# Measuring the effectiveness of Nature-Based Solutions (NBS) in relation to the objectives of the Climate Action Plan for Destination Tourism of Dugi Otok Island

Final Report

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This report was prepared based on the Service Agreement "Measuring the effectiveness of Nature-Based Solutions (NBS) in relation to the objectives of the Climate Action Plan for Destination Tourism of Dugi Otok Island", (CLASS: 641-01/25-02/34; REGISTRATION NUMBER: 251-58-10208-25-4) concluded on 14 October 2025 and the contract addendum (CLASS: 406-01/25-03/73; REGISTRATION NUMBER: 2198-1-88-26-6) concluded on 28 April 2026 between the Service Client, the Public Institution for the Management of Protected Areas of Nature in the Zadar County "Natura Jadera" and the Service Provider, the Faculty of Science, University of Zagreb.

Measuring the effectiveness of Nature-Based Solutions (NBS) in relation to the objectives of the Climate Action Plan for Destination Tourism of Dugi Otok Island is carried out as part of the Interreg Euro-MED project *NaTour4CChange*, which aims to build on successful experiences at the Mediterranean and global level in order to test solutions for increasing the resilience of coastal destinations in the Mediterranean.

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# 1. Introduction

According to the IUCN definition, Nature-based Solutions (NBS) include activities that aim to protect, sustainably manage and restore natural or anthropogenically modified ecosystems to effectively and adaptively address societal challenges such as climate change, water security and availability, and disaster risk (URL1). Nature-based Solutions simultaneously support human well-being and biodiversity, while providing affordable alternatives to conventional engineering solutions.

The Mediterranean Sea region is a climate hotspot warming about 20% faster than the global average (UNEP/MAP and Plan Bleu, 2020). As a result, the Mediterranean has experienced record sea surface temperatures in recent years. Increasingly frequent and intense marine heat waves are severely degrading the Mediterranean marine ecosystem. This warming is causing rapid changes in Mediterranean biodiversity, reflected in a significant increase in invasive species (over 1,000). By the end of this century, air temperature is expected to rise by 2 – 5°C (UNEP/MAP and Plan Bleu, 2020), and precipitation is projected to decrease to 65% of current levels, especially in the southernmost areas.

As a the microtidal area, the Mediterranean and its low-lying regions are particularly vulnerable to the effects of increasingly frequent storm surges and sea-level rise, which is expected to reach or even exceed 1 m by the end of the century (WWF MMI, 2021). Consequently, Mediterranean coasts are threatened by coastal erosion. To mitigate this process, many engineering solutions have been implemented along the Mediterranean coasts. At the same time, the Mediterranean is the world's leading region for tourism, and currently attracting more than 300 million visitors per year, a figure expected to double by 2050 (Piante and Ody, 2015). As a result of this strong, mostly seasonal pressure, the marine ecosystem is experiencing significant pollution, and contamination, and overall degradation. One of the endemic, endangered, and currently protected species of the Mediterranean Sea is the seagrass *Posidonia oceanica* (L.) Delile, 1813., known for its high ecological value underwater. In recent years, both its living meadows and beached debris (also called banquettes) have been recognized as playing a key role in coastal protection, particularly for beach systems. From a geomorphological perspective, banquettes act as traps for beach sediment and form the first line of defence during heavy storm events. In this context, Posidonia banquettes are now considered one of the key coastal assets within the concept of Nature-Based Solutions (NBS) for strengthening the capacity of coasts to resist climate change.

Posidonia banquette management involves environmental and municipal handling of Posidonia necromass debris, which is naturally deposited on the coast. Most major Mediterranean tourist destinations, including France, Italy, Greece, Spain, Croatia, Tunisia, and Cyprus, have removed or continue to remove Posidonia banquettes in response to coastal tourists, who regard the banquettes as waste (Oudin and Boudouresque, 2023). This practice has a range of environmental consequences, among which beach erosion is a key focus of this monitoring. In recent years, there has been increased promotion of more sustainable banquette management along Mediterranean coasts. Such management includes NBS, which aim to leave the banquettes in place or minimise mechanical disturbance and removal (IUCN). In particular, balancing the environmental importance of banquettes and tourism demands on a seasonal basis is the case at Sakarun beach on Dugi otok Island, is a challenging aspect of NBS policy.

To measure the effectiveness of Nature-Based Solutions (NBS) in relation to the objectives of the climate action plan for destination tourism on Dugi otok Island, two pilot project study sites were selected for monitoring over a six-months period: Sakarun Beach and the Natural Bridge Beach, both locations of Posidonia banquette formation.

# 2. Pilot study sites

## 2.1. Dugi otok Island

Dugi otok Island is part of the Zadar archipelago, where it is the largest and longest island, and has one of the most indented coastlines on the eastern Adriatic, with an indentation index of 4.5. According to geomorphological classification, it is also located in the North-western Dalmatia macro-region (Bognar, 2001). On Dugi otok Island, the karst type of relief prevails, due to the lithological composition of the island, which is predominantly characterised by limestones and dolomites. Various endogenous and exogenous karst forms found on the island were formed by karst and fluviokarst processes. The present-day relief forms on the island are the result of post-Pleistocene transgressions of the sea, caused by a glacio-eustatic sea-level rise of over 100 m (Džaja, 2003). Its Dinaric strike is characteristic of most islands in the Zadar archipelago. This type of coast (Dalmatian type) is rare and particularly distinctive in the Zadar coastal area (Von Richthofen, 1901; Pikelj and Juračić, 2013). Dugi otok Island also belongs to the tectonic unit of the Zadar islands, and is characterized by reverse faults and partially overturned structures. Both pilot study sites, Sakarun and Natural Bridge beaches, are located in the north-western part of the island, which is protected as a significant landscape, mainly because of the indented coastline, pine forests, and crystal-clear sea. Both pilot areas were also developed within the lithostratigraphic unit Veli Rat (VR) (Fig. 1). This unit is characterised by thin-layered to laminated pelagic limestones with calcispherulids and globotruncanids alternating with graded bioclastic limestones, chert nodules, and deformed deposits (slump textures) of various thicknesses (Fig. 1; Fuček et al., 2016). The lithology of the bedrock at both study sites was crucial for beach formation, as these rocks are structurally weaker compared to other formations (e.g., ?DOL formation; Fig. 1). To date, only the bedrock of Sakarun beach has been analysed, revealing a mixture of shallow-water and deep-water microfossil assemblages (Godec, 2021). It consists of highly erodible, and thin-bedded bioclastic pelagic packstones and bioclastic floutstones. This composition indicates a deeper sedimentary environment, where so-called carbonate flysch could have formed. These deposits are weaker and prone to mechanical weathering. Furthermore, their subvertical bedding planes enhance and amplify erosional wave action, leading to their rapid destruction (Godec, 2021; Pikelj and Godec, 2021). In areas where such weaker rocks are exposed to dominant wind-waves, enhanced wave abrasion occurs regularly, and the development of pebble beaches is common. The development of Sakarun beach in this manner has already been recognised in various literature (Pikelj and Juračić, 2013; Pikelj and Godec, 2021).

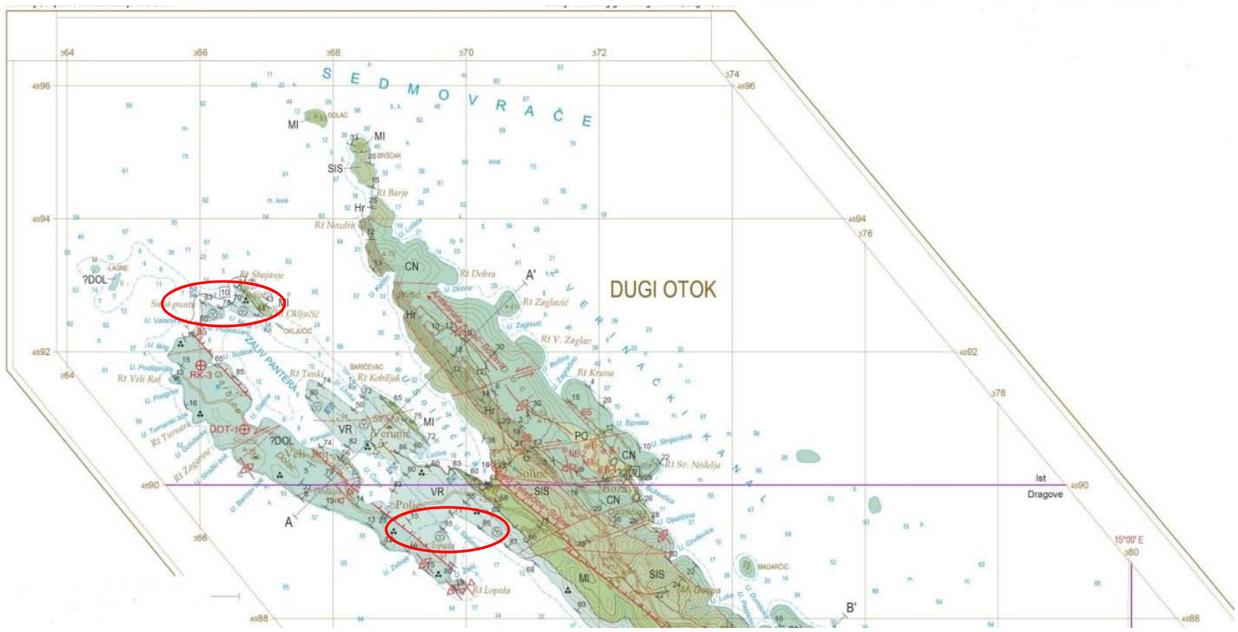


**Figure 1:** Map excerpt from the Basic Geology map of the Republic of Croatia, sheets Ist and Dragove – Sakarun and Natrual Bridge beaches (red ovals) are developed in Veli Rat (VR) Formation (VR) (Fuček et al., 2016).

## 2.2. Sakarun beach

Sakarun Bay is a 900 m long and 700 m wide indented bay, with the beach of the same name located at its north-western end (Figs. 2 and 3). The beach is a 300 m long pocket beach, oriented south-east and directly exposed to Sirocco (SE) wind waves, mostly of shore-normal incidence. It is a pebble beach, typical of Croatian coast. However, a narrow strip of sand regularly occurs along the seaward part of the beach. These subaerial and the intertidal sands are generally very well sorted, slightly gravelly sands or pure sands with a mean grain size of about 0.2 mm. This sand is entirely biogenic carbonate sand of marine origin (Godec, 2021; Pikelj and Godec, 2021; Pikelj et al., 2022). It is composed of crushed shells and skelets of mostly invertebrate organisms, such as molluscs, foraminifera, bryozoans, echinoids, etc. (Godec, 2021; Pikelj and Godec, 2021; Pikelj et al., 2022). Such sediment characteristics indicate continuous wave action. Sediment with similar characteristics occur in the deeper parts of the bay (Pikelj, unpublished data). The rest of the bay's coast is rocky and highly affected by strong marine erosion. The described white sand and rocks, and dark-green surrounding vegetation further emphasise the attractive turquoise colour of the seawater. Therefore, Sakarun Bay and Sakarun beach attract many tourists during the summer, including both beachgoers and nautical tourists.


**Figure 2:** Sakarun Bay and the Sakarun beach. Source: Google Earth 2026.

**Figure 3:** Sakarun beach – aerial view. Natural Bridge is far in the distance (December 2025).

Although Sakarun beach is considered one of the most famous and beautiful beaches in the Zadar archipelago and is an iconic beach of Croatian tourism, the removal of Posidonia banquettes for over a decade, carried out for aesthetic purposes before the tourist season, has been was suspected of causing erosion of sandy sediment from the beach and its general endangerment. According to previous work by Godec (2021), Pikelj and Godec (2021), Pikelj (2021a;2021b), and Pikelj et al. (2022), the weight of sediment extracted from the Posidonia banquettes on Sakarun beach may range from 0.5 to 220 kg of sediment per 1 $m^3$ of banquette, with an average of 64 $kg/m^3$. The banquette sediment was also studied and found to be similar to the previously described beach sand. Furthermore, repeated banquette removal and its deposition far from the coastal system results in the continuous loss of beach sediment, as its removal is approximately. 2.5 times faster than its production within the sea (Pikelj and Godec, 2021; Pikelj, 2021a; 2021b, Pikelj et al., 2022). Without banquettes, the beach is exposed to storms after the tourist season, leading to beach erosion and general depletion of Posidonia debris as the source of nutrients in the marine system. The erosional processes observed on Sakarun beach indicate the need for a development plan for banquette management, in which their permanent removal should be avoided.

## 2.3. Natural Bridge beach

Natural Bridge beach is located at the north-western end of Dugi otok Island. It is a 200 m long pebble tombolo (isthmus) (Figs. 4 and 5). One side of the tombolo faces north towards the open sea, while the other encloses the Pantera Bay from the north. The exact composition and the age of the rock from which the pebbles are derived is not yet known. However, considering that the Veli Rat (VR) unit forms the basement rock of the neighbouring landmasses (Fig. 1), it is likely that the beach pebbles originate from the same rock and developed through similar processes as described in Section 2.1., but, under a different wave climate compared to Sakarun beach.

It is generally known that a tombolo forms where shallow water obstacles, obstacles or an offshore island obstruct incoming waves. This causes wave refraction, meaning the wave front bends around the obstacle, creating a sheltered “shadow” zone behind it. Sediment transported by longshore drift settles in the shadow zone, eventually connecting the offshore obstacle or island to the mainland. Understanding the development of the Natural Bridge tombolo requires knowledge of bedrock, sediment longshore transport, wind and wave climate including wave refraction, as well as the characteristics, structure, and behaviour of beach sediment on both sides.

Fieldwork observations indicate that the inner coastal section of Pantera Bay (Figs. 4 and 5) is mostly composed of very angular carbonate pebbles. Their destruction and production are likely related to the shallowing of high-energy waves entering the bay. The height of these waves increases abruptly within the bay due to its shallow water depth. On such occasions, the wave energy crashes onto the shore, eroding the subvertical, thin-bedded bedrock. Angular pebbles act as an abrasive agent during the repetition of this process, effective in vegetation erosion as well (Fig. 6). These waves can reach the inner side of the Natural Bridge, affecting the sediment and the Posidonia banquettes from inside.

Unlike Sakarun beach, Natural Bridge does not experience banquette removal. Banquettes are present on the beach throughout the year. In addition, Natural Bridge does not receive sandy sediment by waves; only rare patches of the sand between the basement rock in the subtidal occurs on the northern side of the beach.


**Figure 4:** Nature Bridge beach and the Pantera Bay. Google Earth 2026.

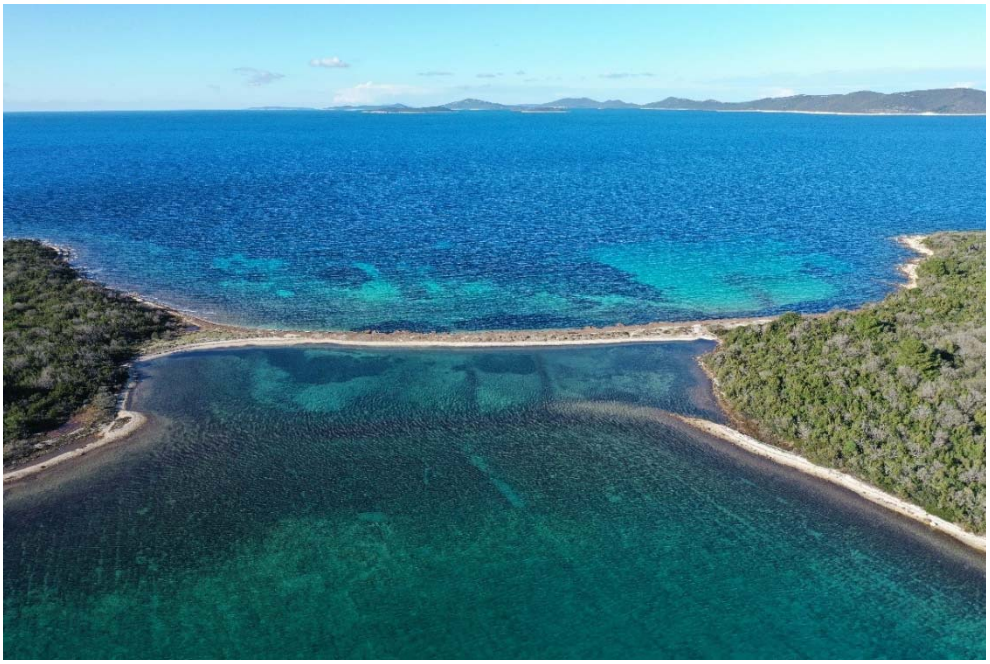

**Figure 5:** Natural Bridge beach – aerial view. Closer is the Pantera Bay; open sea s further away (January 2026).

**Figure 6:** Abrasive effect of angular pebbles in the Pantera Bay coast (February 2024).

# 3. *Posidonia oceanica* system services and nature-based solution

*Posidonia oceanica* is a marine flowering plant endemic to the Mediterranean. It forms extensive underwater meadows at depths of up to 40 m, which are among the most productive and valuable ecosystems in the world (Bourdouresque et al., 2017). These meadows represent the vegetational climax on mobile sediment (Ghirardelli, 1981). Meadows of this seagrass are common throughout the Mediterranean Sea, with total coverage estimated between 19,500 and 37,500 km$^2$ (Pergent et al., 1995; Telesca et al., 2015). Meadows are also common along the Croatian coast and are generally better developed in the central and southern Adriatic (Gamulin-Brida, 1967). For Croatia, data sets regarding Posidonia coverage are currently scarce (Bakran-Petricioli, 2007), and further research and the development of more precise distribution maps are planned (Ministry of Economy and Sustainable Development, 2022). According to mapping of Posidonia in Sakarun Bay carried out in 2017, its meadows cover 110 ha within the Natura 2000 area (Uzelac Obradović et al., 2021). These meadows provide **multiple ecosystem services** (Fig. 7), making them a powerful natural tool for climate adaptation, coastal protection, and marine biodiversity conservation (Boudouresque et al., 2012).

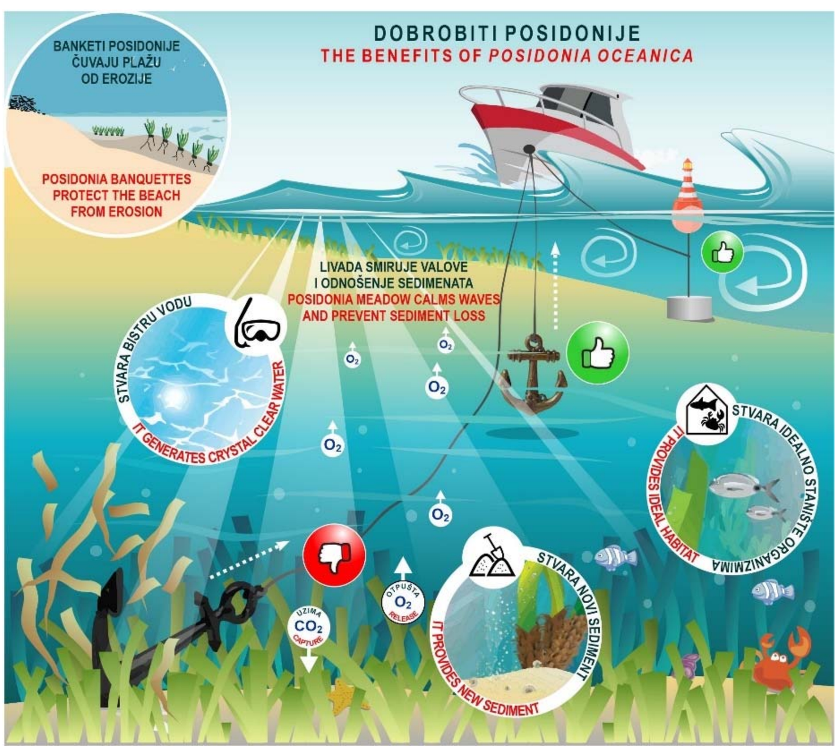


**Figure 7:** Multiple ecosystem services provided by Posidonia oceanica.

One of the most significant functions of *Posidonia oceanica* is carbon sequestration (Hendrix et al., 2007). The plant absorbs carbon dioxide through photosynthesis and stores carbon for centuries within its sediments and root systems. In doing so, Posidonia also contributes to oxygen production in seawater (Koch et al., 2006). Due to their long-term carbon dioxide storage capacity, seagrass meadows are considered important “blue carbon” ecosystems (Macreadie et al., 2021; Monnier et al., 2022; Ozkiper et al., 2024). The protection of existing meadows prevents the release of stored carbon back into the atmosphere, while restoration efforts increase future carbon capture. In this sense, *Posidonia oceanica* acts as a natural climate solution. Another essential role of these meadows is coastal protection (Ward et al., 1984; Koch et al., 2006). Dense underwater leaves reduce wave energy and slow water movement, helping to stabilise sediments and limit coastal erosion (Infantes et al., 2012; Paxton et al., 2024). Dead leaves that accumulate on beaches, often called banquettes, also protect shorelines from storm damage during winter (Simeone et al., 2022; Pikelj et al., 2022). Instead of relying solely on expensive artificial coastal defences such as seawalls or concrete barriers, maintaining healthy seagrass ecosystems offers a more sustainable and resilient alternative. It also supports diversification of endemic bryozoan and hydrozoan species (and many other organisms), whose habitat is restricted to Posidonia leaves (Boero et al., 1985). *Posidonia oceanica* meadows are also biodiversity hotspots. They provide habitat, nursery grounds, food, and shelter for hundreds of marine species including fish, molluscs, crustaceans, and microorganisms. Healthy meadows therefore support fisheries, maintain ecological balance, and contribute to local economies dependent on tourism and fishing (Monnier et al., 2022; Ozkiper et al., 2024). The most recently recognised service of the Posidonia is the entrapment of plastic particles within its sediment meadows and their removal via beached Neptune balls (Sanchez-Vidal et al., 2021; Meklav, 2026) (Fig. 8).

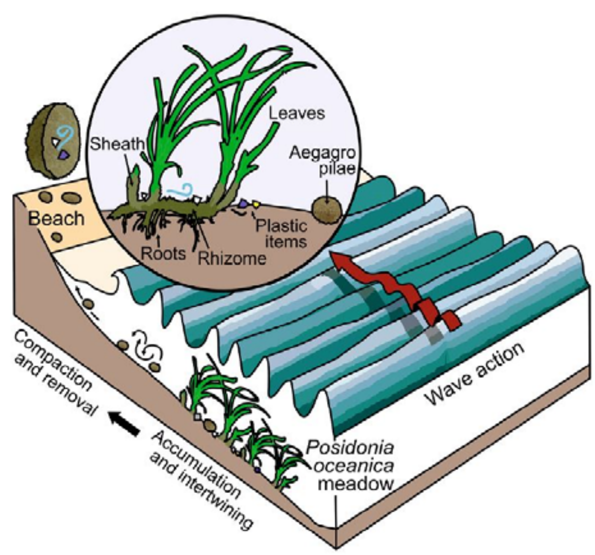


**Figure 8:** Plastic particle pathways from Posidonia meadow to the beach (Sanchez-Vidal et al., 2021).

However, *Posidonia oceanica* ecosystems are under pressure from all aspects of littoralisation, such as coastal urbanisation, pollution, trawling, together with invasive species, and climate change. Due to its slow growth, damage can take decades or even centuries to recover (Monnier et al., 2022). This makes damage prevention and ecosystem conservation especially important.

As mentioned in Section 1., Nature-based Solutions (NBS) are actions designed to protect, restore, or sustainably manage natural ecosystems, addressing environmental, social, and economic challenges, while benefiting biodiversity and human well-being. One of the most important examples of NBS in the Mediterranean Sea is the conservation and restoration of Posidonia oceanica meadows (Moraes et al., 2020; URL1). Nature-based solutions involving *Posidonia oceanica* seagrass generally include: i) protection of existing meadows through marine protected areas and anchoring restrictions; ii) restoration projects using seed-based recovery or transplantation methods; iii) sustainable coastal management to reduce pollution, dredging, and habitat destruction; iv) integration of seagrass conservation into climate and coastal adaptation policies; and v) public awareness and community involvement in marine protection and conservation (Moraes et al., 2022; URL1; Ozkiper et al., 2024).

When discussing *Posidonia oceanica*, NBS refers to using the natural functions of seagrass ecosystems to address environmental challenges sustainably (Macreadie et al., 2021; Moraes et al., 2022). Compared with classic engineered solutions, NBS are usually more cost-effective over the long term and simultaneously generate multiple co-benefits, such as climate mitigation, biodiversity protection, water quality improvement, tourism value, and disaster risk reduction (Paxton et al., 2024; Moraes et al., 2022).

# 4. Fieldwork and research methods

## 4.1. Beach profiling

Beach profiling at both beaches was conducted a total of six times on the same day between October 2025 and April 2026. The schedule of field trips depended on several factors, primarily weather and wave conditions, as well as other commitments. In this context, October had to be omitted due to the official absence. The weather in November was mostly humid, windy, cold, and rainy; however, one fieldtrip was carried out in November, but it was not possible to perform the measurements due to rain and/or the wind. However, it was confirmed that there were substantial banquettes on Natural Bridge (Fig. 9), while they were rather thin on Sakarun beach (Fig. 9). Therefore, the first official measurements were taken in December 2025.

**Figure 9:** Massive banquettes on the Natural Bridge (left) and Thin banquette on the Sakarun Beach (right) (November 2025).

Profiling on Sakarun beach was carried out on seven profiles established in 2021 (Pikelj, 2021a). The profile numbers increase from southwest to northeast (Fig. 10).


**Figure 10:** Position of the profiles on the Sakarun beach (Google Earth 2026).

Before profiling, the starting points of the profiles were determined using a handheld GPS device and marking plate (ground control points; GCP) was placed on each. A second GCP was positioned on each profile in the foreshore zone, at approximately the last stable point on the profile not splashed by waves. Profiling was conducted using a DGPS device with the VRS RTK precise positioning method, corrected by the CROPOS VPPS service. Measurement accuracy was 2 cm horizontally and 4 cm vertically. The measurement intervals on each profile depended on the uniformity of the beach slope and the frequency of changes in its morphology; a point was measured at each significant and noticeable change in beach height along the profile. The length of each profile varied during each field trip, depending on the tide (high or low water) and the wave energy during profiling. Typically, the end of profiling in the sea corresponded to an average depth of about 1.2 m at the time of measurement completion.

The same principle was applied to Natural Bridge beach; however, due to the specific shape of the beach (it is longer on the outer side and shorter on the inner side), only three profiles were selected for beach profiling. These profiles were positioned to start in the Pantera Bay, cross the beach, and end in the sea (Fig. 11). Profile visualization was made using MS Excel, with each profile compared individually across all survey dates.

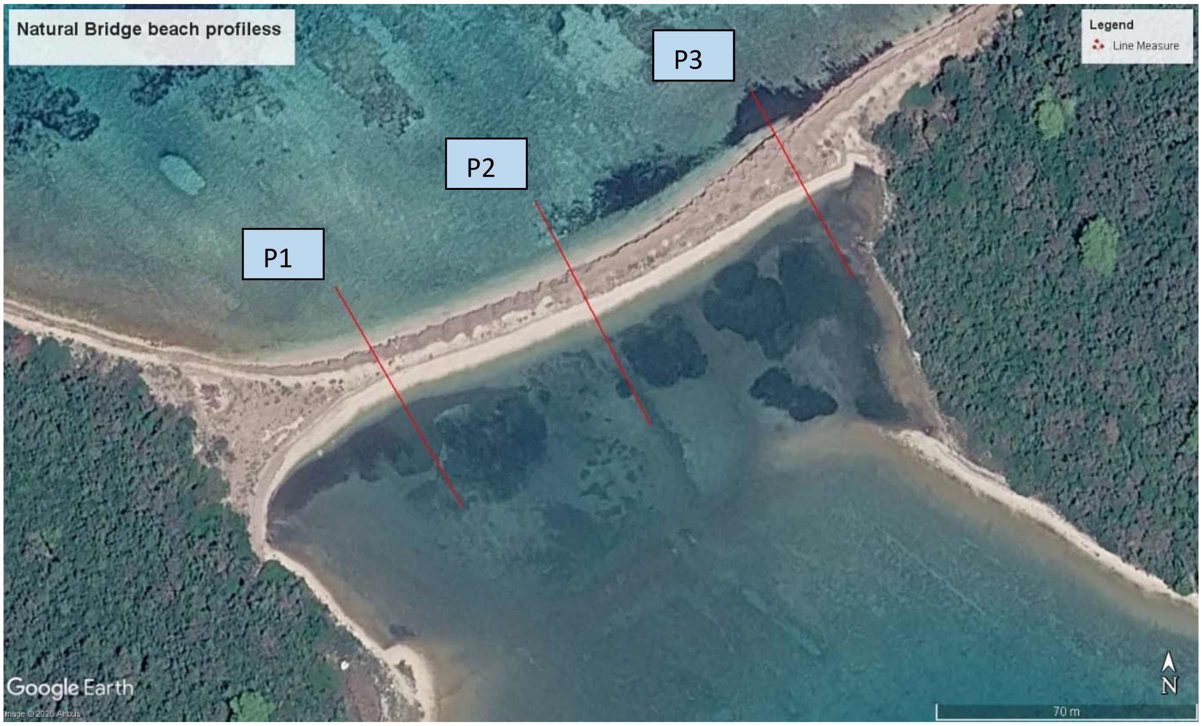


**Figure 11:** Position of the profiles on the Natural Bridge (Google Earth 2026).

## 4.2. Photography collection and 3D modelling for morphological changes

During each field trip, both beach areas were photographed from the air at a height of 40 m and a speed of 2.1 m/s. The number of photographs taken during all measurements ranged from 220-320. The overlap between photographs was set to approximately 80%. Before each flight for photograph collection, a total of 15 movable markers (GCPs) were placed on Sakarun beach along each of the 7 profiles, while 2 fixed markers were placed on stationary surfaces such as wall. For the Natural Bridge, only 10 movable markers were used, with no fixed markers. The precise positions of the markers were measured using the Trimble R8 GNSS receiver and the CROPOS VPPS correction service. The horizontal and vertical accuracies were 2 cm and 4 cm, respectively. The photograph sets were further processed in the Agisoft Metashape Pro software, which is specialised for SfM-MVS (Structure from Motion – Multi View Stereo) photogrammetry. After checking the quality of each individual image, all 2D images were used to build a 3D sparse point cloud, a dense point cloud, and a DSM (digital surface model). Marker position data were then introduced for 3D model georeferencing. The total error (root mean square error; RMSE) of the markers and the model was generally below 5 cm.

Each 3D model was transferred from Agisoft Metashape to Golden Software Surfer as a DSM, where uniform DSMs models were created for each recording date, as well as difference models

(DSM of Difference; DOD) between two successive recording dates. The same beach area was defined for all model pairs to facilitate the creation of difference models. The beach morphology in the DSM and DoDs models is shown in metres. As the DSM models display only morphology, a dense point cloud is attached to each model for the interpretation of change to make it easier to distinguish changes in beach coverage by Posidonia deposits during the monitoring periods.

## 4.3. Sediment analysis on the Natural Bridge

Section 2.3. states that Natural Bridge receives no sandy sediment on the beach itself, except occasionally in the intertidal zone, where sandy sediment is being deposited by waves. This situation occurred twice during the monitoring period: sediment was collected on the outer side of the beach, near profile P1 in the intertidal zone. To characterise this sediment, approximately 100 g of wet sediment was collected and stored in a plastic jar for laboratory analyses. The sediment was analysed for grain size and carbonate content. Grain size was determined by the wet sieving for both samples (S1 and S2), and carbonate content was analysed using carbon dioxide volumetry. Detailed sediment analyses are described in Pikelj (2021a; 2021b) and Pikelj and Godec (2021).

# 5. Results and discussion

## 5.1. General information regarding beach profiling and weather conditions during the monitoring period

During the field trips, each of the seven designated profiles on the Sakarun beach (Fig. 10) was measured to gain insight into changes in the morphology of sediment and Posidonia banquettes, as well as the existence and movement of sand bars in the intertidal and shallow subtidal zones, as described in Pikelj (2021a). To simplify the interpretation of the profiles, data on daily wind speeds and directions for the official weather station in Božava were obtain from the Croatian Meteorological and Hydrological Service (CMHS/DHMZ). Summarised data on the wind climate during the monitoring period are presented in Table 1., with emphasis on episodes of SE winds, to which Sakarun beach and Sakarun Bay are predominantly exposed (Pikelj and Juračić, 2013; Pikelj, 2021a). Given their orientation and exposure to the south, the speed of the SE (Sirocco) wind and the impact of the waves it generates are greater on the beach compared to Božava (which is protected from the south and south-east), as observed during fieldwork. In contrast, Natural Bridge beach is exposed to several winds and the waves they generate. The Tramontana (N) wind directly affects the beach, while the Bora (NE) wind may also have a significant impact. The exposure to the SE wind (Sirocco) is indirect. It was observed that waves coming from the SE refract and affect the beach at a low incident angle. Taking the orientation of the Natural Bridge into consideration, besides Sirocco, N and NE wind event were also used for the interpretation of changes in beach morphology.

**Table 1:** Characteristic events of the SE winds (and waves) during the monitoring period.

| Month | Events of SE, N and NE winds on the Dugi otok Island | Wind description: |
|---|---|---|
| **December, 2025** | 1-3 Dec – SE wind – 8-24 km/h<br>13-14- Dec – N wind -8 km/h<br>16 Dec – SE wind – 8 km/h<br>20 Dec – N wind – 8 km/h<br>25-26 Dec – N wind 8 – 16 km/h<br>30 – 31 Dec – N wind 8 – 16 km/h | light breeze to moderate wind<br>light breeze<br>light breeze<br>light breeze<br>light to gentle wind<br>gentle wind |
| **January, 2026** | 1 Jan – SE wind – 8-16 km/h<br>5-7 Jan – N wind – 8-16 km/h<br>8 Jan – N wind – 8-16 km/h<br>9 Jan – SE wind – 16-24 km/h<br>10-11 Jan – NE wind – 8-16 km/h<br>14-16 Jan – SE wind – 8 km/h<br>22 Jan – N wind – 8 km/h<br>24-25 Jan – SE wind – 8-24 km/h<br>28 Jan – SE wind – 34 km/h | light breeze to gentle wind<br>light breeze to gentle wind<br>light breeze to gentle wind<br>gentle to moderate wind<br>light breeze to gentle wind<br>light breeze<br>light breeze<br>light breeze to moderate wind<br>moderate strong wind |

| | | |
|---|---|---|
| **February, 2026** | 1. Feb – NE wind – 8-16 km/h<br>3-4 Feb – SE wind – 16-34 km/h<br>6-12 Feb – SE wind – 8-16 km/h<br>14 Feb – SE wind – 16-34 km/h<br>15 Feb – NE wind – 16-34 km/h<br>16 Feb – SE wind – 8-34 km/h<br>19 Feb – SE wind – 8-34 km/h<br>20 Feb – NE wind – 8-24 km/h | light breeze to gentle wind<br>gentle to moderate strong wind<br>light breeze to gentle wind<br>gentle to moderate strong wind<br>gentle to moderate strong wind<br>light breeze to moderate strong wind<br>light breeze to moderate strong wind<br>light breeze to moderate wind |
| **March, 2026** | 2 Mar – SE wind – 8 km/h<br>7 Mar – NE wind – 8 km/h<br>10-11 Mar – SE wind – 8 km/h<br>15 Mar – SE wind 8-16 Km/h<br>17-21 Mar – NE wind – 8-16 km/h<br>26 Mar – SE wind – 24 km/h<br>26-28 Mar – NE wind – 24 km/h<br>28-29 Mar – N wind – 24 km/h<br>31 Mar – NE wind 16-24 km/h | light breeze<br>light breeze<br>light breeze<br>light breeze to gentle wind<br>light breeze to gentle wind<br>moderate wind<br>moderate wind<br>moderate wind<br>gentle to moderate wind |
| **April, 2026** | 1-3 Apr – NE wind – 8-24 km/h<br>8 Apr – SE wind – 8 km/h<br>10 Apr – SE wind – 8 km/h<br>12-14 Apr – SE wind – 8-24 km/h<br>15 Apr – NE wind – 8 km/h<br>18 Apr – NE wind – 8 km/h<br>20 Apr – SE wind - 8 km/h<br>22 Apr – NE wind – 16 km/h<br>22-23 Apr – N wind – 8-16 km/h<br>29-30 Apr – N wind – 8-16 km/h | light breeze to moderate wind<br>light breeze<br>light breeze<br>light breeze to moderate wind<br>light breeze<br>light breeze<br>light breeze<br>gentle wind<br>light breeze to gentle wind<br>light breeze to gentle wind |

## 5.2. Sakarun beach

### 5.2.1. Beach profiling

#### *5.2.1.1. Profile 1*

Figures 12 to 18 present a comparison of each profile (profiles 1 to profile 7) during the monitoring period. Profile 1 is located in the south-western part of the beach (Figs. 10 and 12). Throughout the monitoring period, some amount of Posidonia debris in the form of banquette was present along this profile. This presence is visible in Section 5.2.2., dedicated to 3D modelling. Between the first two measurements (20 December 2025 and 30 January 30), there was slight progress of the Posidonia banquette and the beach slightly increased in its width, as shown in Figure 12. This change may be attributed to the episode of relatively strong SE wind at the end of January, immediately before the second survey. Given the mechanism of Posidonia banquette disappearance and emergence on Sakarun beach (Pikelj and Godec, 2021; Pikelj 2021a; 2021b), it is likely that there was a period without banquettes or with only some remains during the SE wind event. However, the weather calmed down sufficiently to allow the banquette to form once again. The intensity and duration of the SE wind event probably influenced the amount of Posidonia debris and the height of the banquette. The step of the banquette present in the first survey profile disappeared prior to the second survey, as shown in Figure 12. The submerged sandbar was present during both surveys, however; the profile is deeper at its end during the second survey compared to the first, confirmed the intensive wave action, probably immediately prior to the second survey, as mentioned above.

The differences in profile 1 between the second and third survey (30 January and 24 February) clearly show that the shape of the profile did not change much; however, a small shift seaward is visible. It is assumed that the starting point between the two surveys was slightly shifted seaward. Nevertheless, there is a visible vertical difference in the Posidonia banquette – it was higher in February compared to January, suggesting that some kind of storm event occurred. Table 1. shows that there were several days in February, before survey no. 3 (16–19 February; Table 1) when strong SE winds could have at least reorganized existing banquettes, or even deposited more Posidonia debris during the weakening of the storm. The submerged part of profile 1 between the second and third surveys is more or less the same, still showing the existence of a submarine sandbar.

The shape of profile 1 between the third and fourth surveys (24 February and 25 March) is more or less the same. However, a small change in the submarine sandbar is visible, showing thickening of the sandbar at 26–30 m from the starting point. There are no significant changes in banquette morphology along the profile; however, changes will be visible in the 3D model, in the area between profile 1 and profile 2, where a new pile of Posidonia debris was deposited. During the period between these two surveys, no significant SE wind was observed (Table 1); only mild SE winds were present in the first part of the month. To be precise, the day after the March survey, a stormy SE wind event occurred (Table 1).

The comparison of profile 1 between the surveys on 30 March and 11 April showed several differences (Fig. 12). The first is in the highest part of the beach, where a lowering of the initial banquette wedge was observed; the second is a rise in the lower part of the banquette. This situation indicates some form of erosional process. Bearing in mind that no significant SE events occurred between these two surveys, only one event could have eroded the banquette – the one that took place on 26 March. Erosion of the sandbar is also visible in the shallowest part, while sand accumulation is observed in the deeper part of the submerged beach. This confirmes the erosional processes and the seaward transport of beach material (Posidonia debris and sand).

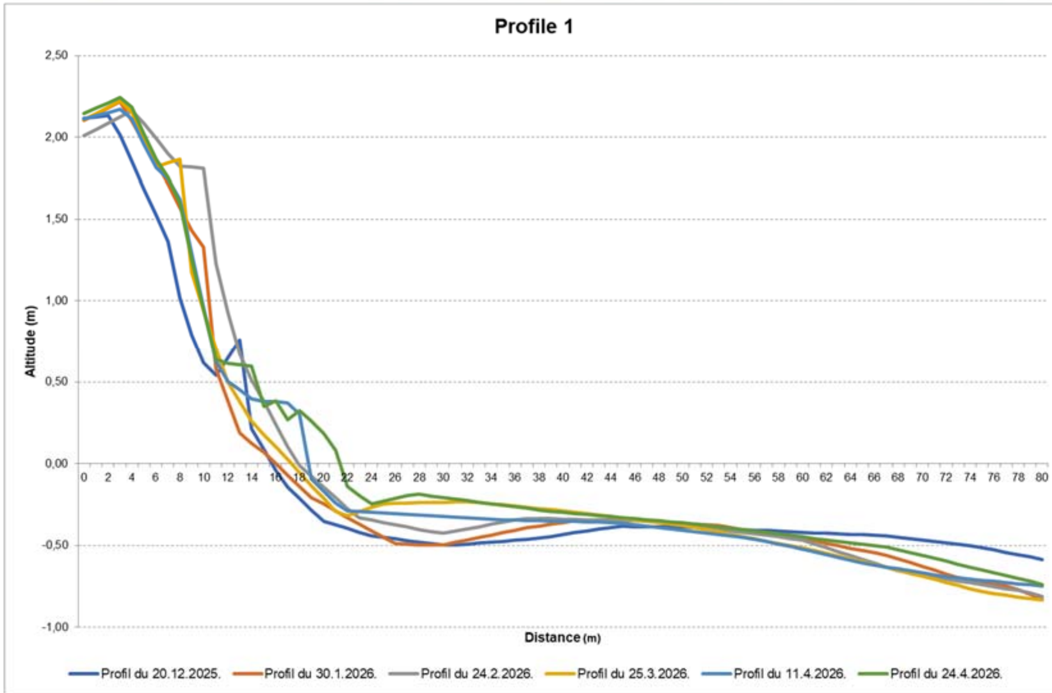


**Figure 12:** Comparison of the morphological changes along the Profile 1 during the monitoring period.

Finally, the last monitored period, from 11 April and 24 April, was quite short. However, during this time period there was an episode of moderate to strong SE wind (Table 1). As a result, part of the beach covered with banquette was slightly altered and lowered.

The maximum measured banquette height on profile 1 varied during the all monitoring periods between **0.53 and 1.42 m**. It should be noted that this height is the difference measured from the sediment to the highest crest of the banquette.

#### *5.2.1.2. Profile 2*

A comparison of profile 2 during the monitoring period is shown in Figure 13. Similar to as profile 1, profile 2 experienced the disappearance of one step of the banquette between the first two surveys (December–January), which can be attributed to the storm immediately before the second survey. It appears that the banquette almost completely disappeared from profile 2; only a thin layer of Posidonia debris was visible during the fieldwork.

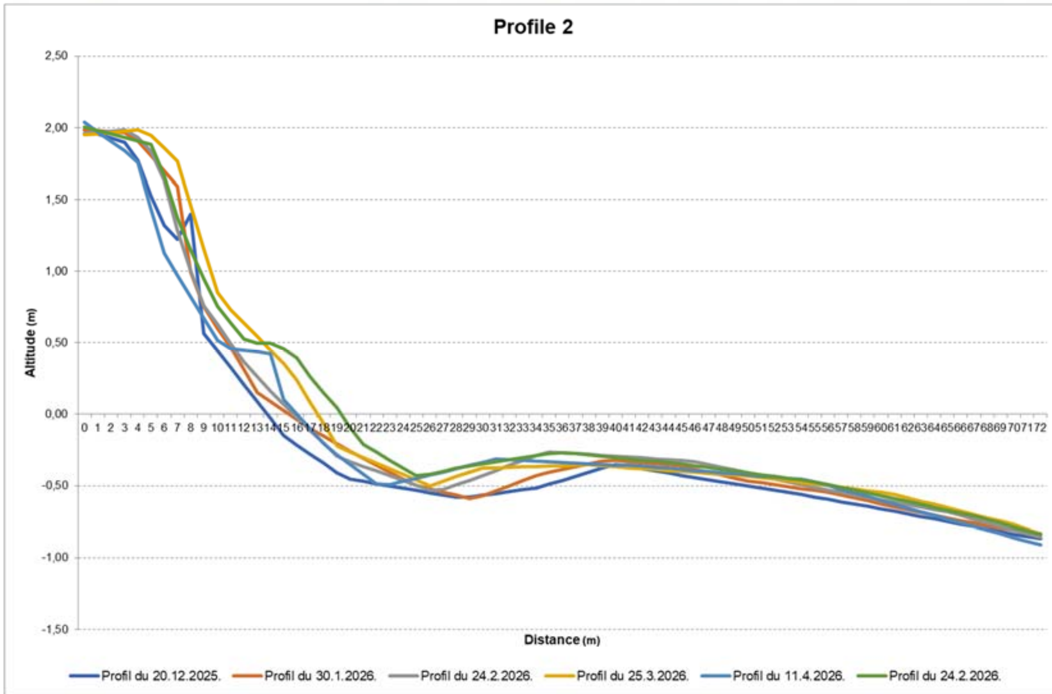


**Figure 13:** Comparison of the morphological changes along the Profile 2 during the monitoring period.

The difference between the second and third (January–February) surveys showed no changes in the profile in the banquette area; however, a sandbar grew slightly, indicating the accumulation of sand in the shallowest intertidal zone. This difference in beach dynamics has already been explained in Pikelj and Godec (2021) and Pikelj (2021a; 2021b): the most dynamic parts of the beach are its "corners". Such a situation indicates that SE wind waves approach from varying SE directions and/or there is longshore transport, after which beached material accumulates in one of the beach "corners". It is likely that both of these processes occur and may even act together.

As with profile 1, there were no significant changes on profile 2 between the third and fourth surveys (February–March). The only significant change was a small shift of the submerged sandbar. This minor small change is likely due to the absence of a banquette here since the previous survey.

Between the fourth and fifth surveys (25 March–11 April), one true storm event occurred. This storm likely deposited a new banquette as weakened, as shown in Fig. 13. This change is visible as a new step in the banquette area. Other changes are less obvious and significant. A sandbar is visible in the submerged part of the beach.

In the final monitoring period (11–24 April), the shape of profile 2 remained unchanged, while the observed shift is attributed to a change in the starting point. A banquette was present on profile 2 and appears to have persisted since the previous survey, with only a slight thickening.

The maximum measured banquette height on profile 2 varied during the all monitoring periods between **0.33 and 0.68 m**. It should be noted that this height is the difference measured from the sediment to the highest crest of the banquette.

#### *5.2.1.3. Profile 3*

During the first monitoring period (December-January), profile 3 did not undergo significant changes in its shape (Fig. 14). It contained a banquette on which only minimal changes occurred. The most notable change was observed in the submerged part, where some shallowing took place, indicating sand transported shoreward by waves.

The second period (January – February) brought a morphological change for profile 3: the step visible on the profile shifted slightly upwards (Fig. 14). This step is not attributed to banquettes, but to the gravel berm. This berm became steeper after the SE storm event in February, immediately before the survey. Evidence for this storm event included large amounts of water lying behind the beach. It is likely that this storm steepened the core of the beach body.

Between February and March, the shape of the profile remained almost unchanged, as was the case with the previous two profiles. A similar pattern was observed for the period March-April 11$^{th}$, confirming that small changes are more noticable in the beach corner, as explained in Section 5.2.1.2.

Finally, the last monitoring period (April 11$^{th}$ –April 24$^{th}$) brought a new change in the morphology of profile 3: more Posidonia debris was present on the last survey date, indicating that a new banquette had been deposited. This resulted from the short and strong SE event (Table 1) before the last survey, as explained in Section 5.2.1.1. Since profile 3 is located almost in the central part of the beach, the described morphological changes were expected. The central part of the beach, similar to its corners, showed the most dynamic morpho-evolution during the 2020/2021 monitoring period (Pikelj and Godec, 2021; Pikelj 2021a; 2021b). The reason for this evolution is that the central part of the beach often receives shore-normal SE wind waves.

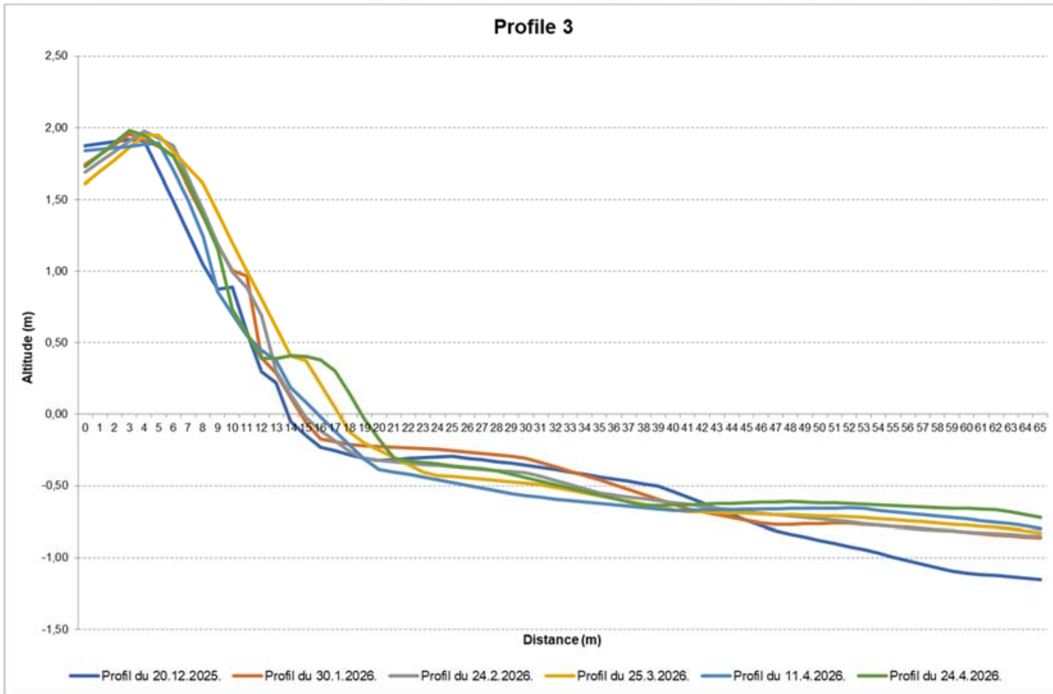


**Figure 14:** Comparison of the morphological changes along the Profile 3 during the monitoring period.

The maximum measured banquette height on profile 3 varied during the all monitoring periods between **0.15 and 0.52m**. It should be noted that this height is the difference measured from the sediment to the highest crest of the banquette.

#### *5.2.1.4. Profile 4*

Profile 4 is located in the central part of Sakarun beach (Fig. 10). Therefore, it is expected to record continuous morphological changes, mainly because the entire beach is exposed to shore-normal SE wind waves, which impact its central area. The initial monitoring period revealed the first significant changes for profile 4: the beach became steeper between the two surveys. Although some changes occurred in the banquette area, the primary cause was the steepening of the berm, resulting from a strong SE event a few days before the survey. It is likely that most of the wave energy is concentrated in the central part of the beach. This change will be more apparent in the section where 3D modelling is shown.

The second monitoring period (January – February) also showed some changes. A strong February SE event in February eroded part of the banquettes, which is evident as a lowering (Fig. 15). Additionally, the sandbar in the submerged part of the beach accumulated more sand, indicating post-storm sand deposition.

The February –March period brought no significant change, except for the further lowering of the banquette and the transport of sand from the sandbar to the deeper part. This is consistent with the rather mild SE events during the February and early March (Table 1).

The next monitoring period (March-April 11th) brought further banquette erosion after the March SE event. This event left almost no Posidonia debris along profile 4, which led to the smoothing of profile 4 (Fig. 15).

The final monitoring period in April (April 11th – April 24th) revealed an increase along the whole profile (Fig. 15). In the upper part, such a change can be the result of the increased plant growth at the top of the beach. The starting point of this profile is in the beach vegetation at the top of the berm. The increase along the most of the rest of profile 4 is ascribed to new banquette formation, caused by the SE storm event in the mid-April (Table 1).

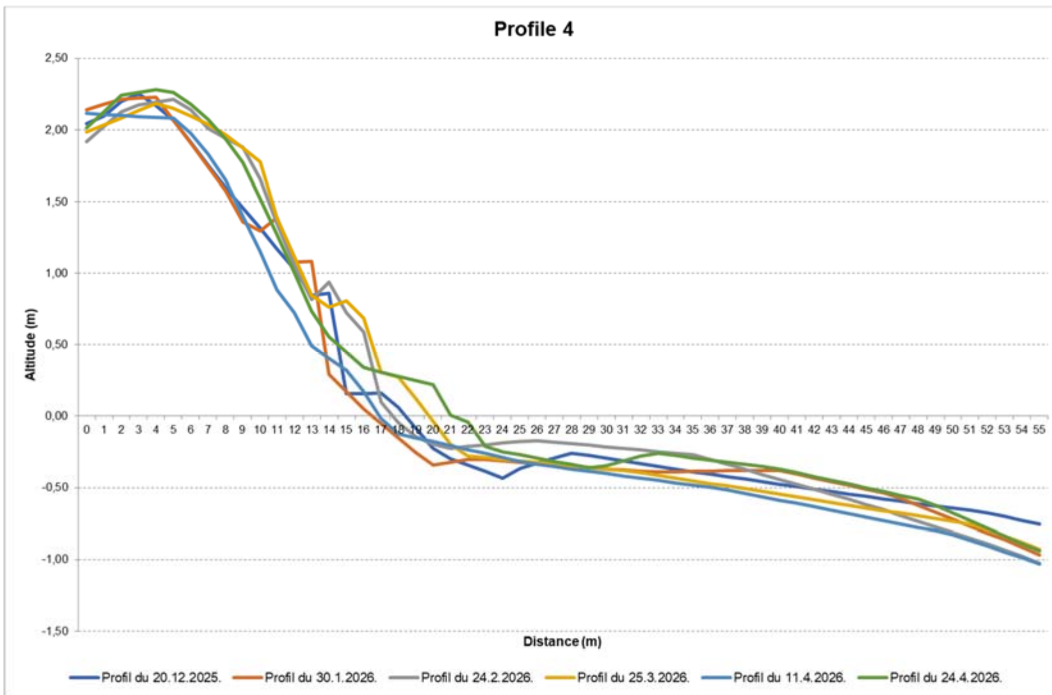


**Figure 15:** Comparison of the morphological changes along the Profile 4 during the monitoring period

The maximum measured banquette height on profile 4 varied during the all monitoring periods between **0.45 and 0.82 m**. It should be noted that this height is the difference measured from the sediment to the highest crest of the banquette.

#### *5.2.1.5 Profile 5*

Similar to profile 4, profile 5 is also located near the central part of the beach (Fig. 10). During the first monitoring period, there was an accumulation of the Posidonia banquette, which is also visible in Section 5.2.2. This upward movement of Posidonia debris resulted from the stormy SE event that occurred immediately before the second survey. This event enabled the accumulation of Posidonia debris as the storm weakened (Fig. 16). Accumulation was also observed in the shallow submerged part of the beach; in this case, it involved sand accumulating in the form of a sandbar.

Between January 30$^{th}$ and February 24$^{th}$ accumulation continued on profile 5 (Fig. 16), which is also visible in the dense point cloud in Section 5.2.2. As with the previous event, the further “climbing” of the banquette is attributed to the mid-February SE event and its subsequent weakening, immediately before the February survey.

The third monitoring period did not bring much change in the shape of profile 5, but only a thickening of the banquette. This, like previous changes, is visible in Section 5.2.2. This further thickening was attributed to the weakening period following the March SE storm event.

During the fourth period (March-April 11$^{th}$) only the lower part of the banquette was eroded, as shown in Figure 16 and Section 5.2.2. The rest of the profile retained its shape, with only minor erosion of the sandbar. This erosion was mild, probably caused by moderate SE events in the first half of April.

The final monitoring period was important for the further lowering of the banquette, indicating erosional processes probably related to the only storm in the mid-April (Table 1).

The evolution of profile 5 confirmed once again the dynamic nature of coastal processes in the central part of the beach. The maximum measured banquette height on profile 5 varied during all monitoring periods between **0.17 and 0.93 m**. It should be noted that this height is the difference measured from the sediment to the highest crest of the banquette.

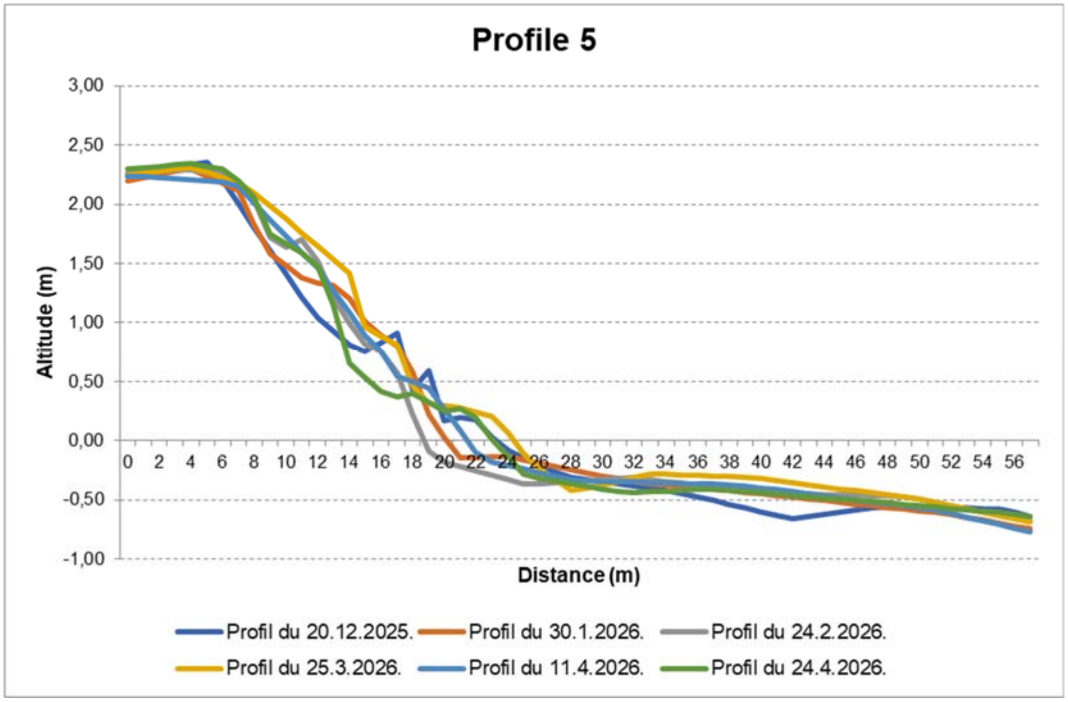


**Figure 16:** Comparison of the morphological changes along the Profile 5 during the monitoring period

### *5.2.1.6. Profile 6*

Along profile 6 (Fig. 17), a weaker dynamic is observed compared to profile 5 (Fig. 16). During the first survey period profile 6 experienced piling up along its entire length. This is probably due to the storm weakening and the fact that this part of the beach does not exhibit the pronounced morphodynamics seen in the beach "corners" and the very central part (Pikelj and Godec, 2021; Pikelj 2021a; 2021b).

The second monitoring period (January – February) was marked by thickening of the existing banquette in its upper part and the disappearance of the banquette in its lower part. Both processes are probably related to the same SE event in the mid-February (Table 1), first to its onset, then to its weakening. However, this event was not sufficiently strong to erode the entire banquette (Fig. 17).

Weak erosion and lowering of the banquette occurred during the February – March period; overall, much of profile 6 remained unchanged. The reason for this, besides the absence of a significant storm, is that profile 6 is located in the "quiet" part of the beach.

The March – April period brought new changes along the profile (Fig. 17): the upper part was slightly piled up, while the lower part eroded in such a way that only barren sediment remained in the upper intertidal. This change is particularly visible in the dense point cloud in Section 5.2.2.

Finally, the April – April period was marked by erosion of the banquette in its upper part and accumulation in its lower part, probably due to the SE event in mid-April.

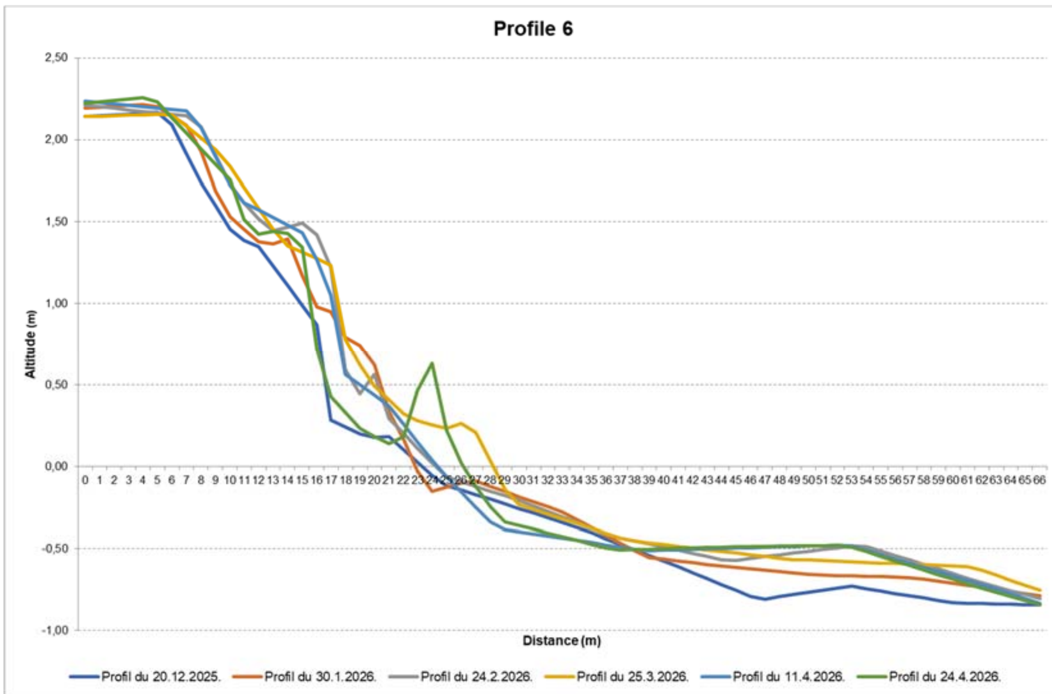


**Figure 17:** Comparison of the morphological changes along the Profile 6 during the monitoring period

The maximum measured banquette height on profile 6 varied during the all monitoring periods between **0.41 and 1.13 m.** It should be noted that this height is the difference measured from the sediment to the highest crest of the banquette.

### *5.2.1.6. Profile 7*

Similar to profile 1, profile 7 is located in the beach "corner", in the north-eastern part (Fig. 10). Both "corners", as previously explained, may experience more dynamic processes due to the changing incident angle of SE wind waves, together with the longshore transport of beached material. During the first monitoring period, profile 7 experienced accumulation of banquette in its upper part and lowering in the lower parts, similar to profile 1 (Figs. 12 and 18). This behaviour is the result of the late-January storm (Table 1).

The dynamics of profile 7 continued in the same way during the January – February period: the upper part of the banquette thickened, while the lower part accumulated due to alternating layers of sand and Posidonia, as observed during fieldwork. As in the 2020/2021 period, the highest degree of mixing of Posidonia and sand was recorded on profile 7, where true biogeomorphological forms developed (Pikelj and Godec, 2021; Pikelj 2021a; 2021b).

During the February – March period, the upper part of profile 7 remained more or less unchanged (Fig. 18), while the lower part experienced further accumulation of Posidonia and sand. This is probably due to the mild weather and wave conditions observed during this survey period (Table 1).

March – April brought new erosion in the lower part of the banquette (Fig. 18), which is likely related to the storm on March 26th. Mild SE wind waves afterwards did not manage to return the Posidonia debris, as seen in Section 5.2.2.

In the end, profile 7 experienced a new accumulation of Posidonia debris in the lower part of the banquette (Fig. 18), probably after the strong mid-April storm (Table 1).

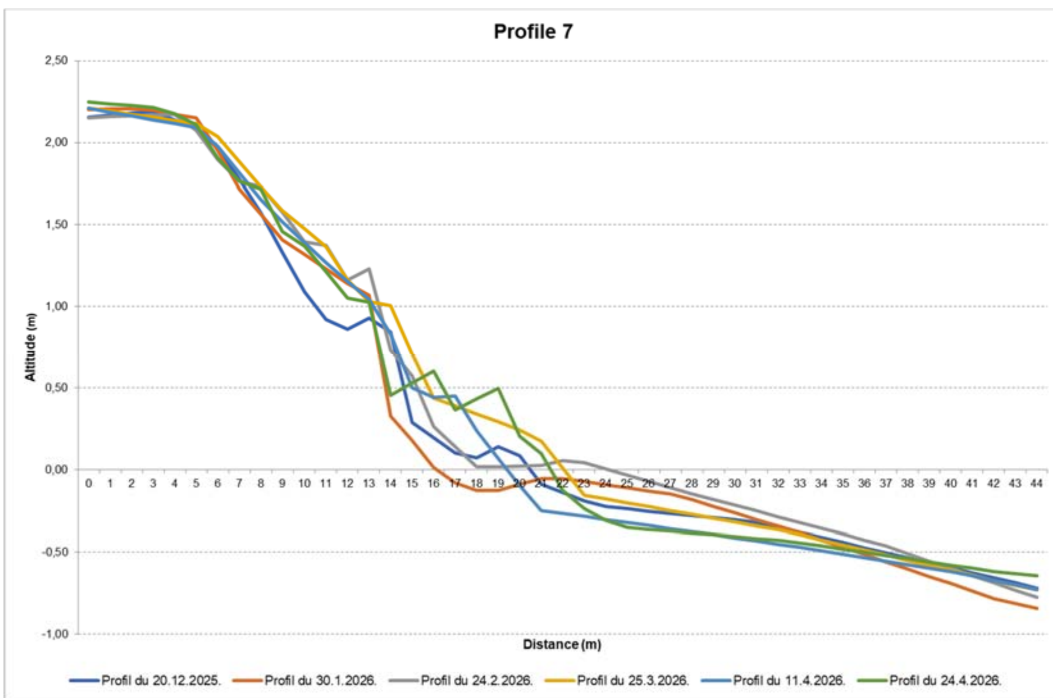


**Figure 18:** Comparison of the morphological changes along the Profile 7 during the monitoring period.

The maximum measured banquette height on profile 7 varied during the all monitoring periods between **0.11 and 0.72 m**. It should be noted that this height is the difference measured from the sediment to the highest crest of the banquette.

### 5.2.2. Morphological changes

For each survey date, dense point clouds and three-dimensional (3D) models illustrating the morphological state at the time of the survey, as well as difference models, are presented in this Section. The latter, which indicate changes between two successive surveys, go beyond two-dimensional (2D) beach profiles by displaying the overall beach behaviour in all directions in a single view, in response to various natural and anthropogenic events, such as storm episodes, anthropogenic interventions on the beach. This provides insight into the morphological changes and whether they resulted from alterations in the Posidonia banquettes or due to changes in the sediment.

#### *5.2.2.1. December 2025-January 2026*

During the first monitoring period, there was a slight change in the distribution of Posidonia banquettes (Fig. 19). The south-western (left) part of the beach received more Posidonia debris in January, and the banquettes became compact on the north-eastern (right) part. This accumulation of banquettes is probably due to the SE event in the days before the January survey (Table 1). The main change in sediment occurred in the central part of the beach, where steepening of the gravel berm is visible. It is likely that most of the banquettes were stripped from the beach, the gravel was steepened, and the banquettes were re-formed during the weakening of the storm, more or less in the same dimensions.

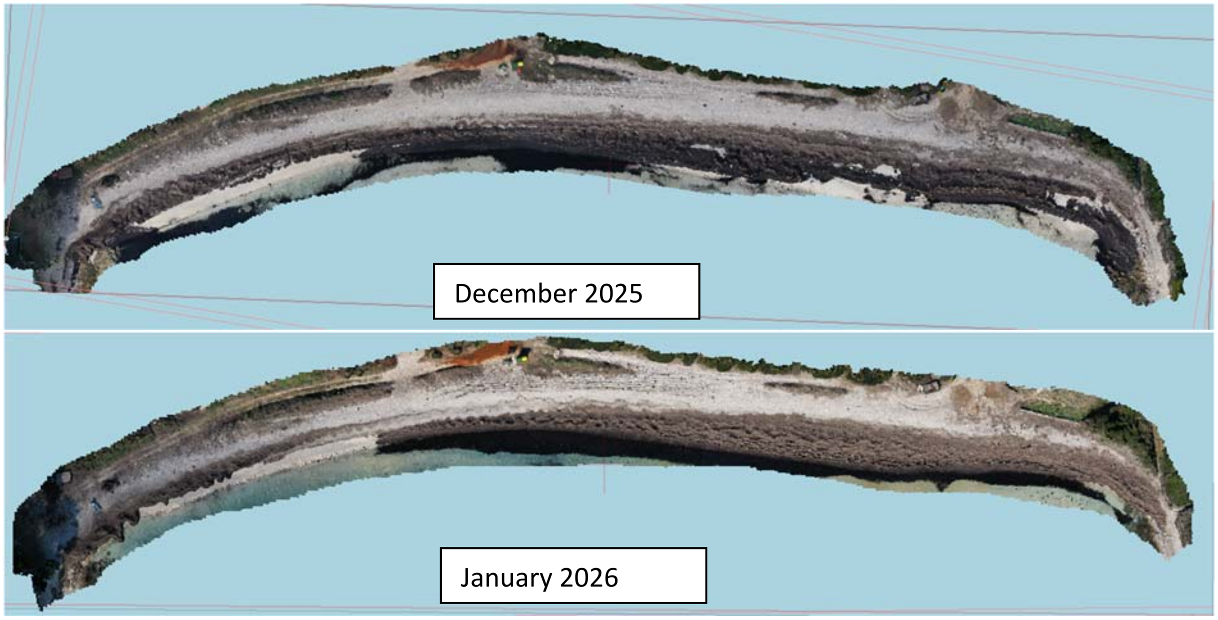


**Figure 19:** Dense point clouds of the Sakarun beach: December 2025 and January 2026.

Accordingly, Figure 20 showed most of the morphological changes in the banquette area, as well as the loss of material in the central part of the beach, where steepening of the gravel berm occurred. These differences were up to 0.5 m.

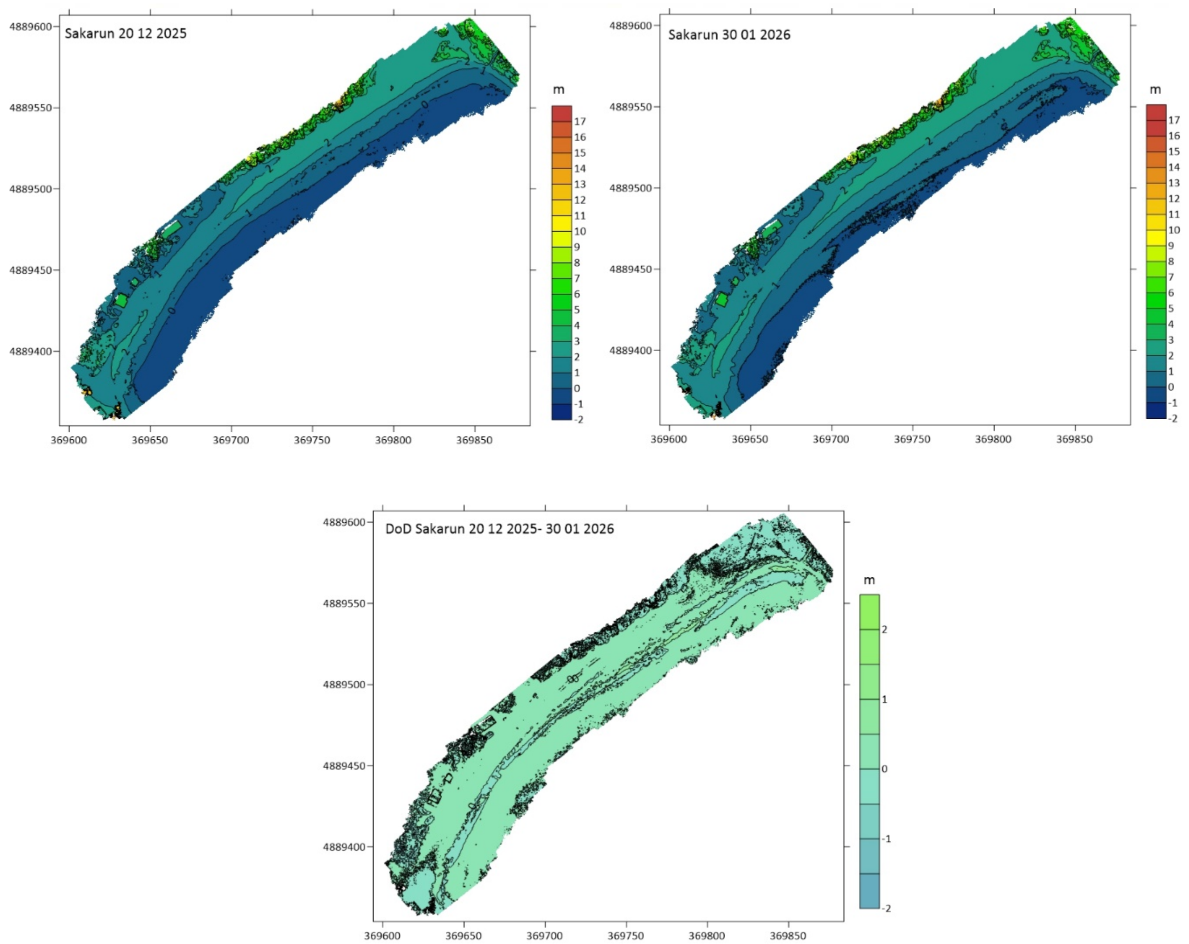


**Figure 20:** 3D models and the model of differences for monitoring period December 2025 – January 2026.

### *5.2.2.2. January 2026 – February 2026*

During the second period (January –February 2026) the beach area lost approximately half of the banquettes (Fig. 21). This is particularly evident on both sides of the beach. It is presumed that some part of the banquettes may have remained on the beach and been rearranged after the February SE event (Table 1). This storm occurred immediately before the February survey, and the beach probably did not have enough time to rebuild the lost banquettes. In the intertidal zone, a large amount of sand was present in February. This is partially due to the low tide during the survey, as well as the weakening of the storm and subsequent rebuilding of the beach. It should be emphasised that a significant amount of water was observed behind the highest beach berm, and several puddles formed beside the swampy part of the beach. This accumulation of water is the result of both rainfall and stormy SE waves.

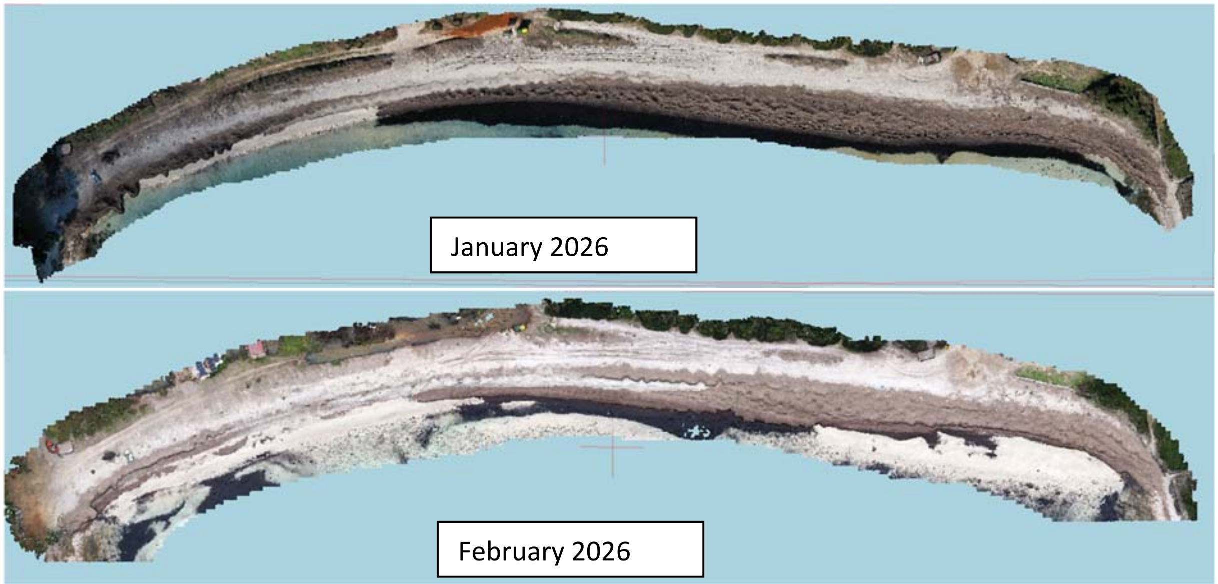


**Figure 21:** Dense point clouds of the Sakarun beach: January and February 2026.

The effect of the February SE storm is visible on the 3D models (Fig. 22). The entire beach is slightly narrower after the storm. Loss of material is evident in the lower part (mostly banquettes were lost), while the upper part has risen slightly due to steepening. Overall changes in elevation on Sakarun beach in this period do not exceed 0.5 m.

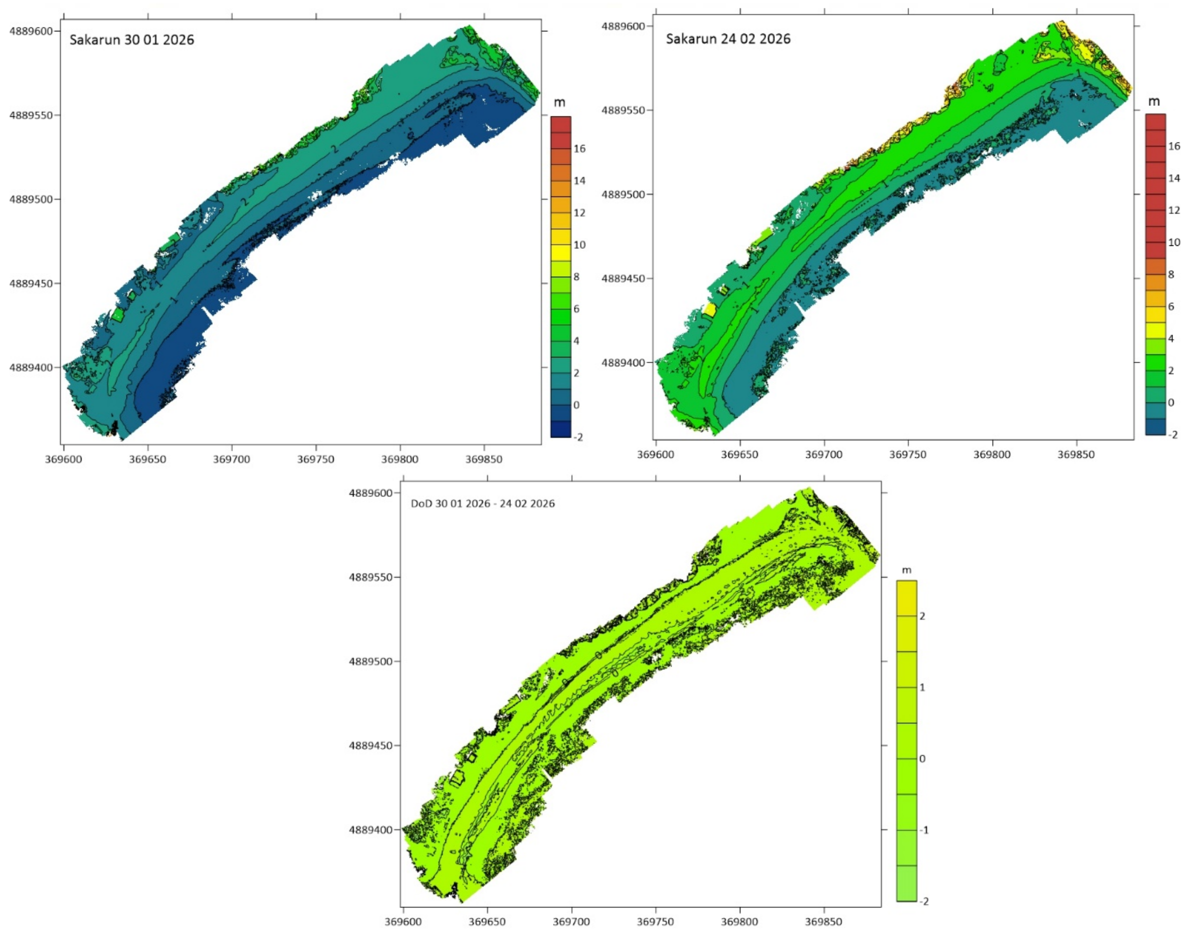


**Figure 22:** 3D models and the model of differences for monitoring period January and February 2026.

### *5.2.2.3. February 2026 – March 2026*

Morphological changes on the beach during the third monitoring period (February – March) were not significant. Most of the change involved further accumulation of banquettes in the lowest part of the beach. Banquettes in the upper part of the beach remained in place and even retained their shapes (central part of the beach). Relatively calm weather conditions, with only one SE event prior to the March survey (Table 1), were insufficient to remove and rebuild the entire banquette area. This is also confirmed in the previous Section, where beach profiles were discussed. In line with this description, major morphological changes are not visible on the 3D models either (Fig. 24). All changes did not exceed 0.5 m.

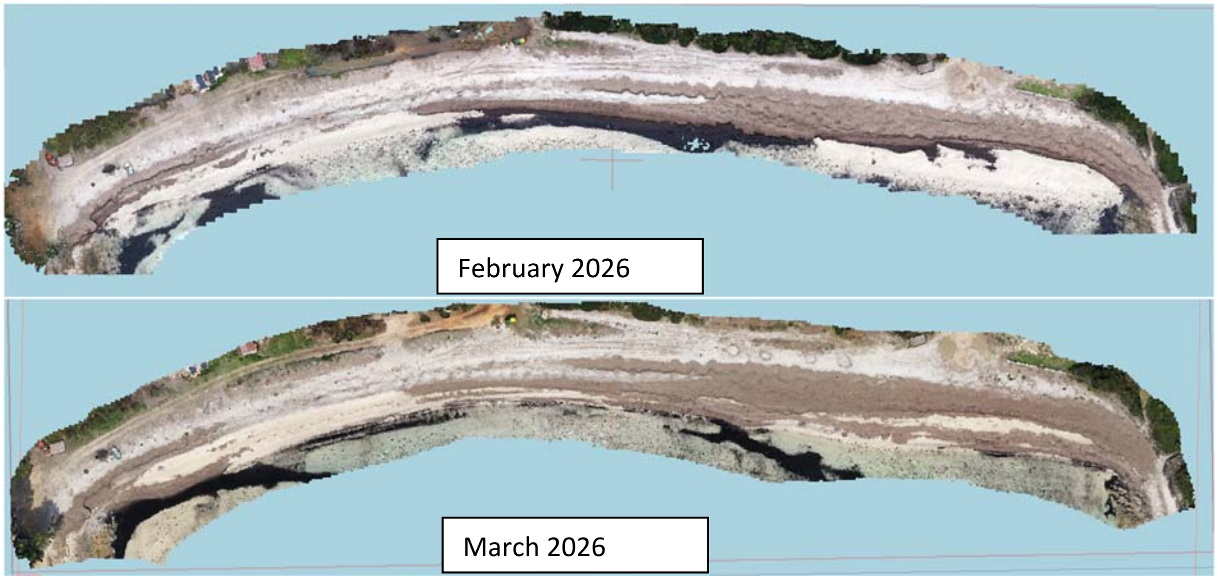


**Figure 23:** Dense point clouds of the Sakarun beach: February and March 2026.

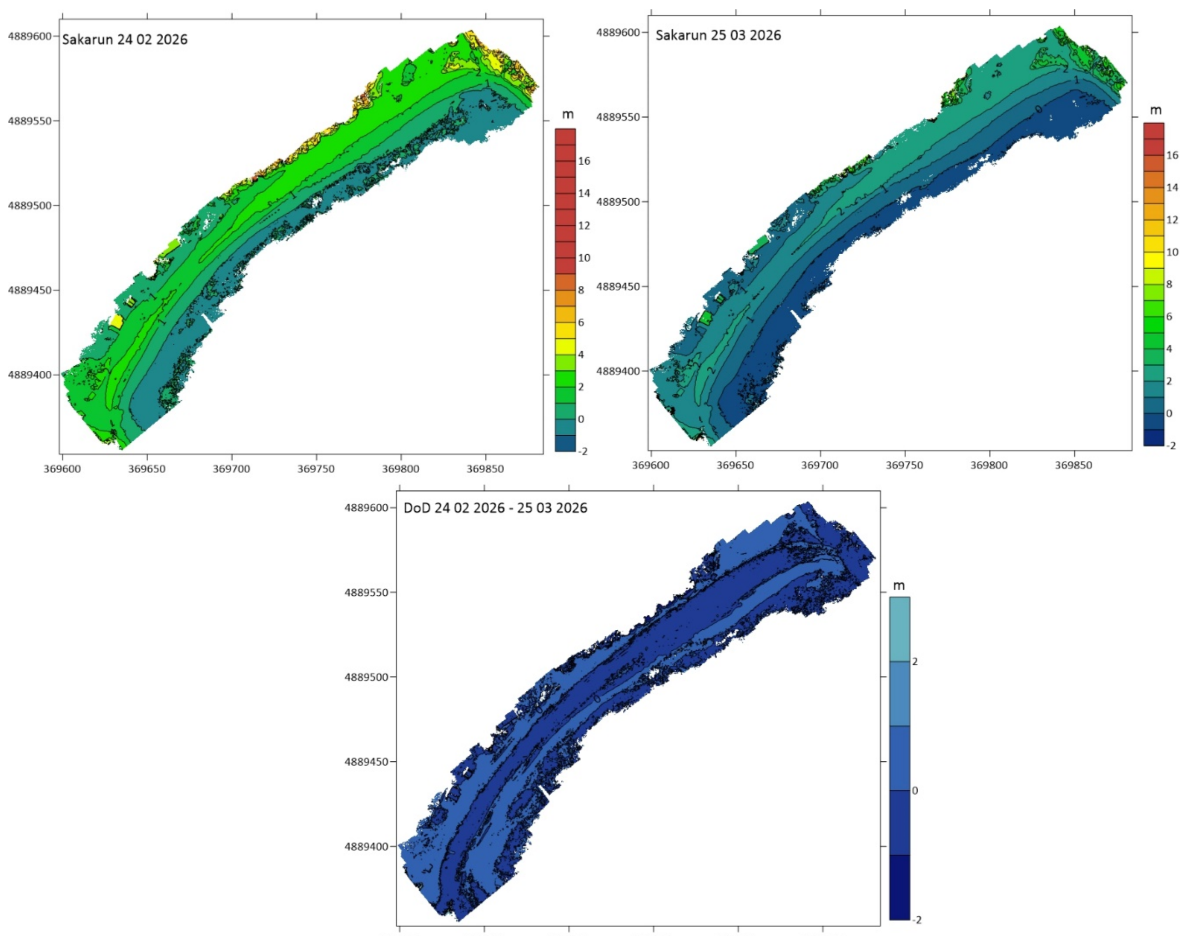


**Figure 24:** 3D models and the model of differences for monitoring period February – March 2026.

### *5.2.2.4. March 2026 – April 2026*

Relatively calm weather conditions persisted over the following 15 days, during which the first April survey was conducted (Table 1). These weather conditions did not result in significant changes during the March – April monitoring period (Fig. 25). Partial rebuilding of the banquette on the south-west (left) part of the beach is visible, while loss of Posidonia debris and sand was observed on the north-east (right) part of the beach. This shift from one side of the beach to the another may be the result of longshore transport. The movement of beached material could have been caused the NE waves. During fieldwork, it was observed that the NE wind is capable of forming only mild waves, as the fetch is too short for larger and more energetic waves. Accordingly, 3D models (Fig. 26) did not show significant changes beach morphology, except for the transfer of Posidonia and sand from one side of the beach to another, as described. All hanges did not exceed 0.5 m.

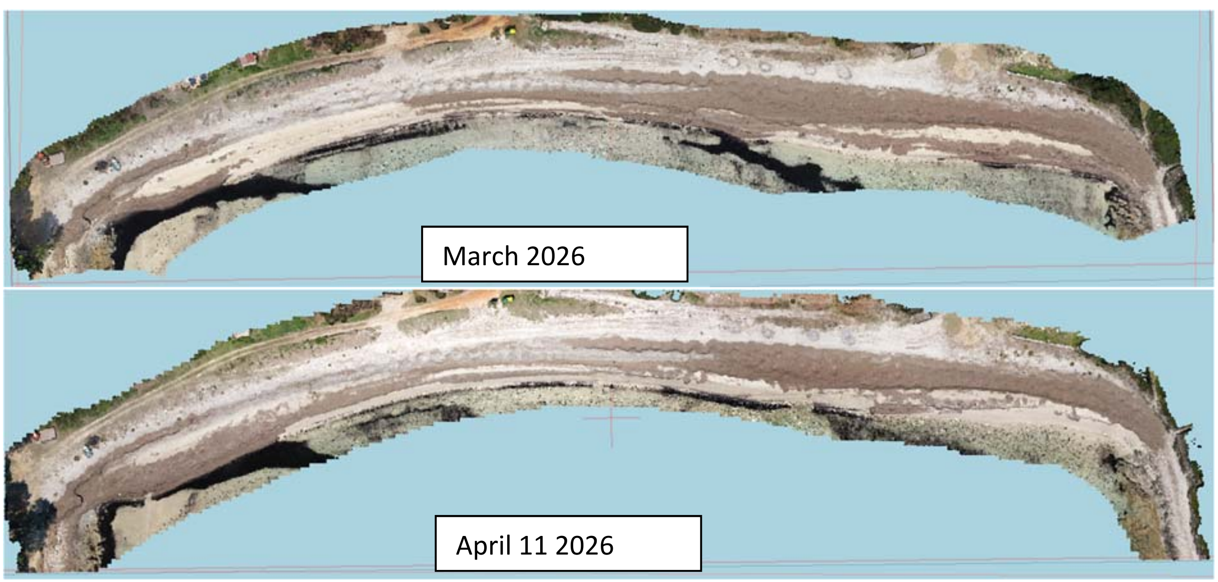


**Figure 25:** Dense point clouds of the Sakarun beach: March and April 2026.

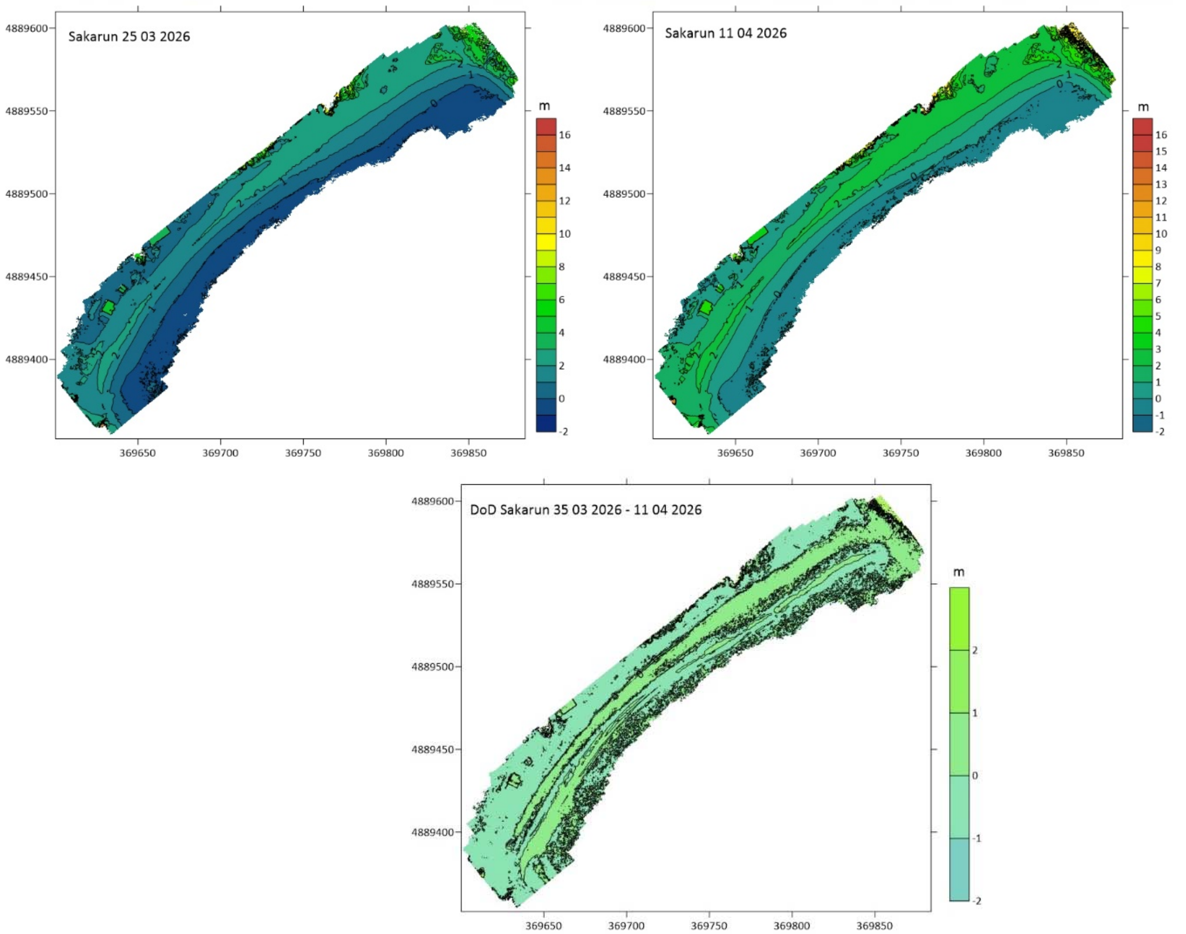


**Figure 26:** 3D models and the model of differences for monitoring period March – April 2026.

### *5.2.2.5. April 2026 – April 2026*

During the April –April monitoring period, one SE event occurred (Table 1). This storm caused partial erosion and subsequent rebuilding of the banquettes. The upper part of the banquettes remained largely unchanged, while only those in the lower part of the beach experienced alternation (Fig. 27). This division of the banquettes is clearly visible as a white line, representing sediment in the middle of the beach. Below this line, the banquettes were rearranged and more Posidonia debris was deposited on the beach after the mid-April storm. Other visible changes relate to vegetation growth. Observed changes did not exceed 0.5 m. Accordingly, 3D models have shown this re-accumulation of the banquettes in the lower part of the beach, with all changes were up to 0.6 m.

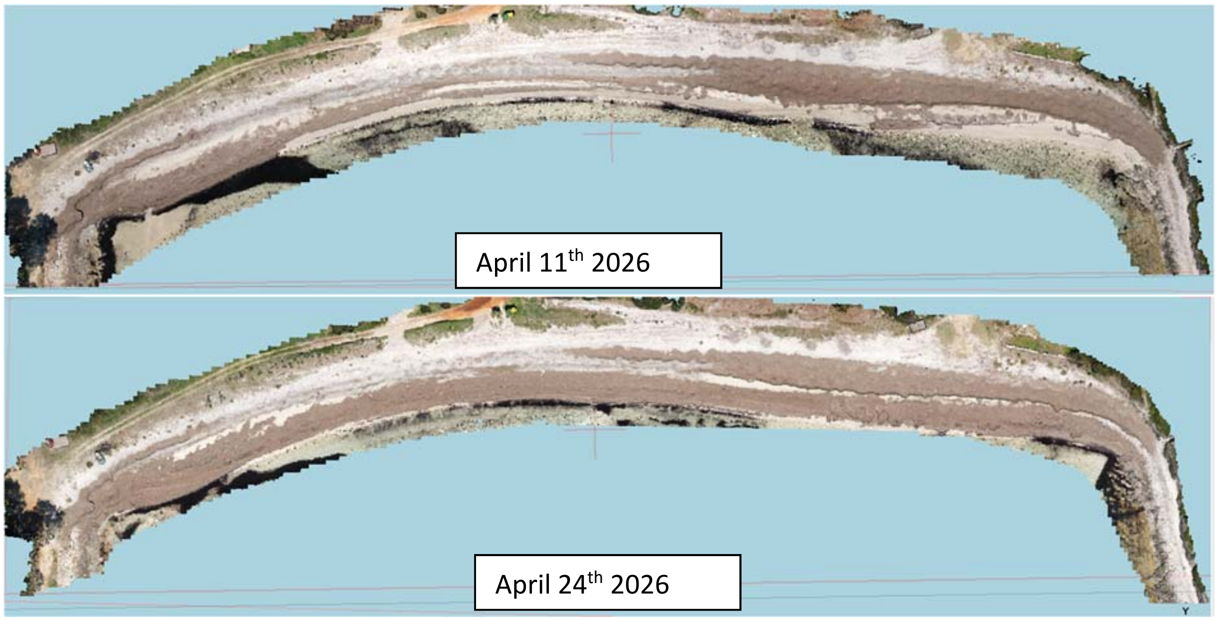


**Figure 27:** Dense point clouds of the Sakarun beach: April 11$^{th}$ and April 24$^{th}$ 2026.

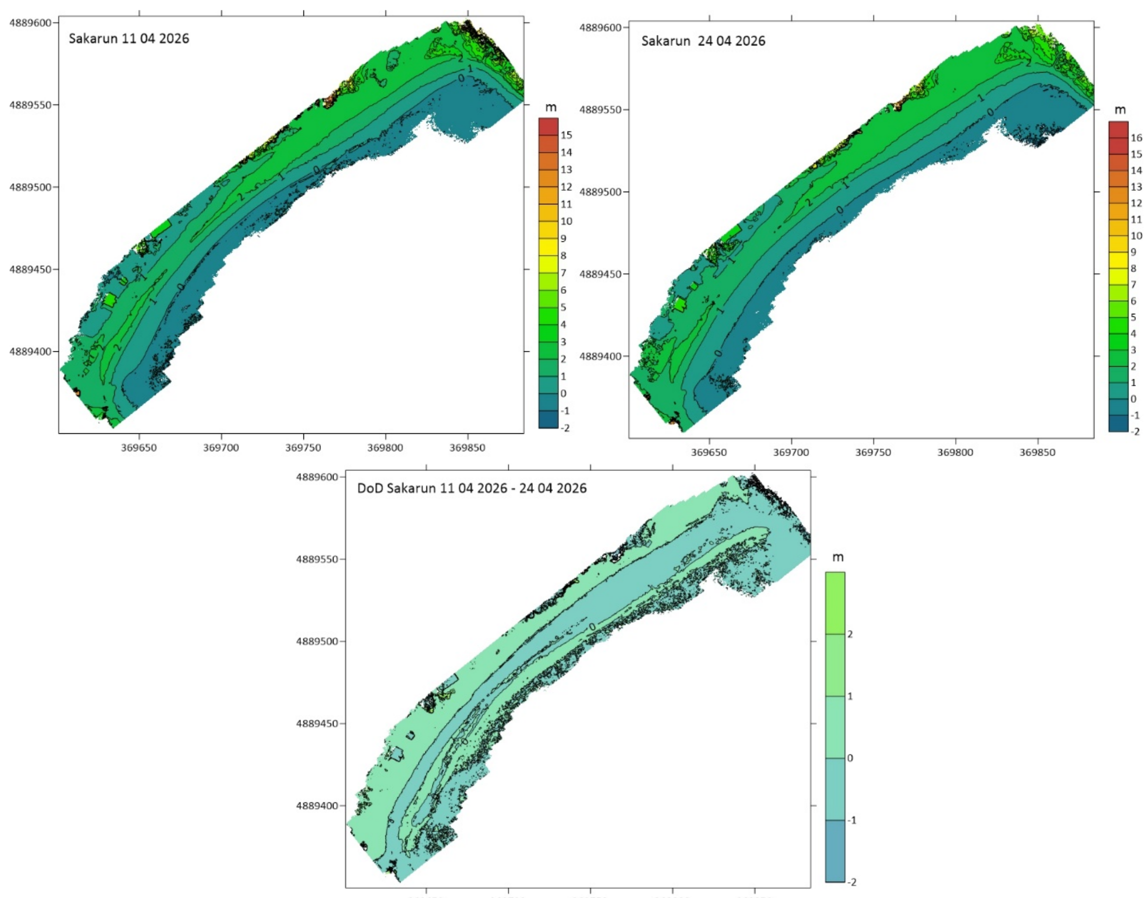


**Figure 28:** 3D models and the model of differences for monitoring period April-April 2026.

## 5.3. Natural Bridge beach

### 5.3.1. Beach profiling

Unlike the profiles on the Sakarun beach, the profiles on the Natural Bridge begin in the enclosed Pantera Bay (left side of the graph), cross the beach, and end in the north-facing open sea (right side of the graph) (Figs. 11 and 29). Due to changes in tide and wave conditions during each survey, it was not possible to define the same starting point as for Sakarun beach. For this reason, the comparison of profile changes at the Natural Bridge differs slightly from that at Sakarun beach: two successive survey dates for the profile are shown side by side, rather than overlapped. Additionally, note that the x-axis length differs on each graph; however, the width of the basal part of the Natural Bridge remains the same. The difference in x-axis length depended on the ability to enter the sea from either side, which was determined by the tide (high or low water) and wave conditions on the day of each survey. Therefore, a rectangle has been added to each graph to facilitate comparison of the profile within the designated area. This is because the greatest changes in morphodynamics on gravel beaches occur on berms and the beach step. In the case of the Natural Bridge, changes to the berms were related to the Posidonia banquettes, while the beach step was at around -0.5 m water depth on both sides. Below -0.5 m, basement rock predominated on the seaward side, while stable sediment prevailed on the inward (Pantera Bay) side.

#### *5.3.1.1. Profile 1*

Figures 29 – 34 clearly show that the Natural Bridge had an almost uniform width of 16 – 17 m along profile 1 on the mean sea level (0 m). The only exception is the beach condition on 24 April 2026 (Fig. 34), which will be explained later. During the first survey period (December 2025 – January 2026), profile 1 showed that the Natural Bridge in its south-western part had a consistent width and height. The maximum observed and measured height of the banquette along profile 1 in this period was **1.75 m**. This height is the total elevation from mean sea level (i.e. geodetic zero) to the highest measured crest of the banquette. Banquettes are known to be are wedge-like structures (Fig. 30), and their maximum height is actually lower if measured from the beach sediment. Changes in the shape of profile1 between the two surveys and the width of the beach at 0.5 m indicated erosional processes, which led to the flattening of the banquette top. During the first monitoring period only one storm event was observed – the one immediately before the January survey (Table 1). Although this event was caused by a SE wind, refraction of the generated waves and their low-angle incidence east would first affect the area where profile 1 is situated, after which longshore transport would occur towards the western part of the beach. The greatest steepness of banquettes was observed on the seaward side of the Natural Bridge, indicating the direction from which the banquettes are formed.

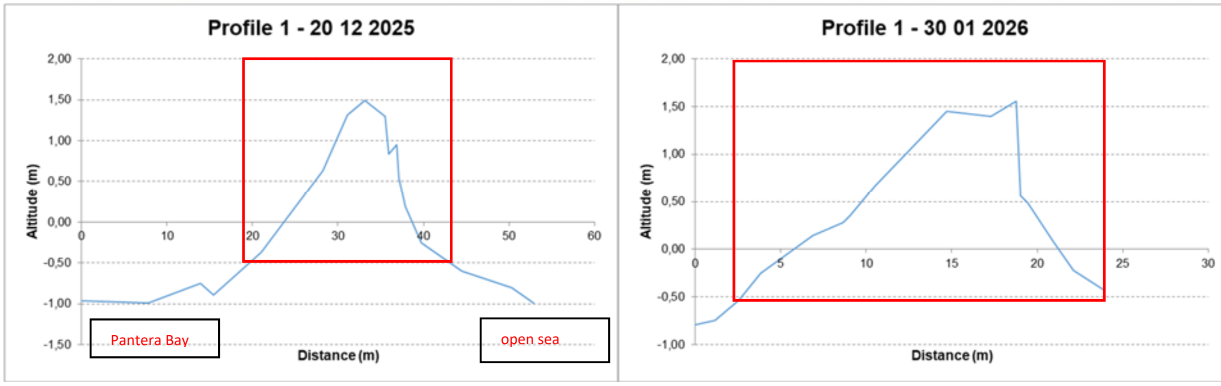


**Figure 29:** Comparison of the Natural Bridge profile 1 – December 2025– January 2026.

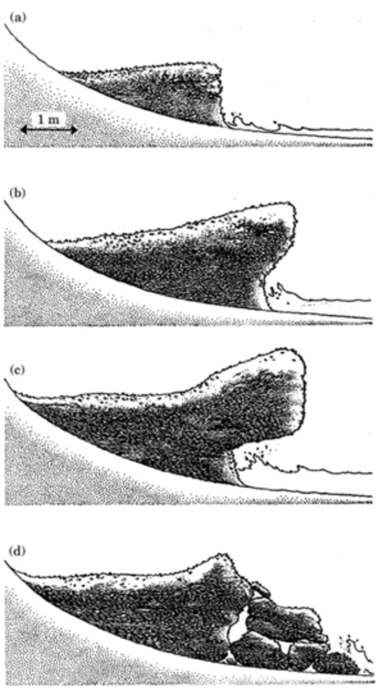


**Figure 30:** Deposition and erosion of banquette (Mateo et al., 2003).

During the second monitoring period (January – February), no significant changes were observed in beach shape along profile 1, except for some minor changes in banquette shape and height at the top (Fig. 31). However, waves cannot rearrange the banquette top without altering their lower parts. Therefore, it is assumed that the SE storm event which occurred prior to the February survey (Table 1) rearranged much of the banquettes in the same way as in the previous period. This seems likely, considering that both SE events were of similar intensity (Table 1). The maximum measured banquette crest height along profile 1 during this period was **1.64 m**.

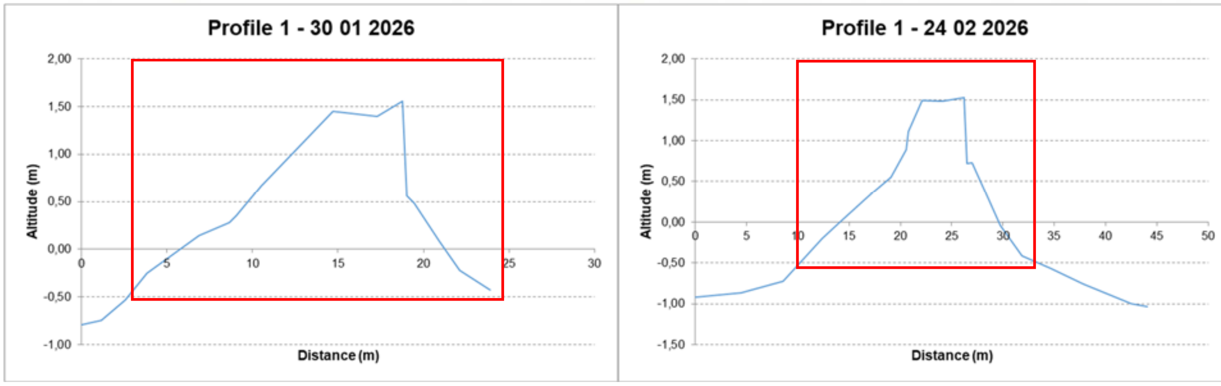


**Figure 31:** Comparison of the Natural Bridge profile 1 – January – February 2026.

The third monitoring period (February – March) along profile 1 showed slight disintegration of the banquette in its lower part on the seaward side (Fig 32). This is also visible in the dense point cloud in Section 5.3.2. The reason for this partial disintegration was found to be the combined effect of NE and SE events between 15 and 20 February (Table 1). Based on the research conducted, it is hypothesised that the effect of NE wind waves on this beach mainly ensures the supply of Posidonia debris, while SE waves are the key forcing mechanism for banquette accumulation and destruction. This should be confirmed in future studies. The maximum banquette height in this period along profile 1 was **1.59 m**.

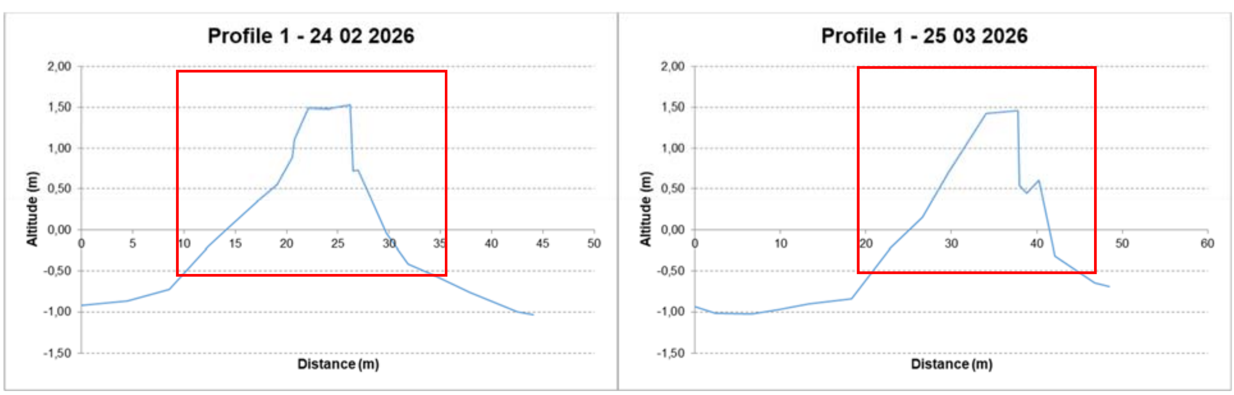


**Figure 32:** Comparison of the Natural Bridge profile 1 – February – March 2026.

The monitoring period of March – April saw further disintegration of the lower part of the banquette (Fig. 33). This is also visible in the dense point cloud in Section 5.3.2. The top of the banquette was slightly altered, but there were no significant changes in banquette height. The highest crest of the banquette during this period was **1.57** m along the profile 1. It should be noted that both winds mentioned can lift dry Posidonia debris from the banquettes and transport it towards Pantera Bay.

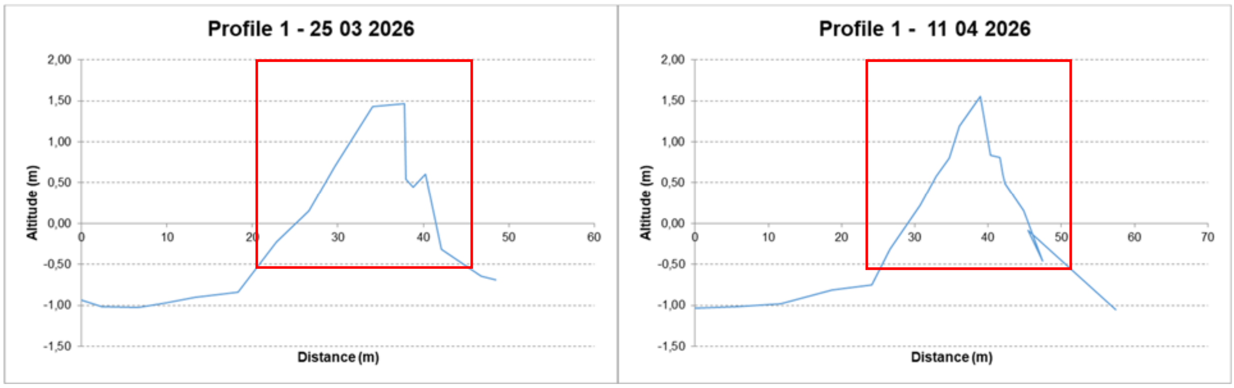


**Figure 33:** Comparison of the Natural Bridge profile 1 – March – April 2026.

During the final monitoring period of approximately 15 days (April – April period; Fig. 34), disintegration of banquettes was observed on the seaward side of the beach, which was also visible in the dense point cloud (Section 5.3.2). This led to widening of the beach at the 0.5 m level. The height of the banquettes did not change significantly, but their shape was altered. This disintegration was attributed to the SE event that occurred during in 12–14 April (Table 1).

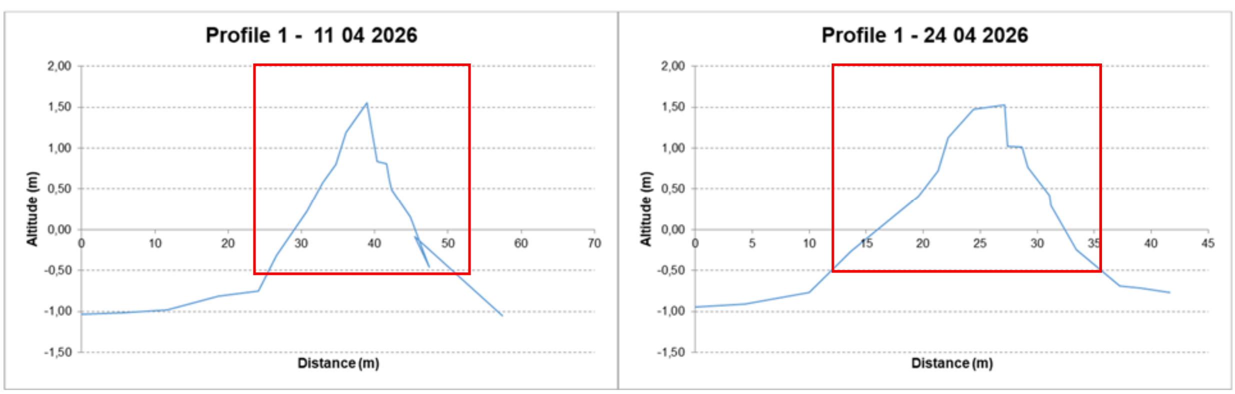


**Figure 34:** Comparison of the Natural Bridge profile 1 – April – April 2026.

### *5.3.1.2. Profile 2*

Profile 2 is located in the central part of the beach (Fig. 10), where the beach is slightly wider (18–20 m) at the mean sea-level (0 m) compared to profile 1 (Fig. 35). During the first monitoring period (December 2025 – January 2026), the general dimensions of the banquette did not change significantly, however, the shape of the profile altered considerably. The top of the banquette was quite indented in December but became flattened by the January survey. This flattening was actually a narrowing and steepening of the lower parts of the banquette: Posidonia steps visible in December were eroded until January, meaning the beach steepened on its seaward side. This suggests erosion, probably related to the SE event prior to the January survey (Table 1). The other side of the beach (towards Pantera Bay) also changed slightly during this period, indicating that SE wind waves could enter Pantera Bay and affect the Natural Bridge from the inside, as explained in Section 2.3. During this process, part of the banquette was removed from the beach and transported into Pantera Bay, as observed during the fieldwork. Most of this Posidonia debris remains on the seabed of Pantera Bay, contributing to the formation of its ecosystem. The maximum measured height of the banquette along profile 2 during this period was **1.86 m.**

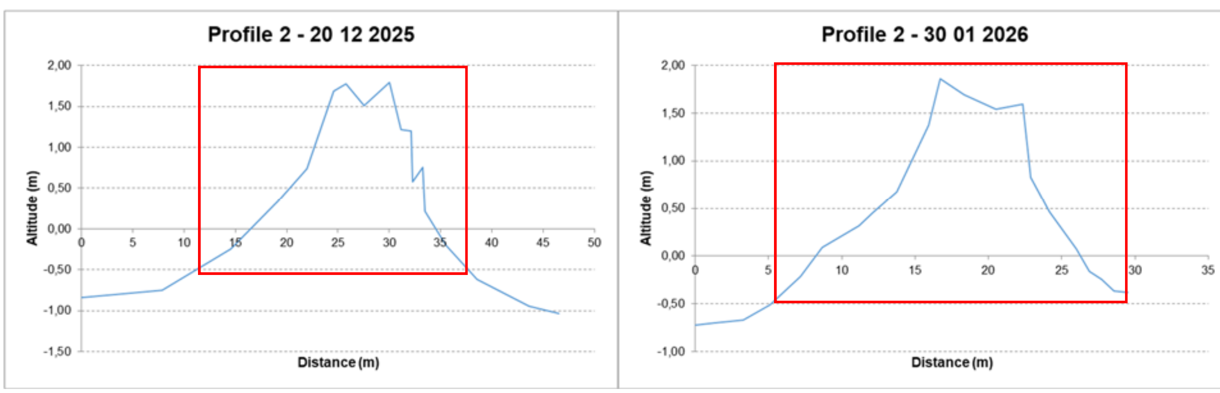


**Figure 35:** Comparison of the Natural Bridge profile 2 – December 2025 – January 2026.

The period January – February (Fig. 36) did not bring significant changes in the dimensions or shape of the beach and banquettes. The main change was the additional build-up of one step on the seaward part of the banquette, probably due to SE wind events during February. Furthermore, the banquette was slightly steepened, indicating an erosional process, presumably caused by the same SE event (Table 1). This erosional process and the steepening of the banquettes were clearly documented during the February survey (Fig. 37). The erosional influence of the waves is also evident in the movement of pebbles, during which lifted pebbles "shave" the seaward side of the banquette, leaving it smooth and steep. The height of this "shaving" process did not exceed 40 cm. It is likely that this process occurs during the SE events, when SE wind waves initiate longshore transport of both sediment and Posidonia debris.The maximum measured height of the banquette crest was **1.83 m**. Note that the DGPS pole is 2 m high (Fig. 36).

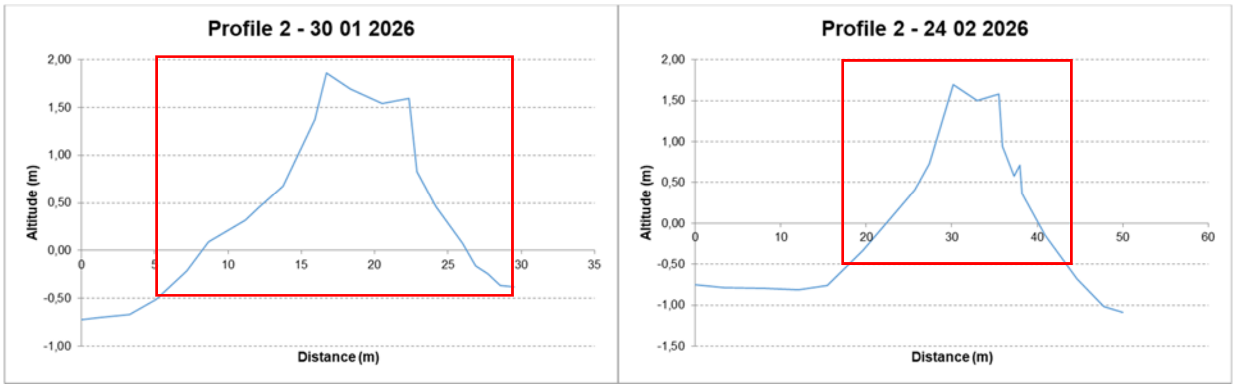


**Figure 36:** Comparison of the Natural Bridge profile 2 – January – February

**Figure 37:** Banquette on the Natural Bridge "shaved" by pebbles raised by waves.

The February – March monitoring period did not bring much change in beach or banquette dimensions (Fig. 38). Only the seaward side of the banquettes was slightly altered in its lower part, most often under the influence of various wave conditions. This largely unchanged profile is attributed to the combined effect of both NE and SE wind events, which occurred consecutively in mid-February (Table 1). The highest banquette measured here was **1.72 m**.

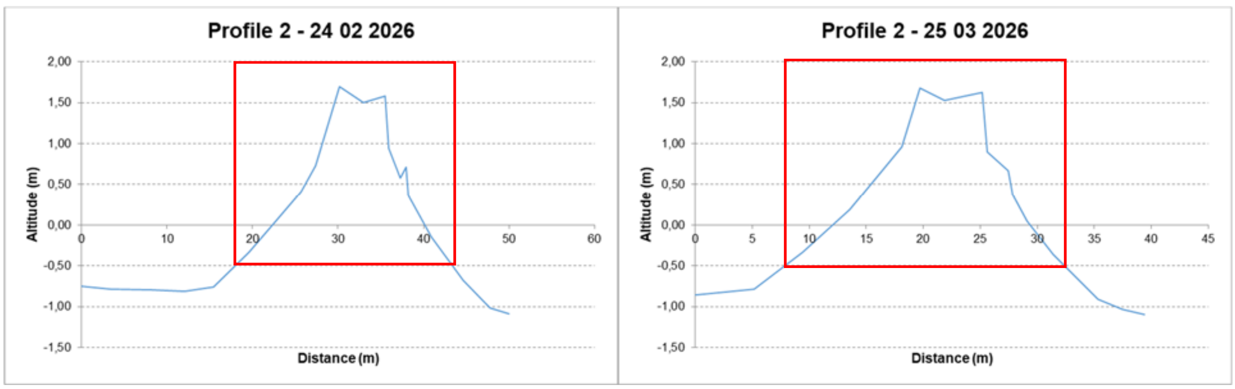


**Figure 38:** Comparison of the Natural Bridge profile 2 – February – March 2026.

According to profile 2, during the period between March and April (Fig. 39), only a mild change was observed on the seaward side of the banquettes, in the form of slight disintegration. This was also confirmed by dense point clouds shown in Section 5.3.2. Other changes observed during this period included the loss of some of the highest crests of the banquettes. This minor change was attributed to occurrence of SE waves after the March survey (Table 1), causing their gravitational instability and lowering. The highest measured banquette here was **1.69 m**.

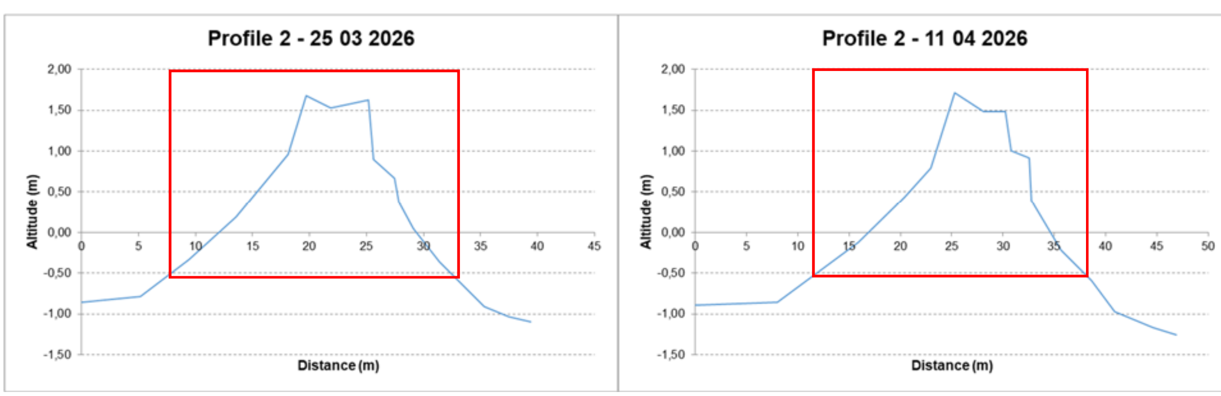


**Figure 39:** Comparison of the Natural Bridge profile 2 – March – April 2026.

During the last monitoring period, profile 2 underwent further reshaping, mainly again from its seaward side, probably caused by SE waves in mid-April (Table 1; Fig 40). This reshaping also resulted in the narrowing of the beach, i.e. mostly banquette. The maximum measured banquette height was **1.74 m**.

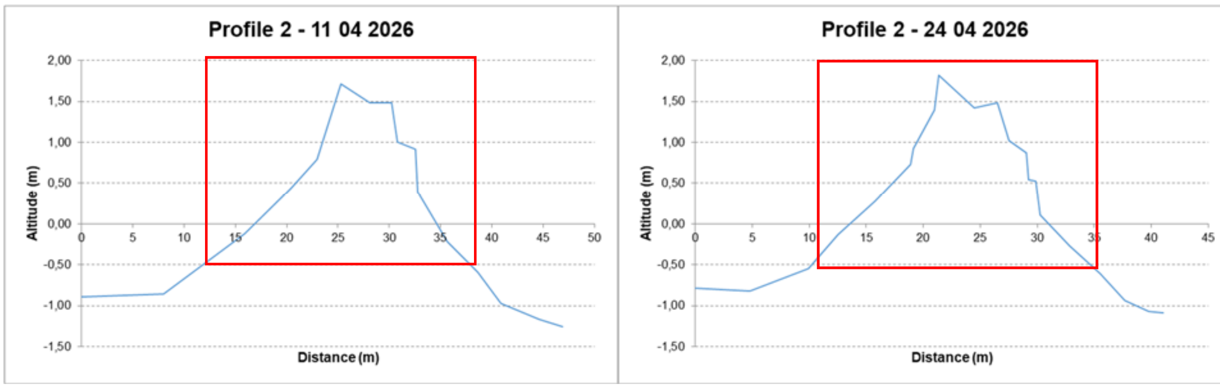


**Figure 40:** Comparison of the Natural Bridge profile 2 – April – April 2026.

### *5.3.1.3. Profile 3*

The beach is widest along profile 3 (Fig. 11). Its inner part ends in a very shallow corner, which causes the general asymmetry shown in all the figures below (Fig. 41 – 45). The width of the beach at the sea-level varies between 22 and 25 m. The first monitoring period showed reshaping of the banquettes from the seaward side, along with narrowing in the upper part and an increase in elevation (Fig. 41). The elevation is particularly noticeable in January, as the banquette height rose to over 2 m. All these processes were attributed to the SE event in January (Table 1).

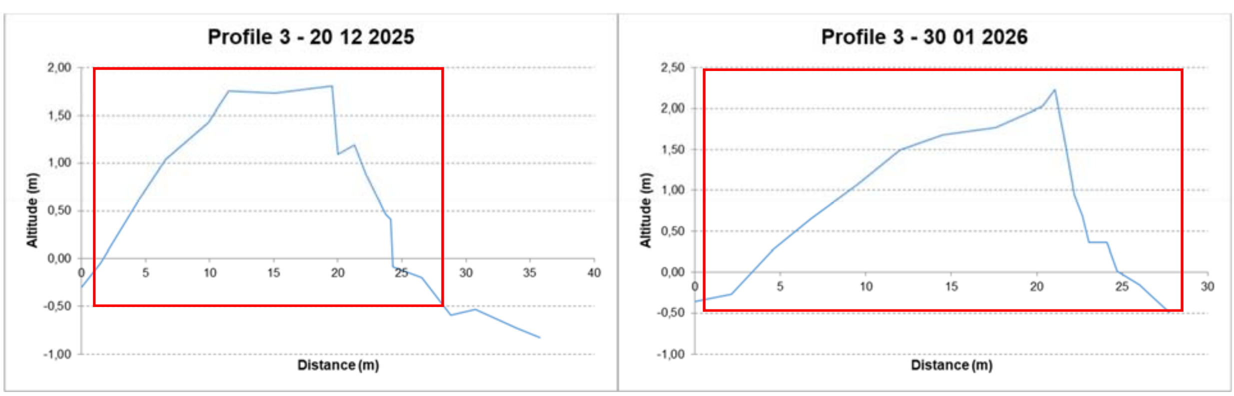


**Figure 41:** Comparison of the Natural Bridge profile 3 – December 2025 – January 2026.

During the second period (January – February), the beach shape changed slightly, mostly again on the outer side of the beach and on the banquette top (Fig. 42). Some new steps formed during this period on the seaward side, while the banquette top rose to the maximum measured height of **2.37 m**. This was the highest value recorded on the Natural Bridge during the monitoring period. All these processes were attributed to the SE event combined with the NE event in mid-February. The supply of Posidonia debris was enormous, and much of it remained in the shallow sea, as visible in the dense point cloud.

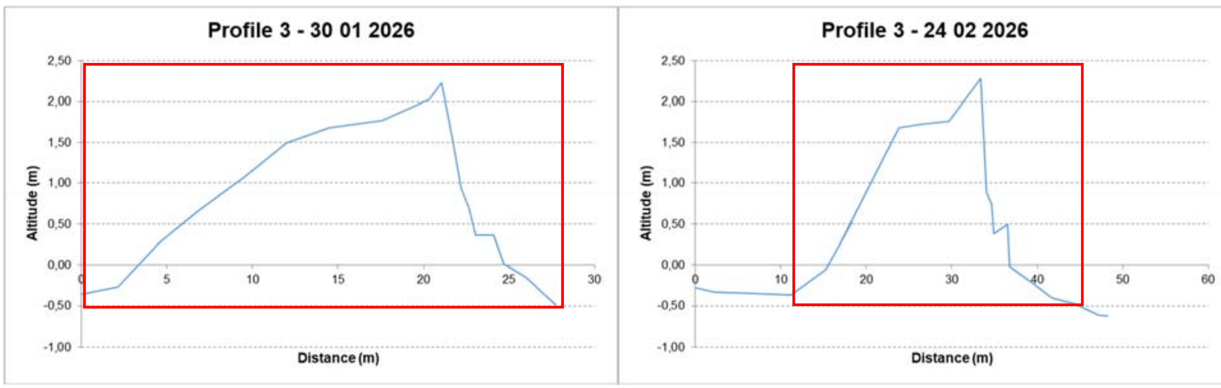


**Figure 42:** Comparison of the Natural Bridge profile 3 – January – February 2026.

During the third monitoring period (February – March) further reshaping continued with the gradual lowering of profile 3 (Fig. 43); however, the sediment base of the beach remained unchanged. Slight disintegration of the lower part of the banquette occurred, and much of the eroded Posidonia debris continuously retained immediately in front of the beach. The erosional processes observed here were mild, and it is assumed that the lowering occurred due to the both the gravitational instability of the highest banquette crests and the erosion of dry Posidonia debris by wind (as observed during fieldwork).

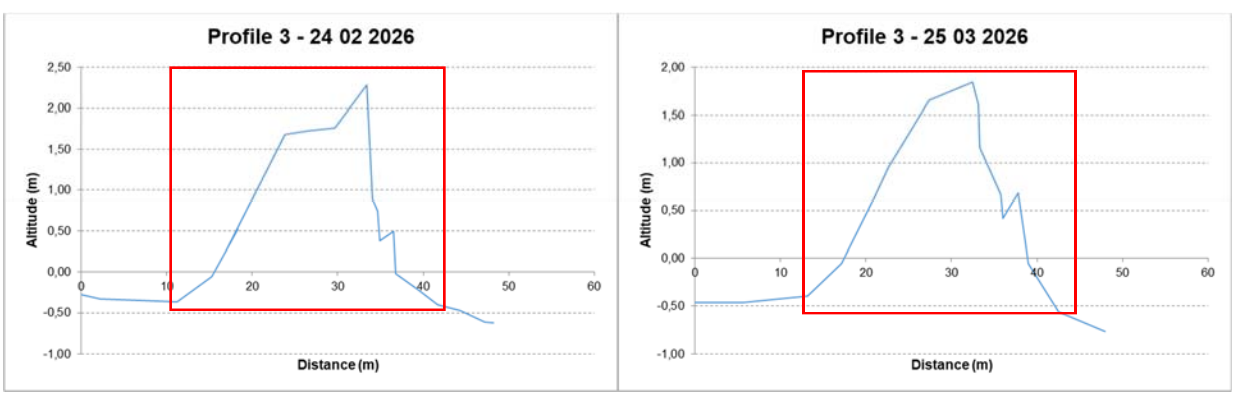


**Figure 43:** Comparison of the Natural Bridge profile 3 – February – March 2026.

Relatively mild reshaping, with lowering of seaward banquette, continued along profile 3 during the March – April monitoring period. It is presumed that a SE event occurred at the beginning of this period (Table 1), initiating wave and wind erosion. The maximum height of banquettes here was **1.75 m**.

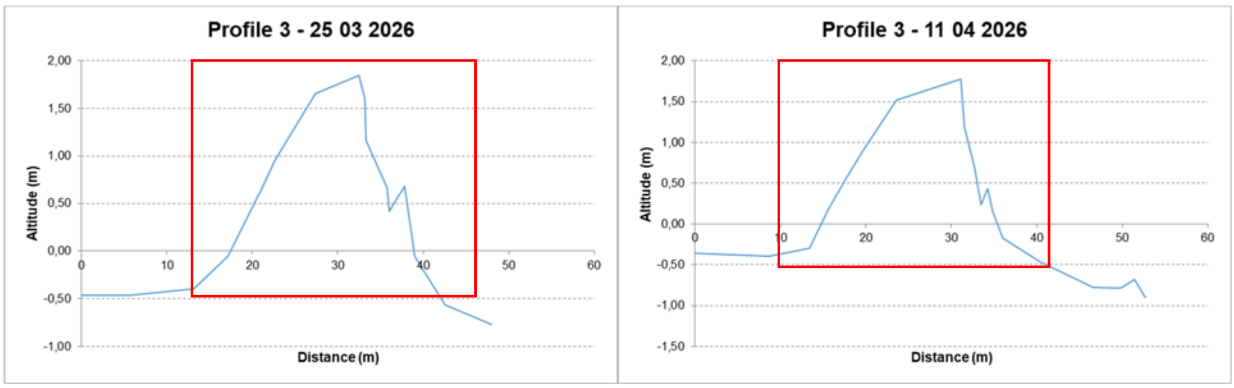


**Figure 43:** Comparison of the Natural Bridge profile 3 – March – April 2026.

The final monitoring period (April to April) brought changes in the profile 3 shape, as shown in the Figure 44. Many of these changes are visible on the banquette top and most are related to the SE event in mid-April (Table 1, Fig. 44). Dense cloud also showed these changes (Section 5.3.2.), and some are attributed to gravitational instability and erosion of Posidonia debris by wind. The maximum measured banquette height during this period was **1.87 m**.

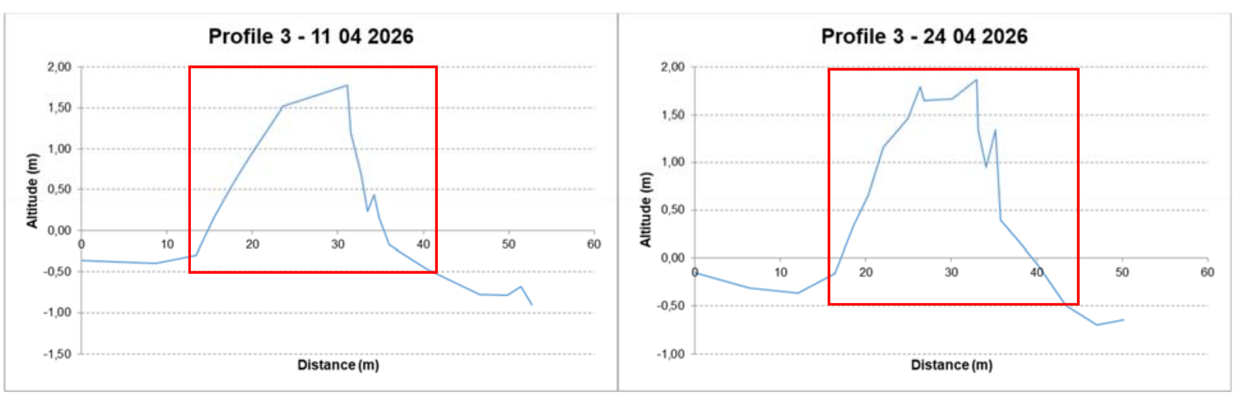


**Figure 44:** Comparison of the Natural Bridge profile 3 – April – April 2026.

### 5.3.2. Morphological changes

During all monitoring periods of the Natural Bridge, morphological changes were most pronounced on the seaward part of the beach, as already observed in the profiles.

#### *5.3.2.1. December 2025 – January 2026*

During the first monitoring period (December 2025 – January 2026), Natural Bridge largely maintained its general dimensions (Fig. 45). Minor changes of up to 0.5 occurred along the entire beach, relating to banquette steepening and slight alterations in the banquettes. These changes were already discussed explained in the previous Section, where the evolution of the profiles was explained in detail. The slight increase in banquette height is attributed to the SE event that occurred prior to the January survey. Steepening is observed on the side facing the Pantera Bay (Fig. 46), where a narrow strip of sediment loss was recorded. This confirms the hypothesis that high-energy SE waves enter the bay and alter the beach morphology, as explained in Section 2.3.

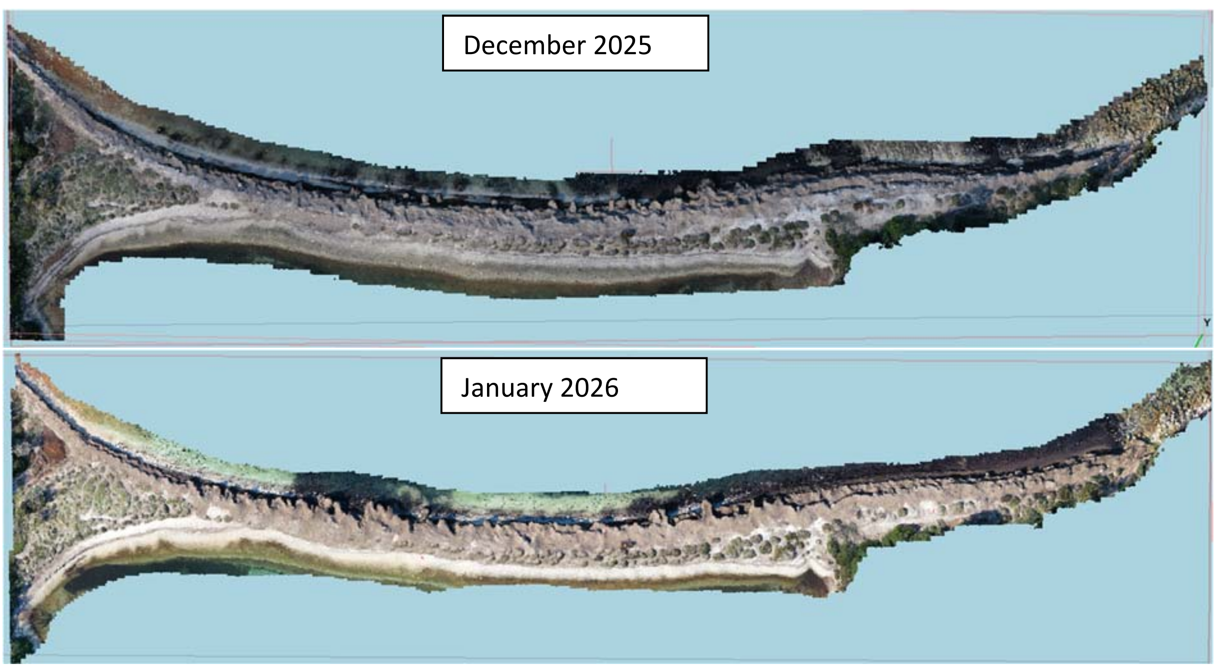


**Figure 45:** Dense point clouds of the Natural Bridge beach: December 2025 and January 2026.

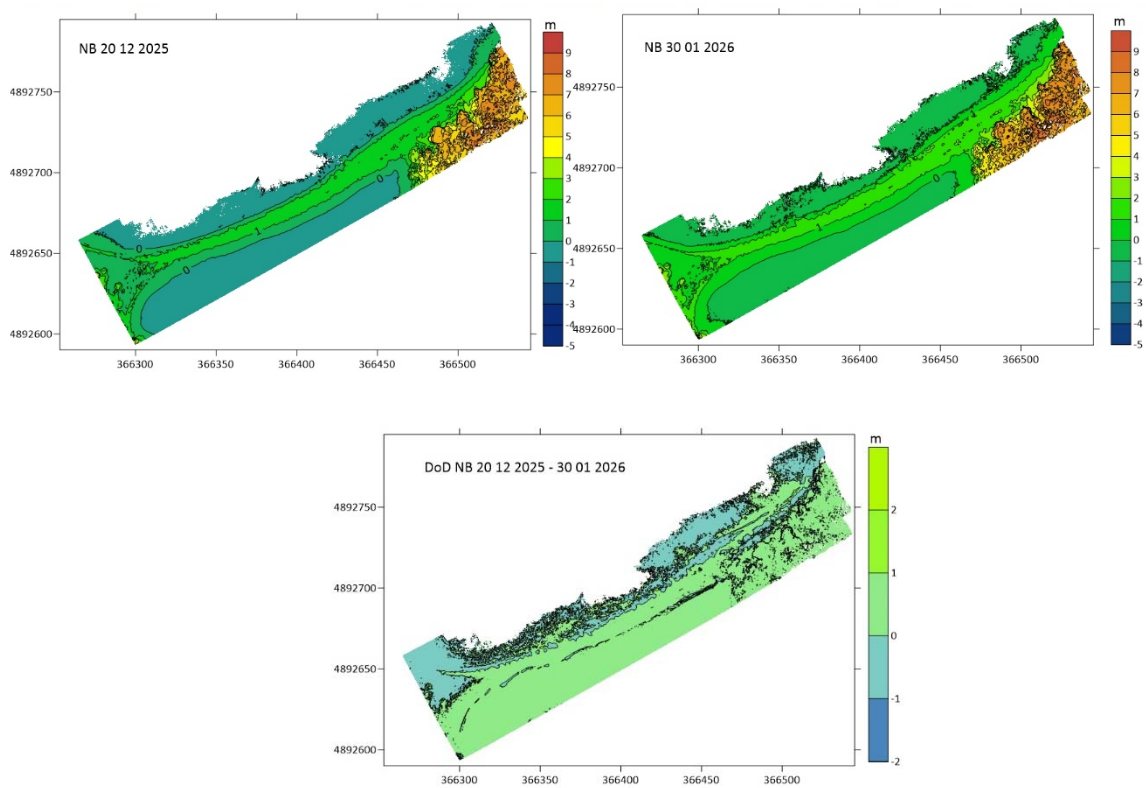


**Figure 46:** 3D models and the model of differences for monitoring period December 2025 - January 2026.

### *5.3.2.2. January 2026 – February 2026*

Figure 47. shows the new evolution of the Natural Bridge between the January and February survey dates. Although the beach appears almost unchanged, the first noticeable change is on the seaward side of the banquettes, where some rearrangement has occurred in the form of steepening. This is attributed to the February SE events. In contrast, the beach vegetation on the other side of the beach (towards Pantera Bay) was more covered with Posidonia debris, likely due to the effect of the NE winds, that also occurred in mid-February. These winds are capable of eroding dry Posidonia leaves and transporting them towards Pantera Bay. Both changes are visible in the 3D model visuals (Fig. 48).


**Figure 47:** Dense point clouds of the Natural Bridge beach: January 2026 and February 2026.

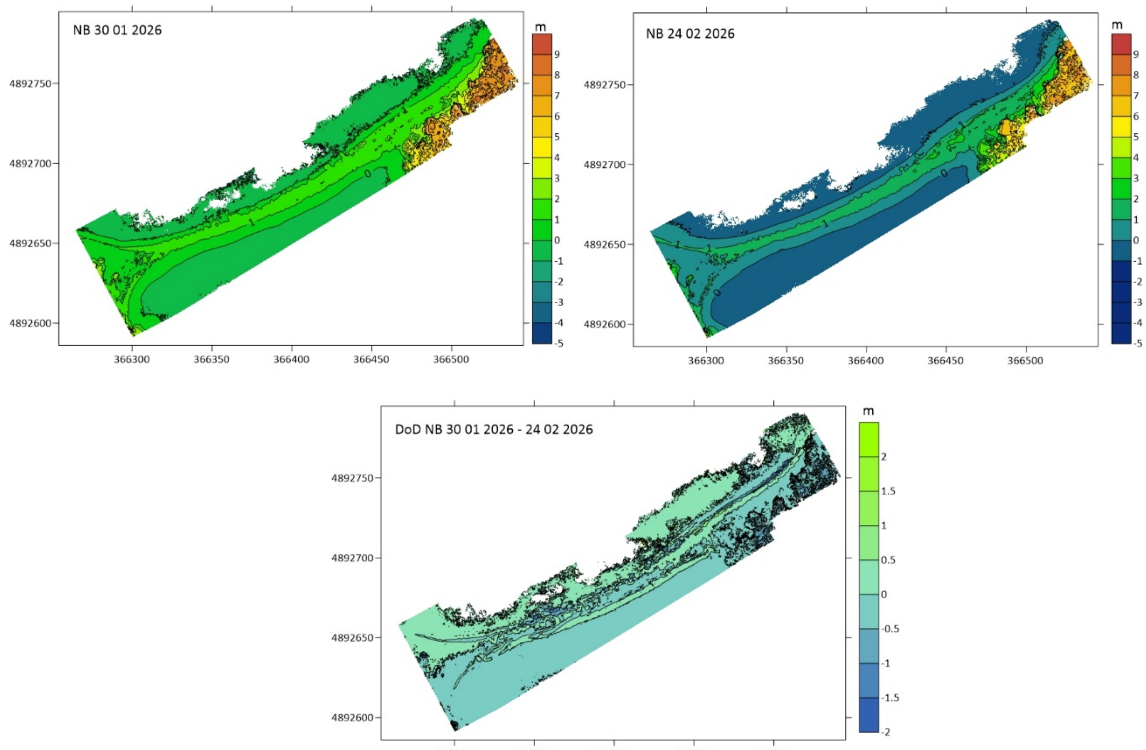


**Figure 48:** 3D models and the model of differences for monitoring period January-February 2026.

### *5.3.2.3. February 2026 – March 2026*

The most significant change during the February – March monitoring period is a new accumulation of Posidonia debris on the lower parts of the seaward side of the beach, as shown in Figures 49 and 50. This situation has been described in the previous Section about profiles. The accumulation is probably due to the combined action of the NE and SE winds (Table 1). The former supplies Posidonia leaves, while the latter ensures their even distribution along the beach. The described accumulation reached over 0.6 m in some places, but was mostly up to 0.5 m.

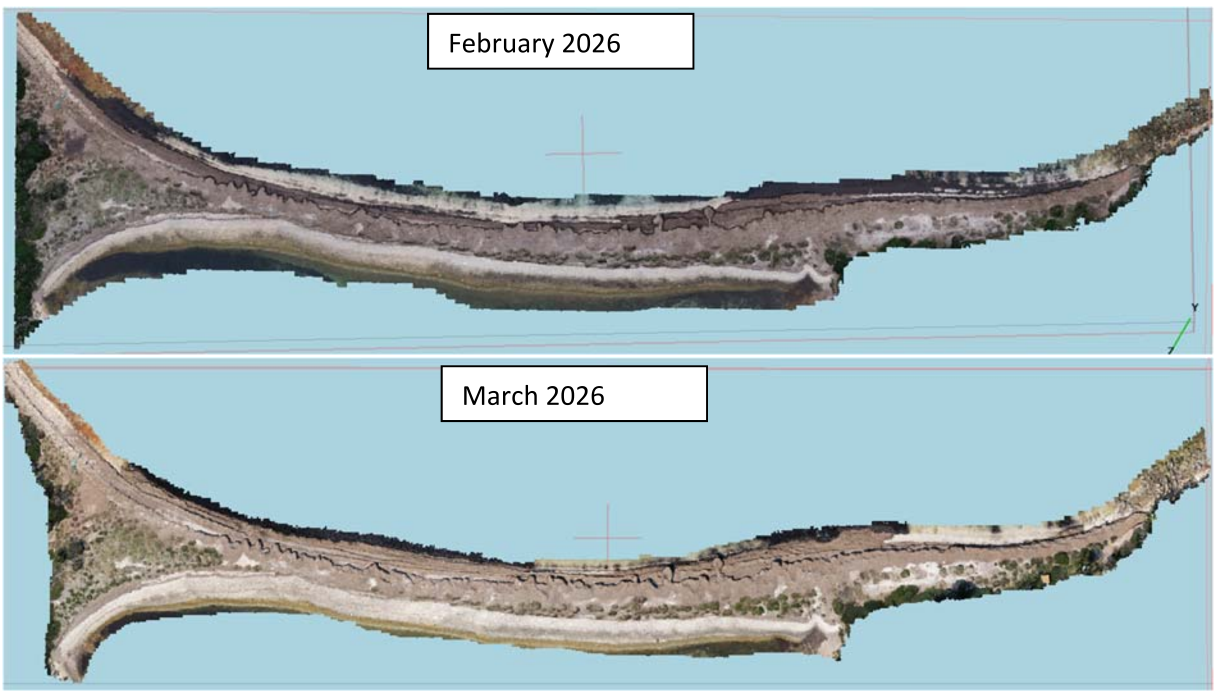


**Figure 49:** Dense point clouds of the Natural Bridge beach: February 2026 and March 2026.

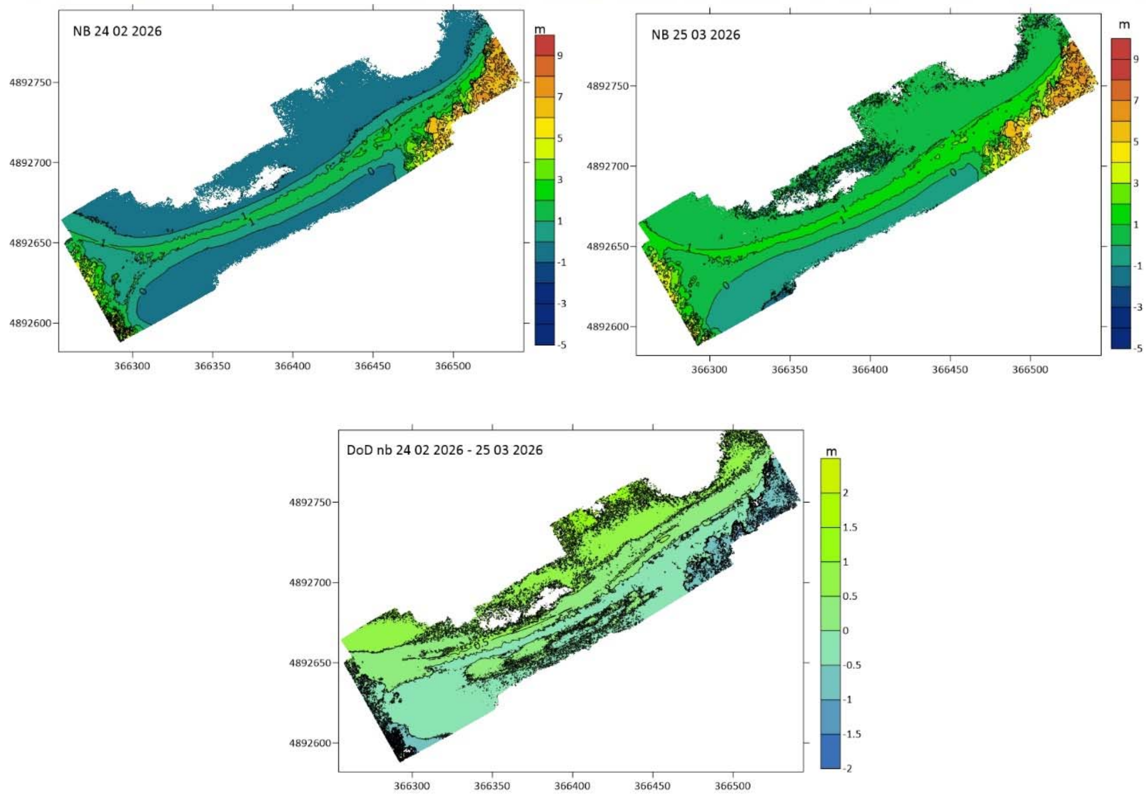


**Figure 50:** 3D models and the model of differences for monitoring period February – March 2026.

### *5.3.2.4. March 2026 – April 2026*

During the March – April short monitoring period, some visible changes occurred on the seaward part of the beach, as previously described in Section 5.3.1. The lowest part of the banquettes was partially eroded and/or pushed towards the beach, causing it to become steeper. This erosion exposed barren sediment, and this change exceeded 0.5 m in places (Figs. 51 and 52). The top of the banquette remained more or less unchanged with occasional variations in its overall height. In the area of profile 3, some parts of the banquette rose over 2 m high. These changes were explained in Section 5.3.1.


**Figure 51:** Dense point clouds of the Natural Bridge beach: March 2026 and April 2026.

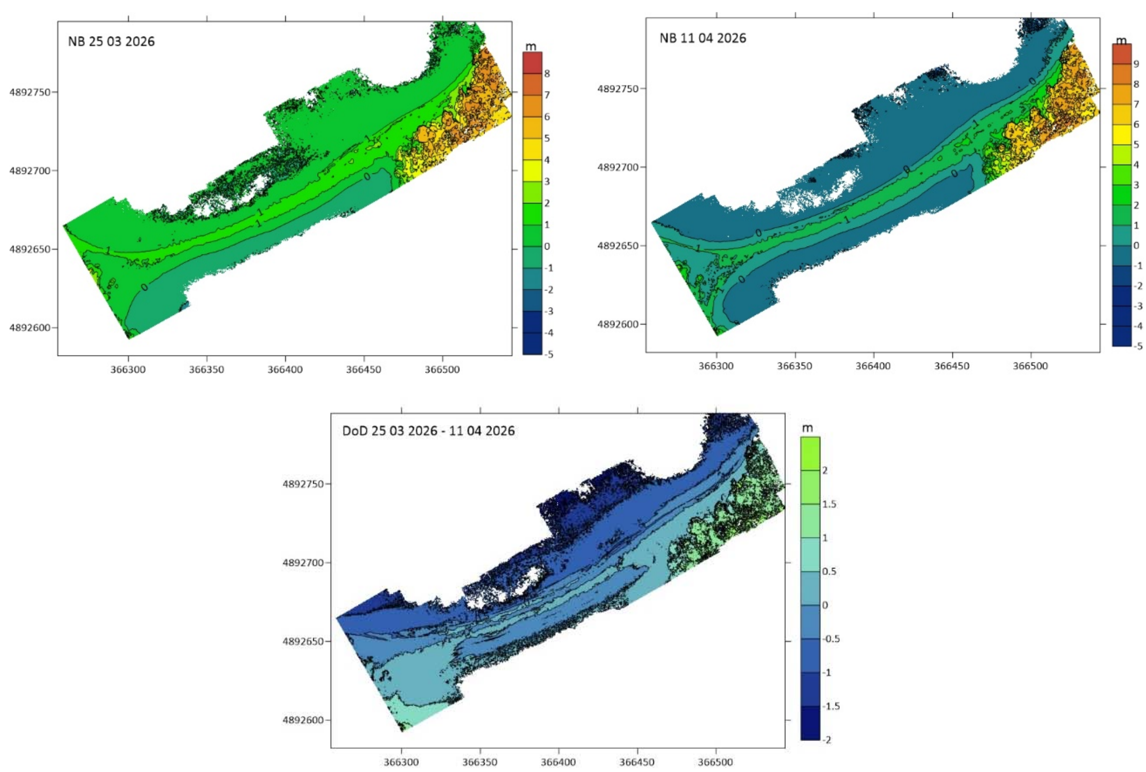


**Figure 52:** 3D models and the model of differences for monitoring period March 2026 – April 2026.

### *5.3.2.5. April 2026 – April 2026*

The last monitoring period (April 11th – April 24th 2026) was also short; however, accumulation of Posidonia debris was recorded on the NE (right) part of the beach. This is probably the result of longshore transport initiated by the SE event in mid-April (Table 1). Specifically, the loss of banquette on its SW (left) side was observed (Figs. 53 and 54). The rest of the banquette retained its general form. Small changes were observed on its highest parts, where more sections of the banquette rose above 2 m compared to the situation at the beginning of April.

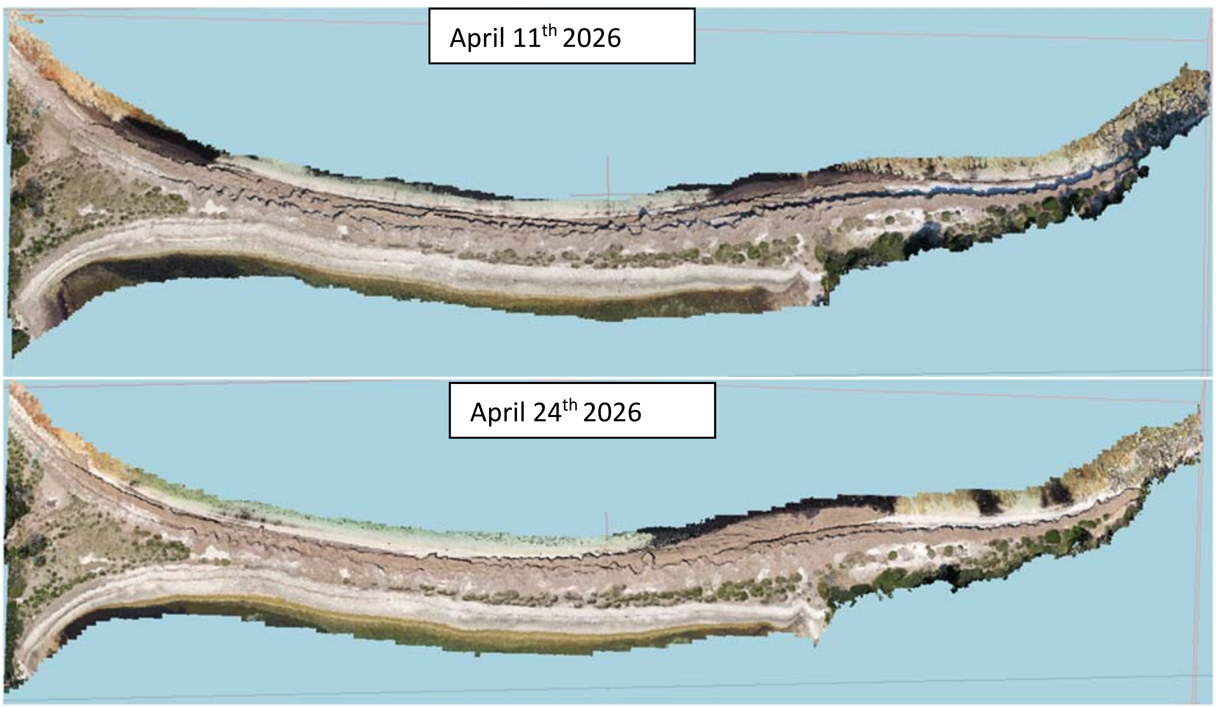


**Figure 53:** Dense point clouds of the Natural Bridge beach: April 11th and April 24th 2026.

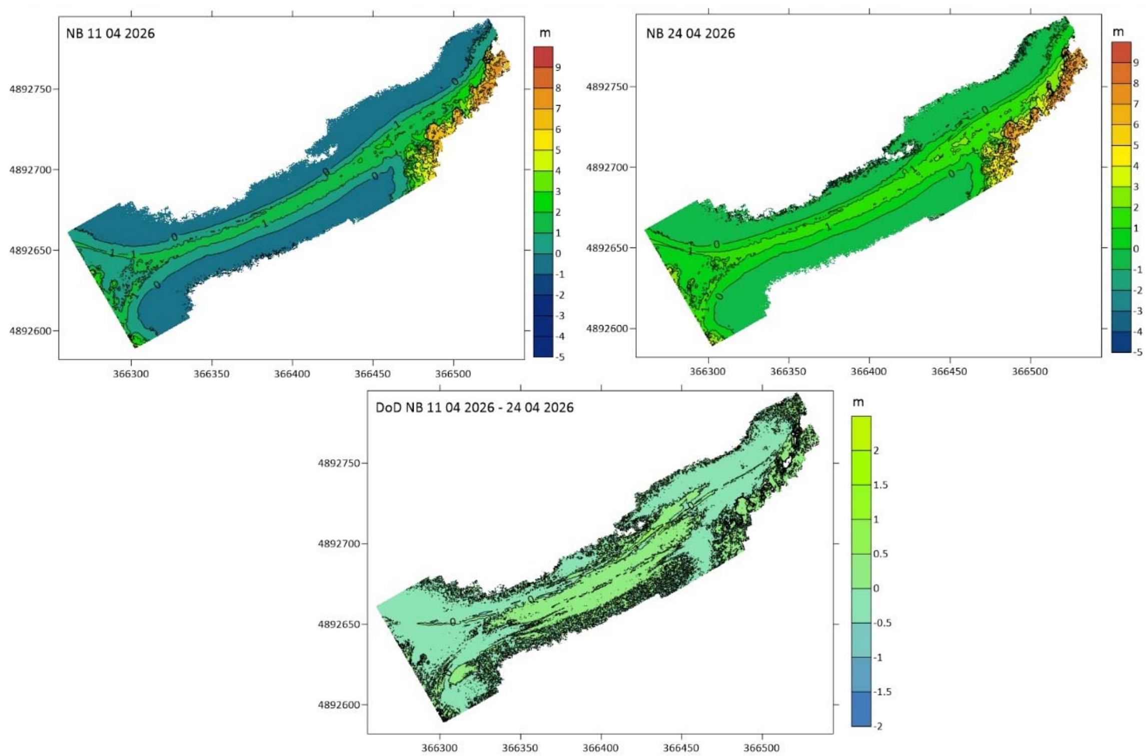


**Figure 54:** 3D models and the model of differences for monitoring period April 11th – April 24th 2026.

### 5.3.3. Sediment analyses

A summary of the S1 and S2 sediment characteristics is presented in Table 2, and the grain size distribution is shown in Figure 55. In both cases, the sediment was pure sand, with median and mean grain sizes within the medium sand fraction. There was a slight difference in sorting, with S2 being slightly better sorted than to S1. Both sediment samples consisted mainly of carbonate minerals. The grain size distribution of each sediment sample is shown in Figure 55. The grain size of the analysed sand is probably partly inherited from skeletal organisms; however, the moderately well-sorted nature suggests continuous wave action in the subtidal and intertidal zones. Part of the sand presumably originates from wave abrasion of the bedrock. The process of pebble rounding on the beach can produce much of the fallen material. The results for carbonate content were expected, given that there is no source of terrigenous material except for the soil eroded by waves during high energy events. It is recommended that future research examine the origin of this carbonate material using mineral analyses and microscopic examination.

**Table 2:** Summary results of the grain size and carbonate content analysis of sediment collected in the intertidal of the Natural Bridge.

| Sample | Sediment type | Mean grain size (mm): | Median grain size (mm): | Sorting | Carbonate content (%): |
|---|---|---|---|---|---|
| S1 | sand | 0.342 | 0.344 | Moderately sorted | 96,34 |
| S2 | sand | 0.357 | 0.357 | Moderately well sorted | 94,06 |

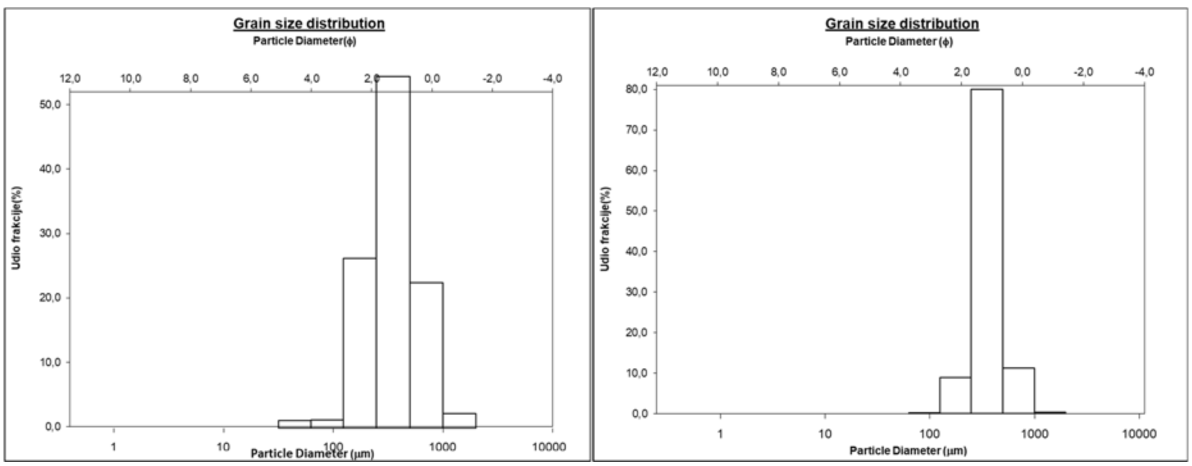


**Figure 55:** Grain size distribution of the sediment samples S1 (left) and S2 (right).

# 6. Conclusions

## 6.1. Sakarun beach

1. During the monitoring period, Sakarun beach exhibited similar behaviour to that observed in the 2020/2021 period. The most dynamic areas of the beach are its corners and the central section. In the first instance, the increased morphodynamics result from longshore transport. This transport may be caused by NE winds, which, due to the short fetch, generate only mild waves. Such longshore transport moves sediment and Posidonia debris to the SW part of the beach (where the Amarcord coffee shop is located). This particular longshore transport was observed during fieldwork. Longshore material transport in the same direction is also possible when SE wind waves enter Sakarun Bay at a smaller angle. Conversely, longshore transport in the opposite direction may occur when SE wind waves enter Sakarun Bay at a larger angle. Such a situation was observed in November 2025, when fieldwork could not be conducted due to adverse weather and wave conditions.
2. According to the official meteorological data set obtained from the Croatian Meteorological and Hydrological Service (CMHS/DHMZ), wind speeds exceeding 34 km/h were not record during this monitoring period. It should be noted that the official weather station used is Božava, located 5 km to the NW and sheltered from SE winds. Therefore, the recorded wind speed of 34 km/h wind is likely slightly underestimated. For this reason, it is strongly recommended to install a local meteorological station on Sakarun beach, to be used at least during future beach monitoring periods.
3. Considering the recorded wind speeds during the monitoring period 2020/2021, slightly higher winds up to 38 km/h may generate waves strong enough erode the entire banquette cover from the whole beach area. For most of the monitoring period 2025/2026, such erosion was not observed: the uppermost parts of the banquettes along most of the beach retained their characteristic undulating patterns, which could be monitored monthly using dense point clouds and 3D models. The exception is the monitoring period from December 2025 to January 2026, when such erosion was hypothesised based on the steepened gravel berm at elevations higher than the highest banquette. The wind speed during that period reached up to 34 km/h. To eliminate any uncertainty regarding this wind-speed threshold, targeted fieldwork should be conducted before, during (if possible), and after extremely strong storms. It should be noted that total erosion of the banquette and sand also depends on the initial state of the beach: the more flattened the beach, the more easily erosion occurs. Therefore, flattening the beach for tourism purposes and increasing thus beach capacity is not recommended and should be completely avoided.

4. Erosion of the beach (mostly banquette and sand) occurs during storm strengthening, as observed in November 2025, while their accumulation takes place during the storm weakening. Mild and fair-weather waves generally only accumulate Posidonia debris in the shallow subtidal zone.
5. During material accumulation of material, large quantities of wooden logs and other waste can be deposited up to the highest part of the beach. Therefore, it is not recommended to increase the number of temporary catering facilities, as they can be destroyed relatively easily by either the waste or the seawater.
6. The heights of the Posidonia banquette on Sakarun beach did not reach the over 2 m recorded during 2020/2021 monitoring period. Banquette heights (from the sediment to the banquette crests) ranged between 0.11 to 1.42 m. Possible reasons for the reduced heights are: i) a decreased quantity of Posidonia debris in the open sea, which is the main source; ii) a reduced amount of Posidonia debris entering the Bay; iii) different meteorological conditions and wave climate that prevent banquette formation; iv) a combined effect of several of these factors. It should be noted that Sakarun beach was also monitored in 2021, 2022, 2023, 2024, and 2025; however, no banquette over 1.5 m high was recorded, at least not on the survey dates. Therefore, targeted fieldwork designed to coincide with strong storms is highly recommended, as stated under bullet point no. 3.
7. Although not specifically emphasised in chapters 1 – 5, slightly higher amounts of sand were observed to be present and to accumulate in the intertidal zone under various meteorological conditions compared to the monitoring period 2020/2021, after years of banquette removal. It can thus be concluded that the loss of this most valuable sediment has been reduced or slowed down.

## 6.2. Nature Bridge beach

1. Morphological changes of the Natural Bridge were monitored for the first time. This tombolo beach has been developed on the easily erodible Veli Rat formation, as has Sakarun beach. It is highly recommended to investigate its development and sediment characteristics for both scientific and management purposes.
2. The heights of the banquettes on the Natural Bridge ranged from 1.59 to 2.37 m. It should be noted that these heights are measured as total heights from geodetic zero, whereas the heights on Sakarun beach represent the true heights of the banquettes, measured from the sediment level. According to DGPS data, most of the banquette heights from the sediment level on the seaward side of the beach were between 1.70 and 1.90 m. Therefore, it can be concluded that the Natural Bridge consistently has higher banquette heights compared to Sakarun beach. The reasons for these differences are presumably: i)

the absence of human intervention on the Natural Bridge (no banquette removal); ii) an undisturbed supply of Posidonia debris from the open sea from various directions (e.g. NE wind waves have been identified as a direct supplier; while SE wind waves can redistribute Posidonia debris along the coast); iii) natural changes in beach and banquette morphology; iv) exposure to NE wind waves, which are shorter in duration and less destructive compared to SE waves.

3. Most of the beach and banquette morphodynamics at the Natural Bridge occur on the seaward side, which is exposed to dominant winds and wind waves. Banquettes are therefore destroyed and rebuilt from the seaward side. Destruction from the other side (Pantera Bay side) occurs occasionally. This destruction is mild and results from the increased destructive force of the high-energy waves, whose heights increase upon entering the shallower bay. According to fieldwork observations, most of these waves are generated by SE winds.

# 7. Guidelines

In the case of Sakarun beach, the Nature-Based Solution (NBS) involves the planned development of a wooden walkway to create a corridor for beach visitors, enabling the sustainable management of banquettes. To assess the effectiveness of Nature-Based Solutions (NBS) in relation to the objectives of the climate action plan for destination tourism on Dugi otok Island, several guidelines were provided for Sakarun beach.

1. The wooden walkway was the first NBS proposed for Sakarun beach, following the first year of monitoring in 2020/2021, when sand erosion from the beach was observed after more than a decade of banquette removal. The wooden walkway was intended as a multi-purpose solution: i) to reduce contact between beachgoers and banquettes, which were regarded as a waste, while meeting tourists' desire for the scenic beauty of the turquoise seawater and enabling more direct access to the sea; ii) to reduce disturbance of banquettes by tourists; iii) to promote sustainable tourism by limiing beach capacity and thus reducing the number of beachgoers; iv) to reduce the likelihood of repeated banquette removal by heavy machinery by visually isolation the banquettes with the walkway; and v) to use the walkway to educate tourists about the ecosystem services provided by banquettes and the NBS policy.
2. The wooden walkway was conceived as a temporary wooden installation, used only during the tourist season. The installation was planned to cover only those parts of the beach where banquettes remain for an extended period. This removable installation was a compromise to balance the high seasonal pressure from of increasing numbers of tourists with the need to ensure the beach functions outside tourist peak season, when morphological changes are most intensive.
3. After six years of monitoring the morphology of Sakarun beach outside the tourist season, and visiting the beach as a tourist, the idea of a the wooden walkway has been called into question for several reasons.Firstly, preparation of the beach for the tourist season usually begins in April. Weather and wave conditions during April, and even May depending on the meteorological year, can be challenging on Sakarun beach, as late episodes of strong south-east winds can still occur. In this context, an installed walkway could suffer significant damage caused by waves and other beached material, particularly wooden logs and coarse waste items. Secondly, although rare, SE storm events may occur during the summer season, in July and August. Prediction of such rapid and usually unexpected storms is not possible, particularly in the context of climate change. Such storms can cause enormous damage to both natural and anthropogenic infrastructure. For example, a storm of this kind occurred in the Split area in July 2025. Destruction of a structure such as a wooden walkway, especially during the summer, may also result in

fatalities. Due to its orientation, this beach is particularly exposed to all influences from the open sea, including storms.

4. Instead of constructing a wooden walkway at Sakarun beach, it is preferable to maintain the policy of not removing the Posidonia banquette, not only during the winter, but also throughout the summer. This approach is strongly recommended, as there are indications that sand loss has somewhat decreased in recent years. It is also advised not to further commercialise the beach, in order to reduce or at least maintain the current number of visitors. Therefore, no additional catering facilities should be built, and existing ones should be informed and educated about the services provided by Posidonia and its role in prevention of beach erosion at this specific location. Focusing on catering facilities is important, as they communicate direclty with beachgoers.
5. Finally, it is strongly recommended to continue monitoring morphodynamics of Sakarun beach. More detailed information on the precise dynamic of banquette erosion and rebuilding is required. Additionally, expanding research into the shallow subtidal zone could assist with monitoring sand volume and understanding processes related to submarine sand dynamics.

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