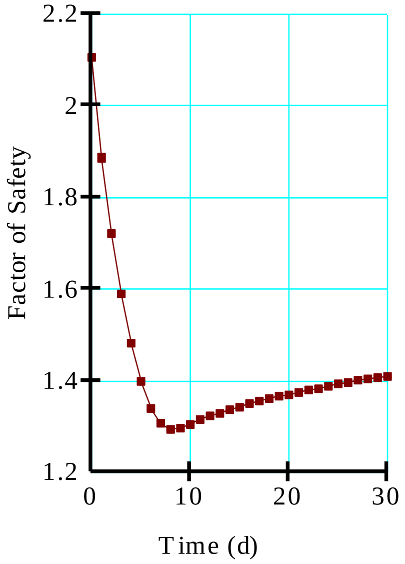

Figure 5 – Graph of the factor of safety values from 10 kN/m^2 cohesion material

In addition, Figure 6 summarizes the factor of safety values derived from the 1 m per day drawdown rate and 15 kN/m^2 soil cohesion. A minimal factor of safety of 1.516 was attained using a combination of 10kN/m^2 cohesiveness and a quick drawdown rate. The factor of safety value obtained is 36.20 % lower than that obtained using the long-term steady-state condition and 15 kN/m^2 cohesion. In general, the results reveal further that under a constant drawdown rate, the increase in soil cohesion increases the minimum factor of safety values. The results in this study comprehend with the study conducted by [12]; whereby, it was observed that changes in cohesion had a significant effect on the factor of safety.

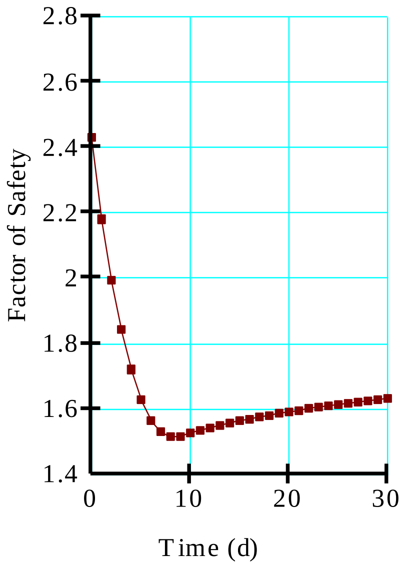

Figure 6 – Graph of the factor of safety values from 15 kN/m^2 cohesion material

ANOVA was used to see if there were any significant changes in the retrieved factor of safety values from the examined operating levels and drawdown rates. From day 0 (defined by the long-term steady-state condition) until day 30 of the rapid drawdown, a total of 31 factor of safety values were considered.

On the examined cohesion values under 1 m per day drawdown rate, a single-factor ANOVA with an alpha value of 0.05 was performed; the results of the ANOVA are reported in Table 2. The factor of safety values based on the investigated cohesion values generated a p-value of 1.91×10^{-41}, as shown in Table 2. The obtained p-value (alpha value) is less than 0.05, indicating that the variations in the list of the factor of safety values from the investigated cohesion values are statistically significant. This was a crucial part of the study since it allowed us to see if the differences in factor of safety values across the cohesion values investigated were substantial [13].

Table 2 – Results from Analysis of Variance

ANOVA: Single Factor						
SUMMARY						
Groups	Count	Sum	Average		Variance	
Cohesion (0 kN/m^2)	31	26.07	0.84		0.0058	
Cohesion (5 kN/m^2)	31	36.27	1.17		0.0182	
Cohesion (10 kN/m^2)	31	44.11	1.42		0.0315	
Cohesion (15 kN/m^2)	31	51.27	1.65		0.0403	
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	11.32	3	3.77	157.53	1.91 x 10^{-41}	2.68
Within Groups	2.87	120	0.024			
Total	14.19	123				

Figure 7 summarizes the minimum factor of safety values from the investigated cohesion values. From Figure 7, it can be seen that the minimum factor of safety values were decreasing with the decrease in the soil cohesion. It is also important to note that, the minimum factor of safety values were retrieved from the 1 m per day drawdown rate.

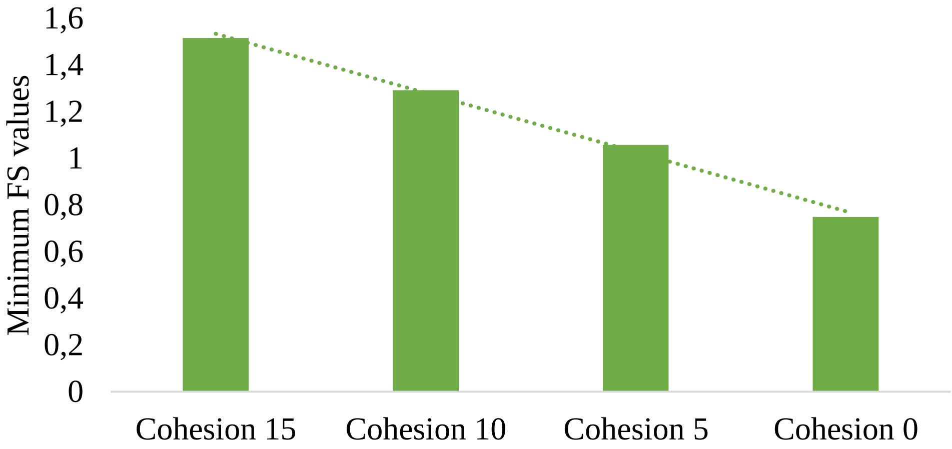

Figure 7. Summary of the minimum factor of safety values from the studied cohesion values

4. Conclusions

Under rapid drawdown loading conditions, the influence of cohesiveness on the slope stability of a homogeneous embankment dam was examined. The following may be concluded:

– According to the Analysis of Variance, the factor of safety values obtained after subjecting the embankment to varied soil cohesion levels provided a p-value of 1.91 x 10^{-41}.

– The estimated p-value (alpha value) is less than 0.05, indicating statistical significance between the analyzed cohesiveness values and the list of the factor of safety values.

– The factor of safety value obtained from the 5 kN/m^2 cohesiveness was 52.6 % higher than that obtained from the 0 kN/m^2 cohesiveness.

– Meanwhile, the factor of safety value of the 10 kN/m2 cohesiveness was equivalent to a 22.2 % increase over the 5 kN/m^2 cohesion.

– Furthermore, the factor of safety value obtained from 15 kN/m^2 cohesiveness was approximately 16.2 % greater than that obtained from 10 kN/m^2 cohesiveness.

– The findings also reveal that as the embankment's soil cohesiveness increases, the discrepancy between cohesion values under long-term steady-state conditions reduces in terms of factor of safety values.

– Based on the results, it is significantly important to investigate the levels of soil cohesiveness during the design phase of an embankment dam.

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