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Article

Effects of Water Table Level on Slope Stability and Construction Cost of Highway Embankment

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Abstract. Highway embankments stability during its service period represents an important factor for the safety of highway users and vehicles. Consequently, the cost of construction of these embankments should be adequate to maintain the safety and durability during this period through proper estimation of the loading on asphalt pavement, slope stability, horizontal and vertical deformation, etc. Slope stability of the embankment mainly depends on the shear strength of the soil layers materials; this shear strength is affected by the water table level through the contribution of the capillary water. Negative pore water pressure above the water table level evolves matric suction in the unsaturated zone above water table; this matric suction increases the shear strength of the soil depending on the soil type, void ratio, etc. This paper studies the slope stability of highway embankment using finite element method analysis by using GeoStudio software to show the effect of the presence of water table and the contribution of the matric suction. A trial slope is shown to have the same factor of safety with reduced cross section due to increasing the shear strength hence, the reduced cross sectional cost is determined.

Keywords: Road embankment stability, factor of safety of slopes, matrix suction.

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1. Introduction

Slope stability analysis and construction cost for highway embankment are one of the most important issues in transportation engineering as well as in geotechnical engineering. Slope stability analysis is conducted to estimate safe and economic design of human-made or natural slopes, such as cuts and embankments of a highway road. Practically, slope stability is one of the leading difficulties for slope failures pose a great threat to human life and infrastructure [1-3].

To assess the slope failure, the factor of safety (FOS) is determined and used by engineers to ensure the stability of slopes [4]. It may be obtained as the ratio of the total force available to resist the slope failure to the total force tending to cause failure. Therefore, the slope is rated "stable" if FOS is greater than 1, usually 1.5 [5], and considered critical when FOS is equal to 1. Water table level below or near the bottom of the embankment is one of the most effective factors that relates to the contribution of the matric suction due to capillary to soil shear strength, which has a direct effect on the design and the cost of the highway embankment. Predominately, water table conditions are the cause of slope failure in human-made or natural slopes because the shear strength and effective stress of the soil are decreased when the pore water pressures from water table are increased [6,7]. Consequently, water table conditions received progressing attention and became one of the crucial issues in recent years, especially for geotechnical engineering researchers [8-11].

2. Previous Work

Various researchers carried out many studies evaluating the impacts of water table level variations on slope stability analysis.

Khanmohammadi and Hosseinitoudeshki [12] created models in plain strain. The achieved results in their study show that the safety factor and strength of slopes decrease when water table level rise and enter into the rupture surfaces in the slopes. Hence, prevention of water penetration into the slopes can increase the stability of slopes. Taghizadeh and Vafaeiyan [13] stated in their study that raising the water level in slopes composed of fine-grained soils causes swelling of soil, and in the case of coarse-grained soils, the internal friction angle of the soil reduces and thus reduces the of ultimate bearing capacity of the soil. They suggested using a drainage system in the slopes to direct water out of the soil profile, in order to prevent slippage and instability of slopes.

The numerical analysis of slope stability in the study of Noroozi and Hajiannia [14] stated that slope angle and rainfall have the most effect in the safety factor analysis. Also, for layered slopes, variable cohesion or friction angle for each layer were studied. In conducting the analysis, Mohr-Coulomb's constitutive model was used in this research. Johansson [15] investigated the influence of water level variations on slope stability and concluded that slope stability increases when the groundwater table level drops for each water-level fluctuation change.

Djamaluddin et al. [16] studied an existing road embankment slope in Indonesia that already has a critical factor of safety; he studied the slope both with and without the water level effect. New design of stepped slope with various angles showed improvement in the factor of safety with and without the water level effect. This improvement was also shown to affect the distribution of mean stress, maximum shear strain, and total displacement. Seyhan et al. [17] studied the effects of groundwater level by investigating the slope stability analysis of embankments and earth-fill barriers constructed on soft clay soil materials. Different scenarios and input parameters were used in the stability analysis, and the analysis results showed that lowering the water table level would slightly increase the factor of safety.

3. Present Work

A sample embankment worked by Puppala et al. [18] is used to show the effect of the variation of the water level on the factor of safety of the embankment against sliding. Two subjects are discussed in this study. The first is the effect of the water table level on the factor of safety of the embankment against sliding and how the matric suction of the unsaturated soil negative pore water pressure can contribute toward increasing the soil strength, thus increasing the factor of safety (as discussed by many researchers). The second is the suggestion to reduce a cross section of the embankment while maintaining the same factor of safety.

According to Puppala et al. [18], their point of view on the water table level concentrated on the differences between the dry unit weight, moist unit weight, and the saturated unit weight of the soil, as well as how this affects the factor of safety of the embankment slope.

In this work, in addition to the difference in the unit weight of the soil, the contribution of the matric suction in the unsaturated soil is considered an important factor in increasing the shear strength of the soil. As stated by the researchers, "Soil suction or negative water pressures have the effect of adding strength to a soil. In the same way that positive pore-water pressures decrease the effective stress and thereby decrease the strength, negative pore-water pressures increase the effective stress and in turn increase the strength" [19]. The shear strength of the unsaturated soil can be expressed by Eq. (1) [20]:

$$\tau_f = c' + (\sigma_n - u_a)_f tan\phi' + (u_a - u_w)_f \frac{S-S_r}{1-S_r} tan\phi' \quad (1)$$

where τ_f is shear strength (kPa), σ_n is normal stress (kPa), u_a is pore air pressure (kPa), ϕ is internal angle of friction, u_w is pore water pressure (kPa), S is degree of saturation, and S_r is residual degree of saturation.

The third term represents the contribution of the matric suction to the shear strength of the soil. The expression of the effective degree of saturation, $S_e = [(S - S_r)/(1 - S_r)]$, can also be represented as $S_e = [(\theta - \theta_r)/(\theta_s - \theta_r)]$, where θ = n×S, (i.e. volumetric water content = porosity × degree of saturation [18].

The other subject is while maintaining the same factor of safety against sliding, the cross section of the embankment is reduced due to increasing the shear strength, consequently reducing the construction cost.

4. Sample Cross Section

The work published by Puppala et al. [18] demonstrated an embankment constructed as approaches to the bridge site, SH 360, Arlington, Texas which was also shown by Saride et al. [21] (see Fig. 1).

The cross section of the embankment is shown in Fig. 2(a) and Fig. 2(b). Though there are some minor differences between the two sections, the one that was adopted is shown in Fig. 3 with the soil specifications shown in Table 1 after [18]. Only one fill material was taken for the embankment (the select fill) because the purpose of this study is to show the water table level effect and not to compare the two materials properties analyzed by the authors Puppala et al. [18], so only one material is needed for this purpose.

The loading used in their work was expressed as four wheels each, with 80 kN for half of the section to represent two lanes in one direction.

For unsaturated soil zone (i.e., above water table level), the Soil Water Characteristic Curve (SWCC) was determined using the estimation capability of the GeoStudio 2012 software due to the lack of provided data. The estimation is based on the saturated volumetric content, the type of material, and the domain of the matric suction that is expected to be covered. The sample SWCC for the two soil materials that may be in an unsaturated condition is the select fill and the soft clay. Figure 4(a) and Fig. 4(b) show the SWCC for both materials, respectively.

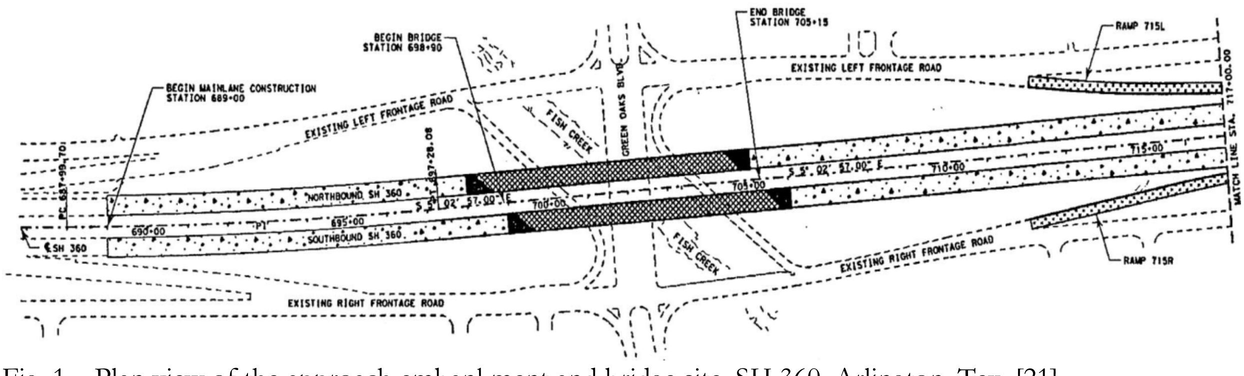

Fig. 1. Plan view of the approach embankment and bridge site, SH 360, Arlington, Tex, [21].

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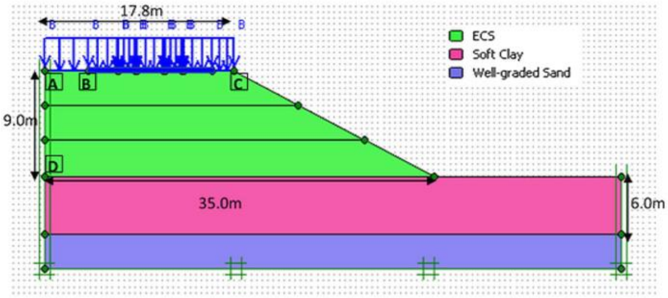
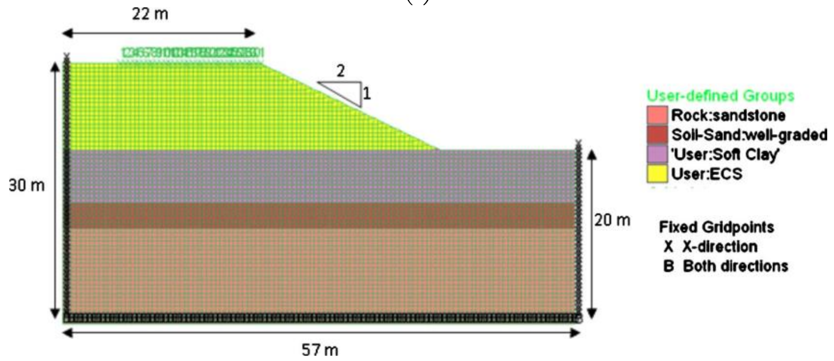


(a)



(b)

Fig. 2 (a) Geometry and boundary conditions, [18]; (b) Geometry and boundary conditions of the model used, [21].

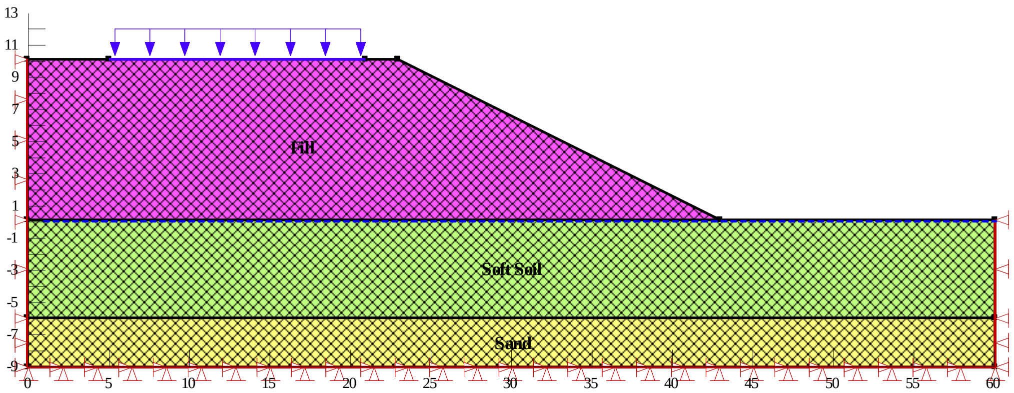
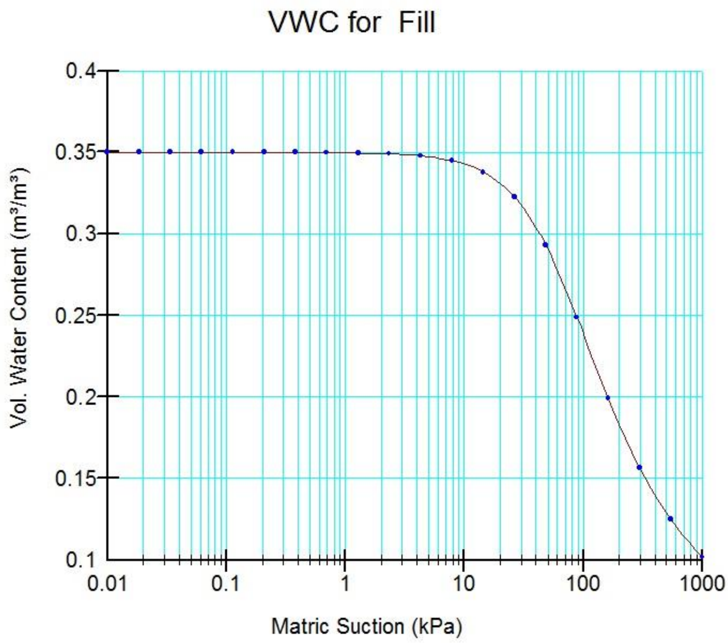


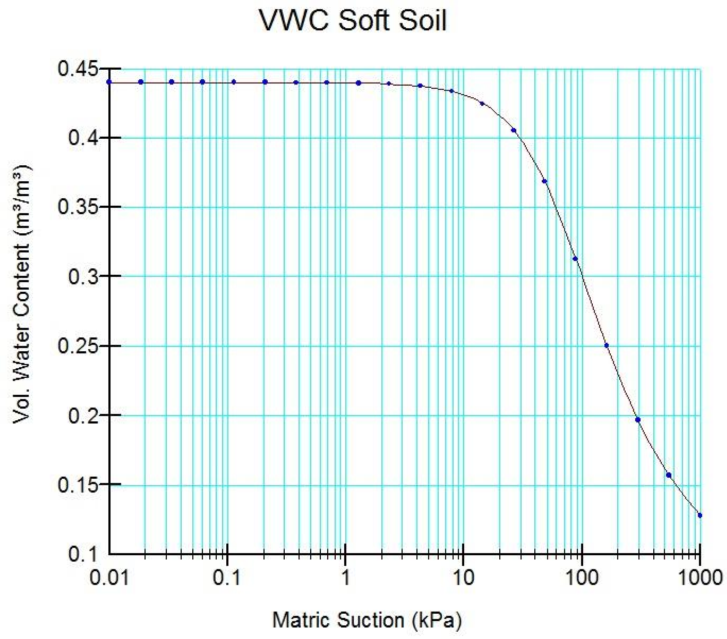
Fig. 3. Adopted cross section with boundary conditions.

Table 1. Materials properties used, [18].

Property	Units	Select Fill	Soft Clay	Dense Sand
Moist Density	kN/m^3	14.8	14.3	15.2
Elastic Modulus	MPa	-	-	182
Poison's ratio	-	-	-	0.15
Cohesion	kN/m^2	20.1	45	0
Friction angle	°	18	5	33
Permeability	m/day	4.39×10^{-4}	8.78×10^{-6}	$5.26\text{x}10^{-2}$
Over consolidation ratio	-	3	3	-
Initial Void ratio	-	0.55	0.8	-
Module used		Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb



(a)



(b)

Fig. 4. (a) SWCC for select fill; (b) SWCC for soft clay.

5. Simulations with Different Water Table Levels

Simulation of the embankment was obtained by using the finite element analysis software GeoStudio 2012, and the cross section is shown in Fig. 3 as mentioned above.

The water table level was taken initially at the ground level (0 m) as shown in Fig. 3, and the factor of safety against sliding was determined. The water table then was lowered 0.5 m. Then another simulation run was obtained, and the factor of safety is determined. This was repeated for each step of lowering the water table level (0.5 m) until the final value of 5 m depth was obtained. (i.e., water table levels of 0, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0 m were simulated). In addition, another simulation was determined without any water table (i.e., dry condition) to compare the stability of the embankment slope at dry soil condition.

6. Maintaining the Same Factor of Safety

After the simulation of different water levels and the factors of safety for each case were determined, and to maintain the same factor of safety of the embankment referred to the factor of safety obtained from the original water level (0 m). An increase in the side slopes was tried by changing the horizontal distance of the sides and maintaining the vertical height of the embankment at the same level; this was done by trial and error to obtain the same factor of safety. This was done for all cross section of depths (0 m to 5 m at 0.5 m steps) maintaining the same factor of safety and changing the side slope value.

The simulations show that a considerable reduction in the values of side slopes can be obtained, hence a reduction in the cross-sectional area of the embankment.

7. Results and Discussion

The initial cross section, shown in Fig. 3 (with 0 m water table level), was taken as reference cross section and the factor of safety was determined. Other water table levels were obtained in steps, of 0.5 m water table level depth, and the factors of safety were determined for each step as shown in Table 2 and Fig. 5.

Figure 6 shows the relationship between the factor of safety and the depth of the water table, showing also the linear fitting line, as described by Eq. (2) with a correlation coefficient of R^2=0.9944:

$$\mathrm{F.O.S} = 0.0573 * \mathrm{Depth} + 2.1463 \tag{2}$$

The finding of this study is compatible with the results in the previous studies [14], [16], and [17]. These findings are that (1) the factors of safety decrease when the water table levels rise and (2) the factors of safety dramatically decline when the water table levels reach a critical depth. Therefore, in high water table level, the slope should be strengthened to guarantee stability. If not, it easily and undoubtedly occurs collapse or landslides. However, in the study of Khanmohammadi and Hosseinitoudeshki [12], the water does not affect the safety factor of slopes unless water table level increases and penetrates into the rupture surfaces in the slopes.

Figure 7 shows the values of relative percentage of factor of safety to the factor of safety of dry condition. This represents a comparison to the condition where there is no water at all (dry or very hot summer conditions). Values approximately below 1 m depth shows clearly the contribution of the matric suction to the shear strength of the soil as the percentage of relative factor of safety if greater than 100%.

Figures 6 and 7 show a clear linear relationship between the depth of water level and the factor of safety against sliding, either as a distinct value or as a relative percentage to the dry condition.

Table 2. Variation of factor of safety and its percentage with respect to water level.

Depth of water level (m)	Factor of Safety	Percentage with respect to dry condition
0	2.130	97.62%
0.5	2.187	100.23%
1.0	2.211	101.33%
1.5	2.236	102.47%
2.0	2.261	103.62%
2.5	2.288	104.86%
3.0	2.315	106.10%
3.5	2.344	107.42%
4.0	2.373	108.75%
4.5	2.404	110.17%
5.0	2.435	111.59%
No Water Table	2.182	100.00%

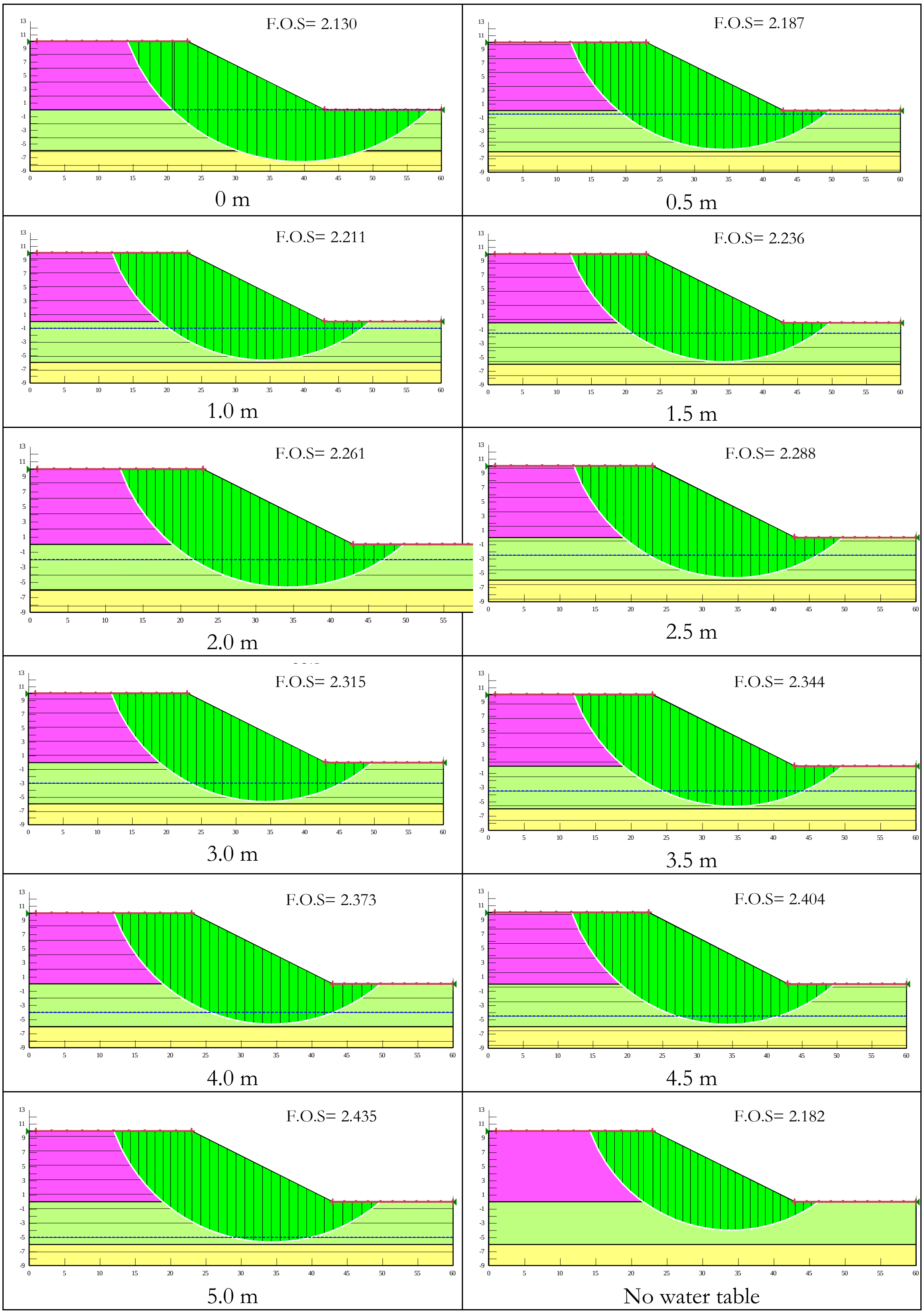


Fig. 5. Simulation of lowering water table level showing the factor of safety.

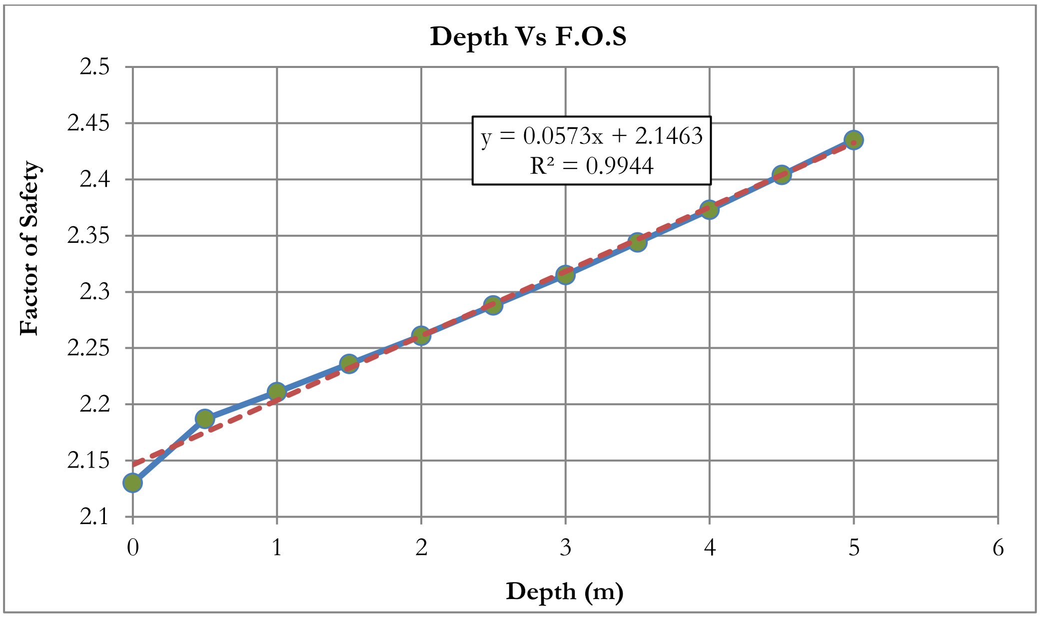


Fig. 6. Variation of factor of safety with respect to water level depth.

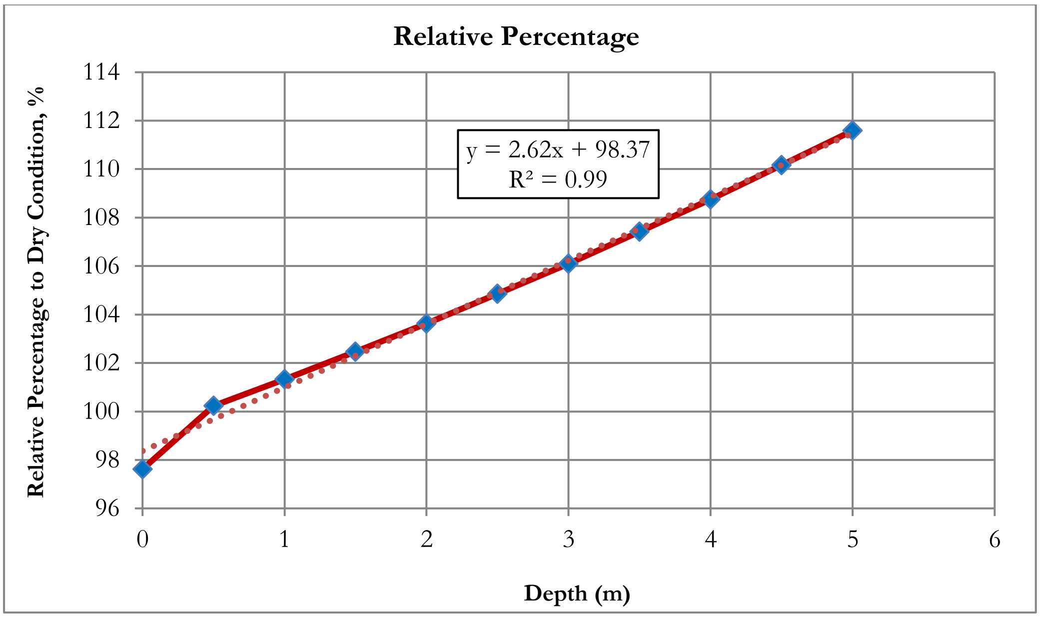


Fig. 7. Relative percentage of factor of safety to the factor of safety of dry condition with respect to water level depth.

8. Slope Variation with Water Table Level Lowering

After obtaining the factor of safety for each water table depth, the factor of safety of the 0 m depth is considered as a reference value (2.13). The next step was to determine the reduced slope of the embankment by reducing the horizontal dimension of the slope and by maintaining the vertical height of the embankment. The calculated values are shown in Table 3.

Table 3. Area, volume, and cost reduction with respect to water level depth.

Depth (m)	Δy (m)	Δx (m)	Slope 1: x	Area (m^2/m)	Percentage of reduction in area	Reduction in cross sectional area (m^2)	Reduction in volume for 1 km length	Reduction in the Cost for half of the embankment ($)
0	10	20	2	330	0.00%	0	0	0
0.5	10	17.75	1.775	318.75	3.41%	11.25	11250	337,500
1	10	16.75	1.675	313.75	4.92%	16.25	16250	487,500
1.5	10	15.5	1.55	307.5	6.82%	22.5	22500	675,000
2	10	14.03	1.403	300.15	9.05%	29.85	29850	895,500
2.5	10	12.85	1.285	294.25	10.83%	35.75	35750	1,072,500
3	10	11.5	1.15	287.5	12.88%	42.5	42500	1,275,000
3.5	10	10.495	1.0495	282.48	14.40%	47.52	47520	1,425,600
4	10	8	0.8	270	18.18%	60	60000	1,800,000
4.5	10	5.2	0.52	256	22.42%	74	74000	2,220,000
5	10	1.35	0.135	236.75	28.26%	93.25	93250	2,797,500

Figure 8 shows the variation of the slope (described as 1:s) with water level depth. The factor of safety is maintained at (2.13) and a considerable reduction in slope is recognized with the water table level lowering. This relationship can be described by Eq. (3), with R2= 0.9837:

$$s = -0.0378D^2 - 0.1424D + 1.8996 \tag{3}$$

where 1:s is slope and D is the depth of water table level.

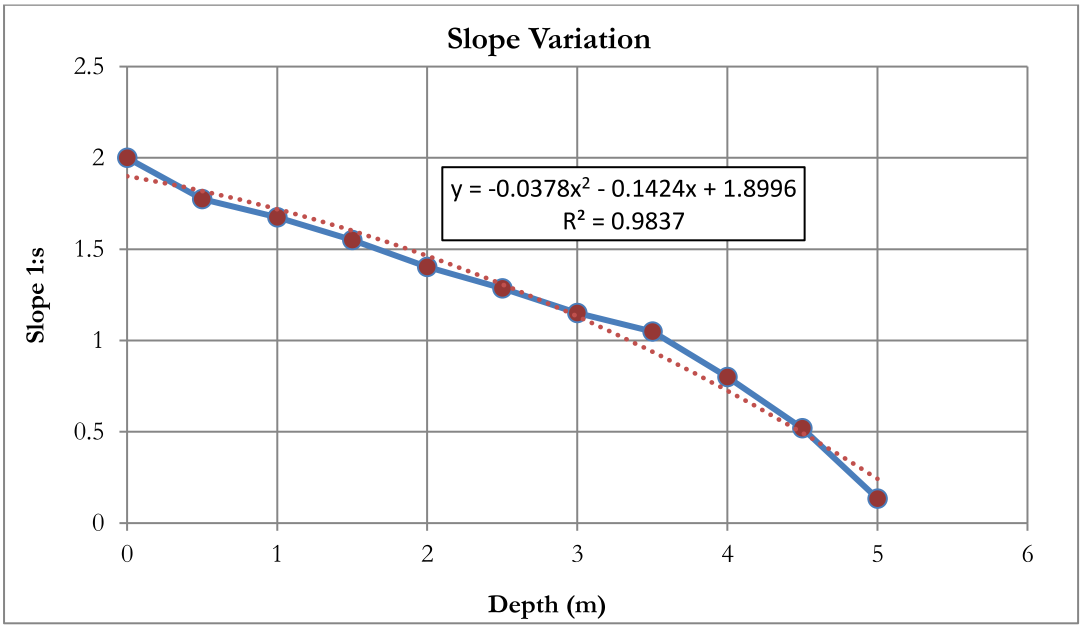


Fig. 8. Slope variation with respect to water level depth maintaining the same factor of safety.

The area of each developed section is shown in the fifth column of Table 3 and also in Fig. 9. The values show a considerable decrease in values of areas as the water table level increases. The difference in the area corresponding to each water table level depth is shown in Fig. 10, taking the water table level of 0 m as reference. This is reflected directly on the cost of the construction of the embankment.

The cost of 1 m3 of embankment (material + work) is about 18,000 I.D. (Iraqi Dinar), which is about (15 $) (at the time of the study). The total cost reduction for 1 km (1000 m) length for the whole embankment cross section is shown in the last column of Table 3, and it is also shown in Fig. 11. A considerable cost reduction is shown to maintain the same factor of safety of 2.13.

According to the highway design manual [22], a minimum slope of high road embankment (above 6m) is 1:1.75 is considered, and this requirement is met by using Eq. (3). Simple calculations were done by applying the slope of 1:1.175 in Eq. (3) to determine the water table level depth that gives the same factor of safety:

$$1.75 = -0.0378D^2 - 0.1424D + 1.8996$$

∴ D = 0.856 m, and this can be also determined from Fig. 8.

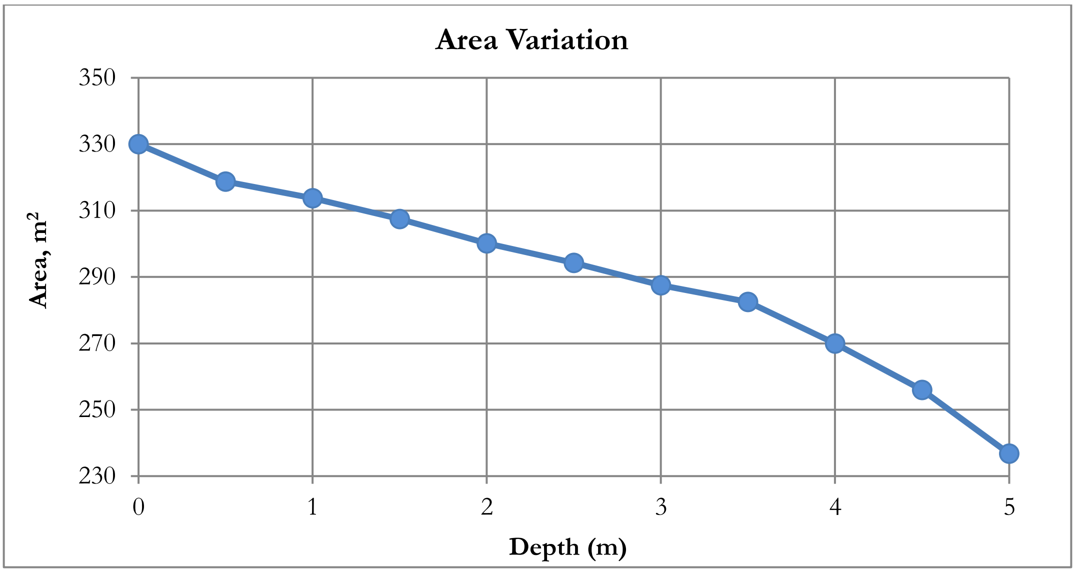


Fig. 9. Area variation with respect to water level depth.

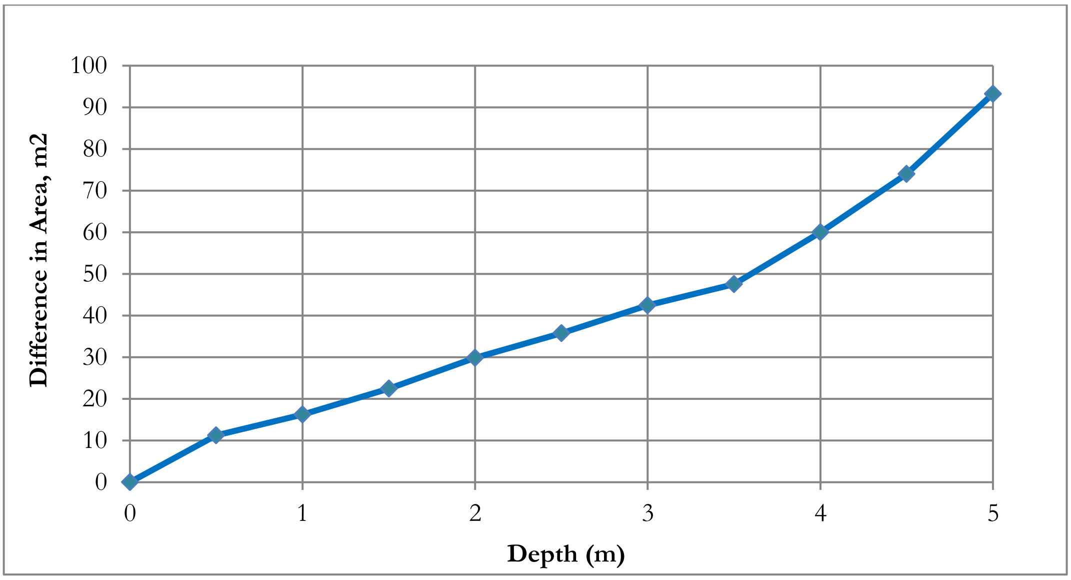


Fig. 10. Reduction in area with respect to water table level.

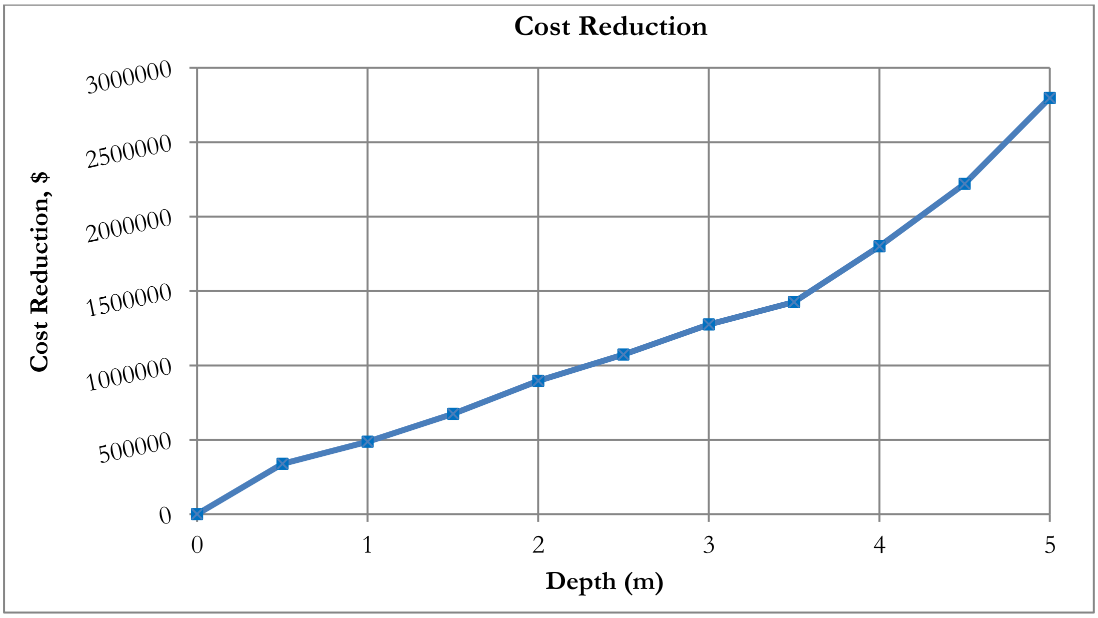


Fig. 11. Reduction in cost ($) with respect to water level depth.

9. Conclusion

We conclude from the work above that the contribution of the matric suction had a relatively great improvement to the soil shear strength; this is reflected in the factor of safety of the side slopes and their stability.

Reducing the cross-sectional area, while lowering the water table level can maintain the factor of safety against sliding, and reducing the construction cost of the embankment through minimizing the side slopes to the minimum required value.

Mathematical models describing the relationship between the water table level and factor of safety, as well as the relationship between the water table level and the side slope, can help in designing and developing the road embankment.

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