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## Assessment of environmental and engineering geological problems for the possible re-use of an abandoned rock-hewn settlement in Urgüp (Cappadocia), Turkey

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**Abstract** The Cappadocia Region of Central Anatolia having a very distinct culture is one of the attractive touristic sites of Turkey due to its spectacular and unique landforms and historical heritages. In this region, the structures carved into thick to massive tuffs survived and kept their original integrity for a number of centuries. Environmental and anthropological factors at the Cappadocia Region have been the main reasons for extensive subsurface and multi-purpose use in the past and present. In addition, thermal insulation properties of the tuffs make these rocks suitable for use in underground openings. The Kayakapi Neighborhood, located in the town of Urgüp, is one of the famous historical sites. This site is situated within the ‘Göreme National Park and the Rock Sites of Cappadocia’ which was inscribed on the World Heritage List in 1985. In order to develop the tourism potential of this abandoned site while preserving its cultural and natural values, a natural environmental conservation and revitalization project was initiated. As an integral part of this project, in this study, environmental and engineering geological problems, including rock fall potential and stability of about 1,200 rock-hewn structures,

were investigated and an inventory was prepared for the possible re-use of the underground openings and other structures at the site, and remedial measures were recommended. The assessments based on observations and experimental studies indicated that the tuffs do not show significant changes both perpendicular and parallel to layering, and discontinuities and rock weathering seem to be more important factors controlling the stability of rock-hewn structures. The major stability problems threatening the re-use of the openings are structurally-controlled block instabilities, overbreaks, and erosion and shearing of the pillars made of tuff. On the other hand, the area at the entrance of the site requires some protection measures such as the construction of a retaining wall, systematic bolting of rock slabs and removal of some blocks having rock fall potential. The inventory for the openings suggests that there are a number of openings that can be re-used after necessary remedial measures.

**Keywords** Cappadocia · Environmental conditions · Kayakapi (Urgüp) · Rock fall · Stability of underground opening · Troglodyte · Tuff

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## Introduction

The Cappadocia Region of Turkey, which involves Nevşehir, Kayseri and Niğde provinces of Central Anatolia (Fig. 1), is one of the sites in the World Heritage List. The region is characterized by Late Tertiary to Quaternary volcanics, mainly represented by volcano-sedimentary rocks which can be easily carved and have thermal insulation properties. Due to numerous historical heritages, which have been hewn into various tuffs, and spectacular and unique landforms of the region such as fairy chimneys (Fig. 2a), the Cappadocia Region is one of the famous touristic sites of Turkey. Underground cities and semi-underground settlements, most of which are more than 1,500 years old, exist in the region (Fig. 2b). Some of the fairy chimneys were dwellings and were inhabited during the Byzantine times. Some such dwellings contain invaluable wall paintings which also provide historical attraction. The structures carved into thick and massive tuffs survived, and kept their original integrity for a number of centuries. Particularly the area between Urgüp, Göreme and Avanos has recently become a museum of rock-cut

structures, which are now converted into restaurants, hotels and shops (Fig. 2c). Besides modern underground openings in the region are being used for lodging, storage of food and fruits, and housing (Fig. 2d).

Environmental and anthropological factors of the Cappadocia Region have been the main reasons for extensive subsurface and multi-purpose use in the past and present. Erguvanli and Yuzer (1977) categorized these factors into six groups as follows:

1. Severe daily and seasonal changes of temperature in the region,
2. Thermal insulation properties of the volcano-sedimentary units covering the region,
3. Self-supporting behavior and construction opportunities in these rocks,
4. Easily carved, particularly soft tuffs,
5. Provide hiding places and camouflage to provide a defensive advantage and safety against enemy attack, and
6. Superior resistance and protection against natural disasters due to earthquake and/or volcanic eruptions in the past.

The town of Urgüp, located in Nevşehir province (Fig. 1), is the most popular settlement of the Cappadocia Region, not only due to its proximity to the historical heritages and open-air museums, but also due to the presence of historical and modern rock-hewn structures in the town. The Kayakapi Neighborhood is one of the interesting and historical sites in Urgüp and is situated within the area of 'Göreme National Park and the Rock Sites of Cappadocia' which was inscribed on the World Heritage List in 1985. In this area, there are about 1,200 rock-hewn underground openings called 'troglodytes' in different dimensions and rock-hewn churches, and masonry constructions such as palaces, historical mosques etc. (Fig. 3). Although the Kayakapi Neighborhood was closed to settlement in 1969 due to local rock falls, it was designated as an urban conservation area in 2001 based on the measures started by the Municipality of Urgüp to develop the tourism potential of the site while preserving its cultural and natural values. As a result of these efforts, a project entitled 'Urgüp-Kayakapi Cultural and Natural Environmental Conservation and Revitalization Project' was initiated in 2002. This recent study, as an integral part of this project, was carried out by the authors to assess the site's geological characteristics, to identify environmental and engineering geological problems and to suggest some remedial measures which can be helpful on the decision of re-using this abandoned historical site.

The study was conducted under three stages comprising field studies, laboratory geomechanical tests, and analyses and evaluations. The site was described by engineering geological mapping and detailed discontinuity data collection through the scan-line surveys.

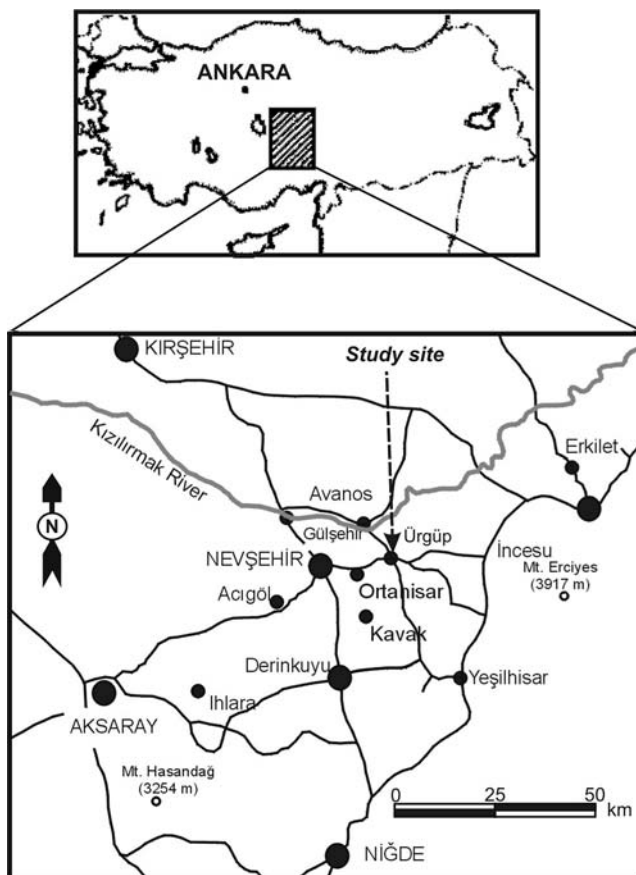
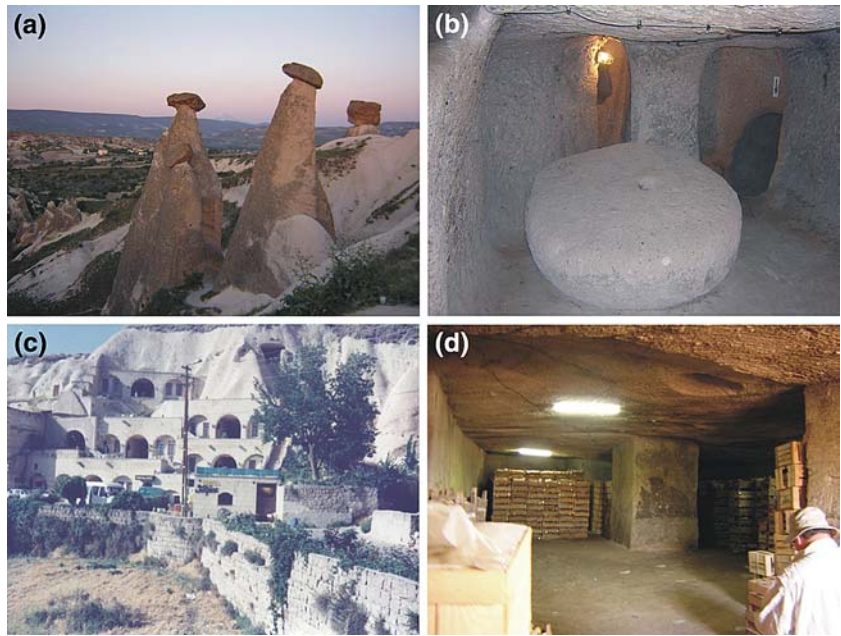


Fig. 1 Location map of the Cappadocia Region and study site

**Fig. 2** **a** A view from the fairy chimneys near Urgüp and **b** the Kaymakli underground city, **c** a rock-hewn hotel in Urgüp, and **d** an underground storage house for fruit preservation at Ortahisar



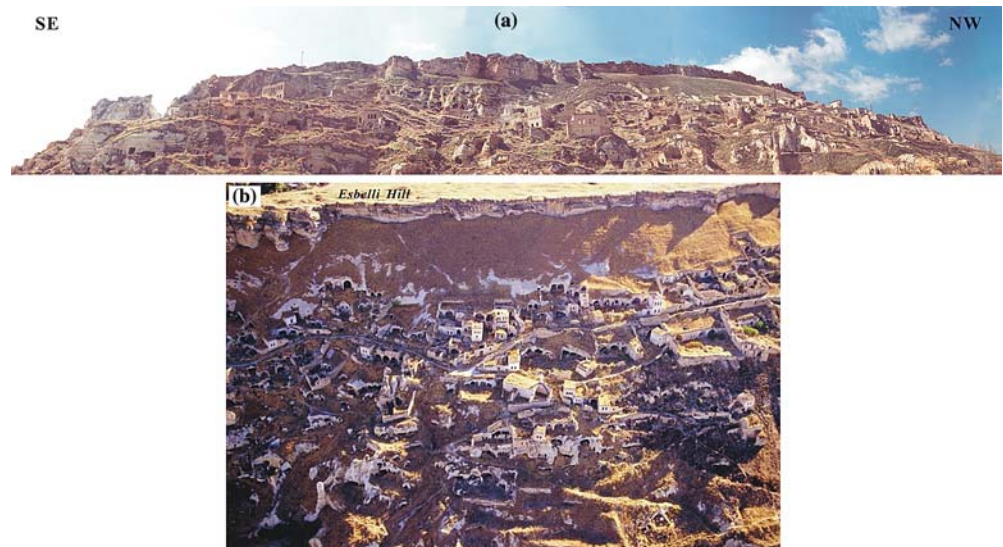
Observations on rock masses and in the underground openings in conjunction with Schmidt hammer tests and rock mass classification in the 1,156 troglodytes were conducted. In addition, environmental conditions such as temperature, humidity and wind velocity were also evaluated by measurements taken in a limited number of openings. Laboratory tests were conducted to define geomechanical parameters and characteristics of these related rock units as they affect the stability of the openings. In order to assess the possibility of re-using the troglodytes, an inventory based on selected criteria was prepared. In addition, some of the structurally-controlled wedge failures that occurred in the roof of some underground openings were

back-analyzed to assess the shear strength of the discontinuities to be used in further engineering analyses. Then remedial measures, which can be considered during restoration and strengthening stages of the project, were briefly discussed. The site was also evaluated in terms of rock fall possibility based on the rock fall simulation analyses.

### Description of the study site and its historical importance

The Cappadocia Region is situated in the Central Anatolia region of Turkey and its altitude ranges

**Fig. 3** **a** General view of the Kayakapi Neighborhood, and **b** aerial view from its central part (with the permission of KA-BA)





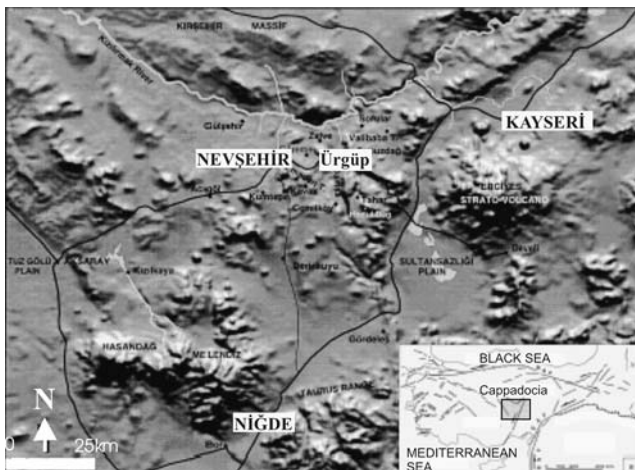
between 1,300 and 1,400 m, forming a high plateau. It has a triangular shape and is surrounded by the Erciyes (3,917 m), Melendiz (2,935 m) and Hasandag (3,254 m) volcanoes (Figs. 1, 4). The Kizilirmak River, which is the longest river in Turkey, flows through the northern part of the region and the Araslan stream flowing from the eastern part of the Urgüp town joins this river. Due to the presence of soft lithological units and smooth topography, the drainage system in the region is dendritic. The Hitites were the first civilization that settled in the region and the region has become the homeland of various civilizations throughout its history.

In Cappadocia, the typical continental climate prevails. The winters are cold with moderate snowfall. Rainfall becomes dominant in spring, while summers are hot and dry. Based on the evaluations of Aydan and Ulusay (2003) on the records from the meteorological station in Nevsehir, the highest temperature occurred in July and August. During the period between 1960 and 1990, precipitation occurred during winter and spring, humidity was low in summer, and the summer season was generally dry throughout the region.

The Kayakapi Neighborhood is a historical area located on the northeastern slope of a hill known as Esbelli in the Urgüp town center, and features many examples of vernacular and monumental architecture (see Fig. 3). The site is situated within the area of 'Göreme National Park and the Rock Sites of Cappadocia'. Slope gradients and altitudes at the Kayakapi Neighborhood range between 20° and 40°, and 1,065 and 1,180 m, respectively. The site contains approximately 260 lots, nearly 180 lots of which are traditional dwellings comprising rock-carving and masonry constructions (Fig. 5a; KA-BA 2005). Among these buildings there are several monuments such as mosques from

the time of the Seljukian period and rock-hewn churches (Fig. 5b, c), a Turkish bath and fountains, some of which are registered. The presence of about 1,200 underground openings (troglodytes) being used for housing for many years is another typical feature of the site (Fig. 5d). Furthermore, there are some 80 lots within the neighborhood boundaries that contain vineyards and orchards. The site carries the legal protection status comprising an urban conservation area, and 1st and 3rd degree natural protection sites.

Although the earliest history of the site is not clearly known, based on the information obtained from local people and Ottoman archives, it can be concluded that the site was an important settlement area with high prestige since the beginning of the eighteenth century or even before (<http://www.kayakapi.com>). However, due to local rock falls that occurred in the 1960s, the site was closed to settlement in 1969 by the General Directorate of Disaster Affairs and the people living there were evacuated. The Municipality of Urgüp, considering the historical and touristic values of the site, had taken measures in the year 2000 to develop the tourism potential of this special area while preserving its cultural and natural values. Then the site was designated as an urban conservation area in the year 2001. The project entitled 'Urgüp-Kayakapi Cultural and Natural Environment Conservation and Revitalization Project' involved the organization and revitalization through tourism-based contemporary functions of the Kayakapi Neighborhood along with its built stock and surrounding natural areas. The primary aim of the project is to provide the conservation of a site of this magnitude which has an architectural setting consisting completely of historic buildings through consolidation and restoration without harming its inherent cultural and socio-economic values. The other important aim is to achieve an internationally accepted conservation project, while realizing a tourism investment that meets international standards.

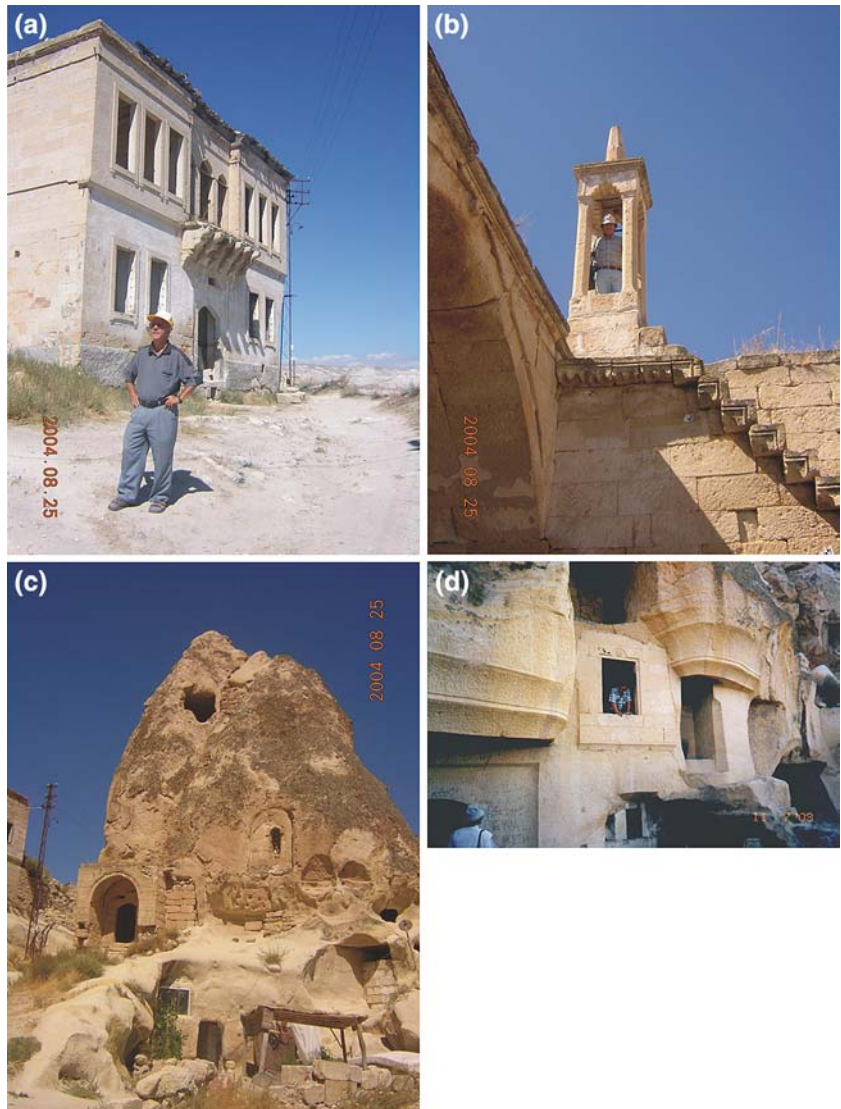


**Fig. 4** Digital elevation model of the Cappadocia Region showing main volcanoes, landforms and settlements (after Temel et al. 1998)

### Geology of the study area

The Cappadocia region covering an area of approximately 40,000 km<sup>2</sup> mainly contains volcanic rocks including ignimbrite (massive tuff), andesite and basalt (Temel et al. 1998) (Fig. 6). The region is generally underlain by thick and extensive deposits of volcano-sedimentary sequence (Miocene–Pliocene) of the Urgüp formation (Pasquare 1968; Toprak et al. 1994). Although the formation comprises a number of well-distinguished members, in the study area only the Kavak member of the formation exists. The Kavak member represents the product of the first intermittent volcanic activity which produced the Urgüp formation. Thus, this member constitutes the basal portion of the

**Fig. 5** **a** A masonry structure (Yusuf Aga's Palace), **b** a mosque from the Seljukian period, **c** a rock-hewn church, and **d** a group of troglodytes in the Kayakapi Neighborhood



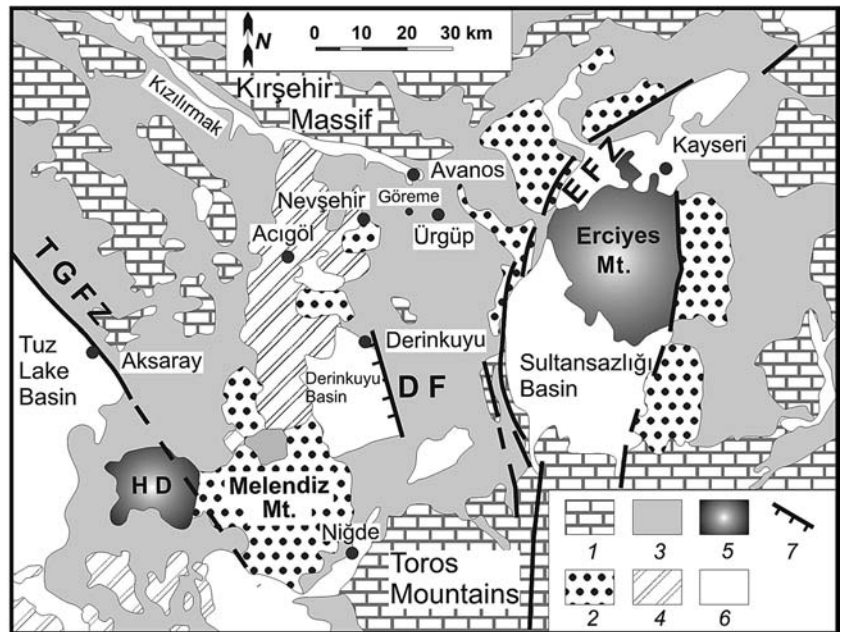
volcano-sedimentary sequence. The chaotic arrangement of pumice fragments within the unit suggests that it is an ash flow tuff deposited in a lacustrine environment. It is dirty white to pink, and contains phenocrysts of plagioclase, quartz, biotite and opaque minerals. Various rock fragments and pumice are also commonly observed. In the matrix, volcanic glass shards are rather common. The volcanic glass shards are partly altered to smectite (Topal and Doyuran 1998; Aydan and Ulusay 2003). Within the almost horizontally layered Kavak tuff, the steeply dipping persistent cooling joints constitute the major discontinuities (Topal and Doyuran 1997).

The Kavak tuff in the study area is characterized by different levels as shown in the stratigraphic column (Fig. 7) and engineering geology map (Fig. 8). At the

bottom, lacustrine sedimentary rocks (10–15 m thick) mainly consisting of marl exist. It is overlain by 15–25 m thick cross-bedded tuff showing distinct layering. Above it, a rather thin tuffite level is observed. Massive and about 30 m thick ignimbritic (tuff) level with distinct systematic cooling joints overlies the previously formed deposits and it is locally covered by channel-fill deposits. At the top of the sequence, the 1–4 m thick Esbelli tuff is exposed.

Two fault systems cut across the volcanic province (Toprak and Goncuoglu 1993). The first system, trending dominantly in the NW–SE direction, is the Tuz Gölü Fault Zone (TGFZ in Fig. 6). The second fault system, Eçemis Fault Zone (EFZ), strikes NE–SW, as seen in Fig. 6. When compared with other regions of Turkey, the Cappadocia region is seismically less active. The

**Fig. 6** Geological sketch map of the Cappadocia Region (after Temel et al. 1998): (1) basement rocks, (2) major Miocene–Pliocene volcanic complexes (stratovolcanoes and monogenetic centers; basalts to rhyolites), (3) tuffs and contemporaneous continental sediments, (4) mainly monogenetic Quaternary volcanism (maars, domes, lava flows and cinder cones, basalts to rhyolites), (5) large Quaternary volcanoes, (6) Quaternary alluvium, (7) major Neogene to Quaternary faults (transcurrents and/or normal, *HD* Hasandag; *TGFZ* Tuz Gölü Fault Zone; *EFZ* Ecmis Fault Zone; *DF* Derinkuyu Fault) (after Le Pennec et al. 1994)



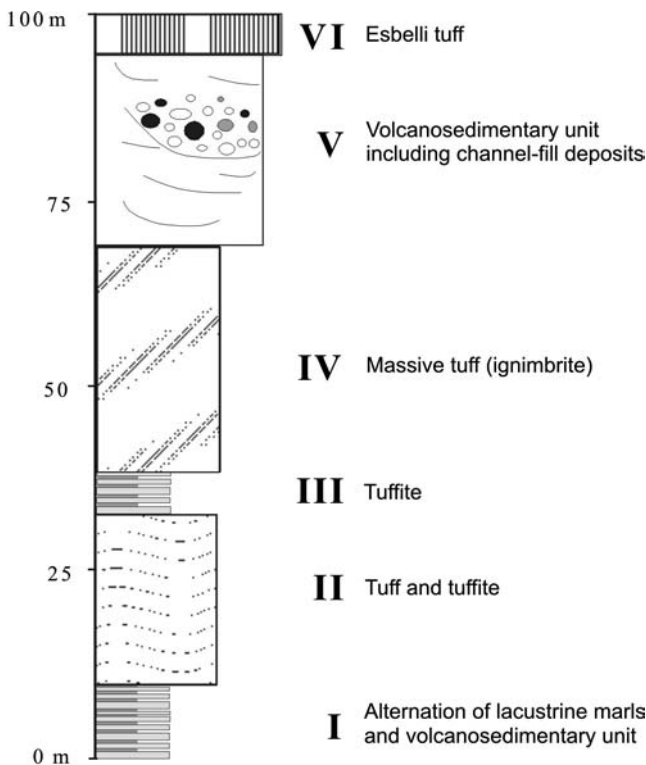
largest earthquake with a magnitude of 5.2 occurred in 1940 near the Erciyes Mountain at the northeast of the region (Aydan and Ulusay 2003).

### In situ characterization of the tuffs and environmental conditions in troglodytes

#### In situ characterization of the tuffs

The orientation and spacing of discontinuities have prime importance on the stability of the underground openings, particularly for those located at shallow depths. In addition, features such as roughness, waviness, type and thickness of infill govern the shear strength of the discontinuities. Therefore, rock mass properties of the tuffs cropping out at the study site were investigated. For the purpose, a systematic scan-line surveying study along 12 lines of totally 330 m length at different parts of the site (see Fig. 8) was carried out in accordance with the procedures suggested by ISRM (1981). The scan-line surveying included all rock units observed at the site except Esbelli tuff, which is rather thin and no underground openings have been caved in this material. Therefore, only the orientations of the discontinuities in this unit were measured to be used in the rock fall assessments. Joints and bedding were the main discontinuity types observed in all rock units. Beds dip at about 7°, while dips of the joints range between 71° and 82°. The contour diagrams of the discontinuities obtained from the tuffs suggest two dominant joint sets (dip/dip direction): 81/089 and 75/005 and bedding plane (7/227) (Fig. 9).

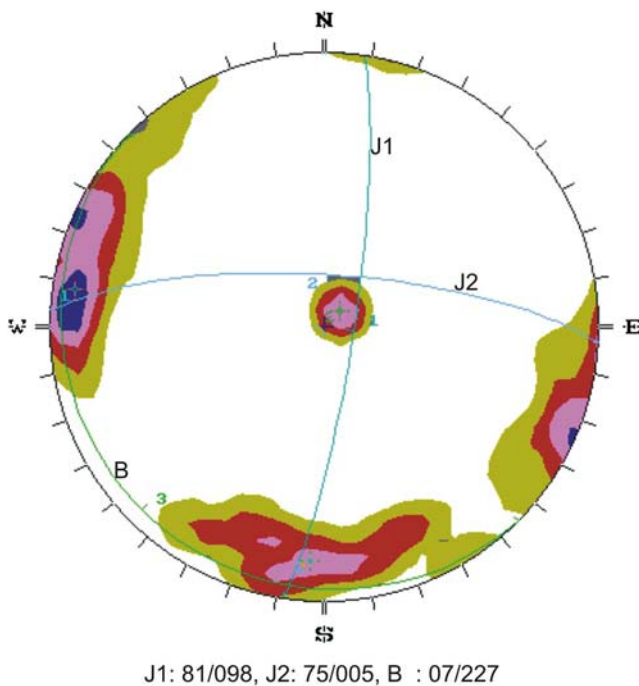
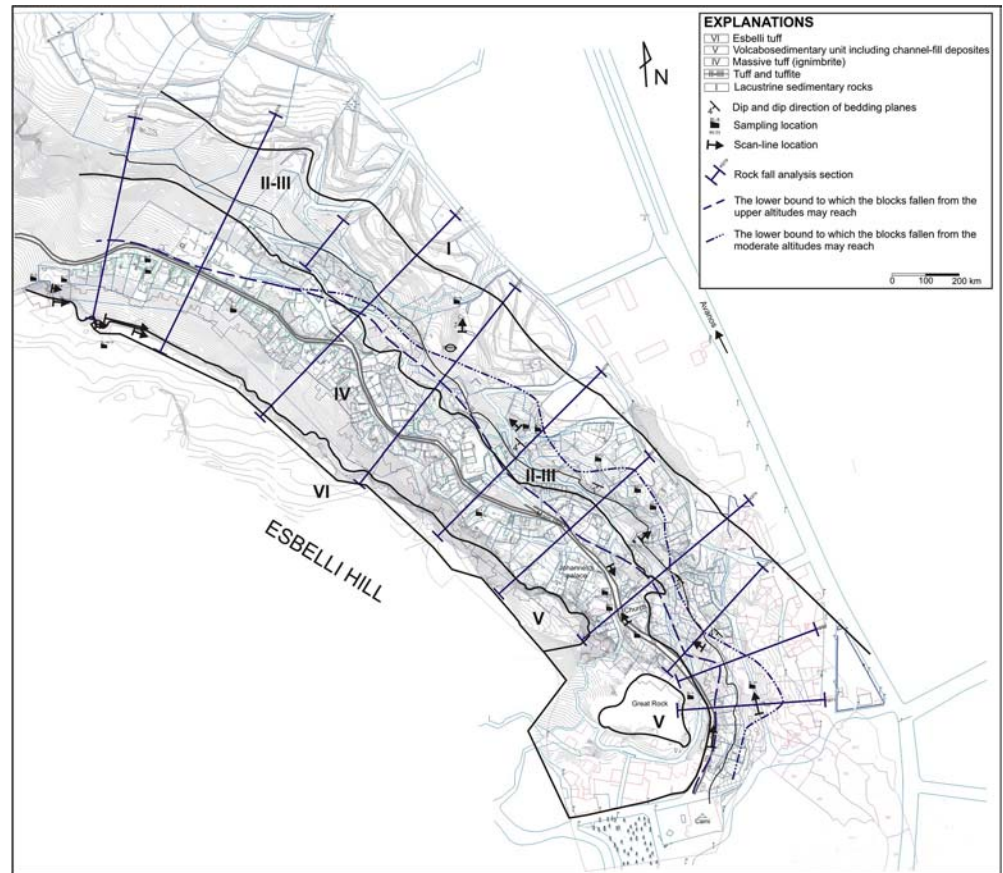
The mean spacing of the joints in the massive tuff and tuffite layers is 1.34 and 0.63 m in the Esbelli tuff (Fig. 10). While the bedding planes are generally planar, joint surfaces are classified as planar-rough and



**Fig. 7** Simplified columnar section of the Kavak tuff observed in the Kayakapi Neighborhood



**Fig. 8** Engineering geological map of the study site (topography and settlement plan are provided from KA-BA)



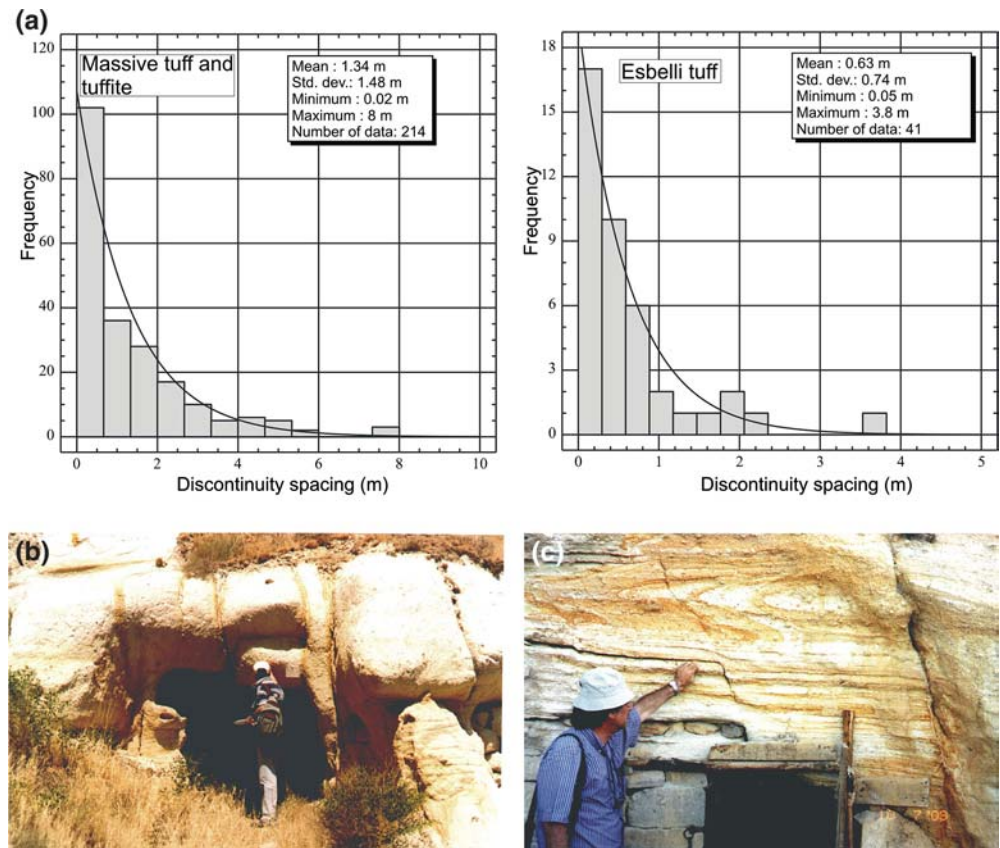
**Fig. 9** Contour diagram of the main discontinuities in the tuffs

undulated-rough. Statistically, the tuffs and discontinuity surfaces are slightly-to-moderately weathered. Due to the relatively steep topography, and slope wash and lack of vegetation, the weathering products are soon removed. Along the persistent joints, discoloration and/or surface staining are commonly observed. Bedding planes are tight, while the apertures of most joints fall within the narrow to tight (1–5 mm) categories. Persistence of the joint systems ranges between 5 and 15 m. During the field inspections no groundwater seepage was noted through the discontinuities.

Schmidt hammer tests were carried out at 150 different locations on the walls of a number of underground openings. Schmidt rebound numbers are mostly concentrated in a narrow range between 19 and 24, and therefore do not show significant changes perpendicular and parallel to layering. There is a good agreement between these values and those obtained by Aydan and Ulusay (2003) who also studied the same tuffs in the Cappadocia Region. As also stated by these investigators, the scatter in the rebound values may be reflecting the effect of soft matrix and hard inclusions of the tuffs.

The rock mass quality of the tuffs observed at the study site was estimated using the rock mass rating (RMR) scheme proposed by Bieniawski (1989). For this

**Fig. 10 a** Spacing histograms for the investigated rock units, and views from thickly bedded and vertically jointed massive tuff **b** and thinly bedded and vertically jointed massive tuff **c** and thin bedded tuffites (c)

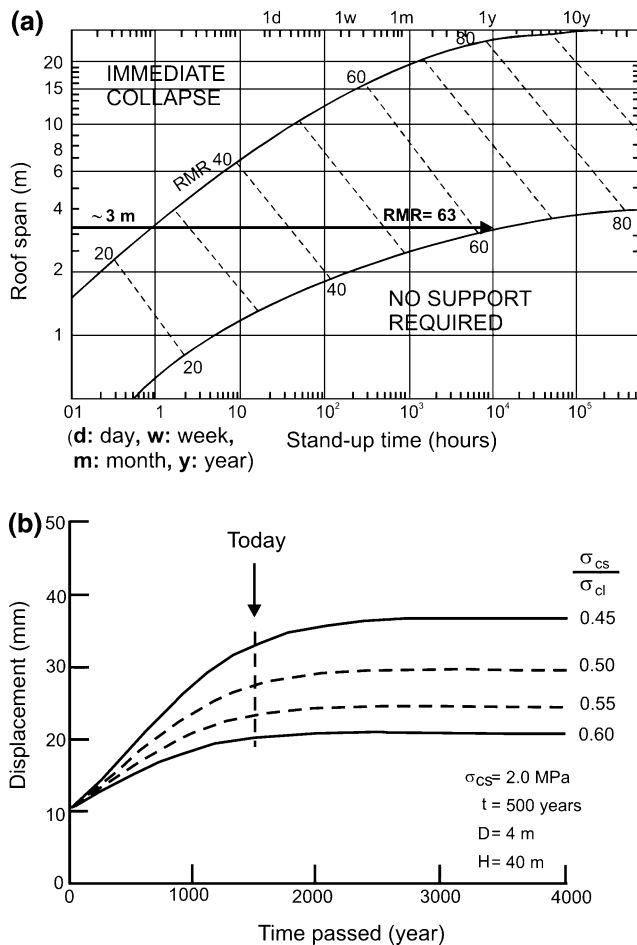


purpose, the necessary rock mass input parameters measured and/or described during scan-line surveying and the values of uniaxial compressive strength, which will be discussed in the next section, were utilized. Because the spacing of discontinuities in the massive tuff and the Esbelli tuff is generally greater than 1 m, RQD is taken as 100%. In tuffites the spacing ranges from a few centimeters to a few 10 cm, and therefore, it is accepted that RQD is less than 25%. Since no consideration is made on a particular engineering application, the effects of orientation of the discontinuities and any adjustment are discarded. The basic RMR values were obtained as 63–67 (good rock), 35–45 (weak to fair rock) and 58–61 (moderate rock) for the massive tuff, tuffite and Esbelli tuff, respectively. The estimation from the massive tuff shows a good agreement with the range of the basic RMR values determined by Topal (1995; RMR = 44–77), and Aydan and Ulusay (2003; RMR = 61–72) who studied the same tuff at different locations in Urgüp and its vicinity. This similarity between the upper and lower bounds of RMR of the tuffs also indicates that the rock mass characteristics of the massive tuff of the Kavak member do not show significant changes. Although RQD in the massive tuff is considerably high, this unit can be classified as a weak rock due to its low strength. The nearly vertical and open discontinuities enhance the

infiltration rate. This situation was validated through laboratory experiments on dry and saturated samples of the Kavak tuff by Topal (1995) and Aydan and Ulusay (2003). Therefore, maintenance of a dry condition is quite important from the stability viewpoint.

Bieniawski (1989) suggested a chart for the estimation of stand-up time of an unsupported underground opening based on the RMR value and dimension of unsupported span. However, this chart is based on observations limited to 14 years (Fig. 11a). By considering the lower bound RMR value (63) of the massive tuff, an unsupported span of approximately 3 m is found from Fig. 11a for an opening without any support. For unsupported spans greater than 3 m, stand-up times of between 1 and 10 years are estimated from Fig. 11a. If the uncertainties associated with time of construction of the underground openings at the Kayakapi Neighborhood are considered, the applicability of the chart in Fig. 11a seems not to be possible for the historical openings in the study site. However, except wedge failures from the roofs of some troglodytes, no rock mass failure or total collapse was observed and many openings have preserved their stability for a long period. This situation suggests that stability in these rock units is mainly controlled by discontinuities.





**Fig. 11** a Relationship between the stand-up time of an unsupported span based on the RMR system (Bieniawski 1989), and b a preliminary elasto-visco-plastic analysis showing the time-dependent displacement of a hall in the Derinkuyu underground city excavated in tuff (after Ulusay et al. 1999)

The long-term stability of underground openings at Cappadocia was investigated by Seiki et al. (1999), Ito et al. (1999), and Ulusay et al. (1999) at Derinkuyu underground city which has been carved in tuffs and located at the south of Urgüp town. The preliminary short and long-term stability analyses of a hall at the 7th floor of this underground city at the depth of 40 m below the ground surface was carried out by the above-mentioned investigators using an elasto-visco-plastic model. The results of these analyses suggested that if the depth is less than 40 m, the behavior of the surrounding rock is visco-elastic without any yielding of surrounding rock mass during the initial stages of the cavities. However, the shrinkage of yield surface with time and rate-dependent deformability characteristics of the surrounding rock were obtained from test results in time-dependent deformations for a considerable period of time and they were influenced by the long-term and

short-term strength. As seen from Fig. 11b, these investigators suggest that the additional deformation must be very small after 1,500 years unless the rock degrades due to weathering. Similar problems are also observed in some openings at the Kayakapi Neighborhood, and therefore, it can be concluded that from stability viewpoint, discontinuities and rock weathering seem to be more important factors controlling the stability of the underground openings.

#### Environmental conditions in troglodytes

Thermal insulation properties of the Cappadocian tuffs (Erguvanli and Yuzer 1977; Aydan and Ulusay 2003) make the underground openings more attractive for various purposes. By considering this, environmental conditions in a limited number of selected underground openings were also evaluated. For the purpose, a digital device measuring temperature, humidity and velocity of wind was used, and these parameters were measured both in the inside and outside of the openings (Table 1). It is evident from Table 1 that the temperature in the openings is 1–6°C lower than that outside. The inside humidity is between 50 and 60%, which is considerably higher than that measured outside. In addition, wind velocity is 0.4 m/s in the openings. Although very limited measurements were obtained in this study, the general trends of the inside and outside temperature and humidity show similarities to those obtained from previous long-term studies in different underground openings in Urgüp and the Derinkuyu underground city (Aydan and Ulusay 2003). All these studies confirm that temperature and humidity variations in these underground rock structures in Cappadocia are small when compared to those recorded outside. In other words, underground space in those tuffs is warmer during winter and cooler in summer which provides a very comfortable living environment as well as energy saving.

#### Geomechanical properties of the rock units

Due to the fact that the Kayakapi Neighborhood is an important historical site of the region and is under protection, the collection of rock samples from different parts of the site is considerably limited. Consequently, based on an official permission, a total of 18 block samples could be collected from the site (see Fig. 8) for laboratory geomechanical tests.

The Cappadocia Region has highly interesting natural rock structures and man-made underground openings. For this reason, in addition to geological and geomorphological interests, several investigations (Doyuran 1976; Erguvanli and Yuzer 1977; Erdogan 1986, 1989; METU 1987; De Witte et al. 1988; Erguvanli

**Table 1** Values of temperature (T), humidity (H) and velocity of wind (VW) measured inside and outside some underground openings at Kayakapi

Opening no.	T (°C)		H (%)		VW (m/s)
	Inside	Outside	Inside	Outside	
240	25.5	26.4	50	35	0.4
Church	22.8	27.0	51	37	0.4
Water tunnel	20.4	27.0	48	37	0.3
98	18.1	22.2	60	50	0.3

et al. 1989; Topal 1995; Binal 1996; Topal and Doyuran 1997; Ulusay et al. 1997; Aydan and Ulusay 2003) on stone deterioration, conservation, engineering geology and stability of the man-made underground structures were carried out in the region. These studies are mainly concentrated on the Kavak tuff, which has widespread exposure in the area, and many historical and recent underground settlements have been observed in this rock unit (Aydan and Ulusay 2003). The aims of the experimental program performed herein are to determine the geomechanical parameters of the tuffs to be used in further efforts such as support selection, stability analyses, restoration etc., and to use them for rock mass classification and rock fall analyses. For the purpose, a series of geomechanical laboratory tests on the core specimens extracted from the block samples was carried out. The geomechanical parameters determined throughout these tests are unit weight, block punch strength index, tensile strength, uniaxial compressive strength, modulus of elasticity, *P*-wave velocity and slake durability index. During the tests the ISRM (1981) suggested methods were employed.

Based on the geological evaluations, the rock units cropping out at the site were classified as beige massive tuff, pink massive tuff, tuffite and Esbelli tuff. The minimum, maximum and mean values of each geomechanical property of these rock units are given in Table 2. As can be seen from Table 2, the unit weights of the rock units are considerably different. The Esbelli tuff has the smallest unit weight (11.7 kN/m<sup>3</sup>) due to its composition, generally consisting of very light pieces of

pumice. The values of *P*-wave velocity of the core specimens, which show the effects of weathering (i.e., limonitization), are lower than those of others. When compared with the beige massive tuffs, the *P*-wave velocities measured on the pink massive tuff samples are, respectively, higher due to their relatively low porosities and microcracks.

In addition to the limited number of blocks, some of the block samples were highly weathered. Therefore, it was impossible to extract standard high quality core specimens to be used in the determination of the uniaxial compressive strength and modulus of elasticity. The uniaxial compressive strength was indirectly estimated from the block punch index (BPI) test by considering that determination of the BPI value requires relatively small disc specimens. This test was recently accepted by ISRM as a Draft ISRM Suggested Method (Ulusay et al. 2001). Following the procedure proposed by Ulusay et al. (2001), the BPI tests were carried out and the results obtained from the tests are summarized in Table 2. The mean BPI value of the pink massive tuff is the highest while that of the tuffite is the lowest (Table 2). In this study, the Brazilian tests were also performed on disc specimens to determine their tensile strength. The mean tensile strength of the pink massive tuff is 2.29 MPa while those of the others are very low (Table 2).

Because the tuffite and Esbelli tuff show layering, the core specimens perpendicular to layering were extracted for uniaxial compressive strength and modulus of elasticity determinations. During uniaxial loading, the deformations were recorded. However, due to very rough surfaces of the tuff specimens, standard strain gauges could not be used to measure the deformation under loading. In order to overcome this difficulty, a strain gauge-type displacement transducer with an accuracy of 10<sup>-4</sup> was employed. The mean values of the uniaxial compressive strength and modulus of elasticity are given in Table 2. Among the rock units tested, the beige massive tuffs yielded the highest uniaxial compressive strength and modulus of elasticity.

The rock units cropping out in the study area are highly prone to slaking due to their clay content

**Table 2** Geomechanical properties of the rock units observed in Kayakapi

Rock type	Unit weight (kN/m <sup>3</sup> )	BPI (MPa)	$\sigma_t$ (MPa)	UCS (MPa)	<i>E</i> (GPa)	<i>V<sub>p</sub></i> (m/s)	Slake durability index	
							<i>I<sub>d2</sub></i> (%)	<i>I<sub>d4</sub></i> (%)
Beige massive tuff	12.4–14.4 (13.8)	1.00–4.00 (2.75)	0.41–1.34 (0.64)	2.3–9.1 (4.6)	0.20–2.34 (1.10)	1,236–2,299 (1,672)	14.9–96.4 (49.3)	8.1–35.7 (90.4)
Pink massive tuff	* (15.3)	* (3.89)	* (2.29)	* (16.2)	* (3.49)	* (2,400)	* (94.1)	* (90.4)
Tuffite	* (16.5)	1.42–2.40 (1.91)	0.56–0.64 (0.60)	* (14.0)	* (2.22)	* (2,008)	62.2–79.6 (70.9)	43.3–70.7 (57.0)
Esbelli tuff	* (11.7)	* (2.36)	* (0.82)	* (7.5)	* (3.04)	* (2,223)	* (86.5)	* (84.5)

*BPI* Block punch strength index;  $\sigma_t$  tensile strength; *UCS* uniaxial compressive strength; *E* modulus of elasticity; *V<sub>p</sub>* *P*-wave velocity; \* determined from only one block sample; the values in parentheses indicate mean values obtained from several blocks

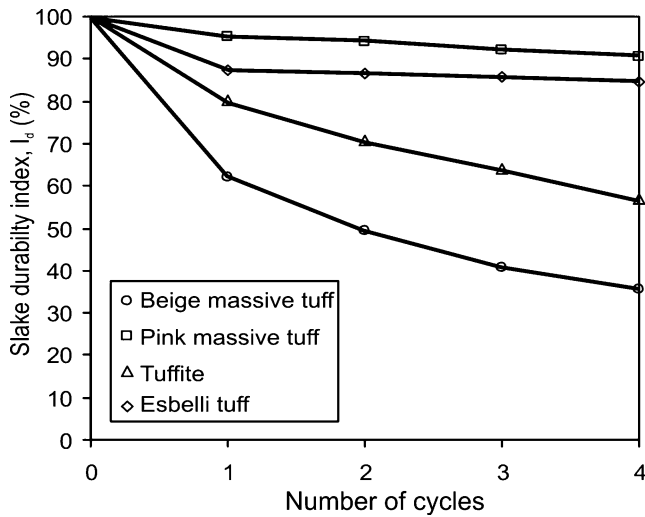


Fig. 12 Influence of the number of cycles on slake durability index of the tuff and tuffite samples from Kayakapi

associated with their composition and weathering. The slake durability index ( $I_{d2}$ ) of the tested specimens ranged between 49.3 and 94.1% (Fig. 12), indicating low to medium durability according to the Franklin and Chandra (1972) durability classification. However, in previous studies (e.g., Moon and Beattie 1995; Gokceoglu et al. 2000) considerable decreases in the slake durability index were noted for clay-bearing and weak rocks as the number of cycles increases particularly at the fourth cycle. In this study, therefore, the number of cycles was also increased up to four. As can be seen from Fig. 12, the slake durability indices of the samples obtained from the beige massive tuff and tuffite show a considerable decrease in the slake durability index as the number of cycles increases. No considerable decrease in slake durability index values of the other units were observed at the end of the fourth cycle (Fig. 12).

Field observations suggested that all instabilities in the roofs of underground openings and along the slopes were controlled by discontinuities. For this reason, the shear strength parameters of the discontinuities have crucial importance in the stability analyses. In the study area, the vertical or nearly vertical joints have a primary role in the development of instabilities when compared with the nearly horizontal bedding planes. Thus the failure envelope of the joints was obtained using the Barton's empirical failure criteria (Barton 1973) given below:

$$\tau = \sigma_n \left[ \text{JRC} \log \left( \frac{\text{JCS}}{\sigma_n} \right) + \phi_b \right] \quad (1)$$

where  $\tau$  is the shear strength of the rough discontinuity surface (MPa), JRC is the roughness coefficient of the discontinuity surface, JCS is the joint compressive strength (MPa),  $\sigma_n$  is the normal stress (MPa) and  $\phi_b$  is

the basic friction angle (degree). The JRC was estimated from the roughness profiles suggested by ISRM (1981) by comparing them with the joint surfaces in the tuffs. JRC generally varies between 10 and 12, and was taken as 11 in the calculations. The values of JCS were obtained from the Schmidt hammer tests. The basic friction angle determined from the shear box test carried out on saw-cut smooth rock surfaces is  $30^\circ$ . The failure envelope of the joints based on Eq. 1 is depicted in Fig. 13.

### Assessment of environmental and engineering problems

#### Definition of the problems associated with underground openings

Based on the observations carried out by the authors in 1,156 underground openings of different dimensions at the study site, a number of environmental and engineering problems were identified. These are briefly described and some typical examples from the Kayakapi Neighborhood are given in the following paragraphs.

#### Block falls in underground openings

The most commonly observed stability problem at Kayakapi Neighborhood is the fall of rock blocks from the roofs or sidewalls of underground openings. These blocks are separated from the surrounding rock mass by

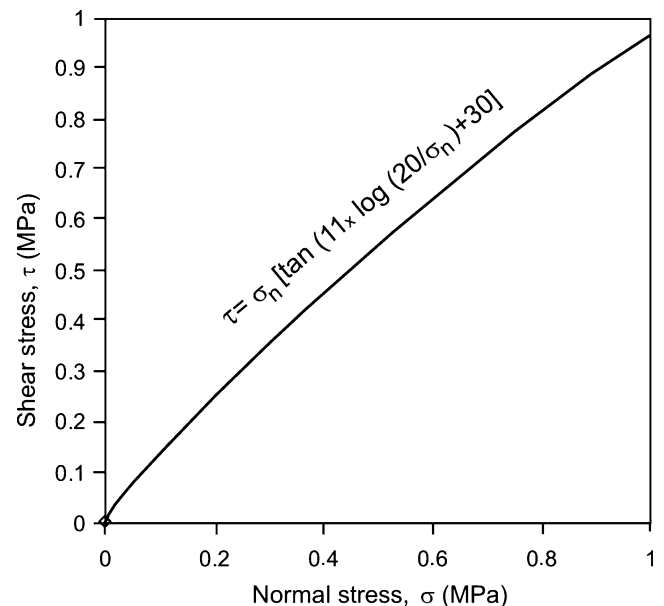
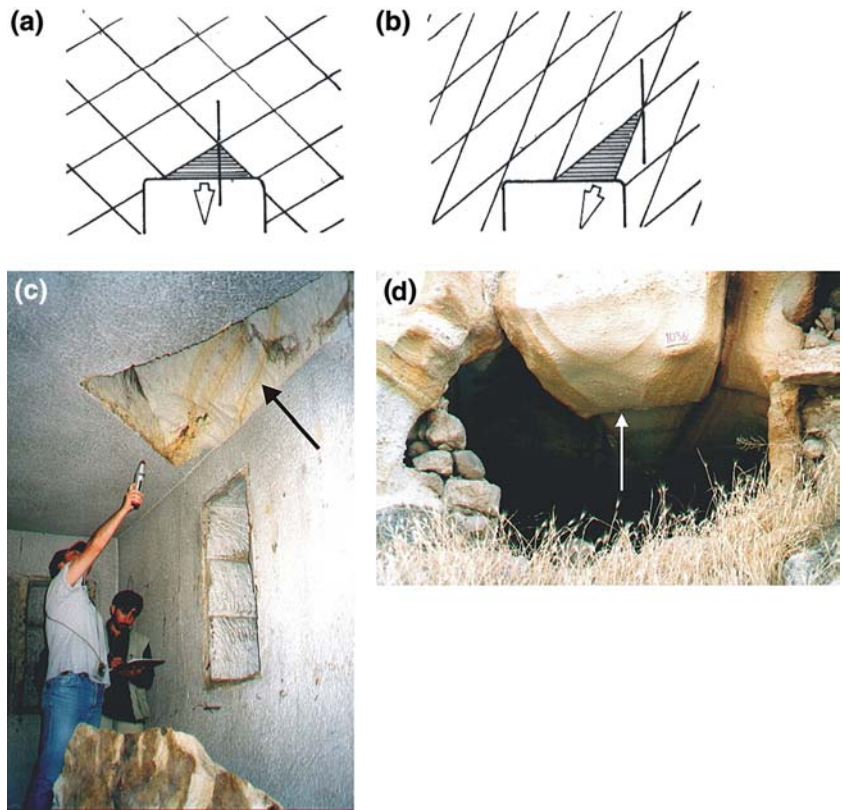


Fig. 13 The failure envelope of the joint surfaces in tuffs



**Fig. 14** Conditions for gravity fall **a** and sliding failure **b** of roof wedges (Hoek and Brown 1980), **c** a wedge block that had fallen from the roof of an opening, and **d** a key block hanged at the entrance of a troglodyte at Kayakapi



intersecting discontinuities and fall under the influence of gravity or slide along the line of intersection of the discontinuities as illustrated in Fig. 14a and b. A typical block fall from the roof of an opening is shown in Fig. 14c. In addition, some hanging blocks, which have not fallen yet, were also observed on the roof or entrance of the openings (Fig. 14d). Such blocks can be considered as the key blocks and pose a threat to the long-term stability of the openings.

#### *Overbreak*

Horizontal or nearly horizontal stratification can be more dangerous where the beds dip  $5^{\circ}$ – $10^{\circ}$  and it may lead to roof overbreak. This instability problem is also commonly observed in the openings at the study site. The instability of the key blocks is followed by the deformation of secondary blocks resulting in an enlargement of the opening as seen in Fig. 15a. This instability phenomenon is also observed in the openings carved in thin-layered tuffites.

#### *Bending*

Particularly in the openings carved in thin-layered tuffites, the beds slowly bend into the opening, and

although the rock was not necessarily detached from the surrounding rock mass, the deformation caused fissures and hollows in the rock (Fig. 15b). In addition, some detached blocks of which bending strengths were exceeded due to bending fall into the opening.

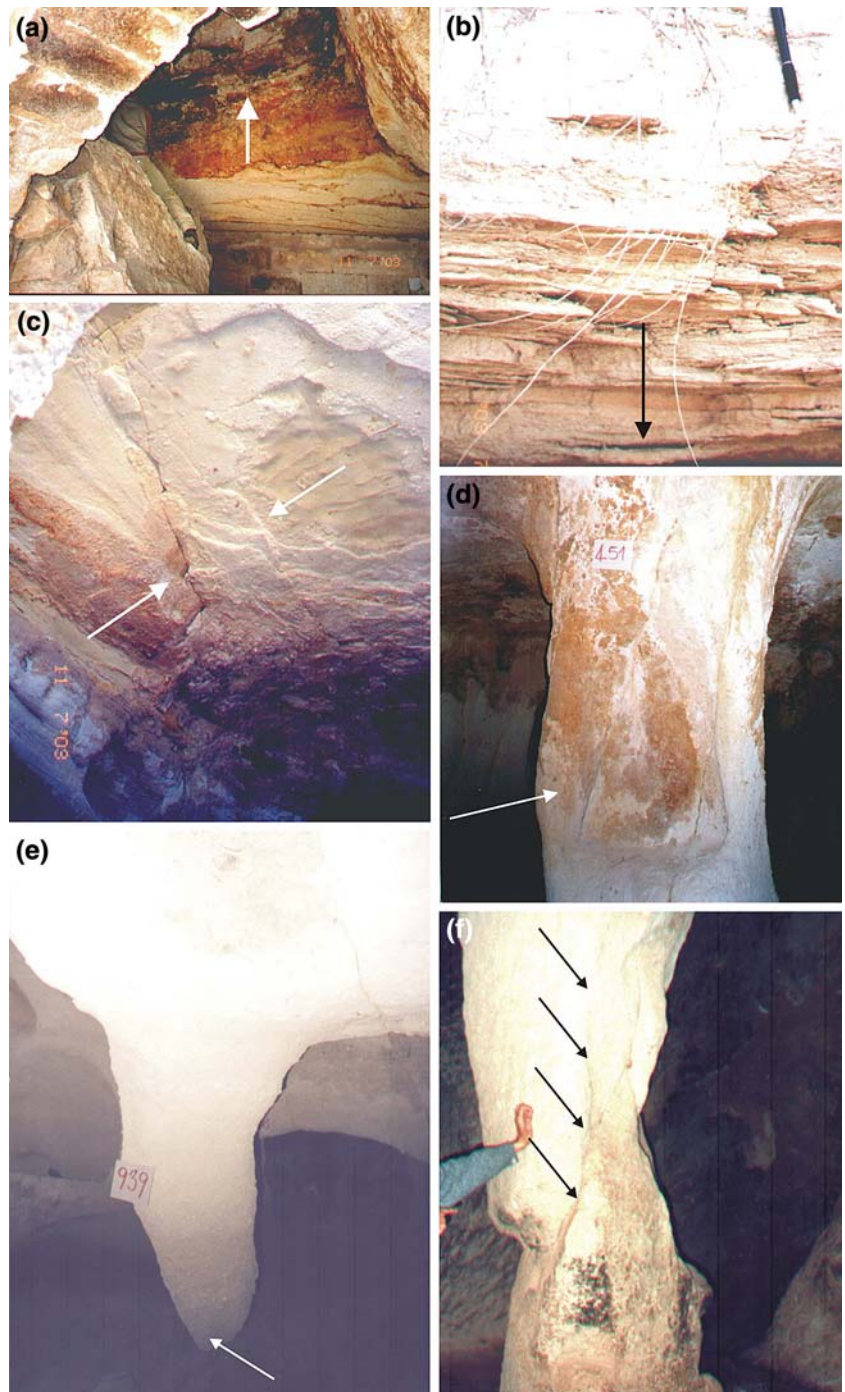
#### *Spalling*

Spalling is another local instability observed in the troglodytes at the Kayakapi Neighborhood (Fig. 15c). Spalling of exposed surfaces, due to alternate freezing–thawing and wetting–drying, is rather common.

#### *Erosion and shearing of pillars*

In some large underground openings, a number of pillars have been left. Under the influence of atmospheric conditions and depending on weathering processes, some of the pillars tend to degrade and erode resulting in the loss of their supporting capability (Fig. 15d, e). In addition to this problem, due to weathering-induced partial loss of the pillar's strength and stresses acting on the pillars, shear cracks are also evident in some pillars (Fig. 15f).

**Fig. 15** Typical stability problems in underground openings at the study site: **a** overbreak, **b** bending, **c** spalling, **d** degradation, **e** erosion and **f** shearing of pillars, **g** effects of thin overburden and external load, **h** collapsed thin slab between the floors of a troglodyte, **i** a block with rock fall potential near the entrance of a group of openings, and **j** a weak arch at the entrance of an opening



#### *Effect of overburden thickness*

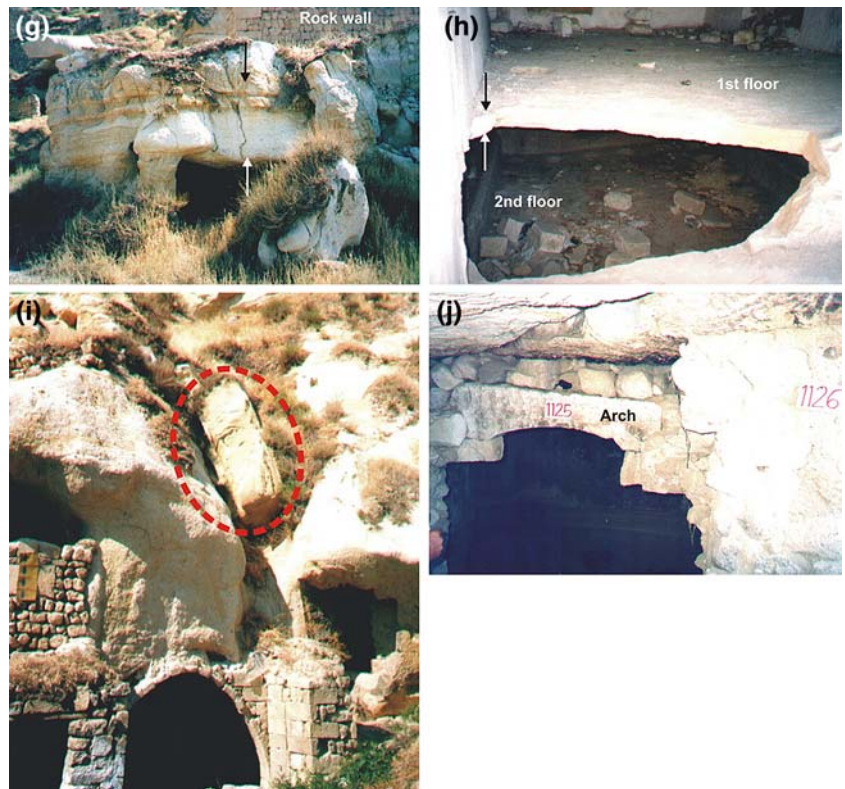
In the study site, depending on the decrease in the thickness of the roofs, some instability problems such as collapse are observed at some locations, particularly in the openings which are located just below the main road or masonry structures (Fig. 15g). In addition, very thin slabs of about 10–15 cm between the floors

of some underground openings have collapsed (Fig. 15h).

#### *Rock fall hazard at the entrances of underground openings*

From the stability viewpoint, one of the most important parts of the underground openings is their

Fig. 15 (contd.)



entrance. Although there is no stability problem associated with the surrounding rock in some openings at Kayakapi, due to the hilly nature of the site there exist some rock blocks which have fallen or rolled from higher altitudes near to the entrances of some openings (Fig. 15i). These blocks may fall due to any triggering factor, and therefore, special attention should be paid to such blocks.

#### *Weakening of the arched-type entrances*

The entrances of some openings have been supported by arches using prismatic blocks made of tuff. However, due to weathering-prone characteristics of the tuffs, these blocks tend to weaken, and consequently their supporting ability decreases (Fig. 15j). The troglodytes with such entrances may face future stability problems.

#### *Back-analysis of the failed blocks in underground openings*

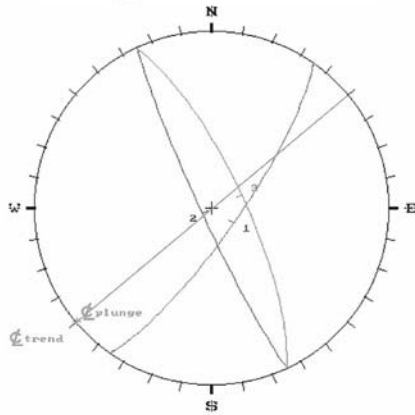
In order to estimate the range of shear strength parameters mobilized along the discontinuities during block instabilities at the roof of openings, five selected structurally-controlled block failures were back-analyzed. Then the results of the analysis were compared

with the experimentally determined shear strength parameters of the discontinuities.

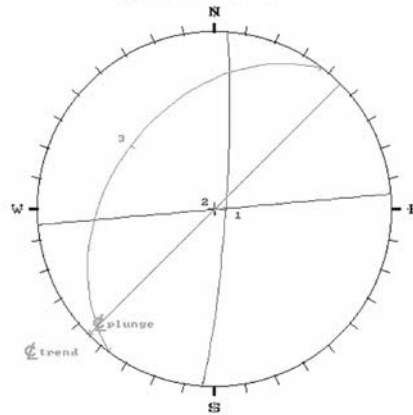
In the analyses, a software 'UNWEDGE', which is based on the method suggested by Hoek and Brown (1980) and developed by Carvalho et al. (1992), was employed and the orientations of the intersecting discontinuities related to the fallen blocks in each of the five selected openings were considered. As a first step, the condition of gravity fall or sliding failure was investigated. In three of the five openings the mode of failure was gravity fall (Fig. 16a–c). The roof instabilities in two openings occurred in the form of block sliding as seen in Fig. 16d and e. The second step included the back-analysis of these failures to determine cohesion ( $c$ ) and friction angle ( $\varphi$ ) of the discontinuities satisfying the sliding condition (i.e., factor of safety of unity). It is evident from Fig. 16d and e that by considering all discontinuity sets contributing to the formation of rock wedges in the roof of the opening numbered 1,036, the values of  $c$  and  $\varphi$  ranging between 0 and 10 kPa, and  $35^\circ$  and  $45^\circ$  satisfy the failure condition. This condition is also satisfied by  $c = 30$  kPa and  $\varphi = 45^\circ$  in the opening numbered 118. The ranges of  $c$  and  $\varphi$  obtained for the discontinuities in the opening 1,036 show a good agreement with those obtained from the failure envelope of the discontinuities (see Fig. 13) based on the normal stress level expected at the study site. In other words, these values may be employed in



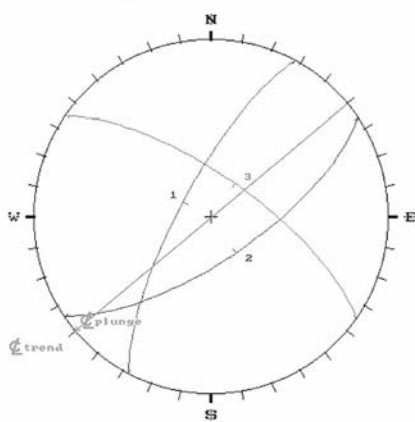
**(a) Troglodyte No. 123**  
**Joint sets:**  
 J1:78/125 J2:85/245 J3:75/065  
**Strike of the troglodyte:** 225  
**Width of the troglodyte:** 5 m  
**Type of failure:** Fall



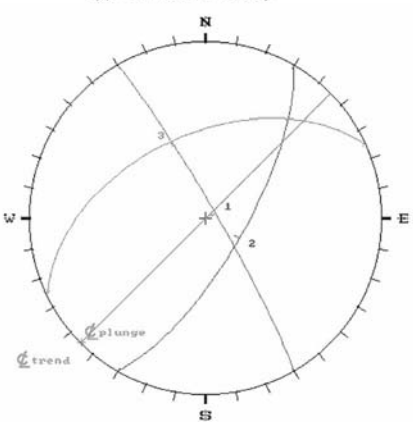
**(b) Troglodyte No. 411**  
**Joint sets:**  
 J1:85/094 J2:90/175 J3: 40/307  
**Strike of the troglodyte:** 230  
**Width of the troglodyte:** 4 m  
**Type of failure:** Fall



**(c) Troglodyte No. 1177**  
**Joint sets:**  
 J1:75/298 J2:70/146 J3: 71/035  
**Strike of the troglodyte:** 230  
**Width of the troglodyte:** 4m  
**Type of failure:** Fall

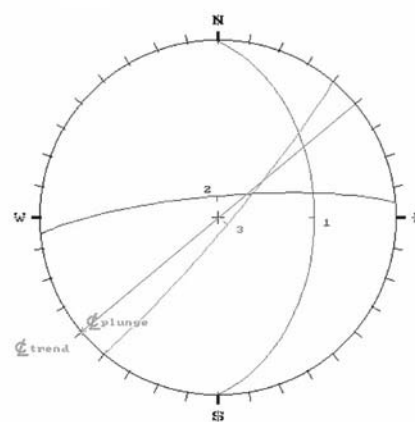


**(d) Troglodyte No. 118**  
**Joint sets:**  
 J1:85/060 J2:72/120 J3: 50/355  
**Strike of the troglodyte:** 230  
**Width of the troglodyte:** 5m  
**Type of failure:** Sliding



c (kPa)	$\phi$ ( $^{\circ}$ )	F
5	45	0.24
20	45	0.69
30	45	1.00

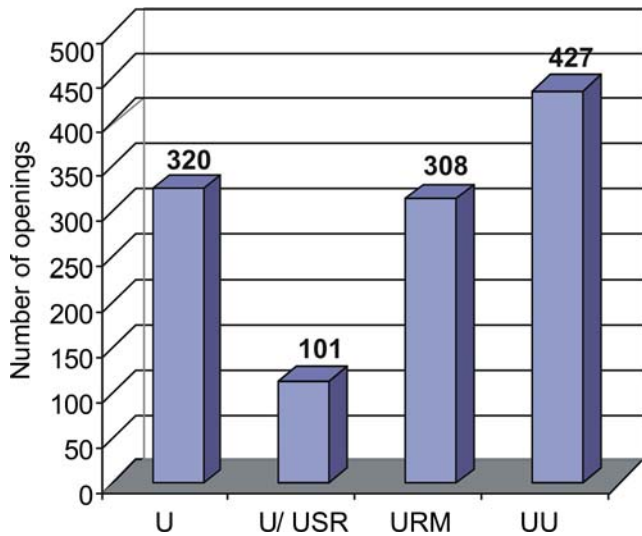
**(e) Troglodyte No. 1036**



**Joint sets:**  
 J1:48/090 J2:80/355 J3: 85/130  
**Strike of the troglodyte:** 230  
**Width of the troglodyte:** 3.65 m  
**Type of failure:** Sliding

c (kPa)	$\phi$ ( $^{\circ}$ )	F
0	35	0.6
0	45	0.86
5	35	0.87
10	35	1.17

**Fig. 16** Stereographic projections of the failed wedges and the results of back-analyses for the selected underground openings



**Fig. 17** Histogram of the categorized troglodytes at Kayakapi based on the troglodyte inventory (*U* usable, *U/USR* usable/usable after some remediation, *URM* usable after remedial measures, *UU* unusable)

further stability analyses associated with remedial measures.

#### Usability of the troglodytes and troglodyte inventory

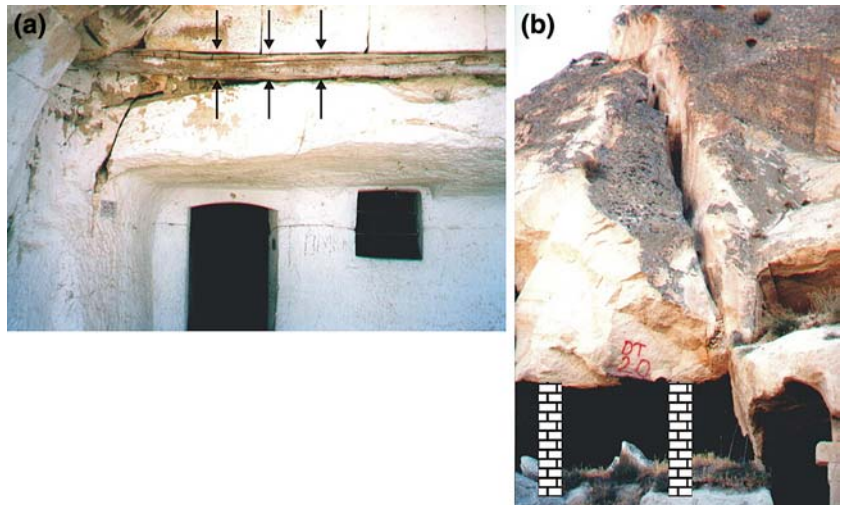
The problems defined in the previous section and characteristics of the discontinuities were recorded on the sheets for 1,156 troglodytes of the Kayakapi Neighborhood. Then the usability of these openings was evaluated to prepare a troglodyte inventory in conjunction with the collected information based on visual assessments. For the inventory work, the troglodytes were

categorized into four classes based on the following criteria.

1. Usable (*U*): the troglodytes which are free from any instability problem and can be accepted as suitable from the civil engineering and architectural viewpoints are included into this category.
2. Usable/usable after some remediation (*U/USR*): this category involves the openings that are usable when considered individually, but are adjacent to problematic openings which may be re-used after remedial measures.
3. Usable after remedial measures (*URM*): in this category, the openings where one or more stability problems mentioned above have been experienced are considered. For their use, the consideration of remedial measures is necessary.
4. Unusable (*UU*): this category includes openings that are located just below the main roads and have thin overburden, and those related with block falls from their roofs and overbreak generally played an important role. The openings where one or more stability problems have been observed and remedial measures do not seem to be effective are included into this category. These particularly include the openings where large block falls from their roofs were experienced.

Based on the above-mentioned criteria and categories, a troglodyte inventory for the Kayakapi Neighborhood was prepared. The statistical evaluation of this inventory is depicted in Fig. 17. The number of troglodytes, which can be directly used, is 320, while there are 427 abandoned openings which should not be re-used. If the necessary remedial measures are done for the classes *U/USR* and *URM* in Fig. 17, the number of usable openings can increase up to 729.

**Fig. 18 a** Improvement of roof stability by timber beams and **b** artificial pillars suggested for supporting the block above the openings numbered 68, 69 and 70



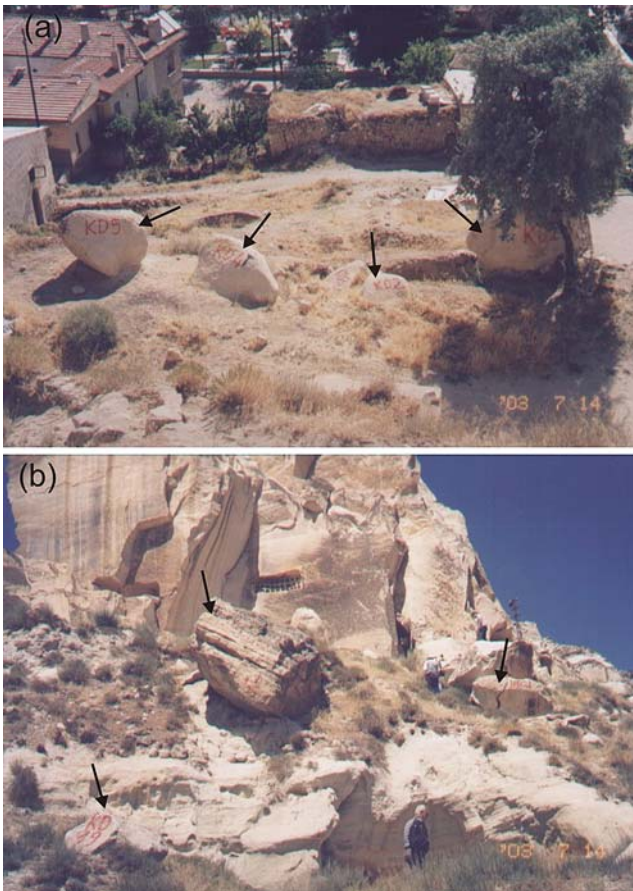


Fig. 19 The blocks that had already fallen at Kayakapi

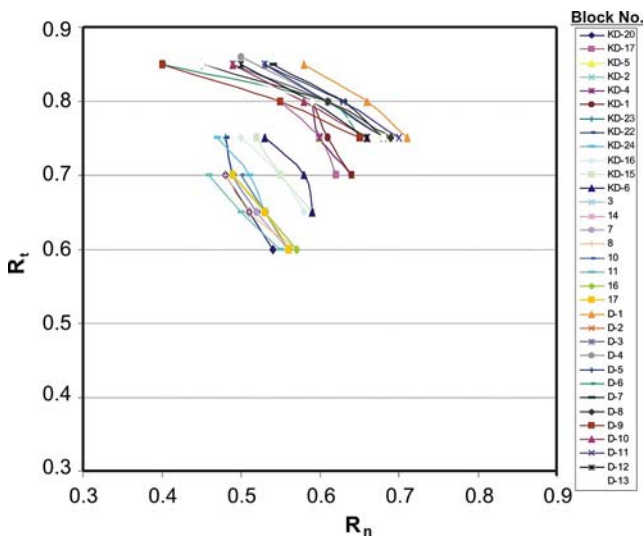


Fig. 20 Variation of the coefficients of normal ( $R_n$ ) and tangential ( $R_t$ ) restitution obtained from the back-analyses for a friction angle of  $35^\circ$

### Recommendation of remedial measures for underground openings

The stability problems experienced in the troglodytes and the inventory prepared for these openings suggest that remedial measures should mainly be concentrated on the prevention of structurally-controlled roof failures, strengthening of pillars, removal of dangerous blocks standing on the sloping ground above the entrances of some openings, and filling the abandoned shallow-seated openings with low-bearing capacity. These measures are briefly outlined and discussed in the following paragraphs.

#### Improvement of stability

One of the methods to prevent structurally-controlled block failures is the supporting of roofs by timber beams as shown in Fig. 18a. This method is the traditional and commonly used roof supporting system in Cappadocia, and provides a good agreement with the original surrounding rock from the aesthetical viewpoint. The second alternative of roof supporting, particularly at the entrance of openings, is the construction of arches using prismatic blocks made of stronger tuffs. In addition, spalling can be minimized by removing the detached surfaces on the roofs and sidewalls of the openings. Although wire-mesh and shotcreting may be another alternative against spalling, the use of shotcrete may not be successful due to the inconsistent bonding between shotcrete and the rock itself and may not be suitable from aesthetical considerations.

Rock bolting is a commonly used measure to prevent block failures and bending. There are different types of rock bolts. However, because the tuffs at the study site are soft and weathering-prone rocks, application and performance of bolting in these rocks seem to be questionable. Therefore, additional works on this measure in conjunction with pull out tests are needed.

#### Strengthening of pillars

Some pillars weakened due to degradation or cracking should be strengthened. For this purpose, such pillars may be surrounded by metal cages and the void between the cage and the pillars is filled by salt-free concrete. Then prismatic stones cut from the same tuff are laid down around the columns.

#### Removal of previously fallen blocks

Some huge blocks, which stand above the entrance of some openings after rolling down along the sloping ground or falling from higher altitudes, should be broken in-place without blasting, and be removed from the

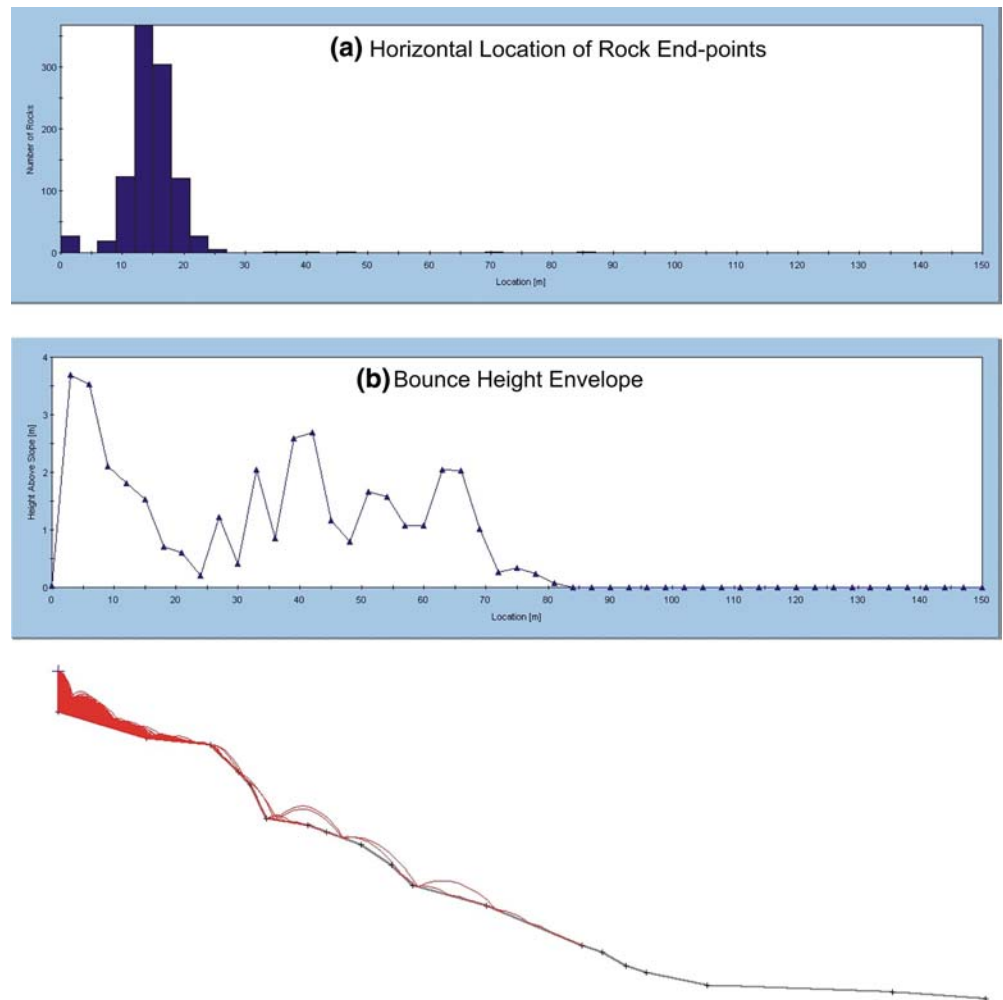


**Table 3** The parameters employed in rock fall analyses

Parameter	Value
Coefficient of normal restitution ( $R_n$ )	$0.57 \pm 0.07$
Coefficient of tangential restitution ( $R_t$ )	$0.74 \pm 0.07$
Friction angle ( $\varphi$ )	$35^\circ \pm 2^\circ$
Profile roughness	2
Initial velocity (m/s)	$1 \pm 0.5$
Rock fall number	1,000
Minimum velocity prevention vale (m/s)	0.1
Sample range	50

site. On the other hand, a huge block threatens three large openings that can be used for multi-purposes in the future (Fig. 18b). Although no evident stability problem associated with this block has been experienced at this stage, due to the absence of any pillar supporting the block and the possibility of a further separation along the highly persistent joint, this block should be supported by artificial pillars as illustrated in Fig. 18b.

**Fig. 21** The variation of **a** fall-out and **b** bouncing height of a rock block 5,000 kg in mass



### *Filling the abandoned and shallow-seated openings*

The presence of some very shallow-seated openings, which have very thin overburden or are located below the road or any structure, indicates bearing capacity problems. Such openings should be filled with blocks and application of injection to fill voids between the blocks to prevent unexpected collapses. Particularly, the troglodytes located below the rock-hewn church (see Fig. 5c) should be filled for structural stability of the church.

### **Assessment of rock fall potential and possible remedies**

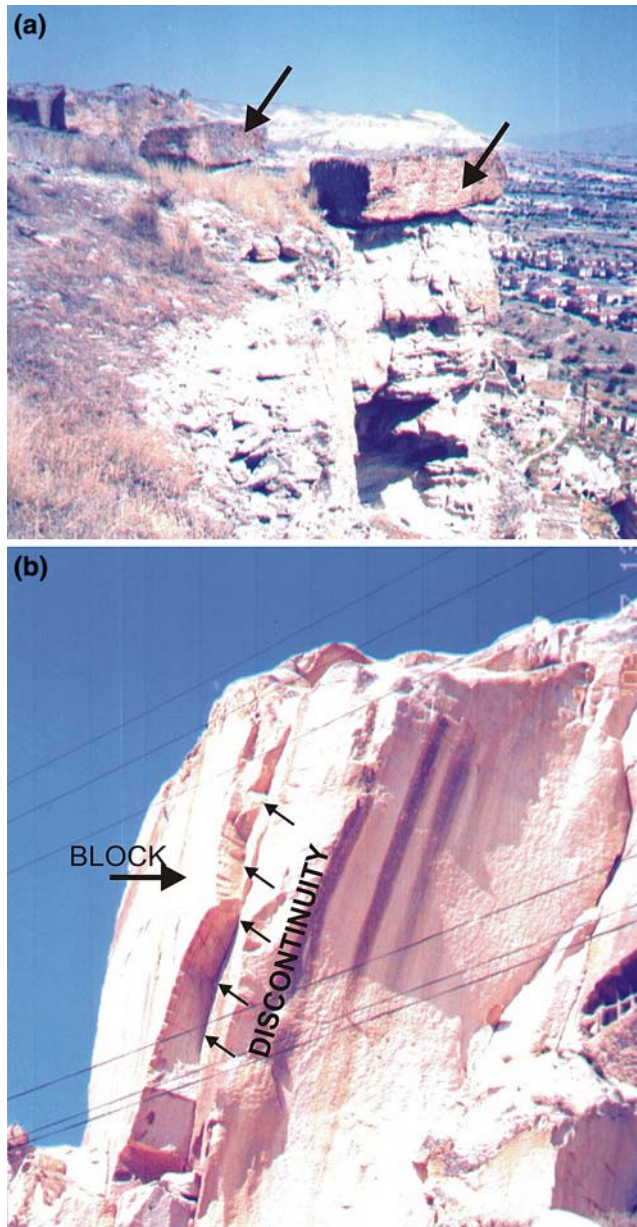
Rock fall is a downslope movement of detached rocks in any size traveling through the air. Rock fall is usually very rapid and may cause loss of life and property. It may occur due to jointing, weathering, freeze–thaw, water effect, earthquake, and tree roots. Depending on the shape of the slope, rock fall may occur in the form of

free fall, bouncing, or rolling (Ritchie 1963). As the profile changes, two or more of the rock fall modes may also be observed. Additionally initial velocity, weight and shape of the blocks, and the properties of the slope forming material may control rock fall event (Giani 1992; Dorren 2003). Empirical/experimental techniques or modeling can be used for rock fall analysis (Giani 1992; Okura et al. 2000). Rock fall analysis with computer modeling can be used to predict the block trajectory, travel distance, velocity, bounce height and kinetic

energy of the blocks (Schweigl et al. 2003). The coefficient of restitution is one of the most important and most difficult parameters to assess for the analysis. This parameter may be significantly different depending on the conditions of each site. Therefore, the coefficient of restitution with normal ( $R_n$ ) and tangential ( $R_t$ ) components is determined individually for each site. Field tests or back-analysis of the fallen blocks may be used for obtaining these coefficients. Based on the analysis, remedial measures such as avoiding the site, cleaning of loose rock blocks, bolting, construction of retaining wall, installation of a protective fence and ditch construction may be taken into consideration to eliminate or mitigate the rock fall hazard (e.g., Chen et al. 1994; Chau et al. 2002; Schweigl et al. 2003).

The field studies performed around the Kayakapı Neighborhood revealed that steeply dipping cooling joints dominantly developed within the massive tuffs and Esbelli tuff create blocks of different sizes to fall down (Fig. 19). More than 30 already fallen blocks were identified in the study area. As part of this study, field tests were also performed by dropping tuff blocks (4–25 kg in mass) from a number of sections. The observations performed during the rock fall tests indicated that the rock falls mostly occurred in the form of rolling, while some blocks bounced. The fall-out distances of the blocks were different. The end locations of the test blocks and the blocks that had fallen in the past were used to perform back-analysis via the RocFall (4.0) software of Rocscience Inc. (2002) in order to assess the normal and tangential coefficients of restitution (Fig. 20). The coefficient of restitution found from the back-analysis ( $R_n = 0.54 \pm 0.08$ ;  $R_t = 0.72 \pm 0.06$ ) and other selected parameters (Table 3) were used to carry out the rock fall analysis along 11 sections shown in Fig. 8. Depending on the block sizes measured along each section, blocks with masses ranging from 5 kg to a maximum of 10,000 kg were used for the analyses. The analyses yielded the fall-out distance, bounce height, kinetic energy and velocity of the rocks along each section. The variation of fall-out distance and bounce height of a block 5,000 kg in weight is shown in Fig. 21a and b. The extent of the fall-out distance indicating the danger zone is shown in Fig. 8. The fall-out distances calculated from the rock fall analyses are found to be in good agreement with the field observations. Based on the analyses, the bounce height ranges between 0.11 and 5.18 m, generally less than 3 m. Similar bounce heights were also observed during the field tests. The maximum kinetic energy is in the order of 840 kJ. It significantly decreases as the size of the fallen blocks decreases. The maximum expected velocity of the blocks during falling ranges between 7.12 and 24.26 m/s.

Based on field observations and rock fall analyses, the entrance of the Kayakapı called Büyük Kaya (Great Rock) is the most dangerous area (see Fig. 8). Many



**Fig. 22** a A block with rock fall potential resting at Esbelli Hill, and b a potentially unstable block needs bolting for stabilization at the entrance of the study site

identified blocks ready to fall in the study area (Fig. 22a) should be removed in a controlled manner. A retaining wall with a height of 3–4 m near the Büyük Kaya location covered with decorative local stones for aesthetic reasons may protect the entrance of the Kayakapı Neighborhood as a rock fall barrier. A large block (potentially unstable) already identified at the entrance (Fig. 22b) must also be stabilized with systematic rock bolting. No blasting should be allowed for the removal of the unstable blocks since it gives rise to widening of the cooling joints which adversely affect block stability. The blocks that seem to be stable at the moment may be unstable with the passage of time due to wetting–drying and freezing–thawing which are prevailing environmental conditions in the region. Therefore, they should be periodically checked.

### Conclusions and recommendations

In this study, environmental and engineering problems at the historical site in Urgüp called Kayakapı Neighborhood, where about 1,200 rock-hewn underground openings caved in soft tuffs and historical structures exist, were investigated and necessary remedial measures were suggested. In addition, an inventory for the re-use of the underground openings called troglodytes was prepared to be considered in conservation, restoration and strengthening works. The main conclusions drawn from the study are given in the following paragraphs.

The study area, located on a sloping ground, consists of soft volcano-sedimentary rocks such as tuffs and tuffites. The tuffites are thinly bedded, and the tuffs are generally massive and constitute the dominant lithology. A thin layer of slightly harder tuff overlies the sequence. These units are prone to atmospheric conditions. Schmidt hammer tests carried out in the different openings indicated that the engineering properties of the massive tuffs do not show significant changes both perpendicular and parallel to layering. This observation was also confirmed by the less pronounced scattering on the geomechanical and rock mass properties of these tuffs. Although the massive tuff rock mass is defined as moderate-to-good rock due to their high RQD, they can be classified as weak rock when their strength is considered. On the basis of rock mass evaluation, observations carried out on instabilities affecting the underground openings and the results of some previous studies in Cappadocia, it is concluded that the discontinuities and rock weathering seem to be more important factors controlling the stability of openings at the study site. Limited amount of temperature and humidity measurements showed a good agreement with those from a long-term monitoring study previously performed by other investigators in Cappadocia, and

suggested that thermal insulation properties of the tuffs imply the suitability of these rocks to be used for underground openings.

Observations in 1,556 underground openings with different dimensions and evaluation of the field data indicated that block fall or block sliding from the roofs, overbreak, bending, spalling, erosion and shearing of pillars, collapse due to thin overburden without sufficient load-bearing capacity, possibility of rock fall hazard at the entrance of openings and weakening of the arched-type entrances are the main stability problems encountered in the troglodytes in the study site. Particularly structurally-controlled wedge failures and the weakening of pillars are the most commonly observed instability problems. Based on the selected criteria, the troglodytes are categorized into four classes for the evaluation of their re-use. The statistical assessment suggests that 320 of all the troglodytes investigated do not show any instability problem and can be directly re-used. However, most of them need some remediation. In order to improve roof stability, roofs should be supported by timber beams as a traditional method common in Cappadocia. Particularly, in the weak entrances of openings, prime consideration should be paid to the construction of arches using prismatic blocks made of stronger tuffs. Although wire-mesh and shotcreting can be considered as remedies against spalling, it may not be technically successful due to the inconsistent bonding between the shotcrete and the tuffs, and may not be suitable from aesthetic viewpoints. Because the tuffs are soft and weathering-prone rock units, the applicability of rock bolting requires further investigations in conjunction with pull out tests. Strengthening of the pillars and the filling of some abandoned shallow-seated openings by blocks are other remedial measures suggested for safely re-using the underground openings in the site.

Results of the rock fall simulation analyses carried out for rock falls originated from the higher altitudes of the study site indicated that the blocks generally would bounce and/or roll, and the bouncing heights would range from 0.11 to 5.2 m and generally not exceed 3–4 m. There is a good agreement between the fall-out distances calculated from the rock fall analyses and the observations performed during the field rock fall tests. In addition, the blocks, which may fall, are expected to reach a district below the main road of the site.

In terms of rock fall potential, the area called Büyük Kaya (Great Rock) at the entrance of the site and its close vicinity is the most critical part of the Kayakapı Neighborhood. In addition to some already fallen rock blocks, there exist some other blocks with rock fall potential. In order to provide safety, both in this area and in the entire site, individual blocks should be broken into smaller pieces without blasting and then be removed from the site. Besides thick rock slabs on the face of a steep slope at Büyük Kaya location should be stabilized



by systematic bolting and a reinforced-concrete retaining wall with a gap behind should be constructed as a rock fall barrier. It is also noted that the long-term stability of the underground openings at the study site is open to further investigations by considering the time-dependent properties of the tuffs.

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## References

- Aydan Ö, Ulusay R (2003) Geotechnical and geoenvironmental characteristics of man-made underground structures in Cappadocia, Turkey. *Eng Geol* 69:245–272
- Barton N (1973) Review of a new shear strength criterion for rock joints. *Eng Geol* 7:287–332
- Bieniawski ZT (1989) Engineering rock mass classifications. Wiley, New York, 264 p
- Binal A (1996) Investigation of the instability mechanics observed in volcanosedimentary rocks at Aksaray-Ihlara Valley. Msc Thesis, Hacettepe University, Department of Geological Engineering, Ankara, Turkey (unpublished, in Turkish)
- Carvalho JL, Hoek E, Bin L (1992) Unwedge-version 2. University of Toronto, Civil Engng. Dept., Rock Engineering Group
- Chau KT, Wong RHC, Liu J, Lee CF (2002) Rock fall hazard analysis for Hong Kong based on rockfall inventory. *Rock Mech Rock Eng* 36:383–408
- Chen H, Chen RH, Huang TH (1994) An application of an analytical model to a slope subject to rockfalls. *Bull Assoc Eng Geol* 31(4):447–458
- De Witte E, Terfve A, Koestler RJ, Charola AE (1988) Conservation of the Göreme rock: preliminary investigations. Proceedings of the 6th International Congress on Deterioration and Conservation of Stone, pp 346–355
- Dorren LKA (2003) A review of rock fall mechanics and modelling approaches. *Prog Phys Geogr* 27(1):69–87
- Doyuran V (1976) Environmental geology problems of Ortahisar (in Turkish). *TJK Bülteni* 19:83–88
- Erdogan M (1986) Investigation of the tuffs in Nevşehir-Urgüp region with regard to material geology. Ph.D. Thesis, Istanbul Technical University, Department of Geological Engineering, Istanbul, Turkey (unpublished, in Turkish)
- Erdogan M (1989) Investigation of the opportunities of the Nevşehir tuffs to be used as light construction stone (in Turkish). *Mühendislik Jeolojisi Bülteni* 11:75–82
- Erguvanli AK, Yuzer AE (1977) Past and present use of underground openings excavated in volcanic tuffs at Cappadocia area. *Rock Storage*, Oslo, pp 15–17
- Erguvanli K, Yorulmaz M, Cili F, Ahunbay Z, Erdogan M (1989) Göreme structural conservation and strengthening project, El Nazar Church. Unpublished Report of Istanbul Technical University, Istanbul, Turkey, 46 p
- Franklin JA, Chandra A (1972) The slakedurability test. *Int J Rock Mech Mining Sci Geomech Abstr* 9:325–341
- Giani GP (1992) Rock Slope Stability Analysis. A. A. Balkema, 361 p
- Gokceoglu C, Ulusay R, Sonmez H (2000) Factors affecting the durability of selected weak and clay-bearing rocks from Turkey, with particular emphasis on the influence of drying and wetting cycles. *Eng Geol* 57:215–237
- Hoek E, Brown ET (1980) Underground excavations in rock. Institution of Mining and Metallurgy, London, 527 p
- ISRM (1981) Rock characterization, testing and monitoring: suggested methods International Society for rock mechanics. In: Brown ET (ed) Pergamon Press, Oxford, 211 p
- Ito T, Akagi T, Seiki T, Ulusay R, Yuzer E, Erdogan M, Aydan Ö (1999) Long term behaviour of tuffs of Cappadocia. Proceedings of Japan–Korea Rock Engineering Symposium, Fukuoka, Japan, pp 359–370
- KA-BA (2005) Personal communication. KA-BA Eserler Koruma ve Değerlendirme Mimarlik Ltd. Sti., Ankara, Turkey
- Le Pennec JL, Bourdier JL, Temel A, Camus G, Gourgaud A (1994) Neogene tuffs of Nevşehir Plateau (central Turkey): stratigraphy, distribution and source constrains. *J Volcanol Geotherm Resour* 63:59–87
- METU (1987) Investigation of the mechanisms of stone deterioration for the purpose of conservation of Göreme tuffs. Progress Report, 61 p
- Moon VG, Beattie AG (1995) Textural and microstructural influences on the durability of Waikato coal measures mudrocks. *Q J Eng Geol* 28:303–312
- Okura Y, Kitahara H, Sammori T, Kawanami A (2000) The effects of rockfall volume on runout distance. *Eng Geol* 58:109–124
- Pasquare G (1968) Geology of the Cenozoic volcanic area of Central Anatolia, Momorie, serie. 8, vol 9, Fasc. 3, Roma, 57–201
- Ritchie AM (1963) Evaluation of rock fall and its control. In: Highway Research Record 17, HRB, National Research Council, Washington, DC, pp 13–28
- Rocscience Inc. (2002) ROCFALL-computer program for risk analysis of falling rocks on steep slopes. Version 4.0, Toronto, Canada
- Schweigl J, Ferretti C, Nossing L (2003) Geotechnical characterization and rockfall simulation of a slope: a practical case study from South Tyrol (Italy). *Eng Geol* 67:281–296
- Seiki T, Tokashiki N, Ito T, Ulusay R, Aydan Ö (1999) The stability assessment of underground structures in Cappadocia. Proceedings of Japan–Korea Rock Engineering Symposium, Fukuoka, Japan, pp 113–124
- Temel A, Gundogdu MN, Gourgaud A, Le Pennec JL (1998) Ignimbrites of Cappadocia (Central Anatolia-Turkey): petrology and geochemistry. *J Volcanol Geotherm Resour* 85:447–471

- Topal T (1995) Formation and deterioration of fairy chimneys of the Kavak tuff in Ürgüp-Göreme area (Nevşehir-Turkey). Ph.D. Thesis, Middle East Technical University, Department of Geological Engineering, Ankara, Turkey (unpublished)
- Topal T, Doyuran V (1997) Engineering geological properties and durability assessment of the Cappadocian tuff. *Eng Geol* 47:175–187
- Topal T, Doyuran V (1998) Analyses of deterioration of the Cappadocian tuff, Turkey. *Environ Geol* 34(1):5–20
- Toprak V, Goncuoglu C (1993) Tectonic control on the development of Neogene-Quaternary Central Anatolian Volcanic Province, Turkey. *Geol J* 28:357–369
- Toprak V, Keller J, Schumacher R (1994) Volcano-tectonic features of the Cappadocian Volcanic Province. International Volcanological Congress IAVCEI-Ankara, Excursion Guide, 58 p
- Ulusay R, Gokceoglu C, Binal A (1997) Physical and mechanical properties of the tuff samples from Cappadocia Region. Technical Report, 32 p (unpublished)
- Ulusay R, Akagi T, Ito T, Seiki T, Yuzer E, Aydan Ö (1999) Long term mechanical characteristics of Cappadocia tuff. Proceedings of the International Congress on Rock Mechanics, Paris, France, pp 687–690
- Ulusay R, Gokceoglu C, Sulukcu S (2001) Draft ISRM suggested method for determining block punch strength index (BPI). *Int J Rock Mech Mining Sci* 38:1113–1119