

Geophysical and Geodetical Investigation of A Landslide Area (Koyulhisar-Sivas, Turkey)

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Abstract. The study area is in the west of Koyulhisar (Sivas) town center and approximately 200x250 m². This area is one of the most active locations where the landslide displacement amount is the greatest. The aim of this study is to determine the depth of the sliding surface with geophysical (seismic refraction tomography (SRT), ground-penetrating radar (GPR)) methods. The results of TÜBİTAK-111Y111 project were also used. According to the geophysical results, within ~20 m of investigation depth, three layers with the average seismic P-wave velocities (V_p) of 650, 1200 and 2100 m/sec were identified. It was determined that the depth of the sliding surface which was between ~3-7 m and the seismic velocities were lower than 650 m/sec from these depths to the surface. The geophysical results demonstrated that the landslide type was identified as planar sliding, with the sliding direction in S-SE, and the tilt of the geological layer was in the same direction with the topography slope, mostly bigger than 5°. It was observed that the deformations in the landslide mass were caused by the geological unit, the layer or topography slope, and precipitation. All of these results can be effective in triggering the landslide area in the future and the landslide activity may continue in the study area. Therefore, the study area contains the risk and the natural hazards, and these threaten the settlement area and other constructions in Koyulhisar.

1 Introduction

A landslide is a mass movement and can occur in different forms. Koyulhisar landslide area is one of the largest landslide areas, significantly, leading to serious loss of lives and property, in Turkey. Three of the most destructive of these landslides occurred in Koyulhisar (Sivas) on 19 August 1998, 20 July 2000 and 17 March 2005. The Koyulhisar landslide area is one of the most important large landslide areas in the country and mass movements there typically occurs in the form of debris or mudflow (Tatar et al., 2007; Duman et al., 2005). Koyulhisar is also an active landslide area and for the past 17 years, there has been observed an increase in landslide activity (Tatar et al., 2007; Över, 2015). The large and small landslides in Koyulhisar landslide area have mostly occurred due to natural causes until today. Artificial causes mainly constitute the landslides caused by human interventions (blasting, drilling, improper planting, loading, loss of vegetation cover, etc.). The last large landslide occurred with the flow of mud in the north of Koyulhisar landslide area in March 2005. Duman et al. (2005) determined that this landslide was in the excessively fast (6 m/sec) class. Demirel et al. (2016), for the landslide in 2000 years revealed an average of 2.5-7.4 mm/year slip rate. Researchers have stated that these landslides usually have a mechanism involving a circular rotation, this old landslide mass maintains its activity and partial landslides occur on the groundmass (Sendir and Yılmaz, 2001; Duman et al., 2005). Therefore, Koyulhisar district center is on an old landslide that occurred in the form of circular rotation. The front of this landslide mass is open, it is always active, activity is not massive and usually in the form of local landslides occurring on the groundmass (Sendir and Yılmaz, 2001).

39 The triggering mechanisms of landslides are often complex and further understanding is needed to
40 facilitate the prediction of mobilizations as well as adequate stabilization and remediation measures. Therefore, it
41 is important to investigate the reasons that affect the formation mechanisms and the formation of landslides.
42 Different engineering (geology, geophysics, geodetic, etc.) disciplines have great role and importance especially
43 in decreasing the landslide effects. They can help to prevent damage by prediction and early warning. In this
44 context, Koyulhisar landslide area was examined in a wide area with detailed **global navigation satellite system**
45 **(GNSS)** methods and the studies of other disciplines (geology, **geochemistry**, seismology, meteorology, remote
46 sensing) (Sendir and Yılmaz, 2002; Tatar et al., 2007; Hatiboğlu, 2009; Hastaoğlu and Şanlı, 2011; Yılmaz,
47 2009; **Hastaoğlu, 2013; Topal and Hatiboğlu, 2015; Hastaoğlu, 2016; Hastaoğlu et al., 2018**). The annual sliding
48 velocity, sliding direction, displacement amounts and natural disaster risk of the landslide have been identified
49 by these studies. It has been determined that the displacement amounts of the landslide velocity vary between 1-
50 8.6 cm/year by topography and geological bedding and that the landslide direction is usually S-SE oriented. In
51 terms of geology, some researchers have carried out geological studies on many issues such as geological,
52 tectonic, geotechnical, geochemical and geomorphological studies at the local and regional scale in which the
53 features of the faults, water, hot water, soil and rock on the **North Anatolian fault zone (NAFZ)** and in the region
54 were investigated. These studies are in geology, tectonics (Toprak, 1989; Uysal, 1995; Sendir and Yılmaz, 2001;
55 Sendir and Yılmaz, 2002; Yılmaz et al., 2005; Gökçeoğlu et al., 2005b; Demirel et al., 2016; Demir, 2018), and
56 geotechnics, geomatics/remote sensing, geochemistry and geomorphology (Toprak, 1989; Uysal, 1995; Duman
57 et al., 2005; Ulusay et al., 2007; Hatiboğlu, 2009; Yılmaz, 2009; Demirel et al., 2016; Demir, 2018). **At the**
58 **interpretation stage, the geophysical findings of this study are related to the results of all these studies mentioned**
59 **just above.**

60 **The geophysical studies were carried out in a limited area where the first geophysical studies took place.**
61 In particular, seismic tomography (**seismic refraction tomography (SRT), multi-channel seismic wave analysis**
62 **(MASW)) and ground-penetrating radar GPR** applications are preferred methods in landslide studies. The
63 structural geometry of the landslide area was delineated based on an interpretation of the collected geophysical
64 data. These are the seismic V_p velocities, thickness, tilt and direction of the layers. Thus, other features such as
65 the sliding surface depth of the landslide, landslide type, advancement direction, and the risk situation were also
66 revealed, and geophysical and other study results were shown to be compatible with each other. The studies
67 carried out by McCann and Forster (1990), Demirağ (1991), Hack (2000), Perrone et al. (2004), Göktürkler et al.
68 (2008), Hu and Shan (2016), Su et al. (2016) and (Popescu et al. 2016) are important in this regard. In addition,
69 Bichler et al. (2004) carried out multi-methodical geophysical studies containing electrical resistivity, GPR and
70 seismic methods in the landslide studies. Otto and Sass (2006) and Ristic et al. (2012) also carried out similar
71 studies on landslide investigation. In these studies, the sliding surface of the landslides and the flow direction
72 properties of the landslide material were generally determined by 2D (two-dimension) and 3D (three-dimension)
73 geophysical sections.

74 **It has been observed that the use of the SRT and GPR methods in landslide studies has increased in recent**
75 **years** (Ristić et al., 2012; Timothy et al., 2013; Lissak et al., 2015; Hu and Shan, 2016; Popescu et al., 2016; Su
76 et al., 2016). The parameters which define the landslide such as landslide geometries and bedrock depth or
77 sliding surface depth have been determined in these studies. Regarding the GPR method, significant studies have
78 been carried out by Davis and Annan (1989) on revealing the soil stratigraphy, by Aldaş et al. (2003), Slater and

79 Niemi (2003) and Green et al. (2003) on the mapping of faults, fractures and cracks and by Benson (1995),
80 Harari (1996), Bano et al. (2000) and Bubeck et al. (2015) on the determination of groundwater levels. However,
81 the accurate determination of the landslide type is also very important as well as landslide elements. Joint studies
82 with geophysics and other disciplines are commonly carried out in determining the landslide type and for
83 different contributions. In addition to these, the seismological history, morphological and topographical features
84 and meteorological data of the study area are always taken into account in the landslide analysis. **These data are**
85 **used to contribute to the interpretations of these studies. Thus, through multi-discipline studies, the landslide**
86 **type can be determined most accurately by determining different sliding behaviors (such as the velocity and**
87 **direction of the landslide, annual amount of displacement) varying from region to region.** The landslides, which
88 generally occur in the form of sliding, may occur with the movements of falling, sliding and flowing or with the
89 combination of a few of these. Therefore, accurate determination of the landslide **type** and the selection of the
90 methods used in the study is very important. It may be possible to perform an accurate landslide analysis only if
91 these requirements are met. In this article, these issues were examined and discussed separately and together
92 with geophysical and geodetic results.

93 **2 The Status of the Study Area**

94 **2.1 Geology and seismology**

95 **Koyulhisar is about 180 km away from Sivas city center. The study area is located in the west of Koyulhisar**
96 **town center and in the north of the NAFZ (Fig. 1). The geological investigation of Koyulhisar has been carried**
97 **out regionally or locally by various researchers (Terlemez and Yılmaz, 1980; Toprak, 1989; Uysal, 1995; Sendir**
98 **and Yılmaz, 2002; Duman et al., 2005; Hatiboğlu, 2009). In these studies, the Plio-Quaternary aged Koyulhisar**
99 **Formation is the youngest unit in the region. It was stated that the youngest unit consisted of the talus (slope or**
100 **deposit) and fluvial conglomerates and was seen along the strike-slip faults (Toprak, 1989). Toprak (1989)**
101 **divided the NAFZ which is represented by a right lateral strike-slip fault zone into five fault sets including the**
102 **North Anatolian Main Fault, Koyulhisar fault sets, Kelkit fault set, Şihlar fault set and Kuruçay fault set. But, the**
103 **Şihlar fault sets affect Koyulhisar district center at the nearest (Fig. 1). Toprak (1989) stated that Koyulhisar**
104 **section of the NAFZ is still active and a right lateral strike-slip fault zone due to the morphotectonic structures**
105 **and seismic activities in the region (Fig. 1 and 2). As it is seen in Fig. 1, the faults closely concerning Koyulhisar**
106 **are the NAFZ, which is the main fault extending in the northwest-southeast direction and approximately 2-2.5**
107 **km away, in the south, and the Çamlıyaka Fault, which is approximately north-south-oriented, in the west. This**
108 **fault which is the closest one to the study area extends perpendicular to the NAFZ in the south. It was also**
109 **reported by Tatar et al. (2007) that large and old landslide masses in Koyulhisar landslide area have lower**
110 **Miocene-aged clay and gypsum levels, Eocene-aged clayey levels and Plio-Quaternary aged sediments. The**
111 **rocks in the region usually have fractures and discontinuities and are crushed because of the NAFZ which is**
112 **tectonically active in the south of the study area (Tatar et al., 2005). There are also many old and new landslides**
113 **in the study area depending on the high tilted topography. For these reasons, the directions of movement of the**
114 **landslides generally threaten the settlement areas (Sendir and Yılmaz, 2001). However, Hatiboğlu (2009) and**
115 **Hastaoğlu et al. (2015) generally observed two geological units in the drillings in the study area. They observed**
116 **that the upper unit was silty sandy clay and sand interbedded silty clay in some places up to about 10 m, and**
117 **advanced as sand interbedded silty clay and sand interbedded clay in some places towards deeper than 10 m. The**
118 **first unit consists of light-dark brown colored, medium-very stiff, low-high plasticity, silty clay. The second unit**

119 consists of light-yellow white colored, low-high plasticity, silty sandy clay interbedded with sand (Hastaoğlu et
120 al., 2015). When the drilling logs are examined, there is generally the second unit in east of study area
121 (Hastaoğlu et al., 2015). Furthermore, it was observed that the content of the second geological unit did not
122 change even if the depth of the drilling increased. Therefore, the second geological unit was taken into
123 consideration in the interpretation of geophysical sections.

124 As it is seen in Fig. 2, the study area is located in an active area in terms of seismicity (Fig. 2). The
125 seismological history, the magnitude (M) of which is greater than 2.5, of the examined area and its surrounding
126 were investigated for this article. Fig. 2 was prepared with the seismological data between 1900-2015 (UDİM,
127 2016). Particular attention was paid to the earthquakes before 2005 in the seismological interpretation. This is
128 because the largest and most recent landslide occurred in the area in 2005 and it was aimed to investigate its
129 relationship with displacements and previous landslides. The type of magnitude which is calculated from
130 seismological data is usually the local magnitude. The depths (d) of these earthquakes with higher $M > 2.5$ vary
131 between approximately 5 and 80 km (Fig. 2). According to the seismic data of the years examined, Koyulhisar
132 and its surroundings have always been active seismically. It was observed that this frequency of earthquakes
133 usually occurred on the NAFZ in the south of the study area. Additionally, it has been analyzed the seismic
134 activity of the region at least for the last 112 (1904-2016) years by Demir (2018). In this study, he express that
135 the most notable is probably the relationships between the magnitude of the earthquake to the number of
136 landslides and the area affected by the landslides and between the magnitude and the maximum distance of
137 landslide observations from the epicenter in different geological, topographical, and climatic conditions (Demir,
138 2018).

139 Large earthquakes affecting Koyulhisar district also occurred in the region. These largest earthquakes are
140 in the south of the NAFZ or Suşehri district and a total of three large earthquakes with $M \geq 5.6$ occurred there
141 (Över, 2015). Among these, the 1992 earthquake is closest to the study area with the least depth but the second
142 largest earthquake (Fig. 2). This earthquake is an earthquake with 6.1 magnitudes that occurred 10 km below the
143 ground. The large earthquakes in the south of Suşehri district which is just 13 km away from the study area
144 occurred in 1909 and 1939. 1909 earthquake occurred 60 km below the ground and is the largest and deepest
145 earthquake with a magnitude of 6.3. 1939 earthquake is also deep and the third largest earthquake that occurred
146 50 km below the ground with a magnitude of 5.6 (Över, 2015). In addition, when Fig. 2 is analyzed, it is seen
147 that the magnitudes of the other earthquakes in the north of the NAFZ and the upper elevations of the landslide
148 generally vary between 2.5-4. Similarly, it is seen that the other earthquakes in the south of the landslide area are
149 the earthquakes with a magnitude of greater than 3.6. All these earthquakes may have triggered the landslide
150 mass from time to time in places where sliding surfaces, layers, and topography in the landslide area are more
151 inclined than 5-10 degrees (according to the geophysical cross-sections in this article, when it is considered that
152 there are loose units and deformations on the sliding surfaces). In particular, they further affected the landslide
153 mass along with the rain and caused large amounts of displacement in the landslide area.

154 **2.2 Meteorological and geodetic results**

155 The data regarding the rainfalls with the effects of triggering the landslides are presented in Table 1 and
156 Fig. 3a and Fig. 3b (MGM, 2016; Hastaoğlu et al., 2015). With these data, the rainfall status of the study area
157 and its surrounding was examined by months as average annual rainfalls and the annual areal amount of rainfall.
158 According to the data obtained between 1950-2015 in Table 1, the rainy periods are generally between October-

159 November-December and January-February-March-April. The highest total daily amount of rainfall in the
160 rainiest years was observed as snowfall in 1950 (110 cm) and as rain in 1991 (55 kg/m²). In Fig. 3a, the annual
161 normal average rainfall value calculated for the years between 1981-2010 was calculated as over 483.4 mm
162 (MGM, 2016). However, 1987-1988 and 1997-1998 were the rainiest years. It is seen that the annual areal
163 amount of rainfall exceeded the normal values and was higher than 550 mm in these rainy years that took place
164 in every 10 years. Similarly, it is also seen that there were high rainfalls for 3-4 years after the years of 1985-
165 1995-2005 with an interval of 10 years. Therefore, annual areal rainfalls were observed to be more before some
166 large landslides like the landslide in 1998. When geological features of the region are taken into account, it is
167 remarkable that the landslide in 1998 and 2000 occurred in the summer months after the winter with a heavy fall
168 of snow. However, the landslide in 2005 occurred during the rainy season.

169 In Fig. 3b, GNSS studies and multi-disciplinary studies of Hastaoğlu et al. (2015) have carried out for
170 many years (about 6 years) to determine the deformation and annual sliding amounts especially after the
171 landslides in 1998-2000-2005. The seismological and meteorological data, which were updated by the geodetic
172 (GNSS (DH), geological (IDH (Inclinometer Drilling Holes)) and meteorological data collected in this local
173 study were reorganized and evaluated. Fig. 3a-b and Table 1 which were reprepared for the study which is the
174 subject of this article were associated with the results of GNSS studies (Fig. 3b). The monthly and annual
175 meteorological data should certainly be evaluated particularly within the scope of monitoring activities, as the
176 area is a landslide area. Hastaoğlu et al. (2015) followed in DH wells in the area in 2013-2014 (Fig. 3b). If Fig. 4
177 is examined, there are seven DH point in the nearest of the geophysical profiles (DH8, DH12, DH16 is near the
178 area A and DH4, DH6, DH9, DH10 is near the area C). The graphics in Fig. 3b was prepared from the combined
179 data (unpublished data in the project) and the temperature (°C), precipitation (m³) and soil moisture content (cm)
180 were compared in these graphics. The temperature and precipitation were observed to be inversely proportional
181 during the summer months called as a dry period. It is seen that the soil moisture is changeable apart from the
182 rainy period and has very high water content during the rainy periods. The soil moisture is very high (average
183 150 cm) in winter, summer, autumn seasons. In the study area, the water contents in the drilling data change
184 from 24.6 % to 13.3 % at between 0-10 m depth and these values are also high (from 29.1 % to 17.3 %) after 10
185 m (Hastaoğlu et al., 2015). Water generated from precipitation and melting snow is blocked by the impermeable
186 layer when it infiltrates downward, and the local moisture content increases (see Hu and Shan (2016)). Thus, the
187 water infiltrates the interface between the permeable and impermeable layer, can form a slip zone. Then, these
188 results were compared with geophysical results in interpretation. The GPR results show that the moisture content
189 of soils at the sliding surface of the landslide mass is relatively high. The drilling data and soil moisture values
190 also show very high moisture content of the sliding surface of the landslide mass in the study area, which is
191 completely consistent with the results obtained from the GPR-SRT profiles, meteorological and geological
192 results. On the other hand, it was understood that the precipitation increased by the decrease in temperatures. It is
193 also seen that the total annual amount of rainfall increased about 2-fold in 2014 compared to 2013 (Fig. 3a-b).
194 According to all results, rainfalls are considered to be effective in triggering of the landslide because the ground
195 of this landslide area, which is filled with loose units and old cracks, is supersaturated with water due to the
196 rainfalls. Besides, Hastaoğlu et al. (2015) determined that the groundwater level gets close to the surface for 4-6
197 m on average at the end of the rainy period, to 10 m at the end of the rainy period and decreases up to 25 m in
198 some wells in the area where geophysical study area is also located, and the groundwater flow direction is SW.

199 Consequently, when the displacements and the landslide directions estimated from the GNSS measurements are
200 also considered, it was determined that these results were compatible with the geophysical sections and the
201 rainfalls were among the reasons that trigger the landslide.

202 **3 Methods**

203 **3.1 Geophysical surveys**

204 The seismic refraction tomography (SRT) and ground-penetrating radar (GPR) methods are applied in
205 tomography format. The SRT method determining the seismic P-wave velocities (V_p) for seismic applications
206 and the GPR method for electromagnetic (EM) applications were used in the geophysical data collection in the
207 area (Fig. 4). The high-frequency electromagnetic waves can reach deeper in the environments with low
208 conductivity like sand. However, the conductive units such as clay and shale decrease the penetration depth of
209 the signal transmitted and lead to absorption (Annan et al., 1988; Davis and Annan, 1989). Firstly, SRT and GPR
210 data were collected along multiple transects in two different areas of the study area named A and C (see Fig. 4).
211 Then, the geophysical profiles were processed to the satellite map according to the coordinates along with the
212 topographical elevation curves and GNSS measurement locations for the ease of interpretation (Fig. 4a).
213 Geophysical measurements were taken due to the geologic bedding and topographic features (Fig. 4b-c). SRT
214 profiles and on these seismic profiles GPR profiles in the area defined by A in Fig. 4b is approximately in the
215 NE-SW (SRT2, SRT4, GPR2, GPR4) and NW-SE (SRT3, SRT5, GPR3, GPR5) directions (Fig. 4b). Similarly,
216 in area C, SRT11-SRT12-GPR11-GPR12 profiles are approximately in the E-W directions, SRT9-SRT14-
217 GPR9-GPR14 profiles are approximately in the NE-SW direction, SRT10-GPR10 profiles are in the NW-SE
218 directions and SRT13-GPR13 profiles are approximately in the NE-SW directions (Fig. 4c). The profile lengths
219 usually range from 25 to 60 m according to the method applied.

220 The profile shooting technique in the seismic study, hammer and iron plate of 8 kg weight as the source
221 P geophone of 14 Hz (the total number of geophones is 12) and Geometrics branded seismic device as the
222 receiver was used while collecting the SRT data. In all profiles, the geophone interval was 5 m, offset distance
223 was 2.5 m, the sampling interval was 256 ms and the record length was 512 ms. The geophones were
224 respectively fixed on the ground within the selected geophone range and their connections with the seismic
225 device were made. Then, seismic measurements were recorded by starting from the offset distance of 2.5 m,
226 reducing to sledgehammer plate and making at least 5 times shots between each geophone, respectively. In the
227 evaluation of the SRT data collected in the field, SeisImager program was used for displaying, processing and
228 evaluation of the seismic refraction waves. The marking of the first arrivals of the SRT data was performed using
229 Pickwin, and the evaluation of the first arrival data was performed using Plotrefa module. The GPR data were
230 collected by Ramac2 device using a shielded antenna of 250 MHz. The GPR data were processed in Reflexw
231 program. In order to collect the GPR data, other parameters were selected 512 ns-number of samples, 16-number
232 of stacking and 0.1 m-trace interval. 2D GPR data processing for data analysis of the GPR data, it includes Static
233 correction (10 ns in dry or wet clay and sandy), Muting, Bandpass filter (100, 200, 300, 400 Hz), Gain (0.512
234 ms) and Migration (0.01 ms) steps. The migration was made to show up small vertical structures invisible during
235 data processing. Thus, very large hyperballs with strong reflections may limit the display of non-migrated GPR
236 data. Moreover, the peak points of hyperbolas observed in GPR cross-sections show the reflection surface of the
237 electromagnetic wave. During data processing, velocity analysis was performed on the reflection surfaces
238 through the hyperbola superposition method and EM wave propagation velocity was calculated in all GPR cross-

239 sections. The topographic corrections were made by selecting the “Correct for two layers” option in Static
240 Correction/Muting in the Reflex program. The height values collected in the study area were manually entered
241 and saved in the “Correct for two layers” option. Thus, the models were converted from m to ns and the GPR
242 sections were prepared for interpretation. Thus, the collected geophysical data were converted into 2D (two-
243 dimension) elevation-distance (SRT) and depth-distance (GPR) sections by assessed in the appropriate software.

244 The geophysical study area is one of the most active locations of the landslide area. As it is seen in Fig.
245 5, geomorphologically the landslide cracks on the surface, displacement traces, and structural damages in the
246 study area and its immediate surroundings can be monitored clearly in this activity area. Visibly, the damaging
247 effects of still active or old landslides on residences, roads and walls are also observed easily by field
248 observations. Therefore, none of the damaged constructions are used in the Koyulhisar.

249 3.2 Geophysical analysis, results and discussion

250 Geophysical interpretations were made according to these sections and compared with the results of the other
251 studies.

252 **SRT sections:** 2D seismic cross-sections giving seismic V_p -depth information are presented in Fig. 6 and
253 7. In the seismic data evaluation, the coincidence was provided with RMS (Root Mean Square) errors ranging
254 between 3.4-4.5% in 2D inversion operation. According to these sections, two or three layers were identified at
255 about 20 m depth (Fig. 6 and 7). It was understood that the tilts of these layers were southeast oriented, and their
256 tilt was greater than 5° . According to the average seismic velocities (V_p) calculated, three layers with the layer
257 velocities of 650, 1200 and 2100 m/sec were defined from top to bottom. Thus, the seismic V_p velocities were
258 observed that they increased towards the depth. It was determined that the depth of the sliding surface varied
259 about between 3-7 m (Fig. 6 and 7). Therefore, these depths were defined as the layer with the risk of
260 dislocation. This area was considered to have a risk of dislocation due to these loose units, rainfall and tilt
261 conditions. The seismic velocity of the first layer is lower than $V_{p1}<650$ m/sec, but the seismic velocity of the
262 third layer may be greater than $V_{p3}>2100$ m/sec.

263 **GPR sections:** The investigation depth was further calculated from the SRT sections compared to the
264 GPR sections due to the differences of geophysical methods in the application. Because GPR sections were
265 obtained in high-resolution for about the first 10 m depth after data processing of the GPR data. It is clearly
266 observed that the strong reflections are within 10 m depth in Fig. 8 and 9. These strong reflections seen in black
267 dashed ellipses are interpreted as deformation areas in the layer. In a similar manner, these areas being
268 interpreted as deformations were also observed in the studies of Bubeck et al. (2015), Hu and Shan (2016), Su et
269 al. (2016) and Popescu et al. (2016). The strong reflected wave signal shows distinctive characteristics,
270 presenting a low-frequency high-amplitude sync-phase axis, which can be inferred as the sliding surface in Fig. 8
271 and 9. In other words, two layers were identified in GPR sections. The first layer is weak, loose, cracked, moved
272 and also have lost their tightness, and their seismic velocity is low. Therefore, in Fig. 8 and 9, it was thought that
273 deformations developed on the sliding surfaces due to the geology of the study area in A and C area. It was
274 identified the deformations, called sliding surfaces, landslide furrows, scarps, collapsed zones, and cracks. If the
275 areas of A and C are compared, the deformations are more in area C than in area A. Therefore, the risk of
276 landslides may be higher in area C. In Fig. 8, the EM wave velocity calculated for the reflection surface in GPR5
277 cross-section -representing the GPR profiles- was shown as an example. The picks were exported with the
278 attribute of two-way travel time and the velocity of propagation of the wave was calculated about 0.1 m/ns (Fig.

279 8). This value is generally observed in dry or wet soil, dry or wet clay and sandy environments (Wilchek, 2000;
280 Cardomina, 2002). Therefore, it was thought that this velocity value was compatible with the geological units
281 and electromagnetic waves led to rapid absorption due to the silty sandy clay layer. Because the first geological
282 unit is medium-very stiff, low-high plasticity, silty sandy clay. The deformation structures as sliding surfaces,
283 landslide furrows, scarps, collapsed zones, and cracks were observed in the GPR cross-sections (Fig. 8 and 9). In
284 other words, the geological unit, the layer or topography slope and precipitation cause deformations in the loose
285 upper unit. Therefore, these structures may develop or occur in the landslide mass, as shown in Fig. 8 and 9.

286 Additionally, the geological units were observed in DH wells in the geophysics study area (Fig. 4). These
287 are mostly silty sandy clay and they have different characteristics above and below about 10 m in DH well. The
288 topography of the study area decreases from 925 m to 840 m and the elevation difference is 85 m (Fig. 4). The
289 amount of slope in the topography increases from south to north ($>5^{\circ}$ - 10°) in the geophysical sections (Fig. 6 and
290 7). It was determined that the landslide type in the area was planar sliding and observed that the direction of
291 sliding was SE. As this information was associated with topography and the field observations, it was observed
292 that the topography was inclined from the north to the south of the study area. The results of the various studies
293 and also the findings of this article have proved that Koyulhisar landslides are generally caused by the known
294 reasons that trigger the landslide. Therefore, it was seen that the geological bedding was compatible with the
295 topographical sloping and the groundwater was compatible with the direction of flow.

296 **4 Conclusions**

297 The landslides may develop under various geological, morphological, topographical and physical reasons. The
298 information provided from many studies (geodetical, geological, morphological, seismological, topographic and
299 meteorological) carried out across the region was compared with the geophysical results (SRT and GPR) and
300 found to be compatible. The seismic P-wave velocity (V_p) of the layers, the tilt, tilt direction of the layers, depth
301 of the sliding surface, sliding direction and the landslide type was determined from the geophysical sections. The
302 study area was identified by the layers with the average seismic velocities of $650 < 1200 < 2100 < \dots$ m/sec.
303 According to the geophysical cross-sections, it was identified that the depth of the sliding surface varied between
304 3-7 m due to the topographical differences. These depths were the depths with low seismic velocities (<650
305 m/sec) and defined as loose units which were also observed in geological drilling logs. It was determined that
306 sliding surfaces, landslide furrows, collapsed zones, scarps, cracks were observed in the landslide mass in the
307 GPR sections. It was observed that the layer tilt was generally more than 5° in all geophysical sections and
308 compatible with the geology and the flow direction of the groundwater. It was determined that the landslide type
309 in the area was planar sliding and the direction of sliding was SE.

310 The geophysical and other results were found to be compatible because it is known that the landslide
311 direction across Koyulhisar is in S-SW and SE. Consequently, the fact that the depth of the sliding surface over
312 the geologic unit is loose, the seismic velocity of the upper layer is low and the tilt is an excessive show that
313 there is a new risk of landslide in the area. The other factors that trigger the landslide were found to be associated
314 especially with the fact that the area is seismically active, receive heavy rain and has a poor vegetation cover. On
315 the other hand, it was thought that blasting and excavation performed by human intervention can trigger the
316 landslides due to the geologically loose unit. Hence, the landslide area can be a potential area which is open to
317 natural/artificial hazards. The identified risks and natural hazards also threaten the settlement area, the buildings

318 and other constructions (e.g. roads, walls, parks et al.) in Koyulhisar. Therefore, there is still a high landslide
319 hazard in the study area and its surroundings, and this hazard will also occur in the future.

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