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Some considerations on the failure of Güney Waterfall, Denizli, Turkey

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ABSTRACT: The Güney Waterfall in Denizli was ruptured by the The 21st July 2003 Buldan earthquake with magnitude 5.6. The ruptured block toppled after 10 years and traveled towards the reservoir of Cindere Dam more than 132 m. The authors attempt to clarify the mechanism and process of the toppling failure of the ruptured block. The authors attempt to analyse the failure process in fundamentally in three stages. The first stage is the initial failure caused by the earthquake. The second stage is the growth of the ruptured block and progress of degradation at the toe of the failed block. Third stage is the final collapse and movement in the valley towards the Cindere Dam reservoir. The pre-rupture stage before the Buldan earthquake and post-rupture and final collapse conditions are analysed through some analytical and numerical techniques to understand the fundamental causes of the failure, which took more than 10 years. This is study is unique in a sense it involves slow and rapid dynamic processes. The authors present the results of the various studies and investigations undertaken so far and and they discuss their implications.

1 INTRODUCTION

The 21st July 2003 Buldan earthquake with magnitude 5.6 ruptured the Güney Waterfall in Denizli, which is the 23rd natural beauty of Turkey. However, the ruptured block of the Güney Waterfall did not toppled at that time. The ruptured block toppled after 10 years and traveled towards the reservoir of Cindere Dam more than 132 m. The initially ruptured block has a prism-like shape with 34m width, 20 m length and 12 m height. Since the 2003 Buldan earthquake, several earthquakes with a moment magnitude more than 5 occurred in the vicinity of the Güney Waterfall, which may further cause at the toe of degradation and additional damage.

The authors attempt to clarify the mechanism and process of the toppling failure of the ruptured block. The failure process can be divided into three stages. The first stage is rupturing of the waterfall due to the 2003 Buldan earthquake. The second stage is the growth of the ruptured block in size and the degreadation and erosion of the toe of the block. This geometrical changes of the ruptured block resulting from the growth and degradation prepared the conditions of the toppling failure. In the third stage, the block toppled and traveled to the Cindere Dam reservoir and disintegrated into several large blocks. The authors investigated the area during the reconnaissance of the Buldan earthquake and after the failure. Besides site investigations and geometrical measurements, samples were gathered and cored to carry out some physico-mechanical properties of travertine. The pre-failure and post-failure conditions are analysed through some analytical and numerical techniques to understand the fundamental causes of the failure, which took more than 10 years. Besides the clarification of the mechanism and the causes of the failure, this is study is unique in a sense it has both slow and rapid dynamic processes. The authors explain the results of these studies and investigations undertaken so far and discuss the implications of this failure event.

2 GEOLOGICAL SETTING

Tufa and travertine are common carbonate deposits in Quaternary and present-day depositional systems (Chafetz and Folk 1984). Tufa deposition in the left abutment of Büyük Menderes River in Güney District in NW part of Denizli Province (western Turkey) has been accumulating for more than thousands of years. The tufa deposition in the area overlays marble and schist of Menderes Masif metamorphic bed rock Rocks belongs to Paleozoic age (Özkul et al, 2010). The tufa deposits cover an area of about 20 hectares (Fig. 1). The Güney waterfall site is an area of unique geological/natural heritage that is visited by many people, especially during spring and summer seasons. There are mainly four springs, having total flow rate about 80 l/s and discharge at 18.7–18.8 8°C. Spring waters in the tufa site are type of $Ca–HCO_3$, and have formed coalescent tufa bodies that occur at elevations between 220–400 m above the Büyük Menderes river bed. The springline tufa body contains numerous primary cavities up to cave size in some cases. There are two main caves in

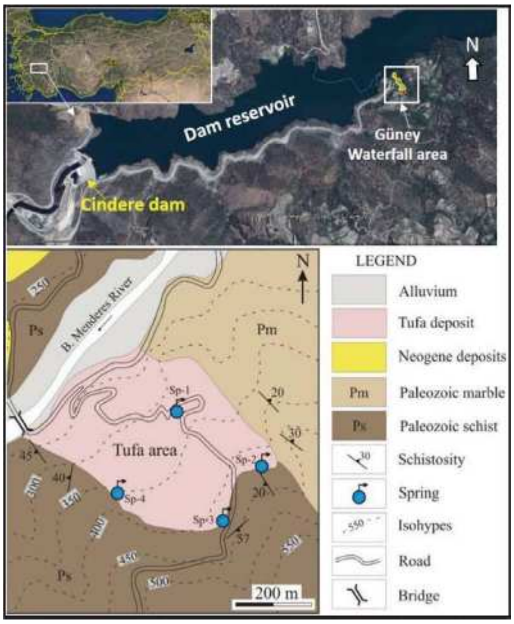

Figure 1. Location map and geological map of Güney waterfall tufa depositional area (After Özkul et al, 2010)

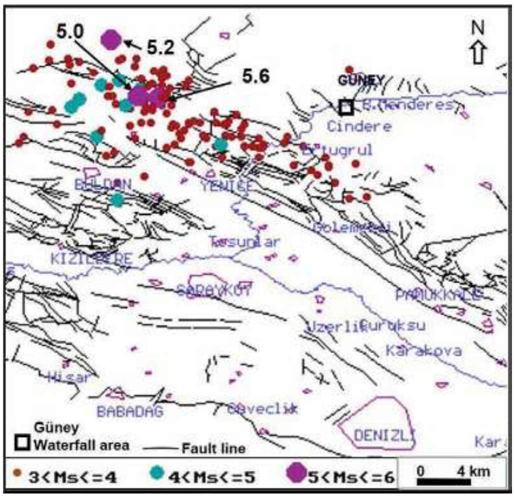

Figure 2. Fault lines and epicenter distribution of 23-26 July 2003 Buldan earthquakes (Kumsar et al, 2008)

the tufa site. ^{14}C age in the range from 2000 yr BP to 5800 yr BP (Özkul et al, 2010).

Fault geometry of Denizli basin consists of segments of different length along the major fault zones of Pamukkale, Babadağ, Honaz, Laodikeia and also secondary-fault zones in Denizli basin. Pamukkale fault is the major active fault bounding the basin in the North (Fig. 2) and it is about 32-35 km long (Aydan et al. 2002; Kumsar et al, 2015). The total length of Babadağ fault zone is about 40 km extending from Tekkeköy in the east to northwest of Babadağ district in the west (Fig. 2), and it consists of several segments, whose lengths change between 5 km and 10 km and trend E-W or NW-SE (Bozkuş et al, 2001; Kumsar et al, 2015)

3 RUPTURE PROCESS OF TUFA BLOCK UNDER DYNAMIC LOADING

The seismic activity in Buldan and surrounding in Denizli basin started with a 5.2 magnitude at 07:56 AM on 23rd of July 2003. Another earthquake with a magnitude of 5.6 occurred at 11:26 AM on 26th July 2003 (Fig. 2). The last shock caused damages on masonry structures, slopes failures and tension cracks on roads and slopes (Kumsar et al, 2003). Güney waterfall, which is located at about 15 km east the earthquake epicenter location, was also ruptured due to 5.6M earthquake. 13 cm wide tension crack developed at 8 m back side from the outer most of the of the waterfall tufa head (Fig. 3), and this crack continued to the base of the tufa (Kumsar et al., 2008). An illustration, showing rupture of tufa block, is given in Fig. 4a. After the earthquake, some part of spring water flowed through the cracks and, the caves within the tufa block were filled up with water (Fig. 4b). The maximum ground acceleration caused by the earthquake at the waterfall site was estimated to be more than 120 gals.

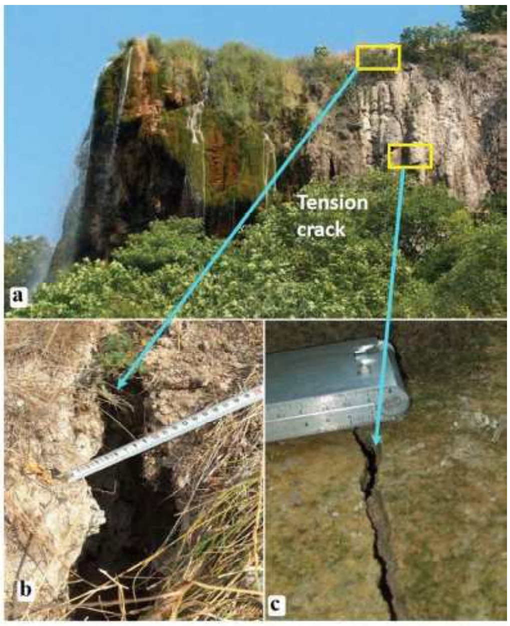

Figure 3. a) Overhanging tufa block of Güney waterfall, b, c) tension cracks developed during 2003 Buldan earthquake with a magnitude of 5.6 (Kumsar et al, 2008).

The tufa block stayed stable for about 10 years. A big block from the most outer part of the tufa block that had been overhanging for more than 10 years, toppled on 13.05.2013 (Kumsar et al, 2013). The unstable tufa block was broken into many parts and partly moved into Cindere Dam reservoir (Fig. 5).

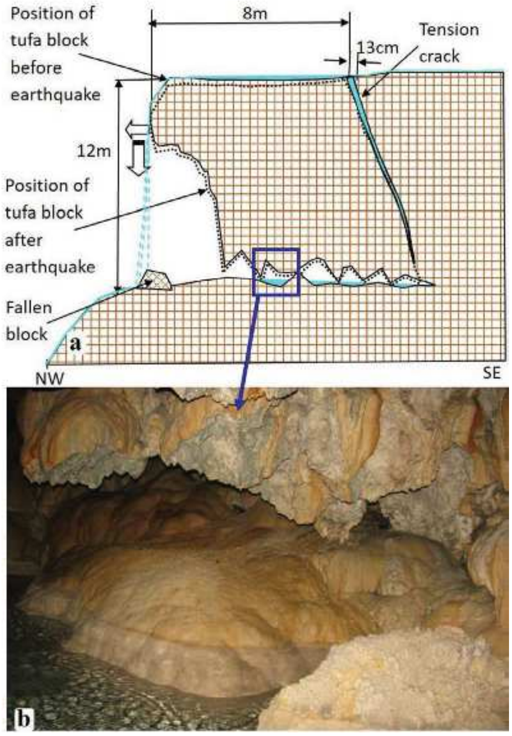

Figure 4. a) Schematic drawing of tension crack development within the tufa block of Güney waterfall, b) view from a cave within the tufa block.

Figure 5. A view of the collapsed waterfall tufa and disintegration from the Cindere Dam reservoir.

4 A MODEL STUDY FOR THE RUPTURE OF TUFA BLOCK UNDER DYNAMIC LOADING

The second author have performed many studies on the static and dynamic stability of the overhanging cliffs. The situation of the waterfall resembles to the overhanging cliffs (Aydan 2015; Aydan et al. 1989b, 2007, 2011; Tokashiki and Aydan 2010). Fig. 6 shows some views of a model experiment on a cliff model with toe erosion using a shaking table (Aydan et al. 2011). The height of the overhanging part was 100 mm high and the erosion depth was 180 mm in this

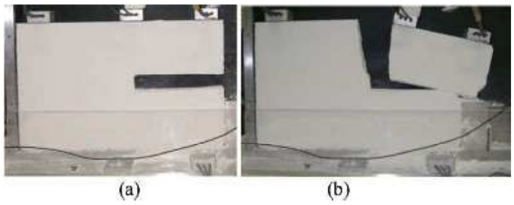

Figure 6. Views of the model before and after the experiment.

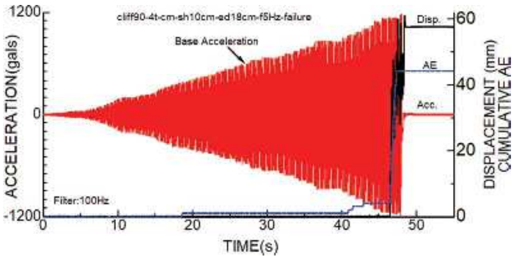

Figure 7. Input acceleration waves and measured displacement and acoustic emission responses.

particular experiment. Fig. 7 shows the input acceleration waves to the shaking table together with displacement and acoustic emission responses of the failed part of the cliff. As noted from the figure, the overhanging block fails in tension after certain acceleration level and moves towards valley side. Acoustic emission events starts long before the breakage of the overhanging part.

5 ANALYSES OF RUPTURE AND FAILURE PROCESS OF THE TUFA BLOCK

5.1 *Analyses of rupture process*

5.1.1 *Analyses by theoretical methods*

Aydan and Kawamoto (1992) proposed an analytical model to analyses the stability of layered rock slopes against flexural toppling failure under static and dynamic conditions. We utilize the method of Aydan and Kawamoto (1992) for a single layer with the consideration of shape of the overhanging body and horizontal and vertical seismic coefficients. Based on this concept, the force condition acting on the overhanging cantilever beam can be modeled as shown in Fig. 8. Thus, the formula for the outermost fiber tensile stress, which is maximum, can be written as follows:

$$\sigma = k_h \gamma h_b L \left(\frac{1+\alpha}{2} \right) + 6 \frac{M_o}{h^2} \quad (1)$$

where

$$\alpha = \frac{h_s}{h_b}; \quad M_o = (1+k_v)\gamma h_b L^2 \left(\frac{1}{2} - \frac{(1-\alpha)}{3} \right)$$

x, h_b, h_s, γ and L are distance from the base, beam height at the base and at the far end, unit weight of

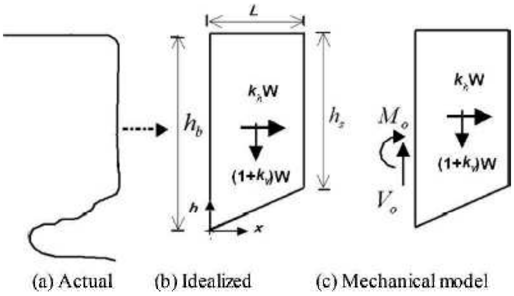

Figure 8. Modeling of overhanging cliffs.

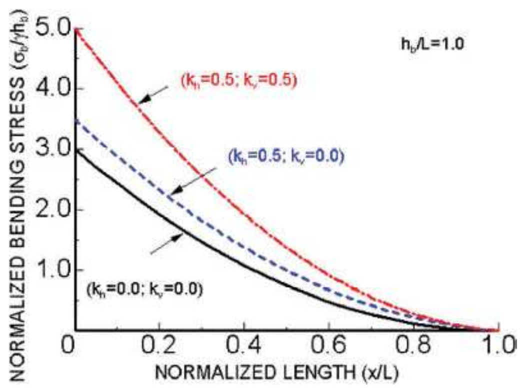

Figure 9. Distribution of bending stress at the outermost fiber of beam subjected to different seismic coefficients.

rock mass and erosion depth, respectively. k_h and k_v are horizontal and vertical seismic coefficients.

As discussed by Aydan and Kawamoto (1992), the cantilevers fail immediately once the tensile stress exceeds the tensile strength of rock mass. In addition to gravitational load, the seismic loads would make the cliffs more vulnerable to failure during earthquakes as seen in Fig. 9. As noted from Fig. 9, the vertical seismic loading has greater effects on the stability, compared to that of the horizontal seismic loading.

The height and length of the overhanging part were measured to be 10 m and 8 m, respectively in view of site observations and investigations as shown in Fig. 4(a). Under gravitational conditions with a unit weight of 20 kN/m^3 for rock mass, the maximum tensile stress at the top of the overhanging waterfall tufa would be 384 kPa.

Although there was no strong motion stations near the waterfall, the ground motions were recorded at the Sarayköy strong motion station of Turkish National Strong Motion Network (DAD-ERD, 2003). The maximum ground acceleration was 155 gals at Sarayköy with a vertical acceleration of 154 gals (Fig. 10). As the distances of Sarayköy and the waterwall from the epicenter of the 2003 Buldan earthquake were quite similar, the earthquake is likely to increase the maximum tensile stress to 467 kPa with the consideration of horizontal and vertical components of the acceleration records. In view of the mass tensile strength of tufa deposits, the rupture of the overhanging part of the waterfall tufa would be possible as observed in the case of this waterfall.

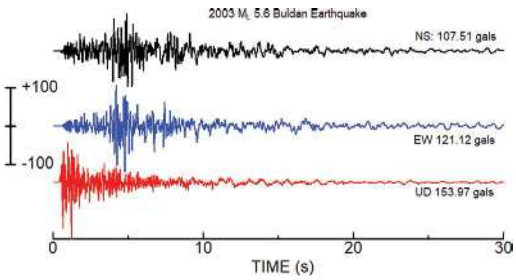

Figure 10. Acceleration records at Sarayköy.

5.2 *Analyses of toppling stage*

Aydan et al. (1989) analyzed various modes of failure of blocky rock mass slopes with the consideration dynamic limiting equilibrium method, which also includes the those of a single block. Although the initiation can be easily estimated from that approach, the utilization of numerical integration techniques is necessary to evaluate the displacement and rotation of the falling tufa block during the motion stage. This approach is used herein. When the overhanging tufa was ruptured by the earthquake, it was separated and fallen over the base and it has became an individual single block as illustrated in Fig. 4a. The mass center of the fallen block was such that it was stable against toppling failure. The bottom side of the fallen block was jagged. The protruding parts of the jagged bottom side of the fallen block could had been damaged during the falling stage. Furthermore, the high stress concentration should also occur at protruding parts. The seeping water from cracks, high stress concentration may lead further deterioration,

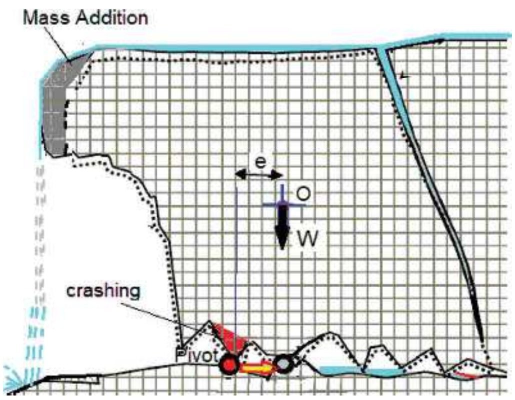

Figure 11. An illustration of the mechanism leading to the toppling of the fallen tufa block.

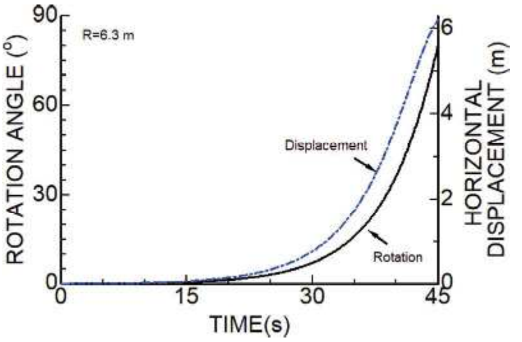

Figure 12. Rotation angle and horizontal responses of the fallen rock block during toppling stage.

degradation and crashing of the tufa at the protruding parts. As a result of this process, the pivot of the fallen tufa block against rotation should have started in space. Furthermore, the mass addition to the already fallen tufa block due to the sedimentation from water flow having dissolved Ca–HCO_3 content would occur. These two processes should had prepared the conditions suitable for toppling failure of the fallen block after a period of 10 years. This situation is conceptually illustrated in Fig.11. The horizontal rate of the movement of the pivot in the space has been estimated to be about 20 mm/year. Furthermore, the mass addition of 10 cm thick and 3-4 m high would had been taken place. This is a slow dynamic process taking place in years.

The block would stay almost in the same position until the horizontal location of the pivot is becomes beyond the horizontal position of the fallen block provided that the vertical position of the mass center does not change with time. Once the location of the pivot becomes beyond the horizontal location of the mass center, the fallen block would start to topple and it would be a very rapid dynamic process. Until the blocks hits the ground, the process is quite simple and it can be easily evaluated as a rigid body motion. However, the process would become quite complicated if the block starts to disintegrate after hitting the ground and/or fracturing during motion in space. Fig. 12 shows the computed rotation angle and horizontal displacement responses of the block shown in Fig. 11. As it is noted from the figure, the toppling rapidly occurs within 45 seconds while the preparation of the fallen block to topple took more than 10 years.

5.3 *Analyses of post-toppling stage*

Models, based on the motion of the failed body, which may be a monolithic mass or several slices, are most commonly used models to obtain estimations of travel distances and the reach angle of slope failures (e.g. Aydan et al. 1992; Aydan 2016). The motion of the failed body on a prescribed basal plane is estimated from the equation of motion with the consideration of effective sliding resistance or rolling frictional resistance. Despite very complicated nature of the problem, the reach angle (α_c) for describing the motion of the failed body can be obtained from the following relation:

$$\tan\alpha_c = \frac{H_g}{L_g} = (1-r_u)\tan\varphi_s \tag{2}$$

where H_g: vertical drop of the failed mass center; L_g: horizontal travel distance of the failed mass center; r_u: pore-water pressure coefficient; φ_s : sliding friction angle. There are different concepts to estimate the sliding friction angle. One of them is to use the rolling friction coefficient. Eq. (2) can be used as it is by just replacing the sliding friction coefficient by the rolling friction coefficient. If the motion path has a V-shape, the equivalent friction angle may be greater than for the planar surface and the wedge factor of the V-shape path can be introduced as (e.g. Kumsar et al. 2000; Aydan and Kumsar, 2010)

$$\tan\varphi_{eq} = \frac{\cos\omega_1 + \cos\omega_2}{\sin(\omega_1+\omega_2)}\cdot\tan\varphi_s \tag{3}$$

where ω_1 and ω_2 are the inclinations of the side walls of the path from vertical and they may be distance dependent. It should be noted that the following relation holds:

$$2\omega = \omega_1 + \omega_2 \tag{4}$$

The tangent of the reach angle of the fallen tufa block is about 0.61. The friction angle between the fallen tufa block and side-walls of the valley is about 32 degrees and the wedge angle is about 150 degrees. As the water flows through the creek, which constitutes the path of block motion, the water may affect the motion of the block. As it is a small creek with small amount of water, the water pressure coefficient (r_u) was estimated to be about 0.05 in view of water height and partial submergence of the block after it stopped the motion. The reach angle from Eq.(2) can be obtained as 31.4 degrees, which is almost the same as that observed.

6 CONCLUSIONS

The authors attempted to clarify the mechanism and rupture and collapse processes of the Güney waterfall in Denizli Province of Turkey. The process involves both slow and rapid dynamics. It was shown that the ruptude was caused by 2003 Buldan earthquake in view of presented model experiments and theoretical considerations. The second stage was a slope process involving the growth of the ruptured block in size and progress of degradation at the toe of the failed block, which took more than 10 years. This process was simulated by taking into account the facts in computational models. The third stage was the final collapse and movement in the valley towards the Cindere Dam reservoir. This is study is a unique contribution to the dynamics of rockfall involving slow and rapid processes.

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