Original scientific article
Received: 2010-11-18

UDC 551.351(497.472)

COASTAL CLIFF BEHAVIOUR: THE CASE STUDY OF DEBELI RTIČ (SW SLOVENIA)

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ABSTRACT

Coastal cliff behaviour has been studied in five sites along the Slovenian coast, in the north-eastern Adriatic Sea, through the comparison of 2515 images collected at the sites and more than 4500 additional pictures collected since 1998. Moreover, a detailed characterization of the geomechanical properties and the quality of rock masses together with the rockfall susceptibility have been studied to determine the geomechanical properties of the studied sites. Significant modifications of the cliff face are located in particular in sites showing poor or very poor rock mass quality. Moreover, photographic surveying suggests that cliffs are affected by a complex behaviour with respect to coastal retreat: during long stable-weather periods, cliff modifications are very low, while major changes in the cliff face occur after great storm events owing to the interaction of both marine and non-marine factors.

Key words: geomorphology, geomechanics, Flysch, cliff retreat, photographic surveying, Slovenia

FALESIE COSTIERE: IL CASO STUDIO DI PUNTA GROSSA (SLOVENIA SUDOCCIDENTALE)

SINTESI

La comparazione di 2515 immagini, raccolte a partire dal 1998 in 5 siti lungo la costa slovena e 4500 immagini aggiuntive, hanno permesso di studiare il comportamento delle falesie costiere di Punta Grossa (Debeli rtič). Si sono inoltre studiate le proprietà geomeccaniche lungo le falesie per definire la qualità dell'ammasso roccioso e la suscettibilità al crollo nei siti indagati. Le modificazioni più significative della falesia sono localizzate in corrispondenza dei siti con qualità più scadenti dell'ammasso roccioso. Inoltre, il rilevamento fotografico ha evidenziato che, nell'area di studio, le falesie sono interessate da un comportamento molto complesso rispetto nei confronti dell'arretramento costiero: durante i periodi di tempo meteorologicamente stabile, le modificazioni sono piuttosto modeste, mentre le variazioni più significative nella morfologia della falesia avvengono in seguito agli eventi di tempesta più importanti, a causa dell'interazione tra processi marini e subaerei.

Parole chiave: geomorfologia, geomeccanica, Flysch, arretramento della falesia, rilevamento fotografico, Slovenia

INTRODUCTION

Cliff retreat is the sum of the sustained action of marine and continental factors. Their interrelations depend on the geological and environmental settings of the area. Genesis and development of coastal cliffs are due to undercutting by marine erosion followed by the collapse of imminent rocky materials (Woodroffe, 2002). The type of rockfall that occurs on cliffs is controlled mainly by local geology, namely joints, bedding and fault planes (Moon & Healy, 1994). Stephenson & Kirk (2000) stressed the importance of cliff rock strength and the following wave action and long shore current processes. The height of cliffs and their lithology play an important role in cliff retreat (Buckler & Winters, 1983; Sunamura, 1983). The higher the cliff the lower the shear stress required for any discontinuities like faults, joints, fractures and bedding planes in the rocks to fail under gravity (Richards & Lorriman, 1987; Komar & Shih, 1993; Bray & Hooke, 1997). Greenwood and Orford (2007) suggested four main factors that control the rates and processes of cliff recession, in particular sea level, properties of sea cliff rocks, slope of cliffs and nearshore, and location of point sources of erosion and deposition. Selby (1993) has estimated the relative contribution of various factors affecting cliff recession, in particular intact rock strength 20%, discontinuities 64%, water erosion 6% and weathering 10%.

Photographic surveying has been successfully used by many authors (Pierre, 2006; Mortimor & Duperret, 2004, Emery & Kuhn, 1980). Few similar analysis were conducted also on Slovenian coasts (Furlani, 2003; 2007). The author provides the background of the problem and some retreat values. Flysch cliff behaviour in the hinterland of Slovenia coast has recently been studied by Zorn (2008; 2009).

Geomechanical surveys and analysis using the GSI (Geomechanical Strength Index) system have been applied to define qualities of rock masses (Marinos & Hoek, 2000; Ulusay & Somnez, 1999). Moreover, GSI is the unique rock mechanic classification developed to study slopes cut in Flysch (Bruschi, 2004).

This work aims at evaluating the behaviour of Flysch coastal cliff at Debeli rtič (SW Slovenia), the factors that trigger the collapse of material and its removal from the cliff foot through a detailed characterization of the quality of rock masses, the rockfall susceptibility and the comparison of a decade-long photographic survey.

MATERIAL AND METHODS

Study area

The study area is located in the northernmost part of the Slovenian coast, at Debeli rtič, in the NE Adriatic (Fig. 1). The turbiditic Formation of Eocene Flysch (cf. Magdalenić, 1972) is characterized by a regular alternation of sandstone and marlstone. Sandstone spacing ranges from centimetric to metric, while marlstone spacing ranges from millimetric to centimetric.

In particular, the studied cliffs are composed by centimetric–metric sandstone with millimetric-centimetric interbedded silty marlstone, showing almost horizontal bedding. The low resistance of the rock masses (Furlani, 2003) allows their rapid retreat and the development of wide shore platforms.

From a geodynamical point of view, the area belongs to the External Dinarides, characterized by a diffuse trend in NW-SE direction, which include the Upper-Eocene thrusts and nappe structure of NE Italy and Slovenia (Placer, 2008).

The climate is Sub-Mediterranean (Ogrin, 1995), characterized by equally distributed rainfall throughout the year, with slightly rainier periods in autumn (mean rainfall 290 mm) and less rain in summer (213 mm). Mean annual rainfall, measured in the 1961–1990 period in Trieste, is 1015 mm/yr (Trieste site, 0 m a.s.l.) (Righini *et al.*, 2002; Stravisi, 2003). The minimum mean value was recorded in February, while the daily peak is 105 mm in November. Storms are more frequent at the end of the summer and in autumn.

On average, there are approximately 31.5% of rainy days, 64.4% of sunny days, 3.0% of snowy days and 1.1% of days with hail (Tommasini, 1979). The hottest month is August (24°C) whereas the coldest one is January, with temperatures below 6°C.

Materials and methods

A multidisciplinary approach has been used to investigate the factors that affect Flysch coastal cliff behaviour. Photographic surveying together with geomechanical analysis have been used.

Photographic surveying started in 1998 using a 35 mm camera (Fuji). In 2002, digital surveying replaced the analog one, first using a Nikon Coolpix 995, then a Canon D300 reflex digital camera. Images have been collected as follows: 1) repeated images have been collected at 5 sites (Table 1) located in the north-western sector of the promontory (Fig. 1), at times reported in Table 2; the number of images collected during the surveying periods is reported in the table, the total amount of repeated pictures is 2515; 2) general images collected along the whole coastal stretch of Debeli rtič, with images from the sea or from the cliffs, in order to survey all the most important cliff changes, even at different sites; the total amount of general images is about 4500.

Considering the aims of this work, besides the acquisition of repeated images in the aforementioned stations, all the modifications of the cliffs and the shore platform have been noted and the relative picture formed. Rockfall, fallen trees and major storms have been documented, even if occurring at other sites.

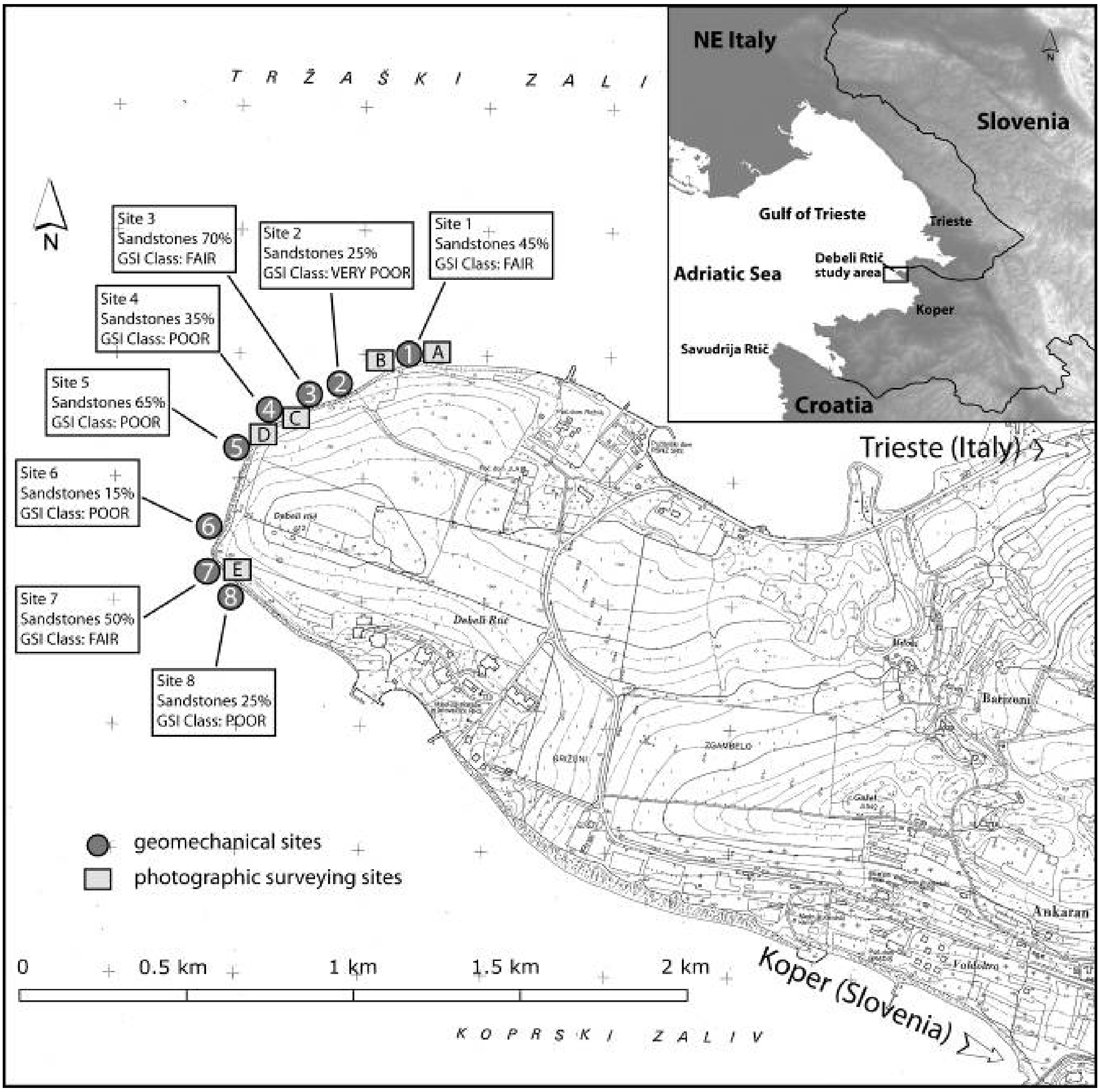

Fig. 1: Location of the surveyed geomechanical and photographic sites.
Sl. 1: Lokacije geomehanskega in fotografskega pregleda.

Tab. 1: Environmental setting of the photographic sites. A) name of the site; B) wind exposure (quadrant); C) altitude (m a.s.l.); D) surveying period; E) maximum fetch (km); F) reasons for the photographic surveying at the site.
Tab. 1: Okoljska umeščenost točk fotografiranja. A) ime lokacije; B) izpostavljenost vetru (kvadrant); C) nadmorska višina (m n.m.); D) trajanje pregleda; E) maksimalni doseg (km); F) razlogi za obravnavo lokacije.

Jv	SR
0.1	100
0.8	90
2	80
4	70
7	60
10	50
15	40
20	30
50	20
120	10

In order to evaluate the quality of rock masses that form the cliffs, geomechanical surveys were conducted along the coast of Debeli rtič (Italian *Punta Grossa)*. GSI classification was chosen because conventional geomechanical system, such as the Rock Mass Rating methodologies (RMR) and Q present serious limitations for the analysis of heterogeneous formations like Flysch (Bruschi, 2004). GSI classification was developed to classify rock masses of slopes consisting of two different lithotypes, such as marlstone and sandstone (Marinos & Hoek, 2000; Ulusay & Somnez, 1999). Flysch in fact is characterized by different mechanical and hydrogeological behaviours: marlstone has a ductile behaviour and is easily eroded by storm surges, while sandstone exhibits higher resistance values. GSI system is based on a simple concept that combines the structural setting of the rocks with the properties of fractures, in order to achieve a quality index value of the rock masses used for the assessment of coastal retreat rate.

Ulusay and Somnez (1999) introduced two parameters; the first, SR, is related to the degree of fracturing of rock mass and is determined according to the number of joints per m^3, Jv (Palmstrom, 2005), and another, SCR, which denotes the ratings for roughness, weathering and infilling material (Hack, 1998). Joint properties were surveyed according to BS 1981 (Hack, 1998). SR values are reported in Fig. 2.

SCR is obtained from the sum of three coefficients:
SCR= Rr + Rw + Rf

Rr parameter (Joint roughness), Rw parameter (Weathering of rock masses) and Rf parameter (Infilling material and aperture of fractures) values are as follows:

Rr parameter (Joint roughness)

Wavy	Slightly wavy	Curved	Slightly curved	Straight
6	5	3	1	0

Rw parameter (Weathering of rock masses)

No weathered	Slightly weathered	Moderately weathered	Highly weathered	Completely weathered
6	5	3	1	0

Rf parameter (Infilling material and aperture of fractures)

Nothing	Hard < 5 mm	Hard > 5 mm	Soft < 5 mm	Hard > 5 mm
6	5	3	2	0

The obtained values of SR and SCR are given in a GSI value chart (Bruschi, 2004).

The value of GSI can vary from 0 to 100, the higher the value the greater the quality characteristics of the rock and its resistance to sea cliff retreat. The quality classes are 5 and are listed below.

Quality classes obtained from GSI values

Very poor	Poor	Fair	Good	Excellent
0-20	21-40	41-60	61-80	81-100

Tab. 2: Images collected during the surveying period. The number of images collected using the analog camera are reported in blue, while the number of images collected using the digital camera are reported in grey. The total number of collected images is 2515. Other 4500 images have been collected in the same area at different sites in order to survey all the most important cliff changes.

Tab. 2: Fotografski material, pridobljen tekom raziskave. Število fotografij, narejenih z analognim fotoaparatom, je podano v modrih okencih, število digitalnih fotografij pa v sivih. Skupno število fotografij je 2515. Ostalih 4500 fotografij je bilo posnetih na različnih lokacijah istega območja, z namenom obravnave vseh pomembnejših sprememb na klifih.

A Site	B Exposure (quadrant)	C Altitude (m a.s.l.)	D Surveying period (years)	E Max fetch (km)	F Aims
A	NE-NW	0	9	50	Acting processes of the cliff
B	NW	0	5	50	Evolution of the cliff foot
C	NW	0	9	50	Evolution of a notch carved at the cliff foot
D	NW	0	4	50	Evolution of the cliff foot
Ea	SE, NW	0	9	120	Acting processes of the cliff
Eb	SE, NW	25	7	120	Analysis of beach material on the shore platform, evolution of the cliff top
Ec	SE, NW	25	7	120	Analysis of beach material on the shore platform, evolution of the cliff top

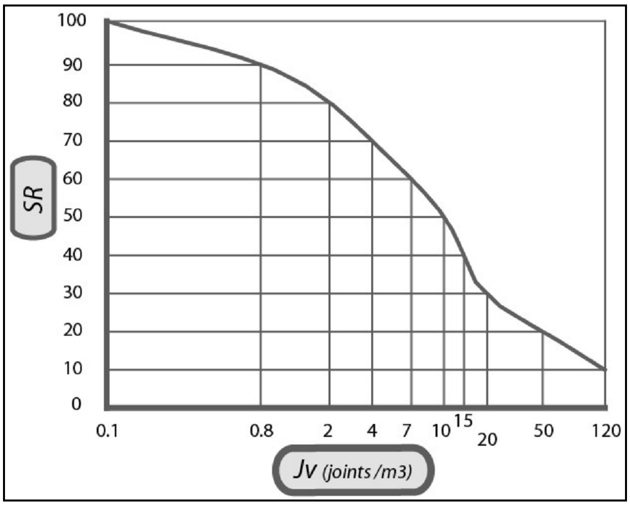

Fig. 2: Relationship between Jv and SR parameter.
Sl. 2: Razmerje med Jv in SR parametrom.

RESULTS

Photographic sites and surveying results

A 12-year-long photographic survey is presented. The features of photographic stations are reported in Table 1.

Examples of major cliff modifications are reported in figures 3, 4, 5 and 6. Regarding site B (Fig. 3), few modifications occurred at the cliff foot, but large amount of beach pebbles are moved, covering and uncovering respectively the shore platform. In site C (Fig. 4), the cliff is undercut. Occasionally, the cliff is threatened by stonefall and the shore platform is covered and uncovered both by beach or collapsed material. In site D (Fig. 5), between January and April 2006, rockfall occurred in the notch. The material at the cliff foot protects the notch from erosion. In site Ec (Fig. 6), at the beginning of 2007, a tree fell from the cliff onto the shore platform and blocked larger rocks for a year.

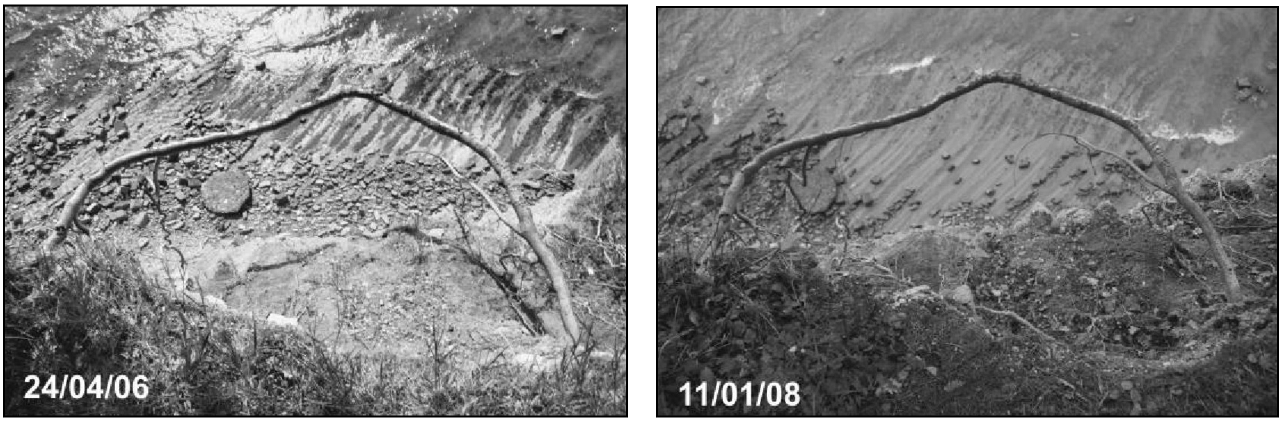

Fig. 3: Morphological changes at site B.
Sl. 3: Morfološke spremembe na točki B.

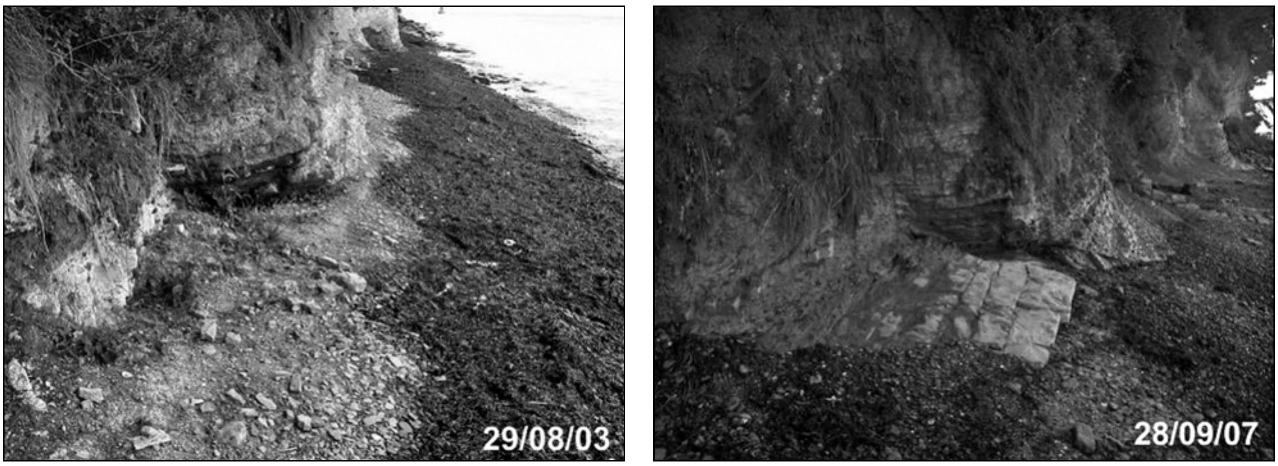

Fig. 4: Morphological changes at site C.
Sl. 4: Morfološke spremembe na točki C.

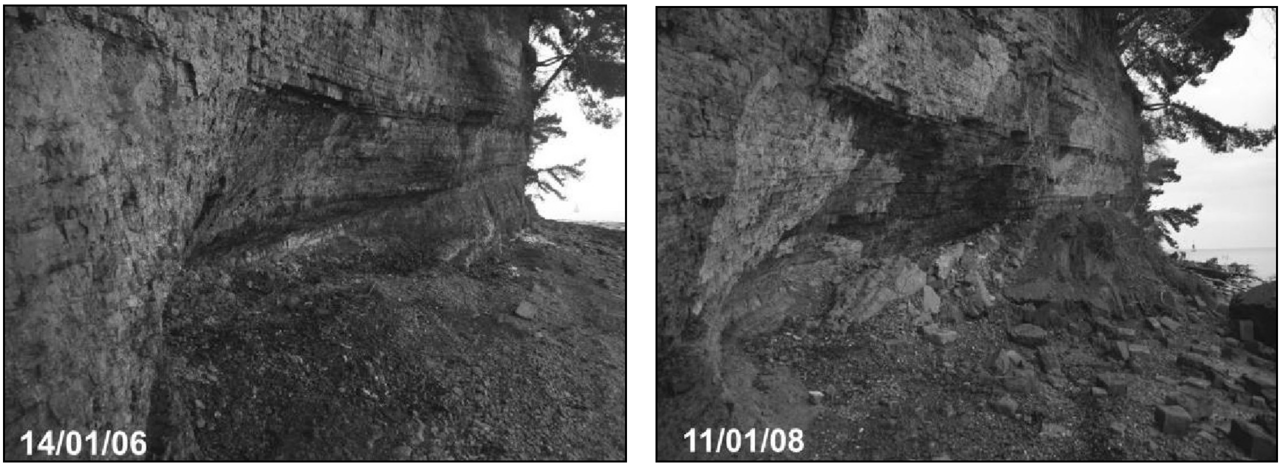

Fig. 5: Morphological changes at site D.
Sl. 5: Morfološke spremembe na točki D.

Fig. 6: Morphological changes at site Ec.
Sl. 6: Morfološke spremembe na točki Ec.

Geomechanical analysis

Geomechanical analyses were conducted in 8 sites and showed high susceptibility of the cliff to collapse. Rock fall are frequent and depend on the high degree of fracturing of the rock mass, erosion at the foot of marly materials and steepness of the walls.

The sandstone is intensively fractured (discontinuity spacing ranges from a couple of centimetres to decimetres) and weathered along the surface. As a consequence of intensive fracturing, the rock mass has good water permeability, resulting in some visible wet zones along the cliffs.

The three joint sets and the orientation of cliffs are shown in Table 3. The bedding has been renamed as joint set K1.

The three discontinuity systems formed boulders of cubic decimeter dimension on the walls. In addition, many sandstone blocks, already collapsed, are located on the shore platform, near steep cliffs (Fig. 7).

The results of GSI analysis are shown in table 4. Rock mass quality exhibits poor or very poor quality in 5 sites (Table 4), while other 3 sites do not exceed fair quality.

Tab. 3: Discontinuity sets along Debeli rtič cliff.
Tab. 3: Točke preloma vzdolž klifa Debeli rtič.

	Slope (Dip direction/dip)	Set K1 (Dip direction/dip)	Set K2 (Dip direction/dip)	Set K3 (Dip direction/dip)
Site 1	310/65	310/05	200/85	145/80
Site 2	330/80	330/20	210/75	145/80
Site 3	330/80	330/14	210/80	140/70
Site 4	345/71	330/20	210/80	140/70
Site 5	320/76	310/24	50/84	140/74
Site 6	300/60	310/21	295/70	145/83
Site 7	250/58	310/21	300/81	140/80
Site 8	220/55	335/5	140/78	230/64

Tab. 4: Results of the GSI analysis at Debeli rtič.
Tab. 4: Rezultati GSI analize na Debelem rtiču.

	Sandstone	Jv	SR	Rr	Rw	Rf	SCR	GSI	Class
Site 1	45%	10	50	3	5	2	10	45	Fair
Site 2	25%	20	30	1	1	0	2	15	Very poor
Site 3	70%	10	50	3	5	2	10	45	Fair
Site 4	35%	20	30	3	5	0	8	35	Poor
Site 5	65%	20	30	3	3	0	6	30	Poor
Site 6	15%	30	25	3	1	0	4	25	Poor
Site 7	50%	10	50	3	3	2	8	42	Fair
Site 8	25%	20	30	1	5	0	6	30	Poor

Fig. 7: Joint system at the cliff-platform junction.
Sl. 7: Razpoklinski sistem na stiku klifa in police.

DISCUSSION

Direct and indirect observations of the studied coastal cliffs indicate slow but persistent sea cliff retreat. Submerged Roman archaeological remains, located nowadays at about 50 m from the shoreline (Antonioli *et al.*, 2004, 2007), suggest that ancient cliffs were located far off-shore. A comparison between the current position of the cliff and the submerged Roman remains suggests that the cliff retreat rates attain around 10–20 mm/yr. Moreover, historical data indicate the presence of a medieval church at Debeli rtič, now completely disappeared (Borri, 1971). Even a trigonometric drome, used by the Austro-Hungarian navy to calculate the speed of ships, has disappeared because of cliff recession. Our data and analysis do not allow the evaluation of sea cliff retreat, however, they enable us to define diversifying zones of the Debeli rtič cliff showing different geomorphological and geomechanical behaviour.

First of all, recession is not consistent from one location to another. The main finding of sea cliff recession analysis is that the recession is primarily composed of both regular small losses, with occasional rapid larger losses over time, as suggested by Hall (2002). Moreover, every station shows different behaviour, both in time and space, related to environmental and geomechanical conditions. Photographic surveying displays, in fact, a complex behaviour of the cliff retreat: during long stable-weather periods, cliff modifications are very low and groundwater solution or slope failures have been observed. Major changes in the cliff face occured after great storm events, because of the complex interaction between marine and non-marine factors. Geomechanical analysis evaluates the role of the lithology: marlstone and siltstone favour the erosion processes at the cliff foot and the detachment and fall of imminent sandstone blocks, while sandstone protects the cliff from marine and subaerial processes. Sandstone and marlstone beds are susceptible to wave attack and sub-aerial erosion, because of their permeable and frittered nature (May, 1977; Quigley & Di Nardo, 1980). Failure processes are linked to joint sets and open discontinuities on sandstone beds (Sites 3, 4, 5) on the cliff, but marlstone and siltstone can be eroded at the foot of slopes and therefore they accelerate the detachment from zones where sandstone is not abundant (Sites 2 and 6).

Marine erosion acts mainly where the rock masses present poor or very poor GSI values and depends primarily on the presence of erodible material at the cliff foot. Fair quality (sandstone) and fallen boulders protect against sea cliff retreat. The field observations and geomechanical analysis demonstrate that boulders, decimetric in size, are related to three discontinuity systems. The isolated blocks are ready to detach and fall.

The results of the GSI in the 8 sites show that the quality of rock masses is little influenced by the properties of the discontinuities that are fairly constant, while Jv is probably the dominant parameter for slope failure.

Extreme care has to be taken when studying and classifying plunging cliffs in a marine environment. For deeply jointed complex rock masses such as Flysch, the GSI chart is a useful tool to evaluate rock mass quality.

The rate of retreat is still difficult to evaluate, but historical and detailed topographic investigations (see the sources for some of these investigations in Zorn, 2008; 2009) can help geomechanical and photographic analysis to infer a "formula" of erosion rate, related to different lithotypes.

CONCLUSIONS

Sea cliff behaviour has been studied at Debeli rtič (SW Slovenia), in the north-eastern Adriatic. The analysis has been carried out through the comparison of more than 7000 photos collected at 5 sites since 1998, at precise times and under any weather conditions. In addition to this, the analysis of the geomechanical properties and quality of rock masses has been conducted at 8 geomechanical sites in the same area.

Coastal cliffs in the studied area are the result of marine and slope processes. Their interrelations are strongly influenced by their lithological composition and local environmental parameters. Most significant changes of the cliff face are observed in sites showing poor or very poor rock mass quality and geomechanical properties. In particular, marlstone is more susceptible to cliff retreat, being highly erodible due to marine processes. Conversely, where the sandstone prevails vertically on highly erodible lithotypes, slopes are affected by rockfall. Boulders at the foot of the cliffs act simultaneously as a barrier to marine processes and elements of abrasion to the slope.

At the same time, photographic surveying suggests that cliffs are affected by a complex behaviour with respect to coastal retreat: during long stable-weather periods, cliff modifications are very low, while major changes in the cliff face occur after great storm events owing to the interaction of both marine and non-marine factors.

The integrated method here proposed, namely the evaluation of rock mass quality beside the direct field validation provided by the repeated photographic surveying, is very useful to outline the behaviour of coastal cliffs or to carry out geomorphic studies related to cliffs and shore platforms.

SPREMEMBE OBALNEGA KLIFA: ŠTUDIJA PRIMERA DEBELEGA RTIČA (JZ SLOVENIJA)

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POVZETEK

Spremembe obalnih klifov smo preučevali na petih lokacijah vzdolž slovenske obale, v severovzhodnem Jadranskem morju, in sicer skozi analizo 2515 fotografij, posnetih na lokacijah, in več kot 4500 dodatnih fotografij, zbranih od leta 1998. S podrobno karakterizacijo geomehanskih značilnosti in kvalitete skalnih gmot ter analizo dovzetnosti za podore smo ugotavljali geomehanske značilnosti obravnavanih lokacij.

Izrazite spremembe pečine se večinoma pojavljajo na točkah, kjer je bila ugotovljena slaba ali zelo slaba kvaliteta skalnih gmot. Poleg tega s fotografskim pregledom ugotavljamo, da so klifi podvrženi kompleksnim spremembam, ki botrujejo umikanju obale: v času daljših obdobij stabilnega vremena so spremembe minimalne, medtem ko so po velikih nevihtah opažene izrazite spremembe pečine, saj prihaja do sovplivanja morskih in drugih dejavnikov.

Ključne besede: geomorfologija, geomehanika, fliš, umikanje klifa, fotografski pregled, Slovenija

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