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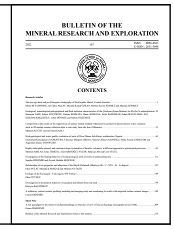

Investigation of the slaking behavior of weak geological units in terms of undercutting rate

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ABSTRACT

It is aimed in this study to measure the undercutting rate of weak geological units under field conditions and to determine the relationship between this parameter and other indexes and physical properties of related rocks. Thus, 11 different locations in which weak materials were found and undercutting problems were observed in the road slopes were selected. In these road cuts, the undercutting depths in many locations were obtained by measurements taken at different dates from the pins installed in the fresh surface of weak units. In addition, undercutting depth was directly taken by using the amount of erosion between durable and weak rock units in the road slopes with a known date of the excavation. Samples having suitable amounts and sizes were collected at the measured locations to be used in physical and durability tests. In the analyses, the applicability of the results of slake index and durability tests, as well as the disintegration ratio in the determination of the disintegration behavior of these geological units, was investigated, and statistically significant empirical equations were obtained. Considering the results obtained from different weak geological units, it was determined that the depth of undercutting values change approximately between 10.1 and 45.8 mm.

1. Introduction

Because of physical weathering processes such as wetting-drying, weak and particularly clay-bearing rocks indicate heavy disintegration behavior due to their mineralogical composition, formation conditions, as well as structure and texture. Many laboratory tests have been proposed to identify and evaluate this disintegration behavior observed in these rocks (Wood and Deo, 1975; Deo, 1972; Franklin and Chandra, 1972). In engineering projects, the slake durability index test (I_d), developed by Franklin and Chandra (1972), is widely preferred in measuring the response of rocks to water absorb-desorb processes and quantifying disintegration. However, Moon and Beattie (1995) emphasized that although many clay-bearing rock materials break into fragments with long axes varying between 10-15 mm as a result of the first cycle of the I_d test, the retained fragments are considered as durable material since the sizes of fragments are larger than the sieve apertures (Ergüler, 2007). Similarly, as emphasized in previous studies (Moon and Beattie, 1995; Gökçeoğlu, 1997; Koncagül and Santi, 1999; Gökçeoğlu et al., 2000; Ergüler, 2007; Ergüler and Ulusay, 2009) due to limitations in the slake durability index, the slaking behavior of rocks cannot be adequately modeled in laboratory conditions. The limitations and uncertainties encountered in the methods proposed in previous studies for evaluating

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the rock slaking behavior show how important it is to measure the slaking behavior that occurs in field conditions. Therefore, in addition to the tests carried out under laboratory conditions, it is thought that it would be very important to successfully implement engineering projects to evaluate the disintegration behavior and rate of clay-bearing rocks in the field.

The undercutting of weak rock units forming the excavation slopes such as highways exposed to different weathering processes causes an instability problem commonly observed in many slopes in Türkiye. Instabilities often occur as a result of time-dependent disintegration of excavation slopes with successive hard units (sandstone, limestone, dolomites, etc.) and soft units (claystone, mudstone, shale, etc.). In these slopes, where stable and unstable units are alternated against weathering processes, hard units are exposed to toe loss over time as a result of weak and mostly clay-bearing rock units reacting faster to atmospheric processes and therefore disintegrating faster than the more stable hard units overlying them.

Various factors are affecting the undercutting rate. These factors are grouped into two main groups in the form of geotechnical properties of clay-bearing rocks and physical properties of excavation slopes. It is stated in previous studies (Deo, 1972; Stollar, 1976; McClure, 1981; Oakland and Lovell, 1985, and Shakoor and Brock, 1987) that parameters such as slake durability, plasticity properties, freezing-thawing durability, clay mineralogy and rock texture are important geotechnical features that control the disintegration behavior of clay-bearing rocks. Parameters such as the direction and angle of the slope, groundwater leakage, surface flow, slope vegetation, debris accumulation and frequency of discontinuities in hard rock units are evaluated as physical properties of excavation slopes (Thornbury, 1954; Sowers and Royster, 1978; Rib and Liang, 1978).

With measurements taken in fourteen different locations, Shakoor and Rodgers (1992) investigated the undercutting rate of the Devonian-Permian aged (approximately 419-251 million years) clay-bearing rocks (Niemann, 2009; Admassu et al., 2012), the physical factors affecting the undercutting rate and the relationship between the undercutting rate and the slake durability index. These researchers stated that undercutting took place in the fastest way in mudstones with massive structural properties with annual undercutting values ranging between 63.5 mm and 95.3 mm. Shakoor and Rodgers (1992) emphasized that the weathering rate in sequences consisting of silty shales is slower than mudstones, and annual undercutting values range from 12.7 mm to 25.4 mm. It was determined that the laminated claystones and clayey limestones have undercutting rates between shales and mudstones (Shakoor and Rodgers, 1992).

Shakoor and Rodgers (1992) stated that there is no statistical correlation between the undercutting rate of clay-bearing rocks and these rocks' clay mineralogy and plasticity properties. In addition, it was determined by these researchers that physical properties such as slope direction and angle did not affect the undercutting rate. However, the parameters such as the fracture frequency of the non-disintegrating units overlying the clay-bearing rocks, vegetation of the slope and debris accumulation are among the important slope physical properties affecting the undercutting rate (Shakoor and Rodgers, 1992). Shakoor and Rodgers (1992) emphasized that the most important result obtained in understanding the disintegration behavior of clay-bearing rocks is the statistically significant correlation between the slake durability index and the undercutting rate.

Niemann (2009) took re-measurements at seven of fourteen different locations investigated by Shakoor and Rodgers (1992) to determine the time-dependent change in the undercutting rates of clay-bearing rocks. Considering the results obtained by Niemann (2009), it was determined that the undercutting rate value was not constant, and a significant time-dependent decrease occurred in the weathering rates of clay-bearing rocks. The total annual precipitation in the Appalachian region (USA), where undercutting measurements were taken by both Shakoor and Rodgers (1992) and Niemann (2009) in later years, varies between 100 and 130 cm (PRISM Group, 2006). Similarly, Admassu et al. (2012) studied clay-bearing rocks in the East and Southeast of Ohio to find the factors affecting undercutting depth. The parameters given below were determined as independent variables to be used in the statistical analysis in the study performed by Admassu et al. (2012):

1. Vertical distance of the undercut unit (hard rock) from slope crest
2. Relative position of the hard rock,

3. Thickness of the hard rock,
4. Spacing of orthogonal joints,
5. Slake durability index of the undercutting (clay-bearing) rock,
6. Initial slope angle of clay-bearing rock,
7. Age of cut slope (difference between the date of excavation and the time of measurement),
8. Other factors such as slope aspect, the amount of rainfall, the amount of water seeping out onto the cut slope, the angle and height of the natural slope above the cut slope, the stratigraphy above the cut slope, and the number of freezing-thawing cycles (Admassu et al., 2012).

Admassu et al. (2012) determined that the slake durability index of the clay-bearing rocks and the slope angle are the most important factors affecting the total depth of undercutting. Contrary to the results obtained by Niemann (2009), these researchers stated that the age of excavation has no significant effect on the undercutting depth. Additionally, according to research conducted by Admassu et al. (2012), there is a nonlinear relationship between the undercutting depth and time.

As emphasized in previous studies (Fookes and Sweeney, 1976; Rib and Liang, 1978; Shakoor and Weber, 1988), rockfalls are known as the most common slope instabilities associated with undercutting. This type of instability, which is frequently observed, is very dangerous due to its high rate and sudden falls (Peckover and Kerr, 1977). Rocks such as claystone, mudstone, siltstone, shale, marl, and less welded pyroclastic are generally encountered in many engineering projects such as road slopes alternating with rock units more stable to erosion._Therefore, in these projects, the upper hanging unit causes the risk of rockfalls with faster disintegration of clay-bearing rocks over time. It is thought that it is very important to develop practical approaches to be used in determining or predicting the change range of the disintegration ratio and undercutting of weak rocks to implement the necessary corrective measures promptly to prevent failure caused by advanced undercutting, especially in the excavation slopes on the roads that have been serving intensively for many years. Thus, besides the tests carried out under laboratory conditions, evaluating the disintegration behavior and disintegration ratio of the rocks bearing clay in the field is very important in engineering studies.

Considering the above-highlighted requirements, studies were carried out in the excavation slopes where undercutting occurred in eleven different locations in Kütahya, Eskişehir and Afyon to estimate the undercutting rate of clay-bearing rocks. The undercutting depths were precisely measured in all locations with the help of pins installed on the freshly undisturbed surfaces of weak rocks. Besides, the excavation dates of the road slopes where the field studies were carried out to determine the behavior of these rocks under atmospheric conditions for many years and to be used in determining the undercutting rates were taken from the General Directorate of Highways. It was determined that the average annual undercutting depth values of these weak Eocene-Quaternary aged rocks vary approximately between 10.1 and 45.8 mm in regions with annual precipitation between 36-56 cm. These undercutting depth values, which are an average value for the period from the date of excavation to the date of measurement, continue to decrease every year until the rockfall occurs.

During the field studies, samples were taken from each of the excavation slopes, and the slake durability index, slake index, and uniaxial compressive strength values of these samples were determined. Shakoor and Rodgers (1992) took into account the statistically significant correlation between the undercutting rate and the slake durability index, and it was also aimed to determine whether the slake durability index could be used to estimate the undercutting rate of clay-bearing rocks. However, as Erguler and Shakoor (2009) stated, many clay-bearing rock units are heavily disintegrated during the slake durability index test, and these pieces are considered to be stable since they do not pass the drum sieve. Erguler and Shakoor (2009) proposed a D_R approach to overcome this problem. Therefore, besides the results of tests such as slake durability index, slake index, within the scope of this study, the availability of the D_R parameter in determining the disintegration behavior of clay-bearing rocks was also investigated. Considering all acquired results, analyses were carried out between the undercutting rate of clay-bearing rocks and the slake durability index and D_R. As a result of the analyses, it was concluded that the D_R approach can be used in estimating the undercutting rate.

2. Geology of the Study Area

Within the scope of this study, sampling areas were selected from Kütahya, Eskişehir and Afyonkarahisar provinces, and taking into account the slope durability caused by undercutting; studies were carried out in 11 (eleven) different locations, all of which consist of road excavation slopes. The locations of the study areas are shown in Figure 1. Previous studies were used in the evaluation of the geology of the regions in this study.

Kütahya and its surroundings were chosen as the first study area to investigate the disintegration in weak geological units. The geological units in the region from old to young are listed as Sarıcasu formation, Arıkaya formation, Ovacık Melange, Sabuncupınar formation, Çokköy formation, Emet formation, Kirazpınar formation, Yakaca formation, Kütahya formation and alluvial deposits, respectively. In the studies of the Kütahya region (L1-L7), the levels where the clay-bearing rocks in the road excavation slopes opened in the Middle-Upper Miocene Çokköy formation were preferred. The unit consisting of conglomerate, sandstone, claystone, marl, tuff, tuffite and limestone is named as Çokköy formation (Özburan, 2009). It is mostly observed in gray, off-white, green tones and brown tones, and the unit takes its green color from the observed layers of marl and clay. Mostly alternation of conglomerate-sandstone-marl-clay is observed, and this sequence is accompanied by tuffs. In the unit, limestones are located at the top level of the series, carbonated sediments starting in the form of clayey limestone, gradually transition to Emet formation with limestone levels (Özburan, 2009).

Field studies, the undercutting depth and sampling in the Eskişehir region were carried out in three locations. The geological units within the provincial borders of Eskişehir are listed from the old to young as Karkın formation, Mamuca formation, Porsuk formation, Ilıca formation, Akçay formation and alluvial deposits, respectively. Location L8 is located in the Quaternary Akçay formation. The unit was formed by loose cemented clay, silt, sand and gravel belonging to older formations (Orhan, 2005). It is generally made up of old alluvial deposits. All pre-Quaternary lithologies consist of different blocks, gravel and sands, mud and schists, and their colors may

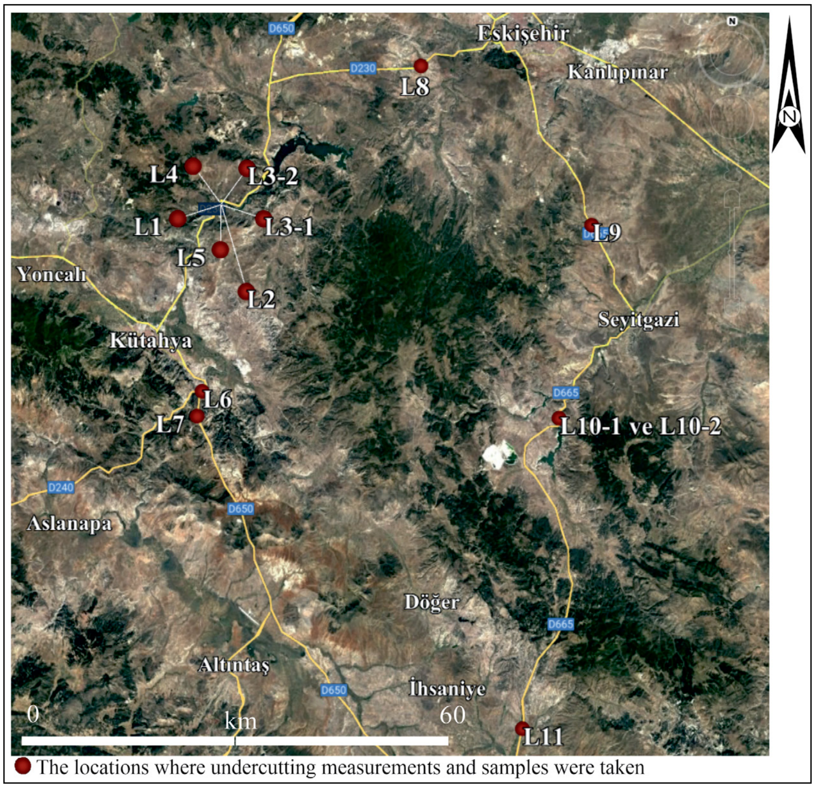


Figure 1- The locations where undercutting measurements were taken in this study (high-resolution satellite image prepared by using Google Earth Pro, 2020).

vary accordingly. It is unconformable with basement rock units and Mid-Upper Miocene sediments. The unit is covered with young alluvial deposits. Its age is Early Pleistocene according to the vertebrate fossils found in clay sequences (Gözler et al., 1997). Location L9 was selected tuffites found in Pliocene aged Ilıca formation. This formation consists of terrestrial and lacustrine conglomerates, sandstones, agglomerates, tuffs and tuffites, marl and clay, terrestrial and lacustrine sediments consisting of clayey, sandy, tuffaceous limestones, and units cut by andesitic and basaltic volcanism (Gözler et al., 1996). Location L10 was carried out in the Eocene aged Mamuca formation. The unit starts with purple, red, wine, gray and gray coloured conglomerate and sandstones, and there are green coloured clays on it. There are the clay, intercalated, clayey and sandy limestones with a rich benthic foraminiferal community in yellowish gray colors towards the upper layers (Gözler et al., 1997).

This study was also carried out in Afyon and its vicinity, and the basic geological units of the region involve the metamorphic rocks of the Afyon zone. Mesozoic aged carbonate and ophiolitic rocks overlie the Afyon metasedimentary group. Cenozoic aged volcanic and sedimentary rocks are the youngest units in the region. The Quaternary formed talus and current young alluvial deposits cover these units. In the Afyon region (L11), field studies and sampling were carried out on tuffites in the Lower Pliocene aged Gebeciler formation. This unit is transitional with terrestrial conglomerate, sandstone, agglomerate alternation at the bottom, lacustrine gray tuff, tuffite, marl and clayey limestone alternation in the middle levels, and porous limestone and lacustrine sediments at the top.

3. Material and Method

3.1. Field Observations

In this study, geotechnical and environmental problems such as frequent rockfalls caused undercutting and filling of road drainage ditches with disintegrated material were observed in the locations selected based on the purposes of this study. During the field investigations, claystone-thick limestone layers having the risk of rockfall due to the undercutting processes of clay-bearing rocks were detected on the road slope excavated about ten years ago. It was determined that the most dangerous condition in terms of rockfall is location L7, which has an average discontinuity spacing of 94.2 cm (30-210 cm) and very thick limestone layers (Figure 2). Also, it was determined that rock blocks rolled down to the slope toe by the rockfalls are of large sizes that can be quite damaging in many locations (Figure 3a). In addition to these geotechnical problems, environmental problems that damage road coverings, such as filling the road drainage ditches with talus materials, have also been observed in locations where the undercutting problem was experienced (Figure 3b).

3.2. The Undercutting Measurements

In previous studies, it was stated that the slake characteristics of clay-bearing rocks should be determined in addition to the results obtained in the laboratory, as well as the disintegration behavior of such rocks in the field. In this study, to determine the weathering rates of clay-bearing rocks on road excavation slopes, the depth of undercutting measurements was taken from claystone-limestone

Figure 2- Thick limestone layers with a wide discontinuity spacing carrying the risk of rockfall due to undercutting processes of clay-bearing rocks (L7).

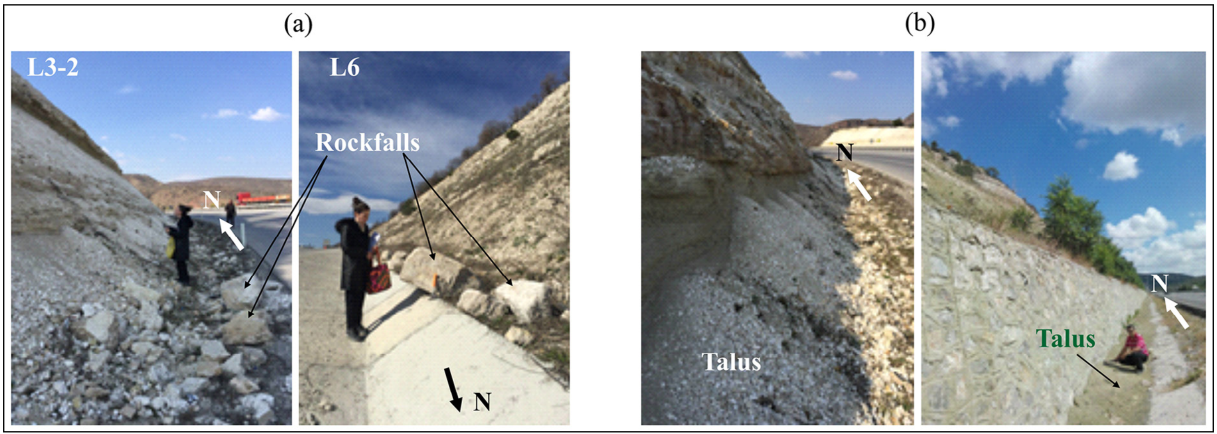


Figure 3- Geotechnical problems due to undercutting processes; a) rockfalls and b) the filling of road drainage ditches (Kütahya-- Eskişehir road, Ilıca location).

units' contact points from certain distances using a tape measure at locations L3-1, L3-2, L5, L6 and L7 (Figure 4). The excavation dates of the examined road excavation slopes were obtained from the records of the relevant departments of the General Directorate of Highways. The time the excavation slope is subjected to weathering processes was determined by taking the time from excavation to the measurement date. Within the scope of this study, an approach was made about the undercutting rates of clay-bearing rocks on the relevant slopes taking into account the measurements taken from the road slopes whose excavation date is known. The depth of undercutting values taken using a tape measure from these study areas, whose approximate excavation date is 2008 (excavation end date: 2010), are presented in Table 1.

It was determined that the values of undercutting depth given in Table 1 vary widely for each location

Figure 4- Measurements of the undercutting depths taken in road slopes with known excavation dates.

Table 1- The values of the undercutting depths measured on clay-bearing rocks in the field.

Excavation date: 2008 (Excavation end date: 2010)* Measurement date: August 3rd, 2014

Location	Number of measurements	The depth of undercutting (cm)		
		Minimum	Maximum	Average
L3-1	21	10.0	25.0	17.2
L3-2	21	12.0	26.0	18.3
L5	21	12.0	38.0	22.7
L6	20	30.0	67.0	43.2
L7	22	80.0	180.0	125.1

*: the excavation end dates were evaluated based on the General Directorate of Highways records.

since the surfaces of the limestone layers accepted as a reference level have indentations and protrusions in the measurements. Therefore, more precise measurement methods of the undercutting rate values of clay-bearing rocks were investigated. For this purpose, in addition to the measures taken directly in the field, steel pins and screws were placed in weak clay-bearing rocks in certain locations (L1, L2, L3-1, L4, L8, L9, L10-1, L10-2 and L11), and the depths of disintegration resulting from physical weathering processes were measured at different time intervals. The pins used were installed on the surface to be zeroed, and by the time the outer part of the pins from the rock surface was measured with a calliper at certain intervals. The photographs representing this direct measurement are given in Figure 5, and a typical example of the time-dependent change of the undercutting depths is shown in Figure 6. The undercutting rate values were determined and presented in Table 2 for clay-bearing rock units in different locations by using both the excavation dates of the slopes and the depth of undercutting values measured by the installed pins.

3.3. Sampling Studies

In addition to determining the disintegration rates of weak rocks under atmospheric conditions, fresh samples, which are not subjected to weathering processes, were taken from these rocks to be used in laboratory tests. The samples were placed in plastic bags and delivered to the laboratory on the same day to prevent disintegration caused by moisture loss and determine their natural water contents. The water

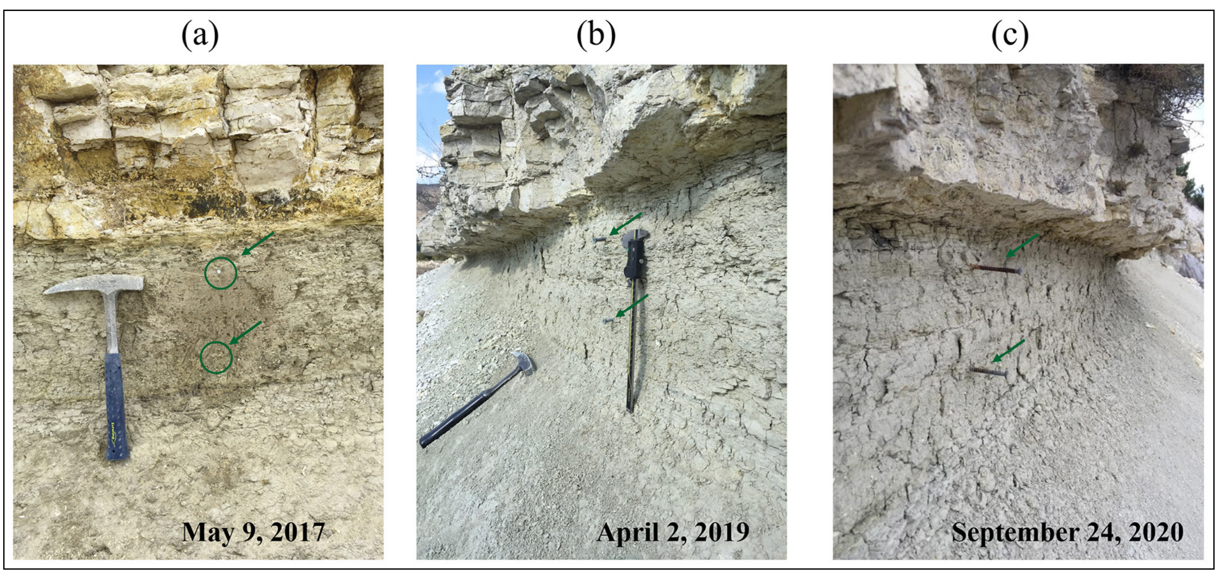


Figure 5- The undercutting depth measurements for location 3-1 using steel pins and screws; a) removing of the disturbed parts where the measures would be taken, obtaining fresh surfaces and installing pins, b) and c) the depth of undercutting observed in the pins on different dates.

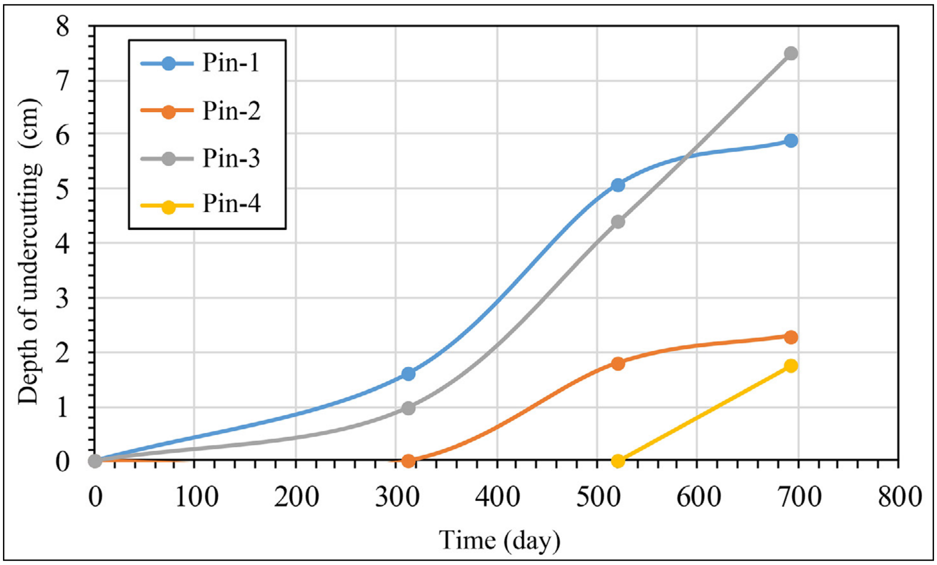


Figure 6- The time-dependent change of the depth of undercutting in pins installed in L1 due to effective weathering processes at natural conditions.

Table 2- The undercutting rate values and ranges measured in the study area.

Locations and coordinates		Rock type	Excavation date	The undercutting rate (mm/year)	
				Measurement technique 1[a]	Measurement technique 2[b]
L1	39°34'18.7"N,30°05'12.0"E	Claystone	2008	-	32.5 (22.0-39.5)
L2	39°34'18.7"N,30°05'12.0"E	Claystone	2008	-	40.6 (35.9-47.0)
L3-1	39°34'18.7"N,30°05'12.0"E	Claystone	2008	43.1 (25.0-62.5)	45.8 (35.9-57.8)
L3-2	39°34'16.5"N,30°05'11.1"E	Claystone	2008	45.7 (30.0-65.0)	-
L4	39°34'26.9"N,30°05'07.8"E	Tuffite	2008	-	33.5 (23.6-52.6)
L5	39°34'16.5"N,30°05'11.1"E	Clayey limestone	2008	56.8 (30.0-95.0)	-
L6	39°34'46.8"N,30°05'42.2"E	Clayey limestone	2008	107.9 (75.0-167.5)	-
L7	39°34'05.7"N,30°05'15.5"E	Claystone	2008	312.8 (200.0-450.0)	-
L8	39°34'45.2"N,30°05'39.0"E	Clay	2006	-	36.4 (30.4-45.1)
L9	39°34'03.2"N,30°05'34.2"E	Tuffite	2005	-	10.1 (9.5-10.7)
L10-1	39°34'02.8"N,30°05'42.7"E	Marl	1982	-	14.8
L10-2	39°34'02.8"N,30°05'42.7"E	Claystone	1982	-	20.9 (15.9-25.8)
L11	38°34'11.4"N,30°05'35.1"E	Tuffite	2017	-	31.4 (30.7-32.0)

[a]: determined by using the excavation dates of the slopes, [b]: specified by installing pins in clay-bearing rocks; the values given in parentheses indicate the range of undercutting rate.

contents of the samples brought to the laboratory were immediately determined and put on hold for slower water content change in laboratory conditions of other samples prepared in certain sizes to define the slake characteristics. The slower drying phase of the clay-bearing rocks provides a less possible disintegration ratio. From each location sample, 12-15 pieces of 40-60 g and 6 samples of 150 g were prepared and kept in an oven at 105 ° C for 24 hours.

3.4. Experimental Studies

3.4.1. Unit Weight and Strength Values of Samples

The dry unit weight values of the collected samples were determined in accordance with ASTM (1994) (Table 3). Due to the rapid disintegration behavior of the selected rock units during the water exchange, their moisturized and water-saturated strengths were not determined. However, the needle

Table 3- Dry unit weight, needle penetration resistance and uniaxial compressive strength values of the samples investigated for their slaking behavior.

Location Number	Rock Type	γ_d (kN/m³)	*NPR* (N/mm)	σ_{ci} (MPa)
L 1-L3	Claystone	14.51	30.27	9.55
L 4	Tuffite	14.22	4.02	1.46
L 5	Clay limestone	17.26	*	*
L 6	Claystone	12.65	13.09	4.38
L 7	Claystone	20.01	33.33	10.45
L 8	Clay	15.59	50.00	15.23
L 9	Tuffite	12.26	25.00	8.00
L 10-1	Marl	18.44	50.00	15.23
L 10-2	Claystone	18.63	30.55	9.63
L 11	Tuffite	16.38	11.20	3.79

γ_d: dry unit weight; *NPR*: needle penetration resistance; σ_{ci}: uniaxial compressive strength *: needle penetration resistance could not be measured due to the broken of the needle tip.

penetration approach was used to determine the uniaxial compressive strength of the samples in dry conditions. The uniaxial compressive strength values of the collected samples were empirically estimated by using Equation 1 developed by Ulusay and Ergüler (2012) and presented in Table 3.

$$\sigma_{ci} = 0.402*NPR^{0.929} \quad (1)$$

where; σ_{ci} shows the uniaxial compressive strength (MPa) and *NPR* shows the needle penetration resistance (N/ mm).

3.4.2. Tests Used to Determine The Slaking Behaviour of Samples

In determining the slaking behaviour of rocks, the jar slake test (Wood and Deo, 1975), slake index test (Deo, 1972) and slake durability index test (Franklin and Chandra, 1972; ISRM, 1981) are generally used. These tests were used to determine and define the slaking behaviour of collected clay-bearing rocks by considering the importance of these tests in international studies. The approach and identification criteria recommended by Wood and Deo (1975) were used for the jar slake test. As seen in Table 4, the same

Table 4- D_R values with the results obtained as a result of the jar slake test (Wood and Deo, 1975), slake index test (Deo, 1972) and slake durability test ISRM (1981).

Location	Rock type	Jar slake test		I_s				I_d			
		t_{30}	t_{24}	2nd cycle		4th cycle		2nd cycle		4th cycle	
				I_s	D_R	I_s	D_R	I_{d2}	D_R	I_{d4}	D_R
L 1-L3	Claystone	*1*	*1*	99.9	0.15	100.0	0.15	*	*	*	*
L 4	Tuffite	*2*	*2*	54.5	0.23	61.2	0.24	*	*	*	*
L 5	Clayey limestone	*6*	*6*	0.2	1.00	0.4	1.00	87.8	1.00	79.38	1.00
L 6	Clayey limestone	*5*	*5*	0.8	1.00	1.1	1.00	87.0	1.00	77.12	1.00
L 7	Claystone	*1*	*1*	99.2	0.25	99.2	0.25	0.6	*	*	*
L 8	Clay	*1*	*1*	92.9	0.16	98.1	0.15	3.9	0.17	1.70	0.15
L 9	Tuffite	*3*	*3*	4.1	0.95	8.7	0.91	84.4	0.91	65.35	0.82
L 10-1	Marl	*3*	*3*	51.5	0.76	53.5	0.53	12.0	0.80	8.36	0.73
L 10-2	Claystone	*1*	*1*	97.4	0.28	97.5	0.28	1.5	0.25	1.34	0.25
L 11	Tuffite	*3*	*3*	33.0	0.60	56.6	0.37	17.0	0.48	8.25	0.30

t_{30}: the category at 30 minutes; t_{24}: the category at 24 hours; I_s: slake index; I_d: slake durability index; *1*: degrades to a pile of flakes or mud; *2*: breaks rapidly and/or forms many chips; *3*: breaks slowly and/or forms a few chips; *4*: breaks rapidly and/or develops several fractures; *5*: breaks slowly and/or develops few fractures; *6*: No changes; *: disintegration occurred so that no sample remained in the drum.

category was obtained at 30 minutes and 24 hours in all locations for the jar slake tests performed in this study. In addition, the slake index (I_s) test developed and proposed by Deo (1972) is a test used to numerically describe the degree of slaking behaviour of weak clay-bearing rocks. After this experimental study, the variations in I_s values of the samples due to the increase in the number of cycles is presented in Table 4. After the slake index tests, it was determined that the disintegration obtained at the 2nd and 4th cycles showing different fragment sizes distribution but larger than 2 mm was also quite intense (Figure 7). Some of the fragment size distribution curves obtained as a result of the 2nd cycle of this disintegration using sieves with different apertures are presented in Figure 8a. Ergüler and Shakoor (2009) suggested the disintegration ratio, D_R approach to model this disintegration in Figure 8a, which occurs in clay-bearing rocks, and to define all disintegrations with a single parameter (Figure 8b). The disintegration ratio values of all samples were determined and given in Table 4 using this approach presented in Figure 8b.

The recommendations suggested by ISRM (1981) were considered for the slake durability tests (I_d). The index values of slake durability obtained as a result of these tests are given in Table 4. As specified in previous studies, it was also identified that the clay-bearing rocks retained in the drum categorized as durable significantly disintegrated in this study. The grain size distribution curves of the fragments retained in the drum, which shows fragmentation at different

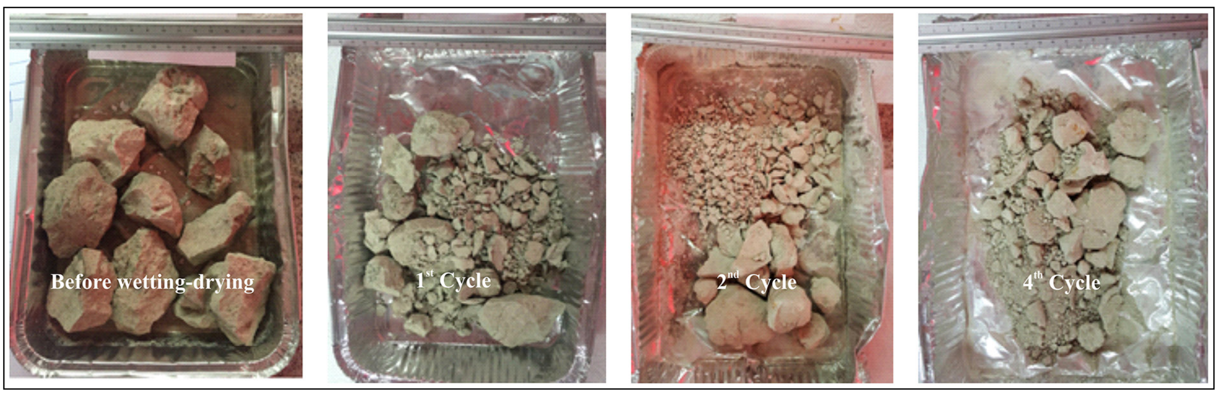
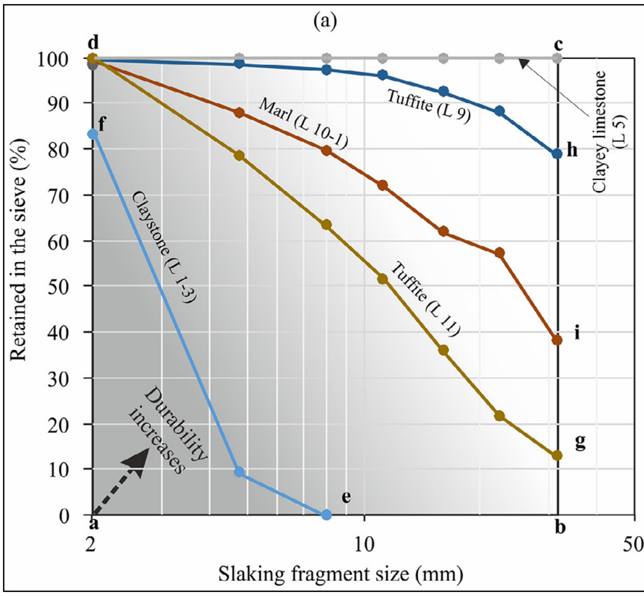


Figure 7- The change of disintegration in marl sample after slake index test depending on the number of cycles (L10-1).



(b)

Rock type	Disintegration ratio (D_R)
Claystone (L 1-3)	$D_R = \frac{Area\ (aefa)}{Area\ (abcd)} = 0,15$
Tuffite (L 11)	$D_R = \frac{Area\ (abgda)}{Area\ (abcd)} = 0,60$
Marl (L 10-1)	$D_R = \frac{Area\ (abida)}{Area\ (abcd)} = 0,76$
Tuffite (L 9)	$D_R = \frac{Area\ (abhda)}{Area\ (abcd)} = 0,95$
Clayey limestone (L 5)	$D_R = \frac{Area\ (aefa)}{Area\ (abcd)} = 1,00$

■ Completely non-durable (D_R=0)
□ Durable (D_R=1)

Figure 8- a) The fragment size distribution curves of clay-bearing rocks after the slake index test and b) the calculation of the disintegration ratio for the clay-bearing rocks (Ergüler and Shakoor, 2009).

rates, were prepared after the 2nd and 4th cycle slake durability test. Similarly, the "disintegration ratio" values specified for the samples used for the slake durability test were determined by using these curves based on the approach suggested by Erguler and Shakoor (2009), and the obtained results are given in Table 4.

4. Discussion

It was emphasized in previous studies (Shakoor and Rodgers, 1992) that there was no statistically significant relationship between the undercutting rate of clay-bearing rocks and their other parameters such as clay mineralogy and plasticity properties. In addition to these parameters of rock units, these researchers stated that physical properties such as slope direction and angle also do not affect the undercutting rate. In this study, the measurements L1, L2, L3-1 and L3-2 were taken from slopes with different slope direction and angle values within the same claystone level. As emphasized in previous studies and as seen in Table 2, it was determined that the ranges of the undercutting rate values taken at locations L1, L2, L3-1 and L3-2, whose slope directions are north, east, west-southwest and east-southeast, respectively, are quite close to each other. Shakoor and Rodgers (1992) determined that the most important result obtained in terms of understanding the disintegration behaviour of clay-bearing rocks was the statistically significant correlation between the slake durability index and the undercutting rate. In addition, Admassu et al. (2012) emphasized that the slake durability index of clay-bearing rocks is one of the most important factors affecting the undercutting depth in the study conducted in the same region in the following years. Considering these results obtained in previous studies, the relationship between the average undercutting rate of clay-bearing rocks and the slake durability index was examined within the scope of this study by taking into account excavation date and pin measurements. As a result of the investigations, it was understood that the undercutting rate values calculated based on the excavation dates affected the general change very much, and these data were not sensitive enough. When the undercutting rate values calculated from the excavation date were neglected, it was determined that the undercutting rate values were controlled by the slake durability index of the corresponding rock unit (Figure 9). The change graphs of the slake durability index and the average undercutting rate values, which are prepared based on the data obtained in this study and the data obtained in the study carried out by Shakoor and Rodgers (1992), are given in Figure 9. As seen in this way, the undercutting rate values show a rather wide range of distribution with the condition of I_{d2} <20. It is thought that such scatter is since the studied clay-bearing rock units have different geological ages and are exposed to weathering processes under quite different climatic

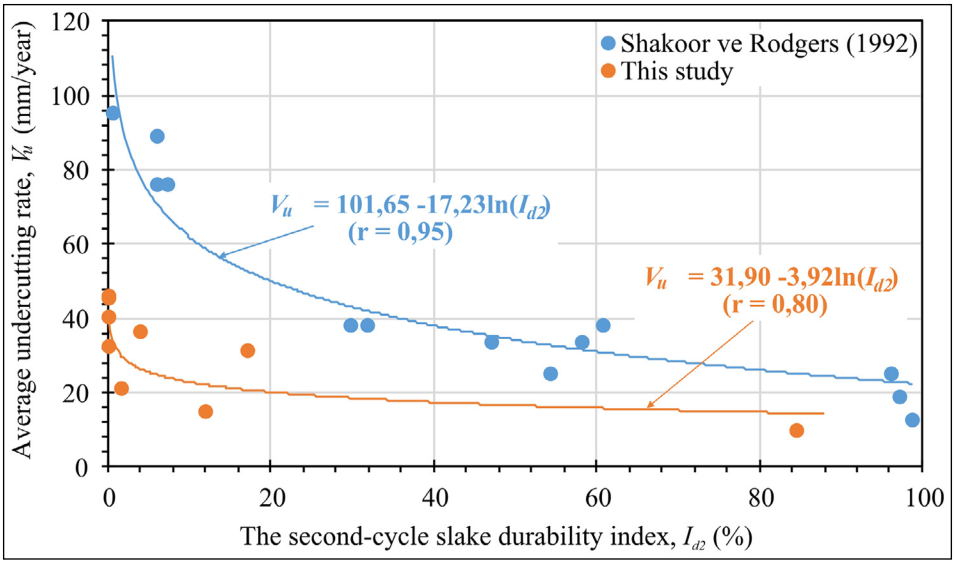


Figure 9- The relationships between average undercutting rate values and second-cycle slake durability index values obtained in this study and studies carried out by Shakoor and Rodgers (1992).

conditions. The durability classification suggested by Gamble (1971) was modified to include the parameter of annual undercutting depth by using the empirical equations given in Figure 9 (Table 5). With the help of this suggested new approach (Table 5), the possible undercutting depth of weak clay-bearing rocks under atmospheric weathering processes can be predicted for different geological ages and climatic conditions.

It is thought that considering the overall fragmentation greater than 2 mm obtained in both slake index (I_s) and slake durability (I_d) tests might be important in determining the slaking behaviour of clay-bearing rocks. Therefore, the disintegration ratio approach proposed by Erguler and Shakoor (2009) was used in the result of these two tests, and the achieved disintegration ratio values determined by this approach were compared with the average undercutting rate values identified by both the excavation date and the measurements taken from the pins. This comparison reveals that the average undercutting rate values calculated based on the excavation dates were not sensitive. Therefore, these data were neglected, and the only undercutting rate values determined from the pins were compared with the disintegration ratio values determined as a result of the 2nd and 4th cycles of the I_s and I_d tests and the obtained results were presented in Table 6. When this table is considered, it is clearly understood that the disintegration ratio values received as a result of the 4th cycle better represent the slaking behaviour of clay-bearing rocks.

Moriwaki and Mitchell (1977) stated that the slaking behaviour of rocks occurs in four different ways: dispersion slaking, swelling slaking, body slaking, and surface slaking. It was determined in both field observations and laboratory tests to assess the slaking behaviour that clay, claystone and marl samples (L1, L2, L3, L6, L7, L8, L10-1 and L10-2) exhibited dispersion slaking and tuffite samples (L4, L9 and L11) exhibited surface slaking behaviour. However, the clayey limestone samples (L5 and L6) indicate a body slaking behaviour to form fragments in various sizes. Although clayey limestone samples have very high durability values against wetting-drying processes (Table 4), as seen in Figure 10, very high undercutting rates are acquired as a result of the

Table 5- Annual depth of undercutting values for durability classes suggested by Gamble (1971).

Gamble (1971) class	I_{d2} (%)	Annual depth of undercutting	
		Shakoor and Rodgers (1992)*	This study**
Very high durability	>98	<22.7 mm	<13.9 mm
High durability	95-98	23.2 - 22.7 mm	14.0 - 13.9 mm
Medium-high durability	85-95	25.1 - 23.2 mm	14.5 - 14.0 mm
Medium durability	60-85	31.1 - 25.1 mm	15.8 - 14.5 mm
Low durability	30-60	43.0 - 31.1 mm	18.6 - 15.8 mm
Very low durability	<30	<43.0 mm	<18.6 mm

* Recommended values for Devonian-Permian (approximately 419-251 million years) aged clay-bearing rocks with total annual precipitation ranging from 100 to 130 cm; **: values measured in weak rocks younger than Eocene (55.8 million years) with annual precipitation ranging from 36 to 56 cm (DMI, 2019).

Table 6- Empirical equations between undercutting rate and disintegration ratio obtained from the tests of I_s and I_d.

Undercutting rate (V_u)	Test	Empirical equations	
		2nd Cycle	4th Cycle
V_u (cm/year)	I_s	$V_u = 4.82 \times e^{-1{,}49 \times D_{R(wetting\text{-}drying)}}$ ($r^2 = 0.88$)	$V_u = 1{,}03 \times D^{-0{,}73}_{R(wetting-drying)}$ ($r^2 = 0.93$)
V_u (cm/year)	I_d	$V_u = 4.20 \times D^{-1{,}38}_{R(slake)}$ ($r = 0.85$)	$V_u = 4.22 \times e^{-1{,}61 \times D_{R(slake)}}$ ($r = 0.93$)

I_s: slake index test; I_d: slake durability test; D_R (wetting-drying): disintegration ratio obtained from wetting-drying tests; D_R (slake): disintegration ratio obtained slake durability test

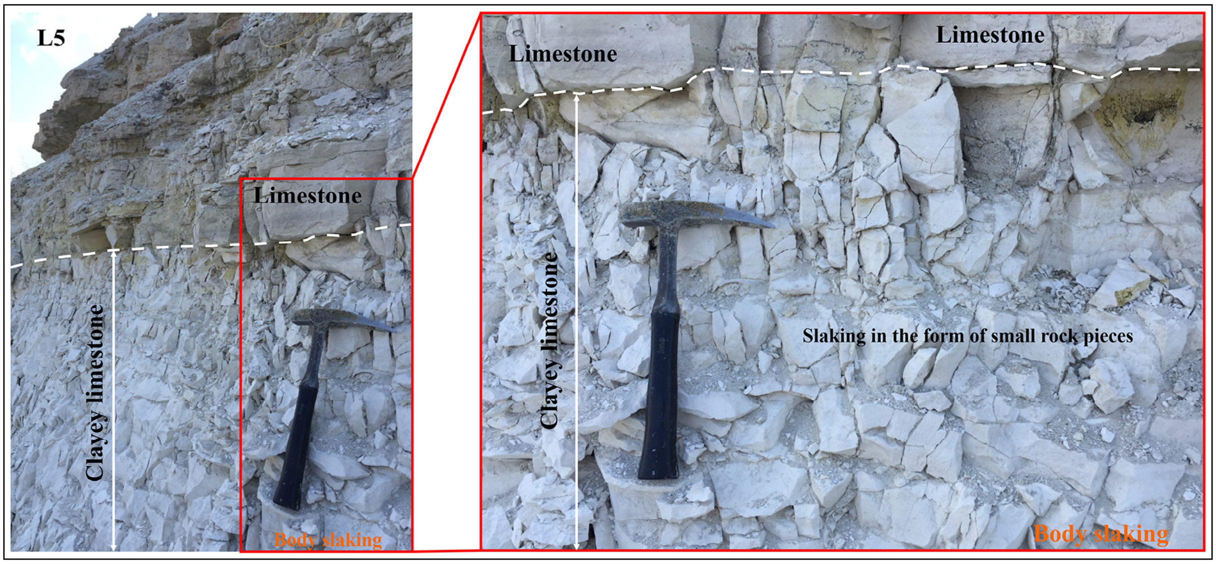


Figure 10- A typical example of the body slaking behaviour in clayey limestones in the form of small rock pieces in atmospheric conditions (L5).

breaking off small pieces of rock that originated from the body slaking behaviour of these rock units.

5. Results

This study aimed to investigate the disintegration behaviour of weak and clay-bearing rocks under atmospheric conditions, determine the undercutting rates occurring after disintegration, and practically predict these undercutting rate values with simple laboratory tests. For this purpose, the following results were obtained with the evaluations and analyses of the outputs achieved from the field studies and laboratory tests.

The average annual depth of undercutting values varies between approximately 10.1 and 45.8 mm for the Eocene-Quaternary aged weak rocks found in regions with a yearly precipitation of 36-56 cm. However, the values of extremely high annual undercutting depths of up to 95.3 mm were also recorded in previous studies for the older (Devonian-Permian aged) clay-bearing rocks outcropped in areas where the average annual precipitation varies between 100 and 130 cm. These results taken directly in the field for the undercutting rate show that it would be particularly useful to consider problems such as time-dependent rockfall in the durability analyses of slopes involving weak clay-bearing rocks alternately outcropped with geological units such as thick limestone highly resistant to erosion.

Although clayey limestones have high durability against slaking processes, high undercutting rate values are obtained in slopes involving these rock units due to breaking off and soon removing small rock pieces after the body slaking.

Statistically significant empirical equations were obtained between the average undercutting rate, which was acquired by measurement on pins and screws installed in weak and clay-bearing rocks, and the slake durability index value of the related rock unit. However, considering the results acquired in this and previous studies, it was determined that the slake durability index and the average undercutting rate values showed a wide range in the condition of I_{d2} <20. It was specified that this distribution originated from studying rock materials having different geological ages and subjecting to weathering processes in quite different climatic conditions.

Many weak and clay-bearing rock units heavily disintegrate into pieces during the slake durability index test, and these fragments are specified as durable due to not passing the drum sieve. The D_R approach was suggested in the literature to overcome this problem. This approach was used in the durability assessment of the fragmented samples obtained as a result of both I_s and I_d tests, and the obtained D_R values were compared directly with the undercutting rates determined with the help of pins. As a result of these analyses, statistically significant empirical equations were obtained to estimate undercutting rates.

Although the disintegration and undercutting depths were measured in the locations where clayey limestone samples were found, significant slaking behaviour could not be observed in the slake index and slake durability tests performed on the samples collected from these locations. This different behaviour observed in clayey limestone samples is thought to have originated from removing small rock pieces resulting in body slaking.

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