

NATURAL AND HUMAN-INDUCED SUBSIDENCE DUE TO GYPSUM DISSOLUTION: A CASE STUDY FROM INANDIK, CENTRAL ANATOLIA, TURKEY

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Abstract

Gypsum dissolves relatively quickly and gypsum karst can evolve on a rapid time scale that may be accelerated by human-induced change, often resulting in severe subsidence damage. The area close to Inandik stream in Central Anatolia, Turkey, is affected by subsidence in two ways: formation of collapse sinkholes on agricultural land and progressive subsidence in Inandik village that has damaged buildings. This study focuses on these subsidence phenomena. Seven large sinkholes were formed on a terrace where episodic incision of the fluvial system has led to reduced thickness and mechanical strength of the cavity roof; a process that also increases the hydraulic gradient and enhances cavity development in the terrace area. These processes formed a sinkhole-prone terrace surface. The other subsidence phenomena, which have increased progressively in the last decade, relate to human activity in Inandik village. Water consumption increased after domestic water service systems were installed in houses in 2007, and in 2012 a sewer system was built in the village. Due to cracks and breakage, leaking water from buildings and sewer pipes infiltrated the gypsum substratum, resulting in dissolution of the bedrock and superficial cavity formation, as shown by GPR and borehole data. The process leading to subsidence caused severe damage to buildings. Consequently, it was decided to relocate the village three km south of its current location because of the high level of damage.

Introduction

Gypsum has a high dissolution rate that is greater than carbonate rocks (Klimchouk et al., 1996; Martinez et al., 1998); therefore, gypsum karst can evolve at a much faster rate (Benito et al., 1995; Cooper and Saunders, 2002; Gutiérrez and Cooper, 2013; Gutiérrez et al., 2014; De Waele et al., 2017) and be further accelerated by human-induced changes. Such high solubility leads to problems, the most frequent of which is subsidence, thereby threatening property. The subsidence hazard has been observed in various countries with gypsum karst terrain (Sauro, 1996; Jassim et al., 1997; Cooper, 1998; Paukštys et al., 1999; Cooper and Saunders, 2002; Klimchouk and Andrejchuk, 1996, 2002; Delle Rose et al., 2004; Johnson, 2005; Parise and Trocino, 2005; Gutiérrez et al., 2008; Koutepov et al., 2008; Parise et al., 2004, 2009; Thierry et al., 2009; Del Prete et al., 2010; Iovine et al., 2010; Cooper and Gutiérrez, 2013; Gutiérrez and Cooper, 2013; Gutiérrez, 2016; Calligaris et al., 2017). In Oviedo (Spain), subsidence due to gypsum dissolution led to the demolition of 362 flats at a loss of 18 million euro (Pando et al., 2012). Many buildings in Calatayud (Spain) have also been affected by subsidence and some of them had to be demolished due to the extent of the damage (Gutiérrez and Cooper, 2002; Gutiérrez, 2014).

Turkey has extensive gypsum outcrops in the provinces of Sivas and Çankırı (Fig. 1a). Despite the importance of gypsum karst, there are only a limited number of studies aimed at understanding the karstification of gypsum and related problems caused by subsidence. Although gypsum karst studies have been carried out in the Sivas region (Alagöz, 1967; Karacan and Yılmaz, 1997; Günay, 2002; Waltham, 2002; Doğan and Yeşilyurt, 2004; Doğan and Özel, 2005; Yılmaz, 2007; Keskin and Yılmaz, 2016) there has been no research on karst features and related hazards in the Çankırı region, except on some fossil subsidence sinkholes east of Çankırı (Doğan, 2002).

The area encompassing Inandik stream in the south of Çankırı province (Fig. 1b) has been influenced both by progressive subsidence in Inandik village, causing damage to buildings, and the formation of collapse sinkholes on agricultural land (Fig. 1c). This study deals with the triggering factors and their relationship with subsidence hazards in the area, as well as examining the origin of the collapse sinkholes. To our knowledge, the case of Inandik is the first published example of building damage due to gypsum dissolution in Turkey. The results of this study will contribute to understanding the controlling factors of subsidence mechanisms in this country and other gypsum karst areas.

Materials and Methods

The subsidence phenomena were analyzed by geological, geomorphological, and geophysical data. To detect buried collapse sinkholes and their period of generation, multiple sets of aerial photographs (1953, 1956, 1971, 1990, and 2008), orthophotos and satellite images from 2010 and 2016 were used. The importance of multi-temporal analysis for

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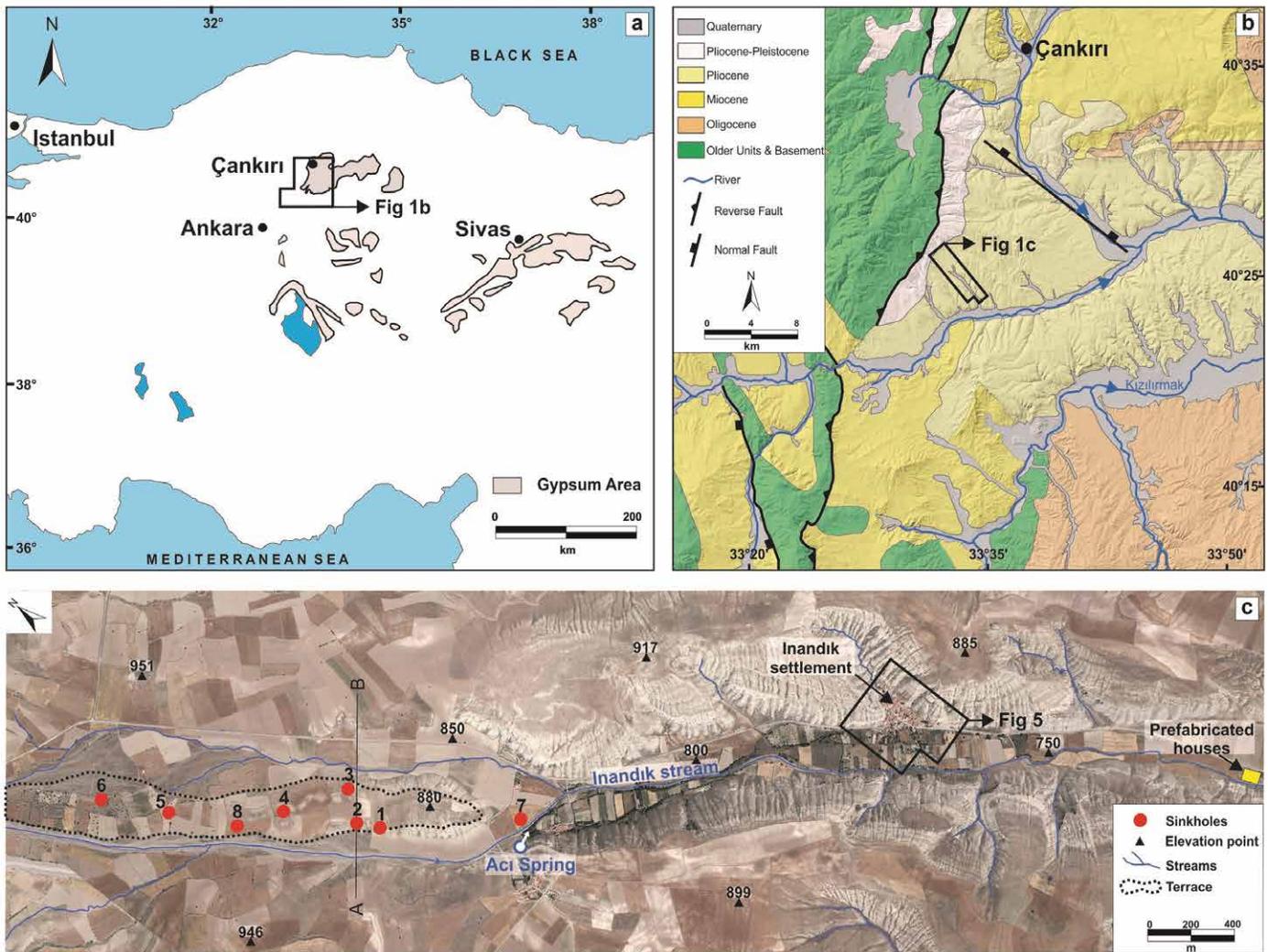


Figure 1. (a) Map showing location of study area. (b) Distribution of evaporite outcrops in study area and surroundings (modified from Karadenizli 2011). (c) Inandık village and vicinity.

understanding the evolution process of sinkholes has been stated on several occasions (Delle Rose and Parise, 2002; Festa et al., 2012; Basso et al., 2013; Calligaris et al., 2017).

Furthermore, the Turkish Disaster and Emergency Management Authority (AFAD) examined the village by digging boreholes and using high resolution near-subsurface imaging with ground penetrating radar (GPR). Images were obtained using a GSSI SIR 3000 portable device fitted with a 270 MHz antenna (Özçelik et al., 2016). For this study, we utilized the AFAD data and also produced a map showing the distribution of subsidence susceptibility. In addition, useful information on current subsidence in the settlement and sinkhole formation was obtained from local residents.

Background

The Çankırı region is located in the Çankırı-Çorum sedimentary basin (Fig. 1a). The basin experienced evaporite formation in the Oligocene, Late Miocene, and Pliocene reaching 7500 m in thickness (Karadenizli, 2011). Lacustrine Pliocene evaporites and the Bozkır Formation crop out around the study area (Fig. 1b). This evaporitic sequence has a thickness of up to 750 m and 60-100 m thick gypsum levels intercalated by mudstone, selenite, clayey limestone (Karadenizli, 2011) and salt, anhydrite and glauberite (Sönmez, 2014). Karst subsidence in the study area is linked to the dissolution of Pliocene evaporites.

The Kızılırmak drainage system developed in the basin at the beginning of the Quaternary, leading to closure of the basin. Karstification of gypsum and subsidence phenomena began when Pliocene evaporites were downcut by the Kızılırmak drainage system and overlain by loose alluvial deposits. The episodic downcutting of Inandık stream and its tributary in the study area generated a terrace 15 m above stream level and 25 m below adjacent ridges. The terrace is located northwest of Inandık village and its surface is overlain by alluvium 0 to 6 m thick (Fig. 1c).

The vicinity of Inandık has a semi-arid climate with a mean annual rainfall of 400 mm. Average temperatures range from -0.9°C in January to 23.1°C in July. Inandık stream, fed by karst springs, does not flow during the summer. The Acı (bitter) Spring, so named because it contains dissolved calcium sulfate, emerges from cavities in the gypsum at the point where the spring waters join Inandık stream.

The village was founded in the 19th century and contains 68 buildings that were mainly constructed in the first half of the 20th century. By 2015, most dwellings in the village were in poor condition due to damage from subsidence in the last decade. The most recent collapse sinkhole to be formed on agricultural land occurred in 2012. For these reasons, the inhabitants of Inandık applied to AFAD in 2015 for assistance to try and solve their problems.

After the investigation by AFAD was completed (Özçelik et al., 2016), the government decided to relocate the village three km south of its current location at a cost of 2 million euro because of the collapse threats. The provincial governorship has installed and allocated 72 prefabricated houses for temporary use until the village is moved (Fig. 1c). Once construction of the new village is complete, the residents will be permanently moved to the new location. Currently, the prefabricated houses are unoccupied and some residents of Inandık continue to live in the old village.

Sinkholes

Sinkholes are closed depressions typical of karst terrain. A significantly-sized cavity is necessary for the formation of bedrock collapse and caprock collapse sinkholes (e.g., Waltham et al., 2005; Gutiérrez et al., 2014, 2019). Other types of sinkholes, such as the cover-collapse sinkhole, may occur in the presence of limited-size cavities and voids (e.g., Gutiérrez, 2016). Cover-collapse sinkholes result from the upward propagation of cover failure, leading to the collapse of the overburden. This type of sinkhole is responsible for most sinkhole hazards around the world (Waltham et al., 2005; Parise, 2010; Gutiérrez et al., 2014). Their detection is made difficult because they are easily buried by farmers due to their relatively small size and depth. Analysis of historical documentation such as topographic maps, old pictures and images is therefore useful for detecting these sinkholes. Moreover, the data obtained can provide insights into their spatial and temporal distribution, as experienced with other types of natural hazards, such as landslides (Parise and Wasowski, 1999; Calcaterra and Parise, 2001; Pisano et al., 2017).

To detect the sinkholes in the current study, aerial and satellite images were compared and eight collapse sinkholes were identified northwest of Inandık. These were numbered according to their date of formation (Fig. 1c, Table 1). Five of them existed before 1953. Except for sinkhole 7, that is the smallest, all the sinkholes are clustered on the river terrace. Local residents reported that sinkholes smaller than a meter in diameter, similar to sinkhole 7, had been found in the valley bottom, but were buried. These cannot be detected in aerial photographs because of their size and having been filled in soon after formation.

Sinkhole 2 (Fig. 2a) is the largest with a diameter of 44 m and depth of 22.5 m at an altitude of 877 m a.s.l. It is the only bedrock collapse sinkhole and was formed before 1953. Blocks were observed in its bottom and many fractures are visible around the sinkhole, indicating that it has enlarged due to mass wasting. This sinkhole in particular shows that large cavities exist under the terrace.

Sinkhole 7 was formed between 1990 and 2008 at an altitude of 832 m a.s.l. This cover-collapse sinkhole was detected in the valley bottom and is relatively small and shallow, with a diameter of 1 m and depth of 1 m.

The most recent sinkhole is number 8 (Fig. 2b), formed in 2012. It is 13 m in diameter and somewhat enlarged since traces of erosion are visible at its margins, and is 10 m deep. The depth of the sinkhole is 5 m greater than the thickness of the alluvial deposit. It is classified as a cover-collapse sinkhole.

The other sinkholes can only be observed in some of the aerial photographs. They have now disappeared because farmers have filled them, canceling the surface features (Fig. 2c, d, e). These buried sinkholes can also be defined as

Table 1. Measurements, age, and type of sinkholes detected at Inandık.

Sinkhole Number	Formation Period	Altitude (m)	Diameter (m)	Depth (m)	Genetic Type
1	Before 1953	877	Buried sinkhole
2	Before 1953	882	44	22.5	Bedrock Collapse sinkhole
3	Before 1953	881	5	...	Buried sinkhole
4	Before 1953	886	12	...	Buried sinkhole
5	Before 1953	916	7	...	Buried sinkhole
6	1953–1971	927	13.5	...	Buried sinkhole
7	1990–2008	832	1	1	Cover collapse sinkhole
8	2012	898	13	10	Cover collapse sinkhole

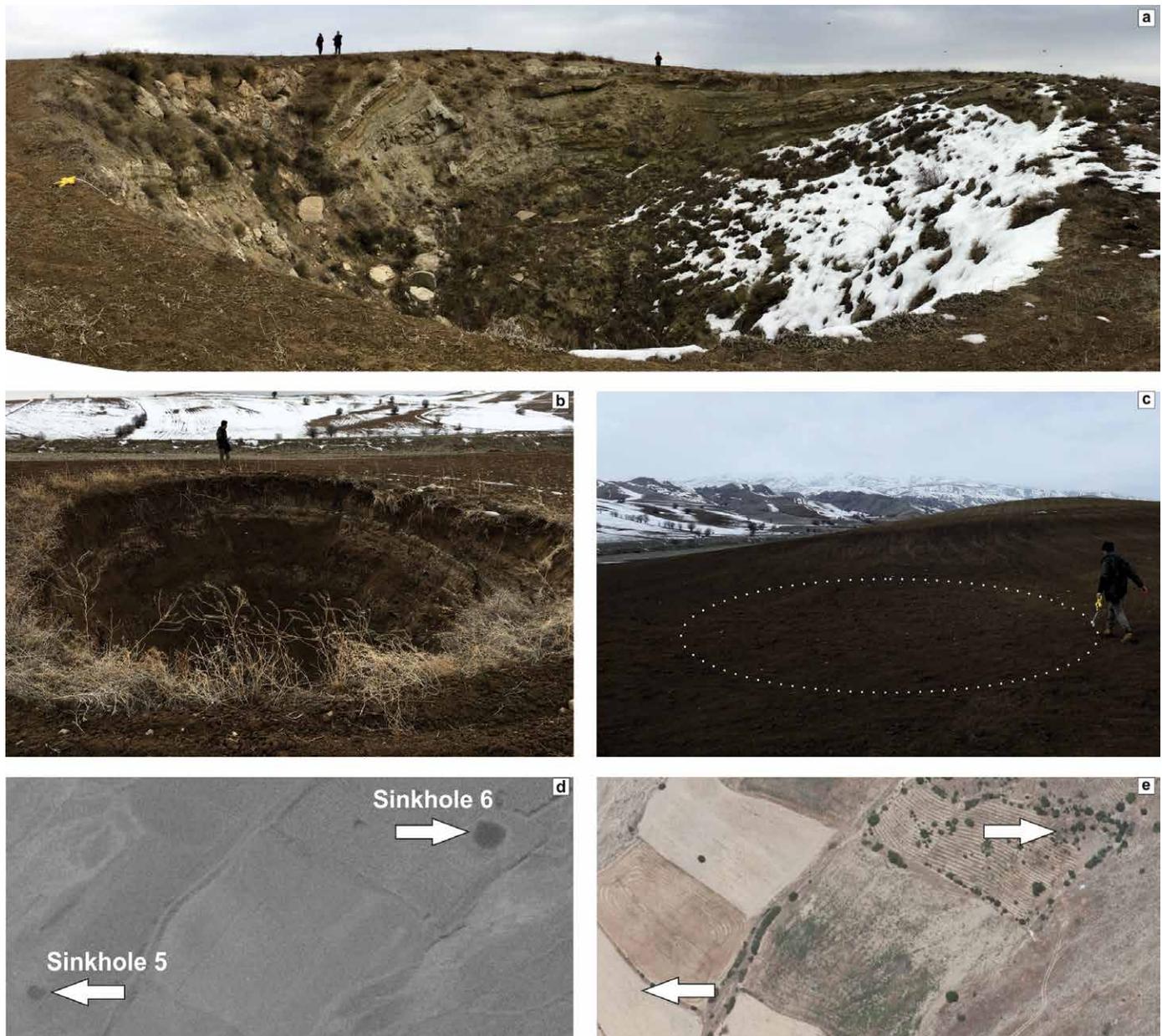


Figure 2. (a) Panoramic view of Sinkhole 2, the deepest and largest sinkhole in study area. Note separated blocks on the sides. (b) Sinkhole 8, most recent sinkhole in study area. (c) Sinkhole 4, buried by farmers. Soil containing small white pebbles brought from elsewhere mark the sinkhole within the boundary indicated. (d) Historical aerial photograph of sinkholes 5 and 6. (e) Recent view of buried sinkholes 5 and 6.

cover-collapse sinkhole because they formed in alluvial deposits.

Existing sinkholes are the predictors of future sinkhole formation. Regarding the spatial distribution of the eight sinkholes, they are clustered in a line of about 0.3 km² along the NW-SE 1.9 km alignment. This area offers the highest probability for formation of new sinkholes.

Subsidence in the village

Inandik village is situated in a tributary valley on the eastern flank of Inandik stream with the SW part of the village within the main valley (Fig. 1c). There is no stream-flow in the valley bottom since precipitation falling in the

area surrounding the village in the rainy season is drained underground. The recharge to Inandik stream includes discharge from Inandik settlement which, we believe, has enhanced dissolution of the bedrock, as documented on paleo-subsidence structures (Fig. 3) which can be observed in many gypsum bedrock outcrops in the village, providing us with data about recent subsidence events. They also demonstrate that subsidence phenomena have been occurring over a long period. In support of this, information from inhabitants and local authorities indicate that the village has been affected by subsidence and sinkholes for generations. Although some damage occurred in the past, the frequency of subsidence events has in-



Figure 3. Paleo-subsidence structures in gypsum bedrock. Cavities are filled with karstic residue and gypsum blocks. (Photograph taken on eastern slope of village).

created progressively in the last decade. Inhabitants have heard noises originating underground, intermittently accompanying micro-seismic activity that was also detected by microtremor measurement (Özçelik et al., 2016), especially between 2012 and 2017, causing some residents to abandon their houses for fear of earthquakes. It is clear that the sounds frightening residents were generated underground by collapsing material in cavities. Although there is no big collapse sink-hole within the settlement, progressive deterioration is seen. Therefore, the subsidence mechanism most likely occurs when sagging is combined with a collapse, causing loss of support under Inandık settlement and has severely damaged nearly all buildings in the village,

which show open fractures and tilted, cracked walls (Fig. 4). Moreover, some of the buildings are very old; therefore they are severely affected by even the slightest subsidence. Several have been demolished because the damage was beyond repair.

We received information from the local authority that the water consumption habits of the inhabitants had changed recently, which has most likely affected the karst system. There was limited water consumption previously in the village but usage increased significantly after in-house water was provided in 2007. The total annual water consumption of the inhabitants reached 118.7 tons in 2015. Around the same time, in 2012 a sewage system was installed in the village. However, some buildings still channel wastewater directly into the ground (Fig. 4b) due to badly-designed drains. Information from the local authority and inhabitants also suggests that the service and sewage pipes crack quite often. Such leaks result in a large amount of water seeping into the karst system in the village.

Spatial distribution of damage

Subsidence damage is caused by several factors including landslides, karst subsidence, and mining-induced subsidence. Land movement tends to be predominantly downward in coal mining and active karst subsidence areas, whilst a combination of downward and outward movement is typically observed in landslide areas (Cooper, 2008). Such movements cause damage to man-made structures and economic loss. Determining the degree and spatial distribution of the damage is necessary to understanding the subsidence mechanism. Therefore, several schemes have been generated to assess the damage to buildings (Cooper, 2008). The National Coal Board (NCB) (1975) in the UK created five categories for defining damage in coal mining areas (Cooper and Calow, 1998). Alexander (1986) and Chiochio et al. (1997) developed a landslide damage classification of seven categories with two extra more severe damage categories but which otherwise closely resembles the NCB scheme. To determine the distribution of the subsidence hazard on gypsum karst, the NCB categories were adapted by Gutiérrez and Cooper (2002).

Buildings were assessed in the present study according to the categories of the NCB (1975) and Gutiérrez and Cooper (2002). Three category levels were used (Table 2) and a damage map showing the spatial distribution of the subsidence was generated (Fig. 5). This method has limitations because the internal damage to buildings was not assessed; moreover, the cause of damage could be related to other factors such as age or building materials. However, buildings in the village that are similar to each other exhibit no signs of damage. Relatively new structures constructed in the last 15 years also appear to be more resistant to subsidence and were evaluated separately on the map (Fig. 5).



Figure 4. (a) Displacement of house wall showing bulging and cracking caused by subsidence, and broken windows due to distortion. (b) Cracks on wall and pipes draining wastewater directly into ground. (c) Open joint in wall of building. (Photographs taken on February 26, 2017).

The map shows that most of the damage is concentrated at the bottom of small tributary valleys, whilst structures located in the main valley experienced no damage.

Ground penetrating radar (GPR) and bore-hole data

Five GPR profiles with a total length of 565 m (Fig. 5) were obtained from the settlement area (Özçelik et al., 2016). Profile 1 (Fig. 6a) mostly concentrates on the in-house and sewage water pipelines and shows shallow and relatively deep anomalies. Shallow anomalies between 20 and 32 m, and between 55 and 70 m are observed at a depth of 1 –

10 m. These reflections with different dips in this profile are likely related to sagging structures. Relatively deep anomalies are also observed 20 m and 40 m from the beginning

Table 2. Categorization of damage to structures in Inandık village (Gutiérrez and Cooper 2002, and references therein).

Category	Typical Damage
No Damage	...
Appreciable	Hairline cracks, several slight fractures (millimetric), doors and windows may stick slightly.
Severe	Open fractures, window and door frames distorted requiring partial or complete reconstruction, displaced tilted walls.

of the profile at a depth of 50-100 m. Profile 5 (Fig. 6b) focuses on the area northwest of the village. It shows anomalies located from the beginning of the profile at 10, 20, and 30 m and having a depth from 10 to 100 m. Shallow anomalies at 10 m and 25 m along the profile show a sagging structure. These anomalies seen on profiles 1 and 5 probably correspond to fractures, cavities, and sagging structures near the surface in the gypsum bedrock (Fig. 6a, b). Profile 1, located below the most damaged area, shows several anomalies more than profile 5, and both the anomalies and damaged buildings decrease towards the end of profile 5. These observations are compatible with the spatial distribution of the damage. Although the effect of subsidence was observed in structures near the other three profiles (Fig. 5), anomalies were not detected in these profiles.

Boreholes 1 and 2 were drilled in the valley bottom of Inandık village (Fig. 5). Both boreholes show dissolution cavities in the gypsum (Fig. 6c). According to this data, the thickness of the alluvium is 1.5-3 m. Borehole 3 was drilled on the bedrock northwest of the village. No void was detected in its log 3 (Özçelik et al., 2016).

Discussion

Sinkholes

Seven sinkholes are clustered on the terrace surface in the study area due to geomorphological and hydrologic factors. There is a relationship between the development of fluvial systems on a karst massif and the generation of sinkholes (Benito et al., 1998, 2000;

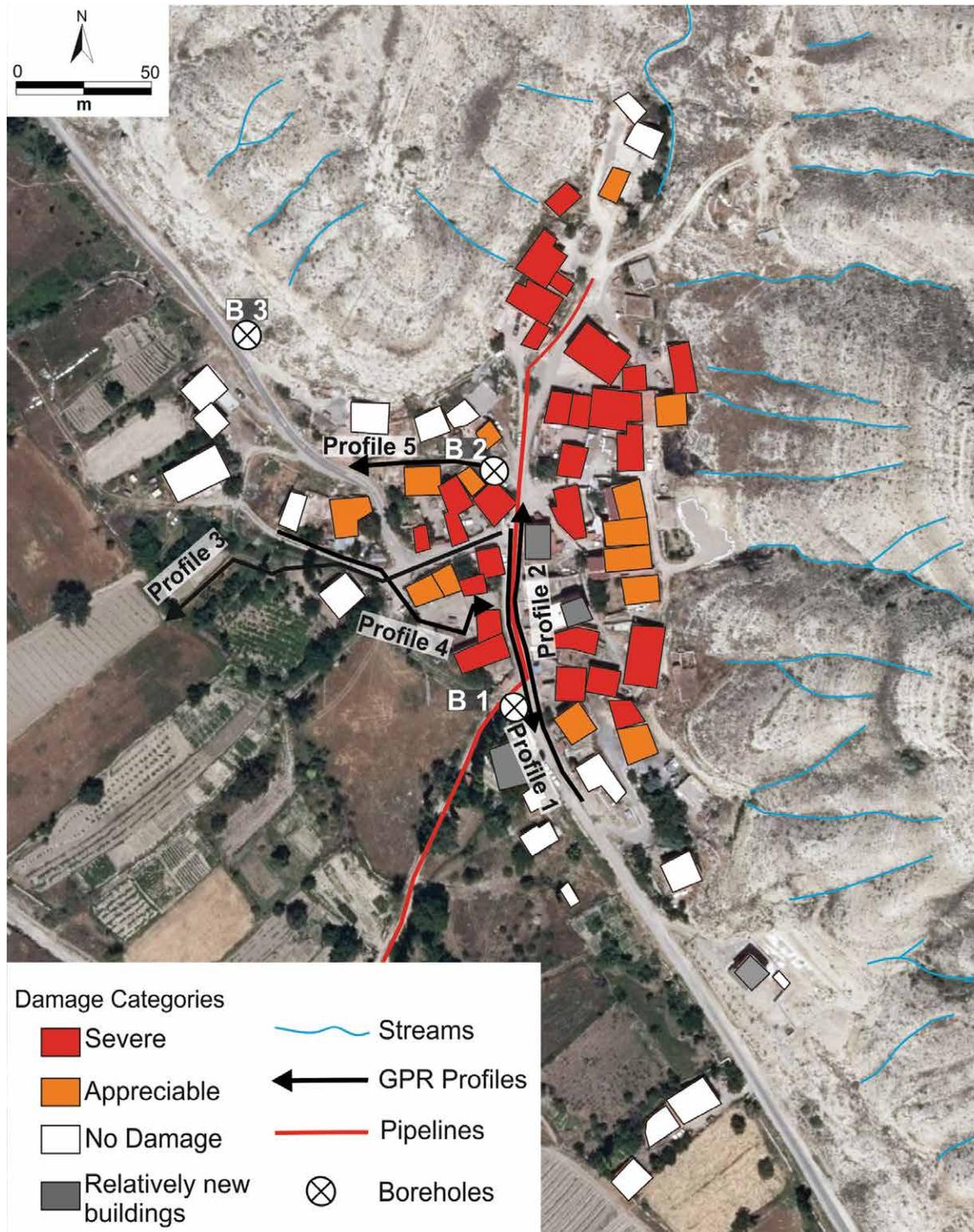


Figure 5. Map of damage distribution in March 2017 showing location of boreholes, GPR profiles (Özçelik et al. 2016) and pipeline.

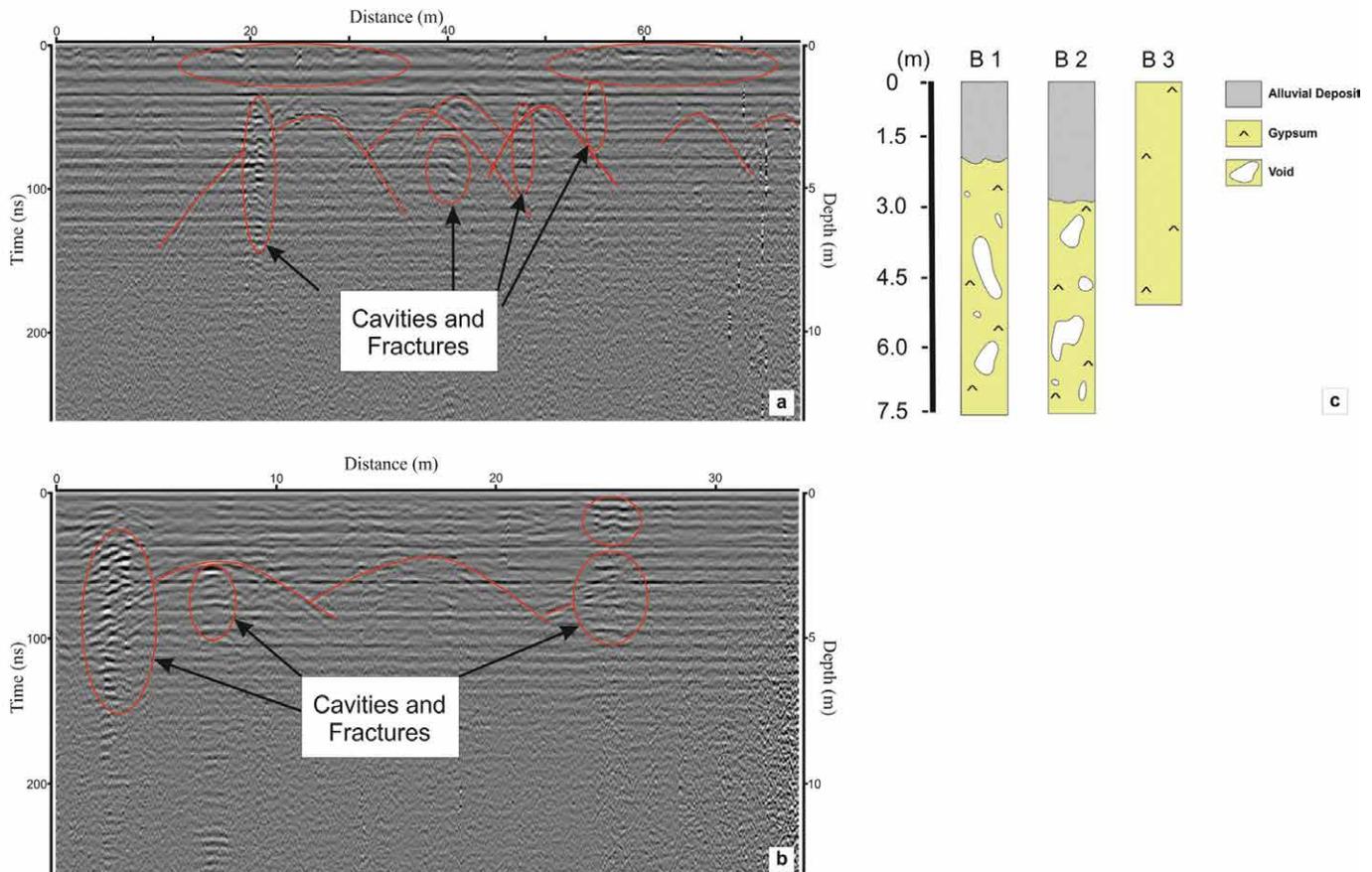


Figure 6. GPR profiles of (a) profile 1, and (b) profile 5. (c) Log of boreholes drilled in Inandık village (modified from Özçelik et al. 2016).

Doğan, 2005; Guerrero et al., 2008, 2013; Gutiérrez and Cooper, 2013; Gutiérrez, 2014). The incision of rivers forms a deep vadose zone and lower water table (Ortega et al., 2013). It also accelerates cavity development and internal erosion and gives rise to diminished thickness and mechanical strength of the cavity roofs.

The current geomorphological features of the area were formed when Inandık stream and its tributaries eroded the surface of the valley, giving rise to a terrace in which the gypsum cavities were less covered (Fig. 7). The streams incised the valley by more than 15 m forming a new, lower base level and a higher hydraulic gradient, thus accelerating cavity development, subsurface erosion, and upward migration of the cover deposits.

There was no sinkhole formation on the adjacent heights of the terrace (Fig. 7) because they have a relatively thick cavity roof. In the valley bottom, the alluvial cover is thicker and the hydraulic gradient is lower; therefore, only sinkholes 1 m wide or smaller were formed there.

The sinkholes we detected are due solely to natural processes. Human-induced factors such as the pumping up of groundwater or extra water input into the ground were not detected. Moreover, most sinkholes were formed before 1953 (Table 1) when human influence was far less. It is plausible that other sinkholes occurred in the Quaternary, but these would have been buried later by the stream system.

Subsidence in the village

In-house service and sewer pipes are more likely to cause subsidence (Fleury, 2009; Parise, 2015) and pipeline breakage gives rise to damage in karst areas (Jassim et al., 1997; Gutiérrez and Cooper, 2002; Cooper et al., 2011; Cooper and Gutiérrez, 2013; Parise et al., 2015). In Inandık, ground subsidence must have caused the abnormally frequent breaking of pipes, which caused extra water input into the ground and triggered progressive subsidence of the land, creating a vicious circle. Moreover, some household waste water flows directly into the ground, which causes localized subsidence. All these processes give rise to dissolution and the formation of new cavities (Fig. 8).

According to the GPR profiles, cavities were detected only on profiles 1 (Fig. 6a) and 5 (Fig. 6b). However, the distribution map of subsidence damage (Fig. 5) shows that it affects a wider area than the GPR result indicates. It is known that the clay content of alluvium is an obstacle influencing the depth that GPR systems can reach (Schrott and Sass, 2008; Pueyo-Anchuela et al., 2009; Nouioua et al., 2013); therefore, the penetration of the GPR system was not satis-

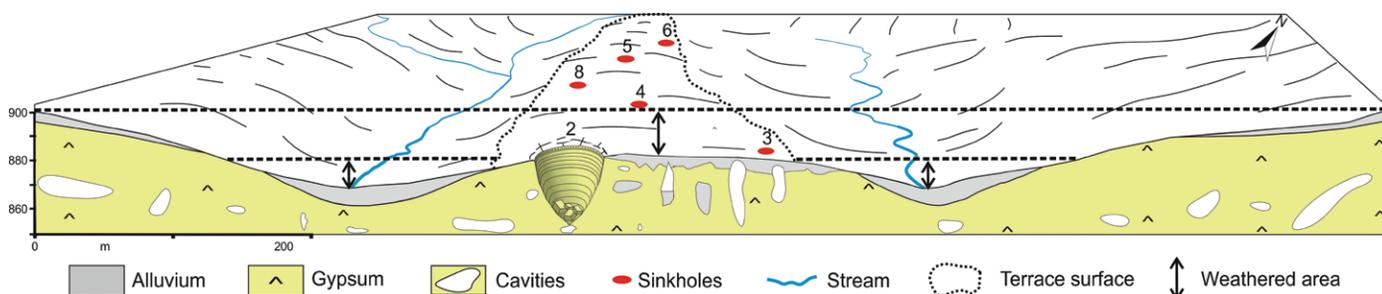


Figure 7. 3D Geomorphological scheme (A-B) of Inandık stream showing flow level differences and sinkholes (See Figure 1c).

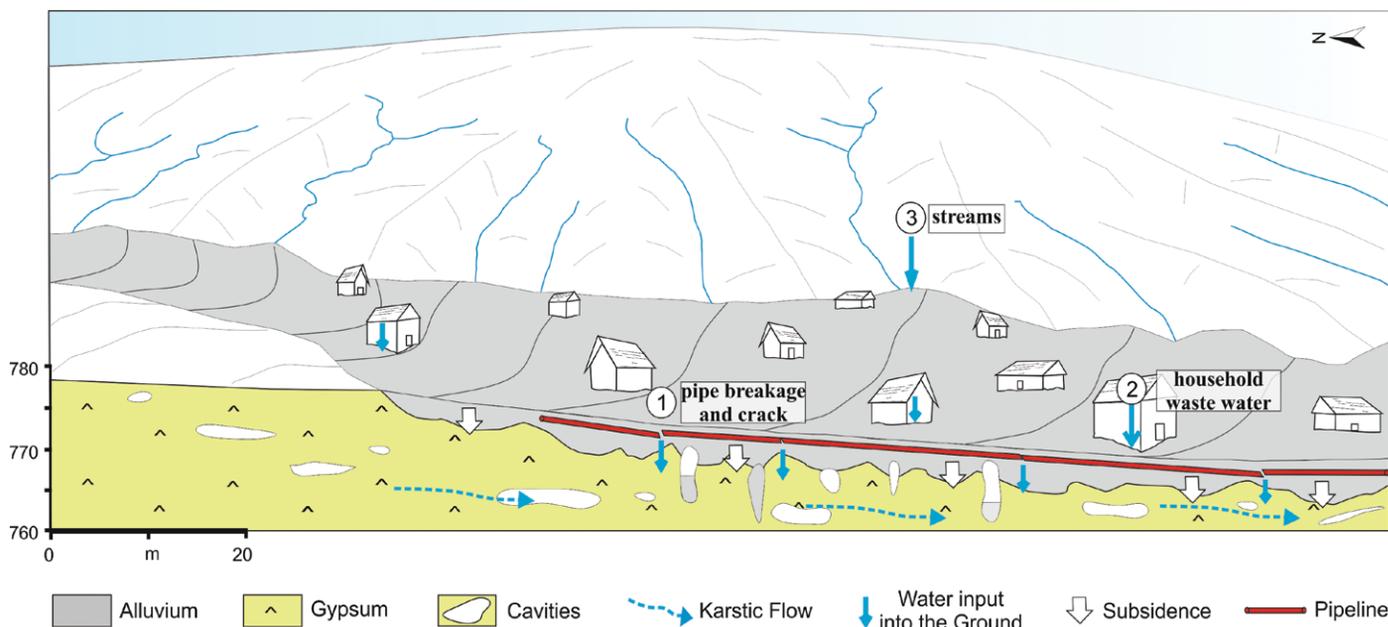


Figure 8. Cross-section of pipeline (Fig. 5) and 3D geomorphological scheme of Inandık village depicting effect of subsidence.

factory in several studies (Gutiérrez et al., 2011; Margiotta et al., 2012, 2016; Carbonel et al., 2014, 2015; Rodriguez, 2014; Zini et al., 2015). This limit to GPR penetration is probably the case in Inandık, explaining the apparent inconsistency between the results of profiles 1 and 2, which are on the same line and only two meters apart (Fig. 5). Therefore, the usefulness of GPR surveying for identification of possible sinkholes in alluvial karst areas may be limited due to high electrical conductivity values, whilst it remains appropriate for bare karst areas.

The Inandık settlement is situated on 1.5-3 m alluvial deposits overlying a layer of gypsum, according to the boreholes (Fig. 6c). These thin alluvial deposits caused the village to be favorable for subsidence. On the other hand, the main valley has relatively-thick alluvial deposits SW of the village and buildings here show no damage (Fig. 5). The center of the village is subject to greater internal erosion because of its thin alluvial cover.

From the borehole logs, registers, and GPR profiles 1 and 5, similar cavities to those in outcrops (Fig. 3) were deduced. They are very superficial, which explains the damage to single-story homes with smaller loads on their foundations.

Conclusion

The aim of this study was to examine the subsidence problems of Inandık village in Turkey. Gypsum dissolution is evident in the entire fluvial system of Inandık stream. A series of ground collapses was identified on a terrace located upstream from the settlement. On this terrace, the surface is more-than-usually prone to the formation of sinkholes because of the reduced thickness and mechanical strength of the cavity roof and the thinness of the alluvial deposits; hence, seven large sinkholes were formed.

In the settlement, in addition to circumstances favorable to the karst phenomena with houses located in an area subject to underground water flow and the presence of cavities (Fig. 3), the process has been accelerated by human action when a water distribution network was installed in homes in 2007, which increased water usage, and a new

sewage system was constructed in 2012. The pipes of these networks cracked and broke frequently and some homes still discharge water directly underground. This leakage has resulted in enhanced subsidence and progressive damage to buildings in the last decade. In consequence, the severity of the damage led to the decision to re-locate the village.

It is hoped that the results of this study will contribute to increasing the awareness among decision-makers who need to consider the karst system of the area they are responsible for in order to take preventative measures. To reduce or prevent hazards related to subsidence in a settlement which overlies gypsum, such as Inandık, extra water input to the subsurface should be minimized (Parise, 2015) and flexible pipes with a telescopic joint should be used to alleviate cracks and breakage.

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