Applications of shallow seismic refraction measurements in the Western Carpathians (Slovakia): case studies

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Abstract: Shallow seismic measurement, specifically seismic refraction tomography, is an effective geophysical method that has applications in various sectors. It enables the search for and determination of the course of the interfaces, thus helping to resolve geological, environmental, hydrogeological, engineering, geotechnical and other problems. The paper demonstrates the possibilities of using these methods through examples of shallow seismic measurements that have been performed at various four locations in the Western Carpathian Mountains. The first case study describes Monastery Pond at Katarínka. It was found that, the basement of the Monastery pond is at a depth of 2–3 m below the surface and the results were also confirmed by electrical resistivity tomography (ERT). The next measurement through the thermal power station waste storage showed that the storage area base runs at a depth of about 20 m under the measured profile. The third case study addresses the depth of groundwater depth in the area of Borská nížina. The measurement confirmed the assumed depth of ground water level at 3.35 m below the surface. In the last case study, border fault between the Turiec Basin and the Malá Fatra Mts. was mapped by application of shallow refraction methods. The results show that shallow seismic methods shed light on the problem and in combination with other geophysical methods are an effective tool with great potential. They provide very useful data for shallow mapping applications.

Key words: refraction seismics, seismic refraction tomography, shallow seismic measurements, Western Carpathians, case study

1. Introduction

In the past, seismic methods were mainly associated with hydrocarbon exploration, whose main benefit is their large depth range. On the other hand

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the shallow refraction measurements were used to determine the parameters of the low-velocity layer for the treatment of processing for deep reflection seismic profiles.

Shallow seismic methods have historical roots dating back to the 1930s, when limited shallow refraction work was performed using the Intercept-Time method (*Steeples, 2000*). The development of technology in both the acquisition and processing has led to substantial progress in the use of shallow seismic measurements since 1980 (*Steeples, 2000; Steeples and Miller, 1990*).

The use of surface waves has also evolved. These waves which overlap the useful signal and have to be filtered out in reflection and refraction processing (especially in the shallow parts of the profiles), have found application in shallow research methods such as a SASW (Spectral Analysis of Surface Waves – *Nazarian et al., 1983*) and MASW (Multichannel Analysis of Surface Waves – *Park et al., 1998, 1999; Xia et al., 1999, 2000*). The use of shallow seismic measurements is excellent, particularly for determining the depth or course of geological interfaces for different purposes: (a) for geo-engineering, geotechnical investigation and the assessment of landslide areas (e.g., *Beng et al., 1982; Shtivelman, V., 2003; Cardarelli et al., 2014; Coulouma et al., 2012; Hack, 2000; McClymont et al., 2016*); (b) for hydrogeological purposes (e.g., *Haeni, 1986; Gordon, 1997; Gabr et al., 2012; Osumeje and Kudamnya, 2014; Pandula, 2000; Shtivelman, 2003; Prekopová et al., 2016*); and (c) for archaeological exploration (e.g., *Tsokas et al., 1995; Shtivelman, 2003; Henley, 2003; Shahrukh et al., 2012*).

The basic parameter for the successful use of seismic methods for any purpose is to achieve the possibilities and limitations of these methods. In some cases, the geological layers cannot be detected (*Soske, 1954* and *Sander, 1978* in *Haeni, 1986*). One of the criteria is an insufficient velocity contrast of layer or thickness in order to return first arrival energy (*Haeni, 1986*). This is related to the vertical resolution of the method. Seismic method vertical resolution depends on the generally accepted one-quarter wavelength axiom (after *Widess, 1973* in *Nanda, 2016*). If the thickness of a layer is less than one-quarter of a wavelength of the incidence wave, the thin bed will not be visible on the time–distance graph (*Reynolds, 1997*). Because the wavelength is a ratio of wave velocity and frequency, in a rock environment with a wave velocity of 2000 m/s and a frequency of 50 Hz, the vertical resolution will be approximately 10 m. Layers thinner than 10 m will not be detected. The vertical resolution decreases with depth because of the attenuation signal of the higher frequency component and higher velocities (*Nanda, 2016*). Better resolution can be expected in shallow parts of the environment. Vertical resolution is attainable with a reflection of about 10 cm as described in *Steeples (1998).* The vertical resolution is sometimes referred to as a percentage of the practical survey depth. For refraction measurement it is presented as 10–20% of depth (*Enviroscan, 2018*). Survey depth for refraction seismic is deposed as 1/5 to 1/4 of the maximum offset (shot-geophone separation) (*Enviroscan, 2018*). The appropriate spacing of geophones is an important parameter for layer detection by seismic refraction (*Reynolds, 1997*). If the distance between geophones is too large, there is not enough sampling for an identification of the layer on time-distance graphs. This is another layer problem. In planning for the use of seismic refraction measurement, one must be aware of another limitation of this method. Based on the principles of the propagation of seismic waves and the conditions for critically refracted wave occurrence, refraction seismic measurements are only able to detect layers when velocity increases with depth (*Reynolds, 1997*).

The most commonly used shallow geophysical methods, especially for non-demanding terrain measurement, are electrical resistivity tomography (ERT) and georadar. However, as one of the selected case studies has shown, these methods are not always successful. Therefore, the aim of this article is to demonstrate that shallow seismic methods have a wide range of applications and are equivalent methods for various shallow survey application. This paper provides case studies from four different locations in the Western Carpathians (Fig. 1). The first case study relates to an archaeological research on the marginal part of the Malé Karpaty Mts. The goal is to map the basment of Monastery Pond. The next case study deals with an environmental issue, namely, waste storage at a thermal power station. The third case study maps the tectonic contact of the Turiec Basin with the Malá Fatra Mts. The last case study features an example of using the shallow seismic methods for hydrogeological purposes. It is aimed at searching for the surface of underground water levels.

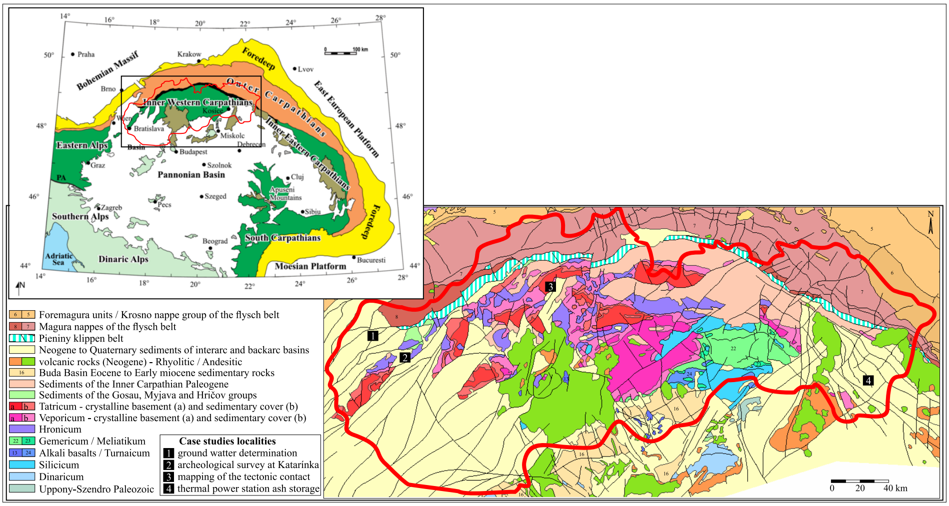

Fig. 1: Geological scheme of the Western Carpathians (after *Bielik, 1998* and *Geological map of Slovakia, 2013*) with marked case studies localities. MK – Malé Karpaty Mts., BN – Borská nížina, TB – Turiec Basin, MF – Malá Fatra Mts.

2. Methodology

Refraction seismic methods use controlled source seismic waves, specifically refraction waves, to determine depths to the interface within the subsurface and the velocities of the layer between the interfaces (Lillie, 1999). In seismic refraction surveys on land, a number of geophones are laid out along a cable in a straight line. In the simplest case, the seismic source (shot) is located at the beginning and end of a geophone line. The source can also be positioned at a location along the geophone spread, or at a discrete distance from the end of the spread. The positioning of shots provides adequate lateral resolution (*Reylnolds, 1997*).

The seismic refraction tomography profile (SRT) requires a higher density of sources and receivers than in conventional surveys to obtain high resolution profile.

The seismic waves spread from the source and the arrival of each wave is detected along the set of geophones. Direct waves and waves critically refracted from interfaces are useful for refraction seismic interpretation. The direct wave comes to geophones as the first to the offset known as the crossover distance. After this offset, critically refracted waves precede the direct wave. During processing, these first arrivals are marked for each geophone on a seismograph. They are associated with travel times and plotted on a time-distance graph. The gradient of this graph changes at the crossover distance from the slope of direct wave arrivals (characterized by the velocity of direct wave) to the slope for refracted signals. The time–distance graphs are then used to calculate the velocity of the interpreted layers and the depth of the interfaces. Several different interpretational methods for seismic refraction have been published. In *Reynolds (1997)*, two methods emerge as the most commonly used are the 'plus-minus' method (*Hagedoorn, 1959*) and the generalized reciprocal method (*Palmer, 1980*).

Seismic refraction tomography is an alternative to conventional seismic refraction analysis methods (*Sheehan et al., 2005*). Conventional refraction methods assume that seismic velocity structures are simple and primarily attempt to map a refractor. Tomography methods calculate travel times and raypaths in a regular grid model and use an inversion technique to reconstruct seismic velocities (*Zhang and Toksöz, 1998*). In the case of 2D refraction vertical tomography, the starting model must first be generated. Ray tracing is used for the calculation of travel times for this model. The synthetic data obtained by ray tracing are compared with the field data and the initial model is modified until the best fit between the model and field data is achieved.

Acquisition and processing

The data for seismic refraction tomography at the Katarínka archaeological site was obtained by a 24-channel DMT equipment with 10 Hz geophones and a hammer with 5 stacks as the source served for better resolution. In the other cases, a 36-channel M.A.E. A6000-S equipment with 4.5 Hz geophones and a hammer as a source was used.

The measured data were processed in Reflexw Version 8.0 software (developed by *Sandmeier, 2016*) for the processing of seismic, acoustic or electromagnetic reflection, refraction and transmission data. At first, the SEG-2 data were imported to the software background for refraction processing and the first arrivals were picked (see Fig. 6b). Then the time-distance curves were created from the picked travel times, and the slopes of primary wave curves and refracted curves from various interfaces were marked for each shot (see Fig. 5a and Fig. 6c). After this analysis and interpretation of first arrivals, the velocity model of the subsurface environment was created. This served as the initial model for seismic refraction tomography. The result of tomography is a velocity model with a continuous velocity gradient across a subsurface which is interpreted depending on the specific case study.

Some examples also show the influence of various factors, such as the changing humidity of the rock environment or its consolidation, to obtained velocity values in the shallow survey. Interpreted velocity interfaces have been verified by other geophysical measurements (mainly ERT) in the Katarínka and Bystrička areas.

3. Case studies

3.1. Mapping the bottom of Monastery Pond at the Katarínka site

Katarínka is a famous archaeological site around the ruins of Saint Catherine's Abbey (founded in 1618) on the hills of the Malé Karpaty Mts. near the village of Dechtice (Figs. 1 and 2). Intensive geophysical research was conducted in this area in 2009 (*INCA, 2009* – International Course on ArchaeoGeophysics) to help find buried ruins of buildings near the monastery, surrounding chapels, a cavern under the presbytery and others. As a continuation of this research, seismic refraction measurements and ERT were applied to identify the bottom of Monastery Pond.

From a geological point of view, the entire archaeological site is located in the territory of the Brezovské Karpaty Mts., which belong to the Malé Karpaty Mts. The Brezovské Karpaty Mts. are mostly comprised of Mesozoic rocks. Triassic sediments are dominant, while Jurassic and Cretaceous sediments are less preserved. The Triassic sediments belong to the Nedzov Nappe Jablonica Group (*Salaj et al., 1987*). In area of abbey ruins bloom out light-grey bedded Wetterstein Dolomite (Ladinian-Kordevolian) (*Geological map of Slovakia, 2013*). Neogene and Quaternary deposits extend to the edge of the mountain range. Quartery deposits are represented by fluvial sediments of alluvial flats (deluvial and eolic sediments, loesses). Neogene sediments, in the prospecting area are represented by Lakšárska Nová Ves Formation – Jablonica Conglomerates (polymict conglomerates, Karpatian) (*Salaj et al., 1987; Geological map of Slovakia, 2013*).

The seismic profile is situated southwest of the Abbey ruins, in the area where the pond was assumed on the basis of historical documents. According to documents in the State Archives in Bratislava, *Matulová (2003)* states that the pond dimensions are about 49 × 31.36 m. Remnants of the pond barrier are still visible in the terrain. Two 46 m long profiles in the SW–NE direction with 12 overlapping geophones for seismic refraction data acquisition were used for this survey (Fig. 3a). Geophone spacing at both profiles was 2 m. Shot points were placed along each profile at a distance of 2 m, with a beginning of excitation −2 m from the first geophone and the final shot being 2 m beyond the last geophone. The ERT was measured at a 94 m long profile with 1-m electrode spacing. The Schlumberger and dipole-dipole resistance methods were used. The Seismic and ERT profile began at the same point and had the same course. Measurements were made

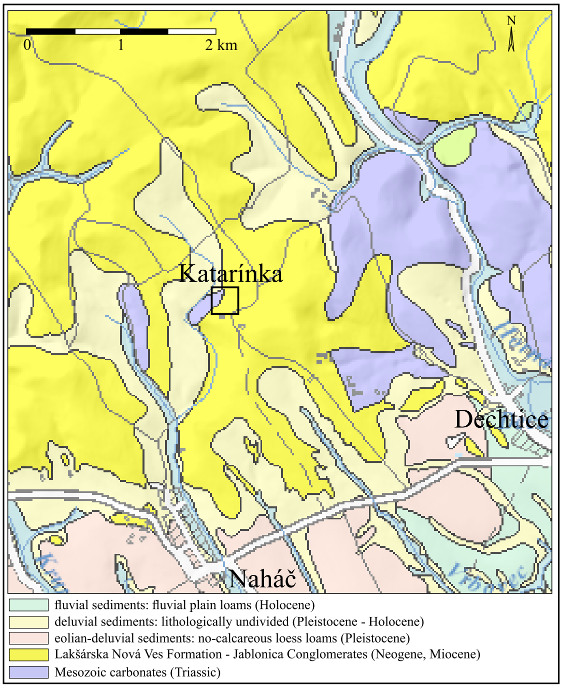

Fig. 2: Location of the Katarinka monastery area on a detailed geological map (after *Salaj et al., 1987* and *Geological map of Slovakia, 2013*).

on different days. If both methods can be measured together, the parallel profiles sufficiently distanced from each other should be used because of the degradation of the signal-to-noise ratio at geophones due to ERT measurement.

The sought after pond floor was interpreted by the velocity refraction profile, ERT profile, and seismic reflection profile (Fig. 3). Based on the

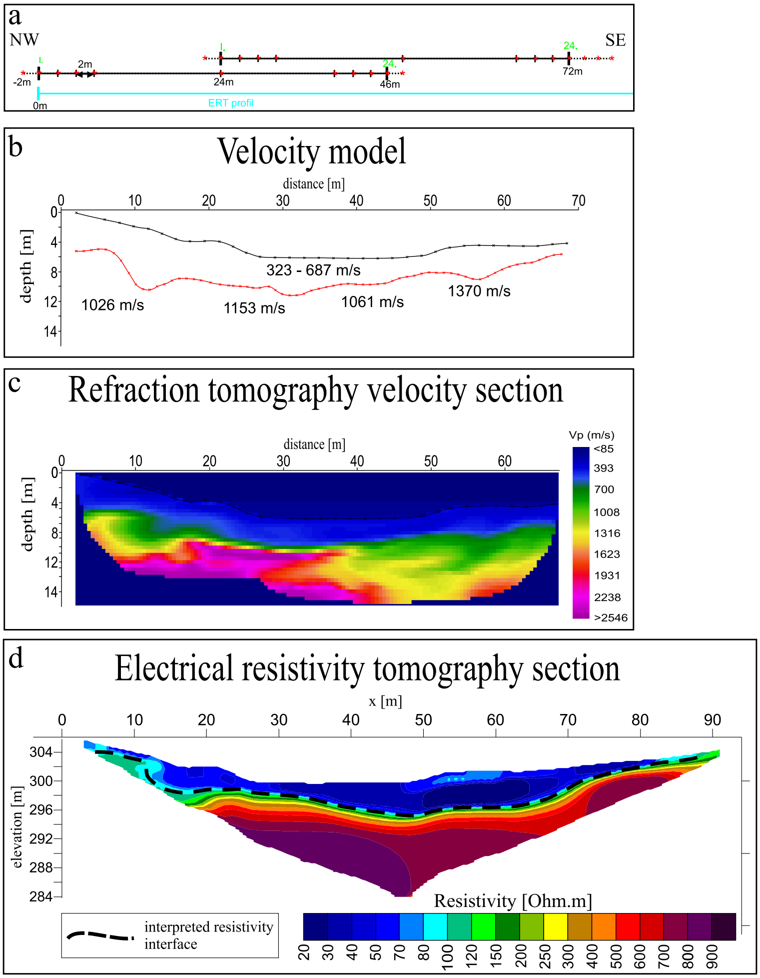

Fig. 3: Results along the seismic and ERT profile at the Katarinka case study locality. a) velocity model, b) SRT and c) ERT.

measured P-wave velocity ($V_p < 700$ m/s) and the resistance ($< 100\,\Omega$.m), the thickness of the surface sediments (scree, vegetal soil), that probably filled the pond space after the collapse of the monastery was determined. The bottom of the pond is anticipated to be at a depth of 2–3 m below the surface. At the bottom of the low velocity layer the conglomerate or dolomite rock bottom should be interpreted. In the upper part next to the surface sediment layer, the disturbed and wetted rocks are assumed due to a relatively low V_p and resistance values. The velocities m/s measured mainly in the NW section of the profile at a depth of 7–8 m correspond with standard Vp values for dolomites or conglomerates (dolomites and conglomerates have mostly the same standard velocity and resistivity range). In the case of dolomites, this can be a continuation of the occurrence of a Wetterstein dolomite rising to the surface at the church ruins. The same result can be interpreted on the ERT profile.

3.2. Estimation of the thickness of coal ash and the run of the bottom at the thermal power station ash storage area

This seismic profile passes through the thermal power station waste storage area. The area of interest consists of a hill of coal ash stored on loam cover on a surface of approx. 0.67 km^2. The area surrounding the dump is mostly formed by Quarternary fluvial sediments (Fig. 4), mainly fluvial plain fine-sandy loam to fine-grained sands or lithofacially undivided loam (*Geological map of Slovakia, 2013*).

The acquisition for seismic refraction tomography was performed on nine overlapping lines each of 175 m in length. The geophones were distributed at 5 m intervals, the acquisition lines lap was comprised of 12 geophones. The source position moved at 20 m intervals. The first shot was acquired at a distance of 20 m in front of the first geophone on the first seismic line. The entire length of the geophone line was 1135 m across the waste storage area (Fig. 4, Fig. 1). There was no ERT measurement because of unsatisfactory findings from the past.

The velocity model of the seismic refraction tomography section clearly shows the thickness and geometry of the ash storage area (Figs. 5b,c). A pronounced change in lithology is indicated by an increase in V_p from ~ 500 m/s to about 1600 m/s. P-wave velocities in several parts of the ash

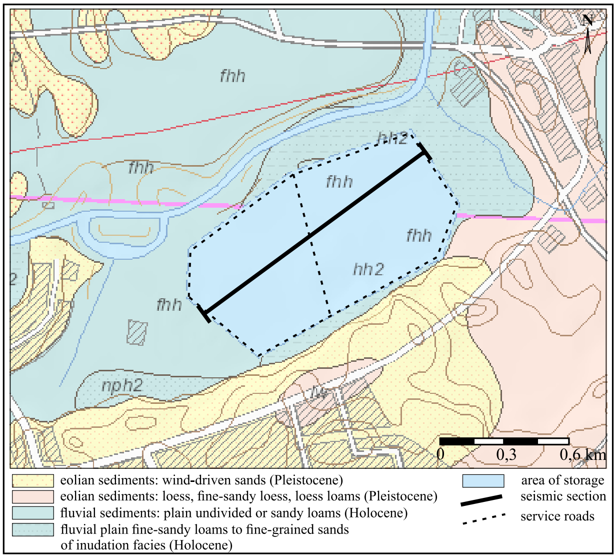

Fig. 4: Location of the thermal power ash storage area and investigated profile on a detailed geological map (after *Geological map of Slovakia, 2013*).

storage area vary from 200 m/s to 560 m/s depending on the consolidation of material, and ultimately to a variation of material moisture (as seen in Figs. 5b,c). At a length of 520–560 m the storage area is divided into two parts. The partition is shown on the velocity model as a zone of higher velocities (450–500 m/s). In the left part of the storage area the velocities are approx. 350 m/s. The velocities in the right part are very similar, but there is a depression on the surface and in area of depression slopes the velocities are lower ($\leq$ 300 m/s, 200–300 m/s). The surface water drains from the slopes and remains at the depression bottom. The velocities are then slightly higher at the bottom of the depression ($\sim$ 380 m/s) than in other flat parts. There is also an increase in V_p to values of about 380–400 m/s at the edges of ash storage area. This should also indicate high ash humidity, but it is likely caused by a consolidation of storage slopes. The storage area base runs at a depth of about 20 m under the measured profile. The velocity on the ground is about 1600 m/s. Higher values are recorded in the right part of the section. These values correspond to ambient Quarternary fluvial sediments.

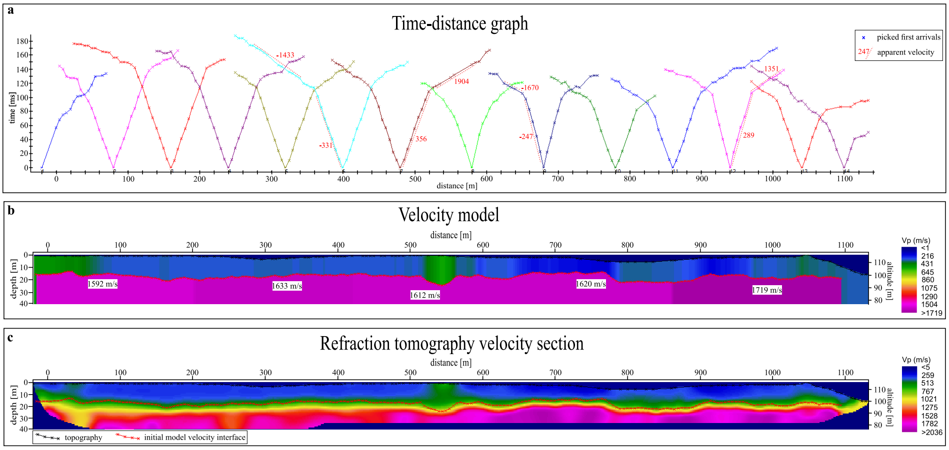

Fig. 5: Results along the seismic profile through the ash storage area. a) selection of time-distance graphs of some shots along the profile and pointing of some account apparent velocities, b) velocity model with velocity interface interpreted as a storage basement and c) SRT.

3.3. Determination of groundwater level

The survey was located in the western part of Slovakia near a village in the area of Borská nížina (Fig. 1). Since there was a shallow borehole with available data close to the measured profile, the velocity output could be directly correlated with geological information (Fig. 6a).

The thirty-six geophones were spaced at 3 m intervals along a straight profile with a length of 105 m, and 12 shots were measured 12 m from each other. The first shot point was at 24 m in front of the geophone line, while the shallow borehole was in the middle of the geophone line length (Fig. 6d,e). According to the borehole data, the groundwater level was expected at a depth of 3.35 m below the surface, while an interface of wet sand and Neogene clay was anticipated at a depth of 8 m.

Results and some examples of processing steps are shown in Fig. 6. The distribution of velocity values in the seismic section correlates with borehole data. Both records, the standard refraction model (Fig. 6d) and the tomography model (Fig. 6e), clearly reveal the level of groundwater. The low velocity layer (< 1000 m/s) is interpreted as dry sand. There is an increase in speed at a depth of 3 m (> 1500 m/s). This indicates the onset of wet

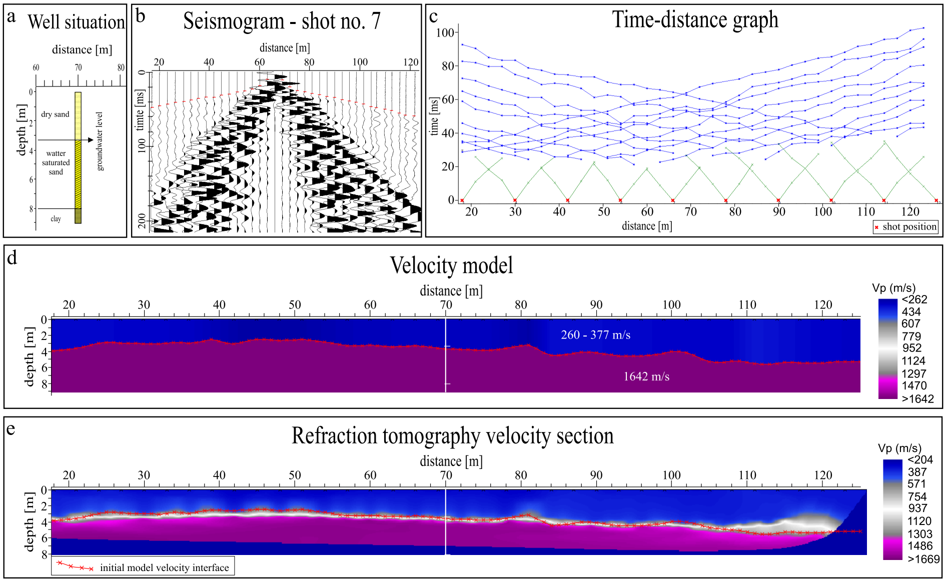

Fig. 6: Results and data along the seismic profile to determine ground water level. a) Well situation, b) example of seismogram with picked first arrivals, c) time-distance graphs of some shots along the profile, d) velocity model and e) SRT.

sand. The next interface – wet sand/Neogene clay, is not recorded at the velocity sections. We expected such result given the assumed low velocity contrast between these two layers.

3.4. Mapping of border fault between the Turiec Basin and the Malá Fatra Mts.

This case study is focused on the development of the tectonic contact of the Turiec Basin with the Malá Fatra Mts. specifically, the determination of the position of the Hradište fault zone.

The Malá Fatra Mts. is part of the Western Carpathians situated in the westernmost part of Slovakia. It is a typical core mountain range with a crystalline core, while its northern side and slopes are overlaid by a Mesozoic cover (*Földvary, 1988*). The Malá Fatra Mts. is divided into two parts – Lúčanská Malá Fatra Mts. (the southern part) and Krivánska Malá Fatra Mts. (the northern part). The crystalline core in the Lúčanská Malá Fatra

Mts. part (*Földvary, 1988*) consists of granitoids (granite-gneiss, biotite-oligoclase granite, granodiorite, quartz-diorite, Magura type granite) and metamorphics (mica schists of Jaraba Group and migmatites).

The south-east Lúčanská Malá Fatra Mts. region is adjacent to the Turiec basin. The Turiec basin is an approximately 40 km long and 10 km wide located between the Malá Fatra Mts. and Veľká Fatra Mts. (*Földvary, 1988*). The pre-Neogene basement consists of the paleo-Alpine alochthonous Mesozoic complexes, and Paleogene post-nappe sedimentary cover in its northern part (*Fusán et al., 1987; Kováč et al., 2011; Bielik et al., 2013*). The remaining part of the basin (*Földvary, 1988*) is filled by Neogene (Pliocene lacustrine and fluviatile deposits, Miocene sandstone and grit) and Quaternary sediments (Holocene alluvium, Pleistocene loess and fluvial gravel).

The eastern and western edges of the Turiec Basin are sharply delimited by fault planes (*Földvary, 1988*). The north-eastern corner is fragmented by SW–NE oriented faults considered to be pre-Quaternary in origin (*Földvary, 1988*). The Hradište fault zone is one of the basinal faults. Its course is not striking on the surface. We attempted to determine its location on a measured shallow seismic profile.

The NW–SE seismic profile of a total length of 440 meters was located SW of the city of Martin above the village of Bystrička (Fig. 7, Fig. 1). Data were measured by three overlapping lines, each 175 meters long with 12 geophones at the cover. The geophone interval for each line was 5 m and the source points were spaced 10 m along the geophone line starting at 2.5 m in front of the first geophone. For better resolution, 7 to 12 stacks were used for each shot.

At first, the typical signatures that the fault impacts on first arrivals as described by *Yan et al. (2005)* were observed on the time–distance graph. The reverse branch which exists far from the fault on the footwall on all shots and an unusual velocity variation pattern for the shot on the hanging wall can be seen (Fig. 8a).

The lateral change in velocities in the refraction velocity profile indicates significantly the Hradište fault (Fig. 8b and also Fig. 8c). A layer with low velocities is found at the top along the entire profile. It can be interpreted as soil and unconsolidated sediments. However, we are interested in the vertical contact of two velocity zones at a depth of approximately 10 m below the surface. A zone with velocities up to 3000 m/s appears on the left part of

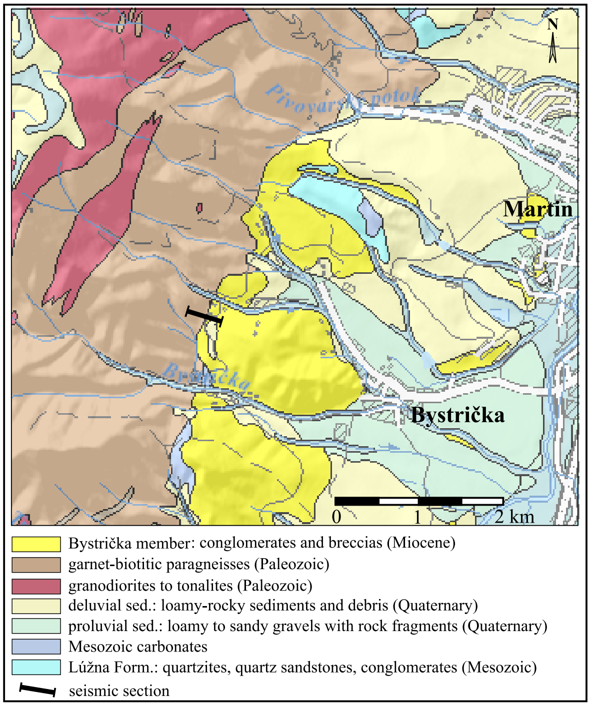

Fig. 7: Location of seismic profile up to the mapped Hradište fault on a detailed geological map (after *Geological map of Slovakia, 2013*).

the profile and can be interpreted as the granitoid rocks which are common in this area. The lateral change in velocity of about 160 m to the right along the measured profile and the zone of lower velocities (2000–2500 m/s) are interpreted as Neogene sediments.

4. Discussion

It is well known that the geophysical results, if possible, would be verified by complex different geophysical methods. Because of the high sensitivity of geophones to any noise, doing seismic measurements with other geophysical measurements on the same profile at the same time can be problematic. ERT is a frequently used method in combination with seismic measurements in shallow geophysical research (*Riddle et al., 2010; Leucci et al.,*

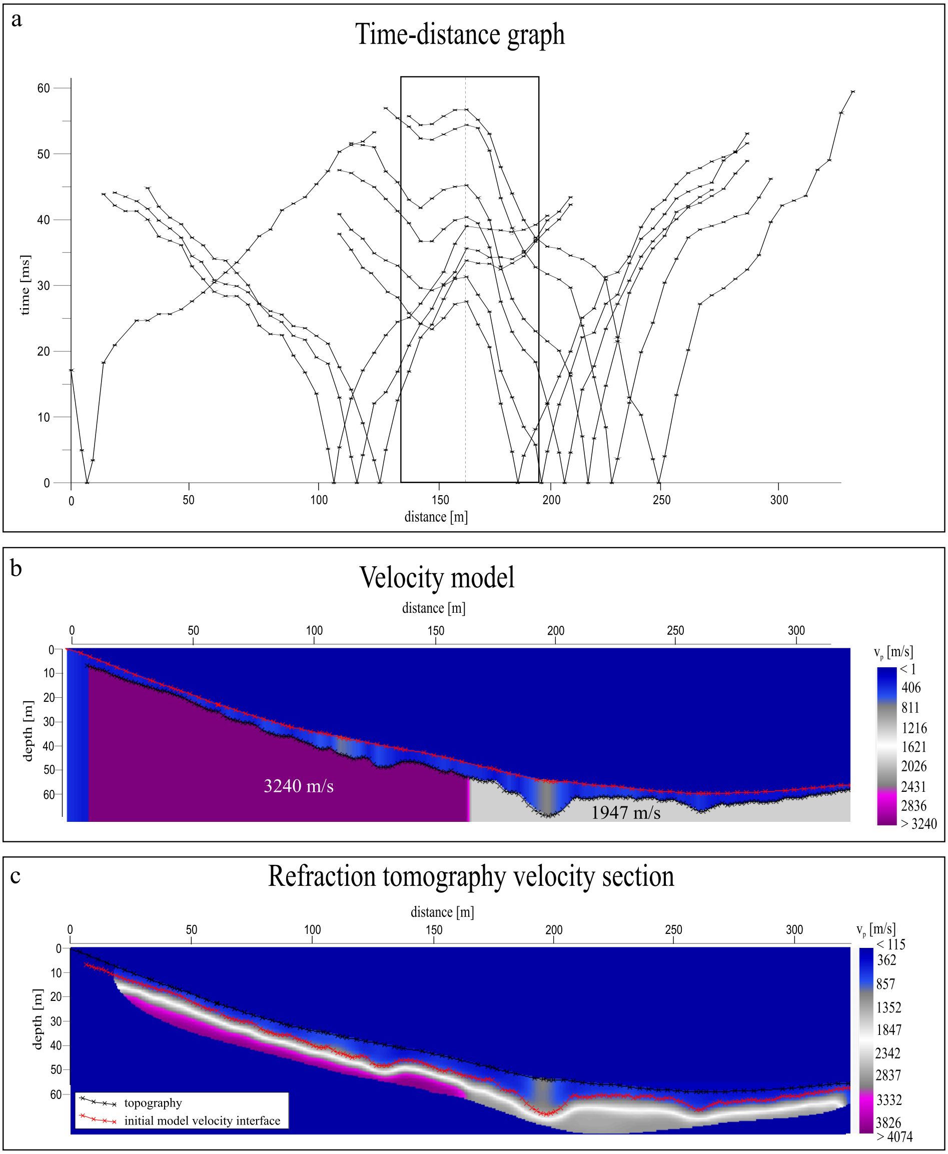

Fig. 8: Results along the seismic profile through the Hradište fault. a) selection of time-distance graphs of some shots along the profile (the dashed line and framed zone highlights fault impact on first arrivals), b) velocity model and c) SRT profile.

2007; Gabr et al., 2012; Shahrukh et al., 2012; Basheer et al., 2012; Hellman et al., 2017). These two methods can be measured together at the same time, but parallel profiles at a sufficient distance from each other should be used to avoid the degradation of signal-to-noise ratio at the geophones due to ERT measurement.

In the case of mapping the Hradište fault, well preserved outcrops, boreholes and geophysical data were available (*Kováč et al., 2011; Kušnirák et al., 2018*). The course of this fault was mapped by several geophysical methods. The data and results presented in this article were re-measured as another device with different equipment and acquisition geometry. It featured the use of 4.5 Hz vertical geophones which are often used for MASW. Geophones of 10–12 Hz are generally used for such a survey. However, the use of low frequency geophones and the larger step of geophones and shots (compared to older measurements during the multimethod geophysical study), did not have a major effect on the results of measurements in this case. Seismic refraction tomography and the effects on time-distance graphs map the fault successfully.

There is not always complete agreement between results obtained by different geophysical methods. In shallow measurements, interpretation may be influenced by various surface factors such as elevated humidity in the surface areas in a rainy season or by the disturbance and weathering of the rock bottom. The shallow zones are also often influenced by human activity. All of these affect the detected velocity values. In the case of the Katarínka measurements, there is no complete match over the interpreted pond bottom in the ERT profile and the seismic profile along the area which is about 50–70 meters of measured profile. The low resistance values recorded in this area in the surface layer on the ERT profile are apparently associated with increased humidity. The measurement was made after the rainy season, and water appears to flow in these places. It also influenced the detected V_p. There are higher values in this zone, which influences the continuance of the interpreted interface (it is interpreted at a slightly smaller depth than ERT).

In the case of the thermal power station, the ERT measurements were made first for the detection of the bottom of the ash storage area in the past, but it did not yield the desired results. The entire environment was too conductive and no interface was recorded. As shown by the results of seismic measurements in this paper, seismic refraction tomography was an excellent alternative to achieving the desired findings.

5. Conclusion

These case studies demonstrate clearly that even shallow seismic refraction methods are valuable tools for research in several areas. Shallow seismic refraction tomography is an ideal method for areas characterized by strong lateral velocity gradients, and thus an effective tool for vertical fault exploration and mapping. It also can play an important role in ground water level estimation, environmental studies of waste storage and archaeological studies. By performing shallow refraction methods (especially SRT), a detailed view of velocity distribution and thus the geological structure of a subsurface can be obtained. It is a cost effective, non-destructive method which also reduces the cost of surveys that use it. However, as in the case of other geophysical methods, it requires input geological and geomorphological information. It is also suitable to verify the seismic interpretation by other geophysical methods. The SRT and ERT represent an appropriate combination which brings satisfactory results and can be measured together by a parallel profile sufficiently distant from each other.

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