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Integrated geophysical-geotechnical investigation of shallow sections of river Danube, Hungary

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ABSTRACT: Shallow river sections present shipping obstacles or even hazards during low water stand periods. Hungarian section of river Danube is an important international shipping route crossing the country and still not regulated by dams. The water stand is naturally controlled and there are several shallow sections along the river. These sections show differences in riverbed morphology and subsurface geology. Understanding these differences and the subsurface layers are key to planning any engineering work and model the river bed development.
Five of the most critical shallow sections of the Danube in Hungary were surveyed in detail including geophysical surveys of the river bed and shallow subsurface layers, sediment and rock sampling, drillhole information and laboratory measurements of grain size distribution and rock-physical properties. Integration of the collected data and possible use for engineering design and modelling will be presented.

Keywords: high-resolution seismics; underwater GPR; river development; dynamic modelling

1. Introduction

Sediment transported by river flow can be calculated as a combination of suspended sediment transport (van Rijn 1984b) and bed load transport (van Rijn 1984a). Dynamic modelling of riverbed morphology, sediment transport and riverbed development requires detailed three-dimensional data for both the water body and the river bed.

High-resolution geophysical surveys can provide detailed input data not only for river bed morphology, but also for thickness of recent fluvial sediments and sediment classification. When no recent fluvial sediment is deposited on the river bed, the underlying base rock is outcropping on the river bottom and provides the boundary condition for dynamic modelling. In each case three-dimensional mapping of the physical parameters of the river bed can be effectively supported by high-resolution geophysical surveys.

High-resolution seismic surveys are typically used for sediment classification (e.g. Radomille Santana and Neto, 2015; Orlando et al., 2017), however combination of seismic and other geophysical survey methods can provide additional information on physical parameters. Ground penetrating radar (GPR) surveys, like seismic surveys use reflected waves for imaging and the amplitude of the reflected waves carry information about the physical properties of the reflecting interface, in our case the water bottom. Unlike for seismic waves, when reflection strength is driven by the acoustic impedance contrast of the reflecting interface, hence the velocity of the compressional waves and density are the key physical parameters, for radar waves reflection strength depends mainly on changes in relative dielectric permittivity. Combining seismic and GPR surveys provide information incorporating both elastic and electromagnetic parameter changes along the water bottom interface.

Calibrating the survey results of combined seismic and GPR mapping with sediment samples taken from the river bed provides three-dimensional input parameters for dynamic modeling of the riverbed. Selected shallow river sections presenting shipping hazards during low water stand periods along river Danube, Hungary were surveyed and mapped in detail. Selection of these results are shown in this paper.

2. Seismic profiling

An IKB-Seistec™ high-resolution single-channel seismic profiler was used for the seismic surveys. The profiler is built on a catamaran frame providing fix distance between the boomer source and the unique design line-in-cone hydrophone group (Simpkin and Davis, 1993). Bottom view of the seismic profiler lifted out of the water is shown in *Figure 1.* Metal plate of the boomer source and the focusing cone around the hydrophone group are well visible in that part of the metal frame, which is submerged into the water during the survey. The seismic profiler is shown during normal operation in *Figure 2.* witht he GPS antenna mounted in the center point of the profiler.

Figure 1. IKB-Seistec™ high-resolution single-channel seismic profiler lifted out of water.

Typical frequency range of the system is 1-10 kHz, with the boomer source providing a very stable, high resolution signal. The seismic wavelet can be estimated with high accuracy using the water bottom reflection providing on one hand quality control for the wavelet stability and also enabling deterministic deconvolution in order to further increase seismic resolution of the sediment layers.

3. GPR surveys

GPR suveys were completed using two different antennas. In case of near shore, shallow water measurements a 300 MHz antenna was towed on the water surface. In river Danube this setup typically provided GPR records suitable for analysis up to 3 m water depth.

For deeper river sections a specially designed 500 MHz underwater antenna was used. This system was developed in the framework of the GEOWATERS project supported by the European Commission under the Fifth Framework Programme in 2001-2002 and built by Radar Systems Inc. (Tóth et al., 2003)

For reference profiles the seismic and GPR data were recorded simultaneously along parallell profiles, or along the same profile towed behind each other. Parallell profiles could be recorded using the minimum survey configuration shown in *Figure 2.*, however towing the two systems behind each other along exactly the same profile required a bigger survey vessel.

Figure 2. Combined high-resolution seismic and underwater GPR survey performed from a small inflatable boat. Seismic system is towed on the starboard side of the boat, the underwater GPR antenna is mounted on the frame on the port side of the boat.

4. Positioning

High-resolution seismic and GPR surveys can provide centimetre accuracy definition of the water bottom and the subsurface layers. In order to make full use of the recorded data and reliably detect temporal changes in the order of centimetre scale, similarly accurate positioning is required in both horizontal and vertical direction. RTK-GPS technology can provide high-enough accuracy for most of the inland waterway surveys, but vertical positioning and positioning under bridges is still a challenge using GPS systems only.

In order to ensure no compromise positioning accuracy a combination of RTK-GPS and robotic survey system was used. The GPS antenna and the 360° prism was mounted below each other at the CDP positions of the profilers. In case of covered areas (i.e. under bridges) a combination of the two positioning systems was used for both vertical and horizontal positioning.

For most of the surveys with open view to the sky, horizontal positioning was based on the RTK-GPS data only, and vertical positioning was completed using combination of both systems. Main reason for this was the inaccurate sub-second timing of the Topcon robotic system, which resulted several decimeter scale horizontal positioning error during the surveys.

5. Data processing

Seismic and GPR data were recorded and processed with focus on reflecting the true amplitude variations along the water bottom reflector and preserve highest possible resolution of the recorded data. One of the key challenges was to compensate for the amplitude decay of the seismic and GPR records with depth.

In case of seismic data the amplitude decay is primarily controlled by the spherical divergence and the amplitude characteristics of the IKB-Seistec™ system. This was estimated from statistical analysis of large datasets recorded over survey areas with water depth ranging between 2-12 m.

In case of GPR data key effect is the attenuation of the electromagnetic waves in the conductive water. Analysis of amplitude decay was based on statistical data analysis and specific test measurements. Results of a test measurement with the fitted amplitude decay curve is shown in *Figure 3.*. The calculated decay curve was used for depth dependent amplitude correction of the GPR reflection from the water bottom. Results of amplitude decay compensation is shown in *Figure 4*. comparing the water bottom reflection amplitudes without (left figure) and with (right figure) compensation applied. Contour lines are identical in both figures indicating water depth, while the colors represent the relative amplitude of the water bottom reflection. Red colors mark high amplitude areas, while blue colors indicate low amplitudes. Without amplitude decay correction the correlation between water depth and amplitudes of water bottom reflections is very strong. In the left panel of *Figure 4.* warm colors coincide with the elevated parts of the river bottom. Following amplitude decay correction, as shown in the right panel of *Figure 4.*, correlation between reflection ampitude and water depth is no longer dominant, changes in reflection strength mark different lithologies outcropping at the water bottom. Best example of this is the approximately East-West trending high amplitude event in the southern part of the area maarked by yellow-red colors.

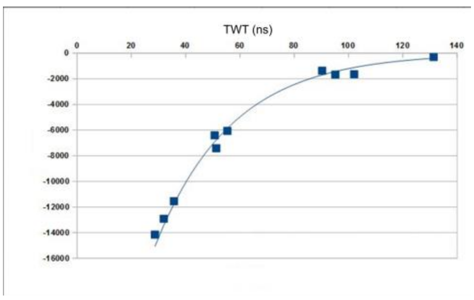

Figure 3. GPR amplitude decay curve calculated from data of test measurement. Horizontal axis shows two-way-travel time (TWT) in nanoseconds, vertical axis is relative amplitude of the GPR reflection from the water bottom.

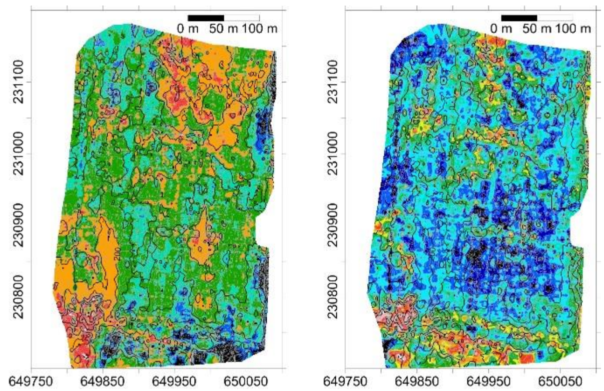

Figure 4. GPR amplitude map of the water bottom without (left) and with (right) amplitude decay compensation. Contour lines indicate water depth in TWT (ns) units, colors mark relative amplitude of the water bottom. Warm colors are indicating high amplitude events. Flow direction is N to S.

6. Survey areas

6.1. Göd survey area

This shallow section of river Danube is characterised by thin fluvial sediment layer below river bottom. Basement rock is outcropping at several locations, strongly influencing river evolution. River flow is controlled by several cross-works, having major effect on river dynamics.

River bed is stable, as little or no mobile sediment is present on the river bottom, but the shallow sections present major shipping problem during low water level periods. Any planned construction work will have to take into account the highly variable bedrock in the survey area. This bedrock is outcropping at a significant part of the surveyed area as shown in the middle image map of *Figure 5*. White areas of the sediment thickness map indicate outcropping bedrock with practically no recent sediment cover.

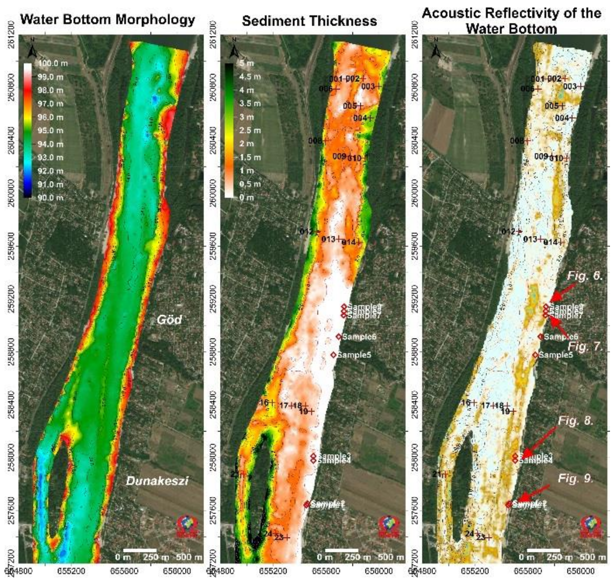

Figure 5. Water bottom morphology, sediment thickness and water bottom reflectivity of the Göd survey area. Elevation scale of the water bottom morphology ranges between 90 and 100 m above sea level, while the sediment thickness scale covers 0 to 5 m sediment thickness typical of the area. Red arrows in right panel mark locations of samples presented in *Figures 6.-9.* Flow direction is N to S.

Variabilty of the bedrock can be directly examined during low water stand periods, when the river bed can be sampled at the near shore section. Samples collected are shown in *Figures 6.-9.* from North to South. Sample locations are marked by red arrows and figure numbers in the right panel of *Figure 5.*

Less than 2 km long section of the Danube riverbed between Göd and Dunakeszi shows strong variability as far as physical properties of the rock strata outcropping at the river bottom is concerned. Oligocene sediments range from very hard volcanic layers to unconsolidated sand and soft clay layers. In many cases rock layers with very different hardness and resistance to erosion are directly overlying each other, a harder, more resistant layer protecting the soft, easy to erode sediment. This is exactly the case for samples 9 and 8 shown in *Figures 6.*

and *7.,* where a hard tuffic sandstone layer is shielding an easy to erode, unconsolidated sand layer. Similar hard tuffic sandstone layers are outcropping at several locations in the river bed (see for example Figure 8.), while soft sediments often are found below these hard layers, or along the shoreline. Example of a soft clay layer forming the soreline nearby Dunakeszi is shown in *Figure 9*.

The differences in rock physical properties are reflected in the acoustic reflectivity map of the water bottom as shown in *Figure 5.*

Figure 6. Sample 9, very hard tuffic sandstone layer outcropping at the river bottom nearby Göd.

Figure 7. Sample 8, unconsolidated Oligocene Sandstone bed right below the hard tuffic sandstone layer shown in *Figure 6*.

Figure 8. Sample 4, hard to very hard tuffic sandstone layers outcropping at the river bottom nearby Dunakeszi.

Based on the above results, it is clear, that along the shallow section of river Danube between Göd and Dunakeszi no significant thickness of recent fluvial sediment is present. Maintenance of the shipping route is therefore not possible by simple dredging of the gravel layer. On the other hand, if any alteration of the outcropping rock starta is considered, carefull planning and detailed mapping of the layers with different rock physical properties are required. Removing a hard, protective layer may initiate unplanned erosion of the underlaying unconsolidated sediments, resulting several meters of unwanted deepening of the riverbed. Seismic profiles show records of similar erosional processes from the past.

Figure 9. Sample 1, strongly fractured, relatively soft Oligocene clay layer outcropping along the shoreline at Dunakeszi.

6.2. Gönyű survey area

This shallow section of river Danube is characterised by thick fluvial sediment layer below the river bottom, a very different geological setting compared to the one in the Göd-Dunakeszi area. No outcropping basement rock or hard rock surface influences river evolution. River Danube is flowing above a subsiding sub-basement of the Pannonian Basin, the Little Hungarian Plain. This difference is best demonstrated with the help of the digital elevation model of the Pannonian Basin shown in *Figure 10.* Wile the Göd survey area is on the southern edge of the so called „Danube bend“, a section of river Danube cutting through the uplifting mountain ranges, the Gönyű survey area is located above a subsding flat land, where topmost layers are stacked fluvial sediment packages of river Danube.

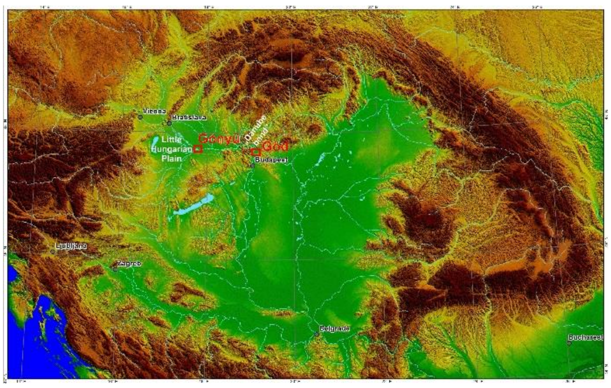

Figure 10. Digital elevation model of the Pannonian Basin showing the marked difference between the Göd and Gönyű survey areas. While Göd area is on the southern edge of an uplifting mountain range, in the Gönyű area river Danube flows above a subsiding flat land.

In the Gönyű area river flow is controlled by several cross- and parallell works, which have major effect on river dynamics.

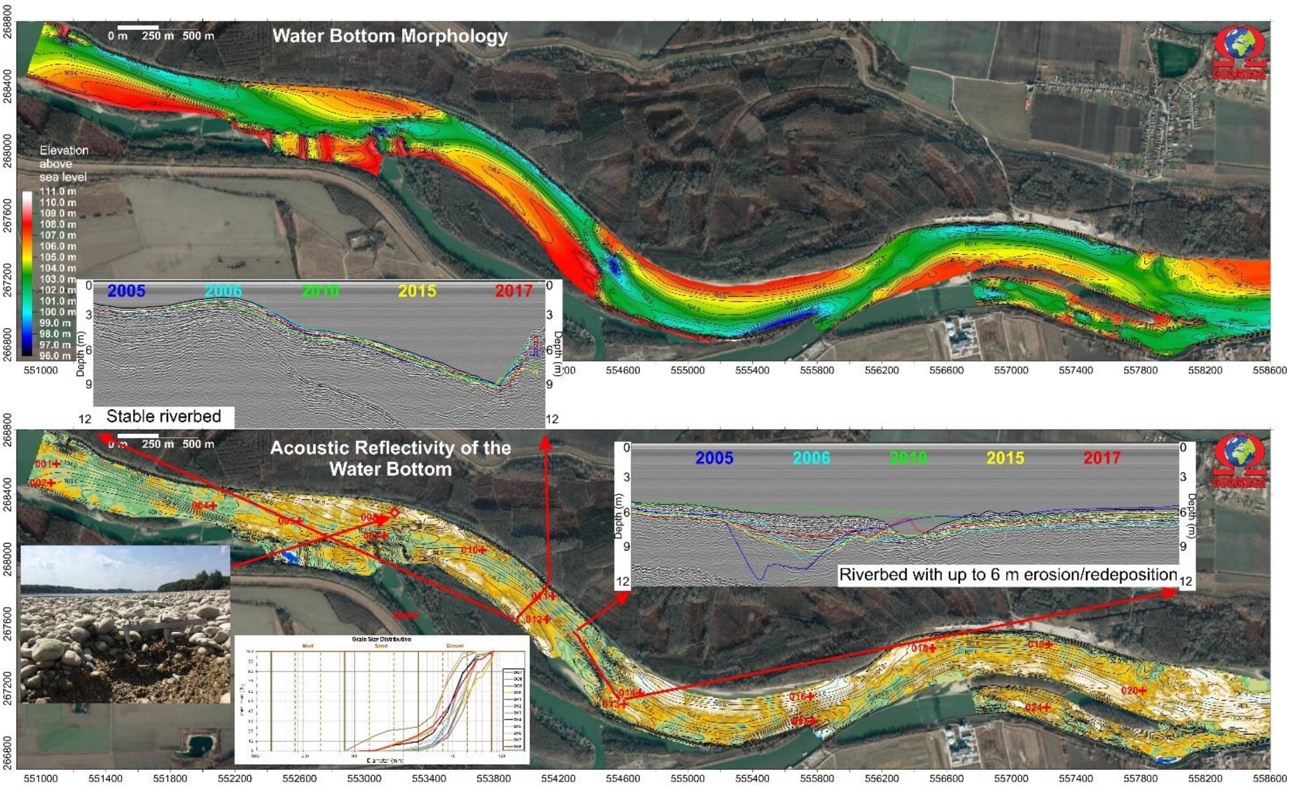

Figure 11. Gönyű survey area showing strongly varying riverbed morphology with several meters of sediments redeposited from year to year. Water bottom morphology of the survey are is shown in the upper part of the figure with elevation above sea level contouring, while the lower map shows reflectivity of the water bottom, green colours indicating lower, white colour high reflectivity contrast. Two inserted sample seismic profiles show a stable and a strongly varying part of the riverbed colour lines indicating river bed morphology measured by ÉDUVIZIG in 2005, 2006, 2010, 2015 and 2017 respectively

Parts of the river bed are very stable throughout the years, while other parts are showing several meter erosion/deposition on annual time scale. *Figure 11* shows examples of both the stable and the highly variable river bed. Both of the inserted seismic profiles shown in *Figure 11* mark 2005, 2006, 2010, 2015 and 2017 water bottom morphology measured by ÉDUVIZIG (Észak-Dunántúli Vízügyi Igazgatóság) with different colour lines. On the insert showing the stable riverbed no significant change can be observed between the water bottom morphology measured in different years. On the other hand the insert showing highly variable water bottom morphology shows over 6 m difference between different years. Internal sediment structure imaged by the seismic profile correlates perfectly with the measured water bottom changes and shows details of the sedimentation and erosion process of the river bed.

It is also interesting to compare the map in the upper part of *Figure 11* showing the water bottom morphology with elevation above sea level contours and colouring, and the map in the lower part of *Figure 11* showing the water bottom reflectivity based on the seismic survey results. Green colours indicate lower reflectivity, ie. smaller contrast between the water and the water bottom sediments, while white colours mark stronger reflectivity contrast, ie. “harder” water bottom. Water bottom reflectivity was corrected for the effect of water depth before beeing displayed in *Figure 11*. Although at several parts of the survey area there is still a good correlation between the water depth and the water bottom reflectivity, this correlation is not valid everywhere, indicating variations in the water bottom sediment quality. This variation was confirmed by water bottom samples taken at several sampling points in the survey area.

Acknowledgement

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References

[1] Orlando, L., Contini, P. and De Girolamo, P. [2017] Seismic scattering attribute for sedimentary classification of nearshore marine quarries for a major beach nourishment project: Case study of Adriatic coastline, Regione Abruzzo (Italy). Journal of Applied Geophysics, 141, 1-12.

[2] Radomille Santana, F. & Neto, A. [2015] Use of seismic attributes for sediment classification. The Journal of Engineering, 10.1049/joe.2014.0133.

[3] van Rijn, L. C. [1984a] Sediment transport, Part I: Bed load transport. Journal of Hydraulic Engineering, ASCE, 110, 1431-1456.

[4] van Rijn, L. C. [1984b] Sediment transport, Part II: Suspended sediment transport. Journal of Hydraulic Engineering, ASCE, 110, 1613-1641.

[5] Simpkin, P. G. and Davis, A. [1993] For seismic profiling in very shallow water, a novel receiver. Sea Technology, 34,. 21-28.

[6] Tóth, T. et al. [2003] Combined interpretation of waterborn seismic and GPR measurements. Oral presentation, 9th Annual Meeting of the EEGS, Prague.