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AN INVERSION OF RAYLEIGH WAVES DISPERSION CURVES AS A TOOL TO RECOGNIZE THE BEDROCK DEPTH IN CHORZÓW STARY, POLAND

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Abstract. Identification of a bedrock beneath soft cover is one of the most important task in engineering geology. The location of boundary-overburden information may be used by investors, builders and municipal authorities to design an infrastructure or land-use plans. In such issues the application of appropriate geophysical methods is useful. However, in urban zones and areas characterized by subsurface soft layer the usage of certain methods (eg.: seismic refraction) is not advisable. The passive method of Refraction Microtremor (ReMi) can fulfill its tasks in the relatively difficult urban environment. The vertical S-wave velocity profiles were carried out as a result of inversion of Rayleigh wave dispersion curves obtained from ReMi method. The change of S-wave velocities allowed to distinguish shallow geological layers in the area of Chorzów Stary. Preliminary measurements allowed to identify the Carboniferous bedrock at a depth of 14-18 m what has been confirmed by resistivity imaging. Furthermore, unconsolidated deposits are also recognized and the seismic results show a good correlation with the available geological information and resistivity imaging data.

Keywords: Ambient seismic noise, ReMi, resistivity imaging, bedrock-overburden boundary, Chorzów Stary

Introduction

Bedrock topography under soft cover is a key parameter for many geotechniacal studies. Geophysical techniques have become useful tools to delineate geological structures in areas with scarce or no well information. However, conventional geophysical data acquisition and processing can be unreasonably expensive in order to cover a large study area; even more so in urban areas. To overcome this limitation, other methods have been studied as an alternative to traditional techniques (Benjumea *et al.* 2011).

Therefore, the main purpose of this paper was to apply Surface Wave (SW) method such as Refraction Microtremor (ReMi) technique proposed by Louie (2001) to identify the Carboniferous bedrock depth in urban areas (Chorzów Stary).

Surface Wave analysis is an efficient tool to retrieve S-wave velocity models at different scales. In geotechnical engineering SWs are used to characterize a few hundred meters in terms of low strain shear modulus or to map bedrock depths for infrastructure design (Boiero & Socco 2011).

In the SW method, which is generally classified into Rayleigh and Love wave, the shear-wave velocity profile is evaluated by an inversion analysis of the measured phase velocity dispersion curve. Surface waves propagate only with discrete wavenumbers (‘modes’) and they are invariably dominated by the fundamental mode and also are dispersive in a layered medium. However, the observed dispersion is usually called an ‘effective’ dispersion, since it rarely comprises pure, plane surface waves (Rayleigh and Love) but a mix of modes and polarizations, in addition to guided and body waves (Hamimu *et al.* 2011).

The low-velocity event that has been traditionally vaguely referred to as ground roll, when sampled properly, reveals its nature. It consists of several modes of Rayleigh waves and of P-guided waves. In many cases, some of these modes may be present simultaneously and superimposed on each other. Different modes may dominate the propagation depending on local conditions, even within a single survey. If surface waves are properly sampled, their analysis and inversion can be used for the characterization of the near-surface geology. The common physical principle of different surface-wave characterization methods is related to the fact that their penetration depth depends on their wavelengths, which, in turn, is responsible for the dispersion (different frequencies have different phase velocity but also different intrinsic attenuation). The dispersion, the attenuation and the amplitude frequency spectra are strictly related to the site properties and hence, can be inverted to a S-wave profile. The sampling needed to enable the use of surface waves for near-surface characterization essentially means observing them over a wide wavelength range (Strobbia *et al*. 2011).

Location and geology of study area

During 2011 year ReMi experimental survey took place in Chorzów Stary with measurements at two profiles (CD and EF – red lines) with a length of 115 m, as shown in Fig.1. The district Chorzów Stary is part of Chorzów city located in Upper Silesia, Poland. Geology beneath survey lines consists of Carboniferous sandstones and mudstones with coal insert (Ruda stratum) as a basement. The bedrock is covered by fluvial sediments consists of Quaternary clays and tills separated by sands and loamy sands (Holocen). The underground water table is located between 2.2 m and 3.0 m (or deeper) below surface.

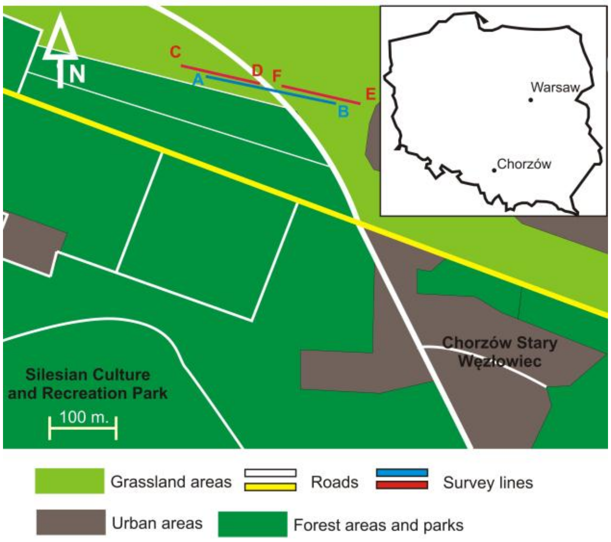

Fig.1. Location of study area, Chorzów Stary, Poland

Beside the seismic studies, the resistivity imaging have been carried out independently at the research area along AB profile (200 m, electrode spacing 5 m) – blue line (Fig.1). 2-D resistivity imaging result has been used to confirm the S-velocity models.

During the electrical study (March 2012) water was observed on the surface probably retained by shallow clays deposit. It was caused by heavy rain period before the survey which raised water level significantly.

Surface-waves acquisition

The surface waves can be generated by two ways. “Active source” 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 “passive source” surveying, also called “microtremor surveying”, or sometimes referred to as “refraction microtremor” (or the commercial term “ReMi”) surveying, where there is no time breask and motion from ambient energy generated by cultural noise, wind, wave motion, etc. at various and usually unknown locations (SeisImager/SW^{TM} Manual 2009).

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 anomalies 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 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/ SW^{TM} Manual 2009).

In this case, a linear array with 24 geophone channels connected to a recorder made by PASI company was applied. Twenty four of 10 Hz geophones were used to record surface waves. The spacing between geophones was 5 m, while the total profile length was 115 m. On each survey line ReMi method have been applied.

The refraction microtremor technique (ReMi) is 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 2 Hz; and (2) a simple, two dimensional slowness-frequency (*p-f*) transform of a microtremor record can separate Rayleigh waves from other seismic arrivals and allow recognition of true phase velocity against apparent velocities (Louie 2001).

The ReMi method acquisition time was 60 s for each measurement with 125 Hz sampling. The measurements have been repeated five times on each profile. During the survey ambient micro-vibrations have been carried out which probably have been coming from road traffic located around 200 m from the profiles. Because of traffic the records mainly consisted of greater noise amplitudes observed on relative higher frequencies, but still belonged to low frequency band. By adopting the classification of Nakamura (1989) this type of seismic noise is named microtremors.

Surface-wave data procesing

Colleceted data were analysied by an application of software provided for the surface waves inversion procedure. The WinMASW program, prepared by Eliosoft firm, has been applied to process survey result. In general, software employs the same matematical technique to analyse active and pasive 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. It is familiar to array analysis as beam forming and has similar objectives to a two-dimensional Fourier-spectrum or f-k analysis (Louie 2001).

The p-τ transform is a simple line integral across a seismic record $A(x,t)$ in distance x and time t (Louie 2001) :

$$A(p,\tau) = \int_x A(x, t = \tau + px)dx\,, \qquad (1)$$

where the slope of the line $p = dt/dx$ is the inverse of the apparent velocity V_a in the x direction.

The p-τ transformed records contain, in the work here, 24 slowness traces, one or more per offset trace in the original x-t records. Each of these traces contains the linear sum across a record at all intercept times, at a single slowness or velocity value. The next step takes each p-τ trace in $A(p,\tau)$ and computes its complex Fourier transform $F_A(p,f)$ in the τ or intercept time direction (Louie 2001):

$$F_1(p,f) = \int_\tau A(p,\tau)e^{-2\pi f\tau}dx\,. \qquad (2)$$

The power spectrum $S_A(p,f)$ is the magnitude squared of the complex Fourier transform (Louie 2001):

$$S_A(p,f) = F_A^*(p,f)F_A(p,f)\,, \qquad (3)$$

where the * denotes the complex conjugate. This method sums together two p-τ transforms of a record, in both forward and reverse directions along the receiver line. To sum energy from the forward and reverse directions into one slowness axis that represents the absolute value of p, $|p|$. 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). In analyzing more than one record from a refraction microtremor deployment, the individual records' p-f images $S_{An}(|p|, f)$ are added point-by point into an image of summed power. So the slowness-frequency analysis has produced a record of the total spectral power in all records from a site, which plots within slowness-frequency (p-f) axes. 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).

Inversion of Rayleigh wave dispersion curves

Dispersion, or change in phase velocity with frequency, is the fundamental property utilized in surface wave methods. 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 concerned with the Rayleigh wave, which is also called "ground roll" since the Rayleigh wave is the dominant component of ground roll.

Before inversion procedure the forward modeling must be carried out to create an initial V_S model based on observed data. The refraction microtremor method interactively forward-models the normal-mode dispersion data picked from the p-f images with a code adapted from Lai & Rix (1998) within their inversion procedure. The interactive modeling can avoid local minima in the objective error function that often result in false velocity inversions with depth, due to the equivalence problem that is inherent in the integrative nature of surface-wave velocities (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 V_S model. Giancarlo dal Moro, author of WinMASW, used GAs to solve the inversion of Rayleigh dispersion curve. 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. Differently from common linear methods, they do not require an initial model to start the optimization and only a search space is designed. An initial population composed by an arbitrarily fixed number of individuals (candidate solutions) is randomly generated and their fitness determined according to the discrepancy with respect to a desired characteristic. This fitness value (determined by means of an objective function) is then considered in the successive selection and crossover operations: the fittest individuals (i.e. the ones with the highest fitness values) are chosen to generate offspring whose characteristics are partly taken from one parent and partly from the other. Next, the best individual(s) of each generation is/are passed unchanged to the next generation in order to avoid possible loss of good individuals. Mutation operators allow good genes (that have never appeared before) to be selected and should also ensure that a potentially good component is not lost during reproduction and crossover operations. The 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).

Inversion of resistivity imaging data

Electrical resistivity surveys have been used for many decades in hydrogeological, mining and geotechnical investigations. More recently, it has been used for environmental surveys.

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. The equation for Ohm's Law in vector form for current flow in a continuous medium is given by (Telford et al 1990; Schön 1996, Loke 2004):

$$\mathbf{I} = \sigma \mathbf{E}, \qquad (4)$$

where σ – the conductivity of the medium, **I** – the current density and **E** – the electric field intensity.

In practice, what is measured is the electric field potential. It should be noted that in geophysical surveys the medium resistivity ρ, which equals to the reciprocal of the conductivity, is more commonly used (Schön 1996).

Resistivity Imaging Method connects features of resistivity prospecting and resistivity sounding (Rudzki, 2002; Loke, 2004). Process of inversion is essential for this method. Determined apparent resistivity values are used during this process to determine resistivity distribution of the rock mass based on theoretical model of the medium.

The aim of inversion is to find such set of model parameters, which minimizes the squared differences **e** between the observed **d** and computed data **f** (forward modeling) for all data points (Loke *et al.* 2003; Loke 2004):

$$\min\{\mathbf{e}^T\mathbf{e}\} = \min\{(\mathbf{d}-\mathbf{f})^T(\mathbf{d}-\mathbf{f})\}. \qquad (6)$$

The inversion routine used by Res2Dinv software is based on the smoothness-constrained least-squares method as follows:

$$\Delta\mathbf{m} = (\mathbf{J}^T\mathbf{J} + \lambda\mathbf{F})^{-1}\mathbf{J}^T\mathbf{e}. \qquad (7)$$

where **F** – matrix of flatness filters, **J –** matrix of partial derivatives (Jacobian), λ – damping factor, Δ**m** – model perturbation vector, **e** – discrepancy vector

One advantage of this method is that the damping factor and flatness filtres can be adjusted to suit different types of data. The process started with initial model parameters $\mathbf{m_0}$ which are modified by Δ**m** vector in following iterations to fit the theoretical data to the empirical one. Iterative process is continued while the required convergence level is achieved (Loke *et al.* 2003; Loke 2004).

Results and comparison with resistivity imaging

Figures presented below (Fig.2 and Fig.3) show results of data processing: the chosen dispersion curve (after *p-τ* transform), calculated statistic best model of dispersion curve and mean model of dispersion curve obtained from all considered models. They also contain of the results of the misfit evolution and the models of S-phase velocity with marked the best and the mean model.

All calculations (inversions) were carried out with the Genetic Algorithm. Inversion parameters were as follows:

1) Choice inversion for fundamental mode only
2) Constrained number of layers: 4 for CD profile and 2 for EF profile
3) Number of considered models: 30
4) Number of generation for genetic optimization procedure: 30

In Table 1 the main inversion results are compared – S-phase velocities and their occurrence depth . Besides the WinMASW software provides calculation of layer densities (Table 1) and another geotechnical parameters as Poisson ratio, shear moduli and V_p (not shown).

Table 1. Final results of ReMi inversion for CD and EF profiles

The CD profile			The EF profile		
Dpt. [m]	V_s [m/s]	Density [g/cm^3]	Dpt. [m]	V_s [m/s]	Density [g/cm^3]
5.4	347 ± 24	1.98	14.0	317 ± 6	1.95
12.1	329 ± 33	1.96			
18.0	446 ± 80	2.04	inf	1002 ± 24	2.21
inf	1257 ± 81	2.26			

On Fig.4 obtained ReMi data (CD and EF profiles) are compared with the inversion results of resistivity imaging. In the resistivity cross-section three anomalous areas can be distinguished: two high resistivity (230-450 Ωm) near surface on the left site and on the bottom and one of low resistivity (0-100 Ωm) spread out along AB profile. Transition zones with medium values of resistivity in the range of 100 Ωm to 200 Ωm are also observed.

The first high resistivity area on the top-left site is probably the Quaternary sand insert surrounded by glacial till and loamy sand (medium resistivity values). These deposits are reminiscent of the presence of a glacier. The Quaternary deposit lies on the Carboniferous complex consisted of dusty clay (weathered mudstones) covers rigid mudstones and sandstones (Wyczółkowski 1957).

Based on the results of seismic and resistivity surveys the four geophysical layers with different physical properties have been distinguished. In table 2 the

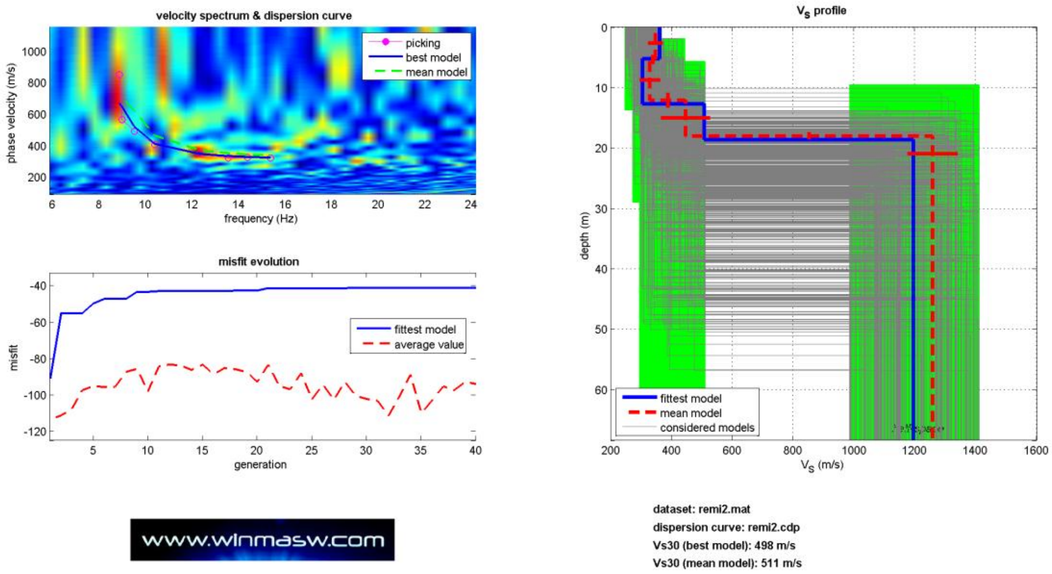

Fig.2. Results for CD profile: **left-top:** Dispersion curves (dotted – chosen, blue – best model, dashed green – mean model), **left-down:** plot of misfit evolution during calculations, **right:** calculated considered models (gray), fittest model (blue) and mean model (dashed red)

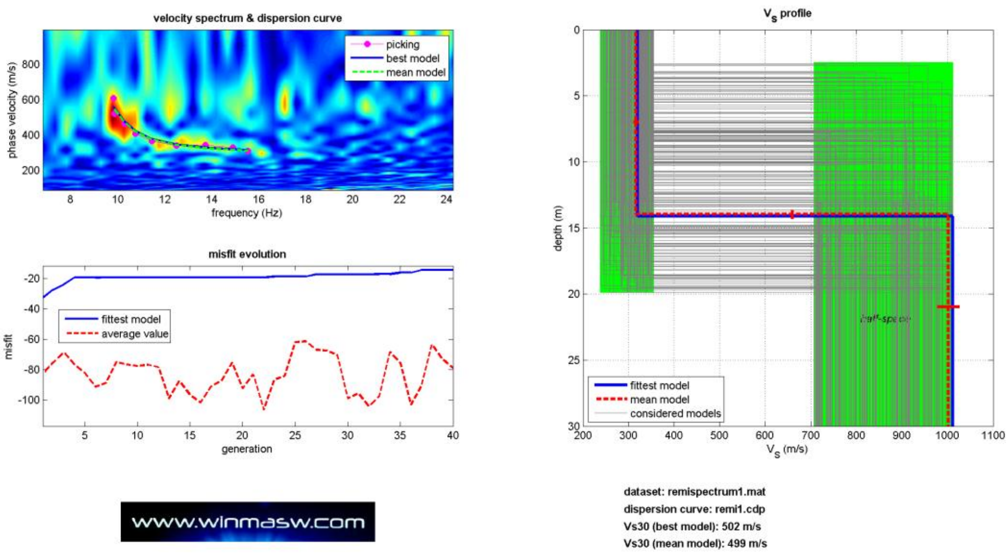

Fig.3. Results for EF profile: **left-top:** Dispersion curves (dotted – chosen, blue – best model, dashed green – mean model), **left-down:** plot of misfit evolution during calculations, **right:** calculated considered models (gray), fittest model (blue) and mean model (dashed red)

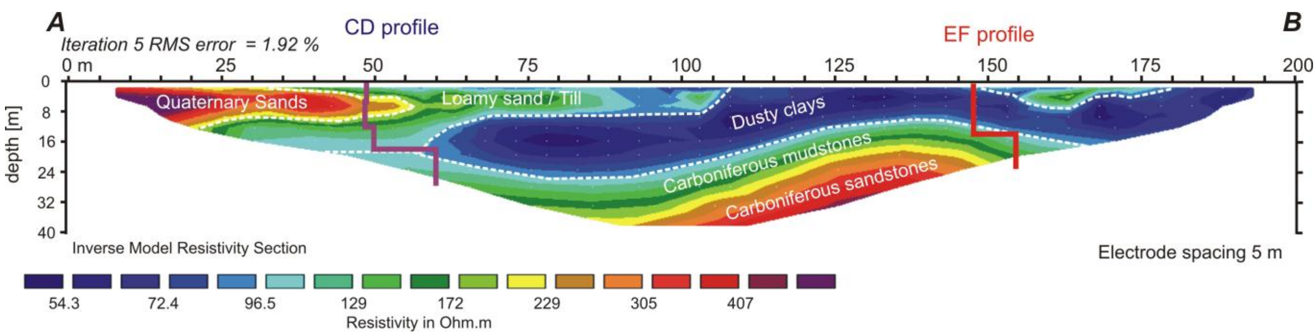

Fig.4. Comparison of 2-D resistivity imaging profile AB with S-phase velocity vertical profiles CD and EF.

comparison of obtained petrophysics parameters are presented. There are average values of S-phase velocity, density and resistivity compared together with types of rocks (Wyczółkowski 1957, Schön 1996).

One my note very good agreement between the depths of observed discontinuities in ReMi inversion and resistivity inversion procedures (Fig.4)

Table 2. Comparison of average values of petrophysics parameters obtained from inversions

Type of rock	V_s [m/s]	Density [g/cm^3]	Resistivity [Ωm]
Dusty clay	320	1.95	0 - 100
Sands	330	1.96	230 - 450
Loamy sand / till	350 - 450	1.98 - 2.04	100 – 200
Carboniferous complex	1000 – 1300	2.26	230 - 400

Conclusion

The obtained results show very good agreement between the seismic and the resistivity data what suggests that ReMi technique is quite good tool to identify subsurface structures in urban areas. Advantages of ReMi are: extremely quick measurement, lack of an active source and simplicity of measurement. Application of Genetic Algorithm has been allowed to quite precise calculation of S-phase velocity, density and layer boundary depths. Even though, the results of dispersion curve inversion have provided to distinguish sands and sandstones from resistivity cross-section (similar range of resistivity).

The hardest part of the processing was to mark the dispersion curve on the phase velocity graph. This is one of the most significant elements of the analysis and the correct selection of the curve should be supported by a broad knowledge of the behavior of the Rayleigh wave modes. The fundamental and higher modes could not appear on the graph or be blurry (or combined in one) making identification of the relevant curve difficult.

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Abstrakt

Rozpoznanie zalegania sztywnego podłoża pod warstwą luźnych osadów jest jednym z ważniejszych zagadnień w geologii inżynierskiej. Informacja o położeniu granicy podłoże-nadkład wykorzystana może zostać przez inwestorów, inżynierów budowlanych lub władze gmin do projektowania właściwych konstrukcji lub planowania zagospodarowania przestrzennego. W takich sytuacjach przydatne stają się rozwiązania jakie proponują właściwe metody geofizyczne. Jednakże w strefach zurbanizowanych oraz charakteryzujących się luźnymi warstwami przypowierzchniowymi zastosowanie niektórych metod (np.: sejsmiki refrakcyjnej) nie jest wskazane. Metoda refrakcji mikrodrgań ReMi (pasywna) spełnia swoje zadania w tych względnie trudnych warunkach. W wyniku inwersji krzywych dyspersyjnych fal Rayleigha otrzymano pionowe zmiany prędkości fali S, co pozwoliło na rozróżnienie warstw geologicznych. W rejonie Chorzowa Starego przeprowadzono wstępne pomiary, które pozwoliły na rozpoznanie zalegania podłoża karbońskiego na głębokości ok. 15 m. Wydzielone warstwy w strefie osadów luźnych wykazały także dobrą korelację z dostępną informacją geologiczną oraz pomiarami inwersyjnego obrazowania oporności.

Słowa kluczowe: szum sejsmiczny, ReMi, obrazowanie oporności, granica podłoże-nadkład, Chorzów Stary.