Discernment of layers in heterogeneous rock masses using Terrestrial Laser Scanning intensity

Goran Vlastelica
Faculty of Civil Engineering, Architecture and Geodesy, University of Split, Split, Croatia, goran.vlastelica@gradst.hr

Branko Kordić
Croatian Geological Survey, Zagreb, Croatia, bkordic@hgi-cgs.hr

Kristina Pikelj
Faculty of Science, University of Zagreb, Croatia, kpikelj@geol.pmf.hr

ABSTRACT: When dealing with site investigations in heterogeneous rock masses such as flysch, some of the most important properties, besides determining lithological aspects, are geometry (dip and dip direction of layers and secondary joints) and spatial distribution of various layers, which is especially important for slope stability calculation purposes. Determining geometrical aspects by using terrestrial laser scanning (TLS) is a well-known procedure is recently widely used, however, potential of determining spatial distribution of different strata (because of its complexity) is not yet fully implemented. In this paper TLS was performed on a typical cut slope in Eocene flysch. Beside outcrop's geometrical characteristics, preliminary analysis of the intensity of returned laser backscatter signal was analysed to determine spatial distribution of points with similar intensity values. When compared with results of lithological logging performed during the fieldwork and results of some basic sedimentological analyses, such as carbonate content, spatial distribution of intensity correlated perfectly with detected layers of different material properties. Therefore, the potential of TLS for remote determination of distribution of various lithology over inaccessible areas such as coastal cliffs, or open construction pits, was confirmed. When the results of TLS are properly interpreted, spatial distribution can then be used for detail rock mass characterisation, modelling purposes, either for general slope stability purpose or for detail analysis of local structural failure of rock slopes.

Keywords: Adriatic coast, flysch, LIDAR, TLS, intensity, rock, cut.

1. Introduction

The main usage of the LIDAR (Light Detection and Ranging) technology by both engineering and non-engineering specialists was directed during the last two decades mostly to generation of 3D surfaces from obtained point clouds, aiming mainly to their measurement, interpretation and comparison [1]. This technique is widely used in geology, mostly by using terrestrial laser scanners (TLS) as a tool for outcrop modelling and analysis [2-8]. Recently, returned laser backscatter signal was introduced as a tool for surface analysis and classification [9-11]. One of the main surface characteristics of the rocks and rock assemblages is lithology, however, the use of TLS intensity for rock lithologies recognition and classification is still greatly underexplored.

The signal received by a TLS detector is mainly affected by four essential factors: instrumental and atmospheric effects, the target scattering characteristics, and the measurement geometry [12].

Stability of the rock outcrops and undercuts largely depends on initial rock composition and it is generally lower within soft rocks [13]. This is mostly due to their tendency to be easily mechanically weathered, especially when containing clayey component. A typical example of reduced stability of both, excavated and natural slopes are those formed in flysch rock assemblage along the Adriatic coast [14-16]. One of the main characteristics of this flysch is heterogeneity of its composition. In general, it comprises a wide range of rocks in alternation, starting from marls, siltstones, sandstones to breccias. As a consequence, mineral composition of flysch complex in the coastal area may vary in small distances from highly carbonaceous to highly siliciclastic [17].

Flysch is a common bedrock cropping out over the coastal zone of the eastern Adriatic [17], however, eastern Adriatic coast (between Italy and Albania) developed in flysch occupies only 6% of its total length [18, 19]. In places where marls dominate, natural slopes are easily weathered, turning gradually into badlands [20-22]. However, in case of the higher heterogeneity of the flysch assemblage, landslides and rockfalls is the most common way of slope processes [16, 23-25].

Above mentioned flysch-related slope processes are recognized as a geohazard in the Split urban area, especially within constructional sites, where collapse in foundation pits may occurs, as well as along coastal cliffs, where cliff foot is being used as recreational beach site [23, 24].

This study investigated possibility of usage of intensity data obtained by TLS in flysch outcrop of the Split urban zone in order to determine main differences in flysch lithology, especially where inaccessible outcrops occur (e.g. coastal cliff). The ultimate aim is to recognize differences in rock composition in order to anticipate and prevent hazardous events and to reduce costs related to supporting and maintenance of less stable slopes.

1.1. Geological setting

The study area belongs to the Split flysch basin and it is located in the city district Žnjan (Split town), entirely built on the flysch bedrock (Fig. 1). The age of the flysch is middle to late Eocene. It represents deep-sea turbidites deposited in a deep basin formed due to the compressional tectonics, after the cessation of the continued Cretaceous-Early Paleogene shallow-water carbonate sedimentation [26].

In the wider Split area, flysch deposits comprise deep water deposits (siltites, marl, clayey limestones) in alternation with coarse-grained calcareous breccia and sandstones (i.e. calcirudites and calcarenites) [17]. Tectonic history of the flysch complex along the eastern Adriatic coast is characterised by a strong compression which resulted in highly crushed, folded and faulted beds. In particular, investigated strata are a part of overturned and disturbed fold, whose detailed tectonic characteristics were not possible to reconstruct due to the partial coverage of the weathered loose material (at the foot of the strata) and shrubbery, and due to the fact that the study area is still a construction area, largely covered by concrete (Figs. 1, 2, 3, 4).

Based on the field determination, studied strata show the alternation of marls and sandstones (calcisiltites and fewer calcarenites).

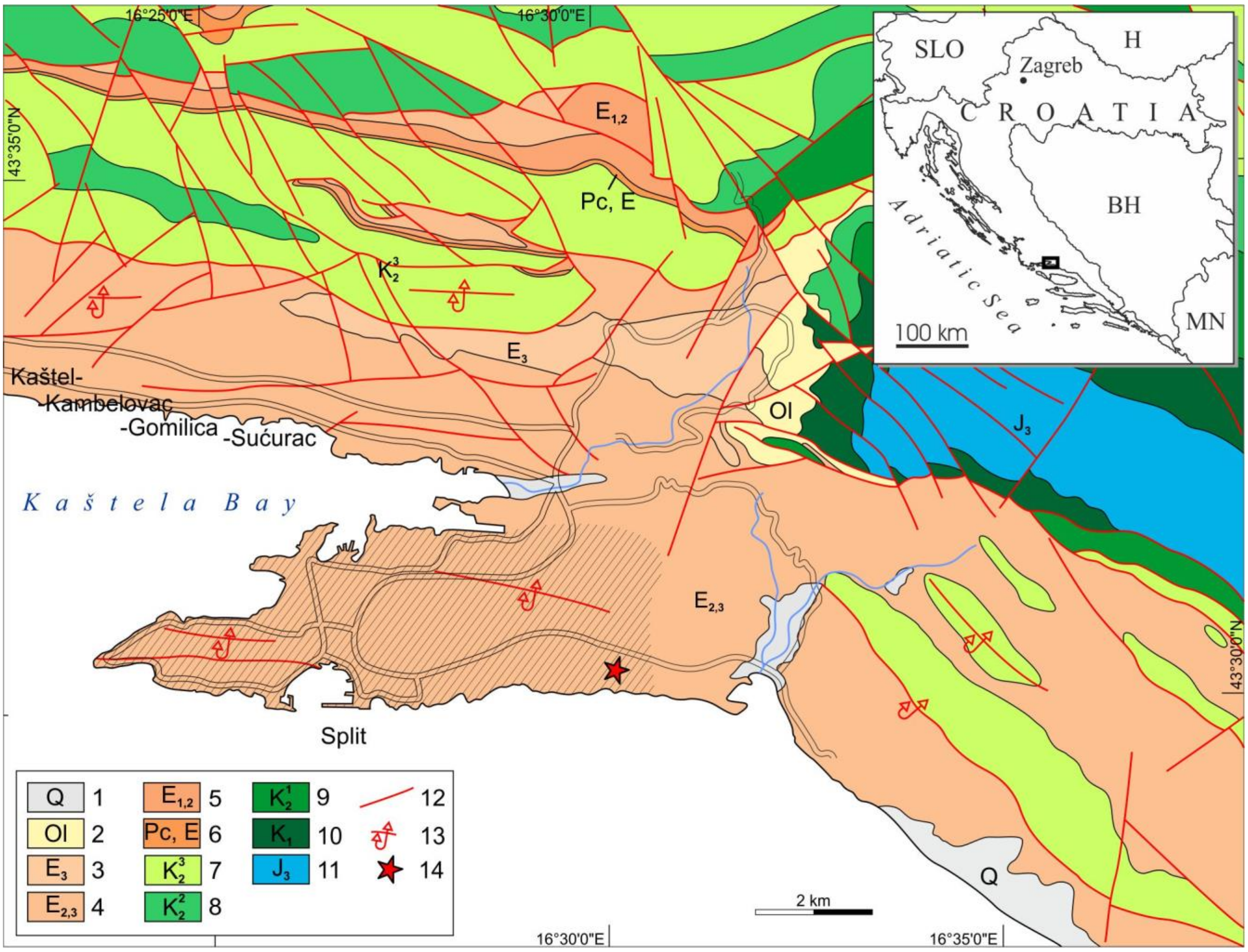

Figure 1. Geological setting of the Split urban area (A) and the location of the studied outcrop.
Legend: 1. Alluvial sediments and colluvial breccias; 2. Poorly sorted carbonate polymict breccias; 3. Carbonate breccias; 4. Marls, sandstones, carbonate breccias; 5. Foraminiferal limestones; 6. Breccias and limestones; 7. Limestones and dolomites; 8. Limestones and dolomites; 9. Bedded limestone; 10. Thick bedded limestone; 11. Thick bedded limestones; 12. Fault with undefined sense of movement; 13. Overturned anticline; 14. Position of the studied outcrop.

Measured thickness of strata ranges between 2 and 100 cm, where the sandstones are mostly thin-bedded (2-20 cm; with the exception of the layer marked as 2A showing thickness of 100 cm), while marl layers range between 40 and 100 cm (Figs. 2, 3, 4). Sandstones are brighter in appearance compared to marls, which occasionally show grey and brown varieties within the same layer (Figs. 2, 3, 4).

Exposed flysch layers are nearly subvertical or slightly dipping towards S and easily distinguishable, without significant inner-bed disturbances. Owing to their ease recognizability and heterogeneity, studied layers are considered adequate for application of TLS intensity research in order to examine and recognise variations in their lithologies.

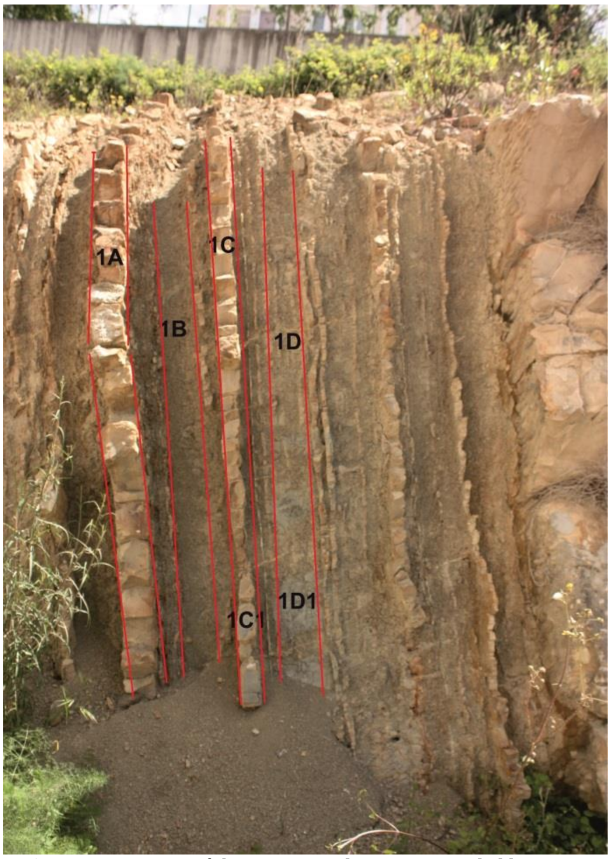

Figure 2. Section 1 of the investigated outcrop; sampled layers are marked as shown.

Figure 3. Section 2 of the investigated outcrop; sampled layers are marked as shown.

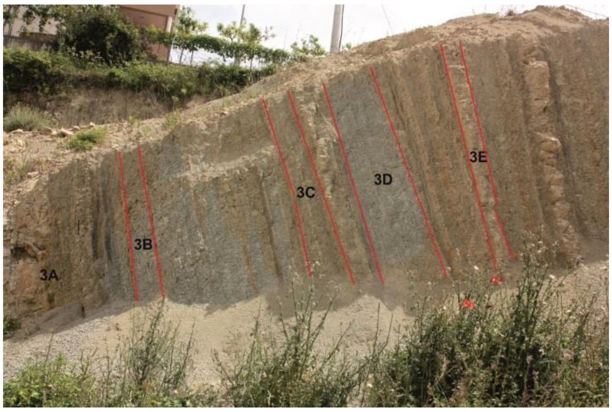

Figure 4. Section 3 of the investigated outcrop; sample layers are marked as shown.

2. Material and methods

2.1. Field research

Fieldwork was performed in two steps. The first one included preliminary examination of exposed flysch layers, selection of those to be sampled, measuring of bed thickness and sediment sampling. Exposed outcrop was roughly divided into three sections according to their accessibility, vegetation coverage and anthropogenic disturbances (Figs. 2, 3, 4). Up to six samples were collected from in each section after fieldwork determination of the main lithologic characteristics. Both colour varieties of the sediment were sampled within layers showing discontinuity in colour or content.

The second step included field-work of outcrop scanning. For the purpose of research Optech ILRIS TLS was used. Optech ILRIS instrument is designed and constructed for long-range measurements. This camera scanner with field of view 40° x 40° uses a Class 1 laser rangefinder in Short Wave InfraRed (SWIR) spectre at the wavelength of 1550 nm. Its maximum range is up to 800 m with a resolution of 1 cm, even when targets having only 20% reflectance. Furthermore, in case of very low-reflectance targets (4%) such as coal stockpiles ranges are up to 350 m [27].

2.2. Laboratory analysis – carbonate content

In order to determine further differences between sampled layers (after fieldwork determination), carbonate content was measured. Amount of carbonate is used here as a basic analysis to distinguish carbonaceous marls from marly limestones and (siliciclastic) sandstones from calcarenites/calcisiltites. Classification used for this purpose was given by [28]. The carbonate content was determined according to Scheibler's method (ISO 10693) [29] based on gas (CO_2) volumetry after sediment treatment by diluted (1:1) hydrochloric acid. Each sample was treated twice with differences between analyses within 2%. Presented results are the average of both measurements.

2.3. Desktop analysis – LIDAR data

The main purpose of the use of TLS was to correlate the main lithological characteristics of exposed layers with obtained intensity. TLS data collected during the fieldwork was parsed with Optech Parser version 5.0.3.1 software in order to transform the instrument binary raw data into a format that can be managed by the TLS data inspection and processing software. For the purpose of this research, Trimble Realworks software version 11.1.1.442 was used. Previous research proved that intensity expressed as 8-bit digital number (DN) and 16-bit DN showed similar intensity frequency distribution plots [30]. For the purpose of this research, the 8-bit DN provided by the parsing software was used instead of raw intensity directly provided by the instrument and expressed by a 16-bit DN. 8-bit DN represents the distance-corrected intensity normalised in the value range from 0 to 255. In practice, it means that an object scanned from the different distances will have the same intensity value [31].

The intensity corresponding to the surface roughness is almost the same if the incidence angle changes. This means that the backscattered signal has a Lambertian-like behaviour and it is not sensitive to the relative position between the instrument and the observed surface [30].

3. Results

3.1. Fieldwork determination of strata heterogeneity

The first section is the narrowest one where six samples were collected from four layers in section 1 (Fig. 2). Layers A and C were determined as sandstones, while layers B and D were determined as marls.

Three samples were collected from two main beds recognised within thick-bedded section 2 (Fig. 3). Layer A was determined as limestone, however, in its lower third slight lithology change was detected and additional sample (2A1) was collected. Layer B was determined as marly limestone, based on the visibly continued clay share increase.

Table 1. Summarised results of the fieldwork lithology determination.

Section:	Sample:	Determination:
1	A	sandstone
	B	marl
	C and C1	sandstone
	D and D1	marl
2	A and A1	limestone
	B	marly limestone
3	A	sandstone
	B	marl
	C	marl
	D	marl
	E	marl

The third section is the widest one (Fig. 4) in which change of the geometry was observed with layers dipping slightly towards S. Marls were determined as dominant lithology of this section, alternating with thin-bedded sandstones. Both, brown and grey varieties recognised were collected within marl layers. Results of the fieldwork determination were presented in Table 1.

3.2. Carbonate content

Amount of carbonates range between 48.4 and 99.8% along all three sections. Detailed share of carbonates in each sample is shown in Table 2. Determination of rock samples after carbonate content determination was not changed much, except in case of sample 3A and 3E which were determined as calcarenite and marly limestone, respectively.

Table 2. Carbonate content in sediment samples.

Section:	Sample:	Carbonate (%):	Determination according to carbonate content:
1	A	61.1	sandstone
	B	48.4	marl
	C	63.0	sandstone
	C1	63.9	sandstone
	D	46.6	marl
	D1	51.1	marl
2	A	99.8	limestone
	A1	82.5	slightly marly limestone
	B	76.9	marly limestone
3	A	74.5	calcarenite
	B	58.3	marl
	C	52.0	marl
	D	59.7	marl
	E	77.3	marly limestone

3.3. Intensity

When color-coded intensity scale is being presented as a grayscale (0-255), differences in intensity values become evident. Therefore, similar rock layers will show approximately the same intensity value regardless of the colour coding used. For example, Section 1 presented in Fig. 2 is shown in grayscale intensity values in Fig. 5., and Section 3 (Fig. 4.) on Fig 6., both showing groups of dark and light stripes belonging to different rock layers. Dark grey values generally represent lower intensity values (towards 0) and light grey indicate higher intesity values (approaching 255). In case of the total reflectivity value 255 would be presented as white, meaning the total reflectivity, i.e. the same amount of energy that was emitted was returned to the device and recorded. In this way, a good and wide intensity sampling base is established, therefore spatial distribution of points with similar intensity values can be more accurately defined.

Segments of obtained point cloud were isolated for each rock layer sampled for carbonate content analysis. Extracted segments were then used to determine the distribution of intensity values for each layer independently.

Intensity values for each studied layer are then organised in form of histograms, and for all of the frequency distribution of intensity values was presented (Fig.8). For example, histogram and shape of the distribution for layer 1A are presented in Figure 7. For all other studied rock layers the same procedure was carried out, and summarised results were presented in Table 3 in form of average intensities and standard deviation.

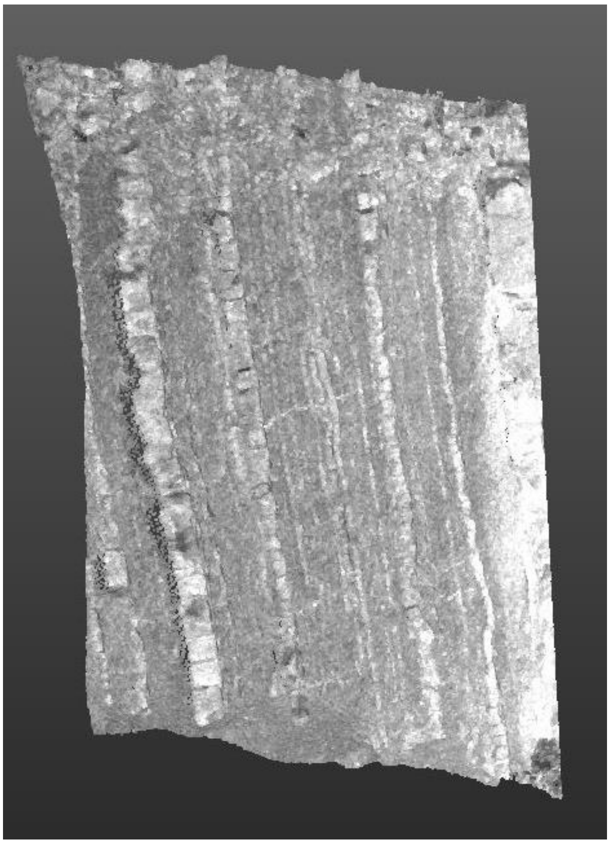

Figure 5. Section 1 of the investigated outcrop; colour coded intensity scale shown in grayscale (0-255).

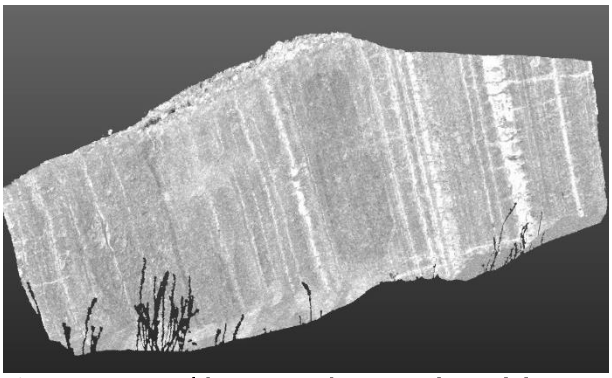

Figure 6. Section 3 of the investigated outcrop; colour-coded intensity scale is shown in grayscale (0-255).

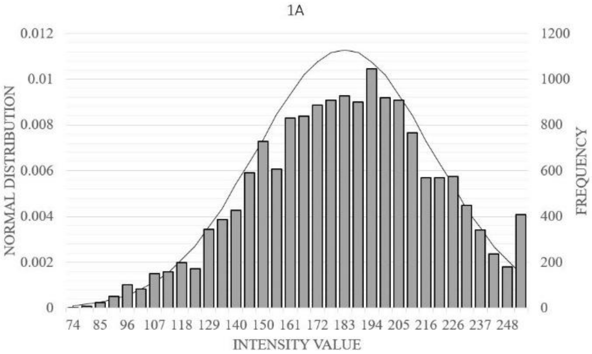

Figure 7. Histogram and frequency distribution of intensities for the layer 1A in the Section 1.

Table 3. Average intensities and standard deviation of studied rock layers. Note that

Section:	Sample:	Average intensities (DN):	Standard deviation:
1	A	193	29
	B	148	19
	C and C1	173	29
	D and D1	153	20
2	A and A1	223	32
	B	207	27
3	A	236	24
	B	174	22
	C	189	20
	D	173	18
	E	231	24

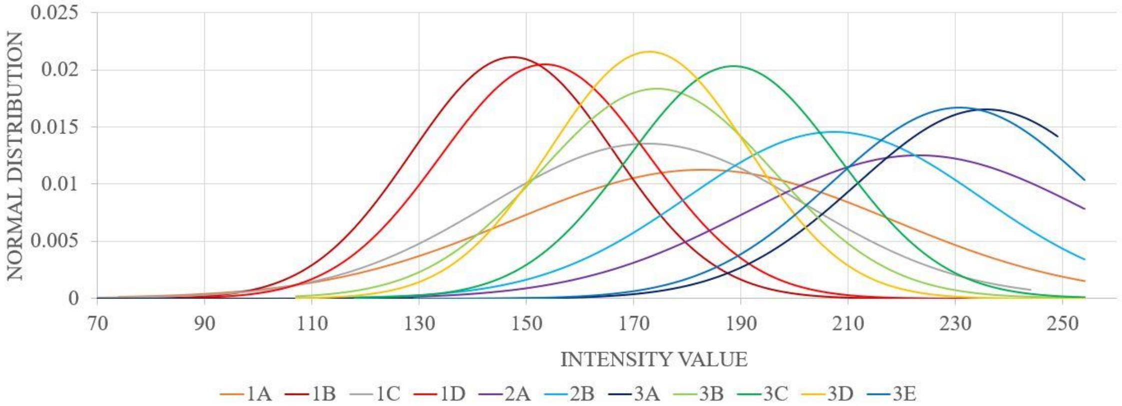

Figure 8. Frequency curves of intensities for all the sampled rock layers.

4. Discussion

LIDAR technology enables geometrical information of object, however, it also allows extraction of additional information about the object besides geometry. Intensity value depends on reflectance properties of the object. The main aim of this research was to examine possible correlation between rock layers lithologies determined during the fieldwork, carbonate content in samples collected from selected rock layers and values of the distance-corrected intensities for each sampled material. As shown in Tables 1 and 2, carbonate content in each sample confirmed the determination of the rocks conducted during the fieldwork, except in case of 3E sample, where marl determined during the fieldwork was renamed into limestone after carbonate content measurement. In case of the sample 3A, initially classified as sandstone, its texture basically remained the same, however, measurement of carbonate percentage showed that most of sand grains in this sandstone are of carbonate composition, and thus, the name calcarenite has been used instead (Table 1 and 2).

To make the methodological approach viable, this research effort is focused on relative discernment of layers only from an single campaign scanning data, in combination with selective sampling for each layer. Data of derived intensity values have shown that rock layers were generally organised into two distinctive groups. The first group contains ones with intensity value > 200 and are classified as limestones. Their carbonate percentage is generally ≥ 75% (Tables 2 and 3). In contrast, rock samples containing < 70 % (mostly < 60%) carbonates were determined as marls and sandstones. At the first glance, one could relate lighter colour of limestones with obtained intensity values. However, it has to be emphasized that the whole outcrop was scanned in changing lighting conditions during sunset, where Section 1 was in overshadowed from midday by a nearby residential building, while the shadow was gradually moving over Section 2 and Section 3 was completely illuminated all the time. Thus, based on the preliminary results, it is concluded that intensity may be correlated with percentage of carbonates in rock samples.

Unlike limestones in Section 3, ones from Section 2 showed peculiar results. Both groups of limestones contain similar carbonate content. However, limestones in Section 2 have lower intensity values and higher standard deviation (Table 3). It is assumed that these lower intensity is due to the presence of concrete waste unevenly dispersed over rock layers in Section 2 (Fig. 3). Namely, the whole outcrop is located in the construction zone, where engineering works are still in process.

Standard deviations of intensity values in limestones and sandstones in all sections are consistently higher compared to ones in marls (Table 3). Both rock lithologies (limestones and sandstones) are more resistant layers in flysch assemblage. They are usually weathered in form of rock fragmentation and rockfalls, after being exposed as cantilever on the slope. Due to the bending action fragments of sandstones and limestones are detached, exposing fracture areas [14]. These surfaces usually contain higher content of moisture, which can affect the intensity values in terms of absorption of laser beam (which was also noted by [13] and [32]), leading to the higher standard deviation for the same rock lithology. Nevertheless, this assumption needs to be further examined in the future, as well as other factors which may influence intensity distribution, such as detailed mineral composition, scanning distance, laser beam wavelength and incident beam angle.

5. Conclusion

Preliminary results of our study showed that various rock lithology in complex rock assemblage such as flysch can be distinguished using intensity distribution over the exposed outcrop. In our case, the first step in this recognition is related to variations in carbonate content. In order to achieve more detailed rock recognition, further analyses (e.g. mineral composition, scanning conditions etc.) have to be conducted. Results of such research could be useful in mapping of distribution of various lithologies over inaccessible areas such as coastal cliffs.

Acknowledgement

For part of the project activities equipment donated during the Japanese-Croatian bilateral research project: Risk Identification and Land-Use Planning for Disaster Mitigation of Landslides was used. Project was sponsored by Japan Science and Technology Agency - JST, Japan International Cooperation Agency - JICA and Ministry of Science, Education and Sport of Republic of Croatia.

References

[1] Kurtz, T. H., Buckley, S. J., Howell, J. A. “Close Range Hyperspectral Imaging Integrated with Terrestrial LIDAR Scanning Applied to Rock Characterisation at Centimetre Scale”., In: Proceedings of the Ipp. nternational Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXIX-B5, XXII ISPRS Congress, 25 August–01 September 2012, Melbourne, Australia, pp. 417–422, 2012. https://doi.org/10.5194/isprsarchives-XXXIX-B5-417-2012

[2] Bellian, J.A., Kerans, C., Jennette, D.C. “Digital outcrop models: applications of terrestrial scanning lidar technology in stratigraphic modeling”, Journal of Sedimentary Research, 75, pp. 166–176, 2005, https://doi.org/10.2110/jsr.2005.013

[3] Vlastelica, G., Miščević, P., Fukuoka H. “Monitoring of vertical cuts in soft rock mass, defining erosion rates and modelling time-dependent geometrical development of the slope. ” In: Proceedings of the International Symposium of the International Society for Rock Mechanics Rock Mechanics and Rock Engineering: From the Past to the Future, Ürgüp, Turkey, 29-31 August, 2016., London: Taylor & Francis Group, pp 1249-1254, 2016.

[4] Pringle, J.K., Howell, J.A., Hodgetts, D., Westerman, A.R., Hodgson, D.M. “Virtual outcrop models of petroleum analogues: a review of the current state-of the art” First Break, 24, pp. 33–41, 2006. [online] Available at: https://pdfs.semanticscholar.org/ac9e/d5a4a4c5e5bd12fb81334f027ec0a57c9778.pdf [Accessed: 17 Sep 2019]

[5] Buckley, S.J., Howell, J.A., Enge, H.D., Kurz, T.H. “Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations”, Journal of the Geological Society London,

165, pp. 625–638, 2008. https://doi.org/10.1144/0016-76492007-100

[6] Rarity, F., Van Lanen, X. M. T., Hodgetts, D., Gawthorpe, R. L., Wilson, P., I. Fabuel-Perez, I., Redfern, J. "LiDAR-based digital outcrops for sedimentological analysis: workflows and techniques", In: Martinius, A.W., Howell, J.A., Good, T.R. (eds.): Sediment-Body Geometry and Heterogeneity: Analogue Studies for Modelling the Subsurface, Geological Society, London, Special Publications, 387, 153–183, 2014. https://doi.org/10.1144/SP387.5

[7] Mallison, H., Wings, O. "Photogrammetry in paleontology – a practical guide", Journal of Paleontological Techniques, 12, pp. 1–31, 2014. [online] Available at: http://jpaleontologicaltechniques.org/pasta3/JPT%20N12/Pdf/JPT_n012_Jul.pdf [Accessed: 26 Aug 2019]

[8] Kordić, B., Matoš, B., Pikelj, K., Lužar Oberiter, B., Vlastelica, G.: Integration of terrestrial laser scanning and UAS photogrammetry in geological studies: Examples from Croatia. (Accepted to be published in Periodica Polytechnica Civil Engineering), 2019.

[9] Burton D., Dunlap D.B., Wood L.J., Flaig, P. P. "Lidar intensity as a remote sensor of rock properties, Journal of Sedimentary Research, 81(5), pp. 339–347, 2011. https://doi.org/10.2110/jsr.2011.31

[10] Lutz, E., Geist, T., Stotter, J. "Investigations of airborne laser scanning signal intensity of glacial surfaces utilizing comprehensive laser geometry modeling and orthophoto surface modeling (a case study: Svartsheibreen, Norway)", presented at ISPRS Workshop on 3-D reconstruction from airborne laser scanner and InSAR data, Dresden, Germany, Oct, 8-10, 2003.

[11] Mazzarini, F., Pareschi, M.T., Favalli, M., Isola, I., Tarquini, S., Boschi, E. "Lava flow identification and ageing by means of LiDAR intensity: the Mt. Etna case", Journal of Geophysical Research, 112, pp. B02201 (1-19), https://doi.org/10.1029/2005JB004166

[12] Kaasalainen, S., Jaakkola, A., Kaasalainen, M., Krooks, A., Kukko, A., "Analysis of incidence angle and distance effects on terrestrial laser scanner intensity: search for correction methods." Remote Sens. 3, pp. 2207–2221, 2011. https://doi.org/10.3390/rs3102207

[13] Vlastelica, G. "The Influence of Weathering on Durability of Cuts in Soft Rock Mass." Split: University of Split, Faculty of Civil Engineering, Architecture and Geodesy. PhD thesis. pp 197, 2015.

[14] Vlastelica, G., Miščević, P., Štambuk Cvitanović, N., Glibota, A. "Geomechanical aspects of remediation of quarries in the flysch: case study of abandoned quarry in Majdan, Croatia", In: Geomechanics and Geodynamics of Rock Masses - Selected Papers from the 2018. European Rock Mechanics Symposium, Sankt Petersburg, Russia, 2018,pp. 679–684.

[15] Vlastelica, G., Miščević, P., Štambuk Cvitanović, N. "Durability of soft rocks in Eocene flysch formation (Dalmatia, Croatia)", Engineering Geology, 245, pp. 207–217, 2018. https://doi.org/10.1016/j.enggeo.2018.08.015

[16] Miščević, P., Vlastelica, G. "Impact of weathering on slope stability in soft rock mass", Journal of Rock Mechanics and Geotechnical Engineering 6, pp 240-250, 2014. http://dx.doi.org/10.1016/j.jrmge.2014.03.006

[17] Marinčić, S. "Eocenski fliš jadranskog pojasa" (Eocene flysch of Adriatic area), Geološki vjesnik, 34, pp. 27−38, 1981. (in Croatian).

[18] Pikelj, K., Juračić M. "Eastern Adriatic Coast (EAC): geomorphology and coastal vulnerability of a karstic coast", Journal of Coastal Research, 2(4), pp 944-957, 2013. http://dx.doi.org/10.2112/JCOASTRES-D-12-00136.1

[19] Pikelj, K., Dragnić, V., Malovrazić, N., "Eastern Adriatic: Slovenia, Croatia and Montenegro" In: In: Prazini, E., Williams, A. (eds.) Coastal Erosion and Protection in Europe. Routledge, 1st ed. Taylor and Francis, Oxford, UK, 2013, pp. 324–344 .

[20] Aljinović, D., Jurak. V., Mileusnić, M., Slovenec, D., Presečki, F. "The origin and composition of flysch deposits as an attribute to the excessive erosion of the Slani Potok Valley („Salty Creek"), Croatia", Geologia Croatica 63(3), pp. 313-322, 2010. http://dx.doi.org/104154/gc.2010.25

[21] Toševski A., Grgec D., Padovan D. " Osnovno o genezi, sastavu i trošenju eocenskog fliša hrvatskog obalnog pojasa." Rudarsko-geološko-naftni zbornik. Vol. 25 str. 47-62 Zagreb, 2012. (In Croatian)

[22] Pollak, Davor; Buljan, Renato; Toševski, Aleksandar Inženjerskogeološke i geotehničke značajke naslaga fliša u području Kaštela // Građevinar : časopis Hrvatskog saveza građevinskih inženjera, 62 , 8; 707-715, 2010. (In Croatian)

[23] Vlastelica, G., Pikelj, K., Kordić, B. "Erosional processes acting on coastal cliffs in the Split urban zone, Croatia", Revue Paralia, 4, pp. 79–84, 2017. https://doi.org/10.5150/cmcm.2017.015

[24] Pikelj, K., Vlastelica, G., Kordić, B. "Evaluation of erosional processes of the eroding flysch cliff in the Split urban zone (Croatia)" In: Seventh International Symposium: Monitoring of Mediterranean Coastal Areas: Problems and Measurement Techniques, Livorno, Italy, 2018, pp. 607-616.

[25] Furlani, S., Devoto, S., Biolchi, S, Cuchi, F. "Coastal cliff behavior: The case study of Debeli Rtič (SW Slovenia)", Annales, Series Historia Naturalis, 21, pp. 77-86, 2011.

[26] Vlahović, I., Tišljar, J., Velić, I., Matičec, D. "Evolution of the Adriatic Carbonate Platform: palaeogeography, main events and depositional dynamics", Palaeogeography, palaeoclimatology, palaeoecology, 220, pp. 333-360, 2005. https://doi.org/10.1016/j.palaeo.2005.01.011

[27] Shan, J., Toth, C. K.: "Topographic Laser Ranging and Scanning: Principles and Processing." CRC, Book, 2008.

[28] Pettijohn, F. J. "Sedimentary Rocks" 2nd ed., Harper & Brothers, New York, USA, 1957 .

[29] ISO 10693 (1995): Soil quality – Determination of carbonate content – Volumetric method.

[30] Pesci, A. & Teza, G. "Effects of surface irregularities on intensity data from laser scanning: An experimental approach." Annals of Geophysics. 2008. https://doi.org/10.4401/ag-4462

[31] Franceschi, M., Teza, G., Preto, N., Pesci, A., Galgaro, A., Girardi, S. Discrimination between marls and limestones using intensity data from terrestrial laser scanner. ISPRS Journal of Photogrammetry and Remote Sensing. 64. 522-528, 2009. https://doi.org/10.1016/j.isprsjprs.2009.03.003.

[32] Živec, T., Anžur, A., Verbovšek, T.: Determination of rock type and moisture content in flysch using TLS intensity in the Elerji quarry (south-west Slovenia). Bulletin of Engineering Geology and the Environment 78, 1631-1643, 2019. DOI: 10.1007/s10064-018-1245-2