Comparative test of active and passive multichannel analysis of surface waves (MASW) methods and microtremor HVSR method

Primerjalni test aktivne in pasivne večkanalne analize površinskih valov (MASW) ter metode mikrotremorjev (HVSR)

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Abstract: Shallow shear-wave velocity structure is important for seismological ground motion studies and for geotechnical engineering, but it is quite difficult and expensive to derive by using conventional geophysical techniques. Multichannel analysis of surface waves (MASW) and microtremor methods are therefore a valuable alternative developed in the last decade. A test of active and passive MASW and microtremor HVSR method was conducted in the southern part of Ljubljana which is characterised by soft sediments and strong seismological site effects. Land streamer which allows fast movement of geophones array in the field was successfully applied for the first time. Shear-wave velocities in the range 50-200 m/s were obtained in the 25 m thick layer of Quaternary sediments overlying Palaeozoic bedrock. The correspondence of velocity profiles obtained with different methods was satisfactory. Active MASW proved most useful in a case of target depth which does not exceed 30 m and passive MASW for greater depths. The advantage of microtremor HVSR is that it yields direct estimate of the fundamental resonance frequency of the sediments.

Izvleček: Hitrost strižnih seizmičnih valov v površinskih plasteh je pomembna za seizmološke analize nihanja tal ob potresu in v geotehniki, vendar pa jo je dokaj težko in drago določiti z uveljavljenimi geofizikalnimi metodami. V zadnjem desetletju pa so razvili nove metode večkanalne analize površinskih valov (MASW) in spektralnih razmerij mikrotremorjev (HVSR). V južnem delu Ljubljane, za katerega so značilni mehki sedimenti in izraziti lokalni seizmološki vplivi na potresne valove, smo izvedli test aktivne in pasivne MASW metode ter metode mikrotremorjev. Pri tem smo prvič uporabili »land streamer«, ki omogoča hitro premikanje geofonov na terenu. V 25 m debeli plasti kvartarnih sedimentov, ki prekrivajo paleozojsko podlago smo ugotovili hitrosti strižnih valov v razponu 50-200 m/s. Ujemanje hitrostnih profilov določenih z različnimi metodami je bilo zadovoljivo. Pokazalo se je, da je aktivna MASW metoda najbolj uporabna na območjih, kjer ciljna globina ne presega 30 m, pasivna MASW metoda pa tudi pri večjih globinah. Prednost metode mikrotremorjev (HVSR) je, da daje neposredno oceno osnovne resonančne frekvence sedimentov.

Key words: multichannel analysis of surface waves (MASW), microtremors, horizontal-to-vertical spectral ratio (HVSR), Rayleigh waves, shear-wave velocity, Ljubljana Moor

Ključne besede: večkanalna analiza površinskih valov (MASW), mikrotremorji, spektralno razmerje horizontalne in vertikalne komponente (HVSR), Rayleighovi valovi, hitrost strižnih valov, Ljubljansko barje

Introduction

Determination of a shallow shear-wave velocity structure is important for any quantitative microzonation study in seismic hazard assessment. The soil classification is according to Eurocode 8 standard for the design of earthquake resistant structures (Eurocode 8, 2003) based primarily on average shear-wave velocity in the upper 30 m of the soil profile ($V_{S,30}$). If this is not available, the results of the Standard Penetration Test (N_{SPT}) or shear modulus (c_u) are also used. All are directly linked to a material's stiffness. From the seismological point of view the shear-wave velocity is the best indicator. Besides determination of a ground type the shear-wave velocity is a critical input parameter for any numerical ground motion simulation and estimation of site amplification. Since it is directly related to the shear modulus, it is also very important in geotechnical engineering and environmental studies.

The conventional approaches for near-surface shear-wave velocity investigations have been shear-wave seismic refraction method and down-hole velocity measurement in boreholes. Seismic signals from these surveys consist of wavelets with frequencies usually higher than 30 Hz. Application of both methods is relatively expensive in terms of field operation, data analysis and overall costs to be adequately included in microzonation studies. Usually such studies should cover large urbane areas and therefore require a pattern of measurements which is dense enough for a given geological setting to be representative. The obvious drawback of a down-hole method is the high cost of drilling. Seismic refraction method is also time consuming because it should be conducted separately using longitudinal- (P) and shear- (S) waves using two sets of geophones (vertical and horizontal) and different ways of signal generation by a sledgehammer. The P-waves are needed to determine the depth structure and the S-waves to obtain relevant velocities for seismological site characterisation. In noisy urban environment, it is often difficult to generate enough strong signal to be effective.

In the last decade a new method called Multichannel Analysis of Surface Waves (MASW) was developed (Park et al., 1999; Wightman et al., 2002) which has several advantages in comparison to conventional seismic refraction and borehole measurements in determination of a shallow shear-wave velocity structure. It is based on the study of the dispersion of surface seismic (mainly Rayleigh) waves. These waves have much lower frequencies (e. g. 1-30 Hz) than body waves used in conventional seismic investigations. The sampling depth of a particular frequency component of surface waves is in direct proportion to its wavelength. This property makes the surface wave velocity frequency dependent, i. e. dispersive. The shear-wave velocity structure can be therefore obtained by the inversion of surface-waves dispersion curve (Xia et al., 1999), depending how the surface waves are generated active and passive MASW techniques are known (Park et al., 2007). In active MASW method the surface waves are generated through an impact source like a sledgehammer, similar as in refraction seismic method. On the other hand the passive MASW method utilizes surface waves generated passively (seismic noise) by natural (tidal motion, sea waves, wind, rivers) or artificial (traffic, industry) activities.

Ambient vibrations (seismic noise of natural and artificial origin) are used also in microtremor method. In this method microtremors are recorded with single three-component seismometer and analyzed in a frequency domain. Spectral ratio between the records on horizontal and vertical component yield fundamental frequency of soft sediments deposited over hard bedrock. The method is therefore called Horizontal to Vertical Spectral Ratio (HVSR) method. It is used mainly in quantitative microzonation to identify the areas where the danger of resonance between sediments (soil) and buildings exist. This method does not provide directly shear-wave velocity structure, but this can be derived by modelling of spectral ratio curve if necessary.

For the Ljubljana (the capital of Slovenia) region a new quantitative microzonation based on microtremor measurements in a very dense grid of 200 m x 200 m (Figure 1) is in preparation (Gosar, 2007b). Particular attention is given to the southern part of Ljubljana, which is built on very soft lacustrine and marsh deposits of the Ljubljana Moor where strong site effects can be expected. Most of this area is based on preliminary data classified as Eurocode 8 ground type S_1 (Zupančič et al., 2004). For S_1 and S_2 ground types Eurocode 8 standard does not give soil factors but prescribes site investigations to derive the amplification factor. Therefore we decided to perform a comparative test of two different MASW methods and microtremor method to asses their applicability for further investigations in this area. The test site was located near Ljubljanica river on Dolgi breg (Figure 1). For this location the depth to the bedrock (approx. 25 m) is known from nearby borehole and from geophysical measurements (Figure 2). In addition Standard Spectral Ratio (SSR) analysis of

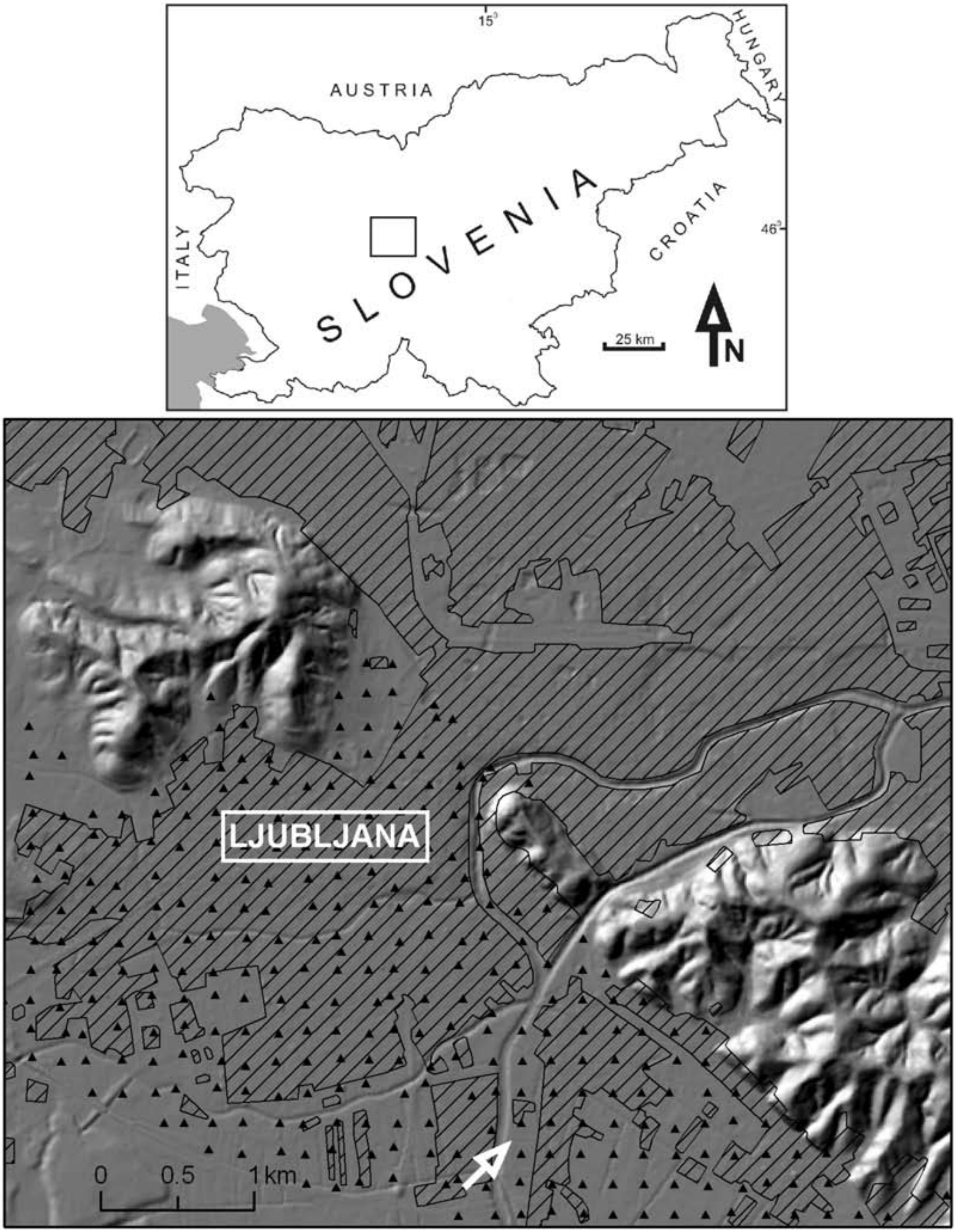

Figure 1. Location map of seismic measurements at Dolgi breg in the southern part of Ljubljana. Triangles indicate planed microtremor measurements.
Slika 1. Položaj seizmičnih meritev na Dolgem bregu v južnem delu Ljubljane. Trikotniki označujejo načrtovane meritve mikrotremorjev.

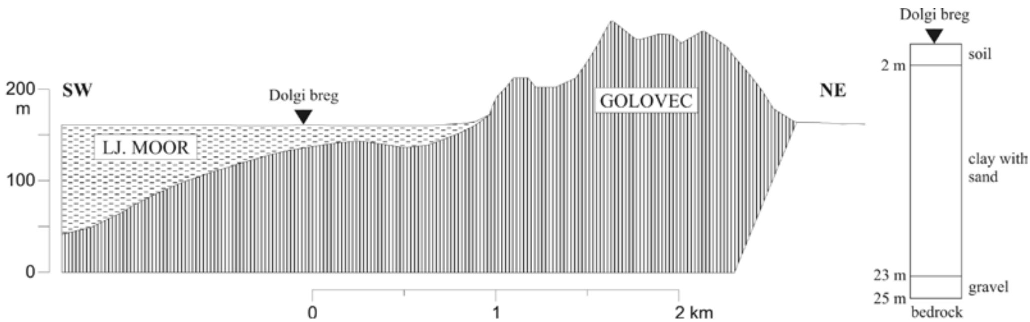

Figure 2. Profile across the Ljubljana Moor (Quaternary sediments) and Golovec hill (Permian and Carboniferous sandstones, conglomerates and shales) with the location of measurements at Dolgi breg
Slika 2. Profil prek Ljubljanskega Barja (kvartarni sedimenti) in Golovca (permski in karbonski peščenjaki, konglomerati in skrilavci) z lokacijo meritev na Dolgem bregu

earthquake data was available (Gosar & Živčić, 1998) which allowed comparison of site amplification.

Seismogeological setting

Ljubljana, the capital of Slovenia is situated in a young sedimentary basin filled with Quaternary deposits. According to the seismic hazard map of Slovenia for 475-years return period (Lapajne et al., 2001), a relatively high seismic hazard is characteristic of the area with design ground acceleration values of 0.20-0.25 *g* for a rock site. At the same time this is the most densely populated area of Slovenia with more than 300.000 inhabitants. The strongest earthquake in the history of the city occurred in 1895, when Ljubljana was hit by M=6.1 earthquake which caused extensive damage of VIII-IX MCS maximum intensity.

Strong site effects were characteristic of the southern part of Ljubljana, which is built on very soft lacustrine and marsh deposits of the Ljubljana Moor. The topography of the basins bedrock is here very rugged and its depth ranges from 0 m to 200 m (Figure 2). It is composed of Permian and Carboniferous sandstones, conglomerates, shales and Triassic dolomites. The Quaternary sediments are very heterogeneous, composed of clay, gravel, sand, lacustine chalk and peat. The uppermost layers are very soft.

The existing microzonation of Ljubljana was prepared in 1970 (Lapajne, 1970) using the nowadays outdated methodology of Medvedev (1965) to be used with the old seismic hazard intensity map of Slovenia which is given in MSK scale. The quantitative parameters to calculate "intensity increments" were obtained from P-wave seismic refraction measurement, but according to the methodology of Medvedev, no S-wave velocity information was collected. After the preparation of a new seismic hazard map of Slovenia (Lapajne et al., 2001) which specifies design ground acceleration for rock or firm soil, a need arose for a new microzonation prepared according to Eurocode 8 and specifying soil factors (Eurocode 8, 2003). The first attempt of a new microzonation of Ljubljana to be used in disaster prevention only, and not for earthquake resistant design, was prepared exclusively from existing data (Zupančič et al., 2004). The majority of the southern part of Ljubljana was classified in this map as ground type S_1 and minor parts in the border shallower parts as ground type E.

The main weakness of used existing data is a lack of shear-wave velocity information, because only at three locations S-wave refraction seismic data were available to calculate soil factors for ground type S_1.

Methodology

Active MASW

The active MASW was introduced by Park et al. (1999). It adopts the conventional seismic refraction mode of survey (Figure 3a) using an active seismic source (usually sledgehammer) and a linear receiver array, collecting data in a roll-along mode. It utilizes surface waves, mainly horizontal travelling fundamental-mode Rayleigh waves, directly from impact point to receivers. Rayleigh waves are characterized by elliptical and retrograde particle motion. Its amplitude decreases exponentially with depth (Figure 3b). Different types of waves are recorded with multichannel array including: direct and refracted arrivals, air waves, reflections, fundamental and higher modes of Rayleigh waves, backscattering of surface waves and ambient noise. Dispersion nature of different types of waves is imaged through a 2D wavefield transformation into dispersion image (Xia et al., 2004). Certain noise wavefields such as back- and side-scattered surface waves and several types of body waves are automatically filtered out during this transformation (Park et al., 2007). From the dispersion image a dispersion curve of the fundamental mode of Rayleigh waves is picked, which is then inverted for a 1D Vs profile (Xia et al., 1999; Roth & Holinger, 1999). Multiples of them recorded in a roll-along mode can be used to prepare a 2D Vs map.

Typical field configuration consists of 24-channels connected to engineering seismograph (Figure 3a). Low-frequency geophones (e. g. 4.5 Hz) are recommended. Although the highest sensitivity is obtained with conventional geophones equipped with spikes, a land streamer (Figure 4) is a very good alternative on a flat ground, because of significant convenience in field operation.

Maximum depth of investigation (*Zmax*) is usually in 20-30 m range. However, it can vary with different sites and different strength of active sources used. Length of the receiver spread (*xT*) is directly related to the longest wavelength (*λmax*) that can be analyzed and is connected to the maximum depth of the investigation. On the other hand, receiver spacing (*dx*) is related to the shortest wavelength (*λmin*) and therefore to the shallowest resolvable depth of investigation. The source offset (*x1*) controls the degree of the record contamination by the near-field effects (Park et al., 2006).

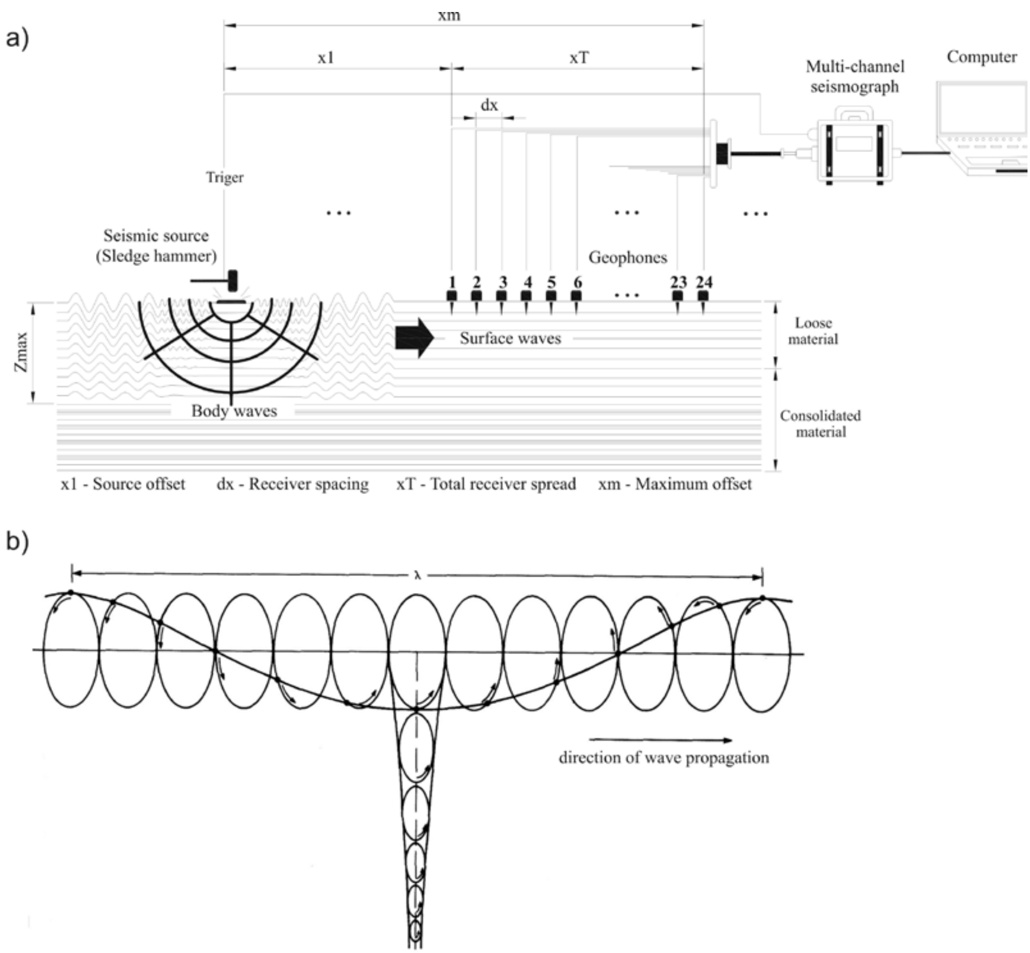

Figure 3. a) Schematic representation of active MASW measurements. b) Particle motion for Rayleigh waves showing amplitude decrease with depth (after SHERIFF & GELDART, 1995).

Slika 3. a) Shematski prikaz aktivnih MASW meritev. b) Gibanje delcev pri Rayleighjevem valovanju, ki kaže upadanje amplitude z globino (po SHERIFF & GELDART, 1995).

Figure 4. Land streamer with 24 vertical geophones and a sledgehammer as a seismic source; on a small insert a detail of geophone mount is shown
Slika 4. Land streamer z 24 navpičnimi geofoni in kovaško kladivo kot seizmični vir; majhna slika prikazuje izvedbo pritrditve geofona

When using sledgehammer or weight drop as a source a vertical stacking of multiple impacts can suppress ambient noise significantly.

Passive MASW

The main disadvantage of active MASW is the maximum depth of investigation which is usually 20-30 m. The amount of active-source energy needed to gain a few more Hz at the low-frequency end of the dispersion image, and thereby to increase investigation depth by several tens of meters, often rises several orders of magnitude, rendering efforts with an active source impractical and uneconomical (Park et al., 2007). On the other hand, passive surface waves generated by natural (tidal motion, sea waves, wind, rivers) or artificial (traffic, industry) activities are usually of a low frequency (1-30 Hz) with wavelengths ranging from few km (natural sources) to a few tens or hundreds of meters (artificial sources), providing a wide range of penetration depths.

This method was originally developed in Japan and called microtremor survey method (Okada, 2003) and adopted a smaller number (usually less than ten) of receivers. It is sometimes called also Microtremor Array Measurements or MAM (Hayashi et al., 2006). Louie (2001) first introduced linear refraction microtremor arrays (ReMi method). These methods were later developed as passive MASW method, which uses 24 or more geophones to fully exploit the advantages of multichannel recording and processing (Park et al., 2007). It therefore has an increased resolution in the analysis of both the modal nature and azimuthal properties of surface waves.

The passive MASW method employs a 2D geophone array such as a cross (Figure 8) or circular layout to record passive surface waves. Other array types as triangular or square are also common, but it is recommended that they have a symmetric shape. Any asymmetry can bias a result toward a specific direction of incoming surface waves that do not necessarily coincide with the actual direction of major surface-wave energy.

Array dimension is directly related to the longest wavelength (λmax) that can be analyzed and is connected to the maximum depth of the investigation. On the other hand, minimum receiver spacing is related to the shortest wavelength (λmin) and therefore to the shallowest resolvable depth of investigation. The typical depth of investigation for passive MASW is up to 100 m.

Data processing and analysis is similar as in active MASW and includes three steps: 1) generation of the dispersion image (phase velocity-frequency chart), 2) extraction of the dispersion curve from the image and 3) inversion of 1D shear-wave velocity profile from the dispersion curve (Park et al., 2006). Some techniques like ReMi use slowness instead of phase velocity.

It is often useful to combine dispersion images from active and passive sets for two reasons: to enlarge the usable bandwidth of dispersion (and therefore the depth range) and to better identify the modal nature of dispersion trends (Park et al., 2005).

Microtremor HVSR

The microtremor HVSR method is in the

last decade widely used for microzonation and site effects studies (e. g. Gosar, 2007a, 2007b). However, the theoretical basis of HVSR method is still debated and different explanations have been given. "Body waves" explanation is based on S-wave resonance in soft sediments layer with minor or neglecting influence of surface waves. More widely accepted is the "surface waves" explanation that HVSR is related to the ellipticity of Rayleigh waves which is frequency dependent (Bard, 1999). HVSR exhibits therefore a sharp peak at the fundamental frequency of the sediments, if there is a high impedance contrast between the sediments and the underlying bedrock. Criticism of the HVSR method was often related to the fact that there is no common practice for data acquisition and processing. Attempts to provide standards were only recently been made (SESAME, 2004). It is widely accepted today that the frequency of the HVSR peak reflects the fundamental frequency of the sediments. Its amplitude depends mainly on the impedance contrast with the bedrock and cannot be used as a site amplification. However, a comparison with results of standard spectral ratio method has shown that the HVSR peak amplitude underestimates the actual site amplification (Bard, 1999; SESAME, 2004). HVSR also does not provide any estimate of the actual bandwidth over which the ground motion is amplified. The main advantages of HVSR method are therefore simple and low-cost measurements and direct estimates of the resonance frequency of sediments without knowing the geological and S-velocity structure of the underground. Any knowledge about the thickness or/and velocity of sediments and the comparison of HVSR results with other methods and with the observed earthquake damage can significantly improve the reliability of the results.

Microtremor HVSR method does not provide directly shear-wave velocity structure, but this can be derived by modelling of spectral ratio curve if necessary. It is usually based on the search for the model whose theoretical HVSR response best matches the observed HVSR by random perturbation of model parameters within preselected limits (Herak, 2007).

Data acquisition and analysis

A comparative test of three different methods was performed at Dolgi breg near Ljubljanica river on the Ljubljana Moor (Figures 1 and 2). This site was selected for several reasons: a) the depth to the bedrock (approx. 25 m) is known from nearby borehole and geophysical measurements, b) the thickness of soft sediments is inside the depth penetration of active MASW method (less than 30 m), c) strong acoustic impedance contrast between sediments and bedrock is known from previous microtremor measurements (Gosar, 2007b) and d) at a nearby location earthquake data were recorded which allows Standard Spectral Ratio (SSR) analysis (Gosar & Živčić, 1998) for comparison.

Data acquisition parameters for all three methods are summarized in Table 1. Active and passive MASW measurements were performed using 24 channel ABEM Terraloc Mk6 seismograph with 24 bit digitiser. Because active MASW and mi-

Table 1. Summary of data aquisition parameters
Tabela 1. Povzetek parametrov zajema podatkov

Survey type	**Active MASW**	**Passive MASW**	**Microtremor HVSR**
Source	8 kg sledgehammer	noise	noise
Seismograph	ABEM Terraloc Mk6	ABEM Terraloc Mk6	Tromino
Geophones	4.5 Hz (land streamer)	4.5 Hz (spike coupling)	three-component electrodynamic
Receiver array	24 channel linear	24 channel cross	
Array dimension (xT)	23 m	55 m	
Receiver spacing (dx)	1 m	5 m	
Source offset (x1)	5 m		
Receiver array move	5 m		measur. at 5 points
Sampling frequency	2000 Hz (0.5 ms)	500 Hz (2 ms)	128 Hz
Recording time	2 s	32 s	20 min
No. of records	20	20	5

crotremor HVSR methods are both sensitive to noise introduced by wind, were the measurements realized on a calm day without wind. Active and passive MASW data were processed and analysed using SurfSeis software (Park et al., 2006) and microtremor HVSR data using Grilla software (Micromed, 2006).

Active MASW

Active MASW measurements were performed along a walking path covered with compacted sand. The 4.5 Hz vertical geophones (24) were mounted on a "land streamer" (Figure 4) designed at Geoinženiring which allows fast movement of the receiver array between measuring points without planting the geophones equipped with spikes into the ground. Land streamer is composed of small sledges equipped with screws to mount geophones, linked with textile ribbon which allows pulling the whole array to a new position. The distance between geophones was 1 m, the source offset 5 m and the array move between subsequent records 5 m. A sledgehammer was used as a source and 10 hits vertically stacked at each point. This produced a clear surface waves signal over the total recording length of 2 s (Figure 5). Together 20 records were measured along a 100 m long profile.

Data were processed in the following way. After data conversion from SEG-2 to KGS format the field geometry was encoded into the header of seismic traces. Dispersion images were calculated separately

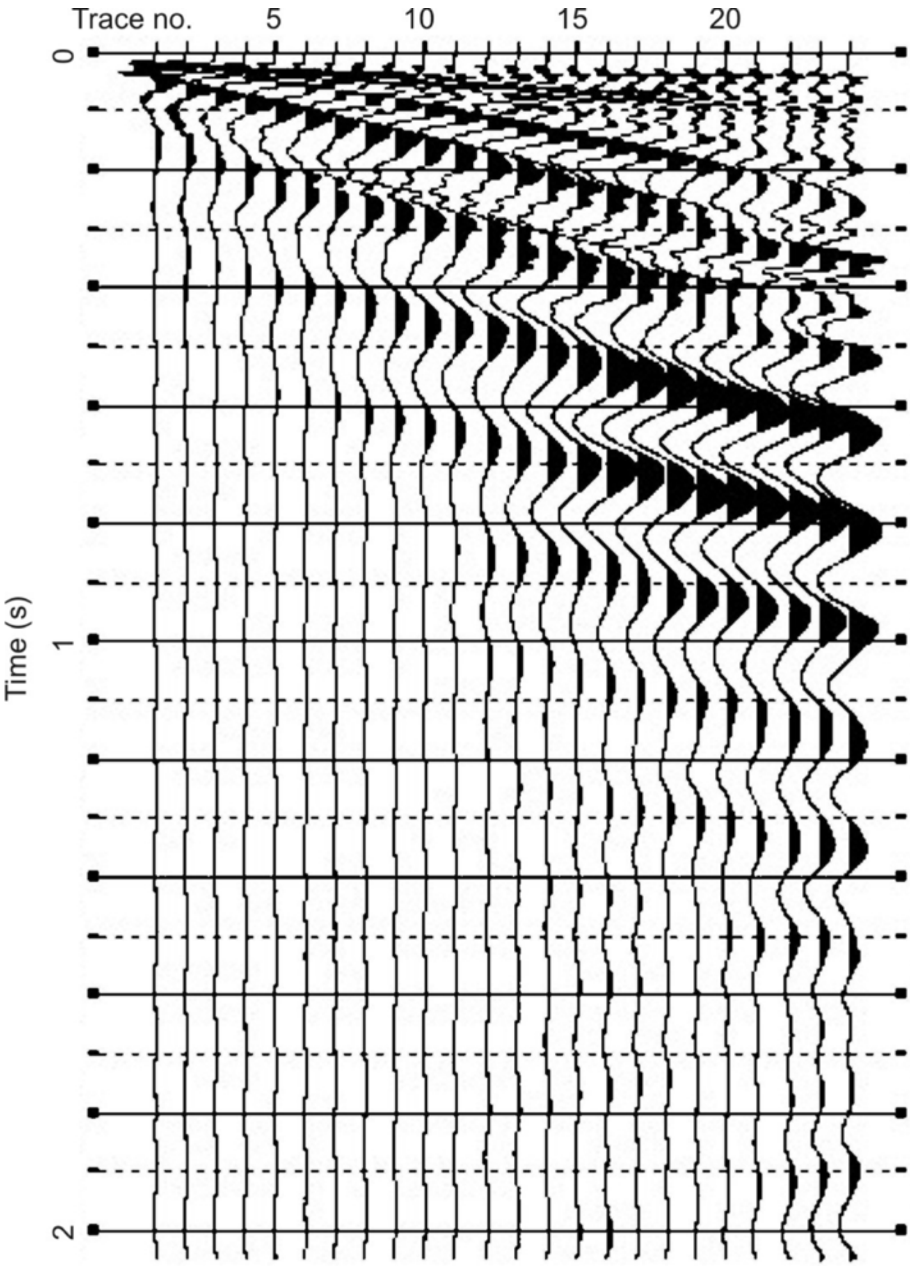

Figure 5. Seismogram example of active MASW measurements
Slika 5. Primer seizmograma aktivnih MASW meritev

a.)

b.)

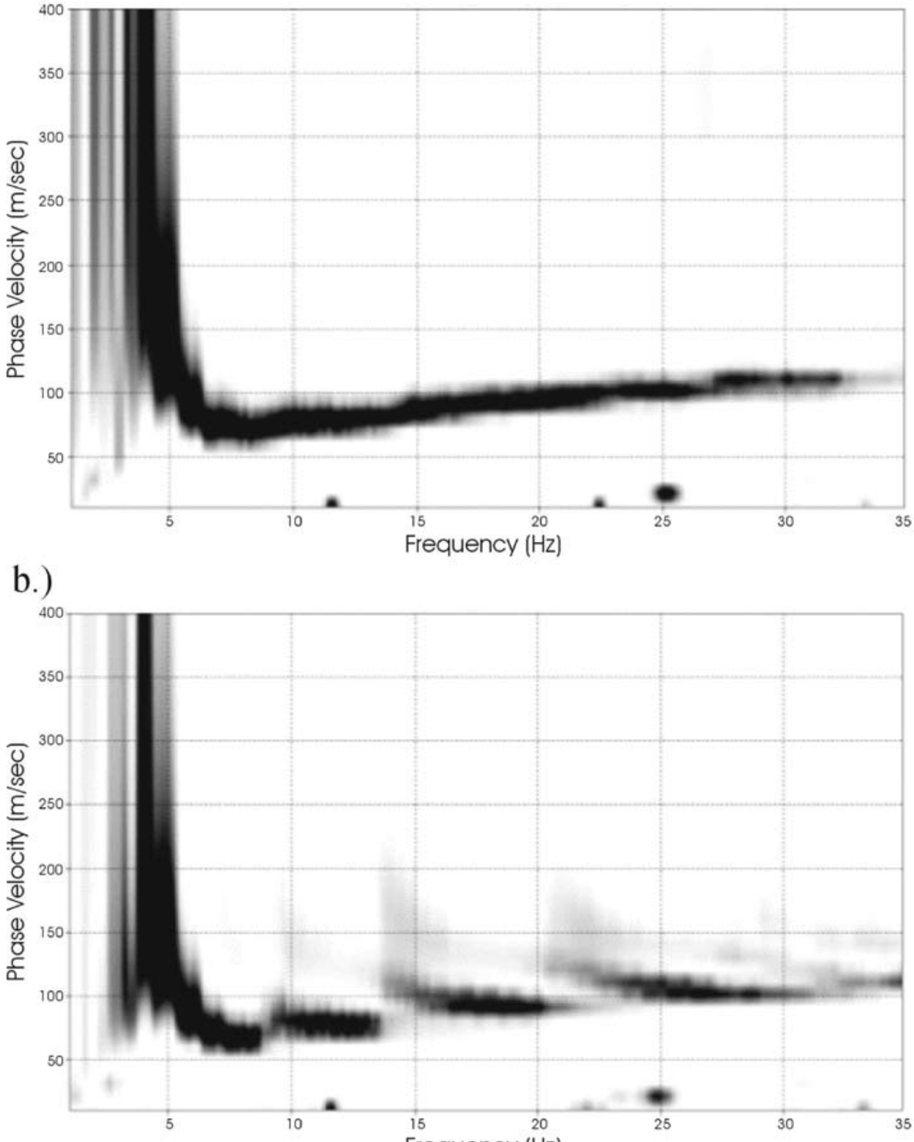

Figure 6. Dispersion images of two active MASW measurements: a) example with only fundamental mode of surface waves visible, b) example with higher modes of surface waves at frequencies ≥8 Hz

Slika 6. Disperzijski sliki dveh aktivnih MASW meritev: a) primer z vidno le osnovno obliko površinskih valov, b) primer z višjimi oblikami površinskih valov pri frekvencah ≥8 Hz.

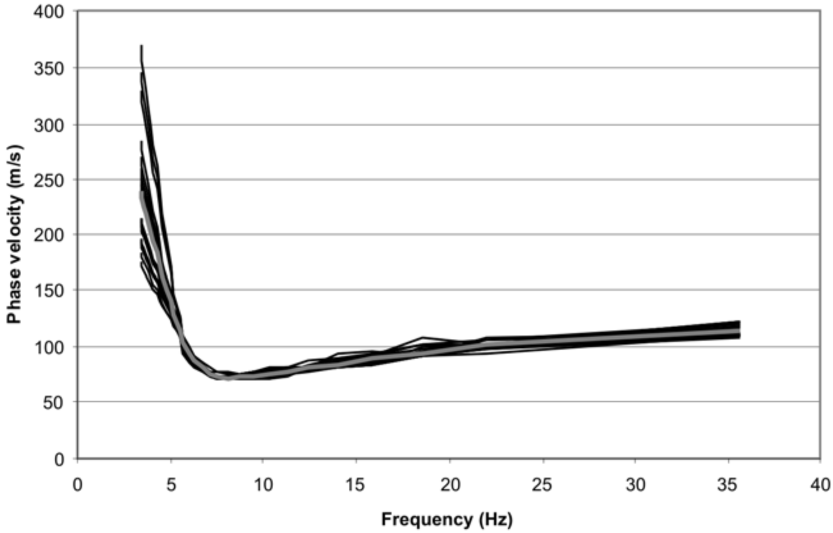

Figure 7. Dispersion curves of twenty active MASW measurements (thin black lines) with average curve (thick grey line)
Slika 7. Disperzijske krivulje dvajsetih aktivnih MASW meritev (tanke črne črte) s povprečno krivuljo (debelejša siva črta)

for all 20 records using frequency range 1-40 Hz and phase velocity range 10-400 m/s. The dominant frequency of surface waves was around 5 Hz. A very good signal to noise ratio was obtained for all records (Figure 6). The dispersion (Figure 6a) of the fundamental mode of surface waves is therefore very clear in the frequency range from 3 to 35 Hz with a steep decrease of phase velocity in the range 2-7 Hz down to minimum phase velocity of around 70 m/s, followed by a slight increasing of the phase velocity up to 32-35 Hz. In some of dispersion images (Figure 6b) some higher modes of surface waves are clearly visible above 8 Hz. After the definition of the bounds (lower and upper limits of phase velocities for the dispersion curve to be extracted) was the automatic picking algorithm successful in extraction of the dispersion curve due to good signal to noise ratio. The total number of points constituting the dispersion curve was set to 30 with equal-wavelength frequency interval used to make the frequency interval more dense at low and coarse at high frequencies. Dispersion curves for all 20 records are together with average curve shown in Figure 7. They are very similar, there is some discrepancy only in the initial part (low frequency) of the curves.

One-dimensional (1D) inversion of dispersion curves was performed using a gradient based iterative solution to the weighted equation (Xia et al., 1999) using Levenberg-Marquardt method. A variable model (the thickness of layers is increasing with depth) of ten layers was applied. The maximum depth defined by the size of the array and the lowest frequency of dispersion curve was around 30 m. The stopping criteria for inversion was maximum 12 iterations or

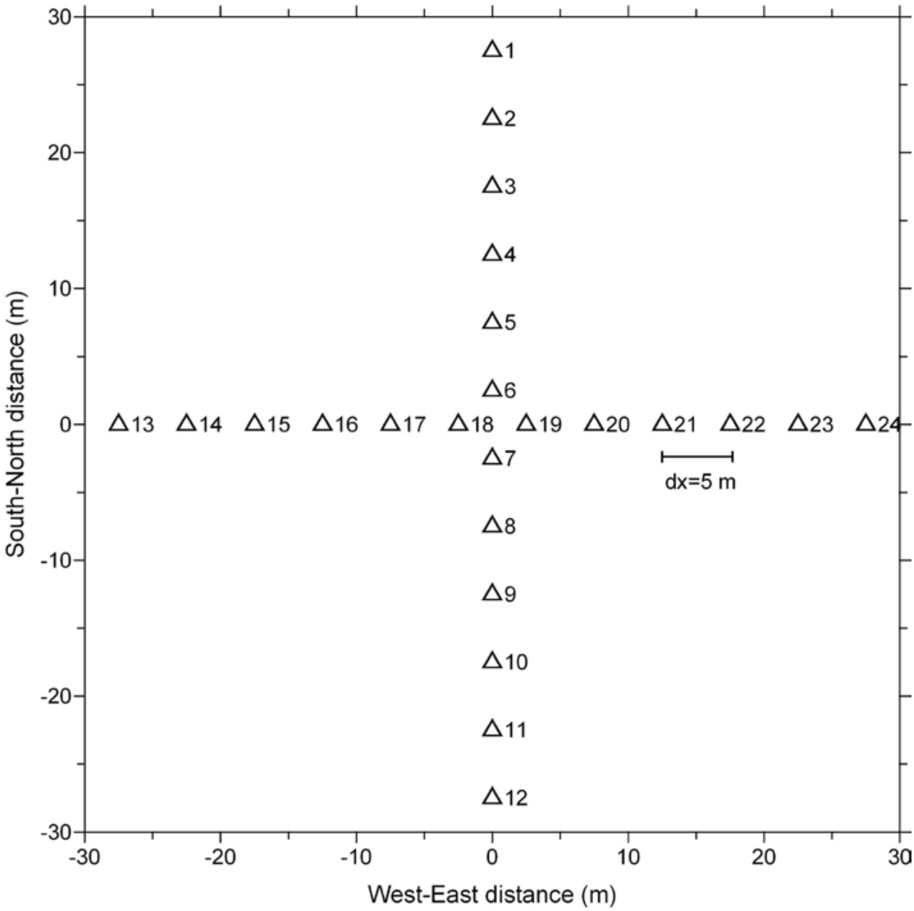

Figure 8. Cross geophone array used for passive MASW measurements
Slika 8. Križna geofonska razvrstitev uporabljena za pasivne MASW meritve

RMS error in phase velocity lower than 5. P-wave velocity was fixed to S-wave velocity using the Poisson ratio of 0.4. The average result of inversion for all 20 records is together with ± one standard deviation shown in Figure 14a. The variability of the results was quite small, because of the similarity of dispersion curves. It becomes greater only below the sediments/bedrock boundary which is clearly defined at around 25 m as a steep increase of S-velocity from around 200 m/s to 350 m/s.

Passive MASW

Passive MASW measurements were performed using symmetric cross-array (Figure 8) on a land covered with grass. The 4.5 Hz vertical geophones equipped with spikes were planted in equidistance with 5 m spacing in N-S and E-W direction. The array dimension in each direction was 55 m, which roughly determines the maximum depth of investigation. Together 20 records of 32 s length (Figure 9) were measured without moving the geophone array.

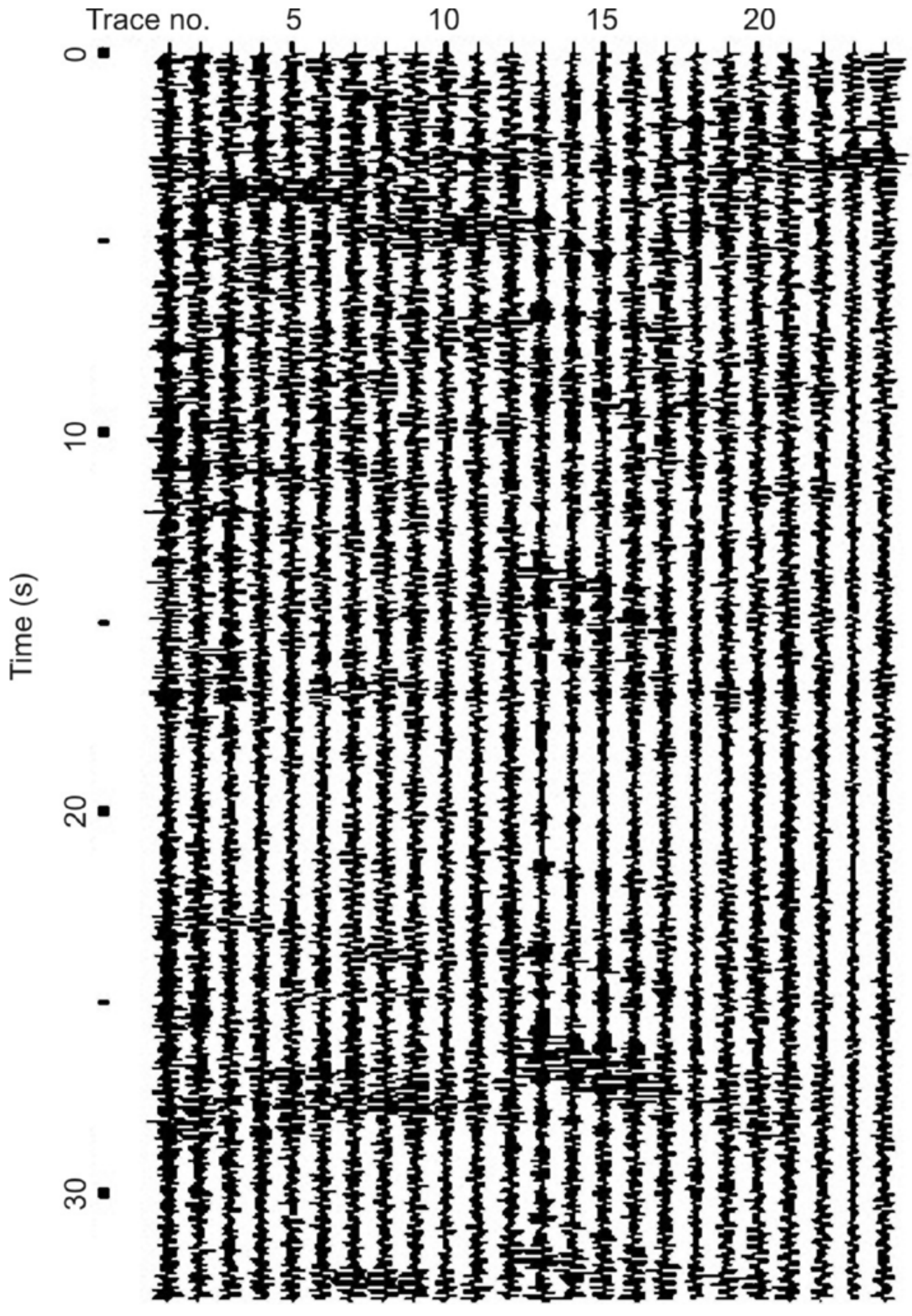

Figure 9. Seismogram example of passive MASW measurements
Slika 9. Primer seizmograma pasivnih MASW meritev

Data were processed in the following way. After data conversion from SEG-2 to KGS format the field geometry was encoded into the header of seismic traces. Dispersion image was calculated separately for all 20 records and the dispersion images than stacked together (Figure 10). The frequency range of calculation was 1-25 Hz and phase velocity range 10-300 m/s. A signal to noise ratio is obviously lower in passive than in active measurements. Nevertheless is the fundamental mode of surface waves quite clear in the frequency range 3-14 Hz, whereas higher modes prevail above 14 Hz. Dispersion curve was extracted in the frequency range 2-14 Hz using the same parameters as in active MASW. Both dispersion curves, average for active MASW and for passive MASW, are shown in the Figure 11. The shape of both curves is similar with a clear bend at around 7 Hz, but the curve of passive MASW is slightly shifted towards lower frequencies and lower phase velocities. In the frequency range 8-14 Hz is the passive MASW dispersion curve almost flat and shows a phase velocity of around 30 m/s.

For one-dimensional (1D) inversion of dispersion curve the same method was applied as in active MASW using a variable model (the thickness of layers is increasing with depth) of 13 layers to obtain a comparable layer thicknesses in upper 30 m as in active MASW. The maximum depth defined by the size of the array and the lowest frequency of dispersion curve was around 56 m. The stopping criteria for inversion was maximum 12 iterations or RMS error in phase velocity lower than 5. P-wave velocity was fixed to S-wave velocity using the Poisson ratio of 0.4. The result of the inversion is shown in Figure 14b.

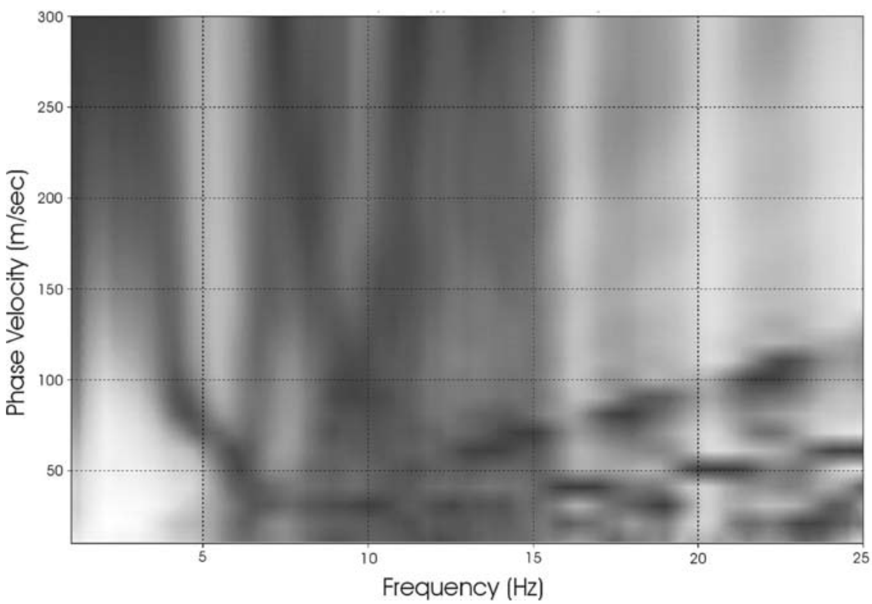

Figure 10. Dispersion image of passive MASW measurements
Slika 10. Disperzijska slika pasivnih MASW meritev

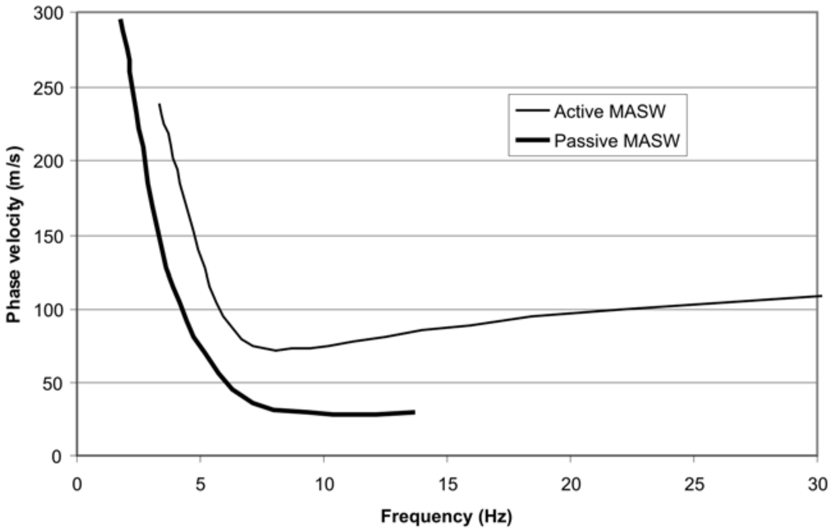

Figure 11. Dispersion curves of active (average) and passive MASW measurements
Slika 11. Disperzni krivulji aktivnih (povprečje) in pasivnih MASW meritev

Microtremor HVSR

Microtremor measurements were performed by using five portable seismographs Tromino (Micromed) composed of three orthogonal electrodynamic velocity sensors, 24 bit digitizer and recording unit with flash memory card. All parts are integrated in a common case to avoid electronic and mechanical noise that can be introduced by wiring between equipment parts. Good ground coupling on soft soils was obtained by using long spikes mounted at the base of the seismograph. Seismographs were deployed along the same 100 m long profile as used for active MASW measurements with 25 m spacing between instruments. The recording length was 20 minutes, which allows spectral analysis down to 0.5 Hz.

HVSR analysis was performed in the following way. Recorded time series were visually inspected to identify stronger transient noise. Each record was then split into 30 s long non-overlapping windows for which amplitude spectra in a range 0.5-64 Hz were computed using a triangular window with 5 % smoothing and corrected for sensor transfer function. HVSR was computed as the average of both horizontal component spectra divided by the vertical spectrum for each window. From the colour coded plot of HVSR functions for all 40 windows, the windows including strong transient noise were identified in order to be excluded from further computation. At the end, the average HVSR function with a 95 % confidence interval was computed.

All five HVSR curves are shown in Figure 12. They all show a sharp peak related to the fundamental frequency of sediments at 1.5 Hz (range 1.4-1.6 Hz). The amplitude of the peak which is less stable parameter

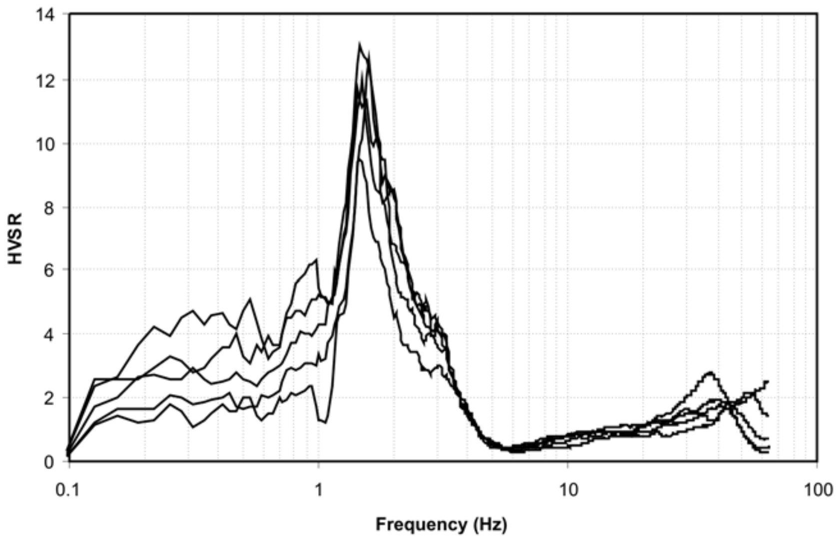

Figure 12. HVSR curves of five microtremor measurements
Slika 12. Krivulje HVSR petih meritev mikrotremorjev

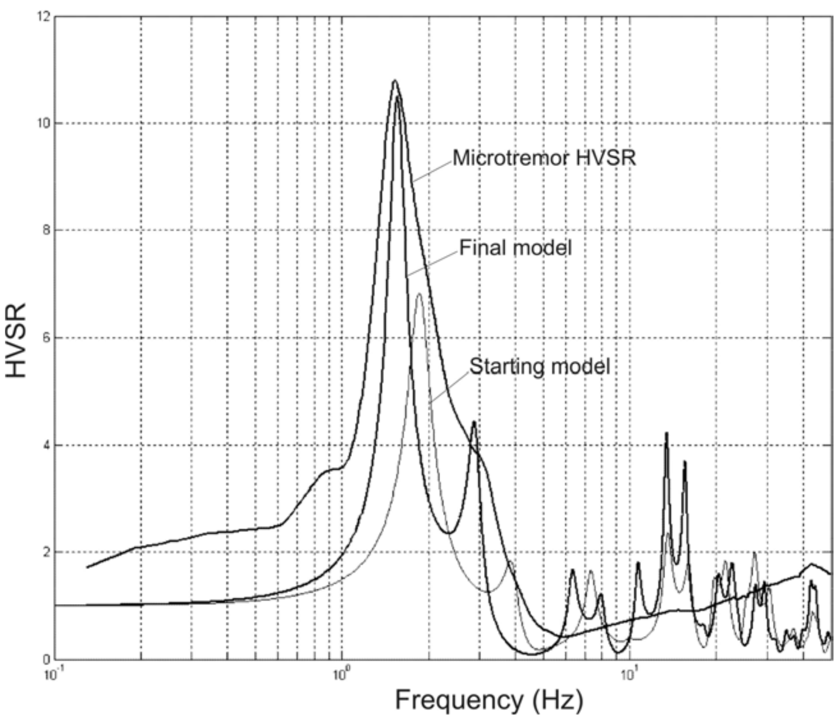

Figure 13. Results of modelling of average microtremor HVSR curve
Slika 13. Rezultat modeliranja povprečne krivulje HVSR iz meritev mikrotremorjev

of HVSR analysis is from 9.5 to 13 (average 10.5) what is an indication of a strong acoustic impedance contrast between sediments and bedrock. Average curve calculated from all five HVSR curves is shown in Figure 13.

The obtained fundamental frequency and HVSR amplitude is comparable to the results of Standard Spectral Ratio (SSR) analysis performed at nearby Rakova jelša, where seismograms of two regional earthquakes were recorded. Their amplitude spectra was divided by the spectra of the records of same earthquakes measured at a rock site on a Golovec hill to obtain a SSR. The dominant frequency of amplification obtained was around 2 Hz and the maximum amplification around 12 (Gosar & Živčić, 1998).

One-dimensional modelling of the average HVSR curve was performed using ModelHVSR program (Herak, 2007) which computes the theoretical P- and S-wave transfer function (amplification) of a layered, viscoelastic model for vertical incident P- and S-waves and use it for the calculation of a theoretical HVSR curve. Since only seismic impedances and travel times through layers have an influence on defining a transfer function, both depths and velocities can not be resolved at the same time. Therefore we used the same layer thicknesses as in active MASW inversion and keep them constant in a modelling procedure. For a starting model we also took velocities obtained by the inversion of active MASW measurement and then in a random model perturbation allowed a maximum 25 % variation of *Vp* and *Vs*. The number of random tries was 1000. The results are shown in Figure 13 as: measured average HVSR curve, curve which corresponds to the starting model and a curve which corresponds to the final model shown in Figure 14c. The fit between measured and calculated HVSR curve in terms of frequency and amplitude is very good, but there is a difference in the width of the peak.

Results

The one-dimensional shear-waves velocity profiles obtained with three different methods are shown in Figure 14. Despite determination of the depth of sediments/bedrock boundary is not the strong part of applied methods, is it clearly reflected at around 25 m in both profiles obtained by active MASW and microtremor HVSR as a sharp increase of S-velocity from around 200 m/s to 350-400 m/s. Passive MASW is less sensitive to the strong contrast of acoustic impedance and therefore is this boundary not so clear. However is the increase of S-velocity to around 300 m/s below the depth of 26 m already indicative for a bedrock.

Comparison of all three velocity profiles inside the sediments shows the following:

a) all the profiles start with thin (1-2 m thick) low-velocity layer followed by 1-1.5 m thick higher velocity layer (120-150 m/s); since the passive MASW was recorded on a grass is the soft surface layer there thicker in comparison to active MASW measurements recorded on a path built of compacted sand,

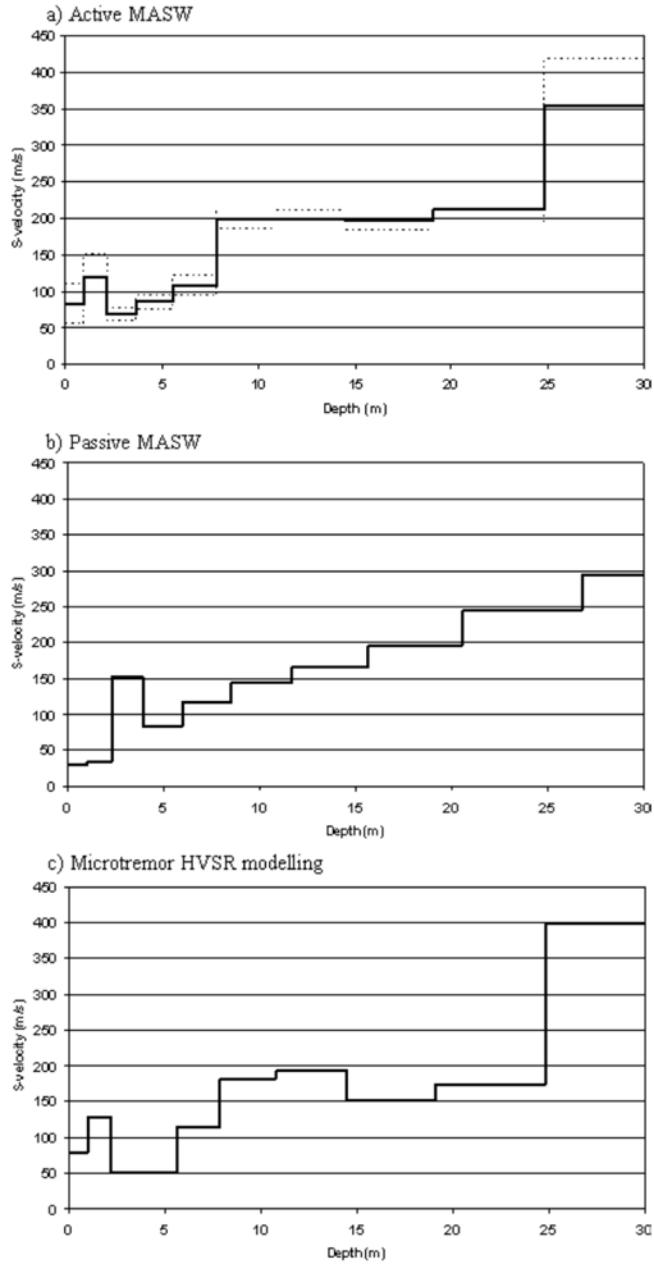

Figure 14. Shear-wave velocity profiles from a) active MASW (with ± one standard deviation), b) passive MASW and c) microtremor HVSR modelling
Slika 14. Profili hitrosti strižnih valov za a) aktivni MASW (z ± enim standardnim odklonom), b) pasivni MASW in c) modeliranje krivulje HVSR iz mikrotremorjev

b) in the depth range 2-7.5 m there is a low velocity layer (50-120 m/s),
c) in the depth range 7.5-25 m is the velocity according to active MASW and microtremor HVSR quite stable (150-210 m/s), while according to passive MASW there is a gradual increase of velocity from 150 to 250 m/s.

The S-velocities from dispersion of surface waves for the upper five meters are comparable to the velocities from shallow seismic refraction measurements performed at geologically similar location at Park Svoboda, also in the southern part of Ljubljana, where the velocities between 95 and 180 m/s were measured in the first five meters (ŽIVANOVIĆ & STOPAR, 1995).

The parameter widely applied in seismic microzonation, also the main parameter for ground type classification in Eurocode 8 standard (EUROCODE 8, 2003), is average shear-wave velocity in upper 30 m ($V_{S,30}$). It is computed according to the following expression

$$V_{S,30} = \frac{30}{\sum_{i=1,N} \frac{h_i}{V_i}}$$

where h_i and V_i denote the thickness (in m) and shear-wave velocity (in m/s) in the *i*-th formation of layer, in a total of *N*, existing in the top 30 metres.

Since the shear-wave velocity in the bedrock can not be well defined with applied methods we computed equivalent average velocity for the total thickness of sediments (around 25 m) and obtained the following values:

- active MASW – 145 m/s,
- passive MASW – 120 m/s,
- microtremor HVSR – 120 m/s.

Considering only this parameter to define the ground type in Eurocode 8, can be the investigated site classified as ground type D (*Vs*<180 m/s). But if we consider also a description of the stratigraphic profile, it is more likely ground type S_1 (*Vs*<100 m/s) described as: deposits consisting - or containing a layer at least 10 m thick – of soft clay/silts with high plasticity index and high water content.

CONCLUSIONS

Performed investigations with three different methods have shown that they are all effective in the determination of a shallow shear-waves velocity profile, but there are also some important differences between them. Obtained one-dimensional velocity profiles are similar to acceptable extent. The average shear-wave velocity in the 25 m thick layer of sediments is between 120 m/s and 145 m/s. The value obtained by active MASW (145 m/s) is 20 % greater than the values obtained by passive MASW and microtremor HVSR modelling (120 m/s). We found no explanation for this, but the difference is not too big to have a considerable influence on the determination of the ground type in seismic microzonation. The ground at investigated site can be therefore according to Eurocode 8 classified as type D or more likely S_1, if we consider also a description of the stratigraphic profile.

Comparison of active and passive MASW has shown that if the depth of investigation does not exceed 30 m much more clear dispersion image of surface waves is obtained with active method and is therefore preferable. A possible solution to increase the usable frequency range of dispersion would be to combine dispersion images obtained from active and passive measurements at the same location with different geophone arrays (Park et al., 2005) or using even the same linear array along a road where the traffic represents strong enough source of surface waves (Park et al., 2006). In the later case a long record is used triggered by a single hit of a sledgehammer. Initial part of the record is then processed as active and the remaining part as passive MASW.

Land streamer array of geophones was tested for the first time and proved very efficient for active MASW measurements along a two-dimensional profile. The only condition is that the surface of the ground is flat enough to assure near-vertical position of geophones. In a case of expected lateral variations of velocity, two-dimensional measurements have additional advantages with respect to passive measurements.

Microtremor HVSR method yield directly the fundamental frequency of the sediments overlying the bedrock which itself is a very valuable parameter of any microzonation, because it provides an estimate of the danger of soil-structure resonance. S-velocity profile can be derived by modelling of HVSR curve only if a reliable constraint on the thickness of the sediments can be done. If this is a case, as shown in our test, also microtremor data can provide a good estimate of one-dimensional S-velocity profile. Moreover, applicability of microtremor HVSR method highly depends on a strength of the impedance contrast between sediments and bedrock. On the contrary, MASW methods provide velocity profiles also for sites with gradual increase of velocity with depth.

Povzetek

Primerjalni test aktivne in pasivne večkanalne analize površinskih valov (MASW) ter metode mikrotremorjev (HVSR)

Hitrost strižnih seizmičnih valov v površinskih plasteh je pomembna za seizmološke analize nihanja tal ob potresu in v geotehniki, vendar pa jo je z uveljavljenimi geofizikalnimi metodami dokaj težko in drago določiti. V zadnjem desetletju pa so razvili nove metode večkanalne analize površinskih valov (MASW) in spektralnih razmerij mikrotremorjev (HVSR). MASW metoda temelji na disperziji površinskih (predvsem Rayleighjevih) valov, ki imajo precej nižje frekvence (1-30 Hz) kot prostorski seizmični valovi. Pri aktivnem MASW generiramo seizmične valove z udarci kladiva, pri pasivnem MASW in pri metodi mikrotremorjev pa uporabljamo seizmični nemir naravnega in umetnega izvora, ki je stalno prisoten v okolju.

V južnem delu Ljubljane, za katerega so značilni mehki sedimenti in izraziti lokalni seizmološki vplivi na potresne valove, smo izvedli test aktivne in pasivne MASW metode ter metode mikrotremorjev. Testno območje se nahaja na Dolgem bregu ob Ljubljanici, kjer je debelina kvartarnih sedimentov okoli 25 m. Pri aktivnem MASW smo prvič uporabili geofone pritrjene na posebnih nosilcih povezanih s trakom (»land streamer«), ki omogoča hitro premikanje linearne razvrstitve 24-ih geofonov v medsebojni razdalji 1 m. Pri pasivnem MASW smo uporabili križno razvrstitev 2 x 12 geofonov v medsebojni razdalji 5 m. Meritve mikrotremorjev pa smo izvedli s posebnimi trikomponentnimi seizmografi. Pokazalo se je, da je aktivna MASW metoda najbolj uporabna na območjih, kjer ciljna globina ne presega 30 m, pasivna MASW metoda pa tudi pri večjih globinah. Prednost metode mikrotremorjev (HVSR) je, da daje neposredno oceno osnovne resonančne frekvence sedimentov. Pri slednji smo hitrostni profil določili z eno-dimenzionalnim modeliranjem spektralnega razmerja obeh vodoravnih glede na navpično komponento zapisa.

V 25 m debeli plasti kvartarnih sedimentov v katerih prevladujeta glina in pesek smo ugotovili hitrosti strižnih valov v razponu 50-200 m/s, v podlagi iz paleozojskega peščenjaka, konglomerata in skrilavca pa 350-400 m/s. Pod 1-2 m debelo površinsko nizkohitrostno plastjo je 1-1,5 m debela višjehitrostna plast (120-150 m/s). V globini 2-7,5 m sledi nižjehitrostna plast (50-120 m/s). Med 7,5 m in 25 m je hitrost po aktivnem MASW in mikrotremorjih dokaj stalna (150-210 m/s), po podatkih pasivnega MASW pa postopoma narašča od 150 do 250 m/s. Ujemanje hitrostnih profilov določenih z različnimi metodami je bilo zadovoljivo. Povprečna hitrost sedimentov v vrhnjih 30 m ($V_{S,30}$), ki se po standardu Eurocode 8 uporablja za klasifikacijo tal v potresni mikrorajonizaciji, je med 120 in 145 m/s. To bi uvrstilo obravnavana tla v vrsto D (Vs<180 m/s). Če pa upoštevamo še dodaten opis stratigrafskega profila, pa je bolj ustrezna uvrstitev v S_1 (Vs<100 m/s) saj profil vsebuje debelejšo plast zelo mehkih glinenih sedimentov z visoko vsebnostjo vode.

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