The effect of suction on differential weathering and stability of soft rock cliffs on the example of Zenta Bay cliff (Split, Croatia)

Ana Raič[1], Nataša Štambuk Cvitanović[1], Goran Vlastelica[1]
[1]Faculty of Civil Engineering, Architecture and Geodesy, University of Split, Croatia, ana.raic@gradst.hr, nstambuk@gradst.hr, goran.vlastelica@gradst.hr

The coastline of the Split area (Croatia) is characterized by soft rock cliffs, as the Split area lies on Eocene flysch formations. The shape of a rock coast is usually a result of local tectonic, geological and climatic conditions. Seasonal and daily temperature changes, precipitation, relative humidity, frequency of high wave storms and many other climatic variables influence the development of coastal processes. Although marine erosion (i.e. the influence of waves and tides) is the most common recession factor, the recession of soft rock cliffs is dominated by the weathering. Flysch formations in the greater Split area are characterized by a layered structure in which the lithological components of the layers alternate between hard clays/soft rocks and hard rocks. The stratification results in differential weathering between the layers, which causes undercutting of hard rocks and ultimately leads to slope instabilities and rockfalls. The dominant soft rock lithotype in the Split region is marl, which varies from clayey marls to calcareous marls. These materials are extremely susceptible to a change in properties due to weathering processes (physical and chemical) that transform the material with soft rock properties into a fine-grained material (Miščević & Roje-Bonacci, 2001). Physical weathering in this area is usually caused by the process of wetting, and drying and it can be assumed that this process is highly related to the unsaturated state of the material, i.e. the development of suction in the pores. The weathering process of Dalmatian marls and its influence on slope stability has been extensively studied (Miščević & Roje-Bonacci, 2001; Miščević & Vlastelica, 2014; Vlastelica et al., 2018a; Vlastelica et al., 2019, etc.).

The problem of differential weathering and cliff instability is observed on the example of Zenta Bay cliff in Split, located on the southern coast of the Split peninsula. The observed cliff is a 14-meter-high steep slope with a landscaped promenade at the cliff toe. The geological structure of the cliff consists of highly weathered clayey marl layers intertwined with calcareous sandstone layers. In March 2019, a geotechnical survey was carried out to evaluate the slope stability. Global stability control of the slope is performed assuming a solid sliding body according to one of the available limit boundary methods using computer program Slide (Rocscience) and in accordance with Eurocode 7, design approach 3 (methodology presented in Vlastelica et al., 2018b). As the slope surface is highly weathered, the surface material is prone to shallow landslides. Consequently, the slope is quasi stable and does not comply to EC7 requirements (i.e. for one profile safety factor of 0.91). If EC7 is dismissed, a safety factor of 1.14 is obtained for the same profile. However, in the case of an extreme situation such as heavy rainfall or earthquake, it can be lower than 1 and thus lead to landslide. In April 2019, heavy rainfall, preceded by dry March and February, caused a large rockfall. Improper cliff reconstruction and stabilisation led to a second rockfall in November 2019, caused by similar weather conditions. Based on the above-mentioned events, where heavy rainfall after long dry periods caused slope movements, suction differential was analysed as an instability trigger and weathering agent for soft rock cliffs and slopes.

Namely, significant changes in suction can occur during the year (monthly and seasonal) or a specific month in the surface zone of marly cliff materials interacting with the environment/atmosphere. This causes significant suction gradients and differential suction (also towards the deeper layers), as well as the process of induced differential swelling and consequently further development of the weathering (through development of the tensile and shear stresses, slaking, decomposition of the binder and loss of resistance). Suction changes were calculated according to the Kelvin's equation (1) for total suction and analysed using the climate data from the meteorological station Marjan-Split. $s = -\frac{RT}{v_{w0}\omega_v}\ln(RH)$ (1)

where: s – total suction (kPa), R – universal gas constant (J mol^{-1} K^{-1}), T – absolute temperature (K), M_w – molecular mass of water (kg/kmol), ρ_w – density of pure water (kg/m^3), RH – relative humidity.

The analysis conducted shows that changes in suction for different annual and monthly periods are significant considering the retention curves for marl. Furthermore, the specific climatic conditions during the year of rockfalls affected the suction changes in such a way that the differences are more pronounced compared to the reference average suction values over longer time periods. The RH on the days of the rockfalls reaches monthly and annual maximum (89%), temperatures are in a decreasing trend and close to the lowest value (about 13°C), precipitation increases significantly after the previous dry period (cumulative precipitation above the 98th and 90th percentile for the period 1961-2000, for the 1st and 2nd rockfall, respectively) and consequently suction is at a minimum (15 MPa). The maximum and minimum values of suction and their differences are given in Table 1.

In summary, monitoring of weather conditions and trends with emphasis on relative humidity and temperature changes prior to the rainfall occurrence and the associated suction changes may contribute to the understanding of rockfall triggering mechanisms and the prediction of rockfall events.

Table 1. Suction differences in the surface zone of marly cliff materials

Period / data source	Type of analysis	Maximum suction s_{MAX} (MPa)	Minimum suction s_{MIN} (MPa)	Difference $\Delta s = s_{MAX} - s_{MIN}$ (MPa)	Remarks
1961-1990 (CMHC)	1	97.0	58.9	38.1	difference July-November
	2	88.3	65.1	23.2	difference summer-winter
1971-2000 (CMHC)	1	97.3	60.7	36.6	difference July-November
	2	89.7	65.1	24.6	difference summer-autumn
2019 (CHMC, WeatherOnline)	1	103.9	44.1	59.8	difference August-November
	2	99.8	65.7	34.1	difference summer-autumn
April 2019 (WeatherOnline)	3	153.5	15.38	138.1	s_{MIN} obtained on the day of the 1st rockfall 10.4.2019
November 2019 (WeatherOnline)	3	101.1	15.37	85.7	s_{MIN} obtained on the day of the 2nd rockfall 20.11.2019 (almost the same conditions)

CHMC – Croatian Meteorological and Hydrological Service/ WeatherOnline – https://www.weatheronline.co.uk/weather/maps/city/

1 – analysis by months in a year, 2 – analysis by seasons in a year, 3 – analysis by days in a month

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