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Long-term performance of the rock-hewn structures in the Zelve Valley, Cappadocia, Türkiye

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Abstract

Mankind has built rock engineering structures in the Cappadocia region of Türkiye going back to at least 3000 years. However, the region experienced the excavation of many semi-underground settlements in deep valleys and underground cities in relatively flat areas. The Zelve Valley is one of the deep valleys where many semi-underground structures were excavated into soft rock. The semi-underground structures were excavated in tuffs formed during different sedimentation epochs and constructed about 1200-1500 years ago in the valley. The mechanical properties of the tuff are quite vulnerable to water content variation and exhibit time-dependent behaviour. The failures of the semi-underground structures have been increasing in recent years. Within the valley, a semi-underground structure was selected, and instruments were installed to monitor the displacement response of cracks, environmental parameters such as rock and air temperature, humidity and air pressure. In addition, the authors have already installed a multi-parameter monitoring station to monitor electrical potential variation, temperature and humidity and rain-fall in the valley since 2006. The authors also installed a triaxial accelerometer in one of the semi-underground structures first time in the world. Laboratory experiments were conducted to investigate the influence of water content on the mechanical properties of the surrounding rock. The authors present some of the recent outcomes of the integrated studies and discuss their implications in rock engineering and heritage conservation practices.

Keywords

Semi-underground structure, Zelve Valley, Long-term, Multi-parameter monitoring.

1 Introduction

Underground space has long been used by humankind for the purposes of human accommodation, religious ceremony, defence, food storage, etc. since early times. Residential uses probably represent the oldest form of utilization of underground space. The vernacular underground architecture constitutes a low-cost solution and a suitable answer to deal with annual large thermal fluctuations.

A number of antique rock structures in the Cappadocia have been excavated in easily carved soft tuffs with large spacing of discontinuities and they are rare rock structures excavated by mankind. In the region, there exists 22 historical underground cities, rock-cut dwellings, churches and semi-underground cliff settlements (Fig1a). In addition, the intriguing landscape of towering cones called "Fairy Chimneys" is the most famous attractive morphological feature of Cappadocia (Fig. 1b). Although these rock structures generally survived and kept their original integrity for a number of centuries, the observations on some cavities showed some indications of yielding and partial collapses at several locations. These structures are of great importance not only from the viewpoints of preservation of these historical structures as assets of mankind, but also, they may provide some data and insight on the long-term performance of man-made structures in rock engineering. In this study, short and long-term behaviour of the surrounding Zelve tuffs, their index and mechanical properties and effects of atmospheric conditions on rock behaviour were investigated. The authors present the outcomes of the integrated studies and discuss their implications for rock engineering and heritage conservation practices.

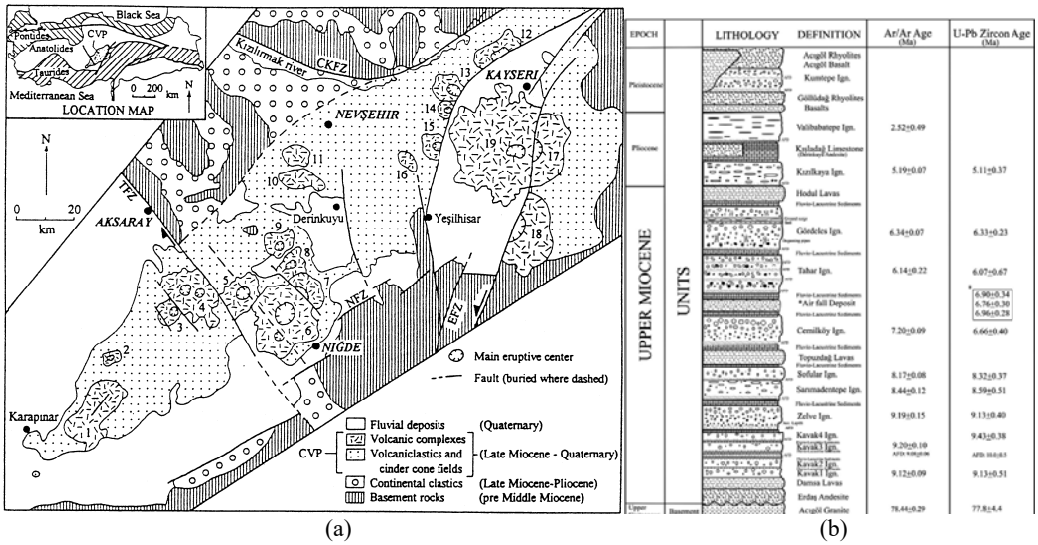


(a) (b) (c)

Fig. 1 Views of (a-b) semi-underground settlements and (c) fairy chimneys in the Zelve Valley, Cappadocia.

2 Geological Features of Zelve Valley and Seismicity

The Cappadocia Region is situated in Central Anatolia forming a high plateau and surrounded by three old volcanoes (Erciyes, Melendiz, and Hasandağ) (Fig. 2). Kızılırmak River, flowing through the northern part of the region, is the principal architect of the morphological features in the Cappadocia Region. Another important physiographic feature of the region is the fairy chimneys generally located along the valleys (Fig.1c).



(a) (b)

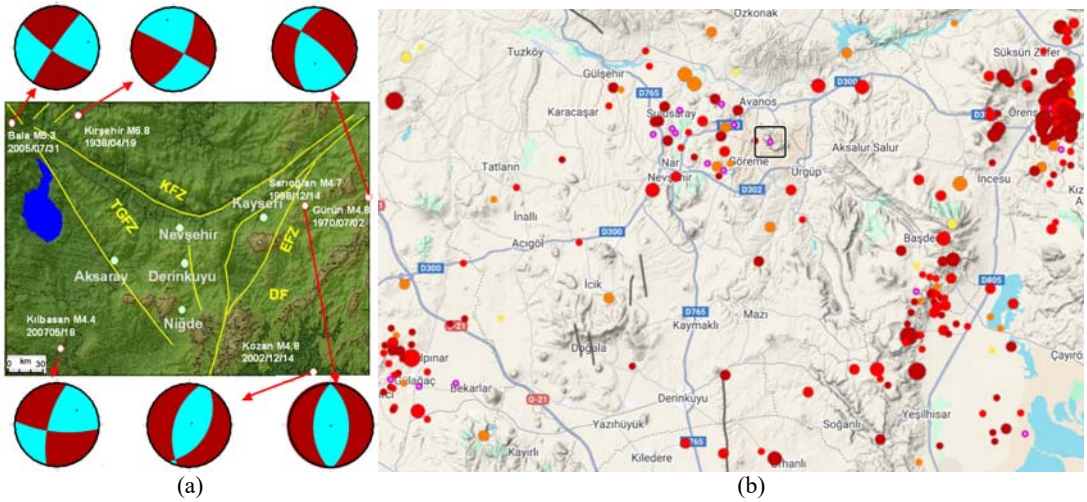
Fig. 2 (a) Geology, tectonics, and (b) stratigraphy of the Cappadocia Region (Temel et al. 1998).

The Cappadocia Region is generally underlain by volcanic rocks of the Neogene-Quaternary period belonging to the Cappadocian Volcanic Province (CVP) (Toprak et al. 1994). Basement rocks, Yeşilhisar formation, Ürgüp formation and Quaternary deposits are the main units observed in the region. The Ürgüp formation, which shows the largest distribution in the region, includes a number of

different tuff members and lava layers (Fig. 2b). The underground and semi-underground rock structures and the fairy chimneys take place in this formation, particularly in its Kavak member with a thickness of between 10 and 150 m. The members of this formation are generally of dirty white, grey and pink colours and of clastic character, showing an alternation from the fine grained to coarse types with enclosed large and small lumps of pumice. Although the bedding planes involved by the Cappadocian tuffs are nearly horizontal, they are not distinct everywhere in the region. Therefore, generally widely spaced and sub vertical joints are the major discontinuities in these tuffs. The Zelve Valley takes place in the pink coloured Zelve tuff which is composed of a pyroclastic single flow with a thickness of 25-100 m.

Three fault systems cut across the CVP. The first system, trending dominantly in N-S to NW-SE direction, is the Tuz Gölü Fault Zone (TGFZ) (Fig.2a). The faults within this system are still active and play role in the recent deformation of the Anatolian Block (Toprak and Göncüoğlu, 1993). The second fault system, Ecemiş Fault Zone (EFZ), strikes NE-SW, almost parallel to the long axis of the province. Although some of these faults are still active, most of them were buried beneath the later eruptions of the CVP (Toprak et al.1994). The third fault system, which is Kızılırmak Fault Zone (KFZ), defines the northern margin of the CVP is composed of several parallel faults along which widespread travertines are occurred. Because it cuts the Quaternary lava flows, it is still active. The KFZ is a normal fault with southern block being downthrown (Toprak et al. 1994). The Derinkuyu fault, which is also well observed within the antique underground city, strikes in almost N-S direction. Furthermore, there are some normal faults passing through Ortahisar and Ürgüp towns. The inferences from the faults observed in these localities (Aydan and Ulusay 2013) using the Aydan's method (Aydan, 2000) implied very similar focal plane solutions to that of the Sarıoğlan (Tuzla Lake) earthquake on December 14, 1998. The focal mechanisms from these faults imply the region is undergoing a streching strain regime in EW direction as seen in Fig. 3.

Despite the Cappadocia Region being bounded by three active faults given above, the region is seismically less active compared with other regions of Türkiye (Fig.3). The Derinkuyu fault, which strikes in N-S direction, is well observed within the antique underground city and considered as an active fault (Aydan and Ulusay, 2013). The largest earthquake with a magnitude of 5.2 occurred in 1940 in the region near the Erçiyes Mountain and except the 14 December 1998 event, there is no earthquake with focal plane solution in the close vicinity of underground and semi-underground settlements. The recent seismicity shown in Fig. 3 implies that the seismicity in the vicinity of Zelve is high despite the magnitudes of the earthquakes relatively small. The vicinity of Hasan Dağ is also active.



(a) (b)

Fig. 3 (a) Major faults and focal mechanisms, and (b) seismicity of the Cappadocia Region since 1900.

3 Instrumentation and Installation of OAMIT Device

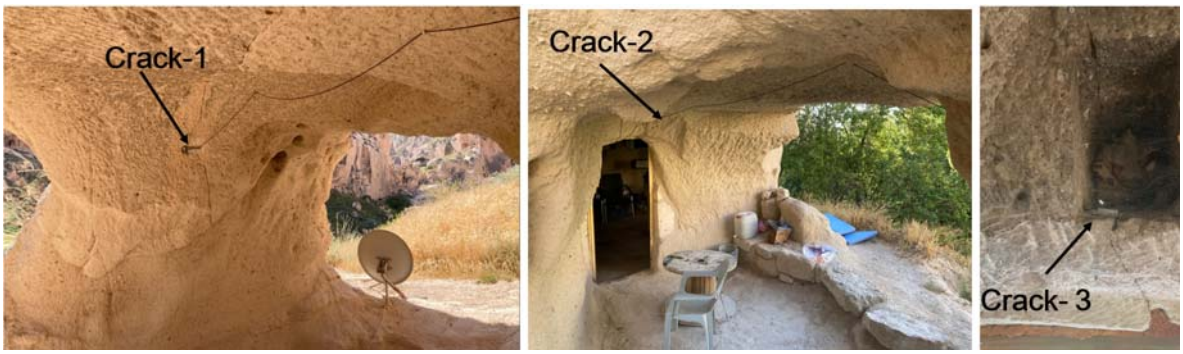
The authors have initiated a multi-parameter monitoring system in Zelve Valley since 2005 and the parameters are geoelectric potential (GEP), rock and air temperature (RAT), atmospheric-pressure (AP), Rainfall (RF) (Fig. 4a-b, see Aydan et al. 2025 for details). A crack gap displacement monitoring of cracks of a semi-underground structure in the valley started in June 2025 (Figs.4c and 5). In addition, a strong motion instrumentation program is initiated on November 22, 2025 using the

accelerometers together with the capability of measuring three-dimensional inclination and named as OAMIT-AIW (Fig.4d). This device is capable of measuring accelerations whenever it is triggerred for a pre-set threshold while the inclination is measured continuously.



(a) (b) (c) (d)

Fig. 4 Views of multi-parameter monitoring devices used in this study.



(a) (b) (c)

Fig. 5 Views of crack locations: (a) Crack-1, (b) Crack-2, (c) Crack-3.

4 Semi-underground Structures of Zelve Valley and Stability Issues

As the Cappadocia Region is seismically less active, the instabilities observed in semi-underground openings (cliff settlements) located in valleys and fairy chimneys are mainly associated with deterioration of the tuffs, discontinuities with high persistence and decrease in overall strength of rock mass due to wetting-drying and freezing-thawing cycles. In addition, wind and rainfall are considered as strong erosion agents. Due to these effects, tuffs particularly those close to ground surface at the toe regions of semi-underground rock structures at the valley bottoms are subjected to weathering, slabbing, spalling and raveling. These changes result in loss of support in the pillars and walls of openings and fairy chimneys at their toe regions close to the ground surface and instabilities and/or total collapses occur when the amount of erosion reaches up to a critical value (Fig.6). In the Zelve Valley, there are some rock-hewn churches, which have widths ranging between 15 and 20 m and have been carved in the Zelve tuff about 1300 years ago, and most of them have collapsed.



(a) (b)

Fig. 6 (a) Failure in 1950s; (b) failure of Geyikli Church on 6 Aug 2008.

5 Properties of Rock and Characterization of Rock Mass

5.1 Properties of Intact Rock

The tuffs in the Zelve Valley are prone to atmospheric conditions, and therefore, susceptible to weathering. Mean values of some dry short-term geomechanical properties of tuffs of Zelve in which rock structures are commonly observed, are given in Table 1. These tuffs are weak to very weak rocks and have high deformability. However, geomechanical properties of the Zelve tuff are lower than those of the other tuffs. The results of UCS and modulus of elasticity of the tuffs measured parallel and perpendicular to bedding plane are scattered around line of anisotropy indicating that their mechanical properties should be fairly uniform. In this study, the needle penetration index (NPI), which is a non-destructive test to indirectly estimate the UCS, was also determined for the Kavak and Zelve tuffs. Although the results show some scattering due to non-homogeneity of the samples and differences in water content during the tests, the presence of a good correlation between the UCS and NPI reveals that the NPI can be useful for such soft rocks and applicable at historical sites under protection (Aydan 2012; Aydan et al.2008b, 2014).

Table 1. Physical and mechanical properties of the Zelve tuff.

Parameter	**Whitish Tuff**		**Reddish Tuff**	
	Dry	**Saturated**	**Dry**	**Saturated**
Unit weight (kN/m^3)	12.9-14.2	15.7-16.9	12.4-13.1	15.7-16.4
Wave Velocity (km/s)	0.95-1.44	0.61-0.71	0.80-0.73	0.65-0.73
Elastic Modulus (MPa)	84	21-37	90.0	16.0
Compressive Strength (MPa)	1.62	0.17-0.35	1.56	0.22

The water content migration results in the swelling and drying of clay-bearing rocks such as the Cappadocian tuffs (Aydan 2003; Aydan et al. 2008a; Ulusay and Aydan 2007). As a result of these volumetric strain variations induced by the absorption or desorption of water, the mechanical properties of these rocks remarkably vary as a function of water content (Fig.7a). Based on the results obtained from some experimental procedures (Aydan and Ulusay 2003, 2013) when compared to those of the Kavak tuff, the largest swelling developed in the Zelve tuff which is quite consistent with the amount of clay content of the samples. It is interesting to note that the swelling strain differs depending upon how many times the sample is subjected to wetting and drying cycles. The large swelling strains probably result in some micro fracturing of the sample so that diffusion of water molecules is accelerated after each cycle. The relation between the saturation and reduction in UCS at dry state suggests that UCS differs as water content increases and the variations in mechanical properties of the Zelve tuff are larger than those for other tuffs. Similar trend is also valid for the modulus of elasticity.

Because the history of rock-hewn settlements in the Cappadocia Region is more than 1000 years, the long-term stability of the cavities, in other words, the long-term properties of the tuffs deserve a great importance (Aydan 2016; Ulusay et al. 1996). By considering this, some tests to assess the long-term properties of the tuffs were carried out and long-term creep strength was determined as shown in Fig. 7b (Ito et al. 2008).

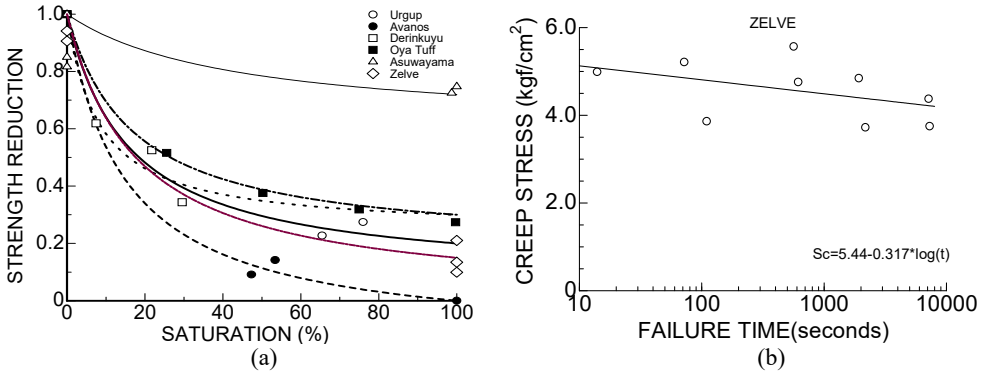


Fig. 7 (a) Strength reduction and (b) long-term strength of the Zelve tuffs.

6 Erosion Rate

The preservation of antique underground cities and semi-underground settlements as well as fairy chimneys in the Cappadocia Region very much depends upon the erosion or degradation rate of the tuffs (Fig. 8). The major factors influencing this rate are the cyclic drying-wetting and freezing-thawing processes (frost action), winds and rainfall, and surface water flow. In order to assess this rate, the authors have recently started a study in the Cappadocia Region (Aydan et al. 2007, 2008a, 2008b; Kaşmer et al. 2008). The erosion rate in the Cappadocia generally ranges between 0.04-0.5 mm/yr (Aydan et al. 2007, 2008a, Aydan & Ulusay 2013). It should be noted that the erosion or degradation rate of the tuffs with larger amount of clay minerals sampled from Avanos, Ürgüp and Zelve is much higher than that of tuffs with less clay mineral content (Aydan et al. 2008a). Kasmer et al. (2008) reported that the annual average erosion could be up to 1.6 mm in the Zelve Valley.



Fig. 8 Views from degradation and erosion at the Zelve Valley.

7 Results of Multi-parameter Monitoring in the Zelve Valley

7.1 Crack Monitoring

There are several open cracks at the semi-underground structures and crack locations are seen in Fig. 5. while Fig. 9 shows the crack gap displacement at three cracks together with the variation of ambient temperature. Despite gap displacements are partially related to the ambient temperature, permanent gap displacements do occur. Particularly, Crack-3 gap displacement for about 1 year indicates permanent opening of the crack.

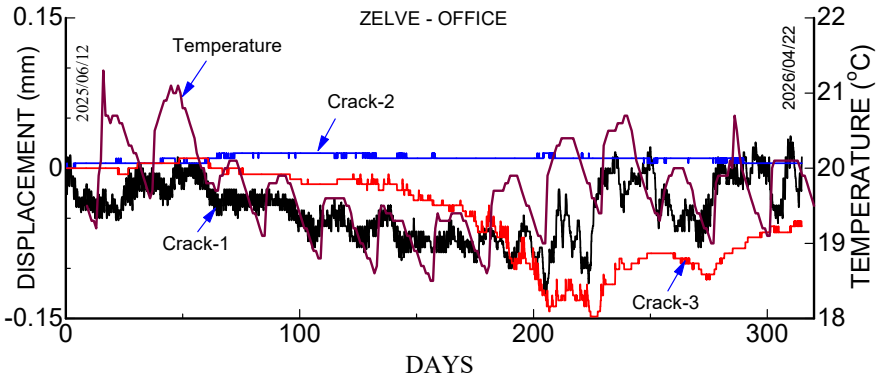


Fig. 9 Gap displacements of cracks between June 12, 2025 and April 22, 2026.

7.2 Rock temperature

At Zelve, rock temperatures were measured at several depths, specifically 0, 5, 10 and 15 cm from the rock surface at a small underground cave. As noted from Fig. 10, there is at least 6 degrees between temperatures at the surface and at 5, 10 and 15 cm depth. The variations between 5 to 15 cm depth are small compared to that at the surface. This implies that rocks are vulnerable to cyclic thermal stresses.

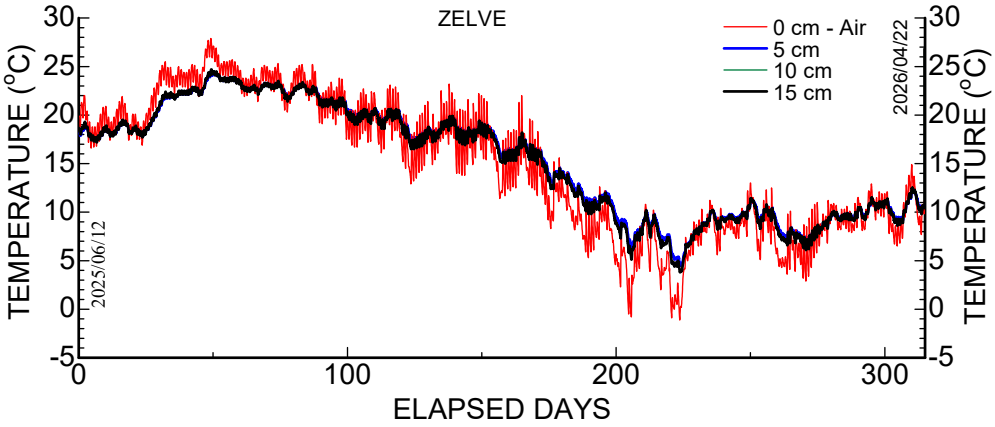


Fig. 10 Temperature of rocks at a small underground opening between June 12, 2025 and April 22, 2026.

7.3 Acceleration and Inclination Measurement

As the threshold of accelerometer was set 10 gals, there is no acceleration record yet and there is no remarkable earthquake in the vicinity of Zelve. However, the inclinations in three directions are plotted in Fig. 11. The tilting angle ranges between -0.3 and 0.3 degrees. In other words, the undergroundstructure is subjected to cyclic contraction and expansion. Particularly, the UD component shows the largest fluctuations. However, the monitoring period is still too short and we need to continue the monitoring before deriving any definite conclusion.

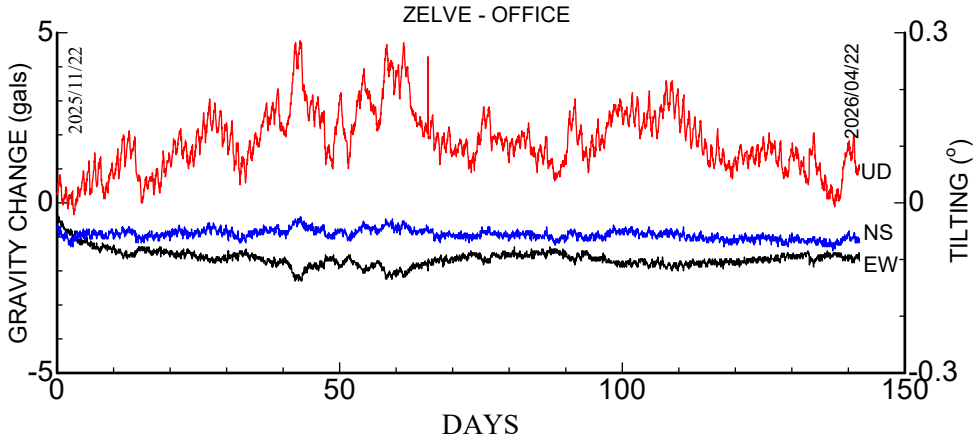


Fig. 11 Inclination variations of underground structure between November 22, 2025 and April 22, 2026.

8 Conclusions

In this study, short- and long-term properties of the softtuffs at the Zelve Valley are investigated and the monitoring results are presented. The main conclusions drawn from the study are as follows.

The tuffs at the Zelve Valleyare weak to very weak rocks with high deformability. The strength of rock is reduced drastically under saturated conditions.

The instabilities observed in semi-underground openings (cliff settlements) located in valleys and fairy chimneys are mainly associated with deterioration of the tuffs.

Monitoring of historical structures is of great importance. Besides the long-term multi-parameter monitoring, the seismic monitoring is also of great importance and such monitoring schemes should be implemented as done in this study. The inclination and temperature fluctuations may be of great importance for assessing the stability of semi-underground structures as observed in this study.

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