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APPLICATION OF PASSIVE SEISMIC TO SHALLOW GEOLOGICAL STRUCTURES IN URBAN AREAS

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Abstract

To study the shallow geological structure the Refraction Microtremor (ReMi) method was applied. This technique uses seismic noise analysis where a source of this small vibrations is the human activity e.g.: traffic, production, factories. The surveys were carried out in selected urban areas in the region of the Upper Silesian Industrial District: Sosnowiec–Pogoń , Chorzów–Chorzów Stary and Bytom–Karb. Each area is characterized by the presence of nearby roads with a very high traffic. The results of passive seismic (ReMi) were confronted with data obtained using Multichannel Analysis of Surface Waves (MASW) and resistivity imaging (RI). Seismic surveys were performed by apparatus PASI with 24 channels using geophones of 4.5Hz. The results showed that passive seismic can be satisfactorily used in such urban conditions. The shallow geological structure interpreted by seismic methods have been well-correlated with resistivity studies.

Key words: passive seismic, Refraction Microtremor (ReMi), seismic noise, Multichannel Analysis of Surface Waves (MASW), Resistivity Imaging (RI), urban area.

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INTRODUCTION

Seismic noise is a ubiquitous ground vibration which propagates in the subsurface layers as a combination of Rayleigh and Love's waves. Seismic noise is caused by natural and anthropogenic sources. Vibration of natural origin (microseisms) differ from those artificially produced (microtremors). Microseisms are generated by sea and ocean waves, whereas microtremors are caused by all human activity such as traffic, industry, plant working etc. Differences exist between microseisms and cultural noise are observed in different values of the frequency band, the type of wave and generated wave modes what can be noticed in Table 1 (Nakamura 1989, Mendecki 2012).

In urban areas the seismic noise level is usually very high, which makes standard seismic survey difficult. Especially concerning the shallow method of seismic refraction and reflection. A source of this small vibrations is the human activity e.g.: traffic, production, factories. Seismic noise vibrations propagate through the subsurface layer, mainly in the form of Rayleigh waves, and finally are recorded and processed by seismic standard equipment. Passive seismic became popular tool to recognize shallow geological structure after work of Louie (2001) who gave fundamental aspects allowing to calculate the parameters of subsurface layers. Louie (2001) in his work based on earlier studies of Liu *et al.* (2000), Satoh et al (1997) and for instance Xia *et al.* (1999). In 21st century many papers was established using the Rayleigh wave dispersion curve inversion obtained from nonsource seismic. The survey result is vertical profile of wave velocities and elastic parameters changing with depth, what was presented by Pullammanappallil *et al.* (2003), Dal Moro *et al.* (2007) Rosenblad and Li (2009) Boiero and Socco (2011) Hamimu *et al.* (2011), Strobbia *et al.* (2011), Mendecki *et al.* (2012) and many other. The information obtained from seismic measurements is very often useful for geo-engineering studies, especially in urban areas where large-scale infrastructures are formed e.g. Lambert *et al.* (2007) used the Refraction Microtremor (ReMi) data to determine shear wave velocity at an urban bridge rehabilitation sit. Many publications considered the application of passive seismic methods to study subsurface structures of subsurface soils and Quaternary sediments, e.g. Gamal and Pullammanappallil (2011) checked the validity of the Refraction Microtremors Method for different soil types in Egypt, Stephenson *et al.* (2005) applied passive and active seismic methods in Santa Clara Valley to compare the results with boreholes data to 200 m. Another example, showed the ReMi method application, was presented by Eker *et al.* (2012) who had studied the local site characterization and seismic zonation by utilizing

Table 1

Characteristics of seismic noise (Mendecki 2012)

Source type	Natural	Anthropogenic/cultural noise
Name (Nakamura 1989)	Microseisms	Microtremors
Frequency band	0.1–0.5 to 1 Hz	0.5 to 10 Hz
Origin	Ocean/wind	Traffic, industry, human activity
Type of generated wave	Surface wave	Surface + body waves
Emission of Rayleigh/ Love waves	Rayleigh	Love and Rayleigh waves
Modes	Mainly fundamental	Fundamental and higher

active and passive surface wave methods in the northern side of Ankara, Turkey. Similar studies can be found in study of Mendecki *et al.* (2012) where ReMi method was used as a tool to recognize the Quaternay sediments and the bedrock depth in Chorzów Stary, Poland.

SITE CHARACTERISTIC

Three sites were chosen to test the applications possibilities of the Refraction Microtremor (ReMi). All three sites are located near to heavy traffic roads in Upper Silesia Industrial District. Survey profiles were situated in cities: Sosnowiec, Bytom and Chorzów.

In city of Sosnowiec, Pogoń district, the measurement profile was near to three roads: express route S86, main route 94 and street Będzinska which is one of the main streets in Sosnowiec. The survey profile is located near to Czarna Przemsza river so in geological profile of study area occurs the river sediments: mainly sands and fluvial deposit. This about twenty-meter thick layers of quaternary complex covered Triassic limestone bedrock (Wagner *et al.*, 2009).

Second site is located in district of Karb, which belongs to city od Bytom. The survey profile is located near the cross-road of main route 88 and main route 94. Shallow geological situation is characteristic for Upper Silesian Coal Basin because over the Carboniferous bedrock occurs the thick layer of Triassic (the Buntsandstein and the Muschelkalk) and next is the layer of Quaternary which consist of sands, loamy sands and sandy loam (Razowska-Jaworek and Brodziński, 2009).

The last site was established in Chorzów, districkt Chorzów Stary. The measurement profile is adjacent to Siemianowicka Street. This site is characterized by the lowest traffic than presented profiles previously but still noisy. The study geological profile consists of Quaternary sands and loam sand, and dusty clays which are product of Carboniferous layer erosion. This complex covered Carboniferous mudstones and sandstones (Wyczółkowski, 1957, Cudak and Wantuch, 2009).

METHODOLOGY

In general the surface waves can be generated by two ways: “passive way” and “active way”. The active way means that seismic energy is intentionally generated at a specific location relative to the geophone spread and recording begins when the source energy is imparted into the ground. This is in contrast to the passive way surveying, also called “microtremor surveying”, or as “refraction microtremor” surveying, where there is no time breaks and motion from ambient energy generated by cultural noise, wind, wave motion, etc. at various and usually unknown locations (Louie 2001, Pullammanappallil *et al.* 2003, Dal Moro *et al.* 2007, Rosenblad and Li 2009, Boiero and Socco 2011, Hamimu *et al.* 2011, Strobbia *et al.* 2011). In this paper beside Refraction Microtremor technique the active method of Multichannel Analysis of Surface Waves had been applied (Park *et al.* 1999, Xia *et al.* 1999).

During study a linear arrays with 24 geophone channels connected to a recorder made by PASI company was applied. Twenty four of 4.5 Hz geophones were used to record surface waves and seismic noise. The spacing between geophones was 5 m, while the total profile length was 115 m offset (for active seismic) was in -5m of the profile. On each survey line ReMi and MASW methods were applied.

The both technique are based on two fundamental ideas: (1) common seismic-refraction recording equipment, set out in a way almost identical to shallow P-wave refraction surveys, can effectively record surface waves at frequencies as low as 4.5 Hz; and (2) a simple, two dimensional slowness-frequency (p-f) transform of a record can separate Rayleigh waves from other seismic arrivals and allow recognition of true phase velocity against apparent velocities (Louie 2001). Collected data were analysied by an application of software provided for the surface waves inversion procedure. The WinMASW program (Dal Moro *et al.* 2007), prepared by Eliosoft firm, has been applied to process survey result. In general, software employs the same matematical technique to analyse active and passive records. Firstly, recorded data in time domain have been submitted for p-τ transformation. This transformation takes a record section of multiple seismograms, with seismogram amplitudes relative to distance and time (x-t), and converts it to amplitudes relative to the ray parameter p (the inverse of apparent velocity) and an intercept time τ (Louie 2001). The next step takes each p-τ trace and computes its complex Fourier transform intercept time direction (Louie 2001). This completes the transform of a record from distance-time (x-t) into p-frequency (p-f) space. The ray parameter p for these records is the horizontal component of slowness (inverse velocity) along the seismic spread (line). If one identifies trends within these axes where a coherent phase has significant power, then the slowness-frequency picks can be plotted for dispersion analysis (Louie 2001). Dispersive phases show the distinct curve of normal modes in low velocity surface layers: sloping down from high phase velocities (low slowness) at low frequencies to lower phase velocities (high slowness) at higher frequencies (Louie 2001). Dispersion, or change in phase velocity with frequency, is the fundamental property utilized in surface wave methods. One-dimension vertical changes of shear wave velocity (V_S) can be calculated by mathematical inversion of the dispersive phase velocity of surface waves. Surface wave dispersion can be significant in the presence of velocity layering, which is common in the near-surface environment. There are other types of surface waves, or waves that travel along a surface, but in this application we are con-

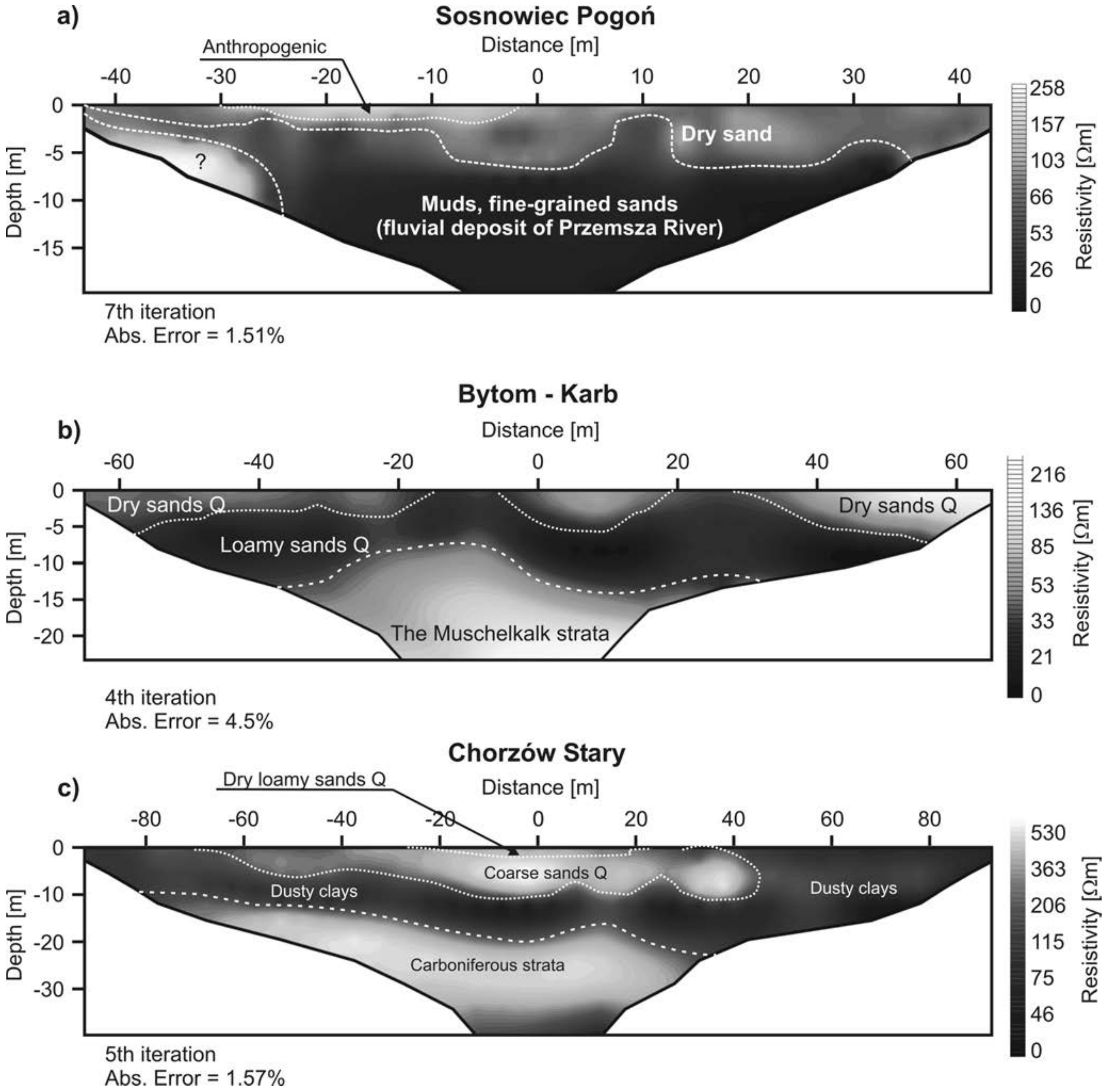

Fig. 1. Resistivity cross-sections with lithological interpretation: a) Sosnowiec, b) Bytom and c) Chorzów.

cerned with the Rayleigh wave, which is also called "ground roll" since the Rayleigh wave is the dominant component of ground roll (Xia *et al.* 1999, Louie 2001, Dal Moro *et al.* 2007).

Genetic Algorithms (GAs) have been proposed to find the best inverse solution and thus the appropriate VS model. Giancarlo dal Moro, author of WinMASW software, used GAs to solve the inversion of Rayleigh dispersion curve (Dal Moro *et al.* 2007). The fundamental aspect characterizing the Genetic Algorithms is evolutional scheme that the fittest models survive and reproduce, the others disappear. The main advantage of this class of optimizations is that they tend to avoid the attraction of local minima and their random-but-driven search schemes try to reach an optimal solution by considering all of the regions of a user-defined search space. The inversion process can stop after a fixed number of generations or when the fitness of an individual reaches a certain previously-fixed value (Ramillien 2001, Dal Moro 2007).

Before the inversion routine the modelling of dispersion curves was performed. Calculated models based on lithological information obtained from resistivity cross-sections. Models allowed to formed ranges of a search space where next GA looked for the fittest model of ground. Main inversion parameters – number of generations and number of individuals in one generation – were set as 30 generation and 30 individuals.

Beside seismic methods, the Resistivity Imaging (known also as electrical resistivity tomography, ERT) was carried out over the survey profile. Electrical resistivity surveys have been used for many decades in hydrogeological (Binley and

Table 2

The seismic result of ReMi and MASW for Sosnowiec–Pogoń profile

	ReMi			MASW		
Parameter	Layers			Layers		
rock type	dry sand	fluvial deposit	Triassic limestone	dry sand	fluvial deposit	Triassic limestone
*Vs [m/s]	167	272	2648	178	263	2679
Vs *STD [m/s]	4	4	421	1	2	485
thickness [m]	8.2	22.2	Inf.	8.7	26.0	inf.
thickness *STD [m]	0.5	0.8	-	0.2	5.3	-
*Vp [m/s]	348	566	5512	371	547	5577
density [g/cm^3]	1.80	1.92	2.47	1.81	1.91	2.47
Vp/Vs ratio	2.08	2.08	2.08	2.08	2.08	2.08
Poisson ratio	0.35	0.35	0.35	0.35	0.35	0.35
shear modulus [MPa]	50	142	17322	57	132	17750

*Vs – shear velocity, STD – standard deviations, Vp – primary wave velocity

Table 3

The seismic result of ReMi and MASW for Bytom–Karb profile

	ReMi			MASW		
Parameter	Layers			Layers		
rock type	dry sand	loamy sands	the Muschelkalk	dry sand	loamy sands	the Muschelkalk
*Vs [m/s]	209	326	2830	190	334	3007
Vs *STD [m/s]	2	8	352	6	16	558
thickness [m]	6.4	11.3	Inf.	6.8	10.2	inf.
thickness *STD [m]	0.3	0.9	-	0.6	0.8	-
*Vp [m/s]	435	679	5891	396	695	6260
density [g/cm3]	1.85	1.96	2.49	1.83	1.97	2.50
Vp/Vs ratio	2.08	2.08	2.08	2.08	2.08	2.08
Poisson ratio	0.35	0.35	0.35	0.35	0.35	0.35
shear modulus [MPa]	81	208	19915	66	219	22619

*Vs – shear velocity, STD – standard deviations, Vp – primary wave velocity

Kenmna 2005, Kowalska *et al.* 2012), mining (Żogała *et al.* 2013) and geotechnical investigations (Rudzki 2002). More recently, it has been used for environmental surveys (Mendecki *et al.* 2012, Kowalczyk *et al.* 2014).

The goal of electrical measurements is to determine the subsurface resistivity distribution. From surface surveys the apparent resistivity is obtained and the real resistivity of the subsurface can be estimated by application of inversion techniques. The fundamental physical law used in resistivity surveys is Ohm's Law that governs the flow of current in the ground. This well-known method was applied for lithological changes recognition. Basics of the resistivity method and data inversion can be found in many studies and paper, especially in Telford *et al.* (1990), Loke *et al.* (2003), Loke (2004) and Binley and Kenmna (2005). Informations about electrical properties of rock are described e.g. in book of Schön (1996).

RESULTS

All seismic measurements were carried out with 115-meter-long profile on surface and provided the 1-D vertical S-waves profile on the center. The seismic result were referred to the central part of resistivity cross-section (Fig. 1) because the middles of both surveys line were situated in the same place. Because different electrode spacing were applied, a different maximum depth of investigation were obtained. It resulted from accessibility of surface space in field.

Sosnowiec–Pogoń

The resistivity measurement were performed on 100-meter-long profile what allowed to obtain about 20 m maximum depth of investigation. The resistivity imaging result (Fig. 1a) mainly consists of relative higher resistivity anomaly (50–100 m) near surface on the entire length of the profile which is related to Quaternary dry sands. In those shallow structures can be distinguish additional higher anomaly with 100–200 m resistivity values. This layer is an anthropogenic remains after terrain leveling near to Faculty of Earth Sciences of University of Silesia. Beneath this complex large low resistivity anomaly with values of 0–50 m can be observed and it is related to fluvial deposit of Czarna Przemsza River. Seismic results from ReMi and MASW yielded similar values for shallow structures. The S-wave velocities in dry Quaternary sands are about 167–178 m/s and thickness of this layer is about 8–9 m. The layer composed of mud and fine-grained sands deposit is characterized by Vs with values in range of 220–260 m/s while a discrepancy of thickness value a is observed in deeper layers. MASW interpreted it as 26 m but ReMi showed 22.2 m. Below Quaternary complex Triassic limestone can be found with S-waves velocities in range of 2600–2700 m/s. Thickness of limestone is assumed as infinity. Because resistivity profile was not long (maximal depth of investigation 19.7 m) the Triassic limestone are not present in central part of the cross-section. Probably, high resistivity anomaly in left part of the section is related to this rigid strata. In table 2 other elastic parameters are shown such as approximately values of density, Poisson ratio and shear modulus.

Bytom–Karb

In this case in central part of the 140-meter-long resistivity cross-section (Fig. 1b) three layer are interpreted. Shallow Quaternary dry sands with resistivity values 40–60 m which covered loamy sands characterized by low resistivity anomaly (0–40 m). This overburden is lying on the Triassic strata related to relative high resistivity values in range of 60 m up to 200 m. Both seismic result yield good correlation of layer thickness obtained from Resistivity Imaging. The shallowest layer is about 6.4–6.8 thick and has S-wave velocities in range of 190–210 m/s. The loamy sands are 10.2–11.3 thick and velocity range is about 320–340 m/s. The Triassic strata S-wave velocity ranges from 2800 to 3000 m/s and their thickness is assumed as infinity. Table 3 contains also information about elastic parameters as previous.

Chorzów–Chorzów Stary

The 200-meter-long resistivity profile (Fig. 1c) showed a Quaternary sand insert (200–500 m) in weathered Carboniferous dusty clays (0–100 m) which covers the Carboniferous rigid strata (200 m). Seismic method interpreted in the Quaternary insert two layers. The first low velocity layer about 90 m/s and 1.3–1.8 m thick. The second, consisting of coarse sands, is characterized by S-waves velocity in range of about 320–360 m/s and 8.1–8.7 m thick. Below are weathered rocks with relative lower value of velocity (287–342 m/s). This layer has a thickness discrepancy. ReMi showed that thickness is equal to 7.4 m but MASW – 9.3 m. The deepest layers are Carboniferous formations where S-waves velocities are changed in range of 2200–2800 m/s and this complex is treated as hemisphere. Table 4 contains all results obtained from both seismic technique.

DISCUSSION

All collected seismic data showed a satisfactory results (Fig. 2), especially for shallow structure, where waves propagate with relative higher frequency for both technique. However, different depth of consolidated rock can be observed in Sosnowiec and Chorzów profile (Fig. 2). It can be explained that the maximum propagated wavelength and hence, the investigation depth, is affected directly by the minimum frequency that can be generated and recorded.

The spatial sampling (receiver spacing) affects not only the minimum wavelength but also the lateral resolution of the spread. Lateral velocity variations and near-surface anoma-

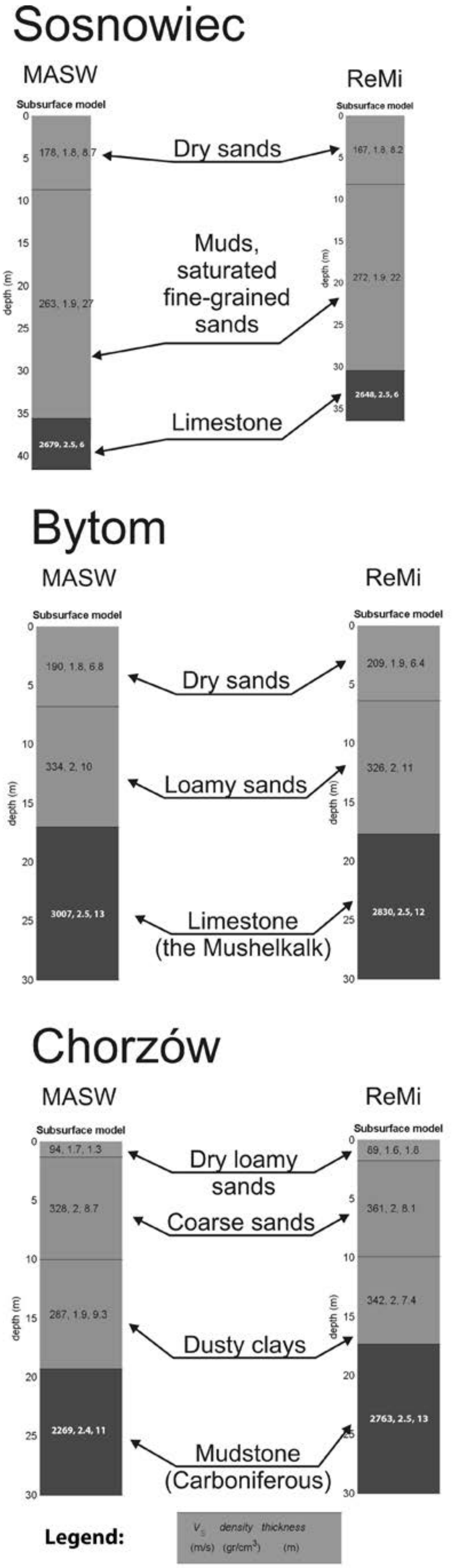

Fig. 2. Comparison of MASW and ReMi results obtained for selected sites. Results represent subsoil models with shear wave velocities (Vs), densities and thicknesses of interpreted layers.

Table 4

The seismic result of ReMi and MASW for Chorzów–Chorzów Stary profile

	ReMi				MASW			
	Layers				Layers			
rock type	dry loam sands	coarse sands	dusty clays	Carboniferous strata	dry loam sands	coarse sands	dusty clays	Carboniferous strata
*Vs [m/s]	89	361	342	2763	94	328	287	2269
Vs *STD [m/s]	2	6	12	285	< 1	4	4	264
thickness [m]	1.8	8.1	7.4	inf.	1.3	8.7	9.3	inf.
thickness *STD [m]	< 0.01	0.6	0.2	-	< 0.01	0.7	0.4	-
*Vp [m/s]	185	751	712	5169	196	683	597	4245
density [g/cm^3]	1.65	1.98	1.97	2.45	1.66	1.96	1.93	2.41
Vp/Vs ratio	2.08	2.08	2.08	1.87	2.09	2.08	2.08	1.87
Poisson ratio	0.35	0.35	0.35	0.30	0.35	0.35	0.35	0.30
shear modulus [MPa]	13	259	231	18739	15	211	159	12389

*Vs – shear velocity, STD – standard deviations, Vp – primary wave velocity

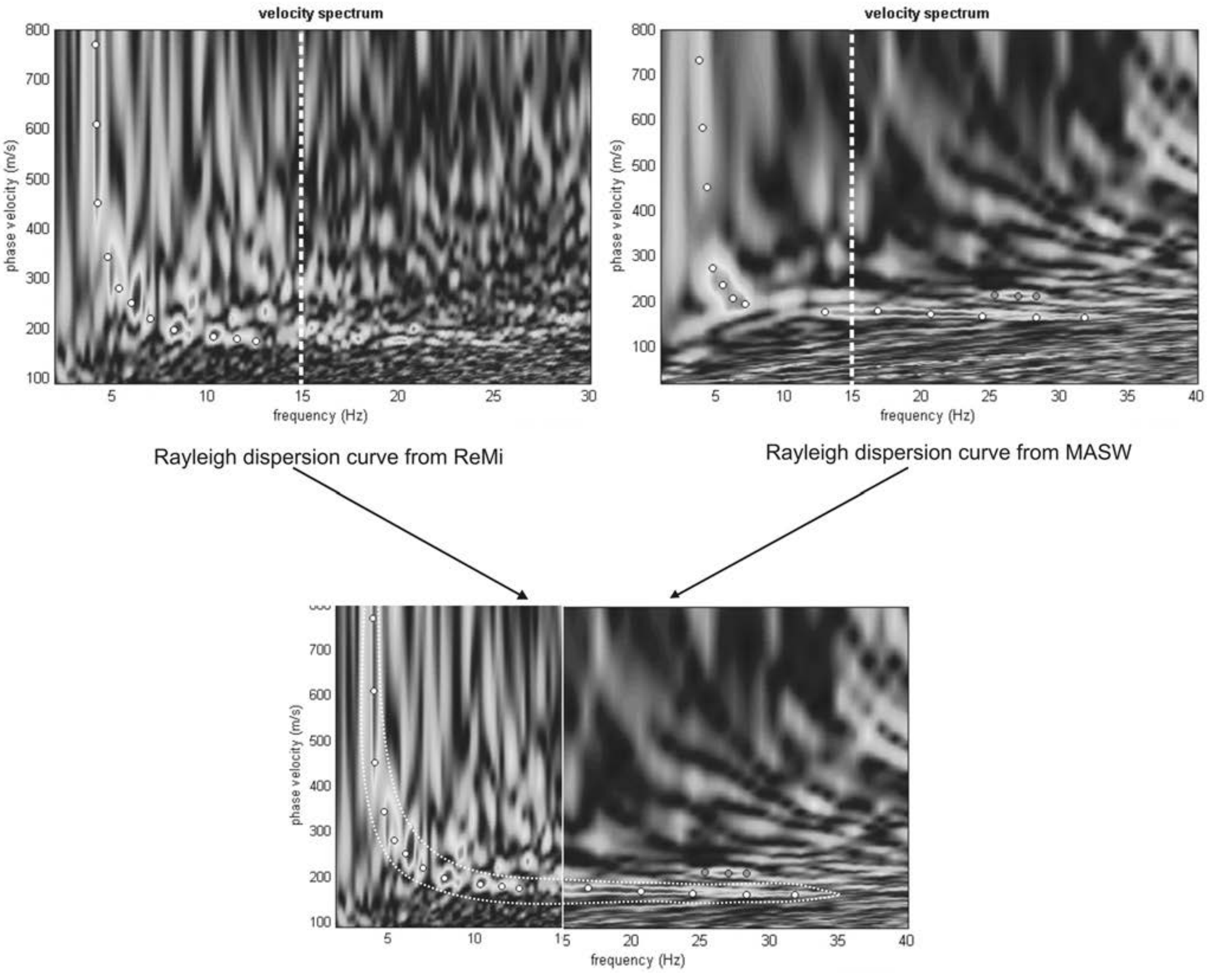

Fig. 3. Mapped entire shape of dispersion curves using data from low-frequency part of modes from ReMi are compared to relative higher-frequency part of Rayleigh modes from MASW.

lies are the main target of the near-surface characterization and they have to be properly spatially sampled (Strobbia *et al.* 2011). In this context, by their nature and proximity to the geophone spread, it can be said that higher frequency active source surface waves resolve the shallower velocity structure and lower frequency passive source surface waves resolve

Table 5

Petrophysics characteristics of interpreted rocks – shear wave velocity (Vs), density, shear modulus and resistivity

Rock type	Vs [m/s]	density [g/cm^3]	shear modulus [MPa]	resistivity [Ω m]
coarse sands	320–360	1.96–1.98	211–259	300–500
dry sand (Sosnowiec)	160–180	1.8	50–60	50–100
dry sand (Bytom)	190–210	1.8	66–81	40–60
dry loam sands	80–100	1.6	13–15	200–300
loamy sands	320–360	2	208–219	0–40
muds (fluvial deposit)	260–270	1.9	132–142	0–50
dusty clays	280–340	1.93–1.96	159–231	0–100
Triassic limestone	2600–2700	2.47	17300–17800	100–200
the Muschelkalk (limestone)	2800–3000	2.5	19900–22600	60–200
Carboniferous strata	2200–2800	2.4	12000–18700	>300

the deeper velocity structure of the rock mass. When the total depth of interest is great enough to require use of passive source surveys, it is still very important to sufficiently sample the shallower depths (SeisImager/ SWTM Manual, 2009). In another words, ReMi technique yields more reliable results from deeper parts of the ground. Furthermore, it could be suggested that both technique should be applied together and shallow structure could be recovered by MASW and deeper layer, especially location of bedrock, could be found by ReMi. Application of both method allowed to reproduce entire shape of dispersion curves when low-frequency part of modes from ReMi are compared to relative higher-frequency part of Rayleigh modes from MASW (Fig. 3).

The considered methods of seismic and resistivity imaging indicated an effective recognition of subsurface Quaternary sediments. The resistivity imaging method allowed to create resistivity cross-sections which showed the changes in spatial distribution of different lithology, while the seismic methods detailed the petrophysical parameter information of observed layers. Such data set, obtained from different methods, allows to carry out a comprehensive study of subsurface structures both for cognitive aims as well as for geotechnical tasks. Due to the presented information and the lack of conclusive results for bedrock it was assumed that the ReMi method results are more reliable. In other words, the data set from shallow layers, obtained by MASW and a data set from deep layers, obtained by ReMi, should be used to further study.

Synthetic studies of Quaternary sediments at selected locations are presented in Table 5 selected only the most important petrophysical parameters studied rocks: S-wave velocity, density, shear modulus and resistivity. Results showed some similarities in values for different site. Slight variations could be caused by differ mineral contents in porous media or small differences in matrix compositions. Quaternary dry sands in each site could be a coarse sands, an increase of petrophysics parameter may be caused by increase of water content and possible clay content in porous space. Coarse sand is very loose material which should be characterized by the lowest values of elastic parameters. The presence of additional content changes those values what is observed in table 5. More complicated geology in Chorzów site showed that dusty clays could have lower elastic parameters than coarse sands. However, one could expect the opposite results. The ReMi results showed that both sediments do not differ significantly from each other. The MASW method yielded lower values and it could be result of inappropriate wave propagation from source to receivers. In table 5 parameters are mainly presented are ranges of values where the edges are the ReMi and MASW values. Results for other rocks indicated a good correlation and could be used as a reference to later studies of subsurface layers and consolidated substrate.

CONCLUSIONS

1. The passive seismic survey in urban area allowed to distinguish Rayleigh dispersion curves on phase velocity spectrum. Anthropogenic noise generated by streets and routes was strong enough and was characterized by relative high frequency, so can be registered by 4.5 Hz geophones.
2. Passive survey can be applied in areas where interference of artificial source is forbidden such as DC emission or sledgehammer impact.
3. Resistivity cross-sections are characterized by very small absolute error from 1.5% up to 4.5% what can suggest that results are reliable. It is also can be confirmed by good agreement between thicknesses of layers resistivity data and thicknesses obtained from seismic methods.
4. Application of both method: MASW and ReMi can correct to inversion solution and makes subsurface model more appropriate because both technique better mapped different part of Rayleigh dispersion curve (Fig. 3).

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