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MORPHOLOGICAL ANALYSIS OF THE SLOVENIAN COAST WITH DATA FROM LIDAR AND SONAR RANGING

MORFOLOŠKA ANALIZA SLOVENSKE OBALE S PODATKI LIDARSKEGA IN SONARSKEGA SNEMANJA

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MATEJA JANČAR

Alternating diagonal layers of sandstone, marl and turbidite composing the cliff of Cape Ronek.
Izmenjavanje poševnih plasti peščenjaka, laporja in turbidita na klifu rta Ronek.

Morphological analysis of the Slovenian coast with data from lidar and sonar ranging

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ABSTRACT: The coastal zone, the land and sea area bordering the shoreline, is an area with unique intertwining features. This article reveals a new study of the coastal zone as an inseparable whole in three-dimensional (3D) space. The starting points of the study were data from lidar and sonar ranging gathered in a 3D space of an approximately 1-kilometer-long coastal zone of Koprsko primorje. According to these data spatial analyses were made: height or depth analysis, slope and exposure analysis, and classification of land and sea interaction. Special attention was devoted to cliffs, abrasion platforms and underwater stone platforms. Spatial analyses gave a new vision of the coastal zone and revealed new features.

KEYWORDS: geography, lidar, sonar, coastal zone, cliff, underwater platform, Koprsko primorje, Slovenia

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Contents

1 Introduction

Using data from lidar and sonar ranging to study the coast represents a challenge for geography as it introduces a new method and a whole new view of the coast. So far the land and sea area bordering the shoreline was usually studied separately based mostly on extensive fieldwork. The gathered data from lidar and sonar ranging in a three-dimensional (hereinafter referred to as 3D) space gives a clear picture of the entire coastal zone and offers many new opportunities and perspectives of research. It offers a view of the land and sea interaction, and a possibility to observe the continuity of processes or the modification of seafloor features. For the purpose of this research the coastal zone of Koprsko primorje was defined as a 500-meter-wide area comprising both sides of the shoreline. This 500-meter-wide area is expanded on land to comprise areas of different activities, nucleated settlements or harbour activities. The size of the entire coastal zone is of 45.2 km.

2 Methods

The survey is based on spatial analyses of data from the multi-beam lidar and sonar ranging, gathered in a uniform digital elevation model (DEM) that made the study of the coastal zone as a whole possible. The article emphasizes the morphological view and complements the process view presented in the article of Šegina, Komac and Zorn (2012).

A digital elevation (or land surface) model and a digital depth model (DDM) of the sea were generated based on data from lidar and sonar ranging with a resolution of 0.5 by 0.5 m. Data merging was difficult because land data extend to the shoreline, however sea data usually end up sooner, about 1 m to 0.5 m of depth, as sonar ranging is impossible in shallow waters.

As a result we have an area of missing data between the shoreline and the gathered data from the sea that in each case differs in width (up to 60 m). The width of this area depends on the configuration of the coast, the widest area is found in shallow lagoons, the narrowest one nearby harbour piers, while the approximate width reaches about 15 m. The interpolation of this area is relatively difficult due to a large amount of data and altering size of the area that needs to be interpolated. The DEM does not always end at height of 0 m (fortified coasts can end at height of 1 m and 2 m), which further complicates the interpolation of the shallow sea area (Kolega 2009).

Spatial analyses were made based on the DEM of the entire survey area. These analyses result from the common raster structure of the DEM generated for a wider area of land and sea (500-metre-wide land area and 500-metre-wide sea area). Different analyses were made: analysis of height and depth that result from the common DEM, slope analysis and surface exposure analysis. The latter was made, on the contrary of the previous two, using a 10 × 10 m DEM (cell size). The reason for that is that the exposure raster (grid-cell) structure is too fragmented because its cells have a resolution of 0.5 × 0.5 m. Each grid cell is a separate unit that measures the exposure of land-surface, which does not give a general (prevalent) surface exposure of a particular area. The seafloor as well is too »rough« to show its prevalent exposure. Based on the common DEM, which is extremely useful for the studying of land and sea interaction and its features, selected coastal zones were studied and arranged in four main natural categories of types of land and sea interaction. Due to the fact that the Slovenian Coast is already highly anthropogenically altered, the classification of land and sea interaction, based on the four main natural categories was not possible. Cliffs were studied in detail as they are one of our most interesting and unique types of land and sea interaction as well as underwater stone platforms, which represent most of the Slovenian stone seafloor and can be associated with cliff retreat. A vertical cross-section of each cliff was made and, to make it even more understandable, displayed in 3D. The methods used for determining the direction of underwater stone platforms are, in order to be more clear, described in their analysis.

3 Morphological analysis of Koprsko primorje

Heights or depths resulting from the DEM of the coastal zone are arranged from the maximum depth of –38.0 m to the maximum height of 156.9 m. Height and depth values are distributed unevenly. While depth and height increase the frequency of value falls. The widest area comprises heights ranging from

0 m to 10 m and constitutes wide flat lands of the Koper and Ankaran Bonifika area, the salt pans of Strunjan and Sečovlje, Lucija and the surrounding area of the old town of Izola. The second widest area comprises depths ranging from –10 m to 0 m. The latter constitutes most part of the sea, particularly the coastal zone, and smaller parts of the Koper and Ankaran Bonifika area, which are situated below sea level. The next area comprises depths from –20 m to –10 m and constitutes a wide part of sea, which is interrupted by a 500-metre-wide area. The narrowest area, the one nearby Piran, comprises depths ranging from –30 m to –40 m. The highest land surface is mostly found in the area of cliffs and in its hinterland. The heights alter slowly and steadily similarly as depths in the sea except for cliffs.

Approximately a third of the surface ranges from 1° to 3° of slope gradient. This area comprises most of the seafloor, which is not surprising as is characteristic of the Slovenian Sea that depths increase slowly and steadily. Areas with high slope gradient are only found by the coast, at the foot of cliffs and nearby Piran. The second widest coastal zone ranges from 0° to 1° of slope gradient. It constitutes wide lands of the Koper and Ankaran Bonifika area, both salt pans and the seafloor close to the coast of Lazaret. From this point on the slope gradients follow in order. The slope gradient increases in inverse proportion to the surface. Only cliffs have the highest slope gradient of 88.5°. The widest area has a northern exposure and constitutes a large part of seafloor between Strunjan and Koper, the north of Cape Debeli rtič and some areas of cliffs. The second widest area has a north-western exposure and is found particularly in the sea and in some flat lands. The third widest area has a south-western exposure and it particularly constitutes the seafloor surface between Koper and Cape Debeli rtič. Completely flat lands are the less frequent.

4 Types of land and sea interaction

The Slovenian Coast is a ria coast, which is a drowned river valley with several parallel rias (coastal inlets) separated by prominent ridges, extending into the sea. This type of coast is perpendicular to the geologic structure. Coastal inland plains and steep sea cliffs constitute the main relief of the coast (Kolega, 2006). Koprsko primorje has 4 natural types of land and sea interaction.

The first type of land and sea interaction is found nearby sea *cliffs*. The land steeply extends towards the seashore where interaction of land and sea occurs and a differently wide abrasion plain can be found. The latter usually continues into an underwater stone platform ending with a drop within a few metres of depth. Underwater stone platforms, including their size, the size of abrasion plains, height and steepness of cliffs, sea depth nearby cliffs and seafloor slope gradient differ greatly from cliff to cliff. Cliffs without abrasion and water platforms do not exist in Koprsko primorje, where cliffs are made of flysch, which is a rather unresistant rock.

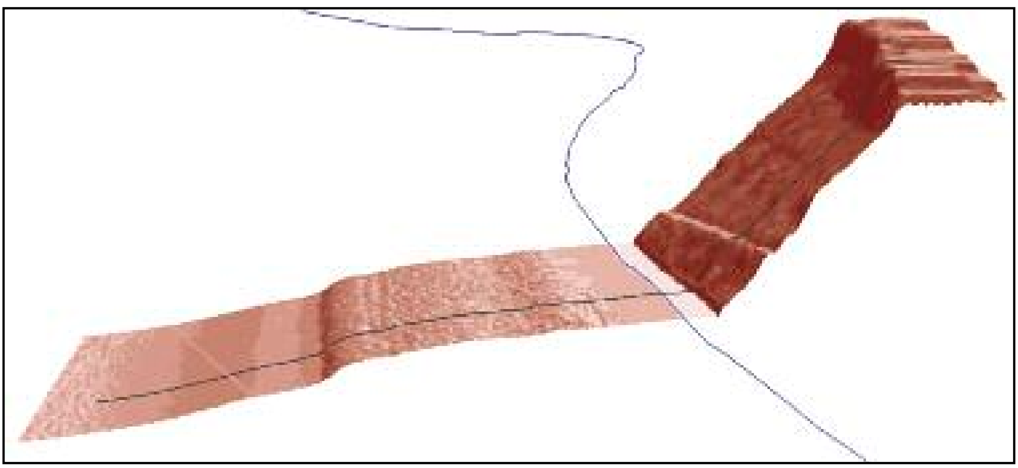

Figure 1: Land and sea interaction at the foot of the cliff in the north of Piran.

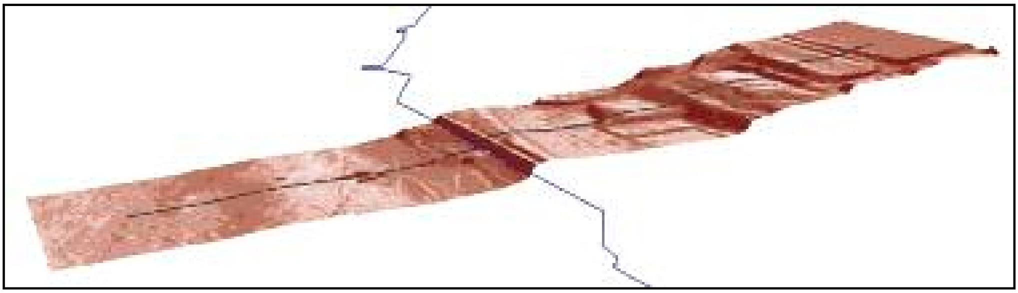

Figure 2: Land and sea interaction in the west of Portorož where land and sea extend with a gentle slope of the surface.

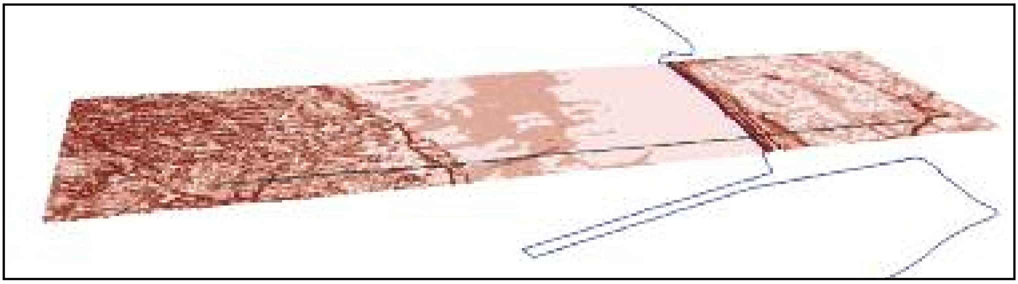

Figure 3: Land and sea interaction on the sedimentary coast of Sv. Katarina.

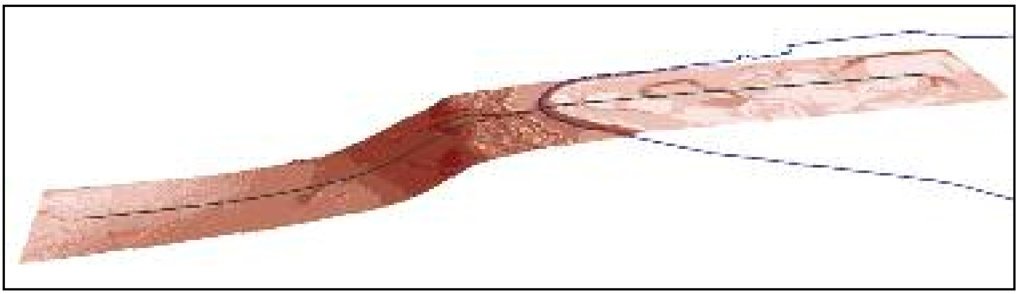

Figure 4: Land and sea interaction with flat land and steep seafloor in Piran.

The second type of land and sea interaction is found by coastlines where *land and seafloor extend to the sea with a gentle slope of the surface.* These coasts are not flat and low but extend from hinterland hills towards the sea. It is similar with the seafloor from the shoreline, where land and sea meet, towards the sea. Observing the relief of this type of land and sea interaction we can see that it does not substantially change either below or above the shoreline. This type of coasts is mainly found in gulfs.

The third type of land and sea interaction is found on sedimentary coasts. It is an extremely flat land that literally »becomes« seafloor. Land height and sea depth are very low at the shoreline, where sea and land meet. These types of sedimentary coasts are found in areas where sediment accumulation has occurred, particularly in gulfs. Photo 3 shows land at the shoreline as a small stone wall and that is why it appears in the relief as a step at the edge of land and sea. Without the wall land would literally become seafloor.

The fourth type of land and sea interaction is found in areas of *relatively flat land* that at the interaction with sea becomes seafloor and rather quickly *transforms into a drop.* Although this type of land has some hilly terrains in its hinterland it extends to the sea with a gentle slope where it rather quickly transforms into a high steep drop. This type of large and steep drop can only be found in the area of Piran Cape, where most likely because of the strong currents the sea is that deep.

5 Cliffs, abrasion platforms and underwater stone platforms

For a detailed comparison and analysis of cliffs three cliffs were selected: the cliff between Fiesa and Pacug, the cliff at Cape Ronek and the cliff below Belveder west of Cape Kane. For a better understanding we named the cliffs as Pacug, Ronek and Belveder.

Figures 5, 7 and 9 show cliffs in 3D, for a more detailed idea of depth there is a layer that represents the sea level. Cliffs are represented by a shaded relief which makes their shape more visible and protruding. For each cliff three vertical cross-sections were made. Photos 6, 8 and 10 display their direction.

Cliffs Belveder and Pacug spread on a rather flat coastal zone which has a northern exposure; Ronek on the other hand lies exactly on the cape which is the reason for its northern exposure on one side and its northwestern or western exposure on the other side. All three of them are proportionally high and have an uneven surface below and above the sea level. All of them have differently shaped underwater platforms, whose size differs from cliff to cliff.

Table 1: Comparison of cliff features measured by vertical cross-sections.

Cliff	Cliff slope gradient (°)	Cliff slope gradient of the entire (abrasion and underwater) platform (°)	Width of the entire (abrasion and underwater) platform (m)	Cliff height (m)	Exposure
Belveder 1	72	–8	Width unknown.	72	N
Belveder 2	69	–7	133	62	N
Belveder 3	75	–5	106	47	N
Pacug 1	65	–9	57	64	N
Pacug 2	51/84	–8	65	80	N
Pacug 3	65	–9	60	64	N
Ronek 1	69	–3	96	59	N
Ronek 2	67	–4	131	50	N
Ronek 3	66	–6	124	43	NW

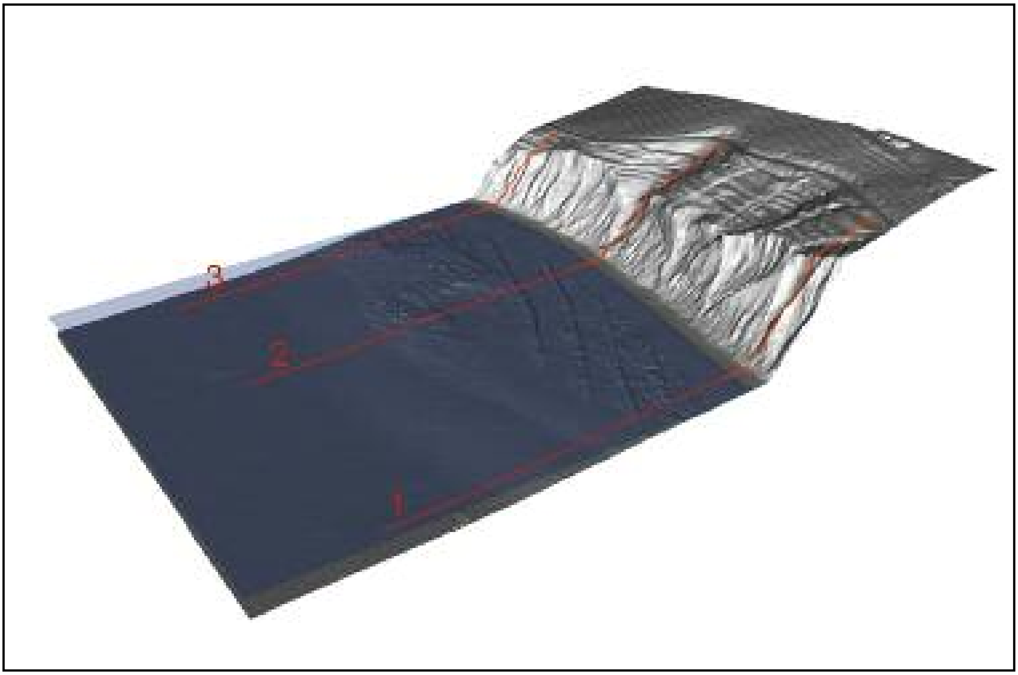

Figure 5: The Belveder cliff.

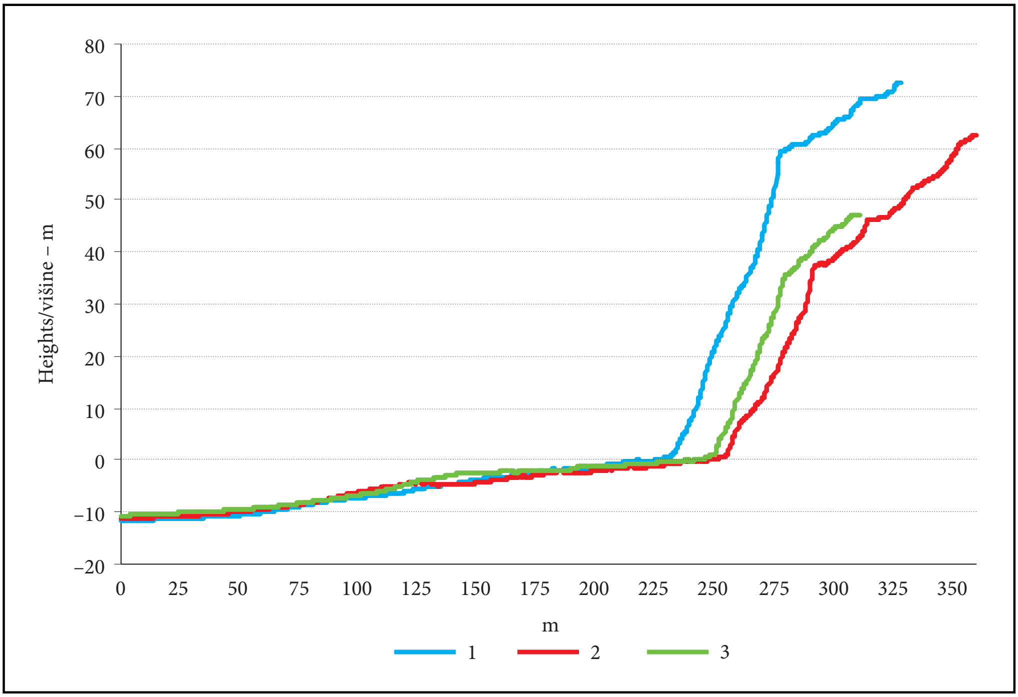

Figure 6: Profile of the Belveder cliff.

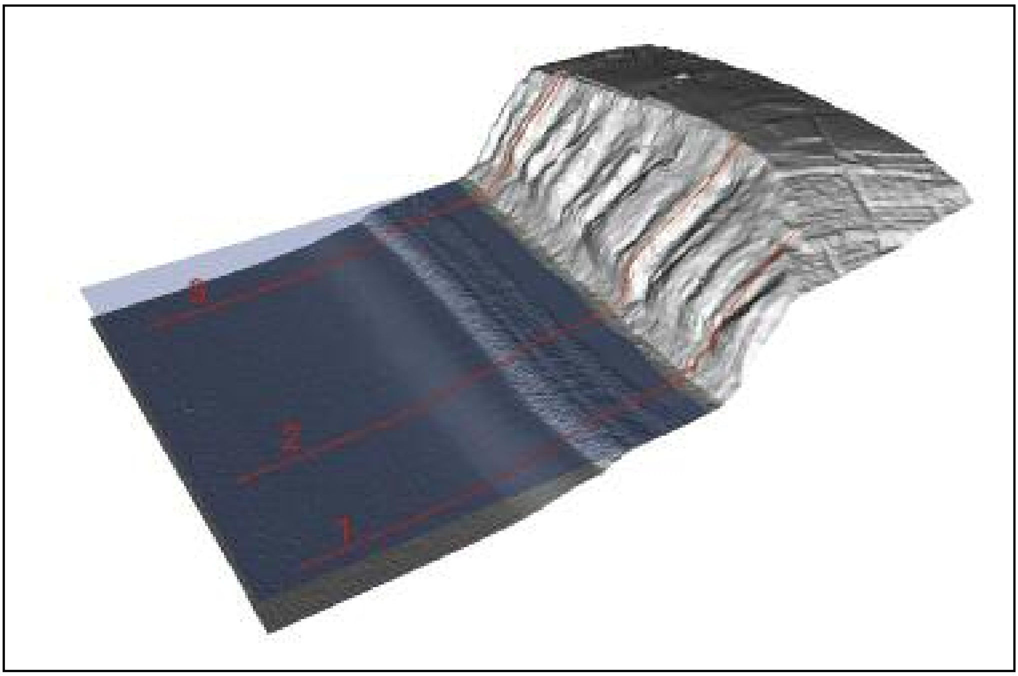

Figure 7: The Pacug cliff.

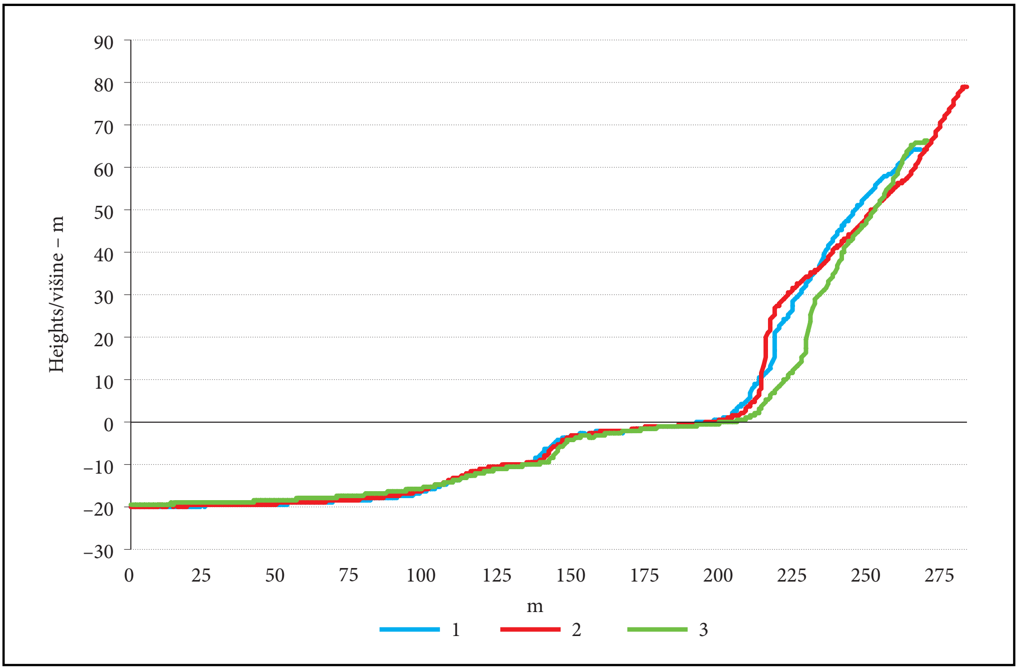

Photo 8: The profiles of the Pacug cliff.

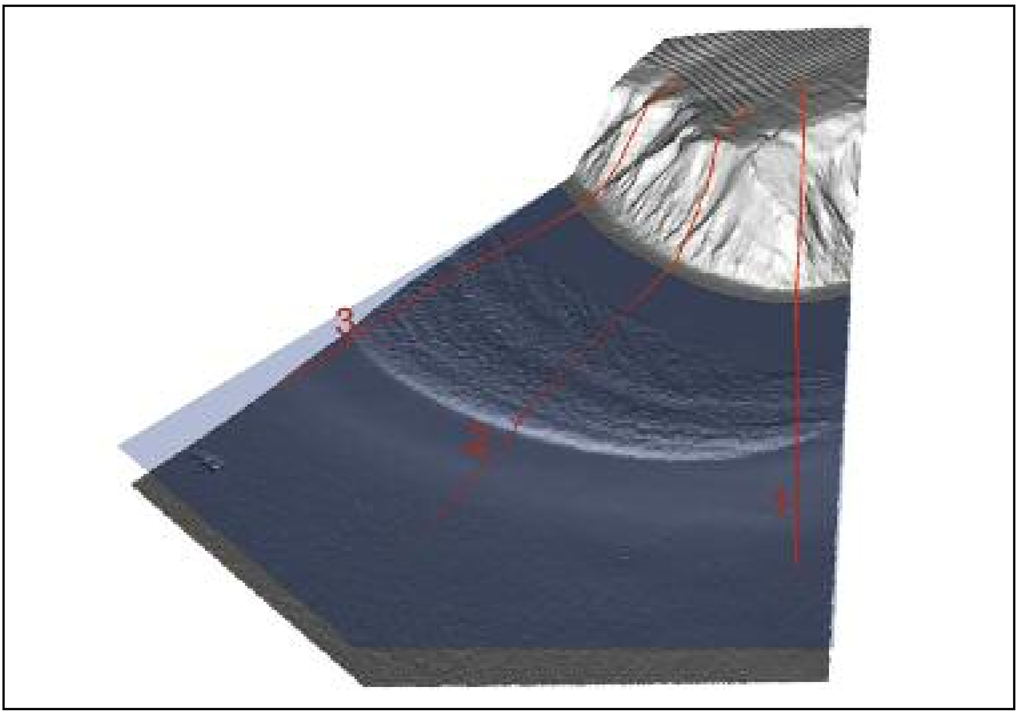

Figure 9: the Ronek cliff.

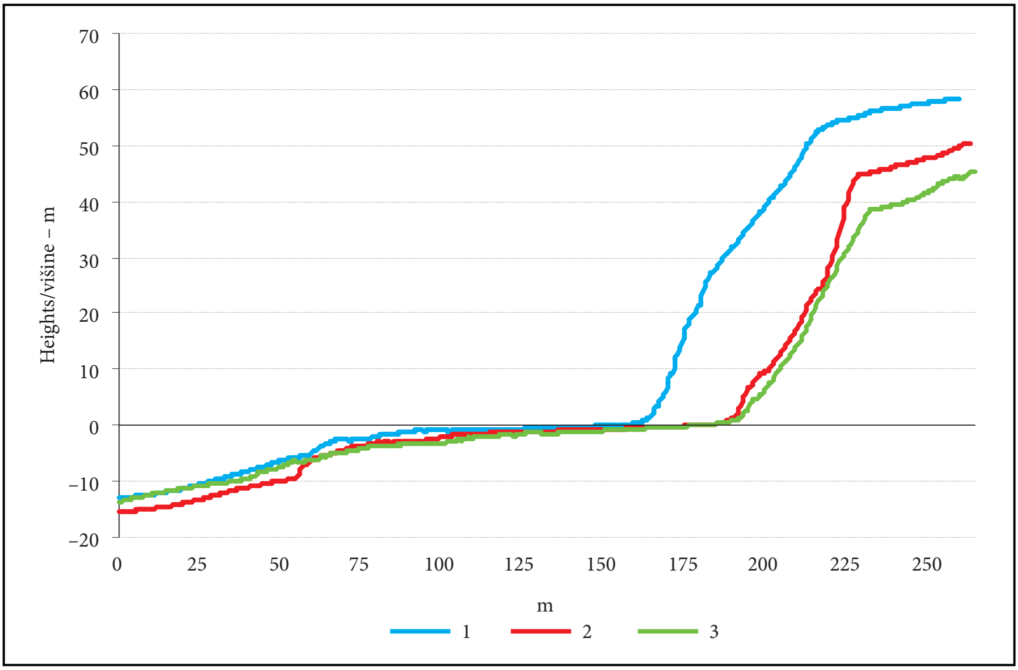

Figure 10: Profiles of the Ronek cliff.

Ronek differs from the other cliffs for having the widest and plainest underwater platform. However the underwater platform below Belveder is rather wide, being even wider in some areas. Cliff Belveder is the steepest, while Cliff Pacug is the highest. The underwater platform of Cliff Belveder is composed of resistant flysch layers whose direction and exposure are clearly visible. The layers are perpendicular to the coast and go from southeast to northwest. The underwater platform of Cliff Ronek gradually narrows from west to east or from one side of the cape to the other. On the east side, near the coast, resistant flysch layers go in the same direction, similarly to the ones below Belveder. The reason why Cliff Ronek has the widest and »the most horizontal« underwater platform is because it is a cape highly exposed to waves that have modified it causing damage to the coast (Gams 1970). Furthermore Furlani (Furlani 2003) observes the positive correlation between the exposure to waves and the length of the platform.

Cliff Pacug as well has a clearly visible underwater platform with a prominent steep slope. Compared to the other two the platform is much more even.

6 Underwater stone platforms and cliff retreat

Underwater stone platforms represent a greater part of the stone seafloor in the Slovenian Sea. Their origin can be associated to the processes of cliff retreat. Most researchers believe that the reason platforms exist is because in the past the sea level remained steady at this height for a longer period (Šifrer 1965). The sea level fluctuated during the last ice age and after it. During the peak of ice age the sea level was decreasing and water was moving towards the south of the Adriatic, while during the mid ice age the sea level was gradually rising. After the last ice age in Würm the sea level was again rising. This global environmental event is called the post-Würm transgression and exists still today. It is important to emphasize that also during this period the sea level was changing (Šifrer 1965). Underwater platforms are the result of a longer period of sea level stagnation below the current level.

Between approximately –2 m and –10 m of depth differently prominent platforms occur. If we consider depth at which the platform occurs there are mainly two platforms from different periods. On a wider

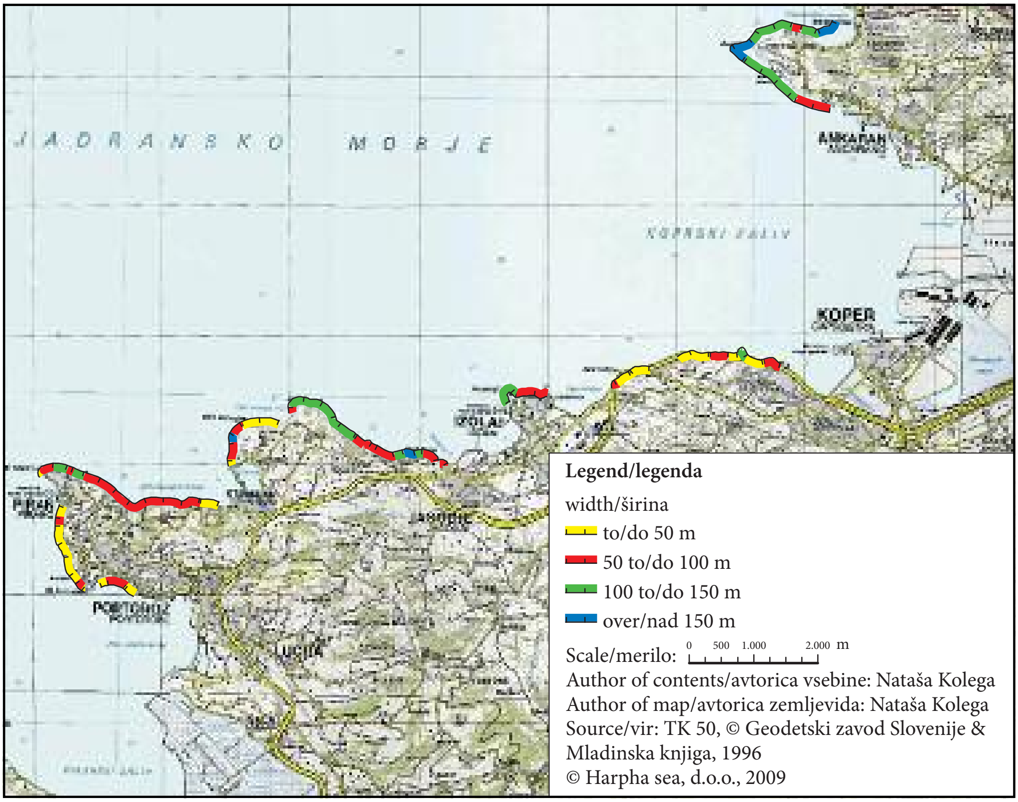

Figure 11: Direction and width of underwater stone platforms.

area of coast at the foot of the cliffs at depth of approximately –8 m and –9 m the edge (drop) of a differently wide underwater stone platform occurs. This type of platform is found along the entire Adriatic coast as well as in other parts of the world, which proves that it is a result of longer sea level stagnation at its current height in the period of the last ice age, when sea level was 10 m to 30 m lower than today (Orožen Adamič 2002). In some areas at the depth of approximately –2 m and –4 m there is another stone platform that called the Roman platform. This platform is less prominent than the one at the depth of approximately 8 m, yet its existence is as well associated with a longer period of sea level stagnation at its current height (Šifrer 1965; Orožen Adamič 2002).

To aid to the information and the mentioned explanation on underwater stone platforms we mapped their direction and width in the Slovenian Sea, where these are visible. We drew a line along the edges of the platforms where according to data they were the most visible and prominent.

Direction, width and depth of underwater stone platforms were determined by raster analysis of slope gradient, seafloor shading and by creating profiles of the seafloor and the interaction of land and sea along the coast, where the platform appears with approximately 80 m of mutual distance. We arranged the platforms according to width into 4 categories shown in photo 11.

Underwater stone platforms are found at the depth of –4 m and –8 m, their size range from 12 m to over 400 m. The widest platform is the one in Lazaret, without a cliff at its back, which is most probably covered in slime layers but clearly visible. The platform in Fizine is similar to the platform in Lazaret, except for being narrower. If we exclude the platform in Lazaret, the widest platform is the one at the foot of Cape Debeli rtič, which is a promontory extending under the sea and being the proof of a receding cape. Photo 11 and table 2 clearly show that the widest platforms appear around capes, which is understandable as capes are exposed to sea activities that contribute to a high rate of cliff retreat. This

Table 2: Width, depth and visibility of underwater stone platforms.

platform location	approximate depth (m)	approximate width (m)	maximum width (m)	Visibility
Lazaret	–6	365	445	good
Debeli rtič	–8	141	312	good
Ankaran	–4	75	79	worse
Koper–Izola	–4	42	120	worse
Izola	od –6 do –8	68	140	good (worse in some areas)
Bele skale	–8	89	160	good (worse in some areas)
Strunjan	od –6 do –8	90	151	good (worse in some areas)
Pacug, Fiesa	–4	65	97	good
Piran	od –6 do –8	87	111	good
Fornače, Bernardin	–4	34	70	good (worse in some areas)
Fizine	od –4 do –5	55	86	good

is mostly the case with Cape Debeli rtič, Cape Strunjan and Cape Ronek, and similarly with other smaller cliffs. The narrowest platform is the one in Fornače. The total length of all visible underwater platforms is of 17.5 km.

If we follow the coast from the border with Croatia to the border with Italy we first encounter a platform covered in slime layers at about –4 m of depth in the area around Fizine. The platform extends also along Bernardin and Fornače at a similar depth. Mostly the platform ends with a vertical steep drop. In the north of Piran the stone platform ends with a drop at about –6 m of depth, the drop ends at –12 m of depth and it continues into a small flat surface with a gentle slope, at about –14 m of depth another drop occurs, this one less steep, which ends at about –20 m of depth. At the foot of the cliff between Fiesa and Pacug the stone platform ends with a rather steep drop at –4 m of depth, the drop ends at –10 m of depth and continues with a small flat surface to –11 m, where another gentle drop occurs and ends at –16 m of depth. The seafloor at the foot of the cliff north of Strunjan nearby Cape Strunjan falls from the coast with a gentle slope. The stone platform is over 150 m wide. Nearer we get to the cape steeper is the drop at between –8 m and –10 m of depth. At the very point of the cape the seafloor steeply falls to –17 m of depth, continuing with a more gentle slope. Steep platforms and drops are not visible. Further on the west side of the Gulf of Mesečev zaliv there is a very gentle slope at –3 m of depth, while in the gulf a small sedimentation occured. Nearby Cape Ronek there is a 90 m wide underwater platform dropping steeply from about –5 m to –10 m of depth. At that depth the seafloor gradually falls. Towards Bele skale (approximately in the middle of Strunjan and Izola) the undersea drop gradually fades away. The underwater stone platform is clearly visible and about 90 m wide. In the area of Bele skale another drop occurs and ends at about –4 m of depth. On the west side of Cape Ronek there is a steep drop between –2 m and –10 m of depth. At the foot of the cliff between Izola and Koper steep platforms and drops are not visible, in some areas there are only faint outlines of platforms and drops between –3 m and –5 m of depth. In the area of Cape Debeli rtič there is a 300 m wide stone platform with a gentle slope falling from about –8 m to –15 m of depth. The cape, at its end, extends for about 400 m under the sea. The sea above the underwater cape at about 300 m from the coast reaches –5 m of depth. The extended cape forms a real underwater ascent as the seafloor rises from –18 m to –3 m of depth and falls again to –15 m of depth. Further on towards Lazaret a prominent platform and drop are visible, with the platform covered in slime layers.

If we consider that underwater platforms are a result of longer sea level stagnation at their current height, we can understand how much the cliff has retreated until today due to abrasion, erosion and denudation. Geomorphic processes continuously alter cliffs making them retreat a few centimetres per year (Zorn 2009), while continuous abrasion helps them maintain their original shape (Savigear 1952). With the exception of Lazaret the average width of platforms range from 50 m to 100 m, except for capes highly exposed to the sea, where the cliff has retreated for over 150 m or over 300 m at Cape Debeli rtič. This is supposed to have happened since the last ice age until today or in about 37.000 years (Orožen Adamič 2002). Since the Roman period the cliff has retreated by about ten metres in some parts (Furlani 2007).

7 Conclusion

The Slovenian Coast is a dynamic, heterogeneous and unique area. The altitude ranges from the maximum depth of –38 m to the maximum height of 157 m. While depth and height increase the frequency of value falls. The vast majority of the area is flat. Proportionate to the height distribution is the range of surface slope values which amount to over 88°. About a third of the surface has a slope gradient that ranges from 1° to 3°. The widest area has a northern exposition due to the location and the direction of the coast.

By classifying the interactions between land and sea we decided to arrange the interactions in four natural categories. Due to the fact that the vast part of the coast is highly anthropogenically altered, the classification of land and sea interaction into the (natural) categories was not possible.

The common DEM of the land and sea part of the coast and spatial analyses opened a new view of the coast as an inseparable whole with intertwining characteristics of land and sea. This added to the understanding of different characteristics of the area, as types of land and sea interaction, characteristics of cliffs and their underwater platforms, which were unknown until today. Separated spatial analyses of the land and sea part of the coast, such as seafloor classification, human impact on the seafloor, vegetation, constructions and so on, offer a lot of information on the coast, however their results will not be mentioned in this article.

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Morfološka analiza slovenske obale s podatki lidarskega in sonarskega snemanja

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IZVLEČEK: Obalni pas je zaradi stikanja kopnega in morja območje s svojevrstnimi prepletajočimi se značilnostmi. Članek prikazuje nov pogled na preučevanje obalnega pasu kot neločljive celote v 3-D prostoru. Izhodišče za izvedeno raziskavo, so bili podatki lidarskega in sonarskega snemanja, združeni v enoten 3-D prostor, ki ponazarja približno 1 km širok obalni pas Koprskega primorja. Na tako pripravljenih podatkih so bile izvedene prostorske analize: analiza višin oziroma globin, naklonov in ekspozicij ter tipizacija stika med kopnim in morjem, posebna pozornost pa je bila posvečena tudi klifom, abrazijskim terasam in podvodnim kamnitim terasam. Prostorske analize so omogočile nov pogled na obalni pas in razkrile nekatere nove značilnosti.

KLJUČNE BESEDE: geografija, lidar, sonar, obalni pas, klif, podvodna terasa, Koprsko primorje, Slovenija

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Vsebina

1 Uvod

Preučevanje obalnega pasu s pomočjo podatkov lidarskega in sonarskega snemanja je za geografijo izziv, saj gre za vpeljevanje novih metod in nov pogled na obalo. Do sedaj se je raziskovanje kopnega in morja v obalnem pasu običajno izvajalo ločeno, temeljilo pa je predvsem na obširnem terenskem delu. Združitev sonarskih in lidarskih podatkov v enoten 3D-prostor nam daje zelo natančno podobo celotne obale ter ponuja mnoge nove možnosti in vidike raziskovanja. Nudi nam vpogled v stik med kopnim in morjem ter daje možnost opazovanja kontinuiranosti procesov ali spreminjanja značilnosti kopnega na morskem dnu.

Obalni pas Koprskega primorja je bil za potrebe te raziskave definiran kot 500 m širok pas na obeh straneh obalne črte. Na kopnem je ta 500-metrski pas ponekod dodatno razširjen, da zajame zaključena območja posameznih dejavnosti, sklenjene poselitve ali pristaniške dejavnosti. Površina tako opredeljenega pasu je 45,2 km^2.

2 Metodologija

Raziskava temelji na izvedbi prostorskih analiz podatkov večsnopnega sonarja in lidarja, združenih v enoten digitalni model višin (DMV), kar nam je omogočilo preučevanje obalnega pasu kot celote. V članku je poudarjen morfološki vidik in dopolnjuje procesnega, predstavljenega v članku Šegine, Komaca in Zorna (2012).

Iz podatkov lidarskega in sonarskega snemanja sta bila izdelana DMV kopnega in DMG (digitalni model globin) morja z ločljivostjo 0,5 krat 0,5 m. Združitev podatkov je bila nekoliko problematična, saj podatki za kopno segajo do obalne črte, podatki za morje pa se običajno končajo nekoliko prej, približno okrog globine –1 m do –0,5 m, ker nadaljnje sonarske meritve v še plitvejšem območju niso mogoče. Posledica tega je, da dobimo med obalno črto in pridobljenimi podatki za morje različno široko (do 60 m) območje manjkajočih podatkov. Širina tega območja se razlikuje glede na konfiguracijo obale, največja je v plitvih lagunah, najmanjša pa ob pristaniških pomolih, v povprečju pa znaša okrog 15 m. Interpolacija tega območja je razmeroma zapletena zaradi velike količine podatkov, spreminjajoče širine in razsežnosti območja, ki ga je treba interpolirati. K temu pripomore tudi dejstvo, da se kopni DMV ne konča zmeraj na višini 0 m (pri utrjenih obalah se lahko konča na višini med 1 m in 2 m), kar povzroča še dodatne zaplete pri interpolaciji območja plitvega morja (Kolega 2009).

Na izdelanem DMV-ju za celotno raziskovalno območje so bile opravljene prostorske analize, ki izhajajo iz skupnega DMV-ja v rastrski obliki za širši kopni in morski pas (razširjen 500-metrski pas kopnega in 500-metrski pas morja). Izvedene so bile analiza višin oziroma globin, ki se pojavljajo na skupnem DMV-ju, analiza naklonov površja ter analiza ekspozicij, ki je bila, v nasprotju s prejšnjima dvema, opravljena na DMV-ju z resolucijo 10 × 10 m. Razlog za to je v tem, da je raster ekspozicije površja z velikostjo celic 0,5 × 0,5 m preveč razdrobljen, saj računa ekspozicijo za vsako celico posebej, kar pa nam ne da slike o splošni (pretežni) ekspoziciji površja na določenem območju. Tudi morsko dno je preveč »hrapavo«, da bi se pokazala njegova pretežna ekspozicija. Na osnovi skupnega DMV-ja, ki je zelo uporaben tudi za preučevanje stika med kopnim in morjem ter njegovih značilnosti, so bili preučeni izbrani obalni odseki in razvrščeni v štiri osnovne kategorije tipov naravnega stika med kopnim in morjem. Ker je slovenska obala že precej antropogeno preoblikovana, tipizacija celotnega stika med kopnim in morjem glede na štiri osnovne naravne kategorije ni bila izvedljiva. Podrobneje so bili preučeni še klifi, saj predstavljajo pri nas eno izmed bolj zanimivih oziroma svojevrstnih oblik stika med kopnim in morjem ter podvodne kamnite terase, ki zajemajo večji del kamnitega dna v slovenskem morju ter jih je mogoče povezati s pojavom umikanja klifov. Za posamezni klif je bil izveden prečni prerez klifa, za boljšo predstavitev pa tudi njihov prikaz v 3-D obliki. Metodologija določanja poteka podvodnih kamnitih teras pa je, zaradi boljšega razumevanja, predstavljena pri analizi slednjih.

3 Morfološka analiza obalnega pasu Koprskega primorja

Višine oziroma globine, ki se pojavljajo na DMV-ju obalnega pasu, so razporejene med največjo globino –38,0 m in najvišjo višino 156,9 m. Razporeditev vrednosti višin in globin ni enakomerna, saj je pogostost vrednosti pada s povečevanjem globine in višine. Najobsežnejši del površja je v razredu višin med 0 m in 10 m. Razlog za to so obsežna ravninska območja na Koprski in Ankaranski Bonifiki, Strunjanske in Sečoveljske soline, območje Lucije in bližnja okolica starega mestnega jedra Izole. Drugi po obsežnosti je višinski pas z globinami od –10 m do 0 m. Sem sodi večji del morskega pasu, zlasti priobalnega, ter manjši deli Koprske in Ankaranske Bonifike, ki se nahajajo pod morsko gladino. Sledi višinski pas z globinami med –20 m in –10 m, kamor sodi obsežen pas morja, ki ga prekine meja 500-metrskega pasu. V pasu preučevanja je med globinami najmanj obsežen razred z vrednostmi med –30 m in –40 m, ki se pojavlja le pred Piranom. Najvišje kopne površine se pojavljajo zlasti na območjih klifov in v njihovem zaledju. Razen na klifih, se vsepovsod drugje višine spreminjajo počasi in enakomerno, podobno kot globine v morju.

Približno tretjina površja sodi v razred z nakloni od 1° do 3°. Sem sodi večji del morskega dna, saj je za slovensko morje značilno, da se globine večajo počasi in enakomerno. Večji nakloni so le ponekod v neposredni bližini obale in pod klifi ter pred Piranom. Drugi površinsko največji del obalnega pasu sodi v razred z nakloni od 0° do 1°. Tu se nahajajo obsežna območja na Koprski in Ankaranski Bonifiki, obojne soline ter morsko dno ob obali Lazareta. Od tu naprej si razredi naklonov sledijo po vrsti, njihova površina pa se obratno sorazmerno z naraščanjem naklonov manjša. Največji naklon, 88,5°, dosežejo le klifi.

Najobsežnejši del površja ima severno ekspozicijo. Sem sodi velik del morskega dna med Strunjanom in Koprom, na severni strani Debelega rtiča in posamezni deli klifov. Druge po površini so površine s severozahodno ekspozicijo, ki se pojavljajo zlasti v morju in na nekaterih ravninskih območjih kopnega. Tretja po površini je jugozahodna ekspozicija, ki se pojavlja zlasti na morskem dnu med Koprom in Debelim rtičem. Najmanj pogosto se pojavljajo popolne ravnine.

4 Tipi stika med kopnim in morjem

Slovenska obala sodi med obale riaškega tipa, za katere velja, da je glavna smer obale prečna na geološko zgradbo. Zanjo so značilni dolgi zalivi v potopljenih rečnih dolinah, med katerimi segajo daleč v morje višji polotoki. Poglavitne reliefne oblike so obalne ravnice v notranjosti zalivov in strmi klifi na obalah polotokov (Kolega, 2006). Tako lahko v grobem v Koprskem primorju ločimo štiri naravne tipe stika med kopnim in morjem.

Prvi tip stika med kopnim in morjem se pojavlja na območju *klifov*. Gre za kopno, ki se strmo spušča proti morju, na stiku kopnega in morja pa je lahko različno široka abrazijska ravnica. Ta se pod morsko gladino običajno nadaljuje v kamnito podmorsko teraso, ki se na nekaj metrih globine konča s previsom. Pojavnost kamnitih podmorskih teras, njihova širina, širina abrazijske ravnice, višina in naklon klifa, globina morja pod klifom ter naklon dna, se od klifa do klifa zelo razlikujejo. Klifov, ki abrazijske in podmorske terase sploh ne bi imeli, temveč bi se kot stena spuščali v morske globine, pri nas ni, saj so klifi v Koprskem primorju iz fliša, ki je dokaj neodporen na preperevanje in krušljiv.

Slika 1: Stik med kopnim in morjem na območju klifa na severni strani Pirana.
Glej angleški del prispevka.

Drugi tip stika med kopnim in morjem se pojavlja na obalah, kjer se *kopno in morsko dno položno spuščata*. Gre za obale, ki sicer niso ravne in nizke, temveč se iz gričev v zaledju počasi položno spuščajo proti morju. Podobno velja tudi za morsko dno od stika med morjem in kopnim dalje. Če pogledamo profil takšnega stika med kopnim in morjem, lahko vidimo, da se ta pod in nad obalno črto ne razlikuje bistveno. Takšne obale pri nas nastopajo zlasti ob straneh zalivov.

Slika 2: Primer stika med kopnim in morjem, kjer se kopno in morje položno spuščata, na zahodni strani Portoroža.
Glej angleški del prispevka.

Tretji tip stika med kopnim in morjem se pojavlja na *akumulacijskih obalah*. V tem primeru gre za izjemno položno kopno, ki se praktično »prelije« v morsko dno. Višina kopnega ob stiku je zelo nizka, prav tako globina morja. Takšne obale se pojavljajo povsod, kjer prihaja do akumulacije, zlasti pa v zalivih. Na slikah 5 in 6 je kopno na stiku končano s kamnitim zidkom, zato je na profilu tudi videti stopnico na prehodu med kopnim in morjem. Če tega zidka ne bi bilo, bi se kopno »gladko prelilo« v morsko dno.

Slika 3: Primer stika med kopnim in morjem na akumulacijski obali na Sv. Katarini.
Glej angleški del prispevka.

Četrti tip stika med kopnim in morjem se pojavlja na območju *razmeroma položnega kopna*, ki se ob prehodu v morsko dno dokaj hitro *spremeni v previs*. Gre za kopno, kjer se v zaledju sicer pojavljajo vzpetine, vendar se kopno do morja spusti razmeroma položno, v morju pa kmalu nato pride do izrazitega previsa in večjih globin. Do tako izrazitega in obsežnega previsa prihaja zgolj na območju piranske Punte, kjer je, najverjetneje zaradi močnih tokov ob rtu, morje tako globoko.

Slika 4: Primer stika med kopnim in morjem na stiku položnega kopnega in strmega dna v Piranu.
Glej angleški del prispevka.

5 Klifi, abrazijske terase in podvodne kamnite terase

Za podrobnejšo primerjavo in analizo klifov so bili izbrani trije klifi: klif med Fieso in Pacugom, klif na rtu Ronek in klif pod Belvederjem zahodno od rtiča Kane. Zaradi lažjega pojmovanja smo klife poimenovali kar Pacug, Ronek in Belveder.

Na slikah 9, 11 in 13 so prikazani klifi v 3D-pogledu, za nazornejšo predstavo o globini pa je dodan tudi sloj, ki predstavlja morsko gladino. Klifi so prikazani kot senčeni relief, saj je njihova oblikovanost tako najbolj vidna in izstopajoča. Na vsakem klifu so bili narejeni trije prečni prerezi, katerih potek je prikazan na slikah 10, 12 in 14.

Klifa Belveder in Pacug se nahajata na razmeroma ravnem, proti severu obrnjenem delu obale, Ronek pa na samem rtu, zato je na eni strani obrnjen proti severu, na drugi pa bolj proti severozahodu oziroma zahodu. Vsi trije so sorazmerno visoki in površinsko razčlenjeni tako pod, kot nad vodo. Pri vseh treh klifih lahko pod vodo opazimo različno izoblikovane podmorske terase, katerih dimenzije se od klifa do klifa razlikujejo.

Slika 5: Klif Belveder.
Glej angleški del prispevka.

Slika 6: Profili klifa Belveder.
Glej angleški del prispevka.

Slika 7: Klif Pacug.
Glej angleški del prispevka.

Slika 8: Profili klifa Pacug.
Glej angleški del prispevka.

Slika 9: Klif Ronek.
Glej angleški del prispevka.

Slika 10: Profili klifa Ronek.
Glej angleški del prispevka.

Preglednica 1: Primerjava lastnosti klifov, ki jih je bilo mogoče odčitati iz prečnih prerezov.

ime klifa	naklon klifa (°)	naklon celotne (abrazijske in podmorske) terase (°)	širina celotne (abrazijske in podmorske) terase (m)	višina klifa (m)	ekspozicija
Belveder 1	72	–8	Ni jasno do kod sega.	72	S
Belveder 2	69	–7	133	62	S
Belveder 3	75	–5	106	47	S
Pacug 1	65	–9	57	64	S
Pacug 2	51/84	–8	65	80	S
Pacug 3	65	–9	60	64	S
Ronek 1	69	–3	96	59	S
Ronek 2	67	–4	131	50	S
Ronek 3	66	–6	124	43	SZ

Najbolj izstopa Ronek, saj ima najširšo podmorsko teraso, ki je prav tako najbolj položna. Vendar je podmorska terasa tudi pod Belvederjem precej široka, na nekaterih mestih celo širša. Največji naklon ima klif pod Belvederjem, medtem ko največjo višino doseže klif v Pacugu. V podmorski terasi klifa pod Belvederjem sta lepo vidna potek in smer odpornejših flišnih skladov, ki so obrnjeni prečno na obalo, potekajo iz smeri jugovzhoda proti severozahodu. Na Ronku se širina podmorske terase od zahoda proti vzhodu oziroma od ene do druge strani rta oža. Na vzhodni strani bližje obali je, podobno kot pod Belvederjem, videti potek odpornejših flišnih skladov, ki prav tako potekajo v enaki smeri. Razlog, da ima klif na Ronku najdaljšo in »najvodoravnejšo« podvodno teraso je v tem, da gre za rt, ki je zelo izpostavljen valovom in ga je zato morje že precej premaknilo v škodo obale (Gams 1970). Prav tako Furlani (Furlani 2003) ugotavlja pozitivno korelacijo med izpostavljenostjo valovom in dolžino terase.

Klif v Pacugu ima prav tako lepo vidno podvodno teraso, še bolj pa izstopa previs pod njo. V primerjavi z drugima dvema klifoma je terasa veliko bolj enakomerna.

6 Podvodne kamnite terase in umikanje klifov

Podvodne kamnite terase predstavljajo večji del kamnitega dna v slovenskem morju, njihov nastanek pa je mogoče povezati tudi z umikanjem klifov. Večina raziskovalcev meni, da so terase nastale zaradi daljšega zadrževanja vodne gladine v tej višini v preteklosti (Šifrer 1965). Med zadnjo poledenitvijo in po njej je gladina morja precej nihala. Gladina morja se je na višku ledenih dob umikala proti jugu Jadrana, v vmesnih medledenih dobah pa se je zviševala. Po zadnji ledeni dobi v Würmu, se je gladina morja zviševala. To imenujemo postwürmska transgresija, ki traja še danes, vendar je potrebno poudariti, da se je tudi v tem obdobju višina gladine morja spreminjala (Šifrer 1965). Daljše zadrževanje morske gladine pod sedanjo ravnijo je povzročilo nastanek podvodnih teras.

Med globino približno –2 m in –10 m globine naletimo na več različno izrazitih teras. Če upoštevamo globine, na katerih se terasa pojavlja, gre v glavnem za dve terasi iz različnih obdobij nastanka. Na večjem delu obale pod klifi je na globini približno –8 m do –9 m viden konec (previs) različno široke podvodne kamnite terase. Takšno teraso je mogoče slediti ob celotni Jadranski obali in tudi drugod po svetu, kar dokazuje, da gre dejansko za posledico daljšega zadrževanja morske gladine v tej legi v obdobju zadnje poledenitve, ko je bila gladina morja od današnje nižja za 10 m do 30 m (Orožen Adamič 2002). Na globini približno –2 m do –4 m je ponekod opazna še ena kamnita terasa, tako imenovana rimska terasa. Terasa je manj izrazita kot tista na približno 8 m globine, njen nastanek pa je prav tako povezan z daljšim obdobjem zadrževanja višine gladine morja na tej višini (Šifrer 1965; Orožen Adamič 2002).

Da bi o podvodnih kamnitih terasah dobili čim več informacij ter podkrepili omenjeno razlago, smo potek in razsežnost podvodnih kamnitih teras v slovenskem morju kartirati, kjer so le-te vidne. Terase in njihove meje smo zarisali tam, kjer so bile v podatkih najbolj vidne in izstopajoče.

Slika 11: Potek in širine podvodnih kamnitih teras.
Glej angleški del prispevka.

Potek, širine in globine podvodnih kamnitih teras so bile določene z analizo rastrov naklonov in senčenja morskega dna ter s pomočjo izdelave profilov morskega dna ter stika med kopnim in morjem, ki smo jih naredili vzdolž obale, kjer se terasa pojavlja, s približno 80 m medsebojne oddaljenosti. Širine teras smo razvrstili v 4 razrede, ki jih prikazuje slika 15.

Podvodne kamnite terase se pojavljajo na globinah med –4 m in –8 m, širine teras znašajo od 12 m do prek 400 m. Najširša terasa je na Lazaretu, vendar pa v njenem zaledju ni klifa, terasa pa je najverjetneje zasuta z muljem, je pa kljub temu zelo jasno vidna. Podobno velja tudi za teraso na Fizinah, le da je ta precej ožja. Če ne upoštevamo terase na Lazaretu, je najširša terasa na Debelem rtiču, kjer imamo opravka s podaljškom rta pod morsko gladino, kar jasno priča tudi o obsežnosti umika rta. Iz slike 15 in preglednice 2 lahko vidimo tudi, da se najširše terase pojavljajo ob rtih, kar je razumljivo, saj so rti najbolj podvrženi delovanju morja in je tam umik klifov najobsežnejši. Izstopajo predvsem Debeli rtič, rt Strunjan in rt Ronek, podobno pa je opaziti tudi na ostalih manjših rtih. Najožjo teraso zasledimo ob Fornačah. Skupna dolžina vseh vidnih podvodnih teras znaša 17,5 km.

Če spremljamo obalo od meje s Hrvaško proti meji z Italijo, najprej naletimo na z muljem zasuto teraso pri Fizinah na približno –4 m globine. Terasa se na podobni globini nadaljuje tudi vzdolž Bernardina

Preglednica 2: Širine pod vodo, globine in vidnost podvodnih kamnitih teras.

lokacija terase	približna globina (m)	povprečna širina (m)	največja širina (m)	vidnost
Lazaret	–6	365	445	dobra
Debeli rtič	–8	141	312	dobra
Ankaran	–4	75	79	slabša
Koper–Izola	–4	42	120	slabša
Izola	od –6 do –8	68	140	dobra (na posameznih mestih slabša)
Bele skale	–8	89	160	dobra (na posameznih mestih slabša)
Strunjan	od –6 do –8	90	151	dobra (na posameznih mestih slabša)
Pacug, Fiesa	–4	65	97	dobra
Piran	od –6 do –8	87	111	dobra
Fornače, Bernardin	–4	34	70	dobra (na posameznih mestih slabša)
Fizine	od –4 do –5	55	86	dobra

in Fornač. Večinoma sledi terasi izrazit previs. Na severni strani Pirana se v globini približno –6 m konča kamnita terasa s prvim previsom, ki se konča pri –12 m globine in nadaljuje z manjšo uravnavo blažjega naklona, pri približno –14 m globine pa pride do še enega previsa, ki je nekoliko manj izrazit in se konča pri približno –20 m globine. Pod klifom med Fieso in Pacugom sega kamnita terasa do globine –4 m, nato precej strm previs do globine –10 m, manjša uravnava do –11 m in ponovni, blažji previs do –16 m globine. Dno pod klifom severno od Strunjana pred rtičem Strunjan se spušča bistveno bolj položno. Kamnita terasa je široka tudi prek 150 m. Bolj ko se bližamo rtu, bolj izstopa previs v globini med –8 m in –10 m. Na samem rtu se dno precej strmo spušča do globine –17 m, od tu naprej pa se spušča bolj položno, izrazitih teras in previsov ni videti. Dalje na zahodni strani Mesečevega zaliva je opazen zelo blag previs v globini –3 m, v zalivu pa je nastala manjša akumulacija. Ob rtu Ronek je prisotna okrog 90 m široka podvodna terasa, ki se približno na globini –5 m strmo spusti do globine –10 m. Od tu naprej se dno počasi spušča. Proti Belim skalam (približno na sredini med Strunjanom in Izolo), postaja previs pod vodo vse bolj zabrisan. Kamnita terasa pod vodo je sicer lepo vidna, njena širina, pa se giblje okrog 90 m. Na Belih skalah se ponovno pojavi previs, ki se spušča do približno –4 m globine. Na zahodni strani rta Kane je izrazitejši previs med globino –2 m in –10 m. Pod klifom med Izolo in Koprom izrazitejših teras in previsov ni opaziti, ponekod so le zelo blagi obrisi teras in previsov pod njimi na globini med –3 m in –5 m. V okolici Debelega rtiča se nahaja do 300 m široka kamnita terasa z blagim previsom, ki se spušča od približno –8 m do –15 m globine. Na koncu rta je pod vodo viden približno 400 m dolg podvodni podaljšek rta. Morje nad podvodnim rtom še dobrih 300 m stran od obale ne preseže globine –5 m. Podaljšek rta tvori pod vodo pravo vzpetino, saj se dno iz globine –18 m dvigne na –3 m in ponovno spusti na –15 m globine. Izrazito teraso in previs je opaziti tudi naprej proti Lazaretu, le da je tu terasa zasuta z muljem.

Če izhajamo iz ugotovitve, da so podvodne terase dejansko posledica daljšega zadrževanja gladine v tem nivoju, nam to pove tudi, koliko se je od tega obdobja do danes klif umaknil zaradi abrazije, erozije in denudacije. Geomorfni procesi namreč klife nenehno preoblikujejo, kar povzroča umikanje klifa za nekaj centimetrov na leto (Zorn 2009), zaradi stalne abrazije pa ob umikanju ohranjajo svojo prvotno obliko (Savigear 1952). Z izjemo Lazareta so povprečne širine teras med 50 m in 100 m, razen morju najbolj izpostavljenih rtov, kjer naj bi se klif odmaknil tudi za prek 150 m oziroma prek 300 m na Debelem rtiču. To naj bi se zgodilo od zadnje poledenitve do danes ali v približno 37.000 letih (Orožen Adamič 2002). Od rimskega obdobja naj bi se klif ponekod odmaknil tudi za nekaj deset metrov (Furlani 2007).

7 Sklep

Slovenska obala je razgibano, raznoliko in specifično območje. Nadmorske višine so razporejene med največjo globino –38 m in najvišjo višino 157 m. Pogostost vrednosti višin in globin pada obratno sorazmerno s povečevanjem globine in višine. Večji del pasu je uravnan. Razporeditvi višin primeren je tudi razpon vrednosti naklona površja, ki znaša prek 88°. Približno tretjina površja ima naklone med 1°in 3°. Najobsežnejši del površja ima severno ekspozicijo, ki je posledica lege in poteka obale.

S tipizacijo stika med kopnim in morjem smo ugotovili, da stik med kopnim in morjem lahko razdelimo v štiri naravne tipe. Tipizacija celotne obale ni bila izvedena saj je večji del obalnega pasu antropogeno preoblikovan in je zato tipiziranje v takšne (naravne) tipe nemogoče.

Izdelava enotnega DMV kopnega in morskega dela obalnega pasu in na njem opravljene prostorske analize so omogočile nov pogled na obalni pas kot neločljivo celoto s prepletajočimi se značilnostmi v kopnem in morskem delu pasu. To je omogočilo spoznavanje posameznih značilnosti območja, ki so do sedaj bile skrite, kot so tipi stika med kopnim in morjem in značilnosti klifov ter podvodnih teras pod njimi.

Veliko informacij o obalnem pasu nudijo tudi ločene prostorske analize bodisi kopnega bodisi morskega dela obalnega pasu, kot so na primer tipizacija morskega dna, človekovi posegi v morsko dno, vegetacija, pozidanost ipd., vendar njihovih rezultatov na tem mestu ne bomo omenjali.

8 Literatura

Glej angleški del prispevka.