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Slope Stability Analysis and Mitigation Measures in the Area of the Sighişoara Medieval Citadel

The Sighişoara Medieval Citadel has a very big importance to the cultural, architectural and historical heritage of Romania. The citadel is situated on the Fortress Hill and it is the only inhabited fortress in Romania. But underneath the beauty of the Citadel lies some problems that only the inhabitants and the authorities know. These problems consist in the presence of the slope instability phenomenon. Throughout the years the slopes of the Fortress Hill, because of a series of factors, became instable. Thus landslides occurred that affected the Citadel fortress walls. There are still some areas of the walls that have never been reconstructed yet. So a slope stability analysis shall show if the slope instability phenomenon is still active and the mitigation measures recommended will stop the activity of this phenomenon.

Keywords: *slope, stability, analysis, mitigation, citadel*

1. Introduction

A landslide represents the geodynamic phenomenon of restoration of the natural equilibrium of a slope, with slow movements, sometimes quite accelerated, of some part of a slope, as a result of a long time physical and mechanical process (Florea M.N., 1979).

The instability phenomenon in the area of the Sighişoara Medieval Citadel is not a problem that appeared recently. Since the year 1970, in the area landslides were triggered that affected mostly the Citadel's walls. Since then the phenomenon has destroyed some parts of the walls. If we take in consideration that Sighişoara is situated in the Târnava Mare Corridor it is understandable why the slope instability phenomenon is present. Throughout the Târnava Mare Corridor there are a series of landslides that have affected the landscape. Also the Sighişoara Municipality is affected by numerous landslides.

The study area geographically, geomorphologically and geologically speaking is a part of the Transylvanian Basin. The geology of the Transylvanian is a result of a sinking of the crystalline-mesozoic relief, which took place from the beginning of the superior cretaceous until the Pliocene. Hence the geology is represented by a pretertiary bedding structured in the crystalline bedrock and a Mesozoic sedimentary covering, and over them lie the tertiary formations (Mutihac et al., 2004). The tectonics reveals that Transylvanian Basin is a post-tectogenetic basin and it has formed at the end of the Jurassic (Săndulescu, 1984).

In 1990 a series of geotechnical drillings were executed in the area of the Citadel. Disturbed and undisturbed sampling was undertaken in the soil investigation program. The samples were analyzed in the geotechnical laboratory. Humidity tests, plasticity tests, grading tests, share tests and compressibility tests were applied to the samples.

Using the geotechnical and geological information from the drillings, 8 geological sections were proposed for the slope stability analysis. In Figure 1 there is presented the limits of the Citadel, the drillings and the 8 geological sections.

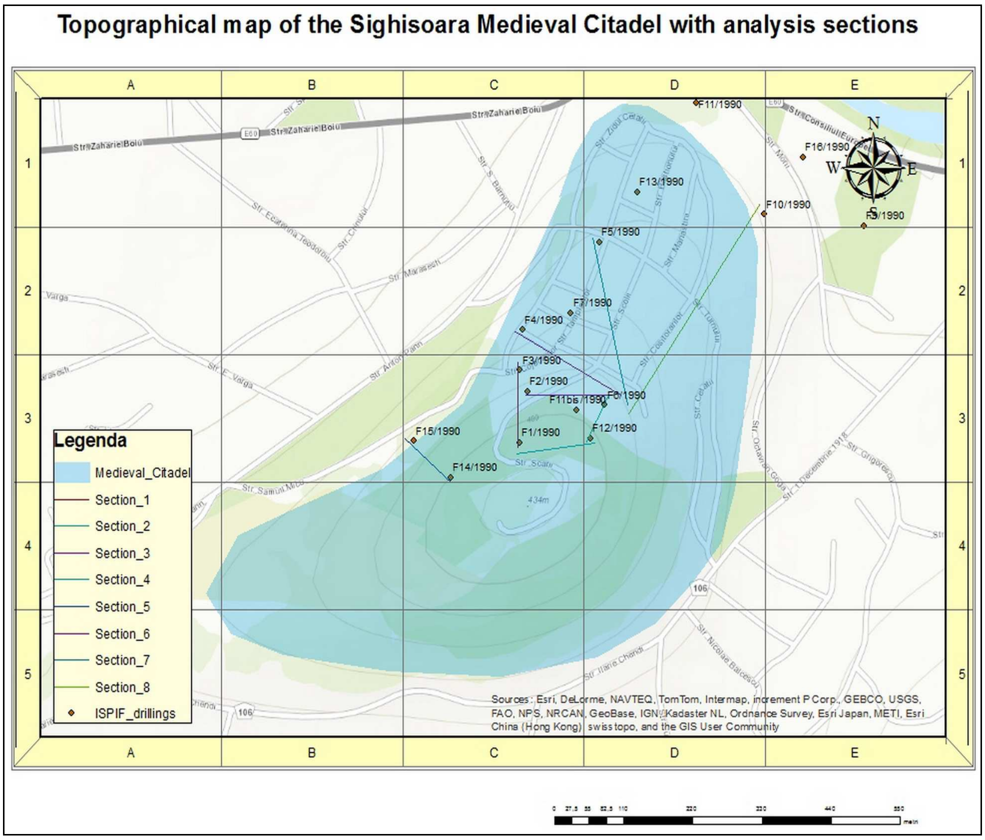

Figure 1. Topographical map of the Sighişoara Medieval Citadel with drillings and geological sections

2. Slope stability analysis

The slope instability phenomenon in the study area is generated by a series of factors, such as (1) the geological setting, (2) the geotechnical properties of the geological layers, (3) the gradient of the slope, (4) the water table and (5) the surcharges loads on the slope.

Given the instability situation in the study area it was decided that the slope stability analysis will be accurate using three analysis methods, namely the Fellenius, Bishop and Janbu methods. The software used was GEOSTUDIO SLOPE/W.

The most important feature in the slope analysis is the geotechnical properties of the geological layers. So, based on the geotechnical laboratory test results, in Table 1 there are presented the values of the geotechnical parameters used in the analysis.

Table 1. Geotechnical parameters values for the slope stability analysis

Geological layer	Moist volumetric weight γ [kN/m^3]	Friction angle φ [°]	Cohesion c [kPa]
Geological section No. 1			
Diluvium	19,10	30,00	10
Silty clay	20,40	12,30	45
Silty sand	20,20	25,44	39
Clayey sand	19,10	30,00	10
Sandy clay	21,00	5,20	63
Geological section No. 2			
Diluvium	19,10	30,00	10
Silty clay	21,00	37,00	18
Silty sand	19,10	30,00	10
Geological section No. 3			
Diluvium	19,10	30,00	10
Silty clay	21,00	37,00	18
Silty sand	20,20	25,44	39
Clayey sand	19,10	30,00	10
Geological section No. 4			
Diluvium	19,10	30,00	10
Silty clay	21,00	37,00	18
Silty sand	19,10	30,00	10
Geological section No. 5			
Diluvium	19,10	30,00	10
Silty clay	19,70	29,27	8
Silty sand	20,20	25,44	39
Geological section No. 6			
Diluvium	19,10	30,00	10

Silty clay	21,00	37,00	18
Silty sand	20,20	25,44	39
Clayey sand	20,10	14,59	44
Geological section No. 7			
Diluvium	19,10	30,00	10
Silty clay	21,00	37,00	18
Silty sand	20,20	25,44	39
Clayey sand	19,10	30,00	10
Geological section No. 8			
Diluvium	19,10	30,00	10
Silty clay	21,00	37,00	18
Silty sand	20,20	25,44	39

In the slope stability analysis it was necessary to demonstrate how the factor of stability varies in different situations regarding the triggering factors of the instability phenomenon. Hence, a number of 4 hypothesis were adopted, namely (1) the slope in a natural state, (2) the slope with a water table at a depth of – 1,00 m, (3) the slope with surcharges loads and (4) the slope with surcharges loads and a water table at a depth of – 1,00 m. The 4 hypothesis will show how the slope will behave, besides the natural state, under a shallow depth of the water table and surcharges loads.

The slope stability analysis was undertaken for shallow rupture surfaces because of the geological setting and the geotechnical properties of the geological layers. For instance, in the geotechnical laboratory investigation phase it was observed that the diluvium deposits and the silty sands have very poor geotechnical properties. It was also observed, in the field survey, that the existing landslides in the area were triggered in such deposits. Also the areas with significant signs of instability were identified in shallow deposits.

3. Slope stability analysis results

The results of the slope stability analysis revealed a value interval for the factors of stability (F_s) ranging from 0,881 to 7,831. The F_s values for the 3 slope stability methods applied and for the 4 hypothesis taken in question, are presented in Table. 2.

Table 2. Slope stability analysis results

Hypothesis No.	1	2	3	4
Method	Factor of stability (F_s) values			
Geological section No. 1				
Fellenius	6,448	5,693	1,089	1,089
Bishop	6,549	6,018	1,289	1,289

Janbu	6,391	5,611	1,133	1,133
Geological section No. 2				
Fellenius	6,870	5,492	0,920	0,881
Bishop	7,831	6,005	1,047	1,051
Janbu	6,617	5,416	0,944	0,916
Geological section No. 3				
Fellenius	6,480	5,778	1,016	0,997
Bishop	6,511	5,924	1,168	1,145
Janbu	6,224	5,730	1,057	1,039
Geological section No. 4				
Fellenius	4,397	3,997	0,969	0,978
Bishop	4,484	4,084	1,099	1,107
Janbu	4,353	3,969	1,071	1,001
Geological section No. 5				
Fellenius	4,812	3,207	-	-
Bishop	4,942	3,657	-	-
Janbu	4,772	3,290	-	-
Geological section No. 6				
Fellenius	6,555	5,089	1,593	1,593
Bishop	6,807	5,785	1,830	1,830
Janbu	6,193	4,949	1,645	1,645
Geological section No. 7				
Fellenius	3,851	2,784	0,935	0,895
Bishop	4,115	3,052	1,047	1,005
Janbu	3,758	2,795	0,953	0,913
Geological section No. 8				
Fellenius	6,137	4,900	1,254	1,248
Bishop	6,573	5,338	1,425	1,422
Janbu	5,919	4,834	1,259	1,252

On a first view over the Fs values it is clear that the slopes analyzed are stable/instable depending on the hypothesis taken in the analysis. Hence in hypothesis no. 1 and no. 2, all the slopes analyzed are stable, because the equilibrium conditions of the slope is that Fs>1. The first two hypotheses are referring to the slope in a natural state, but those hypotheses are not real, there are supposed.

The last two hypotheses, where surcharges loads from the existing constructions (houses, roads) in the area were taken in consideration, the Fs values are much smaller than in the case of the first two hypotheses. In many cases the equilibrium conditions of the slope that Fs>1 is not reached. These results are also influenced by the applied method. The situations in these last two hypotheses are the realistic ones.

4. Conclusion

The Fortress Hill of the Sighişoara Medieval Citadel was, is and will be affected by the instability phenomenon. As presented, it is not a local phenomenon but a general phenomenon identified throughout the entire Târnava Mare Corridor. The slopes in the study area have many instability issues.

The stability analysis in the study area presented that the slopes have a behavior at the edge of instability. This situation is a conclusion of the F_s values obtained in the last two hypothesis. It is clear that the presence of a water table at a depth of -1,00 m and the surcharges loads from the existing constructions have a big influence over the stability of the slopes in the study area. But a bigger influence over the stability of the slopes has the water table. At a shallow depth, mostly because of the precipitation quantities, with the aid of other factors such as the geology and the geotechnical properties of the soils, can and will trigger landslides.

For assuring the stability of the study area slopes it is mandatory to adopt mitigation measures. The slope stability in the study area will be assured by draining the underground water at a depth equal to the bedrock formations.

The stability analysis gave information about the areas prone to landslide occurrence. In these areas the mitigation measures are: (1) drainage systems, (2) retaining walls with pile foundations, (3) the recovery of the existing ditches and the construction of supplementary ones. In this way the integrity of the Sighişoara Medieval Citadel is assured, maintaining the stability of the slopes with the mitigation measures proposed.

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