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GEOTECHNICAL ASSESSMENT AND SAFE SLOPE DESIGN OF A LANDSLIDE IN A LIMESTONE QUARRY (ORDU/NE TURKEY)

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Abstract. Limit equilibrium analyses have been carried out to investigate the stability of a limestone quarry near Unye (Ordu/Turkey) after a landslide that took place, and slope remediation studies were conducted to procure long-term stability. A 1/5000-scale geological map of the landslide was prepared through field measurements and topographic maps, and stability analyses were carried out on 4 different cross-sections along the slope. Factor of safety values as low as 0.8 were determined for one of the slopes for pseudo-seismic condition, therefore a stable slope design was created. The stability of the new design was also tested with limit equilibrium analyses and the results indicate the factor of safety values will remain above 1.3 even with the seismic effect.

Keywords: *stability, limit equilibrium, geotechnical assessment, landslide, slope remediation, Ordu*

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1. Introduction

Eastern Black Sea region of Turkey has the highest mass movement potential in the country with a thick residual material covering the steep slopes of mountainous terrain, and heavy rainfalls during most of the year. In addition to these natural favourable conditions, common slope design errors, uncontrolled excavation and blasting applications in road cuts and open-pit mines increase the possibility of mass movements like landslides. Many such landslides have occurred in the region, with Catak (Trabzon, NE[1] Turkey) disaster of 1988 being one of the most known and catastrophic, where 64 lives lost as a result of failure of a roadcut due to heavy rainfall and slope design errors (Jones *et al*. 1989; Genc, 1993). In 1981 and 1982, 36 people died in Rize city because of successive floods and landslides in the area. 57 people were lost, and thousands of buildings were damaged in Trabzon city in 1990 as a result of floods and landslides after a week-long ceaseless heavy rain in the city. In the last 80 years, more than 700 lives lost, along with almost 1 billion dollars of financial damage, because of over 50 known flood and landslide incidents throughout the region (Bulut *et al*., 2000; Akgun *et al.*, 2008; Kesimal *et al*. 2008; Nefeslioglu & Gokceoglu, 2011; Alemdag *et al*., 2013; Karaman *et al*., 2013; Osna *et al*., 2014; Topsakal & Topal 2015; Kaya *et al*., 2016, 2018; Kaya, 2017; Kul Yahşi & Ersoy, 2018).

[1]NE = northeast

Slope stability analysis techniques have been both an important and controversial aspect of geotechnical engineering for decades (Duncan, 1996). Numerical analyses such as limit equilibrium (LE) and finite element (FE) methods are widely used by geotechnical engineers, and it is known that the methods have different advantages and disadvantages over one another (Tschuchnigg *et al*., 2015). LE analysis methods such as Fellenius (1927), Bishop (1955), Janbu (1954), Morgenstern-Price (1965) and Spencer (1967) rely on the equilibrium calculations of soil slices for static condition and neglect the stress-strain behaviour of the soil mass. Also, these methodsare based on the assumption that the soil will fail along a shear surface passing through artificial slices, but they are very easy to use and give acceptable factor of safety values. FE methods such as Shear Strength Reduction (SSR), on the other hand, can better model the geotechnical properties of the soil mass, and failure occurs naturally between the boundaries of meshes without apre-defined failure surface (Griffiths & Lane, 1999). These analyses require powerful workstations or PCs due to sophisticated calculations, but they have become accessible through recent decades which makes them preferable for slopes that are relatively complex in terms of geometry and geological material. In this study, stability analyses were carried out to investigate post-shear stability of a failed soil slope in a limestone quarry in Ordu city (NE Turkey), and slope remediation studies were conducted to ensure long-term safety. Considering the relatively simple geometry of the slope, lack of groundwater, and availability of failure surface of the landslide, Bishop's method of LE analysis was adopted in the analyses.

2. Location and geological setting of the study area

The Eastern Pontides orogenic belt of north-eastern Turkey is a well-preserved magmatic arc of Alpine orogeny (Eyuboglu *et al.*, 2011). The belt has been divided into three sections as northern, southern and axial zones based on the lithology, facies and tectonic characteristics (Bektaş *et al*. 1995; Eyuboglu *et al*. 2006). The northern zone is characterized by Mesozoic-Cainozoic volcanic rocks and granitic intrusions (Arslan *et al*. 1997, 2013; Aydin *et al*. 2008). The southern zone includes Palaeozoic metamorphic intrusions and Mesozoic-Cainozoic sedimentary complexes. Upper mantle peridotites are extensively exposed farther south in the axial zone (Eyuboglu *et al*. 2007, 2010).

The study area, which is in the northern zone, is located in Cevizdere region of Ordu city, approximately 6 km southeast from Unye town center (Fig. 1). Andesite, dacitic tuff and bentonite clays (a residual soil formed by the weathering of dacitic tuff) of Late Cretaceous Tirebolu Formation are the base units in the area, which are conformably overlain by limestone, marl, siltstone and sandstone units of highly fossiliferous, Late Cretaceous Akveren Formation (Gedik & Korkmaz, 1984; Guven, 1993). Quaternary alluvium and marine terrace overlay other geological units in the area and cover most of the stream beds and Black Sea coast.

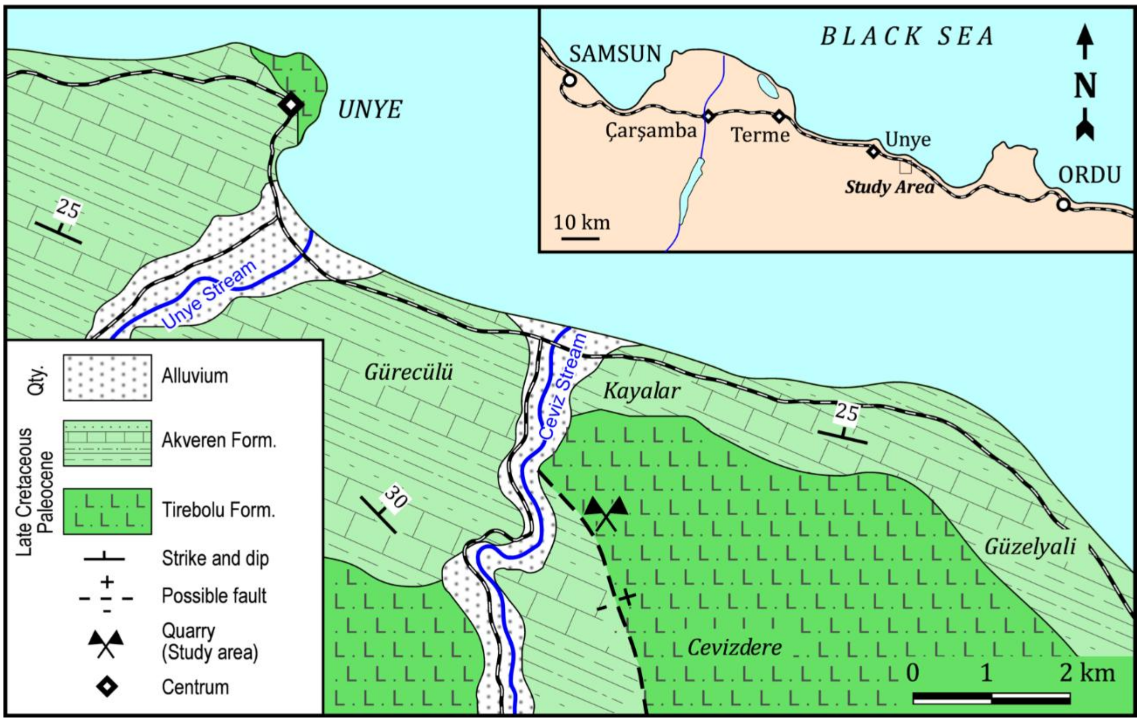

Fig. 1. Location and geological map of the study area

3. Geotechnical assessment of the landslide

A landslide took place in the quarry in 2007. Preliminary field investigations in the study area revealed that the residual soil above the limestone moved towards the production site, basically because of heavy rainfalls in the area and the excavation and relocation of the limestone during the production in the quarry which resulted in formation of high and steep rock and soil slopes. The displaced material formed a 10-meter-thick pile in the open-pit site, suspending the production completely (Fig. 2). This study was carried out to investigate any further mass movement risk with post-shear slope geometry and conduct slope remediation studies for safe excavation of the landslide material and future production in the quarry. Field surveys and laboratory tests were conducted to determine the soil's in-situ physical and geo-mechanical properties which are extremely important on the stability of slopes under the influence of rainfall (Huang *et al*., 2012).

The residual soil consists of 28% sand, 38% silt, and 34% clay-sized particles. Its liquid limit values vary between 63-76% and plastic limit values between 24-34%. Using Unified Soil Classification System, the soil was classified as CH, highly plastic inorganic clays. Main clay mineral in the residual soil is montmorillonite, a highly plastic and water susceptible material. The soil also contains small percentages of minerals like albite, calcite, quartz and gibbsite (Sünnetci, 2015). The limestone unit is moderately jointed, and significant cracks oriented perpendicular (280/15) to the quarry face are present. The layers are parallel to the slopes, inclined 10-15° to the northeast. Stratigraphically the limestone unit is above the residual soil, yet in the study area it's exactly the opposite, which suggests a reverse-faulted contact between these units.

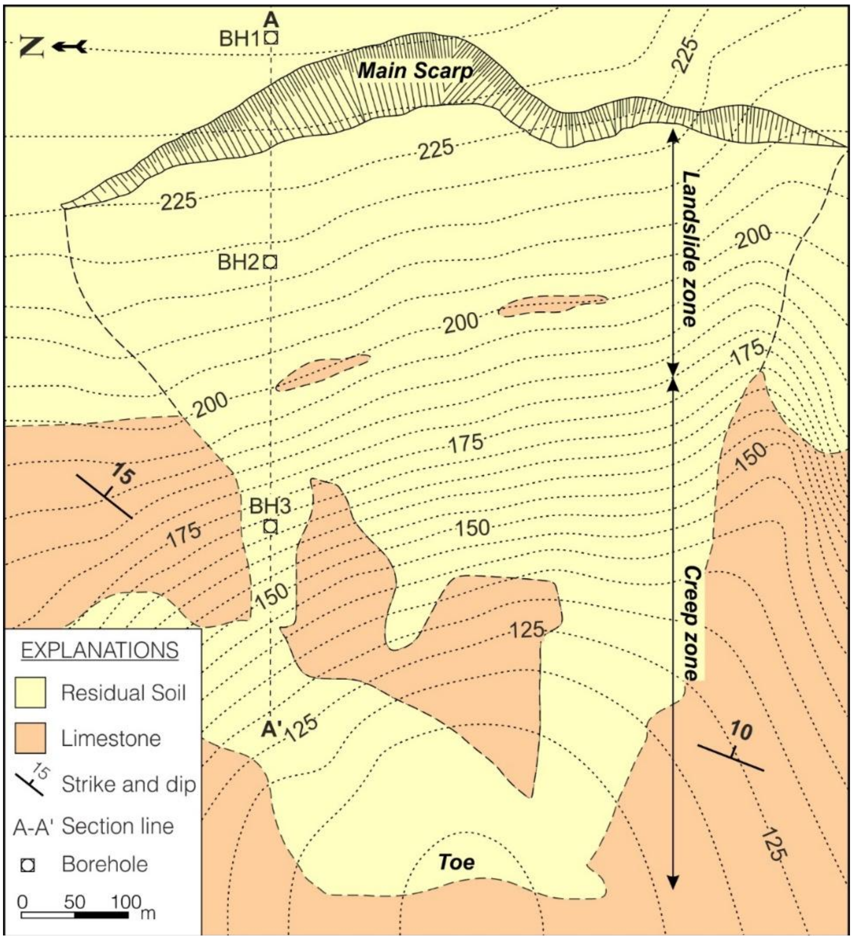

Fig. 2. Geological map of the landslide

Stability analyses were conducted using Rocscience Slide®6 software. The software is used to conduct limit equilibrium slope stability analysis for thousands of possible shear surfaces. Material properties like unit weight, cohesion and internal friction angle should be introduced to the software along with slope geometry, geological units, tension cracks and groundwater (if any). Hence, the geometries of the slope and landslide were determined via field measurements and topographic-geological maps. A detailed geological map of the landslide was also prepared at 1/5000 scale. Data from three separate boreholes, which were drilled prior to the production of the quarry, used to create geological cross-sections of the landslide to be used in the stability analyses (Fig. 3). Index and plastic properties of the material were also determined in accordance with corresponding ASTM standards (Table 1).

In order to determine the shear strength parameters of the residual soil, 30 undisturbed soil samples were acquired using cylindrical samplers from 5 test pits (each with 3 meters depth) throughout the landslide.

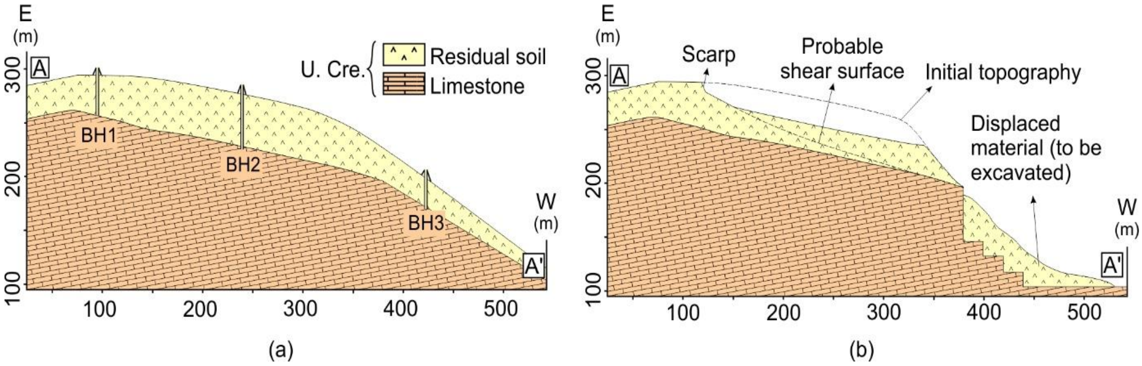

Fig. 3. A-A' cross-section before the production process in the quarry (a) and after the landslide (b)

Consolidated-drained (CD) direct shear tests were carried out on 15 of the samples in accordance with ASTM D3080/D3080M test standard (ASTM, 2011) to assess long-term stability of the slope considering the production process in the quarry. The test parameters for the CD direct shear test were determined by conducting one-dimensional consolidation (oedometer) tests on undisturbed residual soil specimens and using the following equation suggested by the standard:

$$t_f = 11.6 * t_{90} \quad (1)$$

where:
t_f: total estimated elapsed time to failure, minutes,
t_{90}: time required for the specimen to achieve 90% consolidation under the maximum normal stress increment, minutes.

Table 1. Physical, plastic and strength characteristics of the residual soils

LL: Liquid limit; PL: Plastic limit; PI: Plasticity index; γ_{sat}: saturated unit weight

	Atterberg limits %			Grain Size Distribution %			γ_{sat}	c	φ
	LL	PL	PI	Clay	Silt	Sand	(kN/m^3)	(kN/m^2)	Degrees
Max	76	34	45	40	42	40	23.73	48.62	25.64
Min	63	24	35	27	33	19	19.81	45.31	22.22
Mean	69	29	39	34	38	28	20.10	47.18	24.17
Std. dev.	3.42	2.92	3.10	3.57	2.73	5.37	1.12	1.09	1.74

t_{90} value of the soil specimen was determined to be 3.76 minutes using oedometer test data. Minimum time to failure was then calculated as ~45 minutes using Eq. (1); yet, according to the recommendations of the corresponding test standard for CH soils, time to failure was chosen as 24 hours to prevent emergence of excess pore water pressure in the specimen during the test. The relative lateral displacement was applied as 10 mm to ensure shearing of the specimen and determine its residual shear strength parameters. All tests were repeated three times under different normal loads, and results were interpreted on a residual shear stress-normal stress chart. To prevent instability problems in the long-term, residual shear stress values were used in the calculations and stability analyses. Cohesion (c) and internal friction angle (φ) of the material were determined to be 47 KPa and 24 degrees respectively via the chart.

4. Slope stability analyses

The stability analyses were conducted in two steps. First, limit equilibrium analyses were conducted for post-shear slope geometry to investigate further mass movement risk in the quarry. Then, a new safe slope geometry was designed to safely relocate the landslide material and restart production. Considering the earthquake hazard map of Turkey (Ministry of Reconstruction and Settlement 1996, unpublished report), all stability analyses were conducted with and without seismic effect.

4.1. Stability analysis for post-shear condition

Limit equilibrium analysis has been carried out to investigate potential mass movement risk in the quarry with post-shear slope geometry. The geometry of the slope has been determined via topographic maps, field observations and geodeticspatial measurements using a total station. Data from three different boreholes in the landslide area, which were drilled during the prospecting stage of the quarry, used to create geological cross-sections along the slide direction and limit equilibrium analyses were carried out on these cross-sections. The shear surface was predicted by combining the main scarp and the toe of the landslide in accordance with borehole data. This prediction was necessary because the harsh topography and thick bentonite clay mud prevented the borehole machines to reach slope surface after the landslide. Stability analyses were conducted on 4 different cross-sections along the slope, and the cross-section with the lowest factor of safety values was evaluated for slope remediation studies. The remedial design was then applied to all cross-sections and, eventually, to whole slope. Residual shear strength parameters and saturated unit weight of the landslide material were introduced to the Slide®6 software. Mohr-Coulomb failure criterion was used, and shape of the sliding surface was selected as circular and composite. Simplified Bishop was selected as stability analysis method. For the analysis with seismic effect, horizontal peak ground acceleration (PGA) value of 0.1g was applied according to before mentioned earthquake hazard map. Considering the long production life of the quarry, PGA value was used as is, without a reduction based on the distance from the major North Anatolian Fault.

The results of the analyses indicate that there is a landslide risk with post-shear slope geometry along one of the cross-sections with seismic effect (Fig. 4).

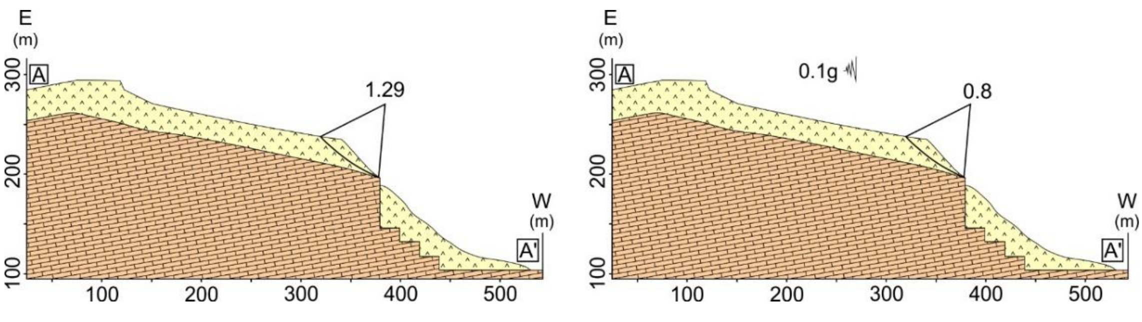

Fig. 4. Post-shear stability analyses with (a) and without (b) seismic effect along A-A’ cross-section

4.2. Design and stability analyses of the new slope geometry

The production in the quarry has been suspended completely as landslide material covered the open-pit site. A new stable slope design was needed to safely excavate the displaced material and restart production, and also eliminate the mass movement risk on theslope. New slope geometry has been designed with Slide®6 software, using the back-analysis support design module of the software (Fig. 5). This module calculates the required counter-force on the slope surface for a given factor of safety (in this case 1.5).

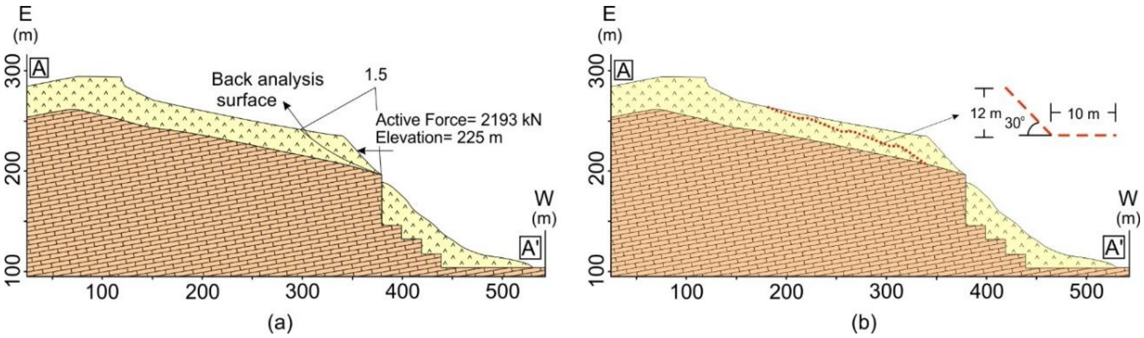

Fig. 5. Support back-analysis (a) and new slope design (b) for the slope

As it can be seen from the Fig. 5, the required counter-force on the slope surface is 2193 kN for a factor of safety of 1.5. This is a relatively high force and building a retaining wall which can withstand such a force would be unsuitable for this project, where excavating is an application performed frequently. Rock bolts are an alternative support type, yet they must be socketed into the intact limestone which is the material that is being produced in the quarry. Also, the shear surface is at a depth of 15 meters at most, which is too much for practical use of rock bolts. For these reasons, slope remediation studies were centred on dividing the slope into smaller and gentler stable slopes. Consideringboth residual soil's physical-mechanical properties and the geometry of the slope, different new slope designs were created. Stability analyses for the new slope were carried out both with and without seismic effect to assess long-term stability (Fig. 6). The results indicate that the factor of safety value of the new slope would be above 1.3 even with the seismic effect.

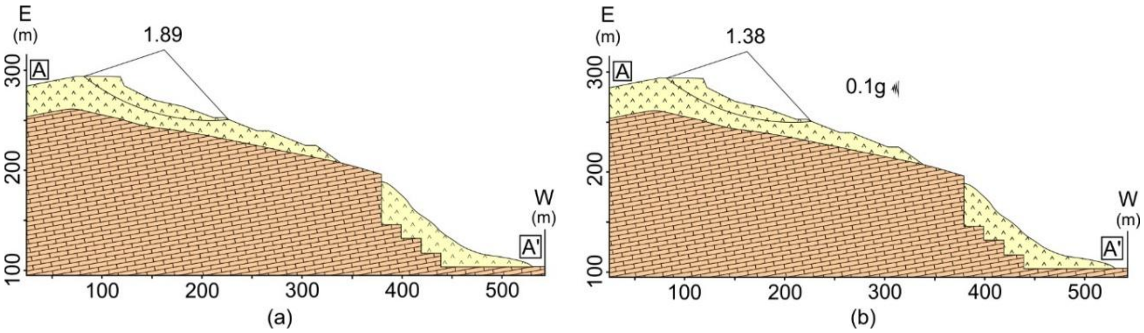

Fig. 6. Stability analyses with (a) and without (b) seismic effect for the new slope geometry

5. Conclusion

Stability of a slope in a quarry in Ordu city has been investigated and limit equilibrium analyses for the post-shear state and future production were carried out using Rocscience Slide®6 software. Slope stability analyses have indicated that there is a landslide risk with the post-shear geometry of the slope along one of the cross-sections near the heel, where factor of safety drops to values as low as 0.8 for pseudo-seismic condition. To implement stability of the slope during the relocation of the displaced material and production in the quarry, new stable slope geometry has been designed. The stability analyses for the new design proved that the slope will remain stable, even in the event of an earthquake. The new slope design was applied to the slope in recent years, and no implications of a mass movement have been observed as of today (Fig. 7).

(a)

(b)

Fig. 7. The view of the slope before (a) and after (b) the remediation studies

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