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RHEOLOGICAL ANALYSIS OF A SUB-MARINE LANDSLIDE IN THE MARMARA SEA (TURKEY)

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Abstract: When seismic and multi-beam bathymetric data from the northern shelf and slope of the Cinarcik Basin are interpreted, some sub-marine landslides are observed clearly. Additionally, seismic data indicate that upper surface of the submarine extension of the Paleozoic aged rocks has NNE-SSW oriented basin and ridge type morphology controlled by the secondary faults of the NAFZ. Basins are fulfilled by Plio-Quaternary sediments, which are cut by strike-slif faults on the shelf and slope. Thickness of these deposits increases up to 130 m toward the concave shaped northern slope of the Cinarcik Basin. A relatively recent sub-marine landslide, Tuzla Sub-marine Landslide, cuts the concave slope of the Cinarcik Basin. Detailed morphological investigation indicate that Tuzla Landslide is a deep-seated rotational landslide, which possibly triggered by the NAFZ. Morphological analyses also indicate that thick Plio-Quaternary deposits on the Paleozoic Basement were slided during the Tuzla Landslide event. This landslide is considered as a key event for modeling the future landslide potential of the northern shelf and slope of the Cinarcik Basin. For this reason, the main purpose of the present study is to perform some rheological analyses to understand the behaviour of the events. As the main results obtained from the analyses, the runout distances and the velocities were calculated.

Keywords: earthquake, sub-marine landslide, the Marmara Sea, rheology

1. Introduction

The Marmara Sea and its straits (Strait of Istanbul and Strait of Canakkale) locating in the NW Turkey separate the Thrace and Anatolia peninsulas (Fig. 1). This waterway constitutes the unique connection between the Black Sea and the Mediterranean. The Marmara Sea consists of a highly complex morphology including shelves, slopes, basins, sub-basins and ridges. Shelf areas appear at the southern and northern sides of the Marmara Sea. This very complicated basin-ridge system is called as Marmara Trough indicating that this very complicated morphology of the Marmara Sea is strongly related with the E-W oriented northern segment of the North Anatolian Fault Zone (NS-NAFZ) in the Marmara Sea.

Gazioglu et al. (2005) reviewed the submarine-landslides in the Marmara Sea, which were previously observed by Gazioglu et al. (2002), and Gokasan et al. (2002 and 2003), and they suggested that five major sub-marine landslides existed in the Marmara Sea. The most impressive one of these landslides was observed at the northeastern corner of the Cinarcik Basin, named as Tuzla Sub-marine Landslide (Gazioglu et al., 2002; Fig. 2). Gazioglu et al. (2002) estimated that the surface area of this amphi-theatre-shaped landslide is approximately 8 km^2 and slope failure originates in water depth about 700 m, with an average inclination of 17º and terminates at about 1140 m. Authors suggested that displaced material has disintegrated with highly steep outcrops, thus, the type of Tuzla Landslide may be a rotational slide (slump). Occurrence of Tuzla Landslide is possibly related with the activity of the NAFZ (Gazioglu et al., 2002). On seismic profiles from the northern shelf and slope of the Cinarcik Basin, Tur (2007) clearly indicated existence of a relatively thick Plio-Quaternary deposit overlying the Paleozoic Basement, which was cut by several secondary faults of the NAFZ (Fig. 3a and 3b). This condition may provide future occurrence of sub-marine slides on the slopes of the Marmara Sea.

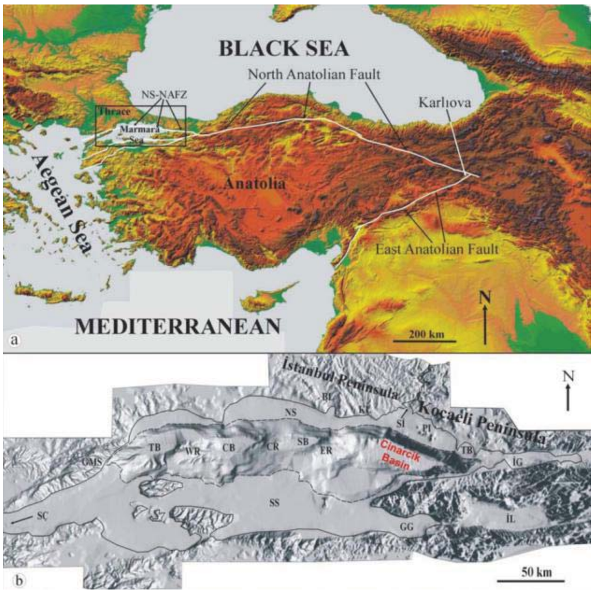

Fig. 1. Location maps of the study area. a) Location of the Marmara Sea and major faults on digital elevation model of the Anatolia and surrounding areas. b) Detail digital elevation model of the Marmara Sea produced by multi-beam and single-beam bathymetric and digital topographic data (modified from Gazioglu et al., 2002). Thin dashed line indicates the Marmara Trough, and dashed rectangular area is the study area focused in this study. AP=Armutlu Peninsula, GI=Gulf of Izmit, SB=Silivri-or Kumburgaz- Basin, CB=Central Basin, TB=Tekirdağ Basin, ER=Eastern Ridge, CR=Central Ridge, GMS=Ganos Mountain System, WR=Western Ridge NS=Northern Shelf, SS=Southern Shelf, GS= Gulf of Saros, PI=Prince Island, BL=Buyukcekmece Lagoon, KL=Küçükçekmece Lagoon, TP=Tuzla Promontory, TL=Tuzla Landslide, GG=Gulf of Gemlik, IL= Iznik Lake, SC=Strait of Canakkale (Dardanelles), SI= Strait of Istanbul (Bosphorus) (Gokceoglu et al., 2009).

In this study, we focused on the rheological analysis of the sub-marine landsides of the northern slope-shelf area of the Cinarcik Basin. Existence of thick sediment deposits on the shelf, and occurrence of the Tuzla Landslide in history of the slope implied that this area has a high landslide potential in the future. Thus, we believe that this place is a case area for understanding the previous and future landslide occurrence in the Marmara Sea. For this purpose, northern slope and shelf area of the Cinarcik Basin are analyzed rheologically. During the analyse stage, possible volumes of slide materials are estimated due to their lithology and possible slide surfaces. This interpretation probably provides to make better determination of source mechanism and more realistic tsunami models.

2. Materials and Methods

The seismic data (Fig. 4) were collected by the Turkish Navy, Department of Navigation, Hydrography and Oceanography (TN-DNHO) during the cruises in 1988, 1995, and 2004. The seismic sections displayed in the figures have about 10 times vertical exaggeration. Parts of the seismic data were studied by Demirbag et al. (1994), Oktay et al. (2002), Eris et al. (2007), and Tur et al. (2007) in tectonic and sedimentologic sense. Tur (2007) prepared a paleo-topographic map illustrating the upper surface of the Paleozoic rocks, and a sediment thickness map of the basin deposits from the Tuzla Bay to the Marmara Sea entrance of the Strait of Istanbul. Multi-beam bathymetric data (Fig. 4) were also collected by TN-DNHO in 1999 and 2005 cruises. Digital Elevation Models were generated from multi-beam data with Erdas Imagine and Arc View softwares. Part of these data was previously used by Tur (2007).

In order to forecast the characteristics of a grain-fluid mixture, it is, therefore, necessary to start with the determination of its rheological properties. A number of rheological models have been proposed, including Bingham, Herschel-Bulkley, and bilinear rheologies of viscoplastic fluids. Several researchers have studied on the behaviour of grain-fluid mixtures. O'Brien and Julien (1988) investigated physical properties of natural mudflow deposits which consist of silt and clay, by rotational viscometer. They depicted the Bingham model to describe the rheology of mudflows. Major and Pierson (1992) measured the rheology of slurries consisting of ≤2 mm sediment from a natural de-

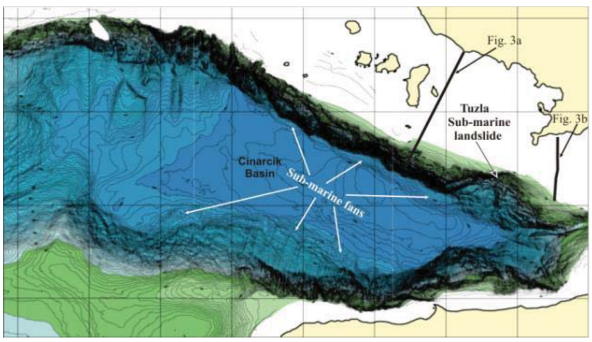

Fig. 2. Sub-marine fans constituting the continental ridge along the Cinarcik Basin and the sub-marine landslide subjected in this study on the northern slope of the basin on digital elevation model (modified from Rangin et al., 2001). Lines indicate the seismic profiles on Fig. 3 (Gokceoglu et al., 2009).

bris flow deposit by using a wide-gap concentric-cylinder viscometer. They found that at shear rates above 5 s^{-1} the behavior approached the Bingham model; below 5 s^{-1}, sand exerted more influence and slurry behaviour deviated from Bingham idealization. Imran et al. (2001b) improved a 1D numerical model of muddy debris flows in subaerial and subaqueous environment. This version incorporates the Herschel-Bulkley, and bilinear rheologies of viscoplastic fluids. The more familiar Bingham model is integrated into the Herschel-Bulkley rheological model. Bilinear model, developed by Locat (1997), is verified by comparing with experimental data of O'Brien and Julien (1988). It showed that a good match the rheology of silt and clay mixtures (Fig. 5). Marr et al. (2002) observed differences in debris flow runout distance on the Isfjorden and Bear Island fans. The subaqueous debris flows are composed primarily of silt and clay with some sand. They assumed that the Bingham model was the best suitable rheological model for these debris flows. When the fine and clay fraction (d<40 μm) constitutes 10% of the grain size distribution, the material is classified as muddy debris (Bin et al., 2000). In addition, sediment concentration and composition play a key role in the choice of a rheological model (Franzi, 2000). Locat et al. (2004) investigated the mobility of the Palos Verdes debris avalanche by numerical analysis. They assumed that the debris flow rheology can be approximated by bilinear model. They obtained the peak front velocity, distance from slope break and depositional thickness of debris avalanche by BING model.

During the Marnaut expedition in the Sea of Marmara, Gorur et al. (2008) performed a number of dives with submersible Nautile. Their main objective was to investigate the stratigraphy of the rocks cropping out on the NAFZ scarp in the Marmara Sea. They observed on the dive traverse rocks belonging to the Palaeozoic of Istanbul. Also, they

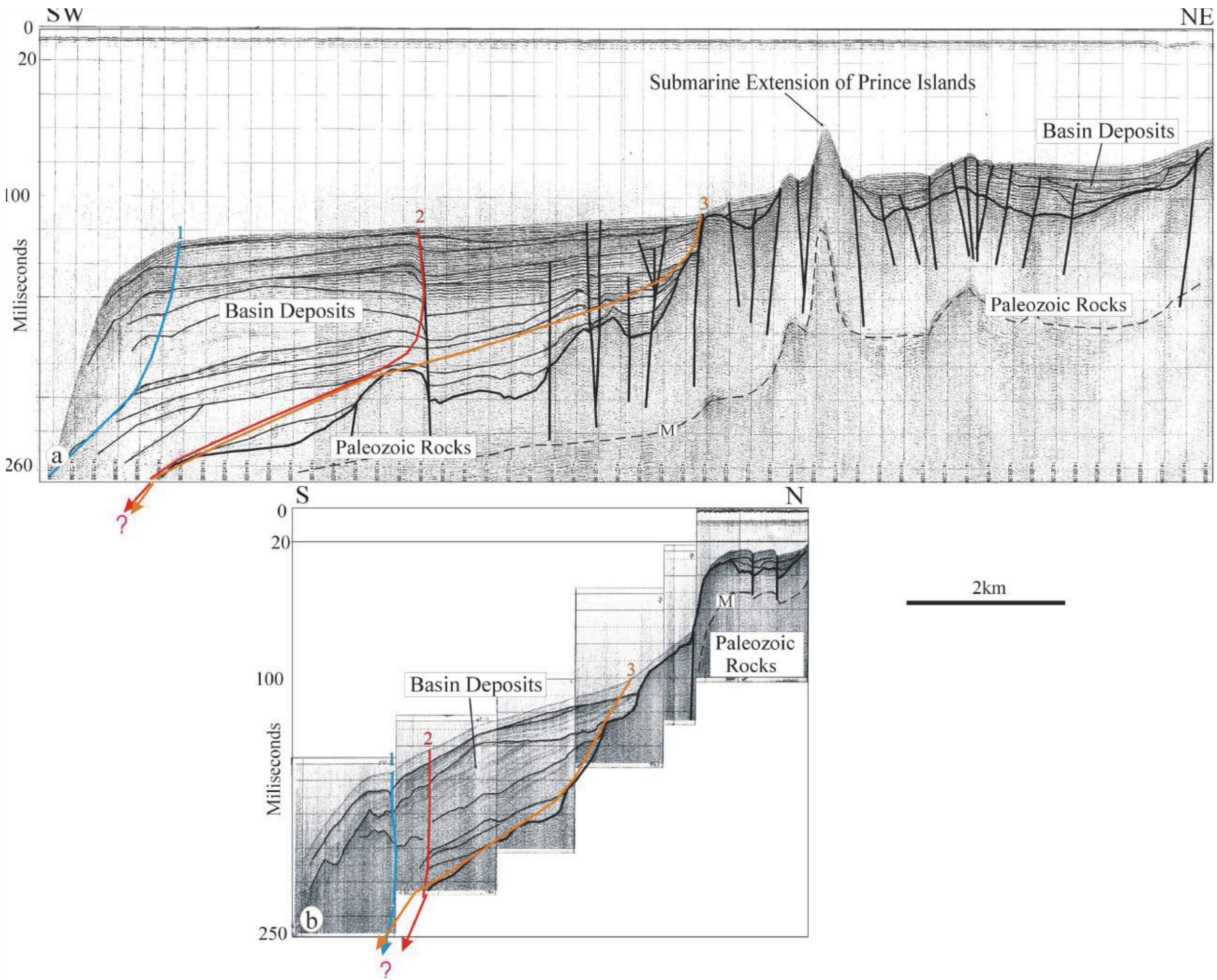

Fig. 3. a-b) Interpreted seismic profiles from the eastern portion of the northern shelf (modified from Tur, 2007). Colour lines 1, 2, and 3 are potential slip surfaces of future submarine landslides. M=Multiple, (Gokceoglu et al., 2009).

founded that these rocks forms a steep scarp with beds dipping mainly toward the southern with an angle of approximately 60 degrees. Sampling of the outcrop revealed that they are made up of dark grey to black and thinly to medium bedded shale and carbonates. Ergin and Sakitas (2008) investigated sediment samples which were taken at 4 stations using free fall gravity cores on the slopes of the Cinarcik basin by onboard the R/V MTA Sismik-1. In core 2 off Yalova where is this study location, grayish-dark green mud predominates. Sediments contain 90-100 % mud (silt and clay) and sand and gravel portions do not exceed 10 %. For this reason, we assumed that these sediments could consist of clayey silt or silt mixtures. In our anaylsis, based on the findings discussed above, we decided to analyze the rheological properties of the potential submarine landslides of the northern slope shelf area of the Cinarcik Basin by a bilinear rheological model.

3. Submarine Geomorphology of the Study Area

The main geomorphologic units of the study area consist of shelf, abyssal plain and a continental slope connecting the shelf and abyssal plain (Fig. 6). The Tuzla submarine landslide developed the area between continental shelf and abyssal plain and it deformed the morphology and the aspect of the northern slope of the Cinarcik Basin. The eastern and western neighbor slopes of the landslide are similar since their average slope angles resemble, and these slopes were classified as steep continental slopes. This indicates that the slope was unique before the Tuzla Landslide.

Morphology of the Tuzla Landslide is represented by convexity on the upper part of the slope and hummocky topography where the mass of the landslide deposited. Slope morphology indicates that the Tuzla submarine landslide is probably a deep-seated rotational failure. For this reason, this landslide should have been controlled by a deep discontinuity surface, such as a fault rupture, as well as submarine processes. In fact, Tur (2007) observed some NW-SE oriented strike-slip faults cutting the northern shelf and slope area of the Cinarcik Basin extending to the Tuzla Landslide (Fig. 7).

4. Rheological Analysis

In order to analyze of the post failure stage of the Cinarcik Basin (Figure 8a), the BING model was used. The one dimensional flow dynamics model

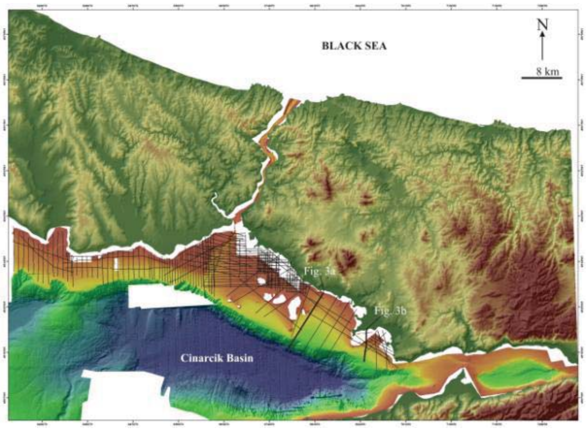

Fig. 4. Locations of the seismic profiles on the northern shelf of the Marmara Sea (Gokceoglu et al., 2009).

BING is developed for simulating the flow of submarine debris flows by Imran et al. (2001a). The model incorporates the Bingham, Herschel-Bulkley, and bilinear rheologies of viscoplastic fluids. However, to run this model, the parameters of yield strength, strain rate and ratio of strain rate parameters are needed. For this reason, for the direct calculation of the yield strength in debris flows, Johnson's formula (1970) was used;

$$\tau_{ya} = H_f \gamma' \sin \beta_f \qquad (1)$$

where γ' corresponds to the buoyant unit weight of the debris flow mixture. Thickness of the depositional area (H_f) and various slope angles (β_f) were calculated from cross-section (Figure 8b). Crosta (1984), distinguishes an intermediate type of flow called "hyperconcentrated flow", with densities of 1.3-1.8 g/cm^3 (12.75-17.65 kN/m^3). Therefore, unit weight of the material is accepted as 15 kN/m^3.
The Johnson's formula (1970) was used by Locat et al. (2004) in the post failure analyse of the Palos Verdes debris avalanche. In this study, Locat et al. (2004)'s approach was used for the parameters of runout distance, depositional thickness, depositional slope angle of the submarine landslide in the Cinarcik Basin were determined using the cross section in Figure 8a. The results obtained from the cross section, runout distance was determined as 5600 m, the depositional thicknesses varied between 10 and 15 m and the average depositional slope angles (β_f) was about 3^0 (Fig. 8b). Using the Eq. 1, average yield strength, τ_{ya}, was calculated for the slope angles of 3^0 (β_f=3^0), and depositional thickness of 10-15 m (H_f=10-15 m) (Fig. 9).

The gray zone in Figure 9 indicates the range of the yield strength for the observed thicknesses varying between 10 and 15 m. Based on this calculation, a yield strength was obtained as 10000 Pa and this value was used in the analyses.

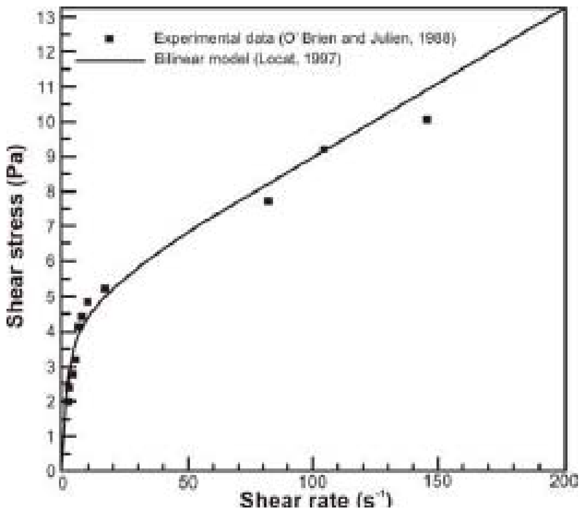

Fig 5. Comparision of bilinear rheological model with experimental data of O'Brien and Julien (1988) (Imran et al., 2001b).

In the second stage of the analyses, to calculate the parameters of strain rate and ratio of strain rate, the BING model was run for the yield strength of 10000 Pa and the unit weigth of 15 kN/m^3. The ratio of strain rate was fixed to 1000, and the strain rate was varied between 0.5 and 1000. During these analyses, the runout distance were investigated (Fig. 10a). Then, the strain rate was fixed and the analyses were repeated (Fig. 10b). The runout distances obtained from both analyses were compared with the landslide in the Cinarcik basin. The main purpose of this comparision is to select the proper input parameters for the BING model.

Results of the seismic studies on the easthern part of the northern shelf area of the Cinarcik Basin were indicated several faults. Plio-Quaternary deposits on the Paleozoic Basement have cut by these faults. Therefore, five cross sections are drawn as these fault systems (Figure 11) and according to submarine landslide, some cross section "west" and some cross section "east" were classified. The submarine-landslides potential of the northern slope-shelf area of the Cinarcik Basin have three different scenarios for the western and eastern parts (Fig. 12). These potential landslide materials are determined with seismological and geographic information system studies (Table 1).

If the strain rate is 1 and ratio of strain rate is 1000, the model produced similar results with the

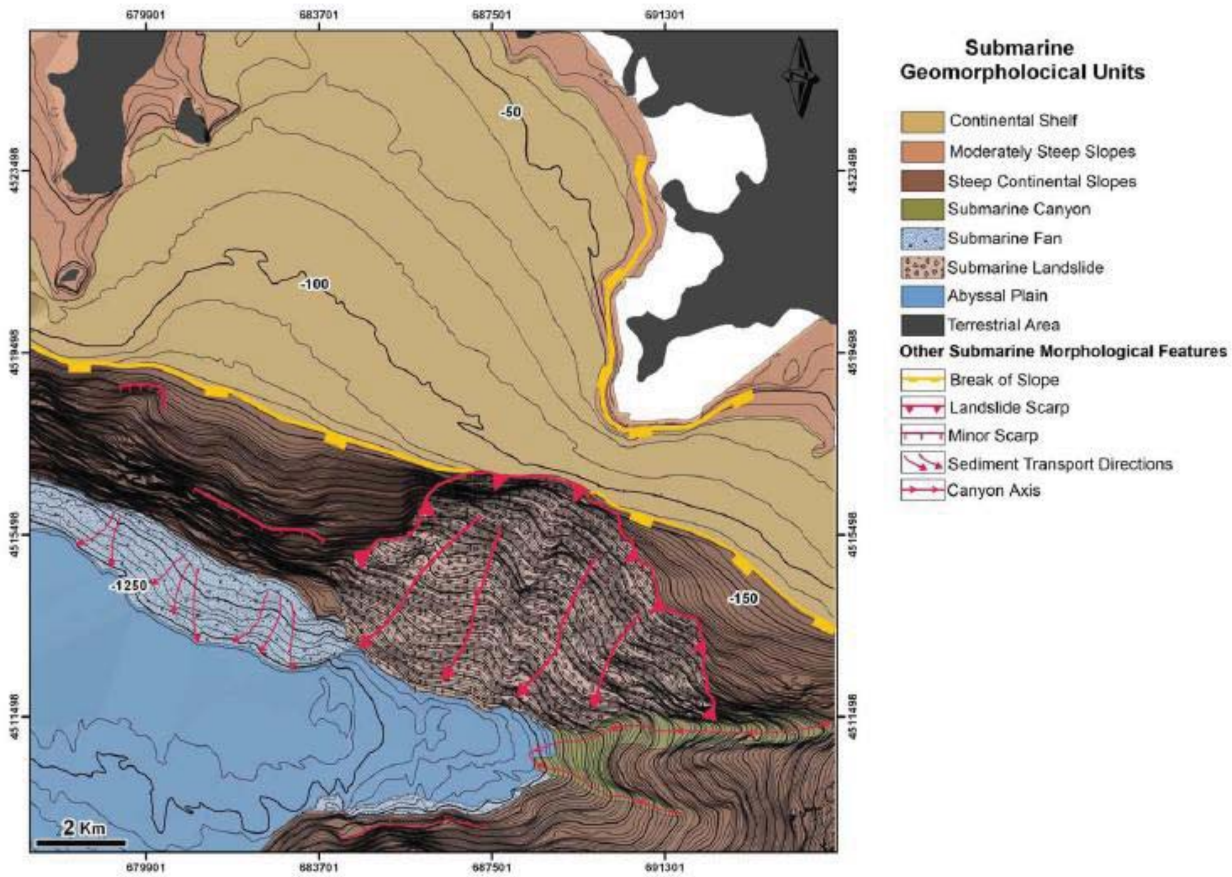

Fig. 6. Sub-marine geomorphological units of the study area (Gokceoglu et al., 2009).

landslide in the Cinarcik basin. As a result of this comparison, the necessary input parameters for the BING model were obtained. Using these inputs, the BING model was run. During the analyses,

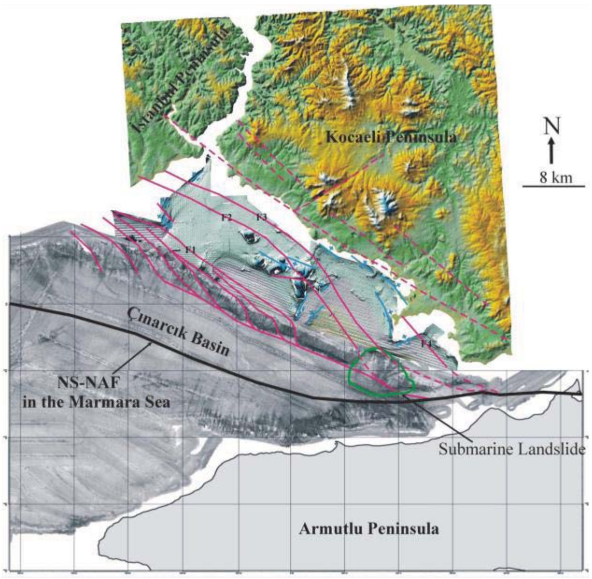

Fig. 7. Potential landslide depletion zones of the study area (Gokceoglu et al., 2009).

three different scenarios for the western and eastern parts of the slopes in the Cinarcik basin were considered (Fig. 13). Consequently, total six different cross-sections were analysed and the results obtained from the analyses were summarized in Table 2.

When making a close inspection on the results obtained from the BING model, peak velocity values for three different scenarios at western parts vary between 12.83 m/s and 14.45 m/s. Depositional thicknesses of west-2 and west-3 scenarios (35.5 m) are greater than west-1 (33.5 m). Peak velocity values for the east scenarios vary between 1.49 m/s and 6.13 m/s while depositional thicknesses of these scenarios are between 29 m and 35 m. Also, it is seen that the runout distance and velocity of the landslides are proportional with the amount of displaced material. The amounts of the possible displaced materials at the western and the eastern parts can be compared (Fig. 14). There is a good accordance between the amounts of the displaced materials, and the runout distances and the thickness of the deposition. The slope angles of the toe of the possible landslide at the western part (60^0-70^0) are higher than those at the eastern part (40^0-50^0) (Fig. 14). Considering the results of the BING model, three maps showing the maximum runout distances were drawn (Fig. 15).

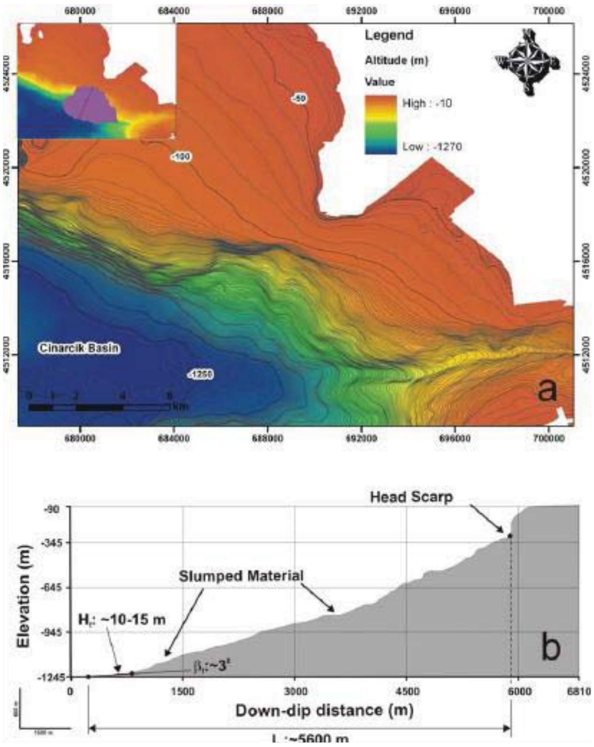

Fig. 8. Multi-beam bathymetric map and cross-sections of the Tuzla sub-marine landslide (see 8a for the locations of cross-sections) (modified from Gokceoglu et al., 2009).

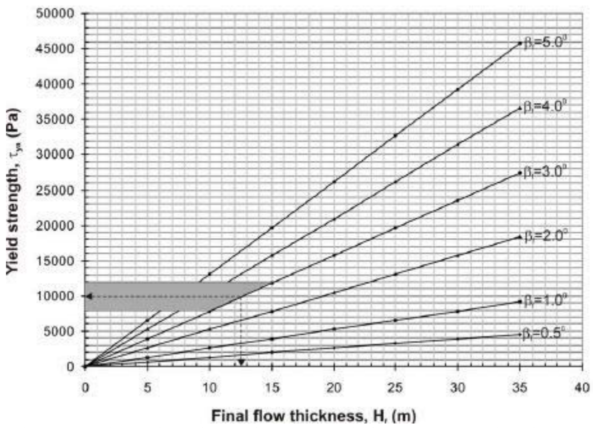

Fig 9. Using the flow deposit thickness (H_f) in the runout zone to estimate the yield strength using the relationship proposed by Johnson (1984).

5. Results and Discussion

Tuzla Landslide is a deep-seated rotational failure and it developed between the northern shelf and abyssal plain of the Cinarcik Basin. Morphological image of this landslide implies that it is very recent formation. The main slide surface of the Tuzla Landslide consists of two convex sub-slopes distinguished by a cape of the submarine extension of Tuzla Promontory consisting of Paleozoic aged

Table 1. Estimation of the potential submarine landslide materials in the Cinarcik basin.

Location of landslides	Surface area (m^2)	Thickness (m)	Volume (m^3)
West-1	15 907 419	98	1 558 927 062
West-2	30 698 026	94	2 885 614 444
West-3	55 645 716	82	4 562 948 712
East-1	6 813 219	38	258 902 322
East-2	13 721 922	50	686 096 100
East-3	26 167 853	60	1 570 071 180

Table 2. The results obtained from the BING model for the possible submarine landslide scenarios

Location of landslides	Peak front velocity (m/s)	Distance from slope break (m)	Runout distance (m)	Depositional thickness (m)
West-1	13.37	5231.25	3311	33.5
West-2	12.83	11141.53	7191	35.5
West-3	14.45	18690.20	11640	35.5
East-1	1.49	2179.04	1129	29
East-2	2.89	5294.70	2814	34
East-3	6.13	8595.75	4820	35

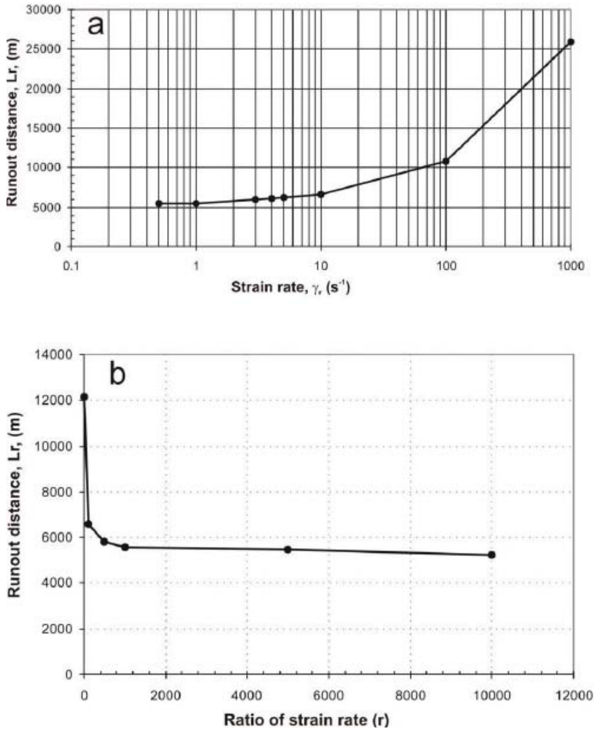

Fig 10. Parametric analysis on the values of the strain rate (γ_r) and the ratio of strain rates (r), using the runout distance L_R for the proper input parameters for the BING model.

rocks. This cape was possibly exhumed by activation of the Tuzla Landslide with sliding of the covering Plio-Quaternary deposits. This scenario implies that the Paleozoic basement may resist to the slidings in the area and sub-marine landslides can only occur in the Plio-Quaternary deposits. Thus, during analyses of the sub-marine landslide models along the northern shelf and slope of the Cinarcik Basin, thick Plio-Quaternary deposits locating on the western and the eastern sides of the Tuzla Landslide were considered as potential sliding areas.

To forecast the post-failure behaviour of the potential landslide scenarios, a series of the bi-linear rheological analyses were performed. Before the bi-linear rheological analyses, the yield strength was determined by considering Johnson's Formula (Johnson, 1970). However, the unit weight of the material was accepted as 15 kN/m^3. In addition, the parameters of strain rate and the ratio of strain rate were obtained by the back-analyses of the Tuzla landslide.

According to the mobility analyses, peak velocity values for six different scenarios change between 1.49 and 14.45 m/s. Depending on increase in the amount of possible displaced material and slope angle, the velocity values also increase. Depositional thicknesses of the different scenarios were obtained as more or less similar although the possible displaced materials of the scenarios were quite different. The main reason for this result is that the runout distances were different.

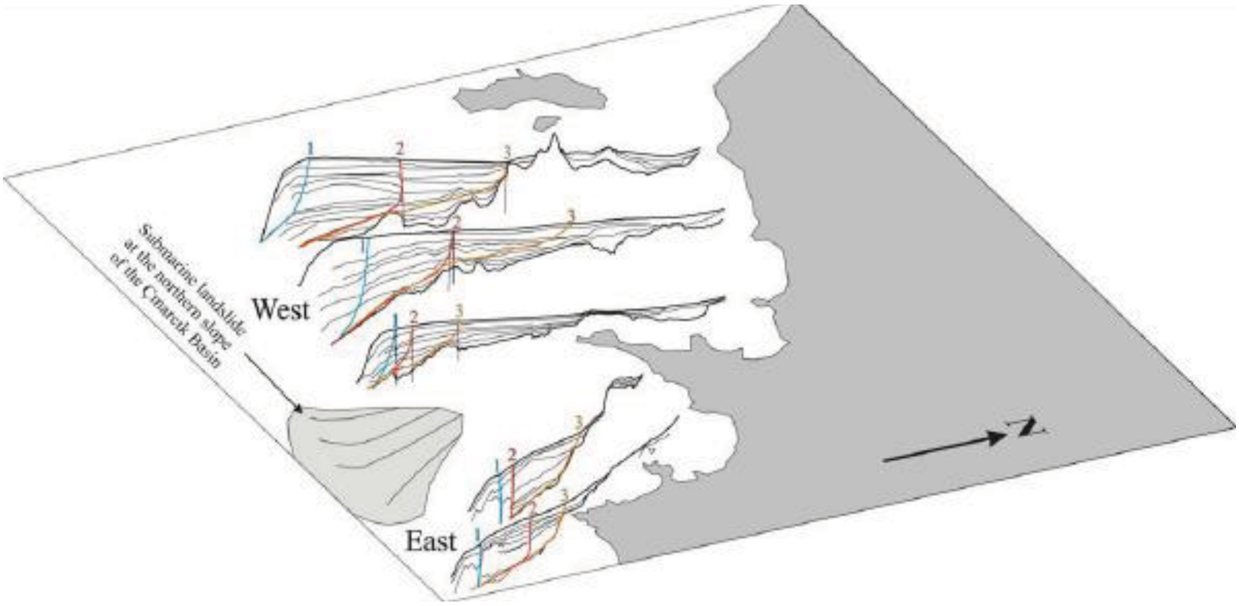

Fig 11. A projection of some seismic profiles from study area showing the geometry of the slip surfaces of potential submarine landslides (Gokceoglu et al., 2009).

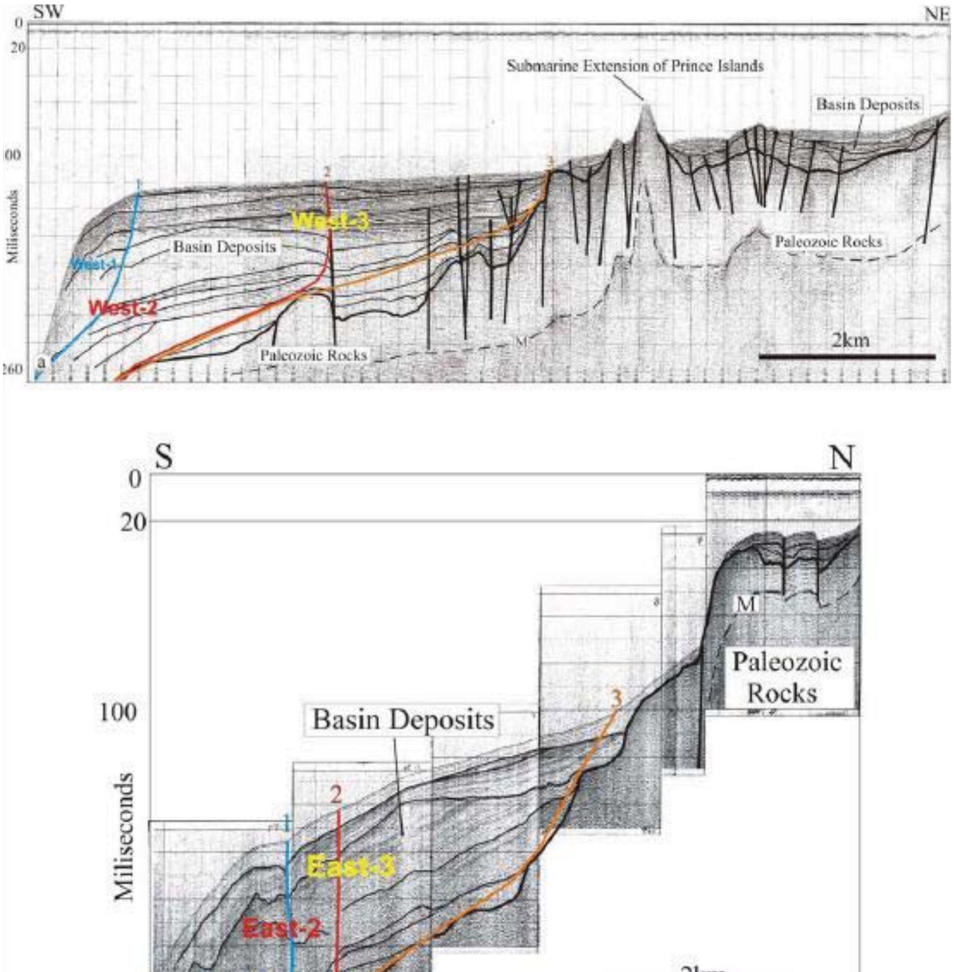

Fig. 12. Potential landslide depletion zones of the study area.

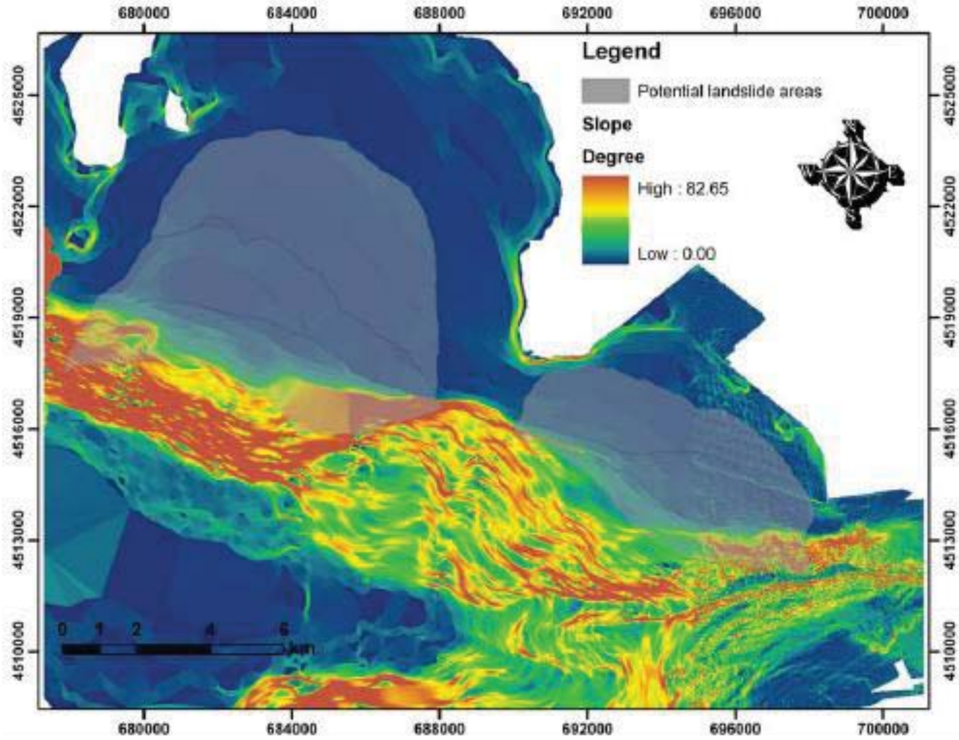

Fig 13. One of the cross sections for (a) west area and (b) east area (Gokceoglu et al., 2009).

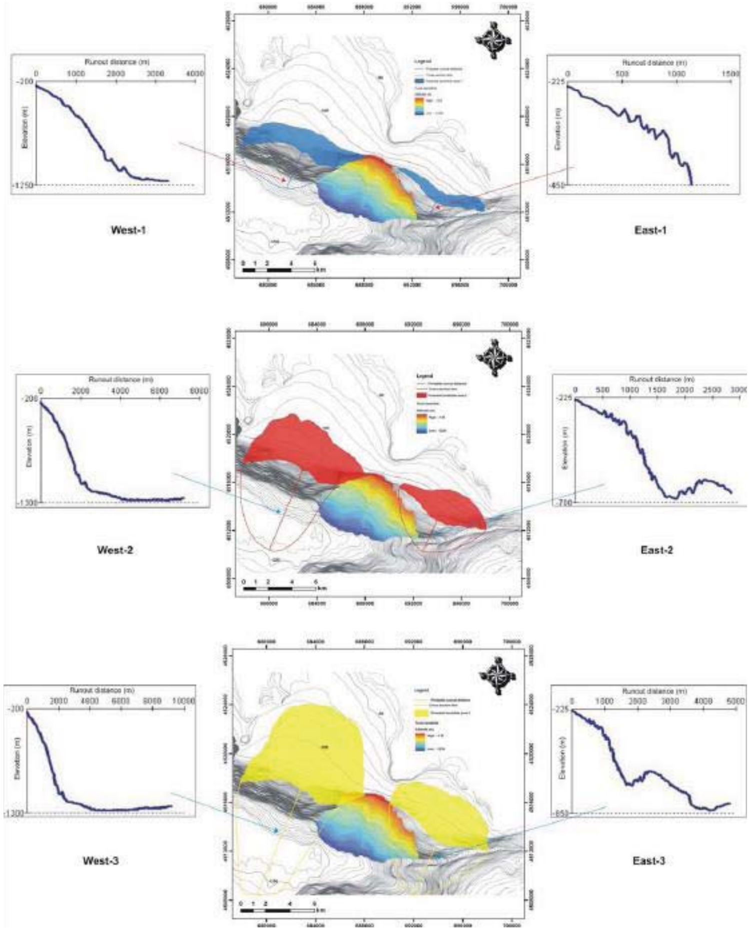

Fig 14. Slope map of the potential landslide areas.

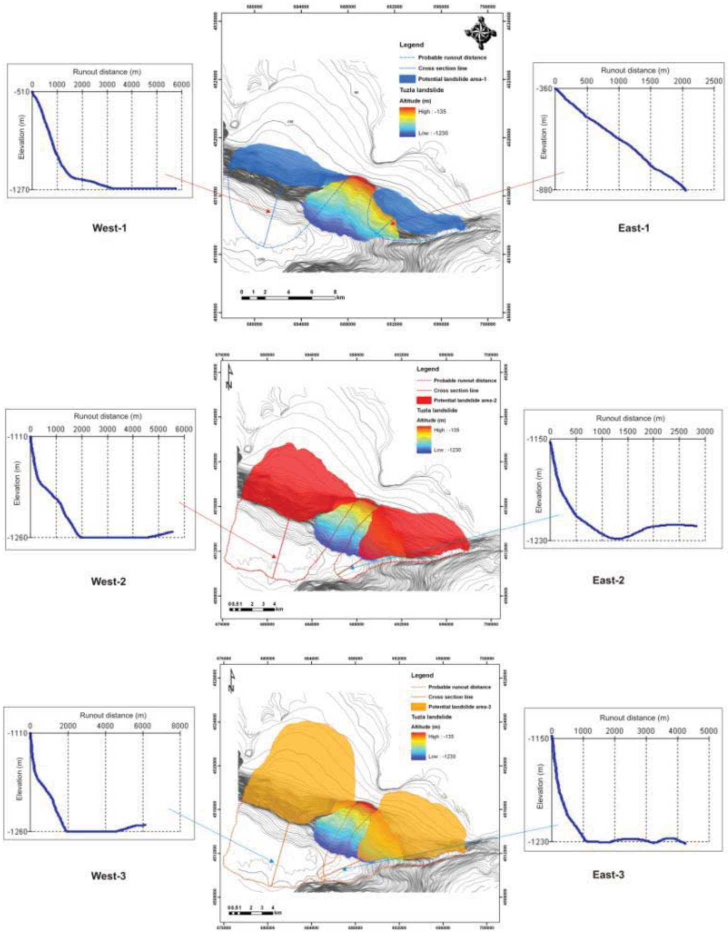

Fig 15. Maps showing the maximum runout distances obtained from BING model for different scenarios ((modified from Gokceoglu et al., 2009).

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