Conférence Méditerranéenne Côtière et Maritime
EDITION 4, SPLIT, CROATIA (2017)
Coastal and Maritime Mediterranean Conference
Disponible en ligne – http://www.paralia.fr – Available online

Erosional processes acting on coastal cliffs in the Split urban zone, Croatia

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Abstract:
The terrestrial laser scanner was used for the first-time assessment of erosional rates of the Duilovo flysch cliff situated along the predominantly carbonate Croatian coast, and to characterize processes involved. Cliff retreat rates ranged between 3 and 18 cm/y and stronger erosion occurs during the cold season due to the slaking process. Cliff erosion detected is a combination of flysch weathering, gravitational instability of degraded material and wave erosion. Understanding of cliff erosion processes in the urban zone is needed for the management purposes in the future.
Keywords: Flysch, Cliff, Erosion rate, Adriatic Sea

1. Introduction

Rocky coasts were neglected for a long time in terms of coastal morphodynamics compared to low lying coastal landforms. This is attributed to the general lack of continuous changes in coastal morphology operating on the rock coasts (KENNEDY *et al.*, 2014). The emergence of new technologies such as laser surveying allowed quantifying erosional processes along the retreating rocky coasts to centimetre scale (LIM *et al.*, 2005). The obtained information is required to predict the position of the shoreline in the future in order to develop appropriate management decision.

Soft rocky coasts tend to develop complex cliff environments more susceptible to erosion. Coastal cliff erosion is largely episodic, preceded by numerous physical, chemical and biological changes of rocks. These changes are site-specific and a result of an interplay of particular rock lithology exposed to subaerial and marine processes, frequently aided by the anthropogenic impact. Thereby, weathering pattern, closely related to climatic characteristics of the coastal region, may have an important role. In particular, repeated wetting and drying of clay-rich rocks, such as those found in the

https://dx.doi.org/10.5150/cmcm.2017.015

wider Split area (MIŠČEVIĆ & VLASTELICA, 2014) may trigger various processes leading in the end to erosion.

The study site is a vegetation-free part of the ~30 m high coastal cliff formed in Eocene flysch assemblage (interbedded marl, siltstone, sandstone), located on the southern side of the Duilovo plateau in the Split urban area (figure 1). Flysch is a less prevalent rock assemblage along the carbonate-dominated Croatian shoreline and cliffs are a rare landform (PIKELJ & JURAČIĆ, 2013). Top of the studied cliff is an inhabited area, containing tourist and agricultural infrastructure, and threatened by ongoing erosion. In order to make an adequate erosion risk assessment in the future, this study aims, for the first time, to quantify flysch cliff erosion rate on the Croatian coast and to detect main erosional processes involved. To quantify cliff erosion, terrestrial laser scanner (TLS) was used.

Figure 1. Position of the TLS (left) and the conus like material (right, in red circle).

2. Materials and methods

Cliff-face morphology was scanned 8 times over 5 years (2012-2017) using the Optech ILRIS-3D laser scanner. The instrument was deployed each time on the 200 m distant concrete platform (figure 1) (detailed methodology is given in VLASTELICA *et al.*, 2016b. Trimble RealWorks software was used for point cloud construction and postprocessing. The first point cloud was georeferenced using orientation points determined by Trimble R8 GNSS receiver using CROPOS VPPS virtual reference station real-time kinematic (VRS RTK) positioning service. Horizontal and vertical accuracies were within 2 cm and 4 cm, respectively. The second scanning was done after 2 years, while other repeated surveys were conducted in 6 months interval. Subsequent point clouds obtained were georeferenced based on the first one using stable common surfaces (houses, platters, walls) visible on all point clouds. All point clouds were overlapped and four representative cliff profiles (P1-P4) on the vegetation-free cliff-face area of 1400 m^2 were chosen (figure 2) and compared to estimate erosional rates.

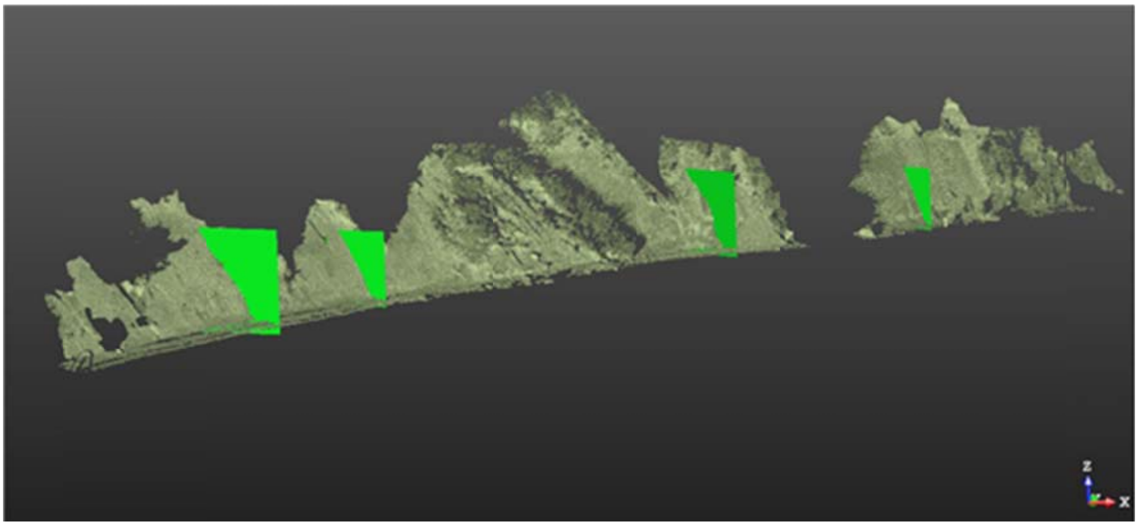

Figure 2. Position representative profiles (P1 to P4, starting from left to the right) on the vegetation-free cliff-face.

3. Results and discussion

Upper parts of all profiles showed both, erosion and accumulation of sediment material on the cliff face, without obvious rule or trend in an alternation of these processes within the survey period. Piling-up of the material on the 50-60º steep cliff face was attributed to the gravitation-driven accumulation of the previously weathered flysch coming from the uppermost parts of the cliff. The same process was assumed to be mostly responsible for the displacement of this particular material downward. Accumulation of the loose sediment is probably due to the occurrence of the more resistant sandstone protruding from the cliff strata. Due to repeated accumulation-erosion cycles, an estimation of cliff retreat rates in these heights was unreliable due to the non-ascertained position of the boundary between loose disintegrated sediment and “firm” cliff material. Continued accumulation prevailed during the five-year period in places where inclination decreases (30-40º), such as found on P3 and P4.

A middle part of the cliff is the steepest one along with all profiles (80-90º) with continued erosion registered. Calculated erosional rates ranged mostly between 3 and 16 cm/y, while extreme erosional rates (28 and 34 cm/y) were observed during the autumn/winter period 2014/2015 on nearly vertical sites along the P4 and P3, respectively.

Cliff base is a sub-vertical (70-80º) slope, with a sharply angular transition to the beach (figure 1), where continued cliff retreat of rates between 7 and 18 cm/y was observed along all profiles and eroded material accumulates on the cliff toe (figure 3). Fine-grained part of this sediment is regularly removed by waves and transported offshore. Eventually, the sandstone rock fall occurs due to the bending of the exposed overhang (MIŠČEVIĆ & VLASTELICA, 2014), providing coarse-grained beach sediment, as shown by PIKELJ *et al.*, (2014). All profiles revealed that accumulation was predominant on the cliff toe during the spring/summer season, while erosion prevailed during the cold period, which might be related to enhanced marine abrasion.

Figure 3. Accumulation of the eroded material in form of the cone pile.

In case of long-term and/or massive erosion, talus cone may form on the cliff toe (figure 3). Cone piles were recorded on the P2, where its emergence and disappearance occurred twice during the observed period. Such forms might be eroded between two surveys (as in case of surveys 7 and 8) or persist for a year (surveys 3 and 4).
TLS surveys over a 1400 m^2 of cliff-face documented a total of 298 m^3 of eroded material (table 1). During the first two years, a total of 104 m^3 of material was removed from the cliff, while the each of next three years showed 99 m^3, 69 m^3 and 26 m^3 of erosion, respectively. Despite the highly variable annual erosion, the seasonal trend is visible: double amount (or more) of weathered material was removed during the cold season (table 1). This might be related to higher moisture saturation during the winter season along the Adriatic and the tendency of flysch to decompose under repeatedly dried and wetted condition (slaking), (VLASTELICA *et al*., 2016a).

Table 1. Volumetric changes of the surveyed Duilovo cliff face.

Survey no.	*Survey date*	*Volume eroded (m3)*
1	March 7, 2014	/
2	April, 1, 2014	104
3	October, 3, 2014	24
4	March 31, 2015	75
5	September, 29, 2015	19
6	April, 1, 2016	50
7	September, 30, 2016	9
8	March, 24, 2017	17

4. Conclusions

Results of ground-based laser surveys over a five-year period were used to characterize and quantify the flysch retreat at the Duilovo study site in the Split urban zone for the first time. Obtained erosional rates of the "firm" cliff material on the sub-vertical to vertical slopes ranged between 3 and 18 cm/y, which are comparable to the average of up to 10 cm/y given by VLASTELICA *et al*. (2016b). Stronger erosion occurs during the cold season, probably due to the slaking, while the annual variability of erosion needs to be further investigated and related to meteorological and oceanographical conditions. Erosional processes operating on the Duilovo flysch cliff include flysch weathering, gravitational response of this loosen material and wave erosion. Understanding of processes involved and known cliff retreat rates are necessary for further land use planning, mitigation measures, appropriate management strategies in this highly inhabited urban coastal area.

Acknowledgments

This study was supported mostly by Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides, sponsored by Japan Science and Technology Agency - JST, Japan International Cooperation Agency - JICA and Ministry of Science, Education and Sport of Republic of Croatia.

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