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Rockfall triggering mechanisms in soft rocks - climatic factors and suction changes effects

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Abstract

Wetting and drying cycles controlled by atmospheric changes, which result in transitions between saturated and unsaturated states and strong changes in suction, are one of the main reasons for weathering and degradation in soft rocks. Split area (Croatia) is characterized by coastline cliffs in Eocene flysch formations, where the recession of soft rockcliffs is caused by the weathering. Differential weathering between the layers of marly materials and hardrocks causes undercutting of hard rocks, which together with other geological, marine erosion and climatic factors leads to slope instabilities.

Two rockfalls occurred in 2019 at the location of Zenta Bay cliff in Split, which is 14-meter-high steep slope with a promenade at the cliff toe. Both rockfalls were triggered by heavy rainfall following dry periods. To better understand triggering mechanisms, these rockfalls were analyzed with regard to slope stability, climatic factors, and suction changes in the surface zone.

The stability analyses in accordance with Eurocode 7 demonstrated that the slopes were in quasi-stable state with a safety factor greater than 1.0. Assuming that relative humidity (RH) in the surface pores and the atmosphere is equal, suction in the weathered surface zone was calculated using Kelvin's equation, and daily/monthly/seasonal climatic factors (temperature, precipitation, RH) analyses were conducted using the data from the local meteorological station Marjan-Split. Suction difference for different time periods was analysed as an additional instability trigger and weathering agent.

It was shown that the rockfallswere caused by a combination of the lowest (monthly and annual) suction value and the highest RH on the day of the rockfall, together with previous significant precipitation after a prolonged dry period and temperatures lower than the average monthly and on a decreasing trend. Such analyses may contribute to the understanding of rockfall triggering mechanisms and the prediction of future rockfall events.

Keywords

Soft rocks, Rockfalls, Triggering mechanisms, Climatic factors, Suction.

1 Introduction

Coastal areas are particularly exposed to environmental stress, and climate change in the Mediterranean region is progressing faster than the global average (MedECC 2020). These changes intensify the alternation between wet and dry periods and accelerate the degradation of the soft rock materials, such as marls within the coastal Eocene flysch formations of the Split area (Dalmatia, Croatia), examined in this study.

Flysch deposits are characterised by a layered structure with alternating soft rocks (clayey marls to calcareous marls) and hard rocks (sandstones), which leads to differential weathering between layers (Fig. 1 left). That is, the weathering of soft rock causes undercutting of hard rock (Fig. 1 right) leading to slope instabilities and rockfalls. Although the weathering of soft rocks and its implications for slope stability have been studied previously (e.g. Miščević et al. 2020; Vlastelica et al. 2018a and 2018b), these studies have not considered suction and the unsaturated state of the material as important factors.

Since drying and wetting cycles controlled by atmospheric changes are a primary cause of physical weathering, weathering is consequently associated with transitions between saturated and unsaturated states and variations in suction. The relationship between degradation/weathering of marls and related suction changes (Cardoso 2009; Cardoso and Alonso 2009, etc.) is becoming increasingly relevant in the context ofaccelerating climate change.

In the area of Split, undercutting of hard rock layers, together with other geological, marine erosion and climatic factors, leads to slope instabilities and the recession of soft rock cliffs. Two rockfalls occurred in 2019 at the location of Zenta Bay cliff in Split, which is 14-meter-high steep slope with a promenade at the cliff toe. Both rockfalls were triggered by heavy rainfall following prolonged dry periods. To better understand the triggering mechanisms, these rockfalls were analysed in terms of slope stability, climatic factors, and suction changes in the near-surface zone.



Fig. 1 Example of differential weathering (left) and fractured sandstone blocks at the site (right).

2 Materials and methods

Morphologically, the cliff is a steep coastal slopealong the shoreline, up to approximately 14 m high, with a slope of approximately 70° over a length of 60 m. The slope and the promenade are exposed to wind and waves from the southwest. In March 2019, a geotechnical ground investigation was carried out to evaluate slope stability and to define appropriate protection measures (University of Split 2019).

The geological structure consists of Eocene flysch ($E_{2,3}$) with highly weathered thin-layered clayey marl intertwined with calcareous sandstone layers. Above the flysch bedrock, fill materials (Q_n) and eluvium - degraded flysch (Q_{el}) with poorer physical and mechanical properties – are present. At the top of the slope, fractured sandstone blocks were identified, with interlayer cracks and gap discontinuities larger than 1 cm, empty, subvertical and subhorizontal (Fig. 1 right). Secondary discontinuities, in combination with interlayer cracks, isolate larger sandstone blocksand create a high risk of rockfalls onto the coastal promenade due to toppling and planar sliding.

2.1 Properties of rock materials

According to laboratory tests, the rock materials consist of marls (49% of calcium carbonate content, $CaCO_3$) and calcareous sandstones (98-99% $CaCO_3$). The uniaxial compressive strength of marls is in the expected range of UCS = 5-15 MPa and the point load strength index is $I_{s(50)}$ = 0.4-1.3 MPa. At the surface, the rock quality designation index RQD is low, ranging from < 25 and 25-50%, whereas values >50% are generally registered with increasing depth. Geological strength index is GSI = 25-50. The maximum horizontal acceleration is 0.22 g for the earthquake return period of 475 years.

Based on these data, two main types of geotechnical layers were identified: *GL1 – flysch bedrock* (rock mass properties were determined using Rocscience RockLab software: cohesion c=40 kPa, internal friction angle φ=30°, unit weight γ=23 kN/m^3), and *GL2 – degraded flysch* at the slope surface (c=10 kPa, φ=26°, γ=20 kN/m^3). These data were adopted as input for the slope stability analyses.

2.2 Stability analyses

The possibility of shallow rotational landslides was confirmed by the slope stability analyses, performed using a limit equilibrium method that assumes a rigid sliding body, implemented in the Rocscience Slide software, in accordance with Eurocode 7 (EC7), Design Approach 3 (DA3). According to the results shown in Table 1, the slope is in a quasi-stable state and does not satisfy EC7 requirements. Even minor changes in environmental conditions, such as intense rainfall or seismic events, may trigger slope failure and endanger the coastal promenade. A detailed description of the performed analyses is provided in the geotechnical investigation report (University of Split 2019).

Table 1. Results of slope stability analyses.

Analysis type	Description	Partial factors	Load combination	Safety factor FS
Global stability	Materials: only GL1 EC7-DA3: YES	$\gamma_{tan\varphi}$=1.25 γ_c=1.25	Seismic	1.15
Local stability(1)	GL1, and GL2 at the slope surface EC7-DA3: YES	$\gamma_{tan\varphi}$=1.25 γ_c=1.25	Seismic	0.85
Local stability (1)	GL1, and GL2 at the slope surface EC7-DA3: NO	$\gamma_{tan\varphi}$=1.0 γ_c=1.0	Static	1.19
Local stability (1)	GL1, and GL2 at the slope surface EC7-DA3: NO	$\gamma_{tan\varphi}$=1.0 γ_c=1.0	Seismic	0.99

(1) Local stability of weathered cliff surface (degraded flysch)

2.3 Analyses of climatic factors and suction changes

On April 10, 2019, heavy rainfall, preceded by dry March and February, caused the first rockfall. Improper reconstruction and stabilization of the cliff led to a second rockfall on November 20, 2019, caused by similar weather conditions. Considering the above-mentioned events, where heavy rainfall after long dry periods caused slope instabilities, suction differential was analysed as an instability trigger and weathering agent for soft rock cliffs and slopes.

External climatic factors, particularly temperature and relative humidity, control soil moisture in the near-surface zone, where pore-air relative humidity tends towards equilibrium with atmospheric conditions. This influence is strongest in the surface zone and decreases with depth, being associated with evaporation-controlled processes occurring over a few centimetres to decimetres (Slavík and Lanzendörfer 2024).

Suction in the weathered surface zone was determined using the assumption that relative humidity in the surface pores and the atmosphere is equal, i.e. calculated from Kelvin equation:

$$\psi = -\frac{R\,T\,\rho_w}{1000\,M_w}\,ln(RH) \qquad (1)$$

where ψ is the total suction (MPa), R is the universal gas constant (8.314 J/mol/K), T is the absolute temperature (K), ρ_w is the density of pure water (998 kg/m^3 at 293.15 K), M_w is the molecular mass of water (18.016 kg/kmol), RH is the relative humidity.

The climatic factors T and RH for different periods and datasets were obtained from data recorded at the local meteorological station Split-Marjan. The results are presented in section 3.

3 Results and discussion

The described methodology was applied to long-term data series for T and RH, as well as to shorter periods covering 2019 and the specific months and days of the two rockfalls. In addition to total suction values (Table 2), the maximum suction differences were evaluated on annual and seasonal basis, and for the months of rockfall occurrence - April and November 2019 (Table 3).

Table 2. Variations in temperature, relative humidity and suction for different data series.

Month	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Remarks**
RH (%)	60.4	59.5	59.8	59.4	59.3	56.3	49.4	51.7	58.3	61.2	63.9	61.5	1961-1990(1)
T (°C)	7.6	8.2	10.5	13.9	18.7	22.5	25.4	24.9	21.4	16.9	12.3	8.9	1961-1990 (1)
ψ (MPa)	65.2	67.3	67.2	68.9	70.2	78.2	97.0	90.6	73.2	65.6	58.9	63.1	
RH (%)		57.9	59.2	59.2	58.8	54.9	49.3	51.7	59.1	62.2	63.0	61.5	1971-2000 (1)
T (°C)	8.0	8.4	10.6	13.7	18.9	22.8	25.7	25.4	21.2	16.8	12.0	9.1	1971-2000 (1)
ψ (MPa)		70.9	68.5	69.3	71.4	81.7	97.3	90.7	71.3	63.4	60.7	63.2	
RH (%)	60.2	52.0	57.0	58.2	62.0	50.0	48.0	47.0	53.0	59.0	71.5	61.0	2019 (2)
T (°C)	7.9	8.3	10.8	14.4	19.1	23.2	26.0	25.7	21.5	17.1	12.6	9.3	1948-2018 (1)
ψ (MPa)	65.7	84.8	73.5	71.7	64.3	94.6	101.1	103.9	86.2	70.5	44.1	64.3	
RH (%)				89.0							89.0		10.4.2019(2,3)
T (°C)				13.4							13.2		and
ψ (MPa)				15.4							15.4		20.11.2019(2,4)

(1) Source – Croatian Meteorological and Hydrological Service (CMHS)
(2) Source – WeatherOnline (WO), https://www.weatheronline.co.uk/Croatia/Split.htm
(3) Daily values on the date of the first rockfall (April 10, 2019)
(4) Daily values on the date of the second rockfall (November 20, 2019)

Table 3. Suction differences in the surface zone (modified from Raič et al. 2021).

Period / data source	**Type of analysis**	**Max. suction ψ_{MAX} (MPa)**	**Min. suction ψ_{MIN} (MPa)**	**Difference $\Delta\psi$ (MPa)**	**Remarks**
1961-1990 (CMHS)	A	97.0	58.9	38.1	Difference July-November
	B	88.3	65.1	23.2	Difference summer-winter
1971-2000 (CMHS)	A	97.3	60.7	36.6	Difference July-November
	B	89.7	65.1	24.6	Difference summer-autumn
2019 (CMHS, WO)	A	103.9	44.1	59.8	Difference August-November
	B	99.8	65.7	34.1	Difference summer-autumn
April 2019 (WO)	C	153.5	15.4	138.1	ψ_{MIN} obtained on the day of the first rockfall 10.4.2019
November 2019 (WO)	C	101.1	15.4	85.7	ψ_{MIN} obtained on the day of the second rockfall 20.11.2019

A – analysis by months in a year, B – analysis by seasons in a year, C – analysis by days in a month

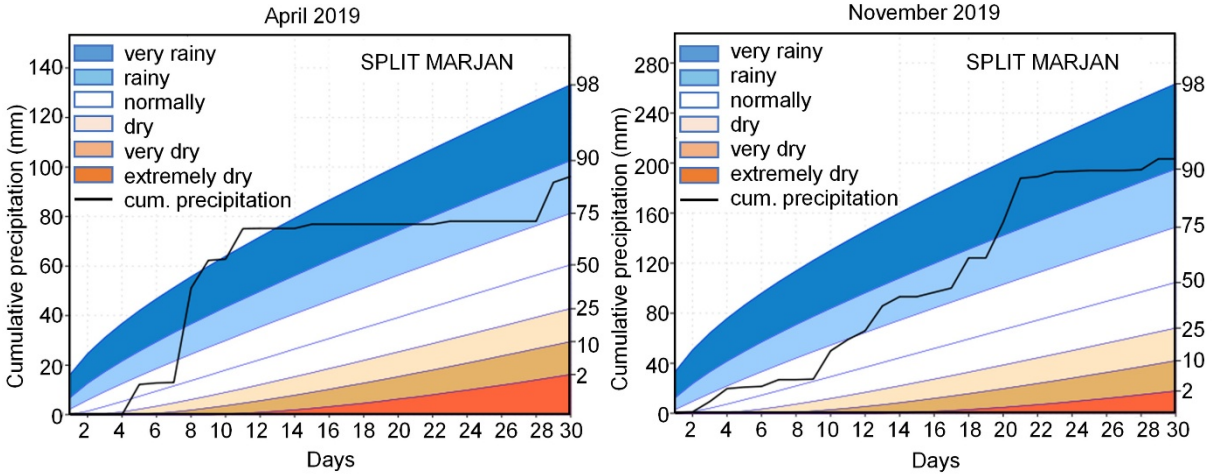


Fig. 2 Cumulative precipitation for April and November 2019 with theoretical percentile curves (2nd, 10th, 25th, 50th, 75th, 90th and 98th) for the period 1961 – 2000 (CMHS).

The extreme precipitation values immediately preceding 10 April 2019 and 20 November 2019 are shown in Fig. 2. Cumulative precipitation is above the 98th percentile (percentile curves for the period 1961-2000) for the 1st rockfall and above the 90th percentile for the 2nd rockfall. Moreover,

corresponding diagrams for the two months preceding these events indicate prolonged dry periods. Other results, obtained as monthly and daily changes, are graphically presented for climatic factors T (Fig. 3), RH (Fig. 4), and suction ψ (Fig. 5).

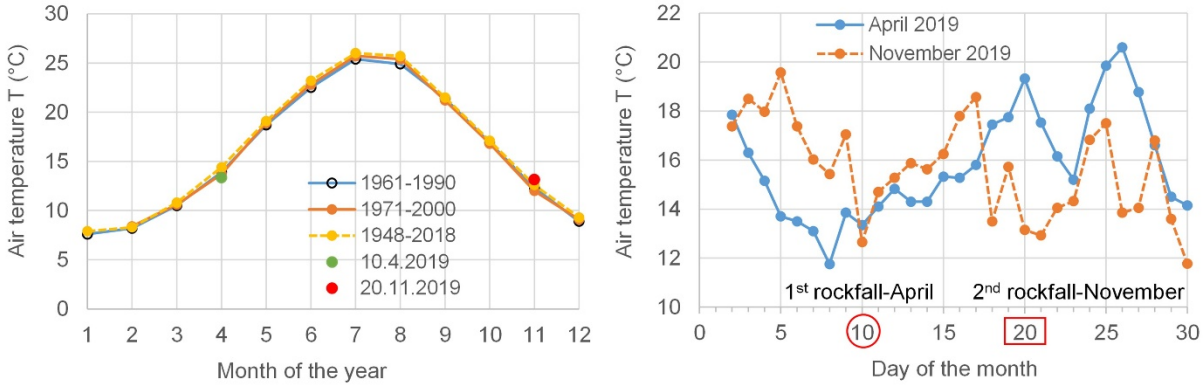


Fig. 3 Monthly and daily changes in air temperature for different data series and both rockfalls.

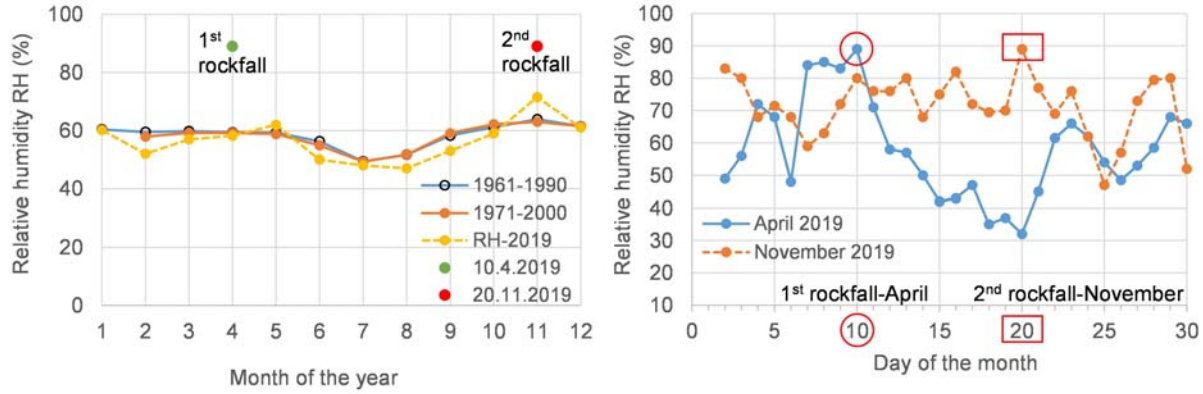


Fig. 4 Monthly and daily changes in relative humidity for different data series and both rockfalls.

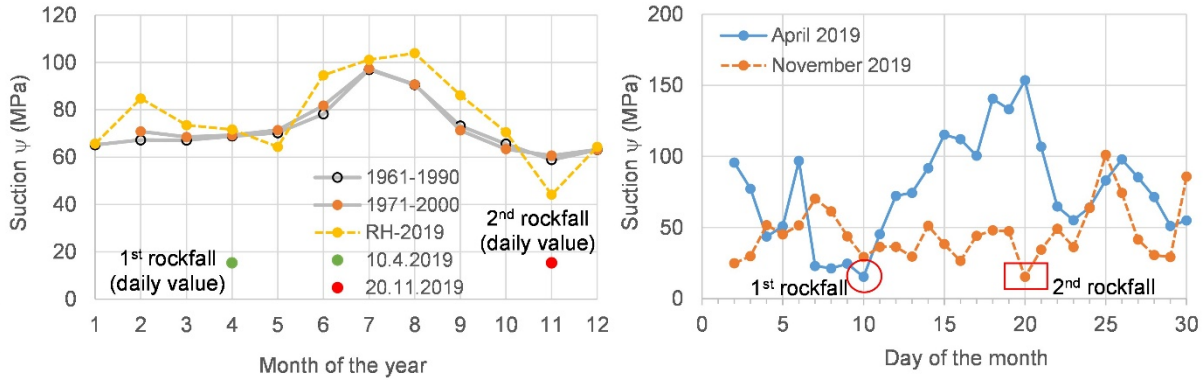


Fig. 5 Monthly and daily changes in suction in the surface layer of marly cliff materials for different data series and both rockfalls.

The results in Table 3 indicate that during the 2019 the suction changes are more pronounced compared to the reference values over longer periods (increase of about 60% for analysis by months in a year and 40-50% by seasons in a year).

Analysis of annual time series of average monthly temperatures (Fig. 3 left) shows no significant differences between datasets, and temperatures on the days of the rockfalls do not deviate significantly from these trends. However, when daily values for April and November 2019 are considered (Fig. 3 right), a decreasing trend in temperature is observed in the days before the rockfalls. On the days of the events, temperatures (13.4 and 13.2 °C, Table 2) were lower than the monthly average and close to the minimum values (12-13 °C). The combination of high precipitation and lower temperatures result in increased infiltration and reduced evaporation (water retention).

Relative humidity (RH) in 2019 exhibited more pronounced variability and seasonal changes (Fig. 4 left). In the months of rockfall occurrence (Fig. 4 right), RH reached its maximum (89%) on the day of each event. This is not only a monthly maximum but also a value significantly higher than the long-term average.

Consequently, suction reached its minimum precisely on the day of rockfall for both events and this value (about 15 MPa; Table 2 and Table 3) is significantly lower than long-term averages (Fig. 5). Variations and differences in max. and min. suction ($\Delta\psi$) are significantly more pronounced for rockfall months than on average (an increase from ≈20-60 MPa to ≈90-140 MPa).

4 Conclusions

The results obtained indicate that significant changes in suction can occur during the year or a specific month in the surface zone of marly cliff materials interacting with the environment. This causes significant suction gradients and differential suction (also towards the deeper layers), as well as the process of induced differential swelling. This process contributes to the progression of weathering through the development of tensile and shear stresses, slaking, decomposition of the binder, and loss of resistance. The tendency of such marls to swell upon wetting further enhances these effects.

For the cases analysed, the rockfall triggering mechanisms can be summarised as follows: a quasi-stable slope state; relative humidity reaching monthly and annual maximum (89%); decreasing temperatures (13 °C) below average; increased precipitation following prolonged dry period (cumulative precipitation above the 90th percentile); and consequently, surface suction at a minimum (15 MPa). Monitoring climatic factors and trends in relative humidity and temperature changes prior to the heavy rainfall, together with the associated suction changes, may contribute to the understanding of rockfall triggering mechanisms and the prediction of rockfall events.

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References

Cardoso R. (2009) Hydro-mechanical behaviour of compacted marls. Dissertation at Instituto Superior Technico, UniversidadeTecnica de Lisboa, Lisbon.

Cardoso R., Alonso E.E. (2009)Degradation of compacted marls:A microstructural investigation.Soils and Foundations 49(3): 315-327. https://doi.org/10.3208/sandf.49.315.

MedECC (2020) Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future. First Mediterranean Assessment Report. Union for the Mediterranean, Plan Bleu, UNEP/MAP, Marseille, France, 632pp. https://doi.org/10.5281/zenodo.7224821.

Miščević P., Štambuk Cvitanović N., Vlastelica G. (2020) Soft Rock Mechanics and Engineering, Chapter 12 Degradation Processes in Civil Engineering Slopes in Soft Rocks. Springer, Cham, Switzerland.

Raič A., Štambuk Cvitanović N., Vlastelica G. (2021) The effect of suction on differential weathering and stability of soft rock cliffs on the example of Zenta Bay cliff (Split, Croatia). EUROENGEO Athens 2020, Athens, 6-10 October 2021.

Slavík M., Lanzendörfer M. (2024) Evaporation from Porous Rock: Deciphering the Importance of Measuring the Evaporation Front Depth. Hydrology 2024 (11): paper 133. https://doi.org/10.3390/hydrology11090133.

University of Split, Faculty of Civil Engineering, Architecture and Geodesy (2019) Report on geotechnical ground investigation at the location of Zenta/Firule in Split (Report No. GEO 31/2019, March 2019, in Croatian).

Vlastelica G., Miščević P., Štambuk Cvitanović N. (2018a) Durability of soft rocks in Eocene flysch formation (Dalmatia, Croatia). Engineering Geology245 (2018): 207-217. https://doi.org/10.1016/j.enggeo.2018.08.015.

Vlastelica G., Miščević P., Štambuk Cvitanović N., Glibota A. (2018b)Geomechanical aspects of remediation of quarries in the flysch: case study of abandoned quarry in Majdan, Croatia. Geomechanics and Geodynamics of Rock Masses - Selected Papers from the 2018 European Rock Mechanics Symposium. 1st edn. CRC Press, London, 679–684. https://doi.org/10.1201/9780429449222.

Weather Online (2026) https://www.weatheronline.co.uk/Croatia/Split.htm. Accessed at March 28, 2026.