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Strengthening the Slope Beneath Bashtapia Castle at the Highest Expected Tigris River Level

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Abstract. This study has been achieved using Geo-Studio Finite Element Software in two sections. First, to study the changes in pore water pressure (PWP) within the soil layers below Bashtapia Castle at different water levels of the river Tigris. The effect of these changes was in focus to check the slope stability of the Castle. On the other hand, the second section was to increase the safety factor using slope reinforcement using different spacings and lengths of the anchor's rods. Modeling output showed that the factor of safety (FS) decreased from 2.83 to 0.838 when the water level raised from 0 to 7 m above the bottom slope layer. Accordingly, anchor bars were introduced in the model, and the safety factor increased. The slope layers were treated and strengthened using reinforcing anchor bars at different lengths and numbers. In general, the analysis results showed the positive effect of reinforcing bars on the stability of the castle slope. The FS of the slope castle increases with the increased length and number of anchors to a certain value, and then there is no effect of this increase on the FS value.

Keywords: Bashtapia castle; porewater pressure; highest Tigris River level; slope reinforcement; anchor rods; Geo-Slope.

1. INTRODUCTION

Bashtapia Castle is one of the most important historical monuments of Mosul city in the northern part of Iraq. It was built in the eighth century AD on the banks of the Tigris River. Its circular wall has a thickness of (0.75) m and a diameter of, (10) m, while the wall height is 16 m. The wall was built by using limestone blocks [1,2]. A defensive ditch to this Castle was dug and became now within the current course of the Tigris River. The geological formation of the layers of the slope on which the Castle rests is called the FATHA formation and comprises clay soil followed by a layer of limestone and gypsum [3-6]. The expansion of the Tigris River to include the ditch near the Bashtabia Castle led to the exposing of this Castle divided into two parts, one of which is still stable. At the same time, the other is still subject to increasing settlement.

This study is focused on the stability of the castle slope during its construction stages and after being exposed to failure due to changing surrounding conditions and then finding the solutions to address failure and the method of implementing these suggestions: the changes in pore water pressure of soil layers beneath the Castle were studied at different water levels of Tigris River, and the effect of these changes on the slope stability. Then, suggested treatment for the critical slope condition by anchor rods. One, two, and three rods reinforced the castle slope. Also, the effect of length, depth, and horizontal distance between these rods on slope stability was studied. The cases mentioned above were modeled using Geo-Studio software.

2. STABILITY ESTIMATION CRITERIA

To estimate the stability of the slope that Bashtapia Castle rests on, a historical review and field survey of the castle site has been conducted. The old images (i.e., 1916) in Figure 1 clarify Bashtapia Castle before failure. It is clear from these images that a trench was dug at that time for defensive purposes, located at (3) m from the lower edge. The Castle and its slope remained stable until exposure to change in the surrounding conditions occurred, as the course of the Tigris River changed and touched the Castle slope [2].

(a) (b)

Figure 1: The wall and Bashtapia castle with the adjacent defensive trench.

Figure 2 shows the details of Bashtapia Castle and the geological layers of the slope on which it rests. Due to the historical importance of this Castle, all the engineering characteristics required to conduct the necessary analyses for this research were obtained from previous studies that were conducted near it [1,7,8,9]. Table 1 shows all engineering properties for the slope layers used in this study. The total vertical stress applied on the slope crest due to the castle structure is approximately (300 kPa) which can be obtained from the castle dimensions offered in Figure 2 for 0.75 m limestone wall thickness and the density equal to (2.53 gm/cm^3) [1].

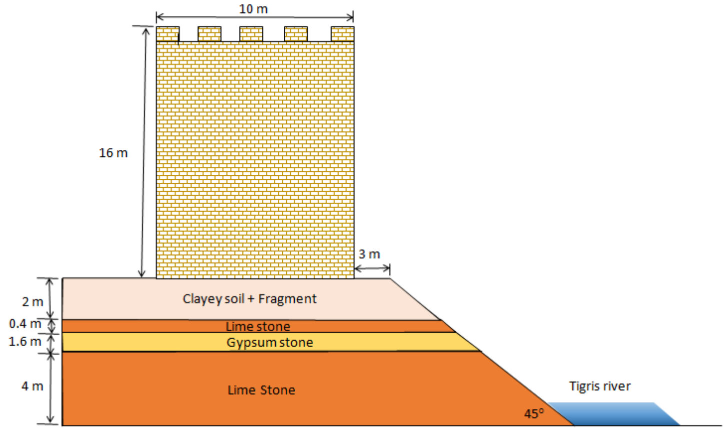

Figure 2: Schematic diagram for Castle with the layer of the slope.

Table 1: Some Engineering Properties for Slope Bashtapia Layers (All tests were carried out in the laboratories of the Northern Technical University).

Material		**Saturated limestone**	**Saturated Gypsum stone**	**Topsoil**
Modulus of elasticity (MPa)		30000	450	50
Cohesion (MPa)		15	10	0.04
Angle of internal friction (degree)		32	25	20
Unit weight (kN/m³)		20.4	23	19
Pore water pressure (kPa)		-40	-35	-50
Saturated volumetric water content (m³/m³)		0.5	0.48	0.4
Residual water content (m³/m³)		0.2	0.175	0.15
Flow parameter, Van Genuchten (Model)	k_x (m/d)	2.5×10^{-5}	2.38×10^{-6}	2.4×10^{-4}
	k_y (m/d)	2.5×10^{-5}	2.38×10^{-6}	2.4×10^{-4}

3. RESULTS AND DISCUSSION

3.1 Castle Slope Stability Analyses through Geo-Studio Finite Element Software

To assess the stability of Bashtapia Castle, a historical review and field wipe of the castle site have been conducted. Figure 1 shows an old image (i.e., 1916) of the Bashtapia Castle site before exposed to failure [9]. From these images, a trench is located at 3 m from the bottom edge of this Castle, which was dug for defensive purposes against external aggressions. At that time (i.e., 1916), the Castle and the slope were stable, but later, weakness in their stability occurred as the Tigris River changed its path toward the Castle trench [2]. The full details of the trench slope and laminations beneath the castle structure are shown in Figure 2. The ground foundation under the castle structure was divided into smaller parts with quad and triangle shapes as required in Geo-Studio Finite Element software [9]. The geometry, boundary conditions, and FE mesh for the slope case study can be seen in Figure 3.

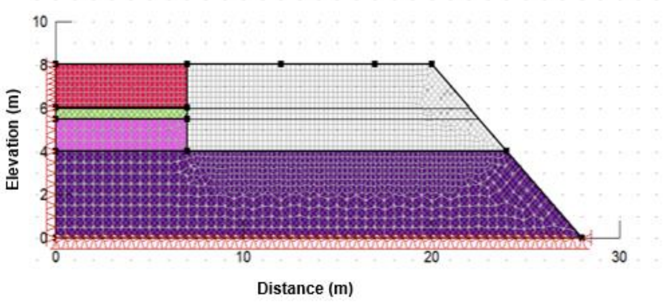

Figure 3: Geometry, boundary condition, and FE mesh form the slope case study.

The global ground foundation dimensions adopted in this study are (8) m height (total layers thickness) and (28) m width with a slope angle (45°) horizontal. In general, the assessment of Bashtapia castle stability has been done in terms of trench slope stability under unsaturated conditions through three steps: a) Establishment of in-situ stress case for the trench slope using SIGMA/W [10]. b) Application of vertical stress (at ten stages) to simulate castle construction steps followed by analyses of each case using coupled stress and pore water pressure. An elastic material model was utilized in these analyses to simulate the material's behavior for the trench slope layers. Finally, c) the analysis of castle slope stability (with and without anchor rods) was achieved by utilizing SLOPE/W [11]. The Mohr-Coulomb failure criterion was used as a material model for the slope layers in slope stability analyses. However, the Water Retention Curves (WRC) curves of the slope layers predicted by Geo-Studio software based on soil grain size distribution and saturated volumetric water content [1,12,13], while the hydraulic conductivity evaluated depending on the residual degree of saturation, WRC, and volumetric water content for these layers [1,10].

3.2 Effect of Increased Pore Water Pressure on Castle Stability

Figures 4 and 5 explain the critical slip, FS, and Pore water pressure contours of slope at the unsaturated case in the natural case after the construction of Bashtapia castle (i.e., the total applied vertical stress equal to 300 kPa). These figures explain the Castle and slope were stable under these conditions. The expansion of the Tigris River basin adjacent to the trench slope led to a change in the pore water pressure (PWP) values of the trench slope layers, especially with the seasonal variation in the Tigris River level. Figures 6 to 7 explain the changes in PWP for the slope layer at Tigris River level (1 and 7) m above the base of the slope. From these figures, the PWP values at the middle of the bottom layer increase from -30 kPa at the unsaturated case to (0.0 and 240 kPa) with the rising river level above the slope base. Figure 8 refers to an increment of about 112% PWP when the river level rises from (0 to 7) m above the trench slope base. This leads to a slope settlement increase from 21 to 69 mm and a decrease in shear resistance and stability of the trench slope materials [12-22]. So, the values of FS reduced to (0.846) when the level of Tigris River elevation was 7 m above the trench slope base, as explained in Figure 9.

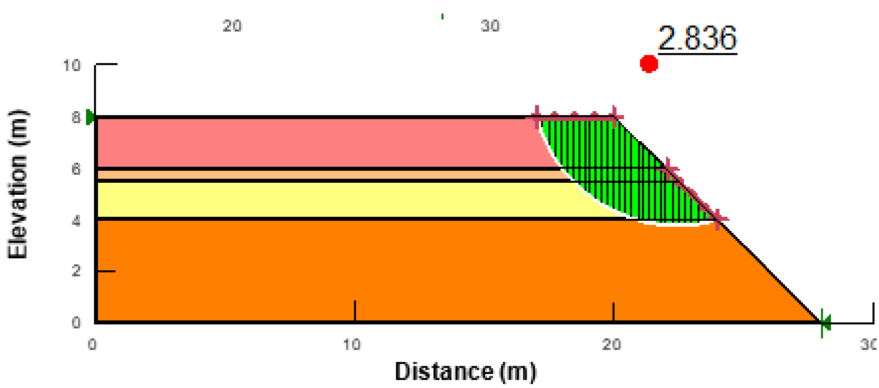

Figure 4: Critical slip and FS of slope at unsaturated case with applied vertical stress equal to (300 kPa).

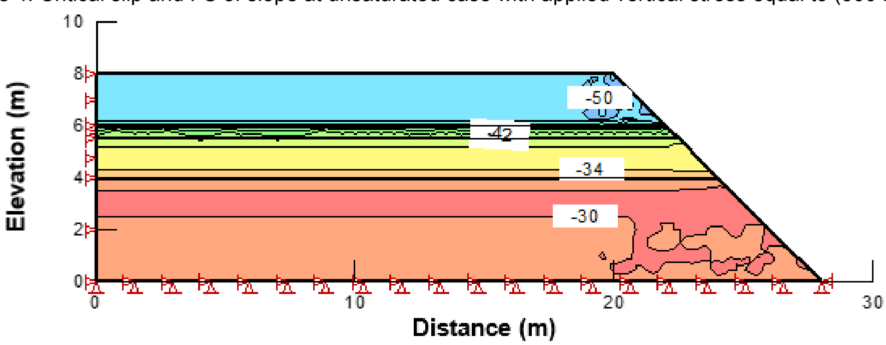

Figure 5: Porewater pressure contours (unit of seen values in kPa) for slope layer after Castle built and at unsaturated case.

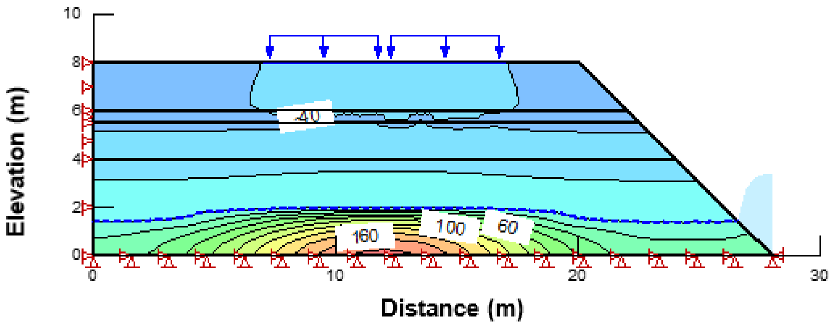

Figure 6: Contours of porewater pressure (unit of seen values in kPa) for slope layers of W.T. at 1 m from the base and after completing the castle construction (compression 300 kPa).

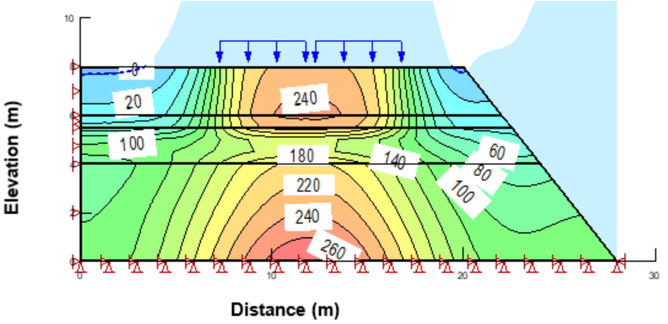

Figure 7: Contours of porewater pressure (unit of seen values in kPa) for slope layers of W.T. at 7 m from the base and after completing the castle construction (compression 300 kPa).

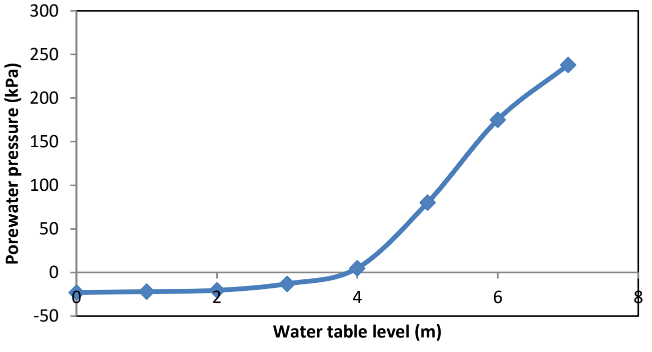

Figure 8: The variation of Power water pressure in the middle top layer thickness with water tale level from the slope base.

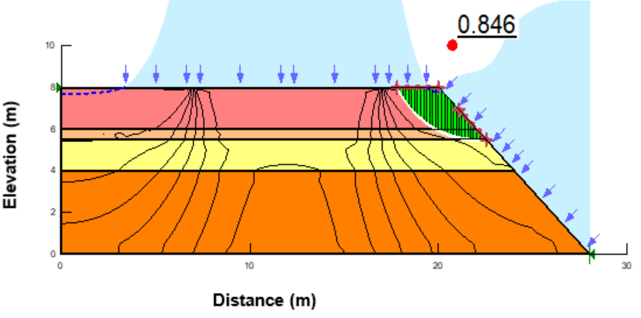

Figure 9: Critical slip and FS of slope at the unsaturated case with applied vertical stress equal to (300 kPa) and W.T. at 7 m from the base.

3.3 Slope Layers Reinforcement Using Anchor Rods

The failed (or near to failure) slopes are focused on by engineers designed to reduce the damages (both materialistic and human) of its collapse. Anchor rods are one of several treatments which can be used to treat failed slopes. The equipped force by the anchor rod must be greater than the force applied by the sliding mass (or which is trying to slide). The reason for the increase in the FS value of the slope when using a reinforcing anchor can be explained by the following equations:

$$\mathrm{FS} = \{(\text{Resisting force}) + (\text{Reinforcement})\}/(\text{Driving force}) \tag{1}$$

Or

$$\mathrm{FS} = (\text{Resisting force})/\{(\text{Driving force}) - (\text{Reinforcement})\} \tag{2}$$

When using different types of reinforcement (such as geosynthetic, nail, pile, and anchor), the pullout resistance must be estimated by choosing a suitable scale of the reinforcement of an adequate amount of bond length (which is the length of grouting and represents the important factor in calculating of the pullout resistance). This paper reinforced the slope using one, two, and three anchors. In all cases, these anchors were placed at a depth (y) below the slope surface with a horizontal distance (x), Figure 10. In general, the inclination angle of anchors varies between (10- 45°) with the horizon [23]. The angle (20°) was adopted in this research because it is close to the average rate above and was used by [24]. The suggested diameter of the anchors is (38.6 mm) with its specifications listed in Table 2. Figures 11 and 12 explain the critical slip and FS of the slope after castle construction when W.T. is located at 7m from the base and using one anchor at (0.5) m below the slope surface and of 0.5 and 2.9 m length, respectively. From this figure, the FS increased by 10.4 to 100.7% for anchor length from 0.5 to 2.9 m.

On the other hand, using two anchors at (0.5) m below the slope surface with space (x =y = 2 m), the FS rises from 37 to 183% with anchors lengths from 0.5 to 2.9 m, respectively, as shown in Figures 13 to 15. Finally, when three anchors were used, the FS increased from 1.52 to 3.74 when the increased length of anchors from 0.5 to 1.0 m, respectively, as shown in Figures 16 to 18. Finally, Figure 19 explains the slope's FS variation with anchor length and number of anchors at the same conditions (depth below slope surface and x,y distance). It could be noted that the FS value increases with the increased number and length of the anchor rods. Moreover, the highest attained FS value at these conditions was 3.734 using three anchor rods of 1.0 m length.

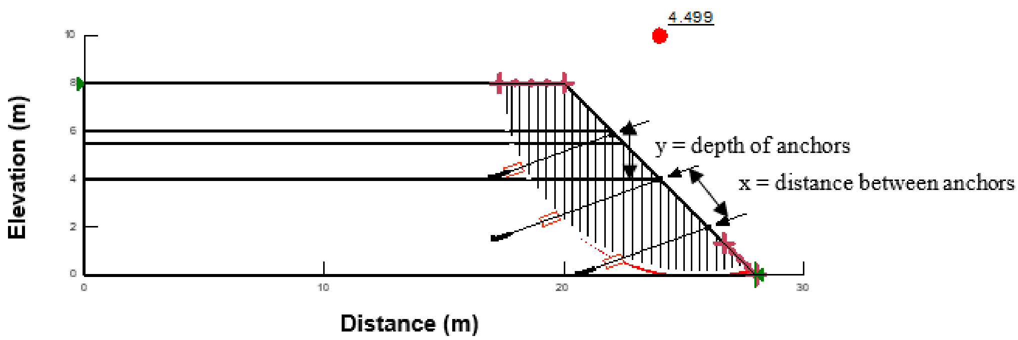

Figure 10: Arrangement of anchors when reinforcing the castle slope.

Table 2: Specifications of the anchor used in the slope reinforcement [Anchoring systems for geotechnical engineering Fresson sustainable technology, 2014].

Steel tendon	Diameter (mm)		Min cross-section (mm²)	Min weight (kg/m)	Ultimate strength (N/mm²)	Ultimate load (kN)
	Nom.	Ext.				
P 10-11	26.5	28.8	552	4.56	1.03	568
	32	34.5	804	6.66		828
	36	38.6	1018	8.45		1048
	40	43.4	1257	10.41		1293
	50	53.2	1964	16.02		2022

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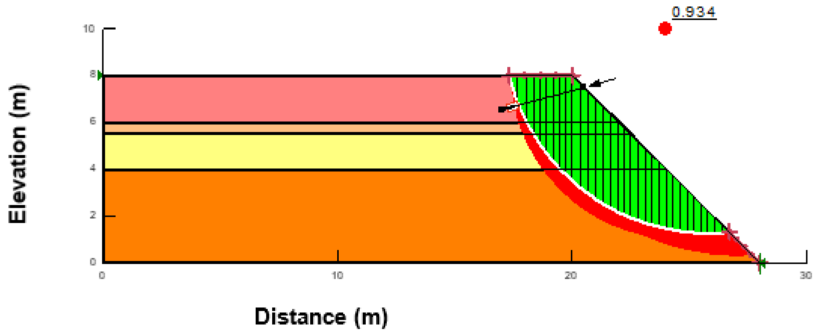

Figure 11: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using one anchor of 0.5 m length.

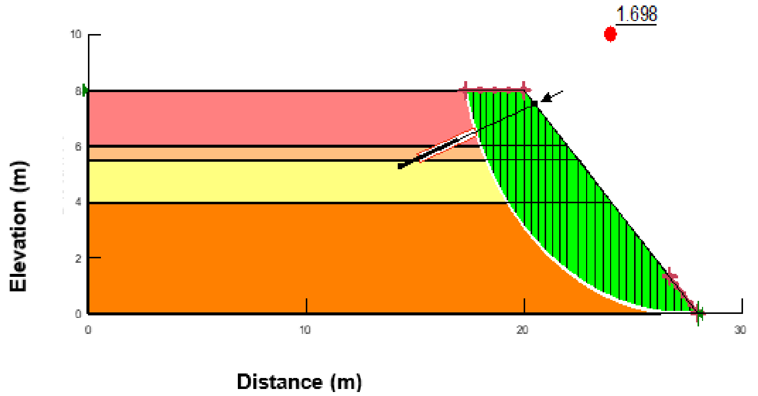

Figure 12: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using one anchor of 2.9 m length.

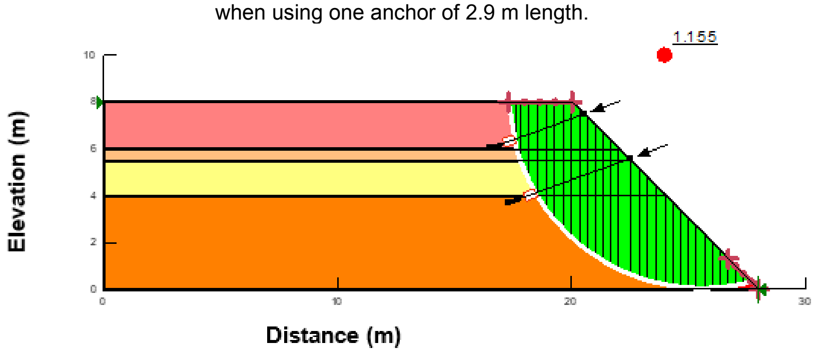

Figure 13: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using two anchors of 0.5 m length.

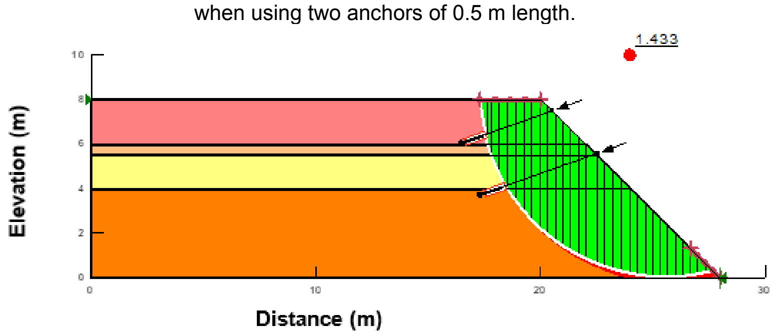

Figure 14: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using two anchors of 1.0 m length.

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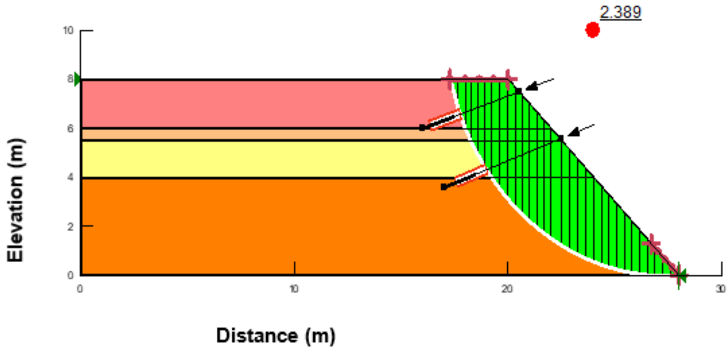

Figure 15: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using two anchors of 1.5 m length.

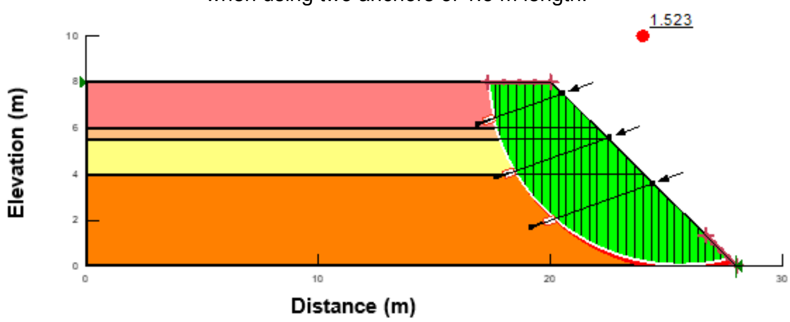

Figure 16: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using three anchors of 0.5 m length.

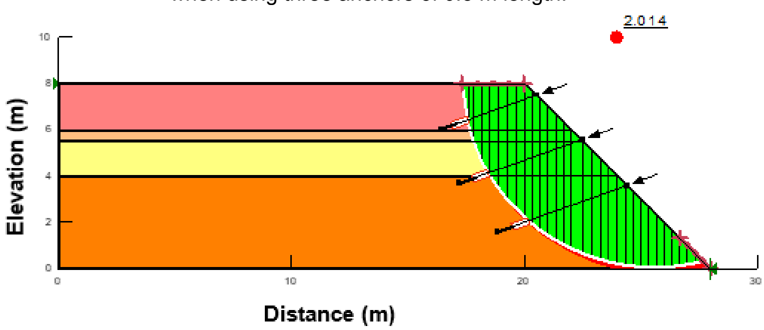

Figure 17: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using three anchors of 0.75 m length.

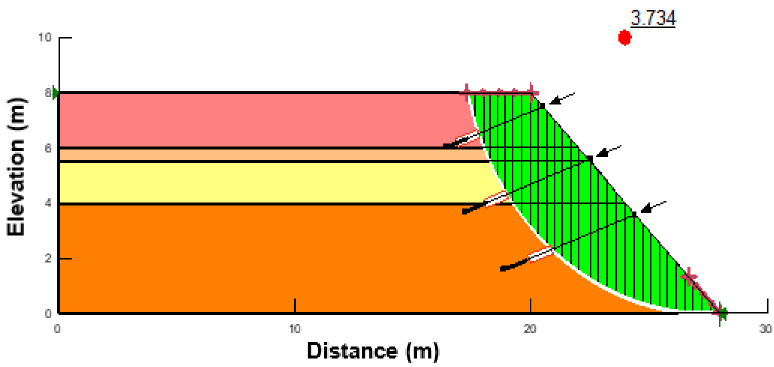

Figure 18: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using three anchors of 1.0 m length.

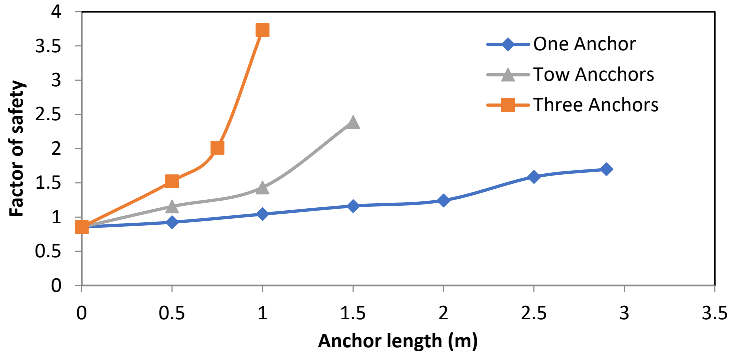

Figure 19: The variation of FS of the slope with anchor length when changing the number of anchors.

3.4 Effect of Depth and Horizontal Distance between Anchor Rods

The effect of the embedment anchors' depth below the slope surface and the horizontal distances between them on the slope stability was studied. Table 3 and Figure 20 show the Bashtapia slope stability analysis results in different cases. In all these analyses, the Tigris River height was 7 m above the castle slope base, and the slope was reinforced with three anchors. The length of these anchors is 1 m, and it was placed at various patterns shown in Table 3. It could be noted that, at a certain anchor's depth, the FS values rise with the horizontal distance between anchors. At anchor depth of 1.0 m, the FS values increased from (1.591 to 5.502) with the horizontal distance between anchors from 0.5 to 2.0 m. This could be attributed to the increase in the area of the concrete faces that support the sliding block. Also, Increasing the horizontal distance provides the suitable surface area of the anchor grouted- sections inside the soil, increases the bonding forces between the soil structure, and hence, causes enhancement in soil shear strength.

It could be noted that, at a specific horizontal distance, a positive effect of increasing the anchor depth below the slope surface on the castle stability was observed. At a horizontal distance of 1.0 m, the FS increased about (84) % when the anchor depth was from 0.5 to 2.0 m. This could be due to the increase in the applied overburden and confining pressures on the embedded anchors [25,26]. Generally, the FS increases with the increased depth and horizontal distances between anchors until it reaches the maximum value (6.81) at depth and distance (1.5 and 2) m, respectively, as shown in Figure 21. Finally, at a depth of 2 m, the FS increases with the horizontal distances until 4.8 m at a distance of 1.5 m. This could be explained as the upper part of the sliding block becomes outside the reinforcement area when the depth and the distance between the anchors reach the value of (2) m.

Table 3: Effect of depth below slope surface (y) and horizontal distance between Anchors (x), which have 1 m length on FS value.

Depth below slope surface (y) (m)	**Horizontal distance between anchors (x) (m)**			
	0.5	1.0	1.5	2.0
0.5	1.437	1.703	2.562	3.734
1.0	1.591	1.954	3.554	5.502
1.5	1.988	2.515	3.877	6.891
2.0	2.373	3.133	4.801	4.499

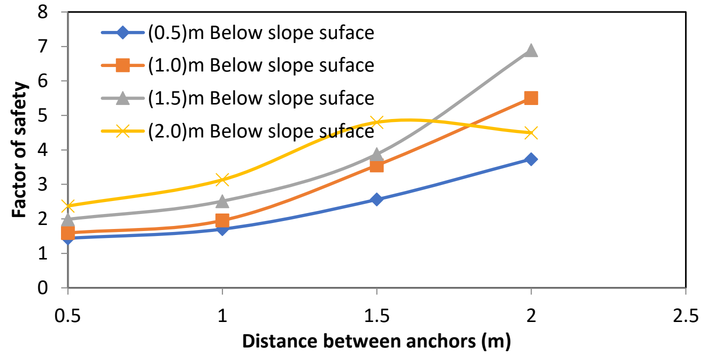

Figure 20: Relationship between FS and distance between anchors that have 1 m length and insertion at the different depths below the sloped surface

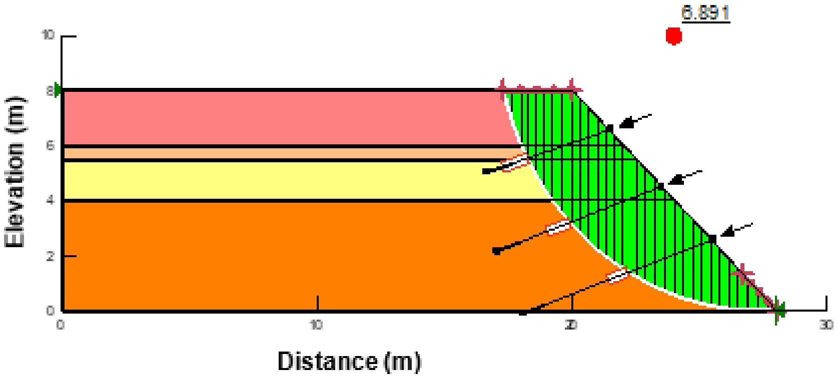

Figure 21: Critical slip and FS of the slope after Castle was built and in the case of W.T. at 7 m from the base when using three anchors in 1.0 m length at anchors depth of 1.5 m and horizontal distance of 2.0 m.

4. CONCLUSIONS

The main conclusions are:

- The castle slope was stable in an unsaturated state.
- The extension and fluctuation of the Tigris River have negatively affected the stability of the Bashtabia castle slope through the following:
  a) Decrease in the shear strength of the slope layers.
  b) An increase in the (PWP) values when the river level rises from 0 to 7 m above the slope base, leading to a decrease in FS from 2.836 to 0.846.
- Reinforcement of slope (by rod anchors) has a positive effect on its stability, as:
  a) The FS value increases with an increase in anchor number. At
  b) The Increased depth of anchors below the slope surface (y) and horizontal distance between them (x) leads to a gradual augmentation of FS to a maximum of 6.891 with an ideal value (y= 1.5 m and x= 2 m).

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