Failure Risks at the Bashtapia Castle Due to Fluctuations in Tigris River Levels

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ABSTRACT

The current study investigates the stability of Bashtapia Castle (BC) in Mosul, northern Iraq, using two different methodological approaches. The first approach was applied during the early stages of the castle construction, before the Tigris River (TR) reaches the site. The second approach involves assessing the castle's stability under changing levels of the TR. These assessments focus on the stability of the castle trench slopes using Geo-Studio finite element software. The evaluation criteria were based on historical studies and field investigations. Unsaturated strength properties for ditch slope materials beneath the castle structure were obtained and incorporated into the Geo-Studio analysis, including water retention curves, hydraulic conductivity, modulus of elasticity, cohesion, and internal friction angle. The results indicate that the castle construction slightly decreased both the Factor of Safety (FoS) and the shear resistance of the trench slope. Meanwhile, the contact between the TR and the trench slope materials increased the Pore Water Pressure (PWP) and settlement, leading to a reduction in the FOS and shear resistance of these materials.

Keywords-Bashtapia Castle; fatah formation; Tigris River levels; slope stability; geo-studio analysis

I. INTRODUCTION

Bashtabia Castle (BC), located in Mosul, Iraq, is a renowned historical monument that has endured through the ages. It was constructed during the 8th century AD and overlooks the western bank of the TR. Its exact location is at 36.355540° N, 43.121425° E. The castle's formidable wall was carefully built from limestone, approximately 0.75 m thick. It reaches an impressive height of 16 m and has a diameter of about 10 m [1, 2]. Originally, BC was built for defense purposes. It was surrounded by a trench that now follows the course of the TR. The geological setting of the castle's site is within the FATHA formation, which consists of layers of clay, limestone, and gypsum stone [3-5]. The settlement near the Tigris-facing section of the castle has caused part of its structure to split. One part remains stable, while the other is gradually settling over time. The stability assessment of BC focuses on the trench slope stability and considers key factors, such as the TR level, ground layer suction values, and the static vertical force applied at the slope crest. The assessment can be conducted in two different ways:

1. Assessment of the building stages: This involves determining whether the castle was stable during the ten phases of construction before the Tigris River started to flow.
2. Estimation of the TR level variations: This section examines the castle's stability in relation to different TR levels.

II. STABILITY ASSESSMENT CRITERIA

A. *Criteria for Stability Assessment*

A detailed study of BC's stability was carried out by combining historical research with on-site observations. Photographs from 1916 depict BC before any major setbacks [1]. During that time, a defensive trench was dug to protect against the external threats. This trench was approximately three m from the castle. At that point, both the slope and the castle remained stable. This balance was disrupted by the expansion of the TR, which then flooded the castle ditch, leading to its deterioration and loss of stability, as shown in Figure 1. Based on previous research, the engineering properties of the trench slope layers were collected from nearby locations to support the required engineering assessments [2, 6, 7]. The information gathered revealed the vulnerability of the castle structure itself. Additionally, the traditional slope design that relies on the FoS can be misleading. The slopes built with significant FoS are not free from failure risk [8]. However, this strategy was chosen to reduce any potential vibrations caused by intrusive site examinations. Furthermore, the soil shear strength parameters are influenced by the water content. Specifically, the soil with its natural water content exhibits a higher FoS for slope stability compared to the saturated soil [9-11]. Thus, changes in the water level cause fluctuations in the FoS for slope stability. The engineering properties of the trench slope layers used in this study are listed in Table I. With a limestone wall thickness of 0.75 m and a density of 2.53 g/cm³, the dimensions of the castle [12] indicate that the total stress applied to the earth layers beneath the castle structure is approximately 300 kPa.

Fig. 1. BC, wall, and the protective ditch beside them.

To assess the stability of BC, the software "Geo-Studio" was used to discretize the entire foundation beneath the castle into small quadrilaterals and triangular elements [12]. The castle foundation dimensions were measured as follows: Height — 8 m, matching the actual castle height; Width — 28 m beyond which the horizontal stress effects are minimal; and a trench slope angle of 45° relative to the horizontal [12]. The assessment focuses on the stability of the ditch slope in an unsaturated state, involving three key steps to accomplish this.

- Creating the in-situ stress case of the ditch slope using SIGMA/W [13].
- Applying the static vertical stress in ten steps (i.e., phases of castle construction).
- Analysis was conducted using a coupled stress and PWP method. An elastic model was employed in these analyses to simulate the behavior of the slope materials.

Finally, the stability assessment of the castle was performed using SLOPE/W [13]. Water Retention Curves (WRC) for the slope layers were predicted using software based on the saturated volumetric water content, as shown in the left side of Figures 2-4 [2, 14]. The permeability estimates, based on the volumetric water content (θ), WRC, and degree of saturation (S), are displayed in the right side of Figures 2-4 [15, 16]. The matric suction values for the layers, listed in Table I, were obtained using the osmotic membrane and saline solution laboratory methods [2, 16].

TABLE I. MAIN BASHTAPIA SLOPE LAYER PROPERTIES

Material	**Limestone**	**Gypsum stone**	**Top soil**
Modulus of elasticity (kPa)	1800	2800	5000
Cohesion (MPa)	6	10	18
Angle of internal friction (°)	20	29	30
Unite weight (kN/m^3)	20.4	23	19
PWP (kPa)	-40	-35	-50
Saturated volumetric water content (m^3/m^3)	0.5	0.48	0.4
Residual water content (m^3/m^3)	0.2	0.175	0.15
Flow parameter (k_x=k_y) Van Genuchten Model (m/d)	2×10^{-5}	2.38×10^{-6}	2.4×10^{-4}

III. RESULTS AND DISCUSSION

A. *Factor of Safety of Trench Slope before and during Castle Construction*

Figure 5 shows the critical slip surface and the FoS of the trench slope prior to the castle's construction. To model the construction stages, vertical stress was incrementally applied to the trench slope layers in ten steps, each adding 30 kPa, for a total stress of 300 kPa. As the applied stress increased, the FoS decreased due to the reduction in the shear strength of the ditch slope materials [12, 17, 18]. This FoS reduction is evident in Figures 6-15. The relationship between the applied vertical stress and FoS is displayed in Figure 16, where the FoS dropped from 2.92 to 2.83 as the vertical stress increased from 30 kPa to 300 kPa. Overall, the castle's construction caused a slight reduction in the trench slope stability, which remained resilient over a long period.

B. *FoS of the Trench Slope in the Presence of the TR*

The expansion of the TR basin, bringing it closer to the trench slope, significantly changed the PWP in the layers of the ditch slope. Seasonal variations in the TR level further worsened this effect. Figure 17 shows a significant 112% increase in PWP as the river level rises from 0.0 m to 7 m at the ditch slope base. As a result, this increase in PWP caused settlement in the trench slope materials and a reduction in the shear strength, leading to instability [17, 18]. Figures 18-24 illustrate a decrease in the FoS values from 2.82 to 0.846 as the river level rises from 0.0 m to 7 m directly above the ditch slope base. This was caused by saturation and a decrease in matric suction, leading to an increase in the effective stress. Meanwhile, the settlement of the trench slope materials increased from 21 to 69 mm, as shown in Figure 25. Authors in [19, 20] found that the relationship between the shear strength and matric suction has two parts: a linear part followed by a non-linear part. The point between these two parts indicates a reversal in stress, which is also considered the peak stress point. As the matric suction increases, the soil elasticity is improved, and all stress variables, including the angle of internal friction, also increase with particles.

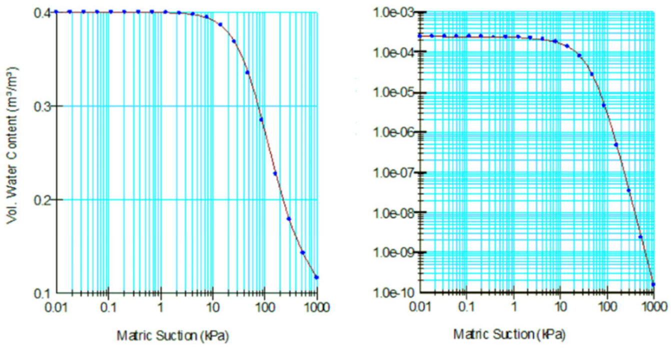

Fig. 2. WRC (left) and hydraulic (right) conductivity of top soil.

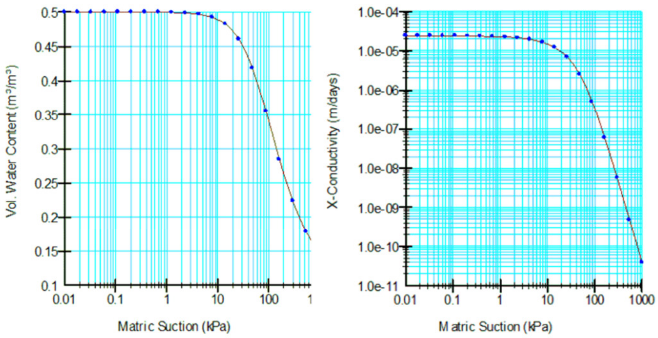

Fig. 3. WRC (left) and hydraulic (right) conductivity of limestone.

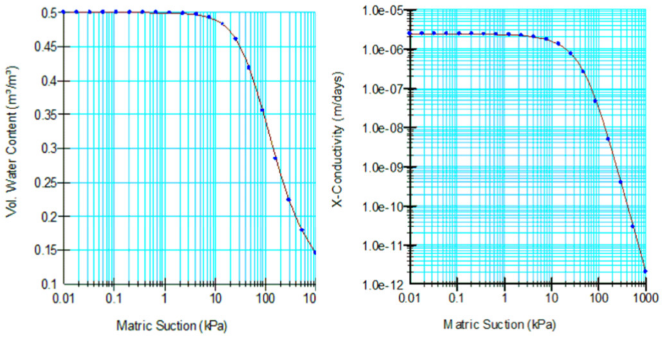

Fig. 4. WRC (left) and hydraulic (right) conductivity of gypsum stone.

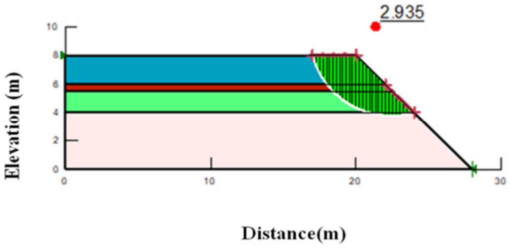

Fig. 5. FoS for slope with slip surface under unsaturated conditions before BC was built.

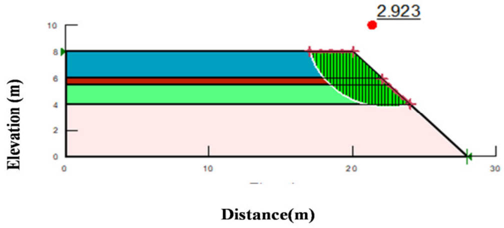

Fig. 6. FoS for slope with a slip surface under unsaturated conditions at a vertical stress of 30 kPa.

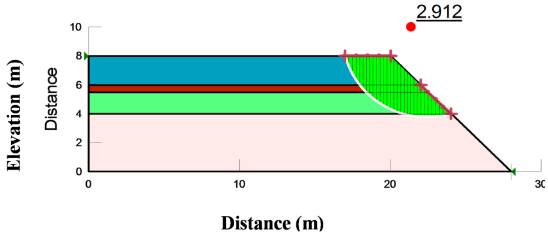

Fig. 7. FoS for slope with a slip surface under unsaturated conditions at a vertical stress of 60 kPa.

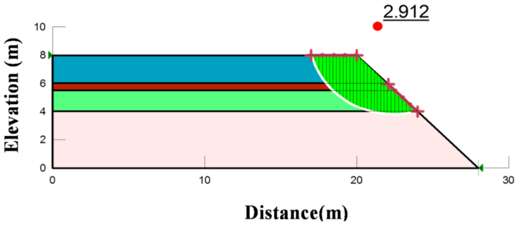

Fig. 8. FoS for slope with a slip surface under unsaturated conditions at a vertical stress of 90 kPa.

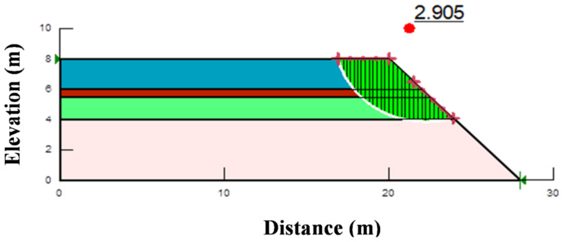

Fig. 9. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 120 kPa.

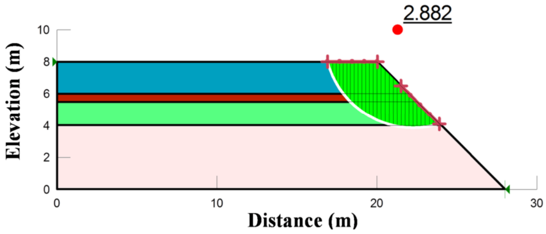

Fig. 10. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 150 kPa.

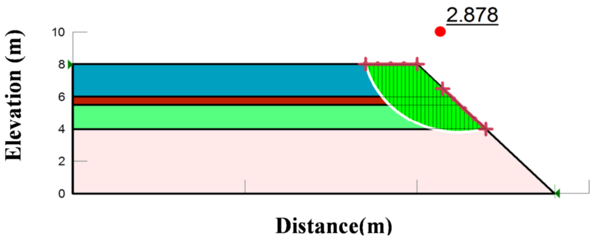

Fig. 11. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 180 kPa.

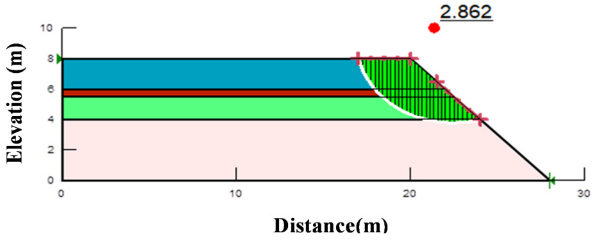

Fig. 12. Critical slip and FoS of slope under unsaturated conditions with an applied vertical stress of 210 kPa.

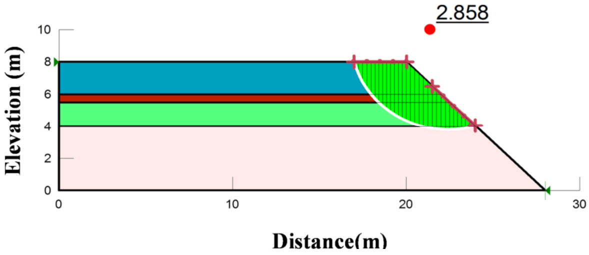

Fig. 13. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 240 kPa.

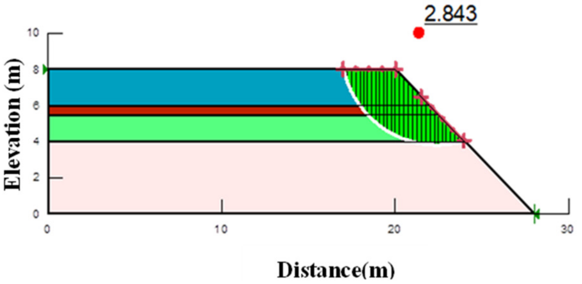

Fig. 14. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 270 kPa.

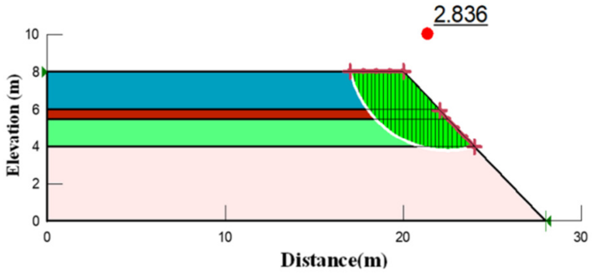

Fig. 15. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 300 kPa.

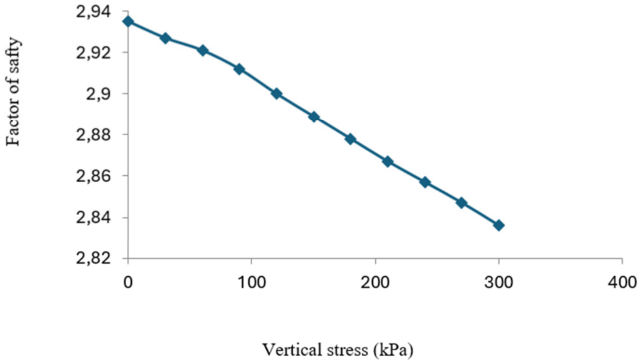

Fig. 16. Relationship between FoS and applied vertical stress during the castle construction.

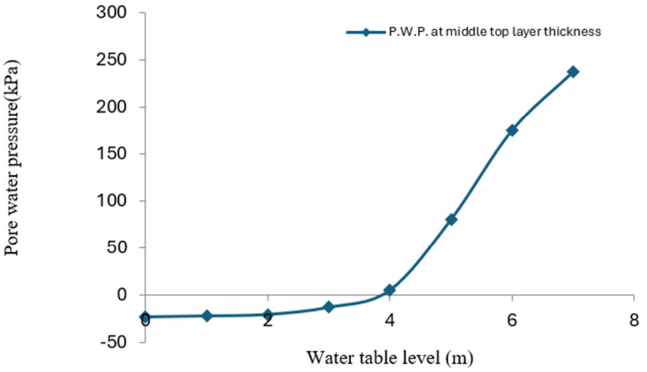

Fig. 17. Change in PWP at the center of the upper layer's thickness relative to the Water Table (WT) height from the base slope.

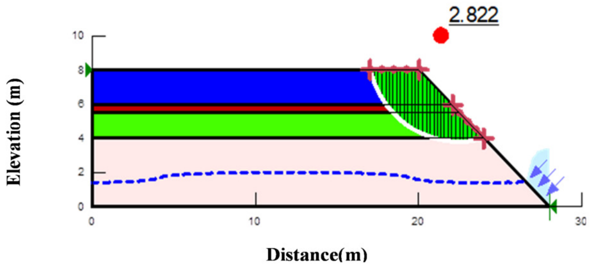

Fig. 18. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 300 kPa and WT upon 1 m up the base.

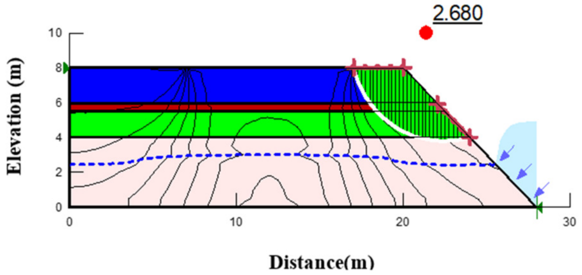

Fig. 19. FoS for slope with slip surface under unsaturated conditiona at a vertical stress of 300 kPa and WT upon 2 m up the base.

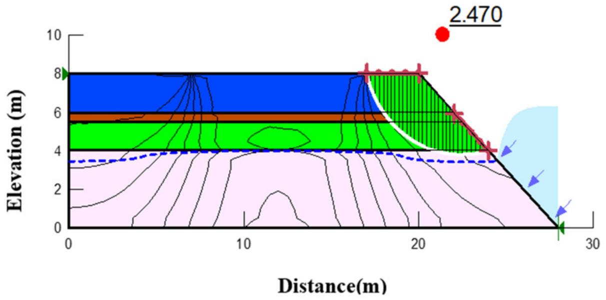

Fig. 20. FoS for slope with slip surface under unsaturated conditiona at a vertical stress of 300 kPa and WT upon 3 m from the base.

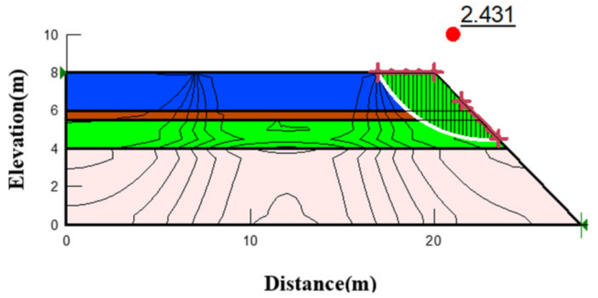

Fig. 21. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 300 kPa and WT upon 4 m from the base.

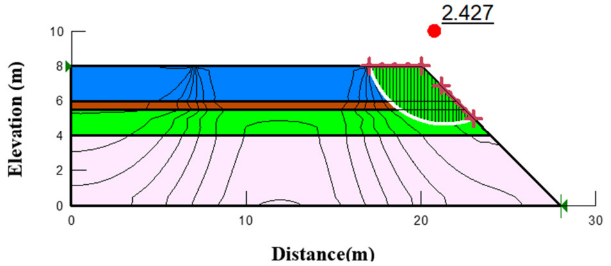

Fig. 22. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 300 kPa and WT upon 5 m up the base.

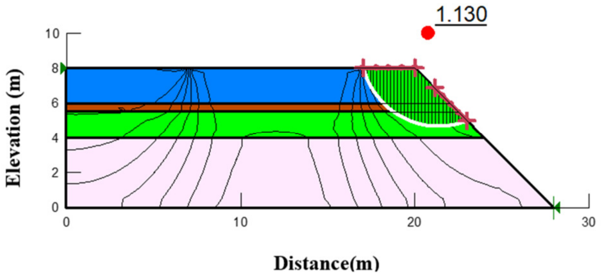

Fig. 23. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 300 kPa and WT upon 6 m up the base.

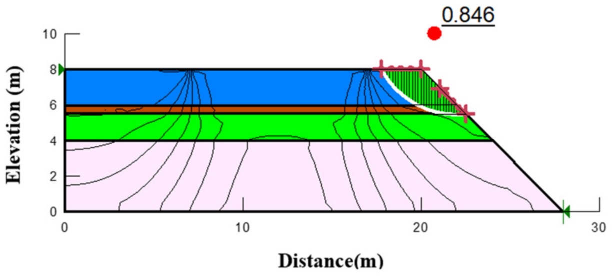

Fig. 24. FoS for slope with slip surface under unsaturated conditions at a vertical stress of 300 kPa and WT upon 7 m up the base.

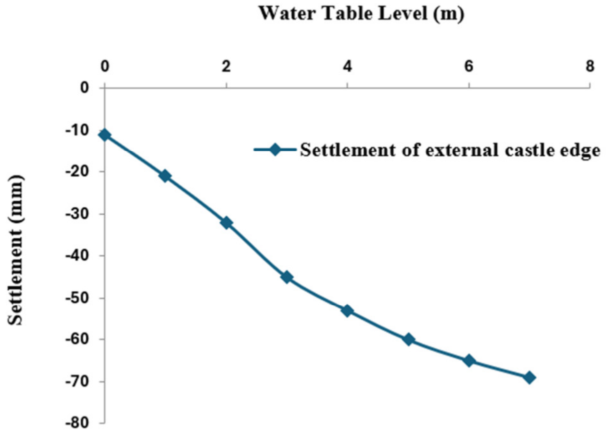

Fig. 25. Variation in settlement of slope crest below external adage castle footing with WT level of TR level.

IV. CONCLUSION

The main goal of this research is to examine the stability of Bashtapia Castle (BC) under the influence of subsequent failure stages and their evolution. Using the Geo-Studio finite element software, the stability of the trench slope was analyzed in two directions to evaluate the castle's stability: a) assessing the fortress during construction before the Tigris River (TR) existed, and b) evaluating the castle's stability under fluctuations in the TR levels. The following conclusions can be drawn:

- The neighborhood and the TR's interaction with the trench slope led to an increase in pore water. The Factor of Safety (FoS) decreased from 2.836 to 0.846 when the Water Table (WT) was 7m above the base of the slope. This change is due to variations in the soil density and moisture content, as well as the disappearance of internal suction stresses, which reduces the shear resistance of the slope soil.
- The construction of the castle caused a slight decrease in the FoS (about 3.37%) and shear resistance of the trench slope stability, which then remained stable for a long time. This is because the soil conditions did not change before the expansion of the TR.
- There is a future study planned to address the failure of the ancient castle's slope by reinforcing it with different materials and distributing the reinforcement in various patterns to demonstrate their effect on FS.

ACKNOWLEDGMENT

This study is part of an integrated research program that deals with the stability of Bashtapia Castle under the influence of successive failure stages and their development.

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