Natural Hazards
and Earth System
Sciences

Open Access

EGU

Discussions

1

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

Sevda ÖZEL[1], Demet ÖVER[2] and Kemal Özgür HASTAOĞLU[3]

[1,2]*Cumhuriyet University, Engineering Faculty, Department of Geophysical Engineering, 58140, Sivas, Turkey, sozel@cumhuriyet.edu.tr.*

[3]*Cumhuriyet University, Engineering Faculty, Department of Geomatics Engineering, 58140, Sivas, Turkey, khastaoglu@cumhuriyet.edu.tr.*

Abstract

This study includes geophysical studies carried out in the last section in the close south of Koyulhisar (Sivas) landslide site. Additionally, the study area is in the most active location where landslide's displacement amount is the highest. The landslide site basically has been examined geophysics (SRT, GPR) and geodesic (GNSS) methods. According to the geophysical results, within ~20 m of investigation depth, layers with the average seismic P-wave velocities (V_P) of 0.30, 1.00 and 2.00 km/s have been identified. It has been understood that the thickness of the first two layers of these layers from top to the bottom is approximately 3 and 6.5 m, and the last layer with Vp>2.0 km/s is the bedrock. Furthermore, it has been understood that the depth of the sliding surface which is the upper limit of the bedrock varies between ~7-10 m, there are loose units on the sliding surface, the type of sliding is planar sliding, and the direction of sliding is S-SE, the tilt of the layer has the same direction with topography, is SE-oriented and mostly bigger than 5^0. It was understood that the deformations in the landslide mass were occured from the geological unit, the layer or topography slope and precipitation and the landslide activity can continue in the study area. Thus, it has proven that precipitation and deformations within the layer are effective in triggering the landslide by the geodetic (IDH) observations, and it is understood that they were compatible with the geophysical results. Therefore, the study area contains the risk and the natural hazards, and these threatens the settlement area and the buldings and other constructions there.

1 Introduction

Today, large landslides occurring in Turkey have reached a considerable amount. It is known that a large landslide occurs in about every 5-10 years in Turkey (Över, 2015). These landslides usually occur in the forms of mud flow or mass movement. Three of the most effective of these landslides occurred in Koyulhisar (Sivas) in 19 August 1998, 20 July 2000 and 17 March 2005. Koyulhisar landslide area is one of the important large landslide areas in the country and occurs in the form of debris or mud flow (Fig. 1 and 8). In addition, Koyulhisar is an active landslide area, the activity of which has increased for the past 17 years. Koyulhisar landslide area, the subject of this article, is one of the largest landslide areas that significantly lead to serious loss of lives and property as in throughout Turkey. 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 vd. (2016), for the landslide in 2000 year 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).

Natural Hazards
and Earth System
Sciences

Open Access

EGU

Discussions

42 As it is known, landslides, as well as natural processes, may also occur with human-induced interventions
43 (during blasting and excavation operations in many studies for roads, tunnels, and mines) performed on or near
44 the landslide area (Lazzari, 2006). Therefore, it is important to investigate the reasons that affect the formation
45 mechanisms and the formation of landslides Different engineering (geology, geophysics, geodesic, etc.)
46 disciplines have great role and importance especially in decreasing the negative effects. In this context,
47 Koyulhisar landslide area was examined in a wide area with detailed GNSS (Global Navigation Satellite System)
48 methods and the studies of other disciplines (Sendir and Yılmaz, 2002; Tatar et al., 2007; Hatiboğlu, 2009;
49 Hastaoğlu and Şanlı, 2011; Yılmaz, 2009; Hastaoğlu, 2013; Türk, 2013; Topal and Hatiboğlu, 2015; Hastaoğlu,
50 2015; Hastaoğlu, 2016). The annual sliding velocity, sliding direction, displacement amounts and natural disaster
51 risk of the landslide have been identified by these studies. In these studies, it has been determined that the
52 displacement amounts of the landslide velocity vary between 1-8.6 cm/year by topography and geological
53 bedding and that the landslide direction is usually S-SE oriented. In terms of geology, some researchers have
54 carried out geological studies on many issues such as geological, tectonic, geotechnical, geochemical and
55 geomorphological studies at the local and regional scale in which the features of the faults, water, hot water, soil
56 and rock on the NAFZ (North Anatolian Fault Zone) and in the region were investigated (Toprak, 1989; Uysal,
57 1995; Sendir and Yılmaz, 2001; Sendir and Yılmaz, 2002; Yılmaz et al., 2005; Gökçeoğlu et al., 2005b; Duman
58 et al., 2005; Ulusay et al., 2007; Hatiboğlu, 2009; Yılmaz, 2009; Demirel et al., 2016; Demir, 2018). The results
59 of all these studies have been associated with geophysical results at the interpretation stage in this article.
60 However, the geophysical studies, the subject of this article, were carried out for a limited area and have the
61 distinction of being the first geophysical studies.

62 In the geophysical study, the hazards that would be caused by the landslide geometry of the last section in
63 the close south of Koyulhisar landslide area and would affect the settlement area were investigated (Fig. 2 and
64 8). The geophysical study was also carried out in this area which is the most active area of the landslide site
65 because Hatipoğlu (2009) identified a movement of about 8.6 cm/year in this area. The SRT (Seismic Refraction
66 Tomography) method determining the seismic P-wave velocities (V_P) for seismic applications and the GPR
67 (Ground Penetrating Radar) method for electromagnetic (EM) applications were used in the geophysical data
68 collection in the area. In particular, seismic tomography (SRT, MASW) and ground penetrating radar (GPR)
69 applications are the most commonly preferred methods in landslide studies. The structural geometry of the
70 landslide area was determined by different parameters by assessing the collected geophysical data with
71 appropriate software. These are the seismic V_P velocities, thickness, tilt and tilt direction of the layers. Thus,
72 other features such as the sliding surface depth of the landslide, landslide type, advancement direction and the
73 risk situation were also revealed, and geophysical and other study results were shown to be compatible with each
74 other. The studies carried out by McCann and Forster (1990), Demirağ (1991), Hack (2000), Perrone et al.
75 (2004), Göktürkler et al. (2008) are important in this regard. In addition, Bichler et al. (2004) carried out multi-
76 methodical geophysical studies containing electrical resistivity, GPR and seismic methods in the landslide
77 studies. Otto and Sass (2006) and Ristic et al. (2012) also carried out similar studies on landslide investigation.
78 In these studies, the sliding surface of the landslides and the flow direction properties of the landslide material
79 were generally determined by 2D (two-dimension) and 3D (three-dimension) geophysical sections.

80 It has been observed that the use of the SRT and GPR methods in landslide studies has increased
81 significantly especially in recent years (Ristić et al., 2012; Timothy et al., 2013; Lissak et al., 2015; Hu and

Natural Hazards
and Earth System
Sciences
Discussions

82   Shan, 2016; Popescu et al., 2016; Su et al., 2016). The parameters which define the landslide such as landslide

83   geometries and bedrock depth (sliding surface depth) have been determined in these studies. Regarding the GPR

84   method, significant studies have been carried out by Davis and Annan (1989) on revealing the soil stratigraphy,

85   by Aldaş et al. (2003), Slater and Niemi (2003) and Green et al. (2003) on the mapping of faults, fractures and

86   cracks and by Benson (1995), Harari (1996), Bano et al. (2000) and Bubeck et al. (2015) on the determination of

87   groundwater levels. However, the accurate determination of the landslide type is also very important as well as

88   landslide elements. Joint studies with geophysics and other disciplines are commonly carried out in determining

89   the landslide type and for different contributions. In addition to these, the seismological history, morphological

90   and topographical features and meteorological data of the study area are always taken into account in the

91   landslide analysis. They are largely used in such studies especially for their contribution to interpretation. In this

92   article, the information obtained from all these data was used in order to make contributions to the geophysical

93   results. For, landslides may develop under various geological, morphological, topographical and physical

94   reasons. Thus, through multi-discipline studies, the landslide type can be determined most accurately by

95   determining different sliding behaviors (such as the velocity and direction of the landslide, annual amount of

96   displacement) varying from region to region. The landslides, which generally occur in the form of sliding, may

97   occur with the movements of falling, sliding and flowing or with the combination of a few of these. Therefore,

98   accurate determination of the landslide type/kind and the selection of the methods used in the study is very

99   important. It may be possible to perform an accurate landslide analysis only if these requirements are met.

100   **2 Geology**

101   The study area is about 180 km away from Sivas city center and is in the west of Koyulhisar district center which

102   is located in the north of the NAFZ (Fig. 1 and 8). The rocks in the region usually have fractures and

103   discontinuities and are crushed because of the NAFZ which is tectonically active in south of the study area

104   (Tatar et al., 2005). There are also many old and new landslides in the study area depending on the high tilted

105   topography. For these reasons, the directions of movement of the landslides generally threaten the settlement

106   areas (Sendir and Yılmaz, 2001). The geological investigation of Koyulhisar has been carried out regionally or

107   locally by various researchers (Terlemez and Yılmaz, 1980; Toprak, 1989; Uysal, 1995; Sendir and Yılmaz,

108   2002; Duman et al., 2005; Hatiboğlu, 2009). According to these studies, the Plio-Quaternary aged Koyulhisar

109   Formation is the youngest unit in the region. It was stated that the youngest unit consisted of the talus (slope or

110   deposit) and fluvial conglomerates and was seen along the strike-slip faults (Toprak, 1989).

111   Toprak (1989) divided the NAFZ which is represented by a right lateral strike-slip fault zone into five

112   fault sets including the North Anatolian Main Fault, Koyulhisar fault sets, Kelkit fault set, Şıhlar fault set and

113   Kuruçay fault set. But, the Şıhlar fault sets affect Koyulhisar district center at the nearest (Fig. 1). Toprak (1989)

114   stated that Koyulhisar section of the NAFZ is still active and a right lateral strike-slip fault zone due to the

115   morphotectonic structures and seismic activities in the region (Fig. 1). As it is seen in Fig. 1, the faults closely

116   concerning Koyulhisar are the NAFZ, which is the main fault extending in the northwest-southeast direction and

117   approximately 2-2.5 km away, in the south, and the Çamlıyaka Fault, which is approximately north-south-

118   oriented, in the west. This fault which is the closest one to the study area extends perpendicular to the NAFZ in

119   the south. It was also reported by Tatar et al. (2007) that large and old landslide masses in Koyulhisar landslide

120   area have lower Miocene-aged clay and gypsum levels, Eocene-aged clayey levels and Plio-Quaternary aged

121   sediments.

122　　　　The large and small landslides in Koyulhisar landslide area have mostly occurred due to natural causes
123　until today. The landslides in and near the study area were triggered by old cracks, displacements, and
124　seismotectonic effects over time because they are on the NAFZ (North Anatolian Fault Zone) which is the
125　largest and most active fault zone in Turkey. The geology, morphology and flora features of the study area and
126　its surrounding have also been the other factors that triggered the landslide. Therefore, the studies carried out in
127　the region have shown that active faults triggered the landslides due to the geological and lithologic features of
128　the region.

129　**3 Methods**

130　**3.1 Geophysical surveys**

131　The SRT (Seismic Refraction Tomography) and GPR (Ground Penetrating Radar) methods which are applied in
132　tomography format were used in the geophysical study. Before applying the SRT and GPR methods in the field,
133　the study area was named as A-C and the geophysical measurements were collected separately in these areas
134　(Fig. 2). Then, the geophysical profiles were processed to the satellite map according to the coordinates along
135　with the topographical elevation curves and GNSS measurement locations for the ease of interpretation (Fig. 2a).
136　Geophysical measurements were taken as both NE-SW and NW-SE oriented due to the geologic bedding and
137　topographic features (Fig. 2b-c). However, SRT12-GPR12 profiles were selected as about E-W oriented due to
138　rugged topography in area C. The profile lengths usually range from 40 to 60 m according to the method applied.
139　10 SRT measurements were taken in all areas in the seismic study for geophysical measurements. 10 profile
140　GPR measurements were taken in areas A and C in the electromagnetic study. The profile shooting technique in
141　the field, hammer and iron plate of 8 kg weight as the source and 12 P geophones of 14 Hz and Geometrics
142　branded seismic device as the receiver were used while collecting the SRT data. In all profiles, the geophone
143　interval was 5 m, offset distance was 2.5 m, sampling interval was 256 ms and the record length was 512 ms.
144　The geophones were respectively fixed on the ground within the selected geophone range and their connections
145　with the seismic device were made. Then, seismic measurements were recorded by starting from the offset
146　distance of 2.5 m, reducing to sledgehammer plate and making at least 5 shots between each geophone,
147　respectively.

148　　　　There are 2 close NE-SW (SRT2, SRT4) oriented seismic SRT profiles and 2 NW-SE oriented seismic
149　SRT profiles in the area defined by A in Fig. 2b. There a total of four GPR profiles on these seismic profiles
150　including NE-SW oriented (GPR2 and GPR4) and NW-SE oriented (GPR3 and GPR5). In area C, there are close
151　E-W oriented SRT10 and SRT11 profiles in the west of the area and GPR10 and GPR11 profiles on these
152　profiles, and SRT9 and SRT14 profiles in the close NE-SW direction in the same area and GPR9 and GPR14
153　profiles located over them (Fig. 2c). There are E-W oriented SRT12 and close NE-SW oriented SRT13 and
154　GPR12 and GPR13 profiles located over them in the east direction of the area.

155　　　　In addition, the landslide cracks on the surface, displacement traces, and structural damages in the study
156　area and its immediate surroundings can be monitored clearly by field observations (Fig. 3). Some landslides in
157　the study area and a portion of the landslide crack traces and the damaging effects of still active or old landslides
158　on buildings can easily be observed in Fig. 3 All damaged structures across the region cannot be used. Therefore,
159　new landslide cracks will emerge over time both on the ground and the existing structures in the region which
160　active in terms of landslide and seismicity, and the formation of new landslides will continue in the area.

161　**3.2 Results, analysis and discussion**

162   In the evaluation of the SRT data collected in the field, SeisImager program was used for displaying, processing
163   and evaluation of the seismic refraction waves. The marking of the first arrivals of the SRT data was performed
164   using Pickwin, and the evaluation of the first arrival data was performed using Plotrefa module. The GPR data
165   collected on the SRT profiles only in the areas A and C were collected by Ramac2 device using a closed antenna
166   of 250 MHz. The GPR data were processed in Reflexw program. The time-depth sections which were ready for
167   interpretation were obtained by increasing the signal/noise ratios of the signals in the data processing. The
168   geophysical sections were prepared by also making a topographic correction in the inversion operation due to the
169   variability of the topography. Thus, the collected geophysical data were converted into 2D (two-dimension)
170   height-distance and depth-distance sections by being assessed in the appropriate software. Geophysical
171   interpretations were made according to these sections and compared with the results of the other studies.
172   Accordingly, 2D (two-dimension) seismic cross-sections giving seismic V_P-depth information are presented in
173   Fig. 4 and 5. In the seismic data evaluation, the coincidence was provided with RMS (Root Mean Square) errors
174   ranging between 3.4-4.5% in 2D (two-dimension) inversion operation. According to 2D (two-dimension)
175   seismic cross-sections, two or three layers were identified at about 20 m depth. It was understood that the tilts of
176   these layers were southeast oriented, and their tilt was greater than 50. According to seismic velocities (V_P)
177   calculated, three layers with the layer velocities of 0.30, 1.00 and 2.00 km/s on average were defined from top to
178   bottom. V_P values of these layers increase towards the deep. Layer thicknesses range between 3 m and 6.5 m on
179   average from top to bottom due to topographical differences. It was understood that the depth of the sliding
180   surface varied between about 7-10 m, and these depths were the upper bound of the third layer. The units are
181   loose up to this depth according to geological drilling logs (Hatipoğlu, 2009; Hastaoğlu, 2015). This area was
182   considered to have a risk of dislocation due to these loose units, rainfall and tilt conditions. Therefore, the layers
183   with an average of V_{P1}=0.3 km/s and V_{P2}=1.00 km/s over these depths were defined as the layers with the risk of
184   dislocation. The layer with a seismic velocity of greater than V_{P3}>2.00 km/s at the lowermost was understood to
185   be the basement layer. On the other hand, the investigation depth was further calculated from the SRT sections
186   compared to the GPR sections due to the differences of geophysical methods in the application. Because GPR
187   sections could be obtained as high resolution for about the first 10 m depth after inversion processing of the GPR
188   data (Fig. 6 and 7). Therefore, it could be said that the GPR and SRT sections are compatible for the first 10 m
189   depth. Besides, the profile lengths of the GPR3 and GPR5 sections in Fig. 7 were evaluated as about 25-35 m.
190   According to the GPR sections in Fig. 6 and 7, there is a layer with a varying thickness of about 3 mm at
191   the uppermost. It is seen that the second layer under this layer proceeds until about 7-10 m depth. These layers
192   are weak, loose and reworked layers with refractions that lost their thickness with low seismic velocity.
193   However, three layers were identified in seismic sections, and their seismic velocity was observed to increase
194   towards the depth (0.30<1.00<2.00<… km/s). Accordingly, the fact that the problems seen in the first two layers
195   decreased and ended towards deeper layers (>7-10 m) is understood from the increase in seismic velocities
196   (>2.00 km/s). Therefore, it was understood from the geophysical and geological data obtained for the landslide
197   basement and the layer over it that new landslides may occur over time in the study area due to the tilt and
198   abrasion and transports during precipitation.
199   The electromagnetic wave velocity in the GPR sections is V=0.1 m/ns. This value is generally observed in
200   dry or wet soil, dry or wet clay and sandy environments (Wilchek, 2000; Cardomina, 2002). The high-frequency
201   electromagnetic waves can reach deeper in the environments with low conductivity like sand. However, the

202 conductive units such as clay and shale decrease the penetration depth of the signal transmitted and lead to
203 absorption (Annan et al., 1988; Davis and Annan, 1989). Hatiboğlu (2009) and Hastaoğlu et al. (2015) generally
204 observed two geological units in the wells in the study area. They observed that the upper unit was silty sandy
205 clay and sand interbedded silty clay in some places up to about 10 m, and advanced as sand interbedded silty
206 clay and sand interbedded clay in some places towards deeper than 10 m. Therefore, it was understood that this
207 velocity value was compatible with the units and electromagnetic waves led to rapid absorption due to the layers
208 with clay content. Furthermore, sliding surfaces, landslide furrows, scarps, cracks was observed in the GPR
209 cross-sections, in A and C area (Fig. 6 and 7). In other words, the geological unit, the layer or topography slope
210 and precipitation cause deformations in the loose upper unit. Therefore, these structures may develop or occur in
211 the landslide mass, as shown in Fig. 6 and 7.

212 **3.3 Seismological and meteorological data and results**

213 The study area is located in an active area in terms of seismicity. The seismological history, the magnitude (M)
214 of which is greater than 2.5, of the examined area and its surrounding between 1900-2015 were investigated for
215 this article (Fig. 8). The map in Fig. 8 was prepared with the seismological data between 1900-2015 (UDİM,
216 2016). Particular attention was paid to the earthquakes before 2005 in the seismological interpretation. This is
217 because the largest and most recent landslide occurred in the area in 2005 and it was aimed to investigate its
218 relationship with displacements and previous landslides. The type of magnitude which is calculated from
219 seismological data is usually the local magnitude. The depths (d) of these earthquakes with higher M>2.5 vary
220 between approximately 5 and 80 km (Fig. 8). According to the seismic data of the years examined, Koyulhisar
221 and its surroundings have always been active seismically. It was observed that this frequency of earthquakes
222 usually occurred on the NAFZ in the south of the study area. Additionally, it has been analyzed the seismic
223 activity of the region at least for the last 112 (1904-2016) years by Demir (2018). In this study, he express that
224 the most notable is probably the relationships between the magnitude of the earthquake to the number of
225 landslides and the area affected by the landslides and between the magnitude and the maximum distance of
226 landslide observations from the epicenter in different geological, topographical, and climatic conditions (Demir,
227 2018).

228 Large earthquakes affecting Koyulhisar district also occurred in the region. These largest earthquakes are
229 in the south of the NAFZ or Suşehri district and a total of three large earthquakes with M≥5.6 occurred there
230 (Över, 2015). Among these, 1992 earthquake is closest to the study area with the least depth but the second
231 largest earthquake (Fig. 8). This earthquake is an earthquake with 6.1 magnitude that occurred 10 km below the
232 ground. The large earthquakes in the south of Suşehri district which is just 13 km away from the study area
233 occurred in 1909 and 1939. 1909 earthquake occurred 60 km below the ground and is the largest and deepest
234 earthquake with a magnitude of 6.3. 1939 earthquake is also deep and the third largest earthquake that occurred
235 50 km below the ground with a magnitude of 5.6 (Över, 2015). In addition, when Fig. 8 is analyzed, it is seen
236 that the magnitudes of the other earthquakes in the north of the NAFZ and the upper elevations of the landslide
237 generally vary between 2.5-4. Similarly, it is seen that the other earthquakes in the south of the landslide area are
238 the earthquakes with a magnitude of greater than 3.6. All these earthquakes may have triggered the landslide
239 mass from time to time in places where sliding surfaces, layers, and topography in the landslide area are more
240 inclined than 5-10 degrees (according to the geophysical cross-sections in this article, when it is considered that

Natural Hazards
and Earth System
Sciences
Discussions

241 there are loose units and deformations on the sliding surfaces). In particular, they further affected the landslide

242 mass along with the rain and caused large amounts of displacement in the landslide area.

243   The data regarding the rainfalls with the effects of triggering the landslides are presented in Table 1 and

244 Fig. 9 (MGM, 2016). With these data, the rainfall status of the study area and its surrounding was examined by

245 months as average annual rainfalls and the annual areal amount of rainfall. According to the data obtained

246 between 1950-2015 in Table 1, the rainy periods are generally between October-November-December and

247 January-February-March-April. The highest total daily amount of rainfall in the rainiest years was observed as

248 snowfall in 1950 (110 cm) and as rain in 1991 (55 kg/m^2).

249   According to Fig. 9, the annual normal average rainfall value calculated for the years between 1981-2010

250 was calculated as over 483.4 mm. However, 1987-1988 and 1997-1998 were the rainiest years. It is seen that the

251 annual areal amount of rainfall exceeded the normal values and was higher than 550 mm in these rainy years that

252 took place in every 10 years. Similarly, it is also seen that there were high rainfalls for 3-4 years after the years

253 of 1985-1995-2005 with an interval of 10 years. Therefore, annual areal rainfalls were observed to be more

254 before some large landslides like the landslide in 1998. When geological features of the region are taken into

255 account, it is remarkable that the landslide in 1998 and 2000 occurred in the summer months after the winter

256 with a heavy fall of snow. However, the landslide in 2005 occurred during the rainy season. Therefore, rainfalls

257 have always been considered as a factor triggering these landslides in many studies and articles (Tatar et al.,

258 2007; Hastaoğlu et al., 2015). Similarly, the authors of this article have always considered rainfalls as a

259 triggering factor in the formation of Koyulhisar landslides. As it is seen, the various studies and the results of

260 this article have proved that Koyulhisar landslides are generally caused by the known reasons that trigger the

261 landslide. Because the seismic activity, the meteorological data and the other conditions mentioned in the

262 landslide area have shown that the landslides could be triggered there.

263 **3.4 Geodetic surveys and results**

264 Hastaoğlu et al. (2015) have carried out multi-disciplinary studies and GNSS studies for many years (about 6

265 years) to determine the deformation and annual sliding amounts especially after the landslides in 1998-2000-

266 2005. It was determined that the tension cracks that occurred in the landslides in 1998 and 2000 in the region

267 were filled with the waters consisting of melting snow and rain waters which are the most important component

268 of the hydrological cycle, lakes were formed in the buttress of each sliding mass, and the changes in the

269 groundwater level were the main causes of deformation (Sendir and Yılmaz, 2001; Topal and Hatiboğlu, 2015;

270 Hastaoğlu et al., 2015). The seismological and meteorological data, which were updated by the geodetic (GNSS

271 (DH), geological (IDH (Inclinometer Drilling Holes)) and meteorological data collected in the local study of

272 Hastaoğlu et al. (2015), were reorganized and evaluated. Fig. 2, 9, 10 and Table 1 which were reprepared for the

273 study which is the subject of this article were associated with the results of GNSS studies (Fig. 10). Then, they

274 were compared with geophysical results in interpretation.

275   The monthly and annual meteorological data should certainly be evaluated particularly within the scope of

276 monitoring activities because the area which is the subject of the study is a landslide area. Hastaoğlu et al. (2015)

277 performed monitoring in IDH wells in the area in 2013-2014 (Fig. 10). If Fig. 2 is examined, there are seven

278 IDH point in the nearest of the geophysical profiles. The graphics in Fig. 10 were prepared from the combined

279 data (unpublished data in the project) and the temperature (^{0}C), precipitation (m^3) and soil moisture content (cm)

280 were compared in these graphics. Accordingly, the temperature and precipitation were observed to be inversely

Natural Hazards
and Earth System
Sciences
Discussions

281 proportional during the summer months called as a dry period. It is seen that the soil moisture is changeable
282 apart from the rainy period and has very high water content during the rainy periods. On the other hand, it was
283 understood that the precipitation increased by the decrease in temperatures. It is also seen that the total annual
284 amount of rainfall increased about 2-fold in 2014 compared to 2013 (Fig. 9 and 10). According to all results,
285 rainfalls are considered to be effective in triggering of the landslide because the ground of this landslide area,
286 which is filled with loose units and old cracks, is supersaturated with water due to the rainfalls.

287 Besides, Hastaoğlu et al. (2015) determined that the groundwater level gets close to the surface for 4-6 m
288 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 some
289 wells in the area where geophysical study area is also located, and the groundwater flow direction is SW. When
290 this information was associated with topography and in line with the field observations, it was understood that
291 the topography was inclined from the north of the study area towards south, the incline of slope decreased from
292 925 m to 840 m, there was an elevation difference of 85 m, and the amount of slope in the topography increased
293 from south to north ($>5^0$-10^0) (Fig. 2a). Therefore, it was seen that the geological bedding was compatible with
294 the topographical sloping and the groundwater was compatible with the direction of flow. Hatiboğlu (2009) and
295 Hastaoğlu et al. (2015) observed that the geological units advanced as silty sandy clay from top to bottom and
296 partly sand interbedded silty clay under the topsoil and as sand interbedded silty clay and sand interbedded clay
297 in some places towards deeper than about 10 m in IDH wells in the geophysics study area. Hastaoğlu et al.
298 (2015) estimated with the GPS measurements that the amounts of displacement varied between 1-8.6 cm/year.
299 The geophysical data were collected in the areas where the amount of displacement varied about 8.6 cm/year.
300 The landslide direction was determined to be in the S-SW and SE direction across Koyulhisar (Hastaoğlu et al.,
301 2015). It was understood that these directions were compatible with the geophysical sections which were
302 prepared later and that the rainfalls are among the reasons that trigger the landslide.

303 **4 Conclusions**
304 This study is the first geophysical study carried out in Koyulhisar landslide area. The information provided from
305 many studies (geodetic, geologic, morphologic, seismological, topographic and meteorological) carried out
306 across the region was compared with the geophysical results (SRT and GPR) and found to be compatible. The
307 bedding status of the landslide area, seismic P-wave velocity (V_P) of the layers, the tilt, tilt direction of the
308 layers, depth of the sliding surface and sliding direction and the landslide type could be determined from the
309 geophysical sections. Accordingly, the study area was identified by the layers with the average seismic velocities
310 of 0.30 < 1.00 < 2.00 <… km/s (or 300, 1000 and 2000 m/sec). The seismic velocity of the landslide basement
311 was found to be higher than 2000 m/sec. According to the geophysical cross-sections, it was understood that the
312 depth of the sliding surface varied between 7-10 m due to the topographical differences. These depths are the
313 depths with low seismic velocities (the average V_P, <0.30 and <1.00 km/s) and defined as loose units which were
314 also observed in geological drilling logs. It is understood that sliding surfaces, landslide furrows, collapsed
315 zones, scarps, cracks are observed in the GPR sections. Furthermore, it was understood that the layer tilt was
316 generally more than 5^0 in all geophysical sections and compatible with the geology and the flow direction of the
317 groundwater. It was understood that the landslide type in the area was planar sliding and the direction of sliding
318 was SE.

319 The geophysical and geodetic study results were found to be compatible because it is known that the
320 landslide direction across Koyulhisar is in S-SW and SE. Consequently, the fact that the depth of the sliding

Natural Hazards
and Earth System
Sciences
Discussions

321 surface over the units is loose, low seismic velocities of the upper layers and the excessive tilt prove that there is

322 a new risk of landslide in the area. The other factors that trigger the landslide were found to be associated

323 especially with the fact that the area is seismically active, receives heavy rain and has a poor vegetation cover.

324 Furthermore, it was understood that there were deformations in the landslide mass and, observed the sliding

325 surfaces, landslide furrows, collapsed zones, scarps and cracks structures. It was understood that these structures

326 were occured from the geological unit, the layer or topography slope and precipitation. On the other hand, it was

327 understood that studies such as blasting and excavation performed by human intervention can trigger the

328 landslides and hence the landslide area is a potential area which is open to natural/artificial hazards. As a result,

329 according to all the results, there is still a high landslide hazard in the study area and its surrounding, and this

330 hazard will be also in the future. As a result, the identified risks and natural hazards are also threatened the

331 settlement area and the buildings and other constructions (e.g. roads, walls, parks et al.) there.

339 **References**

340 Adlaş, G. U., Kadıoğlu, S., Ulugergerli, E. U.: The effects of concealed discontinuities in blast design Pattern, 4th Int.
341 Scientific and Technical Conference of Young Scientists and Specialists, St. Petersburg-RUSSIA, 6-7, 2003.

342 Bano, M., Marquis, G., Niviere, B., Maurin, J. C., Cushing, M.: Investigating alluvial and tectonic features with ground
343 penetrating radar and analyzing differactions paterns, J. Appl. Geophys., 43, 3-41, 2000.

344 Benson, A. K.: Applications of ground penetrating radar in assessing some geological hazards: Examples of groundwater
345 contaminants, faults, cavities, J. Appl. Geophys., 33, 177-193, https://doi.org/10.1016/0926-9851(95)90040-3, 1995.

346 Bichler, A., Bobrowsky, P., Best, M, Douma, M., Hunter, J., Calvert, T., Burns, R.: Three-dimensional mapping of a
347 landslide using a multi-geophysical approach: the Quesnel Forks landslide, Landslides, 1, 29-40, DOI 10.1007/s10346-
348 003-0008-7, 2004.

349 Bubeck, A., Wilkinson, M., Roberts, G. P., Cowie, P. A., McCaffrey, K. J. W., Phillips, R., Sammonds, P.: The tectonic
350 geomorphology of bedrock scarps on active normal faults in the Italian Apenninesmapped using combined ground
351 penetrating radar and terrestrial laser scanning, Geomorphology, 237, 38-51, DOI:10.1016/j.geomorph.2014.03.011, 2015.

352 Cardimona, S.: Subsurface investigation using ground penetrating radar, Presented at the 2nd International Conference on the
353 Application of Geophysics and NDT Methodologies Transportation Facilities and Infrastructure, LosAngels, California,
354 2002.

355 Davis, J. L., Annan, A. P.: Ground-penetrating radar for high resolution mapping of soil and rock stratigraphy, Geophys.
356 Prosp., 37, 531-551, DOI: 10.1111/j.1365-2478.1989.tb02221.x, 1989.

357 Demir, G.: Landslide susceptibility mapping by using statistical analysis in the North Anatolian Fault Zone (NAFZ) on the
358 northern part of Suşehri Town, Turkey, Nat. Hazards, 92, 133-154, https://doi.org/10.1007/s11069-018-3195-1, 2018.

359 Demirağ, O.: Jeofizik yöntemlerle heyelan araştırmaları, TMMOB-JFMO (The Chamber of Geophysical Engineers of
360 Turkish) publications, Jeofizik, 5(1); 43-50, Ankara, Turkey, 1991 (in Turkish).

361 Demirel, M., Tatar, O., Koçbulut, F.: Kinematics of the faults around the Koyulhisar (Sivas) region on the North Anatolian
362 Fault Zone, Geol. Bull., Turkey, 59(3),357-370, 2016 (in Turkish).

363 Duman, T. Y., Nefeslioğlu, H., Gökçeoğlu, C., Sönmez, H.: 17/03/2005 Kuzulu (Sivas-Koyulhisar) heyelanı, Maden Tetkik
364 ve Arama Genel Müdürlüğü Jeoloji Etütleri Dairesi, Hacettepe Üniversitesi, 2005.

365 Gren, A., Gross, R., Holliger, K., Horstmeyer, H., Baldwin, J.: Results of 3D georadar surveying and trenching the San
366 Andreas fault near its northern landward limit, Tectonophysics, 368, 7-23, doi:10.1016/S0040-1951(03)00147-1, 2003.

367 Gökçeoğlu, C., Nefeslioğlu, H. A., Sönmez, H., Duman, T., Can, T.: The 17 March 2005 Kuzulu landslide (Sivas, Turkey)
368 and landslide-susceptibility map of its near vicinity, Eng. Geol., 81 (1), 65-83, DOI:10.1007/s00254-006-0322-1, 2005b.

369 Göktürkler, G., Baklaya, Ç., Erhan, Z.: Geophysical investigastion of landslide: The Altındağ landslide site, Izmir (western
370 Turkey), J. Appl. Geophys., 65, 84-96, https://doi.org/10.1016/j.jappgeo.2008.05.008, 2008.

371 Hack, R.: Geophysics for slope stability, Surv. Geophys., 21, 423-338, 2000.

372 Harrari, Z.: Ground penetrating radar (GPR) for imaging stratigrafic features and groundwater in sand dunes, J. Appl.
373 Geophys., 36, 43-52, https://doi.org/10.1016/S0926-9851(96)00031-6, 1996.
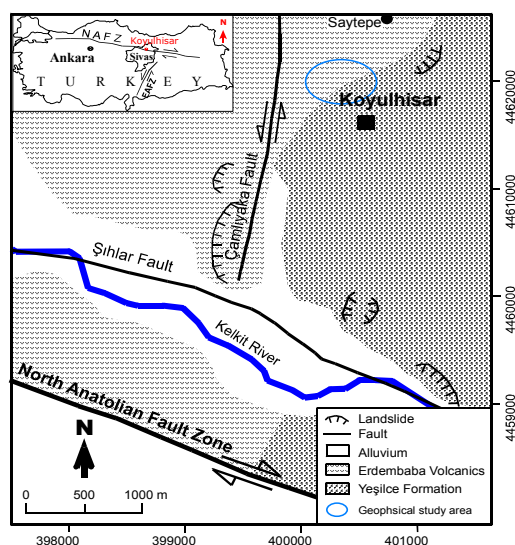
374 Hastaoğlu, K. O.: Investigation of the groundwater effect on slow-motion landslides by using dynamic Kalman filtering
375   method with GPS: Koyulhisar town center, Turkish J. Earth Sci., 1033-1046. DOI: 10.3906/yer-1210-10, 2013.
376 Hastaoğlu, K. O., Şanlı, D. U.: Monitoring Koyulhisar landslide using rapid static GPS: a strategy to remove biases from
377   vertical velocities, Nat. Hazards, 58, 1275-1294, DOI:10.1007/s11069-011-9728-5, 2011.
378 Hastaoglu, K. O.: Comparing the results of PSInSAR and GNSS on slow motion landslides, Koyulhisar, Turkey, Geomatics,
379   Nat. Hazards and Risk, 7, 2, 786-803, DOI: 10.1080/19475705.2014.978822, 2016.
380 Hatiboğlu, O.: Investigation Of Koyulhisar (Sivas) Settlement Area In Terms of Slope Instability, Middle East Technical
381   University, MS Thesis, Ankara, Turkey, 2009.
382 Hu Z., Shan W.: Landslide investigations in the northwest section of the lesser Khingan range in China using combined HDR
383   and GPR methods, Bull. Eng.. Geol. Environ., 75, 591-603, DOI 10.1007/s10064-015-0805-y, 2016.
384 Lazzari, M., Geraldi, E., Lapenna, V., Loperte, A.: Natural hazards vs human impact: an integrated methodological approach
385   in geomorphological risk assessment on the Tursi historical site, Southern Italy, Landslides, 3, 275-287. DOI
386   10.1007/s10346-006-0055-y, 2006.
387 Lissak, C., Maquaire, O., Malet J.P., Lavigne, F., Virmoux, C., Gomez, C., Davidson, R.: Ground-penetrating radar
388   observations for estimating the vertical displacement of rotational landslides, Nat. Hazards Earth Syst. Sci., 15, 1399-
389   1406, doi:10.5194/nhess-15-1399-2015, 2015.
390 McCann, D. M., Forster, A.: Reconnaissance geophysical methods in landslide investigations, Eng Geol 29(1):59-78,
391   https://doi.org/10.1016/0013-7952(90)90082-C, 1990.
392 MGM: Meteoroloji Genel Müdürlüğü (Turkish State Meteorological Service), Ankara Meteoroloji Bölge Müdürlüğü'nün
393   Hidrotermal Şube Müdürlüğü (Hydrothermal Directorate of Ankara Meteorology Regional Directorate).
394   https://www.mgm.gov.tr/ (accepted: 12.11.2008), 2016.
395 MTA: General Directorate of the Mineral Research and Exploration (MTA), (last access: 11.04.2018),
396   http://yerbilimleri.mta.gov.tr/anasayfa.aspx, 2018.
397 Otto, J. C., Sass, O.: Comparing geophysical methods for talus slope investigations in the Turtmann valley (Swiss Alps),
398   Geomorphology, 76, 257-272, doi:10.1016/j.geomorph.2005.11.008, 2006.
399 Över, D.: The Research of The landslide area ground of Koyulhisar district in Sivas with geophysical methods,
400   Cumhuriyet University, MS Thesis, Sivas, Turkey, 2015.
401 Perrone A., Iannuzzi, A., Lapenna, V., Lorenzo, P., Piscitelli, S., Rizzo, E., Sdao, F.: High-resolution electrical imaging of
402   the Varco d'Izzo earthflow (southern Italy), J. Appl. Geophys., 56, 17-29, DOI:10.1016/j.jappgeo.2004.03.004, 2004.
403 Popescu, M., Şerban, R. D., Urdea, P., Onaca, A.: Conventional geophysical surveys for landslide investigations: Two case
404   studies from Romania, Carpathian J. Earth and Environ. Sci., 11(1), 281-292, 2016.
405 Ristić, A., Abolmasov, B., Govedarica, M., Petrovački, D.: Shallow-Landslide Spatial Structure Interpretation Using A
406   Multi-Geophysical Approach, Acta Geotechnica Slovenica, 47-59, 2012.
407 Sendir, H., Yılmaz, I.: Koyulhisar Heyelanlarına Yapısal ve Jeomorfolojik Açıdan Bakış, Cumhuriyet Üniversitesi
408   Mühendislik Fakültesi Dergisi, Seri A: Yer Bilimleri, 18 (1), 47-54, 2001 (in Turkish).
409 Sendir, H., Yılmaz, I.: Structural, geomorphological and geomechanical aspects of the Koyulhisar landslides in the North
410   Anatolian Fault Zone (Sivas, Turkey), Environ. Geol., 42, 52-60, https://doi.org/10.1007/s00254-002-0528-9, 2002.
411 Slater, L., Niemi, T. M.: Ground penetrating radar investigation of active faults along the Dead Sea transform and
412   implications for seismic hazards within the city of Aqaba, Jordan, Tectonoyhsics, 368, 33-50, 2003.
413 Su, L., Xu, X., Geng, X., Liang, S.: An integrated geophysical approach for investigating hydro-geological characteristics of
414   a debris landslide in the Wenchuan earthquake area, Eng. Geol., http://dx.doi.org/10.1016/j.enggeo.2016.11.020, 2016.
415 Tatar, O., Gürsoy, H., Gökçeoğlu, C., Koçbulut, F., Duman, T. Y., Kök S., Süllü, H., Şenyurt, A., İleri, N.: 17 Mart 2005
416   Sivas İli Koyulhisar İlçesi Sugözü Köyü Kuzulu Mahallesi Heyelanı 2. Değerlendirme Raporu,
417   http://www.koyulhisar.gov.tr/bulten3.doc., 2005 (in Turkish).
418 Tatar, O., Gürsoy, H., Altunel, E., Akyüz, S., Topal, T., Sezen , T. F., Koçbulut, F., Mesci, L., Kavak, K.Ş., Dikmen, Ü.,
419   Türk, T., Poyraz, F., Hastaoğlu, K., Ayazlı, E., Gürsoy, Ö., Polat, A., Akın, M., Demir, G., Zabcı, C., Karabacak, V.,
420   Çakır, Z.: Kuzey Anadolu Fay Zonu üzerinde Kelkit Vadisi boyunca yer alan yerleşim alanlarının doğal afet risk analizi,
421   CBS tabanlı afet bilgi sistemi (KABİS) tasarımı: Proje tanıtımı ve ön bulgular. Aktif Tektonik Araştırma Grubu 11.
422   Çalıştayı, TÜBİTAK-MAM Yer ve Deniz Bilimleri Enstitüsü Gebze-Kocaeli, Türkiye, 14-16, 2007 (in Turkish).
423 Terlemez, İ., Yılmaz A.: Ünye-Ordu-Koyulhisar-Reşadiye arasında kalan yörenin stratigrafisi, TJK Bülteni, 21, 179-191, 1980
424   (in Turkish).
425 Timothy R. H. Davies, Warburton J., Stuart A. Dunning, Alodie A. P. Bubeck: A large landslide event in a post-glacial
426   landscape: rethinking glacial legacy, Earth Surface Processes and Landforms, 38(11), 1261-1268,
427   https://doi.org/10.1002/esp.3377, 2013.
428 Topal, T., Hatiboğlu O.: Assessment of slope stability and monitoring of a landslide in the Koyulhisar settlement area (Sivas,
429   Turkey), Environ. Earth Sci., 74(5), DOI 10.1007/s12665-015-4476-6, 2015.
430 Toprak, G. M. V.: Tectonic and stratigraphic characterstics of the Koyulhisar segment of the North Anatolian Fault Zone
431   (Sivas-Turkey), METU (unpublished), PhD. Thesis, Ankara, Turkey, 121, 1989.
432 Türk, T.: Hava fotoğrafı ve optik uydu görüntüleri yardımıyla yatay yer değiştirmelerin belirlenmesi, Havacılık ve Uzay
433   Tekn. Derg., 6 (1), 71-79, 2013 (in Turkish).
434 UDİM: Ulusal Deprem İzleme Merkezi (National earthquake monitoring center), Boğaziçi Universty KOERI (Kandilli
435   Observatory And Earthquake Research Institute), www.koeri.boun.edu.tr/sismo/, (last access: 11.04.2018), Istanbul,
436   Turkey, 2015.
437 Uysal, S.: Koyulhisar (Sivas) yöresinin jeolojisi, General Directorate of the Mineral Research and Exploration (MTA) Report
438   number: 9838, 1995 (in Turkish).
439 Ulusay, R., Aydan, Ö., Kılıç, R.: Geotechnical assessment of the 2005 Kuzulu landslide (Turkey), Eng. Geol., 89(1-2), 112-
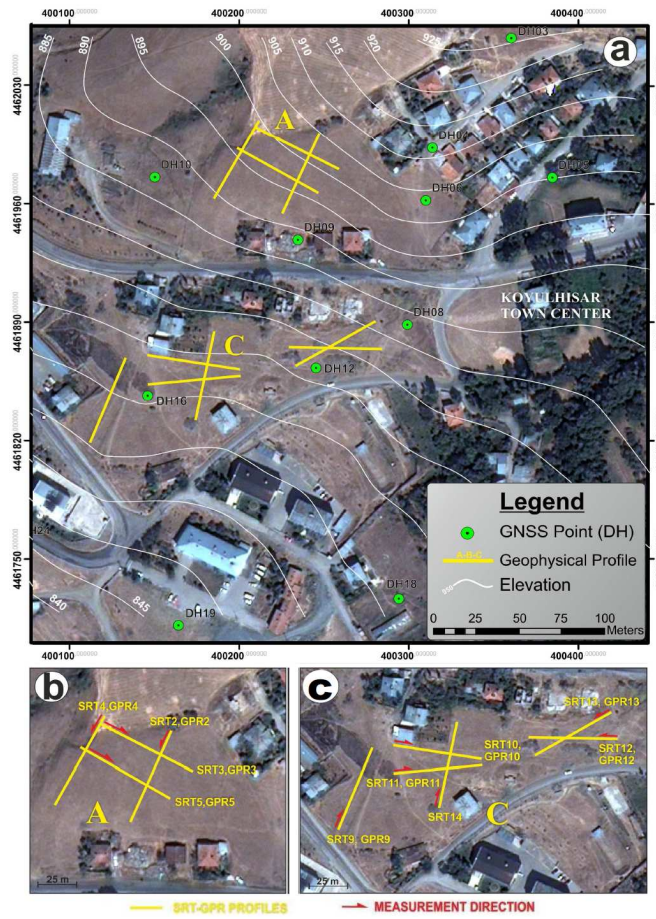440   128, 2007.

441 Wilchek, L.: Ground Penetrating Radar for Detection of Rock Stucture, MS Thesis, Alberta University, Canada, 2000.
442 Yılmaz, I.: A case study from Koyulhisar (Sivas-Turkey) for landslide susceptibility mapping by artificial neural Networks,
443   Bull. Eng. Geol. and the Environ., 68, 297-306, 2009.
444 Yılmaz, I., Ekemen T., Yıldırım M., Keskin İ., Özdemir G.: Failure and flow development of a collapse induced complex
445   landslide: the 2005 Kuzulu (Koyulhisar, Turkey) landslide hazard, Environ. Geol., 49, 467-476, 2005.
446
447   **NHESS - Figures**

448
449   **Figure 1.** Geological map of study area arranged from Sendir and Yılmaz (2002) and Hastaoğlu (2016).

450

Figure 2. (a) Geophysics and geodetic data collection locations in the study area. (b), (c) and (d) geophysics
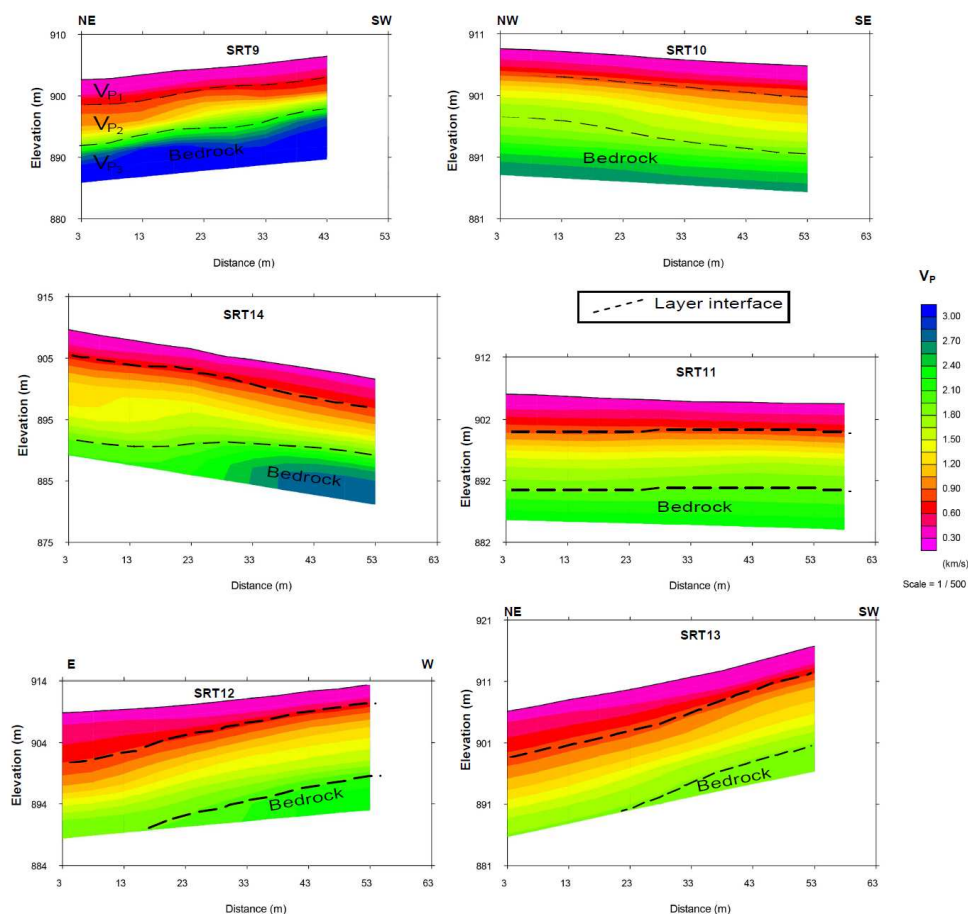profile details.

453

454

Figure 3. Landslide scene photos (landslide, lanslide cracks and constructional damages).
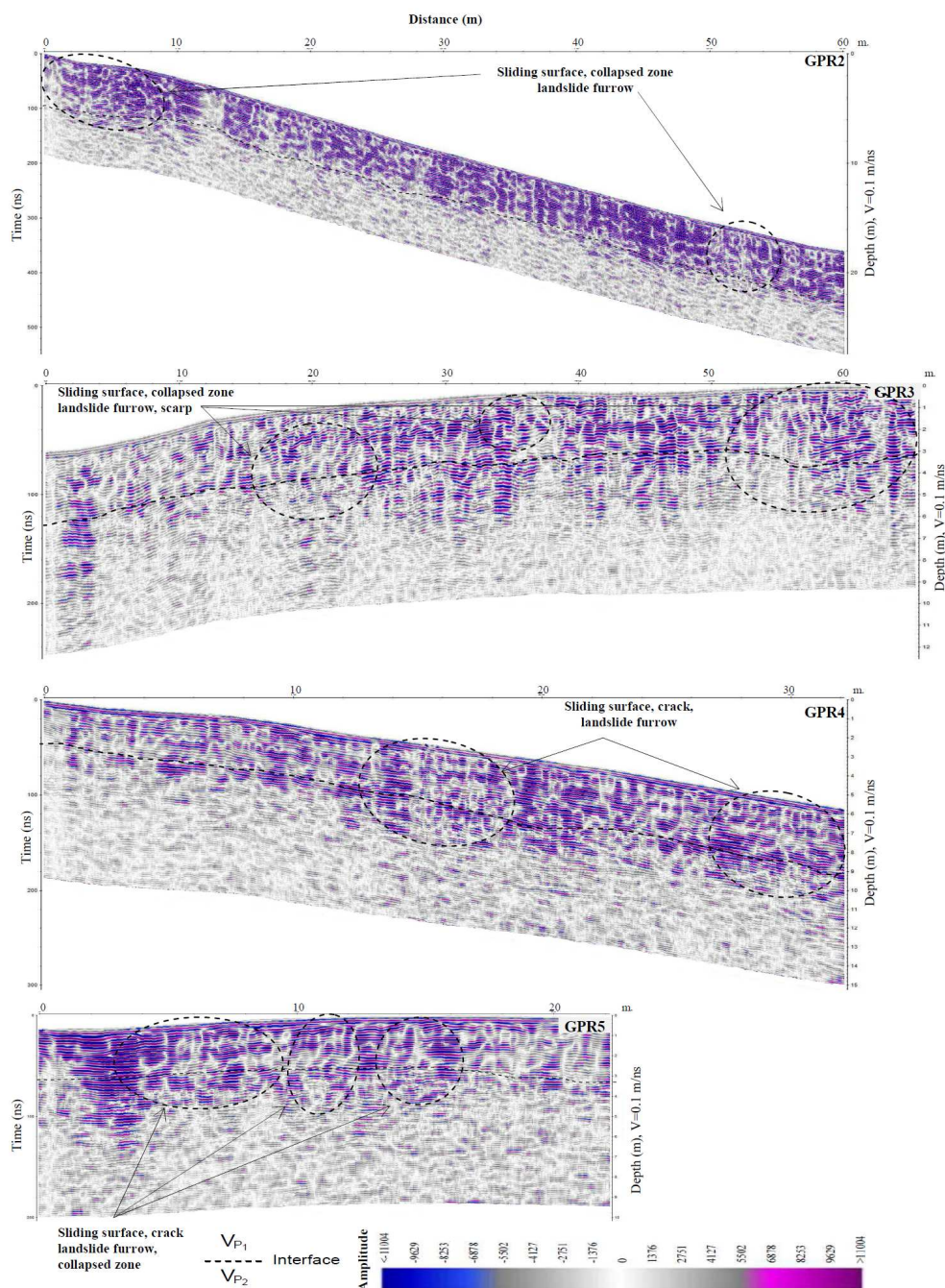
456
457 **Figure 4.** The seismic profiles of the area **A**. The uppermost boundary of the bedrock layer (V_{P3}) on the SRT
458 images is aproximately GPR depth. The lower seismic velocity loose layers (consisting of soil and alluviums, the
459 average seismic V_{P1}=0.3 km/s and V_{P2}=1.0 km/s) are on the bedrock (the average seismic V_{P3}>2.0 km/s).
460

461

462

463

464

465

466

467

468

469

470

471

472

473

474

475

476

Figure 5. The sismic profiles of the area **C**. The uppermost boundary of the bedrock layer (V_{P3}) on the SRT
images is aproximately GPR depth. The lower seismic velocity loose layers (consisting of soil and alluviums, the
average seismic $V_{P1}=0.3$ km/s and $V_{P2}=1.0$ km/s) are on the bedrock (the average seismic $V_{P3}>2.0$ km/s).
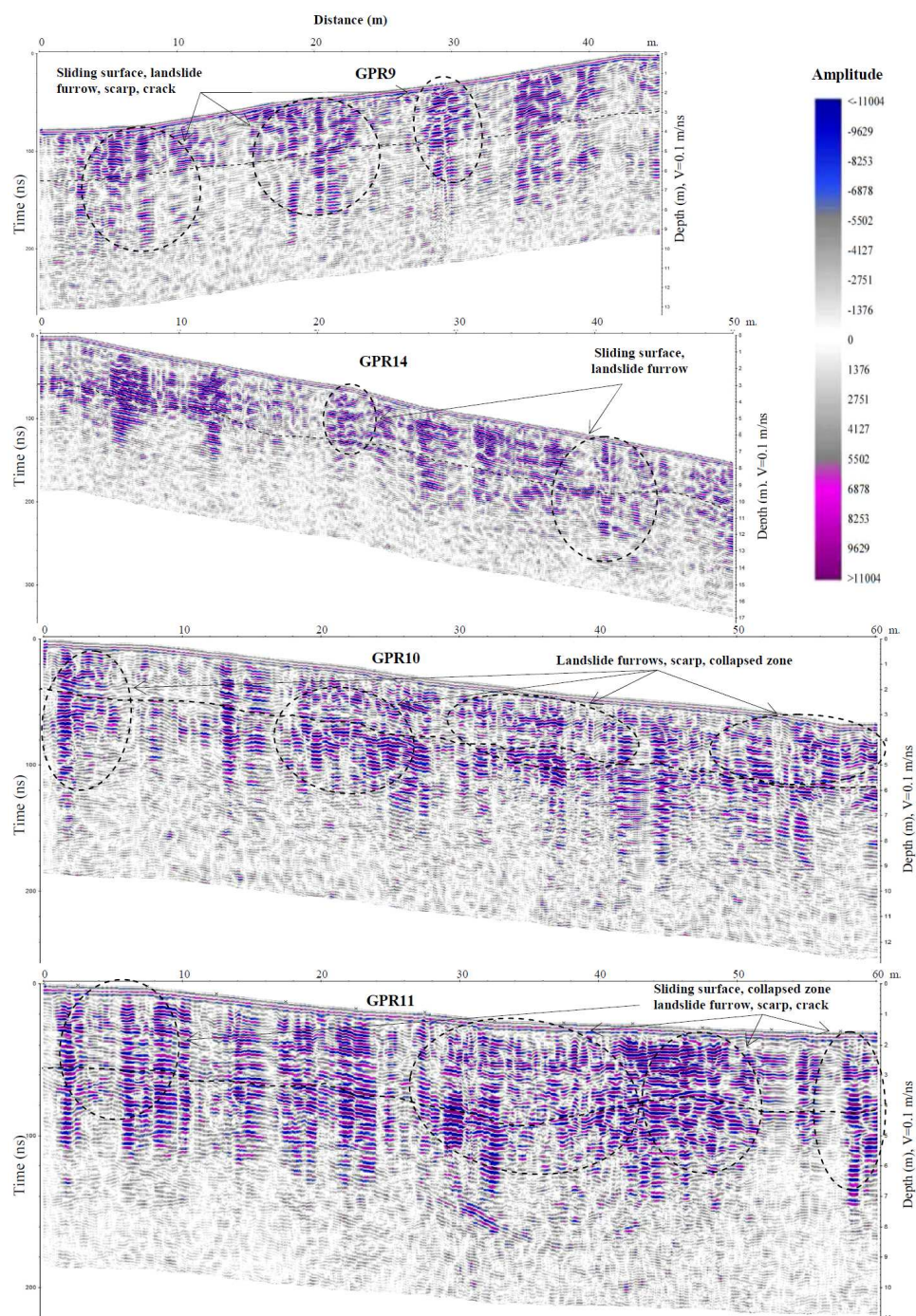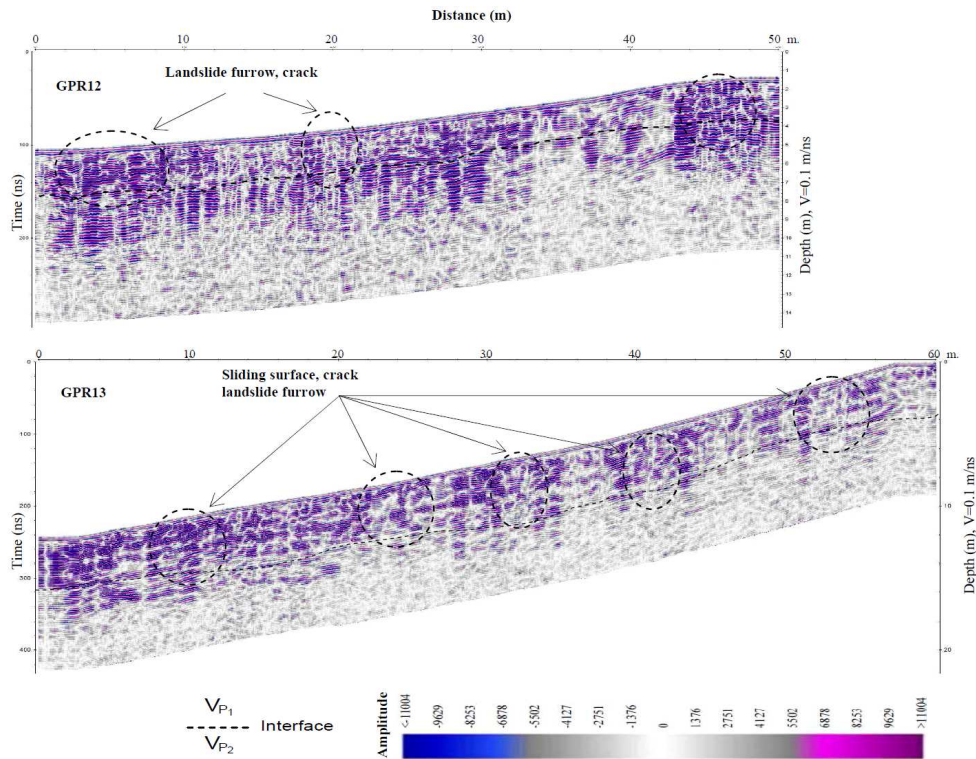
480

481

482

483

484

485

486

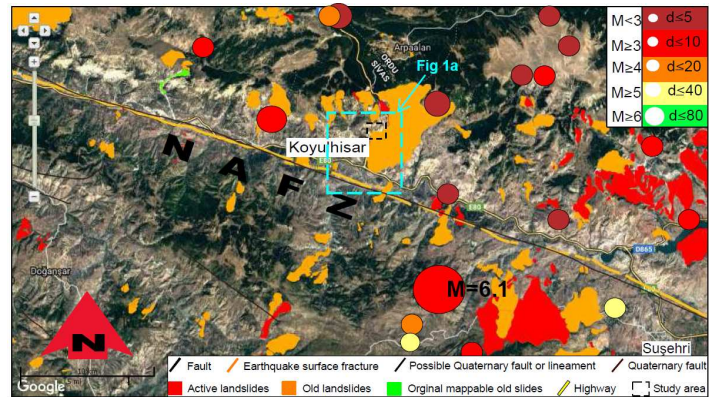**Figure 6.** GPR profiles in A area and the deformations in the loose layers (the seismic V_{P1} and V_{P2} layers).

Figure 7. GPR profiles in the C-west area and the deformations in the loose layers (the seismic V_{P1} and V_{P2} layers).
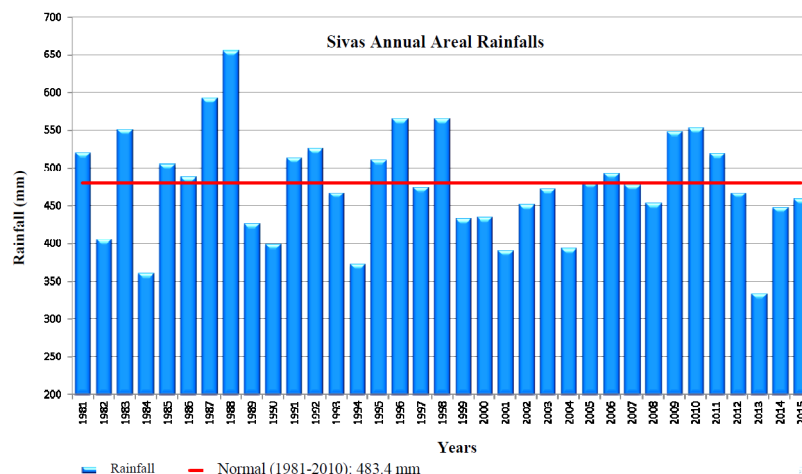
Natural Hazards
and Earth System
Sciences

Open Access

EGU

Discussions

495
496 **Figure 7. (…contiue)** GPR profiles in the C-east area and the deformations in the loose layers (the seismic V_{P1}
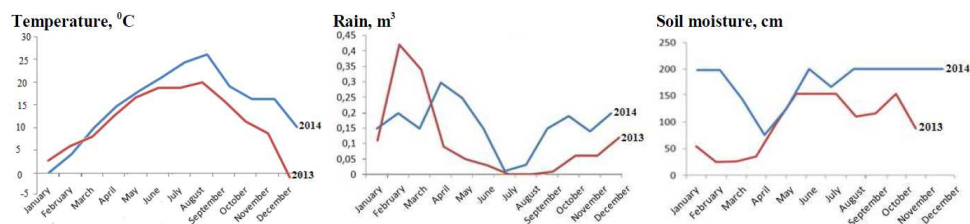497 and V_{P2} layers).
498

499
500 **Figure 8.** Seismic activity of the study area and its surroundings by the data between 1900-2015 and the
501 landslide areas (UDIM, 2016; MTA, 2018).
502

503

504

505
Figure 9. Precipitation distribution in between 1981-2015 years of Sivas (MGM, 2016).
506

507

508
509 **Figure 10.** Average monthly temperature (T, ^{0}C), rainfall (m^3) and soil moisture content (cm) change graphics of
510 the study area and its surrounding for 2013-2014. It was prepared from the project data (Hastaoğlu et al., 2015).
511

512   **Table**

513   **Table 1.** The annual average meteorological values of Sivas by years between 1950-2015 (MGM, 2016).

SIVAS	January	February	March	April	May	June	July	August	September	October	November	December
The average tempreture (^{0}C)	-3.2	-2.0	2.9	9.1	13.5	17.2	20.2	20.2	16.2	10.8	4.6	-0.6
The average the highest tempreture (^{0}C)	1.0	2.6	8.1	15.3	20.0	24.0	27.9	28.5	24.7	18.4	10.6	3.7
The average the lowest tempreture (^{0}C)	-7.0	-6.2	-1.7	3.4	7.2	9.9	12.0	11.9	8.3	4.4	-0.2	-4.2
The average sunshine duration (hour)	2.3	3.3	4.5	6.2	8.1	10.4	12.1	11.4	9.4	6.3	4.1	2.3
The average number of rainy days	13.0	12.4	13.7	14.0	14.4	8.8	2.5	2.1	4.3	8.0	9.5	12.1
The average monthly total rainfall (kg/m^2)	42.0	40.3	46.0	59.1	60.7	34.8	8.5	5.9	16.9	32.9	41.0	44.2
The highest and the lowest values occurring over many years (1950-2015)												
The highest tempreture (^{0}C)	14.6	18.1	25.2	29.0	32.0	35.5	40.0	39.4	35.7	30.5	22.8	19.4
The lowest tempreture (^{0}C)	**-34.6**	**-34.4**	**-27.6**	**-10.9**	**-4.2**	**-0.3**	**3.4**	**3.2**	**-3.8**	**-8.1**	**-24.4**	**-27.0**
Daily total the highest rainfall	2 May 1991	55.0 kg/m^2	Daily the fastest wind			5 Jan. 1996		122.8 km/h	The highest snow		2 Feb. 1950	110.0 cm

514

18