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Review / Pregledni znanstveni članak

Geodetic Mobile Survey Methods for Riverbank Erosion Observations

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ABSTRACT. Rivers are relief features susceptible to change over time more than any other. Dynamic and intensity of those changes depend on a series of factors that have been a research topic for decades, all with the goal of predicting and/or preventing changes that have a negative effect on ecological and administrative systems alike. This is especially evident on big river systems. The topic of water course related erosion, being a phenomenon that changes the shape, position and flow of a water course, has not, to this day, been exhausted, primarily due to a myriad of factors directly and indirectly influencing the process. At the same time, determining the influence of each of those individual factors is not possible without the use of adequate measurement methods that allow fast acquisition of relevant data, based on witch correct conclusions can be made about individual processes. Emphasis on fast acquisition must be made here because rivers are dynamic bodies and the changes they cause are also relatively fast. Geodesy, including measuring techniques and methods that it uses, has experienced major development in the past decades. This has opened new possibilities for addressing those previously mentioned needs of river systems erosional processes and their research. Considering all of the above and supplementing with a fact that Danube is the largest and strongest river flowing through Croatia, it can be concluded that Danube is the one most interesting from the aspect of determining erosion phenomena frequency/intensity in Croatia. For acquiring relevant data in a relatively short time adequate survey methods need to be applied. Hence, Danube and its particularly interesting segments were selected for determining applicability of contactless mobile measurement solutions with the purpose of assessing those systems in determining and predicting erosional risks and cumulative rates.

Keywords: Danube, meandering, loess cliffs, riverbank erosion, TLS, mobile survey, MLS.

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1. Introduction

Croatia is a country whose shape and overall spread has resulted in a long continental boundary (2370.5 km), but also coastal length (6278 km) for a state of land area of 56 594 km^2 (DZS 2015) which makes it a medium sized country in world standards (127th place out of 257 countries) (CIA 2016). At the same time most of its continental borders are comprised of natural barriers, most prominent of which are the rivers. In the north there are Drava and Mura on the border with Hungary, on the west there are (south to north) Dragonja, Kupa, Bregana, a small section of Sava, Sutla, small section of Drava and Mura on the border with Slovenia, while on the east there is Danube on the border with Serbia. Considering Croatia is "enveloping" Bosnia and Hercegovina (BIH), the north border between the countries is, in the longest part, following Sava river, but partially Una as well, on the western side there are Glina and Korana, then Una again as well as Butižnica and Ričina, although that part of the border, just like the southern one, is mostly comprised of mountain chains, and not rivers.

Despite previously mentioned, border rivers, their middle or some other feature, don't define the actual state line. State lines are determined based on historical and administrative records, ease of use and maintenance challenges of borderline areas that two neighbouring states agree upon through international agreements. The last instance, maintenance challenges, is why natural features are often the starting points of border agreement negotiations. But, where rivers are involved, those are not the final points. The issue with rivers is that they are, more than any other natural feature, highly susceptible to change over time. Dynamics and intensity of those changes depends on a number of factors that have, for decades, been the subject of research and investigations with the purpose of predicting and/or preventing changes that have a negative impact on ecological and administrative systems alike.

Danube, which is the subject of this paper, consists of sinusoidal bends forming the Croatian border. This is common for lower parts of rivers carrying small-grain mud and clay, and defines it as a meandering river (Carlson et al. 2011). This is also clearly visible from satellite imagery that show abandoned river sleeves (Figure 1). It is interesting, though, that those bends can, almost entirely, be observed on the eastern side of Danube. That fact indicates Danube's meandering migration tendency is toward the west, more specifically towards the Croatian coast. Causes of this phenomena are various, but the most influential are topography and the Coriolis effect. Since by definition "A stream is a body of running water that is confined in a channel and moves downhill under the influence of gravity" (Carlson et al. 2011), the importance of topography in this segment is clear. Coriolis's effect, on the other hand, is a well-known and described effect causing deflection of movement to the right on Earths north hemisphere. Thus, its effect on north-south flow directions is such that rivers flowing in that direction are, consequently, pushed to the west. For Danube, which flows along Croatian border in the abovementioned direction, it is surely the primary cause for this westward displacement trend.

Since meandering is inseparably coupled with erosional processes, research and monitoring of Danube's coastal erosion in Croatia is necessary. Surveys of riverbank surface not only allow for erosion risks to be assessed, but the tracing of those changes also allows erosion and sedimentation of soil material to be quantified. Common methods of measuring the surface topography with high spatial resolution include contact profile meters, where the surface is gaged with needles, flat-bed

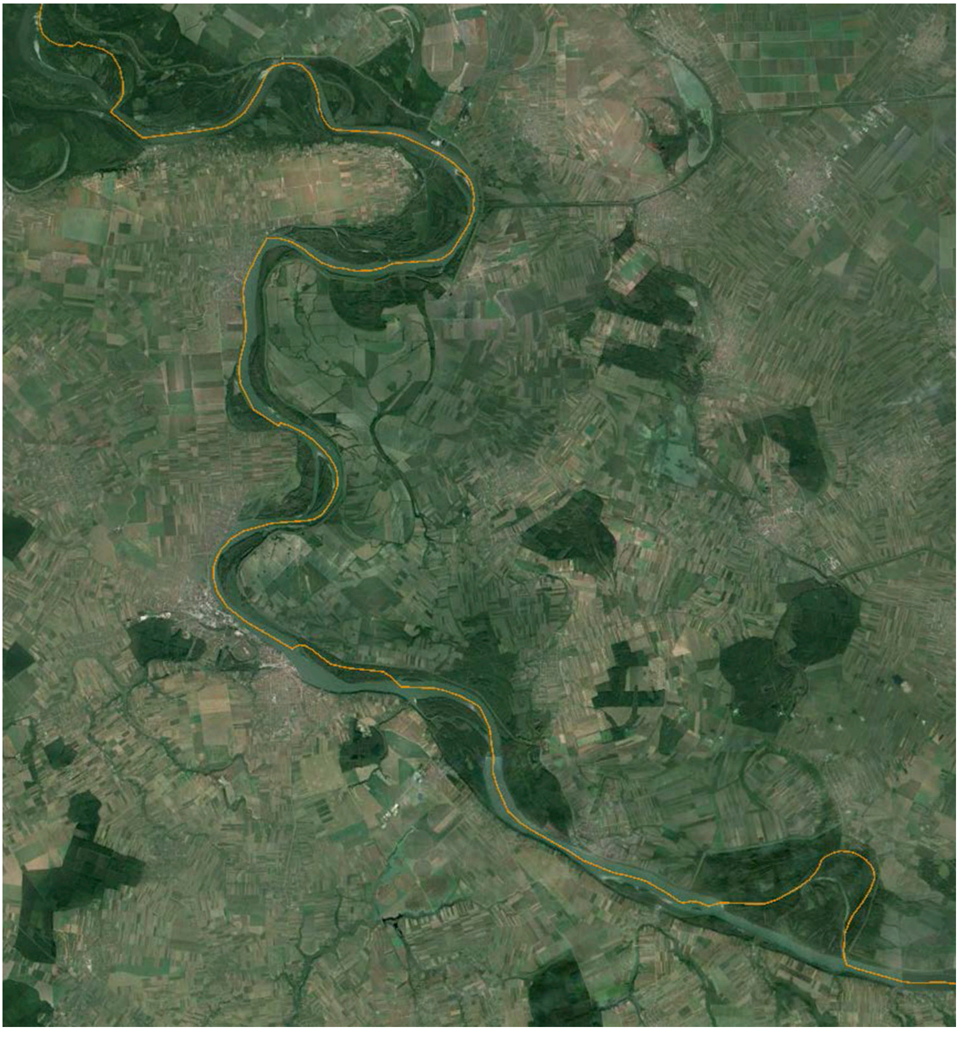

Figure 1. *Previous meander bends on the eastern side of Danube (Croatia-Serbia border) visible from satellite imagery.*

laser triangulation, or stereo-photogrammetric methods (Govers et al. 2000, Huang 1998). These methods have limited performance when used on greater areas where resolution in the mm range is required. Triangulation laser scanning requires a very precise two-dimensional movement system, similar to flat-bed scanners, which must be positioned on the research area. Manual gaging and terrestrial stereo-photogrammetry may be laborious and time consuming, thus, high resolution measurement of surface structure was restricted to small areas and, in most cases, as a part of laboratory studies (Helming et al. 1998, Schmid et al. 2004).

Terrestrial laser scanning (TLS) is one emerging tool that can be employed. TLS can be used to generate high-resolution (subcentimetre grid resolution) topographic models over larger areas (100 m^2 to several ha^2) in a relatively short time (hours to several days) (Heritage and Hetherington 2007, Wawrzyniec et al. 2007). The technology is rapidly evolving to be extremely useful for measuring and monitoring natural systems at a variety of scales (Gulyaev and Buckeridge 2004, Heritage and Milan 2009, Hodge et al. 2009, Lim et al. 2010, Milan et al. 2007, O'Neal and Pizzuto 2011, Resop and Hession 2010, Rosser et al. 2005, Wawrzyniec et al. 2007). Monitoring is important as most bluff erosion processes are episodic, and are not spatially uniform (Day et al. 2013). Even more recent are the Mobile Laser Scanning (MLS) systems. Mobile terrestrial mapping systems have seen remarkable developments recently. Fuelled by an unprecedentedly strong demand for high-resolution and accurate 3D geospatial data, these systems serve the fastest growing market segments (Toth 2009). Their application in coastal change observations has been increasingly researched as well (Alho et al. 2009, Bitenc et al. 2010, Böder et al. 2011, Flener et al. 2013, Incoul et al. 2014, Jaakkola 2015, Kaminsky et al. 2014, Tommaselli et al. 2014). Thus, applicability of such systems with precision and reliability considerations in mind will be explored and presented here.

2. Danube's migration and erosional processes

For determining locations of Danube's greatest migrations, an overview and analysis of historical maps and plans had to be made. Hence, cartographic representations dating all the way from 1733 were obtained to ascertain those locations. Atlas of the Vukovar Landownership (Figure 2) and its accompanying documentation have long had applicable value, and today it is the oldest, the most comprehensive and the only cartographic source for the Vukovar landownership from the first half of the 18th century (Poslončec-Petrić 2006). All plans, apart from the general plan, were made at the same scale that is graphically presented in Vienna fathoms. But even so, the scale and detail of the Atlas were still low in comparison to cadastral maps. Thus, it was only possible to use it as a starting point for investigative actions. For a more detailed and precise identification of migration locations and their amounts, 1863 cadastral plans were used (Figure 3).

Precision and accuracy of those plans is more than adequate from the standpoint of river migration investigations. Even more importantly, survey methods, dimensions and scale of those plans are well documented. Furthermore, representations on the plans have a clear correlation to most recent plans, which allowed for precise dimensioning and georeferencing. The resulting analysis produced discrepancies in excess of 200 m, and even up to 300 m in some areas (Figure 3). Considering the 150-year period, it amounts to an annual riverbank dislocation of up to 2 m/yr. Still, this is an average amount and not an indicator that the coastline actually moves to that extent each year.

As can be seen from the above image, erosion of riverbank is excessive and has a high cutting trend on river bends where the flow direction is deflected away from Croatian coast (left bends). But, at the same time, deposition trends of similar magnitudes can also be observed on areas where the river turns back toward the Croatian coast (right bends). The problem lays in risk to property as well as human life from further bank erosion events, as can be seen from Figure 4.

Undercutting of the bank, usually accompanied by downcutting of the riverbed or in correlation with flood level stages of the river, is a contributing factor to bank

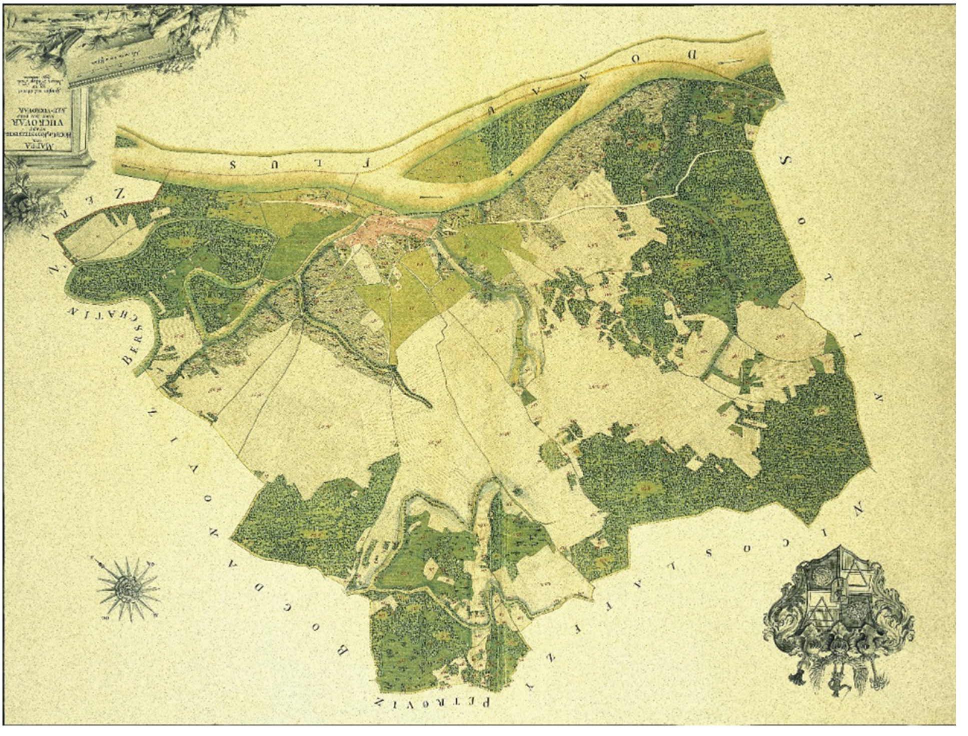

Figure 2. *Atlas of the Vukovar Landownership from 1733.*

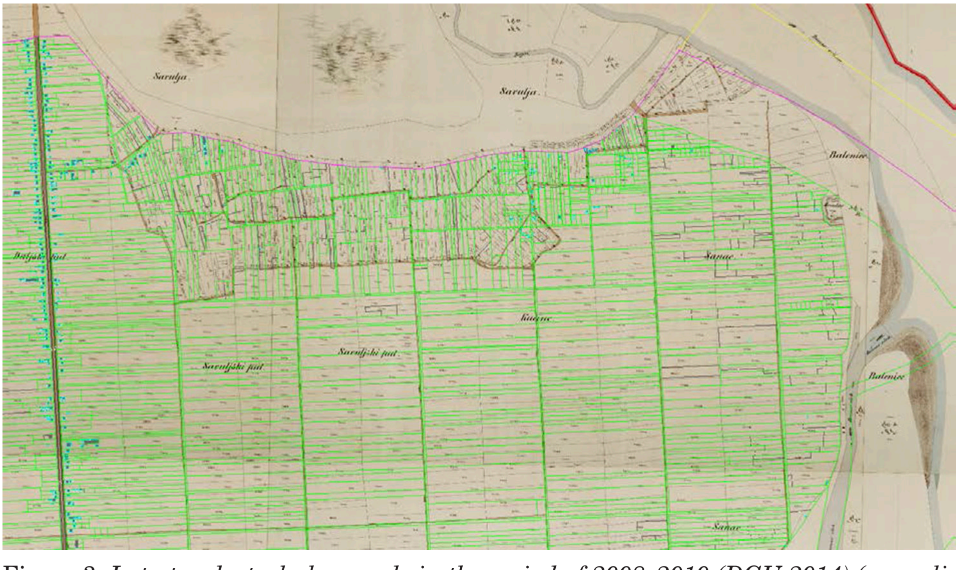

Figure 3. *Latest cadastral plan made in the period of 2008–2010 (DGU 2014) (green lines; vectors) overlaying the 1963 plan (graphic representation) is 250–300 m shorter in the coastal area (upper right side).*

Figure 4. *High loess bank with manmade objects near the edge of the cliff.*

erosion. Rainfall events, underground water levels and material composition of the bank are also factors influencing the extent and progression of erosion (Burnette et al. 2014). This paper does not address all those factors but is focused on monitoring change of the riverbank and describing the optimal method to be used for those purposes found through research. Monitoring and assessing level of risk on such vertical cliffs is a task that cannot be done using Airborne Laser Surveys (ALS) as those only provide representation from a horizontal (plan) perspective, and what needs to be observed are the changes on the surfaces of vertical cliff faces. TLS is also not an option considering the extent of the survey and access difficulties. Hence, the application of MLS on Danube's coastline was considered as a plausible method.

3. Field survey and investigative works

Settlement Savulja, near Borovo Naselje, mostly comprised of vacation homes, was one of the locations chosen for investigative works. Two primary reasons were its accessibility by land vehicle, and, above all, the high erosional trends observed from historical overview. Since "the best" position for a vacation home is next to a water front (in this case a river), the risks accompanied by such positioning are easily discernable when the river in question has a high erosional rate like in the case of Danube. In Figure 5 (left) the problem and property damage resulting from such positioning is obvious. There are numerous other similar settlements on Danube's shores facing events that can and, eventually, will result in, primarily, property damage but also pose a danger to human lives.

As TLS, in terms of accuracy and comprehensiveness, has been greatly explored, it was used to create a reference base and precisely determine the extent of changes on the site. To enable cross referencing with subsequent MLS surveys, georeferencing

Figure 5. *Vacation home endangered by erosion (left) and laser scanning of the bank (right).*

using a combination of GPS and total station surveys were conducted. GPS surveys, used for determining coordinates of total station reference points, relied on the Croatian positioning service called CROPOS. CROPOS is a service utilizing a state network of reference GNSS stations providing real time positioning of 2 cm horizontal and 4 cm vertical accuracy. It requires communication with the server using GPRS/UMTS and NTRIP protocol for real time positioning but also has a post processing service for achieving 1 cm level accuracies.

Surveys were conducted during low water levels prior and following high water level events. During the length of the project (September 2013 to September 2015) there were no significant (flood) water level events that would have caused substantial material displacements and caused major bank collapses easily described in results. Despite such conditions, changes were observed on lower parts of the bank (Figure 6). This clearly shows that there is a constant erosional process at work even during lower water levels. Surface point to point horizontal and vertical differences observed were up to 1.5 m and 1.7 m respectively.

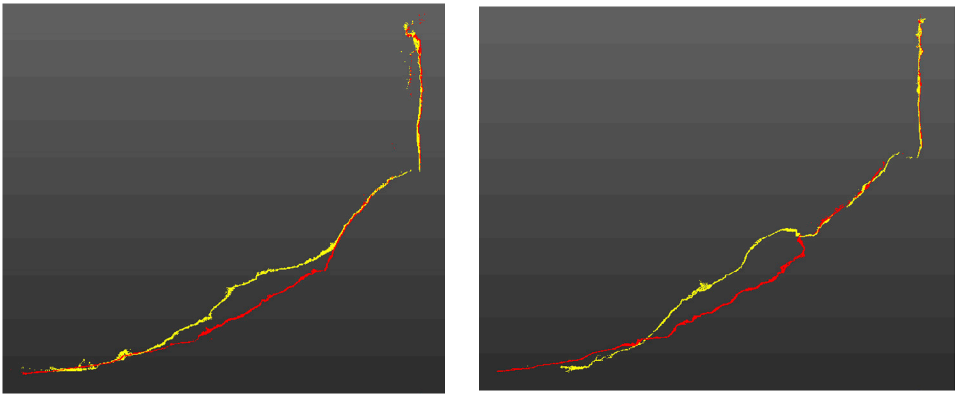

Figure 6. *Cross sections produced from two sessions of survey.*

The extent of that process was calculated using volume calculation, which shoved that, when positive and negative values are taken into account, about 177 m^3 of material is missing over a stretch of roughly 80 m of coast (Figure 7). Also the face of the cliff is shoving a slight sliding trend towards the river which corresponds with the visually identified cracking on the ground surface near the edge of the cliff. The latter indicates a high likelihood of bank failure or slumping sometime in the future if no prevention measures are taken.

But, TLS, although comprehensive, has certain major drawbacks when dealing with hard to access and very large areas that require survey. Primarily, the drawbacks are related to time required to complete the surveys, complexity of operation and, of course, the expenses resulting from such surveys. Thus, MLS is an excellent link and intermediate solution between ALS and TLS, allowing surveys of long stretches of riverbank in an incomparably shorter amount of time. The only issue is whether or not MLS can achieve adequate precision to enable identification of risk zones like the one being described in this paper.

For the purpose of this research MDL Dynascan M-250 was used, which is an entry level mapping grade mobile laser scanning system (Table 1) making it a low

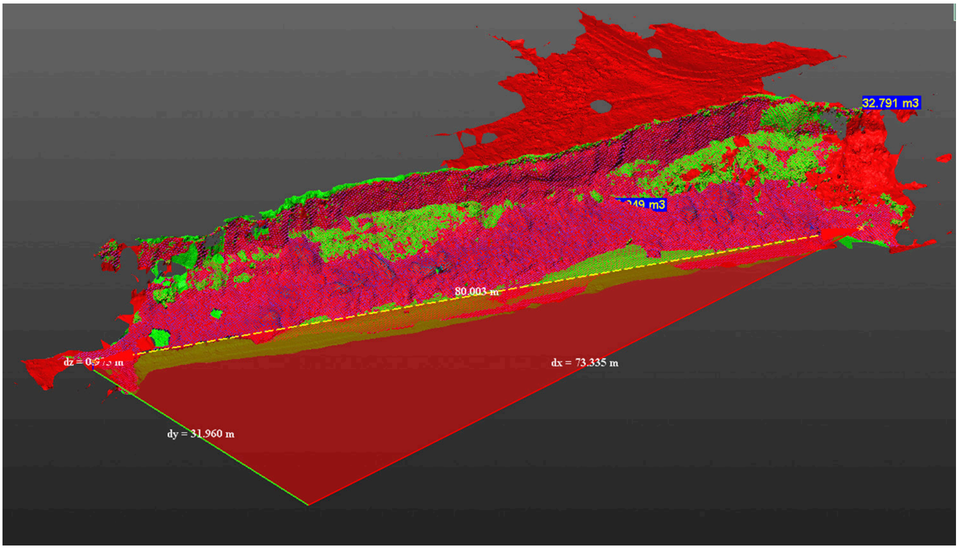

Figure 7. *Volume calculations on a section of the bank for determining material loss.*

Table 1. *MDL Dynascan M-250 specifications.*

	Dynascan M250 (single head)
Laser classification (BS EN 60825-1:2007)	Class 1
Type	InGaAs laser diode
Wavelength (typ)	905 nm
Accuracy*	±5 cm
Range resolution	1 cm
Maximum range	250 m
Minimum range	0.5 m
Scanner field of view	360°
Scanner angle resolution	0.01°
Scan rate	20 Hz (1200 rpm)
Beam footprint at 50 m	130.5 mm × 92.5 mm
Pulse measurement rate (points per second)	36 000
Positioning accuracy (RTK)	2 cm
Pitch-and-roll accuracy (1σ)	0.03°
Dual GNSS antenna heading accuracy (1σ)	0.1°

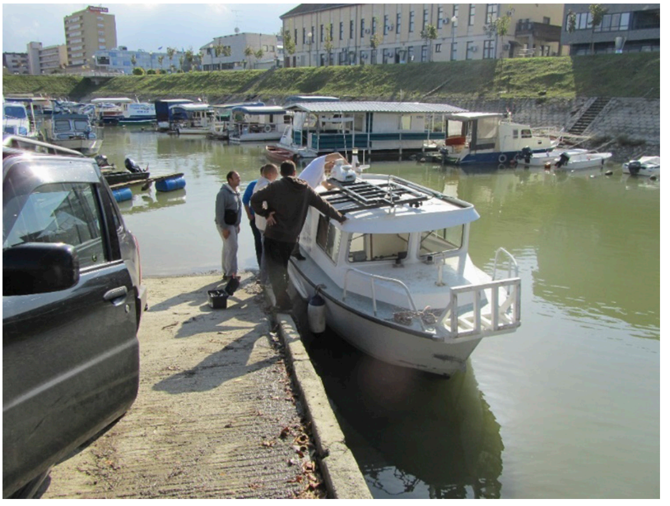

Figure 8. *MDL mounted on a boat.*

cost system in terms of MLS systems price ranges. The system was mounted on a boat (Figure 8), and CROPOS was used for geolocation and data georeferencing. Since the same service was used for TLS positioning (georeferencing) previously, this allowed easy placement of both data sets into the same coordinate system and provided comparable accuracy and precision. Boat based setup allowed fast approach and easy access to even the most demanding sites as water approach capability is, unlike land approach, always 100%. Not only that, but the survey vessel moves along the coast and is not wasting time doing round trips like the ones that would have to be made using land vehicles.

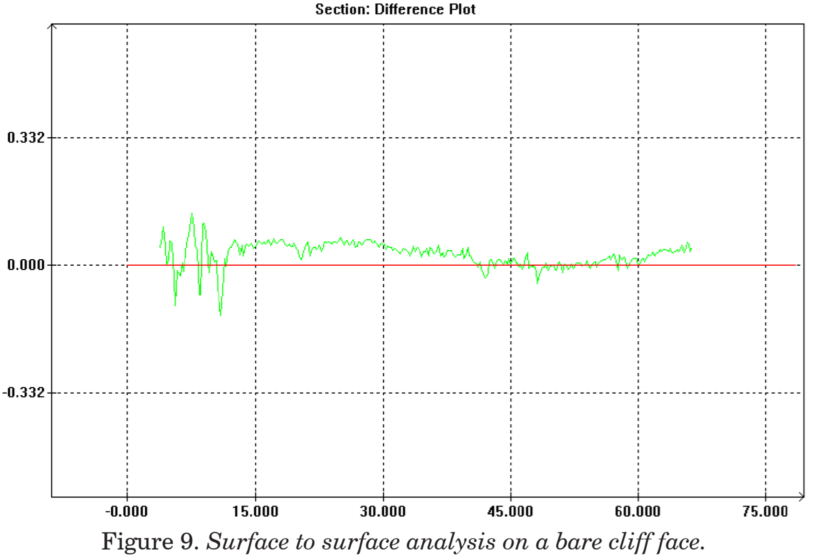

Figure 9. *Surface to surface analysis on a bare cliff face.*

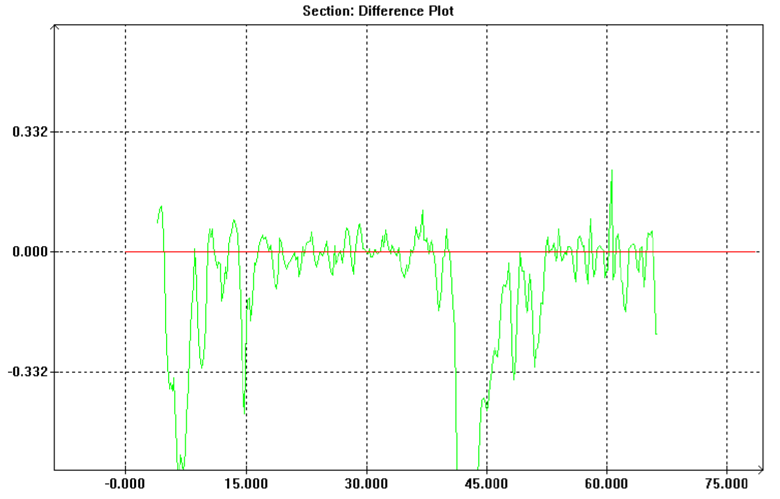

Figure 10. *Surface to surface analysis on vegetation covered areas.*

The resulting clouds acquired through mobile survey were then overlapped with the clouds obtained using TLS. The main issues during overlap were the noise and vegetation cover obstructions causing differences in comparison where, in reality, there are none. Another issue was the level of detail (resolution) obtained using these two systems. The gathered data had to be “cleaned”, meaning the unwanted points had to be removed to allow for adequate comparison. The resolution plays a great part here as the greater the resolution the easier it is for unwanted data to be identified and removed. Since the research area was mostly vegetation free, the minimal amount of “cleaning” was necessary. The analysis of the data showed that the two clouds had a medium of 5 cm discrepancies between them (Figure 9). This was even better in some (clear) areas, but worse in others, where vegetation obstructions were an issue (Figure 10).

4. Conclusion

The results indicate that using MLS systems for monitoring loess cliffs alongside Danube’s coast is beneficial and cost effective. It allows survey of areas that would otherwise be very difficult to reach and time consuming. Such surveys would defeat the purpose, which is timely risk assessment and prediction, hence time is a factor of great importance.

The accuracy of surveys in comparison with TLS measurement has also been proven to be adequate. A 5 cm mean error is significantly lower than the displacements observed from TLS surveys made to determine erosion effects on the investigated stretch. The accuracy drops on surfaces covered with vegetation due to noise in data produced by vegetation. On the other hand, riparian vegetation was proven to provide better stability, consistency and steadfastness of a riverbank, thus making those areas less prone to erosion (Bentrup and Hoag 1998, Wynn 2004). For removing noise caused by obstructions like vegetation, new algorithms are constantly being developed and the existing ones improved (Himmelsbach et al. 2010). This will allow for a more efficient workflow and point cloud data processing in the future, but will also be beneficial in terms of precision and reliability. On bare cliffs, susceptible to higher erosional rates, the accuracy can be improved further using currently available methods. Thus, higher level MLS systems (higher precision systems), surveys in two directions (going both down and up the river) and/or establishing base stations specifically for the targeted area, instead of relying on CROPOS for positioning can be applied, which will result in higher quality of data and subsequent reliability of results.

Identifying undercutting of the riverbank and high risk areas using this method is possible on stretches where the foot of the cliff is above water surface level during low water levels. Unlike rock cliffs where even miniscule movements on a millimetre scale are enough to cause rockfalls, loess cliffs suffer greater displacements prior to bank failure caused by gravitational influence. Hence, the accuracy of MLS systems is sufficient in determining erosional rates and identifying risk areas. MLS coupled with underwater surveys, like multibeam echosounder survey, would provide for a comprehensive inspection and analysis of the erosional processes. Thus, the next logical step is integration of both under and above water level survey systems for monitoring riparian and wetland related changes.

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Geodetske mobilne mjerne metode za praćenje erozije obala rijeka

SAŽETAK. Rijeke su reljefni oblici koji su podložniji promjenama tokom vremena od bilo kojih drugih. Dinamika i intenzitet tih promjena ovisi o nizu faktora koji su desetljećima tema istraživanja sa ciljem predviđanja i/ili prevencije promjena koje imaju negativan utjecaj na kako ekološke tako i administrativne sustave. To je posebno izraženo na velikim riječnim sustavima. Tema erozije pod utjecajem tekućih voda, kao fenomena koji mijenja oblik, položaj i tok rijeka, nije, do današnjeg dana, u potpunosti iscrpljena primarno zbog nebrojenih faktora koji direktno ili indirektno utječu na taj proces. Istovremeno, utvrđivanje utjecaja pojedinog faktora nije moguće bez upotrebe adekvatnih mjernih metoda, koje omogućavaju brzo prikupljanje relevantnih podataka na osnovu kojih je moguće donijeti ispravne zaključke o pojedinim procesima. Naglasak se stavlja na brzinu prikupljanja s obzirom da su rijeke dinamična tijela, što znači da su i promijene, koje one posljedično uzrokuju, također, relativno brze. Geodezija, primarno mjerna tehnologija i metodologija koja se koristi, je u proteklim desetljećima doživjela značajan razvoj. Time su se otvorile nove mogućnosti za zadovoljavanje navedenih potreba pri istraživanju erozivnih procesa riječnih sustava. Uzevši u obzir sve navedeno te dodajući podatak da je Dunav najveća i najsnažnija rijeka koja teče kroz Hrvatsku, moguće je zaključiti da je upravo ta rijeka najzanimljivija po pitanju utvrđivanja učestalosti/intenziteta erozivnog fenomena u Hrvatskoj. Za prikupljanje relevantnih podataka, u relativno kratkom vremenu, nužno je primijeniti adekvatne metode. Stoga je Dunav, odnosno njegovi najzanimljiviji dijelovi, odabran za utvrđivanje primjenjivosti bezkontaktnih mobilnih mjernih rješenja sa svrhom ocjene takvih sustava za određivanje i predviđanje rizika od erozije te njenog iznosa.

Ključne riječi: Dunav, meandriranje, lesni strmci, riječna erozija, TLS, mobilna izmjera, MLS.

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