POLISH MARITIME RESEARCH 2 (98) 2018 Vol. 25; pp. 140-147
10.2478/pomr-2018-0065

A NEW APPROACH OF COASTAL CLIFF MONITORING USING MOBILE LASER SCANNING

Rafał Ossowski
Paweł Tysiąc
Gdańsk University of Technology, Poland

ABSTRACT

The article proposes a new approach of coastal cliff monitoring which bases on a new comprehensive monitoring system, being a combination of mobile scanning from the sea with the geotechnical stability analysis. Mobile laser scanning is an innovative solution for 3D data collection which allows the monitored object geometry to be precisely measured, thus providing opportunities for series of analyses contributing to the development of an improved monitoring system. The authors present selected cliff profiles obtained from mobile scanning in the area of Jastrzebia Gora, complemented by relevant geotechnical analyses. The analysis of current cliff geometry is accompanied by calculations of hypothetical cliff profile changes resulting from possible action of nature forces. Finally, a comprehensive strategy for coastal cliff monitoring is proposed.

Keywords: cliffs, coast protection, mobile laser scanning, monitoring, stability calculations

INTRODUCTION

The stability problems of coastal cliffs in Poland are the object of continuous interest of maritime administration (Maritime Offices), local self-governments, and residents of towns situated on the edges of cliffs. This type of coastline is observed in more than ten segments of Polish coast (Fig.1).

The article focuses on a selected part of coastal cliff situated at Jastrzebia Gora, nevertheless the methodology developed by the authors is general in nature and can be applied to an arbitrary part of coastal cliff, after identifying the geological substratum and the nature of cliff behaviour.

In a sense, the article is a continuation of the research performed over 30 years ago at the Gdansk University of Technology [2]. As a pilot study, mentioned research aimed at identifying landslide hazards along the entire Polish coast. The authors also presented the stability simulation of selected cross sections, using probabilistic tools and limit analysis methods. Unfortunately, they did not have at their disposal such a modern measurement technique as laser scanning.

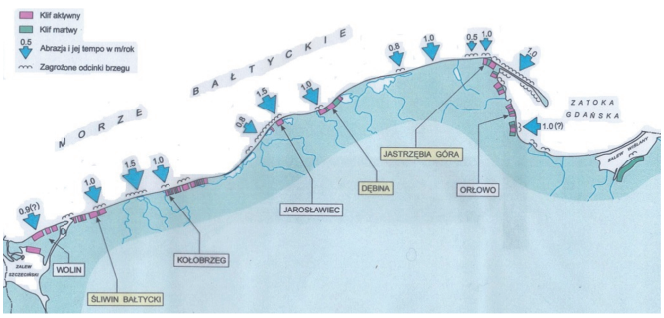

Fig. 1. Locations of cliff coastlines in Poland and their abrasion rate in years 1980-90 [1,2]

Modern measurement techniques which make use of stationary laser scanning have been recently used for coastal cliff measurements [3]. However, they have severe technical restrictions, the main of which include: difficult access from the beachside (narrow strip of mainland), northern exposition (satellite visibility), difficult connection of the cliff foot with its upper parts, etc. Moreover, past measurements focused more on cataloguing coastal cliffs than on monitoring problems [4]. The mobile scanning technology used by the authors of the present article, also referred to as scanning from the sea or maritime scanning, is a relatively new measuring proposal [5,15] which radically reduces the time of measurement of several-hundred-meter long cliff segments, and sometimes is the only applicable technology in situations where there is no access from the sea for terrestrial scanning [3]. What is noteworthy, it simultaneously ensures a similar accuracy level [5,15].

The 3D data recorded during mobile scanning from a watercraft platform make the basis for creating a 3D model of the cliff, which is to be complemented with soil studies. This extended model is then used for numerical stability simulations of individual cross sections of the cliff, intended to localise zones which are most vulnerable to landslide hazard and analyse possible future threats.

CLIFF LANDSLIDE HAZARD

The landslide hazard of the Jastrzebia Gora cliff has been known for several decades. The interest of the society and local self-government in this part of the coast increased in 1988 when the created landslide endangered the leisure centre "Horyzont" (Fig. 2). The average multiannual cliff abrasion rate in this region is approximately equal to 1m/year [1].

Fig. 2. The leisure centre "Horyzont" situated on the edge of an active cliff and damaged in 2002. (photo courtesy of W. Subotowicz)

In 1992, a protection concept was presented for the coastal cliff at Jastrzebia Gora which referred to the cliff segment of about 1 km in length (km 133+500 – km 134+600), [6]. The concept based on building a seawall in the form of a pedestrian boulevard, which was intended to both protect the coastline and, at the same time, play the recreation function. However, that concept has never been put in practice.

In years 1994-1997, a retaining structure was built at the foot of the cliff as a protection for the major part of the abovementioned cliff segment at Jastrzebia Gora. It had the form of a seawall consisting of gabions. At first, it was built along the eastern cliff part, of 200 m in length, where the partially damaged leisure centre "Horyzont" was situated. Unfortunately, first damages of this seawall were already observed as early as in 1998 (Fig. 3).

Fig. 3. Gabions composing the seawall in the region of "Bałtyk", damaged in 1998 (photo courtesy of W. Subotowicz)

In 2000, a cliff segment of 200 m in length was protected using reinforced soil. This reinforcement consisted in reconstructing the cliff using dense sand reinforced with geogrids. Unfortunately, after 10 years this structure was also damaged. It was difficult to decide whether that failure was caused by execution errors (incorrect soil densification, for instance [7]), or design errors (ill-suited drainage, etc.). The fact is that the slope with reinforced soil deformed in both: vertical and horizontal direction. According to the terrestrial measurements performed at the beginning of 2011, the displacement of the artificial cliff slope towards the sea was about 1 m, while the settlement already exceeded 1 m [4]. Details concerning the history of attempts made to protect the Jastrzebia Gora cliff are included in [8].

A general conclusion from the above situation is that all past protection measures revealed low durability (see Fig. 4). Consequently, permanent monitoring of the cliff is indispensable for the safety of tourists and residents.

Fig.4. Degradation of reinforced cliff part at Jastrzebia Gora – situation of January 2017.

MOBILE LASER SCANNING

Mobile laser scanning consists in profile measuring of millions of points when the scanner (scanning device) is situated on a mobile platform. The same principle refers to airborne scanning, in which the platform is the aviation unit and which is widely used to collect 3D data, also on coastal areas [9]. However, whereas the airborne scanning is already in common use, the use of laser scanning on a watercraft unit can be considered an innovative measurement method [5][15][16].

The Jastrzebia Gora cliff was scanned using the mobile system VMZ-400 produced by Riegl GmbH. The system consists of the scanner VZ-400, initially designed for stationary scanning, and the dual frequency GNSS (*Global Navigation Satellite System*) receiver, coupled with the IMU (*Inertial Measurement Unit*), which is responsible for precise evaluation of angular displacement of the platform along its three axes, i.e. in *pitch*, *yaw* and *roll* directions. It is noteworthy that the VMZ-400 system is fairly frequently used in mobile systems [10], for instance to perform measurements in harbours and rivers/channels [11], while scanning from the open sea is still an innovative solution which has to meet severe introductory requirements. A problem to be dealt with when performing maritime scanning is sea undulation, which, after exceeding some critical level, can unfavourably affect the quality of the recorded results.

For maritime laser scanning, hydrometeorological conditions play a crucial role. Factors which are to be considered when planning the scanning include: air temperature, strength and direction of wind, possible precipitation, as well as sea wave parameters. The experience gained in the past indicates that when scanning from the sea and sailing against the wave, the strength of wind should not exceed, approximately 3 Beaufort, and about 6 Beaufort when sailing with the wave. It should be noted that the key role in this situation is played by the watercraft draught level. Another aspect, frequently omitted in laser scanning but considered in classical geodesic measurements, is insolation. This is related with the fact that the applied scanning technology belongs to the group of active remote sensing methods of data collection, and the gained experience indicates that in the case of full insolation, some elements of the infrastructure can be scanned inaccurately, due to unfavourable sunlight reflection. In those cases, it is advisable to perform measurements in cloudy days or at night.

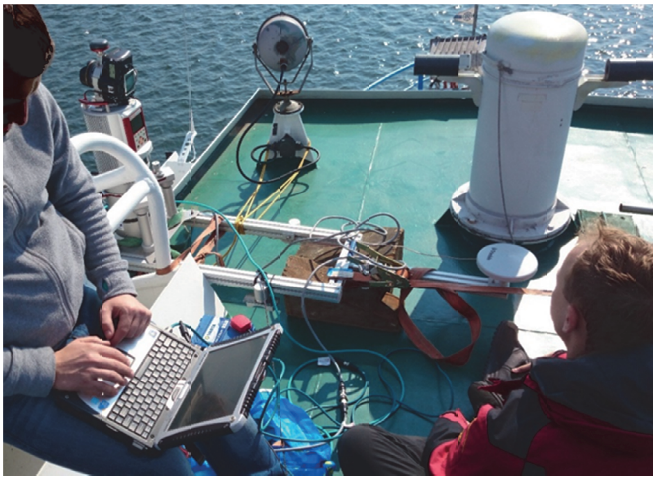

Fig. 5. Scanning from watercraft

To obtain 3D data for the cliff model, basic scanning from the sea was performed along the coast segment from the port of Wladysławowo to the surroundings of the North Obelisk at Jastrzebia Gora (from about km 125 to about km 140). These measurements were complemented by the results of terrestrial scanning, thus providing opportunities for creating a 3D model of the examined cliff (Fig.6). An essential problem in the applied measurement technique appeared to be filtration of raw data to extract the numerical model of the area. For this purpose, an algorithm has been developed by the authors in which the second-degree surface approximation was used in hierarchical process for surface estimation [17].

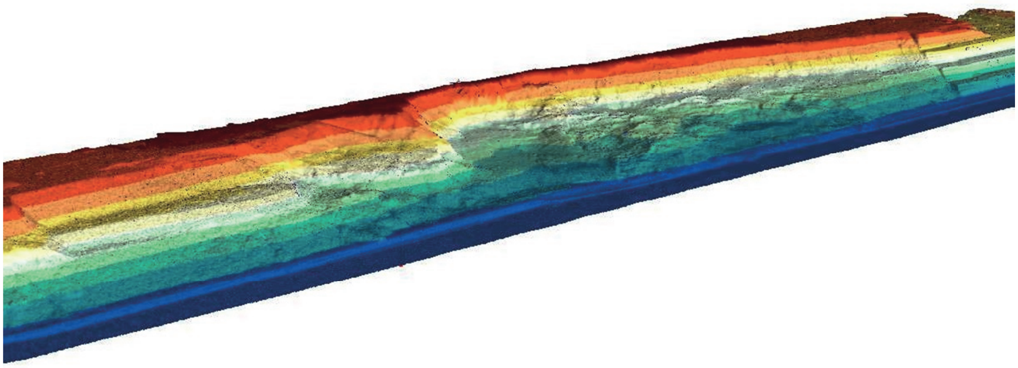

Fig.6. Results of laser scanning – 3D model of the cliff surface.

STABILITY CALCULATIONS

The stability of a natural slope is determined in the soil mechanics by calculating the so-called slope stability factor. In classical limit equilibrium methods (Fellenius method or Bishop method, for instance) it is defined as the ratio of stabilising moments to shear moments at a given rotation point. In this paper, the calculation procedure uses a strength parameter reduction method simulation, based on Finite Element Method calculations. The measure of safety margin is the slope stability factor, defined as the ratio of real strength parameters of the soil to the reduced parameters which correspond to the appearance of the state of limit equilibrium in the slope. This factor is the same for effective coherence and effective internal friction angle:

$$F = \frac{tg\Phi'}{tg\Phi'_m} = \frac{c'}{c'_m} \quad (1)$$

This way of determining the stability factor is also named as the *fi-c* reduction method, or the shear strength reduction (SSR) method.

The stability analyses were performed for 2 characteristic cross sections of the cliff massif, which has a relatively complicated geological structure and is characterised by high spatial variability (Fig. 7). The first cross section in situated at km 133,8, near the descent from the cliff top to the beach. Heavy pedestrian traffic of tourists is observed in this area, therefore of high importance is to determine whether this descent is or is not threatened by the occurrence of landslide. The other cross section, at km 134.1, has been selected in direct vicinity of the leisure centre "Horyzont", which is situated close to the edge of the cliff.

The geotechnical sections created for the analysing purposes were based on archive results, which allowed to reconstruct, in a simplified way, their geotechnical structure and soil-water conditions [2,13], see Tab.1 (overconsolidation effects were neglected in a simulation due to lack of data). The soil material was modelled as the elasto-plastic material with Coulomb-Mohr criterion, while the gabions were simplified to elastic elements, due to small space occupied by them in the model. When the presence of reinforced soil or soil composites had to be considered (which had place in another cliff segment) [14], the model shall be properly modified and appropriate constitutive laws shall be considered. The current geometry of the selected cross sections was determined based on the results of laser scanning from the sea, complemented with terrestrial scans. The geometry of these sections is shown in Figs. 8-9.

Tab.1. Strength and permeability parameters adopted for calculations from [2] and [13]

Soil	φ'	c'	k
	°	kPa	m/day
till (sisaCl)	36.0	40.0	10-3
sandy clay (saCl)	23.5	15.0	10-3
clay (Cl)	22.0	46.0	10-5
fine sand (FSa)	35.5	0.0	2.5
medium sand (MSa)	39,0	0.0	10.0
Clayley sand (clSa)	32,0	18.0	0.25

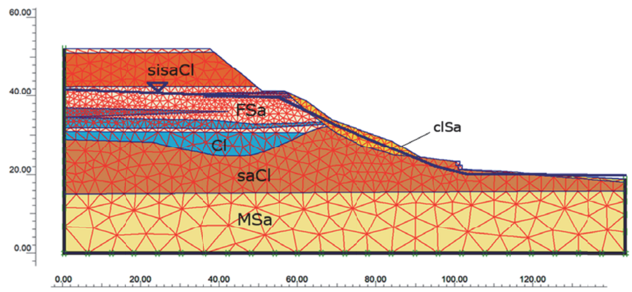

Fig.8. Geotechnical cross section of km 133.8 and its discretisation

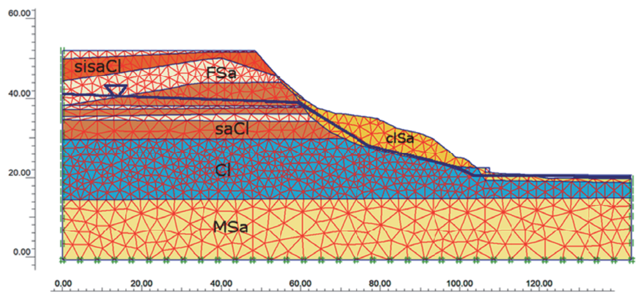

Fig. 9. Geotechnical cross section of km 134.1 and its discretisation

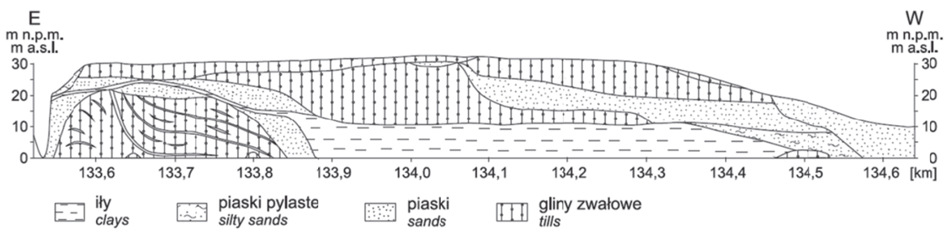

Fig.7. Geological longitudinal section of cliff wall [12]

The stability calculations performed for the selected cross section geometries have demonstrated the global mechanism of destruction and gave the following values of stability factor: SF=1.05 in cross section 133.8 and SF=1.11 in cross section 134.1. These values do not provide a large safety margin, particularly

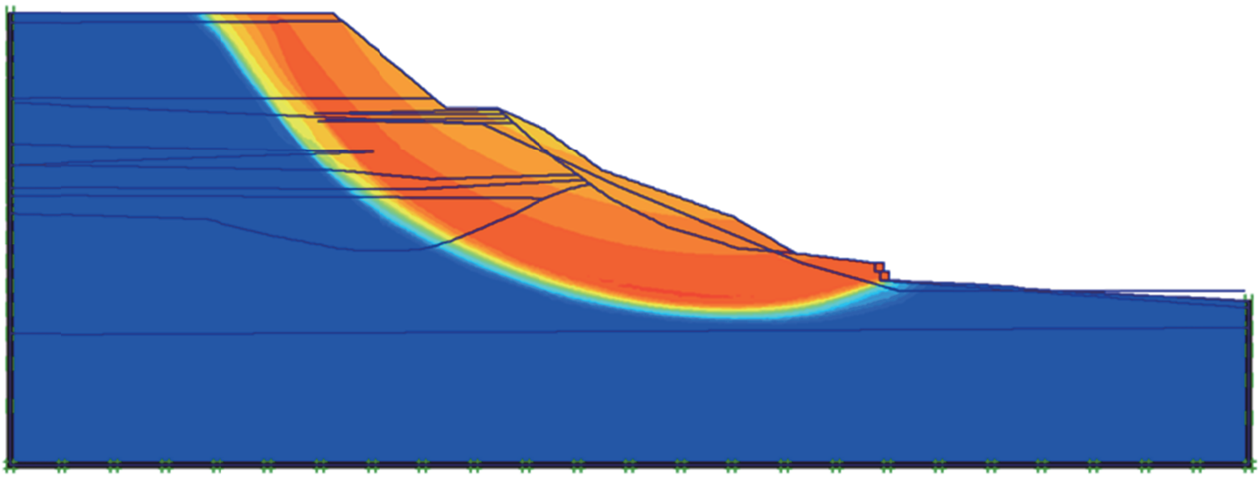

Fig.10. Global destruction mechanism (orange indicates failure) in cross section 133.8 (SF=1.05)

for the section 133.8. The destruction mechanisms for both profiles are shown in Figs. 10 and 11, in which orange and yellow colours represent the largest prognosed displacements.

The next calculation stage included simulation of possible changes resulting from external factors, such as, for instance, elevation of soil water table due to increased precipitation and inflow of soil waters from the South, or sea level rise in storm conditions, or possible soil mass losses caused by abrasion.

It is interesting to compare destruction mechanisms in cross section 134.1 for the current situation (Fig.11) and for the prognosed soil water table elevation by 2m (Fig.12). We can observe that the stability factor after water table rise decreased slightly, but in the former scenario we observe the global destruction mechanism, while in the latter case the local destruction mechanism is initiated.

Fig. 13 shows the simulation of after-storm conditions in which the cliff profile changed with respect to its current shape as a result of abrasion. This situation has been selected arbitrarily as a sample case from a variety of other calculated possibilities. The stability calculations for the cliff geometry changed in the above way gave the result SF=1.09, i.e. slight reduction of the safety factor for this section. This means that in the case of real storm damages, we are able to assess, using numerical simulations, potential threat of stability loss at a given cliff segment and take appropriate measures.

The above numerical simulations compose a small fragment of the entire spectrum of possible destruction analyses. Once the accurate geotechnical and hydrological model of the cliff is known, the simulation can be performed for the entire examined cliff segment (in cross sections distant by 50m, for instance), or the 3D calculation model can be created using one of available numerical code packages.

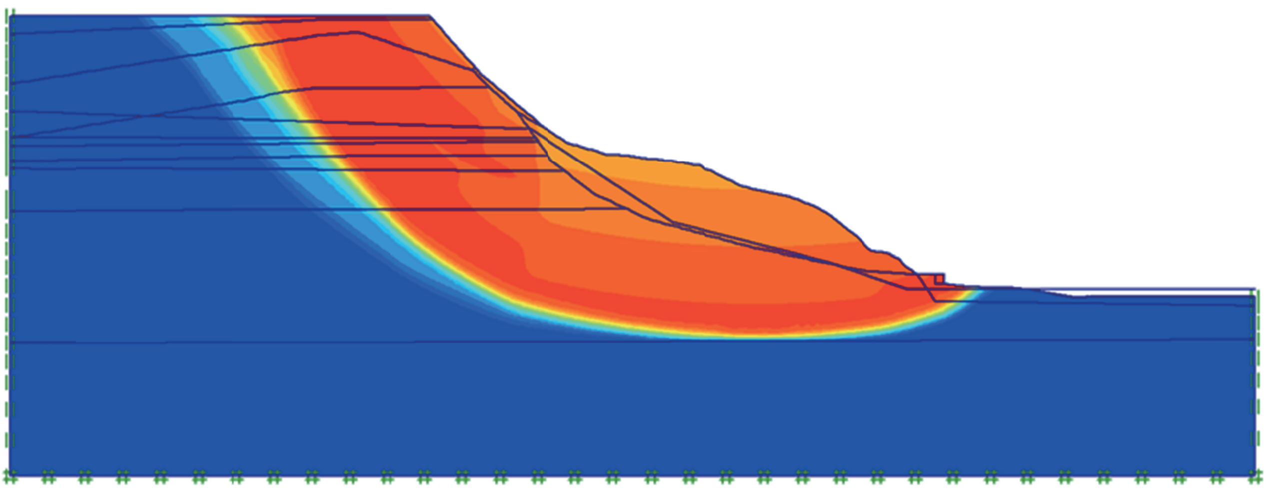

Fig.11. Global destruction mechanism (orange indicates failure) in cross section 134.1 (SF=1.11)

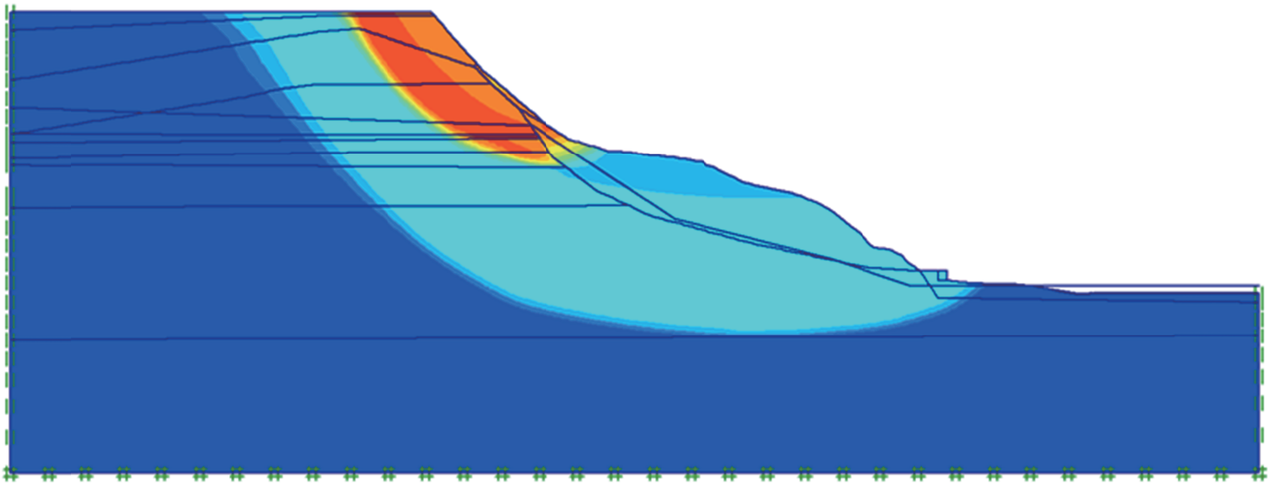

Fig.12. Local destruction with elevated water table (orange indicates failure) in cross section 134.1, SF=1.09

SUMMARY

As a summary of the preliminary examination of the Jastrzebia Gora cliff, the authors suggest implementing a system to monitor selected segments of the coastal cliff. The monitoring procedure can comprise the following steps:

1. Precise scanning of the monitored cliff segment – TLS, MLS ("zero" reference measurement)
2. Detailed geotechnical, geological and hydrogeological examination of the cliff – constructing a complete 3D model of the cliff
3. Numerical stability calculations: either in dense grid of cross sections or using full 3D model, with resultant identification of most hazardous areas
4. Simulation calculations of stability changes caused by the action of nature forces: storms, intensified precipitation (water table rise), partial reinforcement losses, etc.
5. Cliff monitoring making use of MLS: twice a year + additional scanning after major storm, for instance.

The results of preliminary pilot measurements of the Jastrzebia Gora cliff, performed with the aid of mobile scanning, indicate that the maritime laser scanning making use of systems situated on mobile platforms provides results with sufficient accuracy (an order of 10cm) [15]. Combining the data from maritime scanning with those from terrestrial scanning (and, possibly, airborne scanning) makes the basis for constructing a 3D model of the cliff as the basic model for monitoring. The cliff model construction process should necessarily include geotechnical and hydrogeological data. As demonstrated in the article, numerical simulations are helpful not only in identification of current threat areas, but they can also be a good tool for predicting possible future threats caused by changes in sea states, ground water levels, or soil losses caused by storms and/or landslides. When the presence of pre-consolidated soils or weak soil interbedding in the foundation is to be considered, appropriate constitutive laws are to be applied to obtain reliable predictions [18,19]. Stability can also be assessed using stochastic modelling and limit analysis methods [20]. Implementing the laser scanning system in

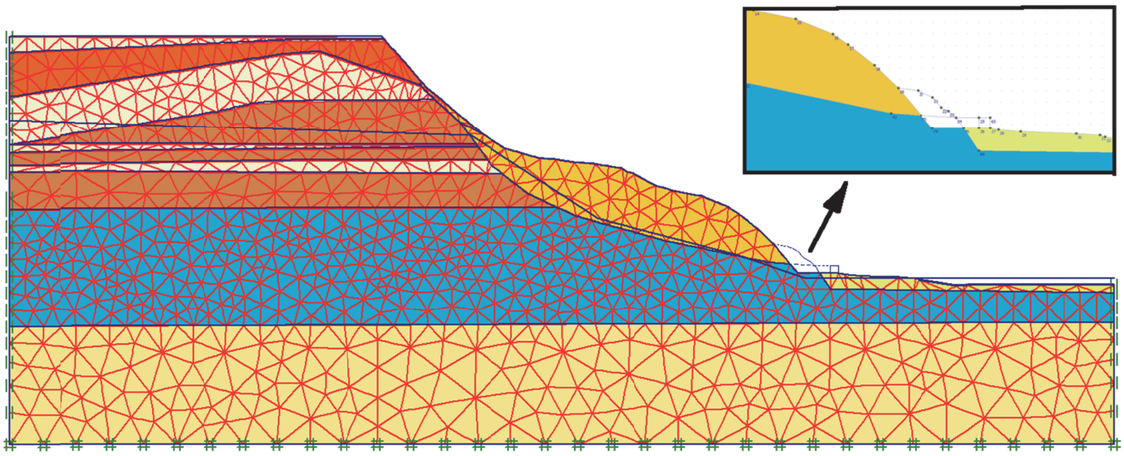

Fig.13. Cross section 134.1 with hypothetical damages caused by storm

certain time intervals can help to identify unsafe zones, which can then be verified by numerical simulations performed on an ongoing basis. What is noteworthy, continuous technology development makes that the processing of huge amounts of data coming from mobile (and terrestrial) scanning does not require considerable numerical effort.

BIBLIOGRAPHY

1. Cieślak A., Subotowicz W.: Report on the state of knowledge about the coastline in Poland and its protection (in Polish), Inżynieria Morska, no. 2/1987, (1987)

2. Tejchman, A., et al.: Stability and protection of cliffs in Polish coastline (in Polish). (1995): Gdansk University of Technology.

3. Szulwic J., Tysiąc P., Wojtowicz A.: Coastal Cliffs Monitoring and Prediction of Displacements Using Terrestrial Laser Scanning, W: 2016 Baltic Geodetic Congress (BGC Geomatics), 2016, IEEE,

4. Kramarska R., Fridel J., Jegielski W.: Using terrestrial laser scanning to assess the geotechnics of the coast, with the Jastrzebia Gora cliff as an example (in Polish), Biuletyn PIG 446, 2011.

5. Burdziakowski P., et al.: MARITIME LASER SCANNING AS THE SOURCE FOR SPATIAL DATA// Polish Maritime Research. Vol. 22, Iss. 4(88) (2015), pp.9-14.

6. Massalski W., Subotowicz W.: Concept for Jastrzebia Gora coastal cliff protection (in Polish), Gdansk, (1992).

7. Wyroślak M.: Establishing Relationships between Parameters of the Controlled Compaction Soil by Using Various In-Situ Tests. IOP Conf. Ser.: Mater. Sci. Eng. 245, 022041 (2017).

8. Sikora Z., et al.: Emergency condition of the Jastrzebia Gora coastal cliff (in Polish), Proc. XXVII conf. Awarie budowlane, (2015).

9. Dudzinska-Nowak J., Wezyk P.: Volumetric changes of a soft cliff coast 2008-2012 based on DTM from airborne laser scanning (Wolin Island, southern Baltic Sea). Journal of Coastal Research, 70 (2014), pp. 59-64

10. Chen C., Liu H., Liu Y., Zhuo X.: High accuracy calibration for vehicle-based laser scanning and urban panoramic imaging and surveying system. MIPPR 2013: Multispectral Image Acquisition, Processing, and Analysis, SPIE 8917 (2013) 89170Y, DOI: 10.1117/12.2031466

11. Bobkowska K., Inglot A., Mikusova M., Tysiąc P.: Implementation of spatial information for monitoring and analysis of the area around the port using laser scanning techniques// Polish Maritime Research. -Vol. 24, no. S1(93) (2017), pp.10-15

12. Zalaszkiewicz L., et al., The Jastrzebia Gora cliff: Stratigraphy of quaternary period and ice sheet disappearance in the Kaszuby Lakeland (in Polish), in VII Conference on “Stratigraphy of Pleistocene era in Poland”, Z.J. red. Uścinowicz S., Editor. (2000), Polish Geological Institute: Gdansk. pp. 117-119.

13. Subotowicz W., et al., Expertise on cliff stability and landslide in the region of the leisure and recreation centre “Horyzont” at Jastrzebia Gora (in Polish). (1988).

14. Ossowski R.: Environmental aspects of coastal earth structures made of soil-ash composites, Polish Maritime Research. -Vol. 24, no. S1 (93) (2017), pp. 166-173

15. Ossowski R., Tysiąc P..: Complex Monitoring of the Coastal Cliffs on the Example of Cliff in Jastrzebia Gora, Poland, In: Geodetic Congress (BGC Geomatics), (2017) DOI: 10.1109/bgc.geomatics.2017.30

16. Janowski A., Szulwic J., Tysiąc P., Wojtowicz A.: Airborne and mobile laser scanning in measurements of sea cliffs on the Southern Baltic, In: 15th International Multidisciplinary Scientific GeoConference SGEM 2015, (2015), DOI: 10.5593/SGEM2015/B12/S2.003

17. Borkowski A., Józków G.: Using polynomial mobile surface in the airborne laser scanning data filtration process (in Polish), W: Archiwum Fotogrametrii, Kartografii i Teledetekcji, Vol. XVI, pp. 63–73, (2006).

18. Dluzewski, J.M., Popielski, P., Sternik, K., Gryczmanski, M.: Modelling of consolidation in soft soils, In: NUMERICAL MODELS IN GEOMECHANICS - NUMOG VII, pp. 569-572, (1999).

19. Sternik K.: Elasto-plastic Constitutive Model for Overconsolidated Clays, INTERNATIONAL JOURNAL OF CIVIL ENGINEERING, Vol. 15, (2017), p: 431-440, DOI: 10.1007/s40999-017-0193-8

20. Dian-Qing L., et al., System reliability analysis of slope stability using generalized Subset Simulation. Applied Mathematical Modelling, vol. 46 (2017), pp. 650-664.

CONTACT WITH THE AUTHOR

Rafał Ossowski
e-mail: ross@pg.edu.pl

Paweł Tysiąc
e-mail: pawtysia@pg.edu.pl

Gdańsk University of Technology
Faculty of Civil
and Environmental Engineering
11/12 Narutowicza St.
80 - 233 Gdańsk
Poland