Reinforced soil retaining walls—restoration of an extended failure on a soft rock formation

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ABSTRACT: The ability of the reinforced soil retaining walls to take deformations and settlements of the foundation formations without losing their bearing capacity suggests it is one of the best solutions for the support of unstable slopes in loose formations.

The failed slope analyzed in this study is located in a thick zone of weathered granite, acting like a relatively loose soil material. The landslide affected a slope sited within the limits of the urban area of Alona village, west of Florina town. Two houses were subjected to serious damages, a secondary road and a path were interrupted and a stream was blocked causing disruption to the local community.

For the restoration of the slope a reinforced soil retaining wall was suggested. This wall allows the reconstruction of the road and the pathway and at the same time restores the initial geometry of the slope without severely changing the pre-failure stress field developed in the foundation formation. The mechanical characteristics of the geological formation were estimated by conducting back analysis of the failure.

1 INTRODUCTION

Reinforced soil technique is a very old ground improvement method applied for more than a thousand years. Different types of reinforcing materials, from bamboo to steel strips and from tree branches to geogrids, have been used in various constructions over the years. Nowadays, the modern reinforcement techniques provide greater durability, strength, and a more sophisticated design approach.

One of the most important properties of the reinforced soil retaining walls is the ability to take deformation and settlement of the foundation formations without losing their bearing capacity. Consequently, these constructions are considered as one of the best solutions for the support of unstable slopes in loose formations. Over the years, many studies have been conducted proving their efficiency, i.e., Desai and Hoseing (2005), Hatami and Bathurst (2004), Ma and Wu (2004), Simonini et al. (2003), Filippo et al. (2000), Pinto and Cousens (1999, 1996), Kapurapu and Bathurst (1995), Palmeira and Lanz (1994), Wong et al. (1994), Bathurst et al. (1992), Juran and Christopher (1989), Jewell (1985) and Hausman and Lee (1978).

The present paper introduces the study carried out for the restoration of a failed slope sited within the limits of the urban area of Alona village, west of Florina town, Greece (Figure 1). The slope consists of weathered granite, acting like a loose soft rock material. Two houses located along the crown of the failure were subjected to serious damage. Furthermore, a secondary road and a pathway were interrupted, while a stream was blocked causing disruption to the local community.
For the restoration of the slope a reinforced soil retaining wall was suggested. This wall allowed the reconstruction of the road and the pathway and at the same time restored the initial geometry of the slope without changing severely the pre-failure stress field developed into the foundation formation. The mechanical properties of the geological formation were estimated by conducting back analysis of the failure.

2 GEOLOGICAL AND MORPHOLOGICAL SETTING—LANDSLIDES
HISTORICAL BACKGROUND

Alona village is located 10 km west of the town of Florina. The morphology of the area is sharp and traversed by a dense hydrographic network. The village is sited at the base of the Sakouleva stream valley (Figure 1).

The landslide took place during a period of intense rainfall in February 2006. The failed slope is 15 to 20 m in height and it is located at the north-western edge of the village (Figure 1). The geometry of the slope was altered, by the residents, some decades ago. Flat surfaces were formed, in the middle and on the top of the slope, and used for the foundation of houses and warehouses, for the construction of secondary roads and pathways as well as for the plantation of small gardens. The maximum slope angle was 50°. Some of the pre-failure morphological characteristics of the slope can be distinguished in Figure 2.

As mentioned above the slope consists of weathered granite. According to the geological map of the wider area (IGME, 1987) this formation is an arenitized granite with granular to psammitic texture. It is composed of quartz crystals, perthitized K-feldspars, totally sericitized plagioclases, discoloured biotite and clay minerals. This soft rock formation acts like a cohesive soil forming rotational slides (Varnes, 1978) (Figure 2).

During the geological mapping numerous signs of prior failures or creep movements were ascertained. At the north-eastern side of the present failure, a plane area delimited by U-shaped slopes indicates the location of an old transitional slide. In addition, signs of creep movements can be recognized all around the study area. Numerous trees present curved trunks and the majority of the old buildings founded on the slope show tensile fractures (Figure 3). All these signs and structures prove that the geological formations composing the slopes of the study area are capable of sliding.

Figure 1. Satellite pictures (© Google Earth™ mapping service) showing the location of the Alona village, as well as the location of the Landslide (Google Earth, 2010).
Upon examining the geological and morphological environment of the failure its preparatory causal and triggering factors can be distinguished. According to the WP/WLI reporting method (1994), the main preparatory causal factors of the failure were: a) regarding the ground conditions, the presence of weathered materials, b) concerning the morphological processes, the fluvial erosion of the slope toe by the crossing stream and c) as for the man made processes, the construction of the terraces (excavation of the slope), the loading of the slope by the buildings weight, and the natural irrigation or the water leakage from the services (gardens and sewage cess tanks). On the other hand, the main triggering causal factor was an intense short period rainfall event (WP/WLI, 1994).

The numerous aforementioned factors show that man made factors were part of the reason for the slope failure. The alteration of the morphology, the application of excessive loads and the lack of the necessary infrastructure (drainage network, protections of the slope toe, etc.) were responsible for a landslide that should have been expected.

The main purpose of this study was to estimate the safety factor of the slope formed after the failure and to suggest remedial measures for the reconstruction of its former geometry.
The stability of the slope was estimated by the application of a global stability analysis using the overall stability module of Larix-5S geotechnical engineering program. Larix estimates the safety factor for sliding by formulating the global equilibrium forces acting on a slice according to the well known methods of Janbu (Janbu 1954; Janbu, Bjerrum and Kjaernsli 1956; Janbu 1957) and Krey (Krey 1936).

The analyses were carried out using both, Janbu and Krey methods. According to Krey’s method, circular slip surfaces of radius \( R \) are assumed and the failure mechanism is a rigid body rotating about the centre of the slip circle. The assumed equilibrium conditions are: \( \Sigma V = 0 \) (vertical forces) and \( \Sigma M = 0 \) (moments). Both horizontal and shear forces act on the sides of the slices and the equation to determine the safety factor (\( F \)) is iteratively solved. In contrast, Janbu’s method involves straight, non-circular, slip surfaces and translational failure with equilibrium conditions \( \Sigma V = 0 \) (vertical forces) and \( \Sigma H = 0 \) (horizontal forces). Again both horizontal and shear forces act on the sides of the slices. This method is especially suited to cases where the morphology of the soil layers indicates a less rounded sliding surface.

Taking into consideration the seismicity of the wider region, seismic loading of the slope was included in the analyses. The seismic loading is specified as a fraction of the seismic acceleration due to gravity \( g \), in the \( x \) and \( y \) directions. The resulting acceleration influences the determination of the weight of the individual slices of the sliding body. In this case study the horizontal, \( \alpha_x \cdot g \), and vertical, \( \alpha_y \cdot g \), earthquake accelerations values were as 0.10 \( g \) and 0.05 \( g \), respectively, following the Hellenic anti-seismic regulation (E.P.P.O. 2000).

In order to estimate the mechanical properties of the formations composing the slope, back analysis of the pre-failure geometry was conducted. Back analysis procedure is the most reliable way to estimate the mechanical characteristics in cases where undisturbed samples cannot be obtained. The ultimate values of the mechanical parameters estimated by that procedure are: \( \phi = 26^\circ \), \( \gamma = 19 \) kN/m\(^3\) and \( c = 50 \) kN/m\(^3\) (Figure 4). During the back analysis process, the loads applied by the buildings were also taken under consideration. Note that there is not any aquifer affecting the stability of the slope.

Taking into account the aforesaid set of mechanical parameters, the safety factor of the after-failure slope was also calculated. The analysis proved that the slope is unstable (Figure 5), arising issues about the safety of the partly destroyed buildings still sited on the top of the slope (Figure 2) and essentially, about the safety of the undamaged habitable residencies buildings located at the toe of the failure. As a result the construction of a retaining structure was imperative.

The construction of a 20 m high concrete retaining wall, although it is possible, requires the design of a heavy and rigid bearing wall or complex of walls, efficient to restore, at least, part of the slope’s pre-failure geometry. This construction requires a specialized static study as well as an extensive geotechnical study of the foundation conditions. In contrast, the

![Figure 4](image-url)

Figure 4. Back analysis carried out at a pre-failure cross section of the slope, for the determination of the ultimate mechanical parameters of the geological formations.
construction of a reinforced soil retaining wall can restore the former geometry of the slope with respect to the pre-failure stress field along the foundation surface.

In order to evaluate the ability of a reinforced soil retaining wall to provide the necessary slope stability safety factor, multiple theoretical wall patterns were applied to the failed slope. The analysis proved that a reinforced soil structure simulating the pre-failure geometry of the slope could stabilize the slope, restoring, at the same time, the previous land use activities. As presented in Figure 6, a 20 m high wall founded in 1 m deep cut-off trench can provide a safety factor equal to 1.2. Taking in account that seismic loads were also applied during the analysis, the safety factor is satisfactory. The retaining wall can be constructed by the use of 1 m tall, gabion blocks with steel mesh tails, reaching to the back of the wall.

Because of the height of the slope, the poor mechanical properties of the geological formation and the loads applied on the top of the slope, a lighter wall could not be sufficient. All analyses conducted by considering a thinner wall’s cross section led to failures mainly along the upper half of the slope.

4 CONCLUSIONS—DISCUSSION

The existence of formations with poor mechanical properties, the height of the slope and the loads applied along its crest require the construction of a retaining structure efficient to bear excessive thrust forces. The selection of a reinforced concrete retaining structure for the restoration of the slope demands the construction of a heavy wall able to bear, beside the thrusts, excessive moments along its base. Considering the lack of accessibility on the top of the slope, as well as the confined space along its base, the most applicable concrete wall for this case study could be a 20 m tall and more than 30 m long, invert T-Wall.
Obviously, in this case study the selection of a reinforced soil retaining wall for the restoration of the slope appears to be the best solution. The construction of a reinforced soil wall can reinstate the original geometry of the slope with respect to the pre-failure stress field along the foundation surface. Moreover, this wall is able to take over all possible deformations and settlements of the foundation formations without losing its bearing capacity. It can be constructed during the dry period of the year in a sort time and it is capable of bearing loads immediately. Furthermore, the geomaterials of the failure can be used for the construction of the wall reducing, in this way, the cost of the project.

This case study could be referred as a typical example of failure that can be restored by the construction of reinforced soil retaining wall.

REFERENCES


