Assessment of kinematic rock slope failures in Mudurnu Valley, Turkey

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Abstract. Slope instabilities are one of the most frequent natural hazards capable of causing severe failures both at regional and large scales. Mudurnu, which is settled on a steep valley, is affected by regional rock slope instabilities. These instabilities constitute a hazard and create an important risk to the community since they threaten human lives, settlement areas, and historically-important structures. In order to minimize the hazard and risk associated with slope instabilities, rock masses along the valley were characterized and the potential failure mechanisms were defined. The west side of the valley, which is the focus of the research, is characterized by Cretaceous pelagic discontinuous limestone, and is prone to complex failures. The aim of the study is to characterize the rock mass along the valley, divide the area into geomechanically-uniform sectors, define possible modes of failure (kinematics) and ultimately quantify the potential failure (kinetics) and the associated risk. For the study, in addition to the field work and scan-line survey measurements, an Unmanned Aerial Vehicle (UAV) was utilized to collect high-resolution images from problematic locations that were not accessible. Then, a point cloud of the area was generated. The images were interpreted and the resulting structural representation of the rock mass was compared with information gathered from the scan-line survey in the field. Afterwards, it was used to identify the possible modes of failure along the valley. Since seismic activity in the area is significant due to the proximity of the North Anatolian Fault Zone (NAFZ), which is the most active fault system in Turkey, dynamic loading was also considered for the stability analyses.

1. Introduction

Mudurnu is a county of Bolu province located in northwestern Turkey. It is an important midpoint between the capital city, Ankara, and the largest city in the country, İstanbul (figure 1). The county center is located in a valley that suffers from regional rock instabilities both in the west and east sides of the valley. The instabilities are the result of the combined effect of geology, topography, weathering, human-made activities and seismicity. The total population of the county is 18.880 and the number of people who live in the county seat is 5.132 [1]. According to the inventory of Mudurnu Municipality, 84 of the damaging hazards that occurred between 1961 and 2016 were caused by rockfalls and mass movements due to precipitation, weathering and secondary effects of earthquakes. The valley can be defined as a high-risk region, given the slope instability casualties that have occurred in the past and those that have the potential to occur. The instabilities throughout the valley threaten human lives,

houses, buildings and small industrial facilities. Moreover, instabilities create a risk for the historically important structures located in Mudurnu such as mansions, historical mosques and a Turkish bath from Ottoman period, and a wooden clock tower by which Mudurnu has been nominated as a candidate for the UNESCO World Heritage.
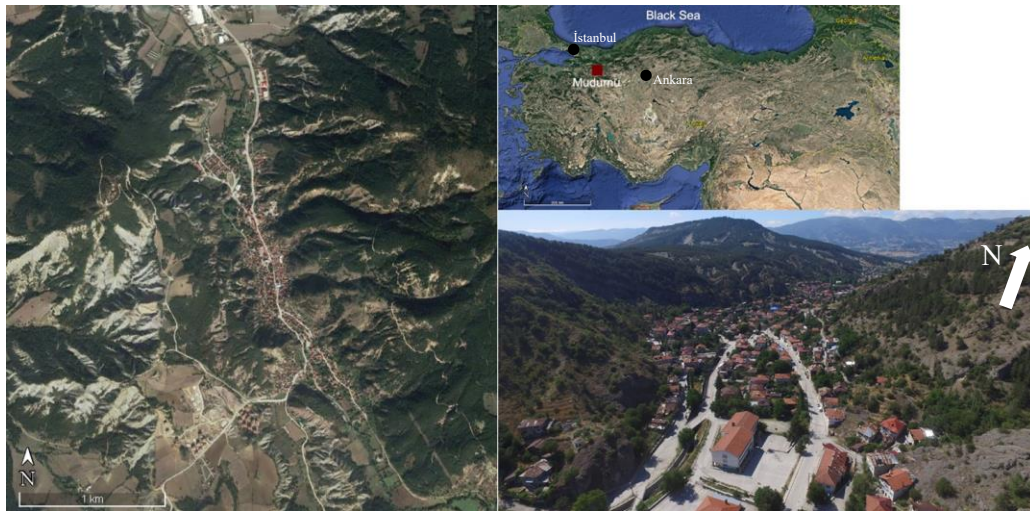

Figure 1. Location of Mudurnu and the general view of Mudurnu Valley.

The slopes of the valley are prone to instability through modes of failure that are different in the west and east sides, as a result of the different rock mass properties. This makes Mudurnu an attractive and distinctive site to investigate rock mass failure. On the east side of the valley, the Mudurnu formation outcrops as volcanoclastic sandstone that is prone to rock falls. Volcanoclastic blocks are held in place by a less durable matrix which has low strength. As a result, the matrix decomposes due to weathering and the rock blocks fall. The discontinuous limestone found on the west side of the study area belongs to the Late Cretaceous Değirmenözü member of the Yenipazar formation. The discontinuous pelagic limestone creates discontinuity-controlled complex kinematic failures (i.e., a combination of planar, wedge or toppling failures). Because of the geological complexity of the site and the distinct instability mechanisms identified, it is imperative to characterize the rock mass at the site.

The purpose of this research is to characterize the rock masses that create the hazards through geomechanical evaluation of the slope instability problems under static and dynamic conditions in the Mudurnu Valley with a focus towards the west side of the valley. The engineering geological and geomechanical properties of the region were assessed through a 3D point cloud generated by an unmanned aerial vehicle. The data were evaluated statistically to define the discontinuous rock mass characteristics and failure modes.

2. General geological and tectonic settings

Geological units that outcrop in the Mudurnu county center are Quaternary alluvium, Cretaceous Yenipazar formation and Jurassic Mudurnu formation [2]. The Middle-Upper Jurassic Mudurnu formation is a flysch-like unit which is composed of tuff and volcanoclastic sandstone, agglomerate and shale. The Mudurnu formation outcrops as volcanoclastic sandstone on the east side of the valley. The discontinuous limestone found on the west side of the study area belongs to the Late Cretaceous Değirmenözü member of the Yenipazar formation.

The study area is in a tectonically active region as a consequence of one of the most important seismically active zones of Turkey, namely the North Anatolian Fault Zone (NAFZ) (figure 2). The NAFZ is a right lateral strike-slip fault with a length of approximately 1500 km. Nine destructive earthquakes have been recorded during the historical period (B.C. 2100-1900) [3] and six destructive

earthquakes have been recorded during the instrumental period in the vicinity of the region of interest. Since Mudurnu is in a tectonically active area, the rock mass formations have been highly altered by the seismicity. As a result, faulting and folding processes have formed discontinuity sets that have led to nonhomogeneous rock masses. The effect of seismic activity in the study area was considered by expected ground acceleration which was defined in [4, 5]
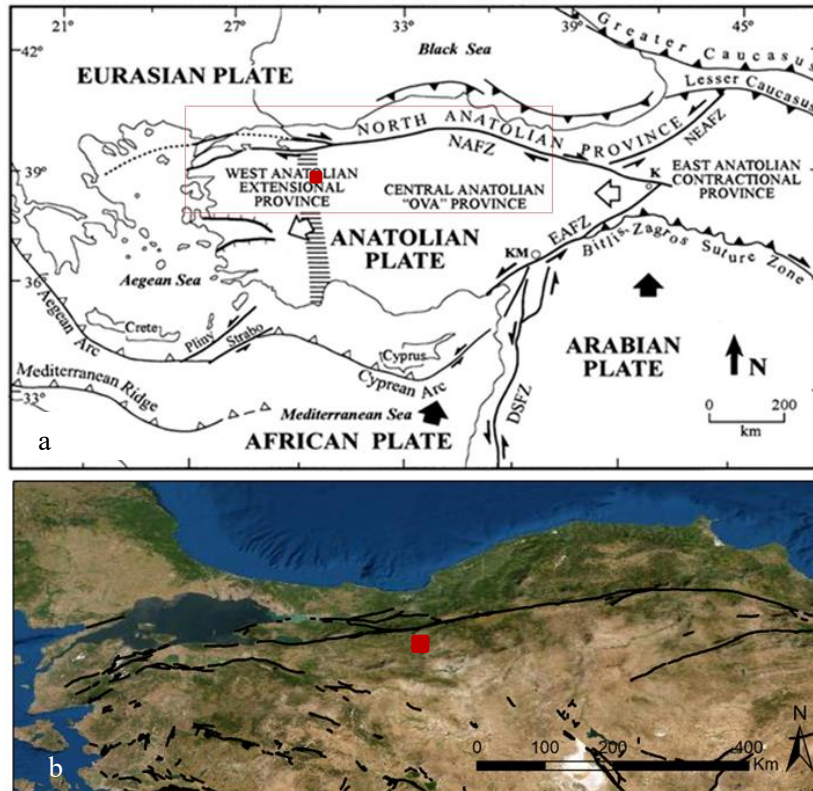

Figure 2. a) Simplified neotectonic map of Turkey [6], b) Close-up view of the rectangle given in figure 2a displaying the fault zones and segments capable of affecting Mudurnu.

3. Methodology

The focus of this study was the valley slopes on the west side of Mudurnu. The methodology that has been followed to evaluate the geological units, structures, discontinuities and their distribution in the area can be briefly described as follows. First, the morphology and geology of the area, which were examined based on an extensive literature review and preliminary field studies were defined. Second, field investigation studies and scan-line survey measurements were completed. Discontinuity properties proposed in [7] were investigated carefully by scan-line surveys in the accessible locations which were performed by fixing a 5 m long measuring tape to the rock face (figure 3). As mentioned earlier, the unit that outcrops in the valley is pelagic limestone. It is pinkish gray to light gray in color (figure 3). In the study area, the scan-line surveys revealed that there were three discontinuity sets: a bedding plane (BP) and two discontinuity sets (J1 and J2). The discontinuity sets had strong to very strong strengths according to field identification [7] and the Schmidt hammer rebound values [8]. In general, the limestone was slightly weathered to moderately weathered in several locations. The discontinuities were described as undulating rough to undulating smooth, and the apertures were classified as open (0.5-2.5 mm) in general, but there were very tight and moderately wide surfaces as well. Clay and silty clay infillings were observed in the apertures. The discontinuities were close to moderately spaced, in

general. Persistence was high. Water leakage was not observed during the field work but color changes were detected in several places. It was expected that surface water would have an effect on the rock masses due to the rate of annual precipitation (mean annual precipitation of 571 mm) in the area [9].

Figure 3. a) A view of discontinuous limestone, b) A photo taken during scan-line survey studies.

In addition to the scan-line surveys, digital images of the area were collected by an Unmanned Aerial Vehicle (UAV) and then a 3D point cloud of the area was generated. This step was crucial because a significant part of the slopes was inaccessible as a result of the steep topography. However, due to the highly irregular and non-homogenous nature of the rock masses, a detailed investigation was necessary. This need was fulfilled by utilizing high-resolution images followed by generating surface models and a point cloud. The point cloud, together with the field observations, was analyzed through the division of the west side of the Mudurnu valley into 11 different sectors of similar rock mass characteristics and discontinuity orientations (figure 4). However, since the rock mass characteristics included significant uncertainty, the determination of representative mechanical values of the rock mass for stability analysis was challenging. The uncertainty of the rock mass properties was addressed through a probabilistic analysis, where the rock properties were obtained from the statistical evaluation of the available data. For this purpose, a detailed statistical characterization study was conducted by utilizing the point cloud. Statistical distributions were obtained for the orientation, spacing and persistence of all joint sets. The Discontinuity Set Extractor (DSE) method was utilized for the identification of the discontinuity set orientations, where changes in joint orientation were evaluated by obtaining the distribution of orientations for each discontinuity set [10]. The DSE is a semi-automatic identification tool of the planar features of a rock mass from 3D point cloud data. In the method, the discontinuity sets were identified by calculation of the local curvature of normal vectors, statistical analysis of discontinuity poles and cluster analysis. For the determination of spacing and persistence distributions, the DSE method uses the previously analyzed point cloud data used to identify discontinuity sets and clusters. The DSE method calculates the normal spacing between a given plane and a plane closest to it, through 3D relationships [11]. For persistence, a co-planarity test was applied to the clusters. Based on the results from the co-planarity check, the cluster parameters were modified and the clusters were merged. Then, persistence measurements were made by a transformation matrix [12]. Afterwards, the results were compared with the field survey measurements of the physically accessible locations to validate the DSE results. Validation was done in Sectors 2, 6, 8 and 10. The results obtained with the DSE were comparable with those extracted from the field observations, suggesting that the DSE results were reliable and, hence, utilization of DSE to extract discontinuity properties in inaccessible sectors was justified. As a result of the analyses described, several sectors were merged and a total of 7 geomechanically-uniform sectors were identified. Finally, kinematic analyses of the sectors revealed that planar, wedge and toppling failures were possible. In the area, it was previously determined that Joint Set-1 (J1) causes planar failures, intersection of Joint Set-1 (J1) and Joint-Set 2 (J2) creates wedge failures and the Bedding Plane (BP) could produce toppling failures [9]. Toppling failures were

associated with blocks of small size, but planar and wedge failures could produce very large unstable blocks. This is the reason why planar and wedge failures are very critical in the region.

Figure 4. Geomechanical sectors defined as a result of a detailed evaluation of the rock mass characteristics

4. Possible failure mechanisms of Sector 8

The focus of the paper is on Sector 8 as a representative high risk example, albeit the methodology and work done to the entire valley. Statistical distributions of the discontinuity characteristics were evaluated in addition to the scan-line survey measurements and field observations. As discussed, the point cloud was used with the DSE method. The discontinuity sets identified with the DSE for Sector 8 are given in figure 5, where each set is represented by a different color. The discontinuity set orientations were 255°/44°, 083°/79° and 141°/80° for the Bedding Plane, Joint Set-1 and Joint Set-2, respectively. The two pairs of numbers provide, in that order, the dip direction and the dip angle.

The discontinuity spacing and persistence distributions were also obtained with the DSE method. The spacing was found to be log-normally distributed. The probability density functions of each set are given in figure 6. The BP spacing has a maximum value of 1.13 m, with a mean value of 0.46 m and standard deviation of 0.28 m. The maximum spacing of J1 was 2.66 m, the distribution had a mean value of 0.77 m and standard deviation of 0.52 m. J2 had a mean value of 0.95 m and standard deviation of 0.51 m where the maximum spacing is 2.22 m. The persistence measurements of Sector 8 are given in figure 7. Table 1 summarizes the values obtained by scan-line survey and DSE method. The results show that the discontinuity sets are persistent and the persistence is limited by the length of the studied sectors.
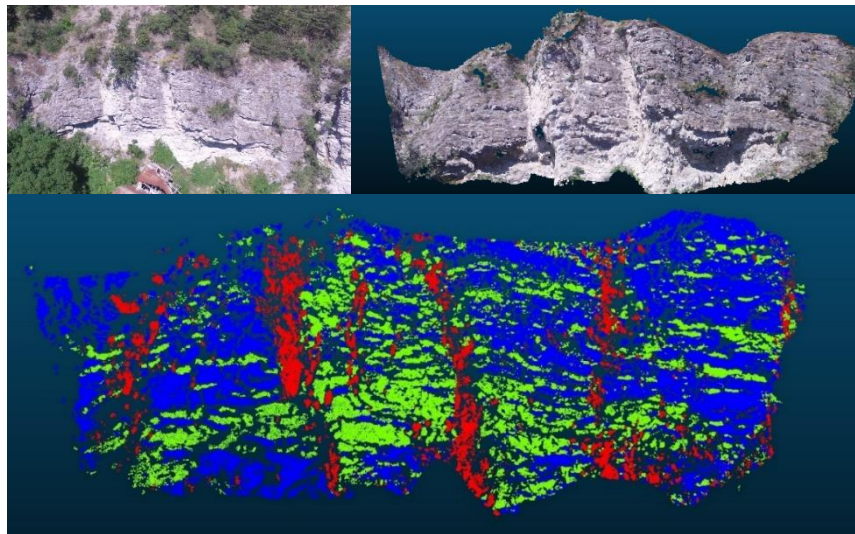
Figure 5. Discontinuity sets and orientations of Sector 8 identified by utilizing DSE.
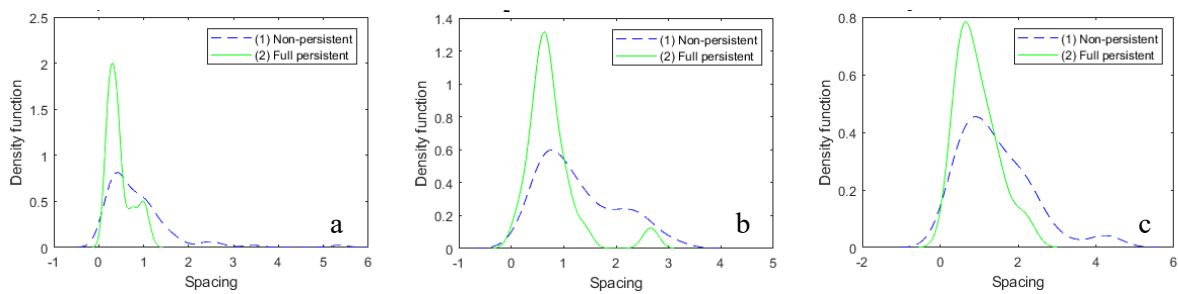

Figure 6. Density function of spacing of a) BP, b) J1 and c) J2 for Sector 8.
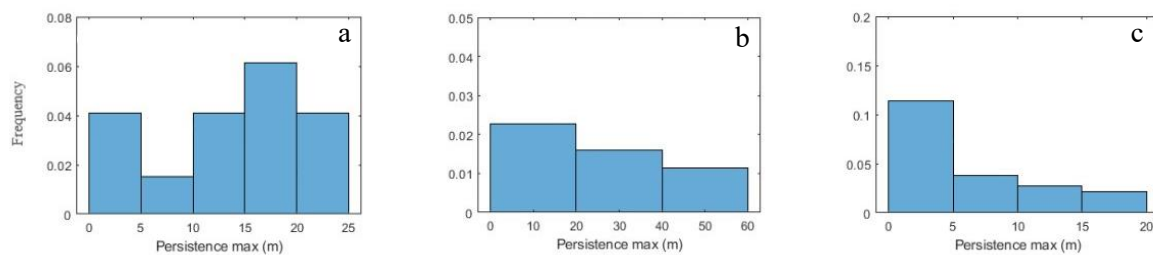

Figure 7. Maximum persistence of a) BP, b) J1 and c) J2 for Sector 8.

Table 1. Summary table for discontinuity characteristics of Sector 8

Method	Scan-line field survey			DSE		
Discontinuity Characteristic	Orientation (dip direction/ dip amount)	Spacing (mm)	Persistence (m)	Orientation (dip direction/ dip amount)	Spacing (mm)	Persistence (m)
BP	244°/38°	100-650	0.05-0.3	255°/44°	140-1113 (460)	0.32-24.0 (13.6)
J1	075°/69°	80-900	0.21-1.0	083°/79°	110-2660 (770)	0.23-44.0 (22)
J2	163°/84°	210-1100	0.08-1.0	141°/80°	260-2222 (950)	0.09-16.0(5.5)

Stability analyses were performed by determining a failure criterion and the strength parameters. The mechanical behavior of natural rock joints can be estimated using the Eqn. (1) [13]:

$$\tau = \sigma_n \tan\left(\phi_r + JRC \log_{10}\left(\frac{JCS}{\sigma_n}\right)\right) \tag{1}$$

where JRC is the joint roughness coefficient, JCS is the joint wall compressive strength, ϕ_r is the residual friction angle and σ_n is the normal stress. The joint roughness coefficient was estimated for each discontinuity set in the field by observing the shape and waviness of the discontinuity surface, and by comparing the surface with the standard profiles defined by [13]. The discontinuity surfaces were classified as undulating rough. The Schmidt hammer test was used to estimate the strength of discontinuity surfaces. According to the method proposed by [8], the uniaxial compressive strength of BP, J1 and J2 were 100 MPa, 140 MPa, 130 MPa, respectively. These values were in good agreement with the strengths estimated using the ISRM rock material strength for field identification [7]. The rock material was classified as strong (Grade R4, compressive strength=50-100 MPa) to very strong rock (Grade R5, compressive strength=100-250 MPa) according to [7]. The values obtained from the field were corrected using the equations proposed by [14] to account for scale effects. It has to be noted that, due to the inherent variability of the natural rock masses, the friction angle estimates using Eqn. (1) could have a significant amount of uncertainty.

Further estimates of the friction angles of the discontinuities in Sector 8 were done through back analysis of failures observed in the field [15]. The blocks identified for the back analysis are shown in figure 8. Those were wedge failures along the joints J1 and J2. The friction angles estimated from the back analysis were 43° and 45° for J1 and J2, respectively. The friction angles obtained from Eqn. (1) for J1 and J2 were 45° and 49°.

Figure 8. Blocks identified in Sector 8 for back analysis.

The shear strength parameters for the identified blocks given in figure 8 were obtained by using SWedge software [16] for the wedge type of failure where the blocks slide along the line of intersection of J1 and J2. After that, by using the estimated strength parameters, the Factor of Safety for both static and dynamic conditions were calculated. A design Factor of Safety of 1.8 and 1.1 were assumed for static and dynamic conditions, respectively. To evaluate dynamic condition in the stability analysis, the horizontal seismic load coefficient estimated was 0.24g according to Turkish Building Earthquake Code [4, 5]. The support force required to ensure these Factor of Safety values for Sector 8 was determined as 9.85 kPa per unit volume of the wedges.

5. Conclusions

The objective of the study was to characterize the rock mass along the Mudurnu valley, divide the area into geomechanically-uniform sectors, define possible modes of failure (kinematically admissible failures) and ultimately quantify the potential failure (kinetic analyses) and the associated risk. All data collected from different sources, namely technical literature, reports, field observations, scan-line survey

measurements, images, point cloud, surface models and cross-sections were combined to define 11 geomechanical sectors on the west side of the valley. Then, kinematically possible failure modes were identified. Identification and characterization of discontinuity set orientation, spacing and persistence were completed using the point cloud data to obtain a statistical distribution of the rock mass properties. Based on this information, the spatial distribution of the sectors on the valley was re-assessed, resulting in merging sectors that possessed similar rock mass characteristics. A total of 7 uniform sectors were identified. Given that discontinuity-controlled failures were present on the west side of the valley, the failure criterion suggested by [13] was used. Two different approaches were used to estimate the friction angles of the three discontinuity sets identified: empirically, by estimating JRC and JCS by two different independent methods. The first method used was field data, where values of JRC and JCS for each discontinuity; and by back calculation of identified wedge failures. The two approaches yielded similar results, which provided confidence in the field data and overall computation methods. Finally, the support force required for stability was calculated for both static and dynamic conditions.

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