CLIFF FAILURE PROCESSES AND LONGSHORE DISPERSAL OF SEDIMENTS, VRGADA ISLAND (CROATIA): INPUT FROM SFM PHOTOGRAMMETRY AND SEDIMENT CHARACTERISTICS

Kristina Pikelj, Nina Furčić, Frane Marković

Abstract: The coastal cliff on the Vrgada island is developed in Pleistocene aeolian-alluvial deposits which are subject to constant erosion. Digital Structure-from-Motion photogrammetry has been used to record and monitor the erosion of the cliff most of which occurs in the form of rockfalls. As a result, an L-shaped beach has formed. The eroded material is reworked and partially washed away by rain and waves. The prevailing waves are generated by the Scirocco wind (SE, and they transport the eroded material from the eastern to the north-western part of the beach. This transport direction is confirmed by heavy mineral analysis, including grain size, and by the carbonate content of the beach sediments. It is expected that the local input of terrigenous sediment may affect seagrass meadows and waterways. Continued erosion of the Vrgada cliff could jeopardize anthropogenic infrastructure and alter the island's coastline in the future.

Keywords: Adriatic, coastal cliff, beach, erosion, long-shore drift, SFM photogrammetry

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Introduction

The Eastern Adriatic coast in Croatia is a high, steep and rocky coast developed mostly in carbonates deposited in Mesozoic [13]. This lithology combined with active uplift led to the development of karstic relief and visible tectonic structures along the coast. Under aforementioned conditions, typical coastal forms such as cliffs, wave-cut platforms and beaches are the exception, while steep and mostly inaccessible rocky coasts predominate, including tectonic cliffs and submerged karstic relief forms [13, 15]. However, during synsedimentary tectonics in the Mesozoic and Cenozoic, deeper basins were formed in which turbidites were deposited [16]. Today, these deposits, together with younger deposits, mostly loess, formed in Pleistocene, form the main bedrock of about 6 % of the Croatian coast [3, 10]. In these stretches of soft-rock coastal segments there are more cliffs and beaches which are currently subject to rapid erosion in some places [1, 12, 17].

One of these places along the Croatian coast is a small section of the Vrgada island. Although it is shown in older geological maps as a pure carbonate island, its north-eastern part contains strongly erodible clastic deposits (Figure 1). They outcrop today in the form of a ~15 m high coastal cliff and consist of aeolian-alluvial sedimentary sequence from the Pleistocene [1]. The cliff is subject to constant erosion, especially along its eastern steeper side. As a result of erosion, an L-shaped mixed gravelly-sandy beach has formed at the foot of the cliff [13]. The aim of this work was to investigate the coastal processes occurring along the cliff and beach in order to explain the main mechanisms of coastal evolution. The first part of the work refers to the cliff erosion and the beach formation, while the second shows the fate of the beach sediment in terms of longshore transport and sediment loss in the sea.

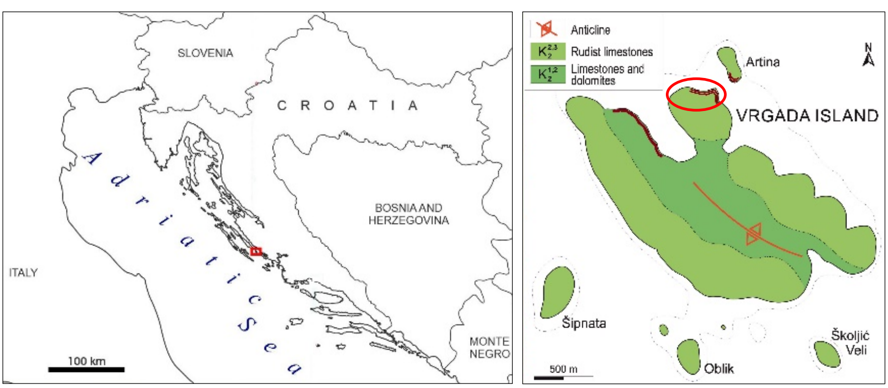

Figure 1 – Location map of the Vrgada Island (left) and carbonate lithology usually shown in old maps [9]. Pleistocene aeolian-alluvial deposits on the island are designated by the brown lines. Study area is shown in red oval.

Material and methods

During the cliff erosion monitoring between October 2022 and November 2023, three consecutive digital models were selected (October 2022; April 2023 and June 2023) to represent the typical processes on the cliff slope. The digital models were constructed using Structure-from-Motion digital photogrammetry in Agisoft Metashape software from 200-300 photos taken by a drone. The overlap of the photos was 80 % and the digital models were georeferenced with movable ground control points (GCPs). Their precise position was determined by virtual real-time kinematics of the reference station using a Trimble R8 GNSS receiver. The correction was carried out using the high-precise positioning service CROPOS (DGU; http://www.cropos.hr/). The horizontal and vertical accuracy of GCPS was 2 and 4 cm respectively. The accuracy of the digital models was within 3 cm.

First 3 cm of beach sediment was carefully collected at 9 locations (Figure 2) on a 40x40 cm square. The sediment was collected for grain size, heavy mineral fraction, and carbonate content analyses. Considering the second analysis, samples were collected as close as possible to the dominant grain size in each square to ensure representativeness, as suggested by [7]. For grain size analysis, sediment samples were air-dried and 100 g of each subsampled sediment was wet sieved using 7 standard sieves with mesh sizes ranging between 4 mm and 63 μm at 1 phi interval. Granulometric parameters were calculated according to [6] using the Gradistat Excell package [2] and the sediments were classified according to [5].

The carbonate content in each powdered bulk sample was calculated from the volumetric measurement of CO_2 released after treatment of each sample with 1:1 diluted HCl acid, using the Scheibler apparatus.

For heavy mineral analysis, additional subsamples were separated from the bulk samples and sieved through 63 μm and 125 μm mesh sieves to obtain a very fine sand fraction. Carbonate particles were dissolved with a mild acid (5 % acetic acid - CH_3COOH) and the samples were treated with 15 % hydrogen peroxide (H_2O_2) to remove organic matter. The 63÷125 μm fraction was separated with sodium polytungstate (SPT), density 2.90 g/cm^3, and centrifuged at 2500 rpm for 5 min. The grain mounts were prepared with Canada balsam (n = 1.54). The heavy minerals were counted using the ribbon counting method. At least 300 grains of transparent heavy minerals were counted per sample.

In addition, the results of grain size and carbonate content analysis published by [13] were also included in this study and discussed in order to obtain the overall picture of the fate of the eroded cliff sediments. As described in [13], the marine sediment was analysed for grain size and carbonate content in the same way as described above. The only exception made for the marine sediments was the microscopic identification of the origin of the sediment grains (skeletal grains vs. grains originating from the cliff material).

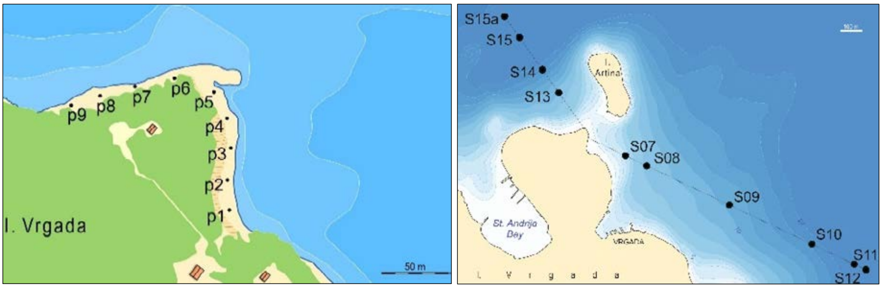

Figure 2 – Location map of beach sediment sampling (left) and marine sediment sampling (right; slightly modified after [13].

Results

Figure 3 summarises the main erosion events that occurred during the monitoring period, namely two massive rockfalls. They occurred at the site where a deep crack had previously formed at the edge of the cliff. The first massive rockfall occurred between October 2022 and April 2023, when only a small part of the detached cliff block collapsed. The second, larger rockfall occurred at the end of the May 2023 or the very beginning of June 2023 (Figure 3) when most of the detached rock mass fell. It is assumed that rockfalls were triggered by higher humidity during winter and intensive rains in May. After both rockfalls, the rock mass partially crushed and the finer sediment material were washed away by both rain and incoming waves.

All beach sediment samples analysed were characterized as sands: On the eastern side of the beach, slightly gravelly sands predominated, while the rest were pure sands. On the north-western side of the beach, half of the samples were slightly gravelly sands and the other half were sands (Table 1). The mean and median grain size showed three cycles of grain coarsening starting from sample P1 to sample P9, both varying between 186÷292 μm and between 185÷312 μm, respectively. The carbonate content varied between 18 and 25 %, with a slight increase from eastern to the north-western part of the beach.

The percentage of heavy minerals in the analysed samples ranged from 6.03 to 51.86 % on the eastern side of the beach, with an average of 24.35 %. The north-western side of the beach contained a much lower percentage of heavy minerals: between 2.43 and 11.03 %, with an average of 6.17 % (Table 1.). A total of twelve species of transparent heavy minerals were identified: garnets zircon, rutile, titanite, tourmaline, chromite, epidote, clinozoisite, pyroxenes - mainly augite, amphibole, chlorite and kyanite. The proportions of all three groups of heavy minerals (opaque, phyllosilicates and transparent) change from east toward west.

The proportions of opaque minerals, phyllosilicates and transparent heavy minerals vary from P1 to P9. Opaque minerals predominate in all samples, but their proportion decreases slightly towards the west. A similar pattern was observed in the phyllosilicates, while the transparent heavy minerals showed an opposite trend and their proportion increased from P1 to P9. Heavy minerals whose density exceeds 4.5 g/cm^3 (rutile, zircon and chromite) showed decreasing trend from P1 to P9, while the remaining minerals with a density between 2.95 and 3.9 g/cm^3 show an opposite trend.

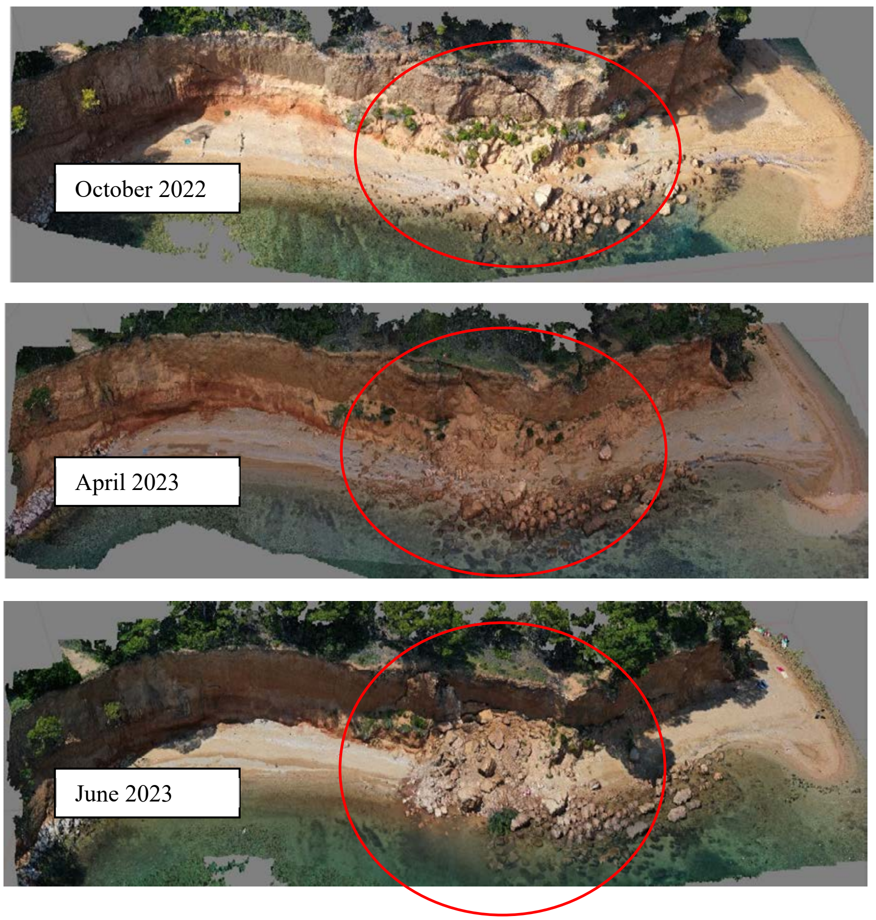

Figure 3 – Digital models of the Vrgada cliff with rockfalls that occurred between October 2022 (upper), April 2023 (middle) and June 2023 (lower).

According to previously published data by [13], the marine surface sediments sampled off the eastern part of the beach (profile S07-S12; Figure 2) are a coarse-grained and highly carbonaceous material, with part of the carbonate fraction and coarse grain sizes originating from the cliff material. In contrast, material deposited off the north-western part of the beach (profile S13-S15a, Figure 2) was finer, contained less carbonates and more quartz.

Table 1 – General characteristics of the beach sediments P1-P9. Legend: S – sand; sgS – slightly gravelly sand; Mz – mean size; Md – median; Carb. – carbonates; HM – heavy minerals; OP – opaque; Phy – phyllosilicates; Tra – transparent.

Sample:	Sediment type	Mz (μm)	Md (μm)	Carb. (%):	HM (%)	OP (%)	Phy (%)	Tra (%)
P1	S	186.6	185.1	18.4	51.86	52	13	35
P2	sgS	235.1	226.2	22.8	6.03	50	7	43
P3	sgS	254.5	251.2	21.5	22.49	57	5	38
P4	sgS	186.6	185.1	20.5	22.57	55	2	43
P5	S	217.1	205.9	24.9	18.78	63	2	40
P6	sgS	248.4	230.1	20.7	8.58	49	2	49
P7	S	206.7	194.6	25.2	2.62	52	3	45
P8	sgS	255.8	232.0	24.2	11.03	51	3	46
P9	S	292.1	312.2	21.4	2.43	49	4	47

Discussion

The Vrgada cliff is one of the rare examples of soft rock cliffs on the Croatian coast. It was developed in Pleistocene aeolian-alluvial deposits, i.e. partially reworked loess [1]. The cliff is L-shaped with a sandy beach at the immediate front (Figure 4). The north-western side of the cliff is less steep and covered with pine forest and is influenced by the mild NW wind waves that occur mainly in summer. The eastern side of the cliff is vertical and bare and exposed to two dominant wind waves: SE wind waves generated by the Scirocco and NE Bora wind waves. As the Scirocco has a larger fetch, its waves are thought to have a dominant influence on the eastern section of the beach. However, according to the locals, the NE Bora wind itself can create a hammer effect directly on the cliff face due to its gales. Digital elevation models from October 2022 (Figure 3) showed debris on the beach immediately in front of the steep part of the cliff, indicating past rockfalls. Many of the fallen blocks are of metric dimension. Another rockfall occurred between October 2022 and April 2023 (Figure 3) when a semi-detached block collapsed. The predisposition of the rockfall was a deep crack (Figure 5). The crack was discovered during the initial fieldwork in 2016 and has slowly widened since then. Most of the semi-detached rock mass was only held to the cliff by strong root branches of Aleppo pine (Figure 5). Considering that the Mediterranean winters are characterized by more precipitation compared to the warm seasons, it is likely that more frequent rain could trigger this rockfall. This assumption was confirmed in the case of the second rockfall that occurred between April and June 2023 (Figure 3). According to the Croatian Meteorological and Hydrological Service, precipitation for May 2023 increased just before the monitoring in early June. During the second rockfall, a large part of the semi-detached rock mass collapsed and was subsequently washed away by rain and waves. The distribution of coarse-grained material on the beach and prevailing wind waves indicate that the long-shore transport starts at the eastern part of the beach and ends at the north-western part. To test this hypothesis, beach and marine sediments were further studied.

Figure 4 – Aerial photograph of L shaped beach in front of the Vrgada cliff.

Figure 5 – Semi-detached part of the cliff with visible crack and root branches of Aleppo pine.

During the fieldwork, obvious differences in the coarseness of the beach sediment became apparent: the eastern part contained much more gravelly material derived from cliff-collapsed material (e.g. blocks, rhizocretions, carbonate crusts, etc. [1]; Figure 4). However, the beach sediment samples analysed in this work were classified as sands and slightly gravelly sands in both beach sections, showing a coarsening rather than a refinement of the sediment toward the west. Nevertheless, such results can be explained by the sampling strategy, which was designed to perform an accurate heavy mineral analysis: Coarse-grained carbonate gravels, pebbles and blocks were avoided during sampling. The second part of the explanation comes from [8]: Coarse-grained sediments tend to contain light minerals such as quartz. Due to their low density, they are much easier to resuspend, while their large surface area is exposed to the resuspending force. Such behaviour could lead to a more effective transport of somewhat coarser material, as found at the two Vrgada beaches. However, the grain size analysis should be repeated in the future to include coarse-grained beach material.

Although that grain size analysis itself did not provide expected results, these were obtained by the heavy mineral analysis. As shown in Table 1, the highest proportion of heavy minerals was found in sample P1. In general, four times the average amount of all heavy minerals was found in the eastern part of the beach (24.35 %), compared to 6.17 % in the north-western part of the beach. This is probably the result of the continuous erosion of the cliff material. Opaque heavy minerals generally had the highest proportion, followed by transparent heavy minerals and less abundant phyllosilicates (Table 1). The highest abundance of opaque minerals is probably due to their abundance in rock cliff material [1]. Their decreasing trend from the eastern to the north-western part of the beach reflects the possibility that they include minerals whose density, exceeds 4.5 g/cm^3 (e.g. rutile, zircon and chromite). Due to their high density, they have remained in the eastern part of the beach. The remaining heavy minerals with a density between 2.95 and 3.9 g/cm^3 show an opposite trend of increasing amounts from the eastern to the north-western beach. The proportions of transparent heavy minerals increase in a north-westerly direction, as their density is lower than that of the opaque minerals. Finally, the phyllosilicates show a decreasing trend in a north-westerly direction. This distribution could be due to the fact that the eastern part of the cliff erodes faster than the gently sloping north-western part, where the vegetation covers further reduces the erosion rate. Furthermore, once resuspended, phyllosilicates are transported over longer distances [14], and in this case perhaps even further out to the sea. In general, the transport of all heavy minerals is directly related to their density and size, and it can be concluded that they exhibit a general long-shore drift from the eastern to the north-western part of the beach.

As for the marine sediments, the sediments collected off the eastern part of the beach contain more carbonates and are generally coarse-grained (gravelly sands and gravelly muddy sands according to [13]. In particular, the sediment sampled near the beach reflects some of the main characteristics of beach sediment and contains rhizocretion, carbonate crusts and other grains eroded from the cliff in coarse fractions. Sediment samples collected in deeper areas are a typical eastern Adriatic sediment with a high proportion of biogenous carbonate material. On the other hand, marine sediments sampled in front of the north-western part of the beach are generally fine-grained (gravelly muddy sand and gravelly muds according to [13], and contain more non-carbonate grains, of which quartz dominates. Such finding is consistent with the mechanisms of transport of light and heavy minerals described above. This generally fine-grained sediment can easily be withdrawn into the deeper sea and deposited on the seafloor.

It is generally well known that the seagrass *Posidonia oceanica* does not tolerate significant input of terrigenous sediment [4]. The fact that *Posidonia oceanica* meadow is found at shallower depths off the eastern part of the beach indicates that no significant amount of terrigenous material enters the sea at the sites where continuous cliff erosion occurs. Instead, eroded cliff material is transported by the long-shore drift from the eastern to the northwestern side and ends up in the sea, in places where *Posidonia oceanica* was sparse.

Finally, the ongoing erosion of the Vrgada cliff may jeopardise anthropogenic infrastructure and change the land use on the cliff top in the future. On the other hand, the eroded material may affect the waterways and related nautical activities.

Conclusions

The soft-rock coastal cliff on the Vrgada island is susceptible to constant erosion. Successive digital models have shown that the predominant slope processes on the cliff are rockfalls. The eroded material is reworked and partially washed away by rain and waves. As a result, an L-shaped beach has formed. The prevailing waves are generated by the Scirocco (SE) wind, which causes a long-shore transport of eroded material from the eastern to the north-western part of the beach. The results of the heavy mineral analysis, partially grain size analysis and carbonate content in the beach sediment confirmed the longshore transport, while the characteristics of the marine sediments deposited in front of the both beach sections further confirmed the long-shore transport. It is expected that the local input of terrigenous sediment may affect the distribution of seagrass meadows distribution, as well as the waterways. The erosion of the Vrgada cliff poses a threat to anthropogenic infrastructure in the future and could alter the island's coastline.

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