

A STUDY OF SITE EFFECT USING SURFACE-DOWNHOLE SEISMIC DATA IN A MINING AREA

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ABSTRACT

The aim of this study is to examine the phenomenon of site effect using surface-downhole seismic data caused by mining tremors in the Upper Silesia Coal Basin (USCB). The USCB is located in southern Poland and as a consequence of underground mining operations about 1000 mining tremors occur annually with a local magnitude of $M_L \geq 1.5$. The strongest event which occurred on 09.02.2010 reached $M_L=4.2$ and the peak ground acceleration (PGA) observed was approximately -2 m/s^2 . Induced events which can be treated as minor shallow earthquakes also have an impact on the surface. Thus, monitoring of ground motion is carried out and provided by the Central Mining Institute in this area – the Upper Silesian Seismological Network USSN (data are available as “episode USCB” on the IS-EPOS platform at <https://tcs.ah-epos.eu/>).

Analysis of the site effect was done using data from two stations each containing 2 sensors, one on the surface and one 30 m downhole. The station includes one accelerometer on the surface and one in the 30 m downhole. This study was done using ground motion recordings of underground mining events with $M_L \geq 2.3$ from January 2014 to June 2017. In the first step, the amplification factors were calculated as a ratio between the surface and downhole PGA. Next, transfer functions of both components were calculated using surface and downhole data and HVSR (Horizontal to Vertical Spectral Ratio) curves were obtained. All those results were compared with each other, particularly in terms of the impact of the vertical component. Profiles of shear waves up to 30 m were also used in this study. The result shows that the vertical component is amplified in a different manner to that of the horizontal. Moreover, the results of these analyses allow for a better understanding of the amplification phenomena caused by the surface layer in this area.

Keywords: amplification, downhole measurement, HVSR, transfer function

1. INTRODUCTION

Site effect is an important component determining seismic effects on the ground. The site response is related to the geological structure of the surface layer and manifests itself as an amplification of measured ground motion. The smaller the shear wave velocity in the surface layer, the greater the amplification effect. Amplification factor takes about value one for firm rock, and for poorly consolidated soil it can have greater values (Kawase, 2003).

The amplification effect of the surface layer can be estimated in many ways. If we consider the amplification factor as the difference between ground motion amplitudes on the surface and on firm rock, then the best way to estimate this is calculating the ratio of acceleration amplitudes on the surface and on the firm rock, respectively (Borcherdt, 1970). However, the surface measurement of ground motion on firm rock is often not available. Therefore, other surface methods could be used, for example: the Horizontal to Vertical Spectral Ratio (HVSR) proposed by Nakamura (1989). Nevertheless, interpreting these results is not so easy (Bard, 2004). The amplification factor depends on the shear wave velocity and geology structure. Thus the 1997 Uniform Building Code (UBC), the 1997 NEHRP (National Earthquake Hazard Reduction Program) Recommended Provisions for Seismic Regulations for New Buildings and Other Structures, and the 2000 International Building Code (IBC) have all adopted 30-meter velocity as the primary basis for classifying a site for purposes of incorporating local site conditions in the estimation of strong ground motion. We can find something similar in the European Code (Eurocode-8). The local geological structure can also have additional

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impact on ground motion (e.g. edge effect). In such case, a detailed knowledge of geological profiles is needed for a proper interpretation of the site effect. Borehole measurements also could help in improving understanding of this phenomenon (Cadet et al. 2012).

Induced events have smaller magnitudes than natural ones, so can be treated as small shallow earthquakes. However, the intensity of such anthropogenic events is often large enough ($M > 5.0$ and up to 7.9, Davies et al. 2013 and references therein) to cause hazards and local or regional devastation (e.g. Di mana et al. 2012; Soeder et al. 2014). Therefore, all the above methods and solutions also could be adopted for induced seismicity research.

The Upper Silesia Coal Basin (USCB) is an area where seismicity is induced by the mining exploitation of coal, and it is one of the regions of Poland where seismicity is relatively substantial. Therefore, a wide range of specialised analyses (e.g. Lasocki and Idziak, 1998; Stec and Drzewiecki 2012; Mutke et al. 2015 Chodacki, 2016, Zembaty et al. 2017) have been conducted on this area. Likewise, site effect studies were also done for other induced seismicity area like the Legnica Głogow Copper District (Olszewska and Lasocki, 2004) or the Karvina region (Lednicka and Kalab, 2016).

Recently, the impact of induced seismicity has been a source of rising scientific and public concern, taking into account growing needs to develop new methods for the exploration and exploitation of geo-resources. The growing importance of seismic-induced issues is also evident in the development of various research infrastructure (RI) for that purpose. An example of such RI is the Thematic Core Service – Anthropogenic Hazard (TCS-AH) which is being developed by fourteen European research institutions in the framework of the work package WP14 of the EPOS IP infrastructural project (H2020-EU.1.4.1.1. in the years 2016–2019). The main TCS-AH service is the IS-EPOS platform which contains special datasets related to induced seismicity – episodes, dedicated applications, and a rich document repository (tcs.ah-epos.eu). The USCB datasets are available through the IS-EPOS platform as a USCB episode.

The paper shows the result of the analysis of site effect carried out using surface-borehole seismic motion caused by mining tremors in the Upper Silesia Coal Basin (USCB). The amplification factors were calculated in a time and frequency domain. The result was discussed for different magnitudes, epicentral range and seismic intensity. The results of these analyses allow for a better understanding of the amplification phenomena caused by the surface layer in this area.

2. RESEARCH AREA

The USCB is located in the southern part of Poland and in the north-east part of the Czech Republic. The USCB is an area where intense extraction of multiple coal seams takes place in geological formations of Carboniferous up to 1200 m deep. Underground coal mining in USCB has been associated with the occurrence of induced seismicity with seismic events of maximum magnitude around 4.0 (Marcak and Mutke 2013). The area of the USCB within the borders of Poland is estimated at about 5400 km². Current exploitation takes place in about 19% of an area which is heavily urbanised. Because of this, the seismic impact on buildings and residents is a major problem. Therefore, monitoring of induced seismicity is carried out, independently from the mine service, by the Central Mining Institute. The datasets are available through the IS-EPOS platform (<https://tcs.ah-epos.eu/login.html>) as a USCB episode. The network for ground motion monitoring is equipped with 7 free-field surface triaxial accelerometers GeoSIG AC-63 and 2 downhole accelerometers GeoSIG AC-63DH located in 30 m deep boreholes. Thanks to that, 2 sites with surface and downhole ground motion measurements (Imielin and Miechowice) are available. The location of these stations along with the epicentres of the recorded seismic events during the time period Jan 2014 up to Jun 2017 are shown in Fig. 1. The areas of these mines in which underground work induced the recorded events are also shown. The magnitude of the registered events varies from 2.3 up 4.1. The PGAs registered by surface stations were up to 0.37 m/s².

The signal to noise ratio was checked using Power Spectral Density (PSD) in order to choose records with good quality and recognize an appropriate frequency band. The station Imielin registered 273 and Miechowice 56 events with appropriate quality by both surface and downhole sensors. The appropriate frequency is up to 20Hz. The distribution of magnitude, epicentral distance and surface Peak Horizontal Acceleration (PHA) of both sites are shown in Fig. 2. The PHA is the maximum length of horizontal acceleration, $PHA = \max_t(\sqrt{a_{NS}(t)^2 + a_{EW}(t)^2})$, where $a_{NS}(t)$ and $a_{EW}(t)$ are the time histories of acceleration in two perpendicular horizontal directions. The spatial distribution of events is related to the mine areas. Station Imielin is located in an area free of mining work, therefore, the smallest epicentral distance was 2.5 km. In contrast, Miechowice

site is located close to 3 different mines, so the closest seismic event to this station occurred within a distance of 0.7 km. Moreover, the registrations at that site may be classified, according to epicentral distance, into two groups. The first one consists of the records with the smallest epicentral distance – less than 2.1 km which had an extreme PHA (Fig. 2b – almost all red dots); the second group consist of records with a distance up to 10 km or more which had a PHA less than 0.013 m/s^2 (Fig 2a – blue, grey and 4 red dots). The Miechowice stations did not register events with epicentral distance between 2.1 to 10.0 km due to the spatial distribution of the mine areas. The maximum PHA was 0.37 m/s^2 for the Miechowice surface station. The surface-Imielin station's maximum PHA was 0.16 m/s^2 .

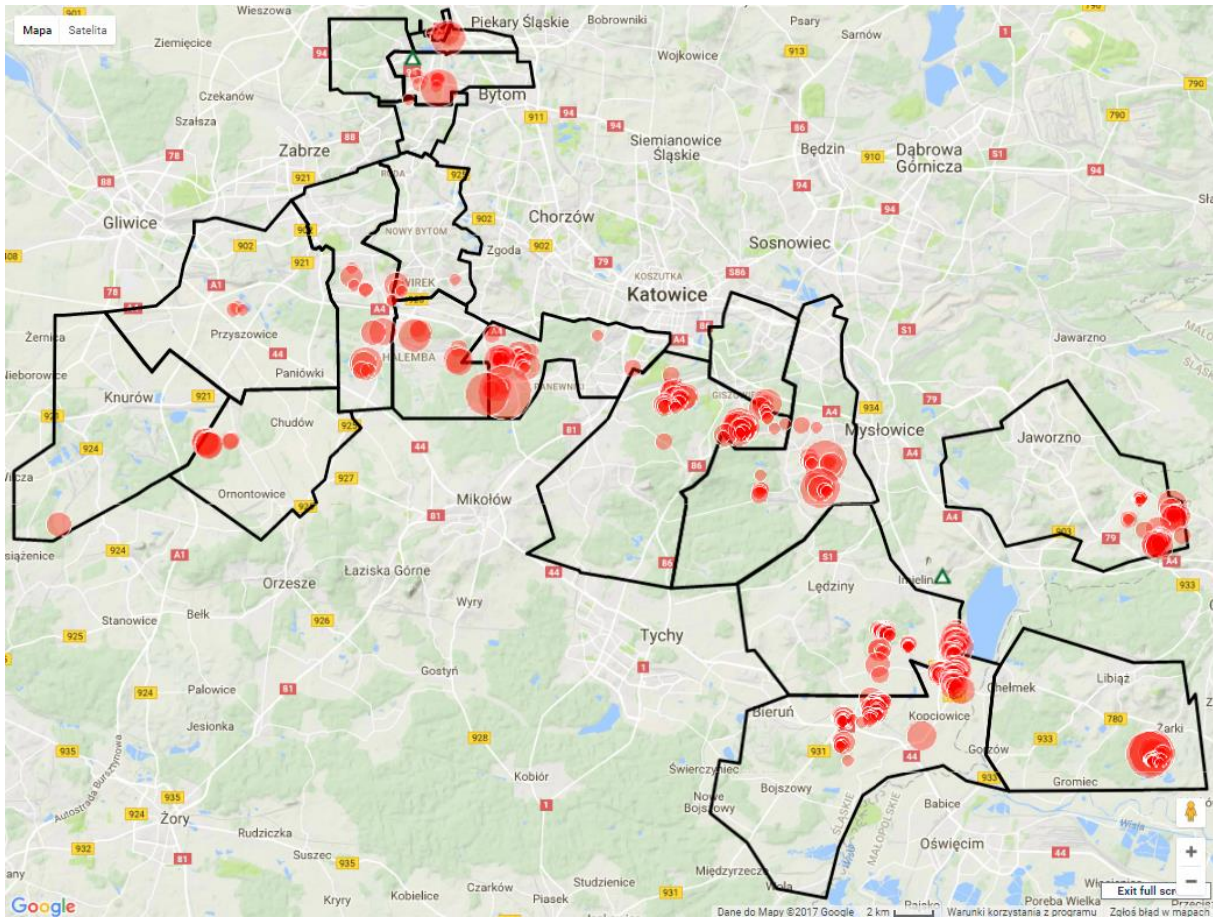


Figure 1. Map with the location of ground motion stations and the epicenters of seismic events which induced accelerometric signals. Triangles indicate the locations of the stations. Red circles – epicenters of events. Black lines – mine areas.

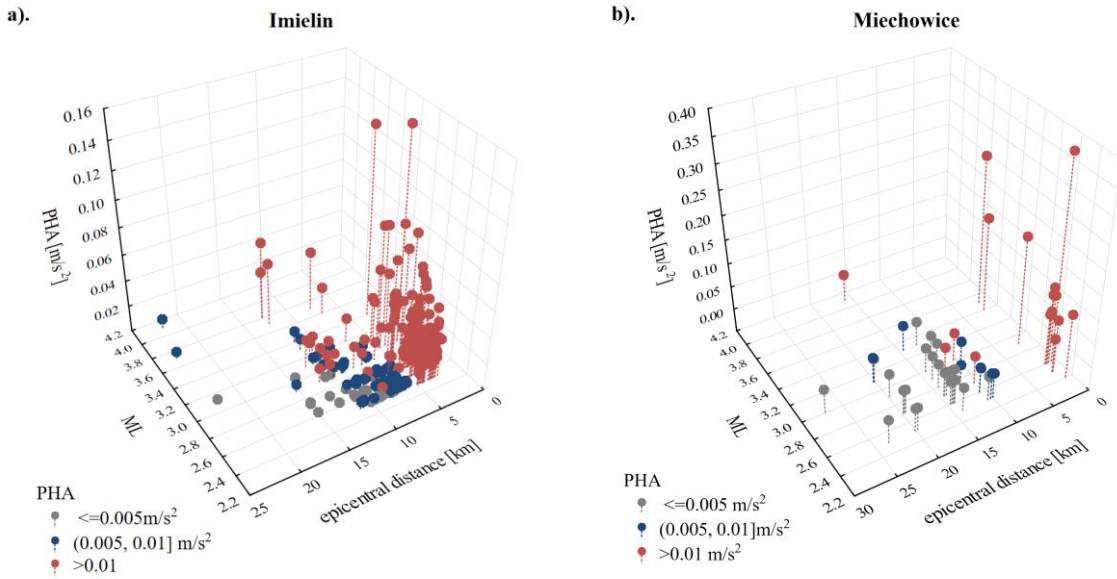


Figure 2 A distribution of ground motion data with respect to source magnitude and source-receiver epicentral distance registered by Imielin (a) and Miechowice (b) surface station.

We expect that the body-waves are mostly recorded – the epicentral distances are too small that surface waves could be observed. However, in the case of events with greater magnitudes, at a depth of up to 1 km and an epicentral distance to the stations greater than 3 km, surface waves could be also observed. The amplification behaviour of these waves by the surface layer may differ from the corresponding body wave amplification. Therefore, the results will be calculated for different epicentral distances, magnitudes and PHA range. In particular, differences of local amplification at Miechowice station are expected, due to the epicentral distance variations of the events.

Fig. 3 presents examples of ground motions recorded at Imielin and Miechowice stations. The graphs illustrate the ground motion for every component (surface and downhole) caused by the event from Ziemowit Mine occurring on 2015-01-08 at 20:14:13 with a local magnitude of 2.7, at a distance of 3.5 km (Fig. 3a-b). The observed amplification factors at Imielin station were 2.19, 3.95 and 2.01 for the NS, EW and vertical component, respectively. Fig. 4 presents the records at Miechowice station (surface and downhole) caused by an event that occurred in Bobrek Mine on 2015-01-05 at 18:50:44 with a local magnitude of 2.6, at a distance of 0.7 km. The amplification factors for Miechowice station for that event were 16.84, 3.48 and 1.42 for the NS, EW and vertical component, respectively. The significant difference in amplification coefficients at these stations may be related to the various geological and seismic factors.

The Carboniferous formations are covered with triassic and quaternary deposits. Triassic and especially quaternary soils are characterised by low S-wave propagation velocity and constitute the primary cause of seismic amplification in the USCB area (Mutke and Stec, 1996). Quaternary sediments (sand, gravel, clay) are found in the entire USCB area - from 0 to 100 m and are characterised by S-wave velocity in the range of 100 to 400 m/s. The shallow seismic survey was done close to both sites in order to recognise the shear velocity profiles (Fig. 5). A mean shear velocity up to 30 m is equal to 423 m/s at the Imielin site and 352 m/s at the Miechowice site. These gives the ground types B at the Imielin site and C at the Miechowice site – according to the European Standard ‘Eurocode 8: Design of structures for earthquake resistance (Part1)’ (Eurocode:8, 2005). Despite this fact the stratigraphy profiles (Fig. 5) show that geological structures for those stations are completely different. The lithological profile in Miechowice clearly shows that the quaternary formations are 11 m high and are located directly on Triassic dolomites. In Imielin, the quaternary overburden is 10 m and is located on tertiary clay. The main difference in the geological structure of the two studied sites is the characteristics of the layers under the quaternary soft layers.

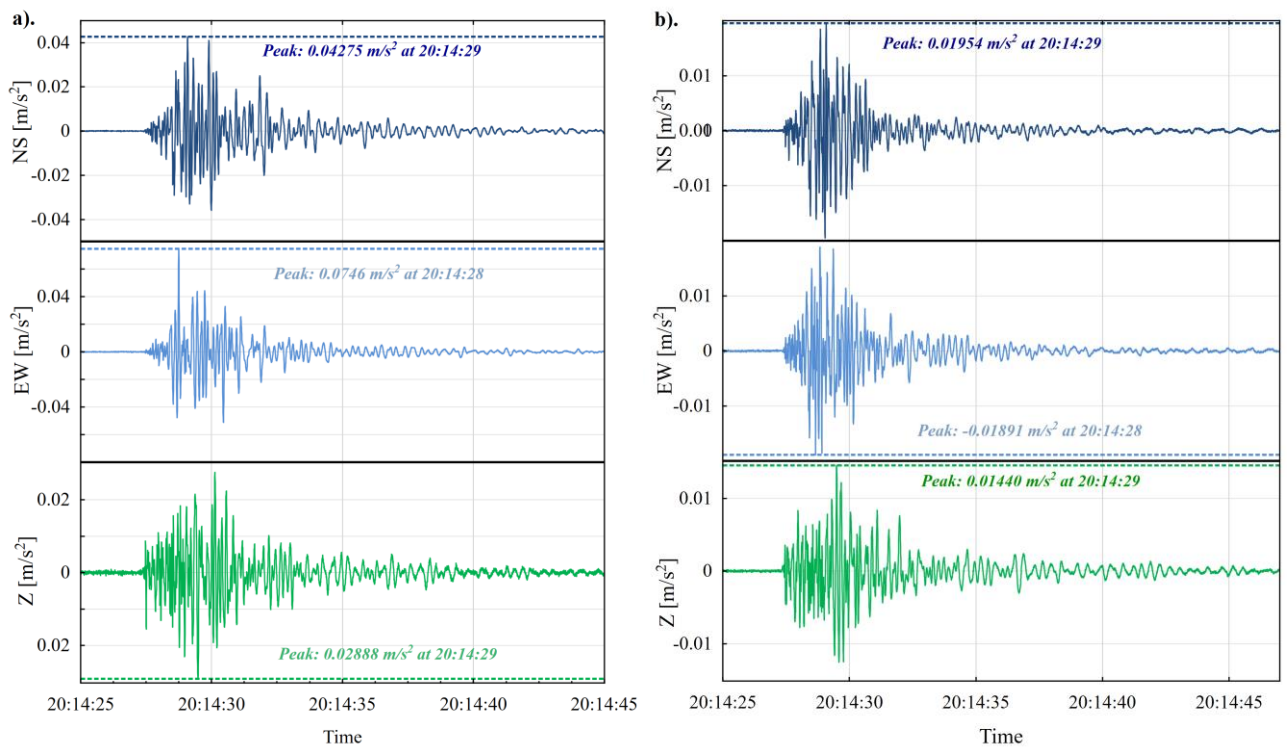


Figure 3. Ground motion record at Imielin station (a-surface, b-downhole) caused by an event occurring in Ziemowit Mine on 2015-01-08, at 20:14:13, with a local magnitude of 2.7, at a distance of 3.5 km.

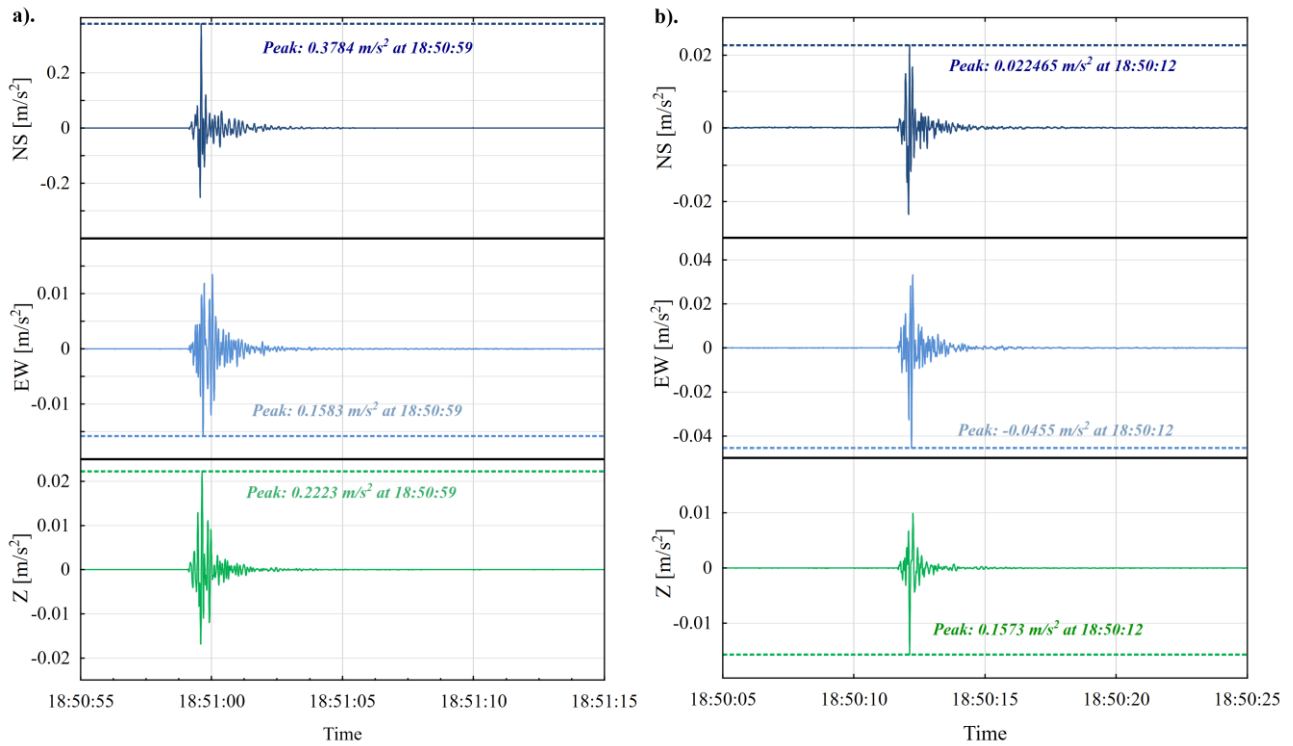


Figure 4. The ground motion record at Miechowice station (a-surface, b-downhole) caused by an event occurring in Bobrek Mine on 2015-01-05, at 18:50:44, with a local magnitude of 2.6, at a distance of 0.7 km.

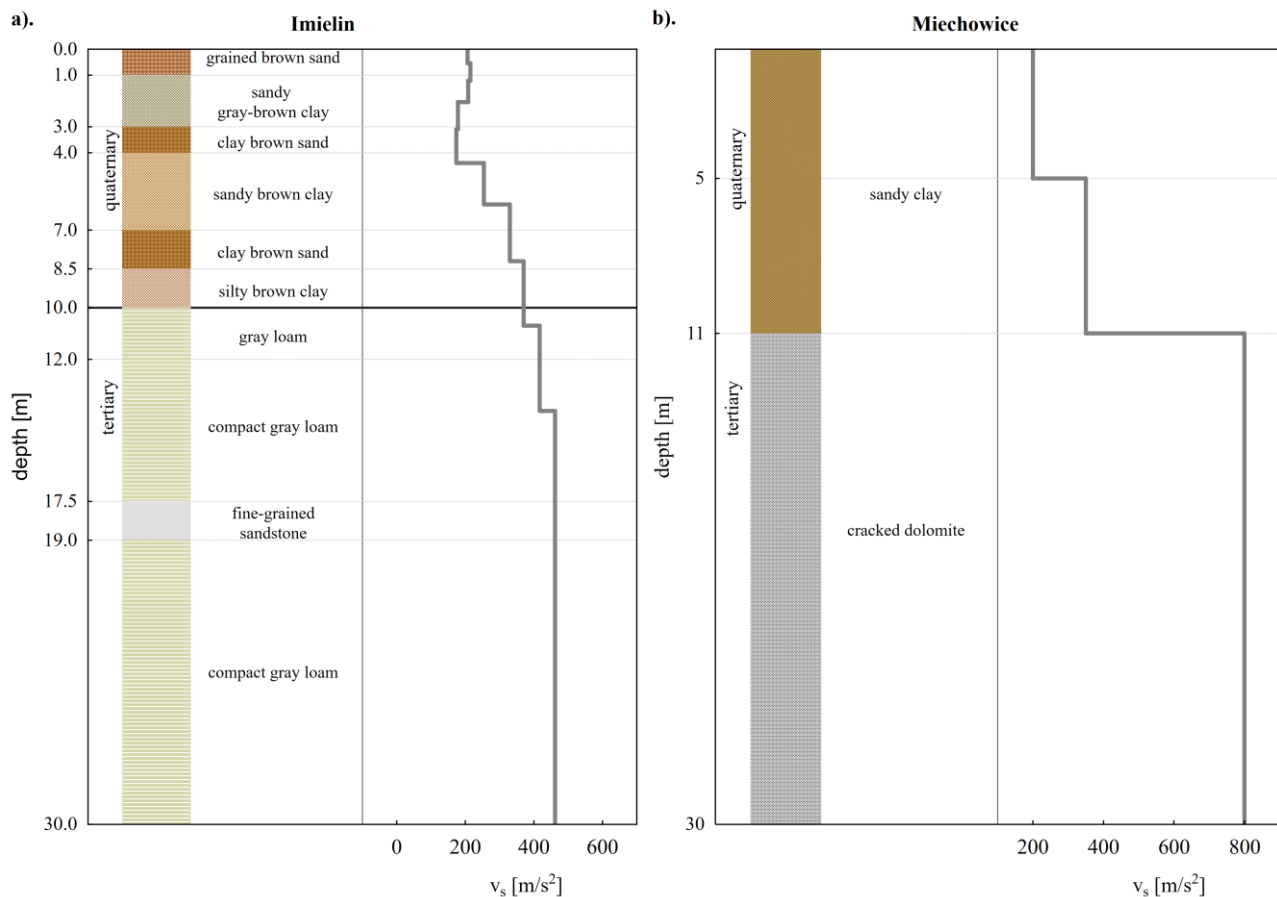


Figure 5. Geology and shear velocity profile of Imielin (a) and Miechowice (b) stations.

3. METHOD

The amplification factors were calculated in time and frequency domains. The amplification factors in the time domain were calculated as a ratio between surface and downhole PGA for every component. They were determined as an average PGA ratio obtained for particular events. That shows how many times surface PGA is greater or smaller than the downhole measurements for all components. Analysis was done for both horizontal components (NS, EW), the vertical one and also for the combining horizontal component (PHA). The amplification in the frequency domain was calculated using two methods, both applying spectral ratio (SR) calculations. The SR between the surface and downhole measurements of every component were calculated in the first method. This corresponds to the transfer function (TF) between 30 m and the surface, which shows how the components are amplified by this layer in the frequency domain. It is similar method as the Standard Spectral Ratio (SSR) described by Borchardt in 1970 but downhole station was used instead station located on a bedrock outcrop. The second frequency method is the HVSR (Nakamura, 1989) method. The HVSR method is one of the mostly well-known and widely used methods for site effect estimation (e.g. Bard, 2008; Mucciarelli et al., 2009 and references therein) using only surface measurements. A main assumption of this method is that the vertical component is not amplified by surface layer and therefore it may sustain an adequate approximation of the downhole measurements. The HV ratio could be obtained from earthquake records or from ambient seismic noise vibrations (Mucciarelli et al., 2003). The obtained results depend on the wave type and its origin. Therefore, it is very important to know the details on the nature of the corresponding waves in both cases (Bard, 2004).

The records of induced seismic events were used for spectral ratios calculation. The body waves are mostly expected due to a small epicentral distance (median around 3 km). Nevertheless, surface waves may also appear in the measured wavefield especially when greater epicentral distances are considered. Thus, the interpretation of results was done for different epicentral distances.

The spectral ratios – surface-downhole and surface HV – were calculated in the same manner as recommended by the Sesame user guide (Bard, 2004). The records of induced seismic events were used in both calculation

of SR – surface-downhole SR and HVSR. In the first step, Fast Fourier Transformations (FFT) were obtained, next the spectra were smoothed using the Konno and Ohmachi smoothing technique (Konno and Ohmachi, 1998). The horizontal component was merged as a geometric mean of the two components. Then, the appropriate spectral ratios for each event were calculated. The following SR were calculated: Surface-downhole SR of vertical, NS-horizontal, EW-horizontal and merged horizontal components as well as the surface horizontal and vertical SR (classic HVSR). As a last step, the average and standard deviation of all SR types was obtained. Moreover, the average and standard deviations SR of the surface-downhole measurements was also calculated for the chosen class of local magnitude, the epicentral distance and the surface peak horizontal acceleration (PHA).

4. RESULTS

4.1 Amplification in the time domain

The amplification factors in the time domain were calculated as a ratio of the surface and downhole PGA at Imielin and Miechowice stations. That factors were obtained for NS, EW and merged horizontal components and for the vertical one. Table 1 shows the summary statistics for the amplification factors of each component. Comparing the results for these sites, it can be seen that the average amplifications at the Imielin site for each component are almost the same, whereas at the Miechowice site they differ significantly. The Imielin amplification factors were around 2.1 - 2.4, only the value for the EW component was slightly greater (2.68). The greatest amplification factor was obtained for the Miechowice site for the NS horizontal component (6.7). A significantly smaller amplification factor was obtained for the EW-horizontal and vertical component at this station. The standard deviations of the amplification factors indicate that the Miechowice station coefficients are characterised by greater variability than at the Imielin site. The ground class for those station (B- Imielin, C-Miechowice) also shows that amplification effect at Miechowice station is greater than Imielin Station. Furthermore, a significant dependence was found between the amplification and epicentral distance as well as the surface PGA for horizontal components.

Table 1. PGA amplification factor from downhole to the surface at the Imielin and Miechowice stations.

| Component | Imielin station | | | | Miechowice station | | | |
|---------------|-----------------|-----|-----|-----|--------------------|-----|-----|------|
| | mean | SD | min | max | Mean | SD | min | max |
| Horizontal-NS | 2.3 | 0.6 | 1.3 | 5.4 | 6.7 | 2.8 | 1.8 | 16.7 |
| Horizontal-EW | 2.6 | 0.7 | 1.1 | 5.3 | 4.8 | 3.0 | 1.0 | 19.4 |
| Vertical | 2.1 | 0.5 | 0.8 | 4.5 | 3.3 | 3.9 | 1.1 | 29.9 |
| Horizontal | 2.4 | 0.5 | 1.0 | 5.4 | 4.6 | 2.2 | 1.5 | 18.1 |

4.2 Amplification in the frequency domain

In the next step of the analysis, the surface-downhole spectral ratios (SR) were calculated using data from Imielin and Miechowice stations. That is the transfer function (TF) between a depth of 30 m and the surface, which shows how components are amplified by this layer in the frequency domain. Calculations were done for NS, EW and the merged horizontal component and the vertical one; likewise a calculation of amplification factors was done. Fig. 6 presents the obtained averages with standard deviations of the surface-downhole SRs for both sites and for all components. The shape of TF curves for Imielin and Miechowice differ in the number of local maximum and its frequencies. From the graph in Fig. 6a, three local maxima of horizontal components for frequency 2.5 Hz, 6.7 Hz and 10.8 Hz can be clearly seen. The amplitudes of those peaks are respectively- 5.8 up to 7.5 Hz, 5.3 up to 5.9 Hz and 4.8 up to 4.9 Hz. The greatest values of those peaks are for the EW component and the smallest are for the NS-component. Similarly, the amplification factor for the EW component was greater than the NS component (Table 1). The thickness of the layers which could be responsible for those peaks may be equal to about 40 m, 16 m and 10 m, respectively, according to $v_{s,30}$ for that station. From the Imielin lithology profile in Fig. 5a, it can be seen that at about 16 m there is contact between fine-grain sandstone and loam, and at about 10 m tertiary and quaternary deposits come into contact. Additional information about geological structures are needed to find out the layers which are responsible for the first peak. It is difficult to find such clear peaks based on the Miechowice site's results (Fig. 6b). Taking into account the merged horizontal component of TF, local maximums are found for frequency 5.0 Hz, 6.2 Hz,

7.5 Hz and 10.2 Hz. The amplitudes of those peaks are 9.3, 7.8, 7.3 and 5.4, respectively. Thus, the thickness of resonance layers, according to the mean shear velocity, could be equal to 17.6 m, 14.2 m, 11.7 m and 8.6 m. As shown in Fig. 5b, there is a main layer boundary at a depth of 11 m. The remaining boundaries of the layers may be related to the degree of sandstone graining or how the dolomite was cracked. Moreover, the Imielin transfer functions for horizontal components are comparable, unlike Miechowice. There are a few of differences between NS and EW-horizontal components of TF for the Miechowice site. The differences are related to the shape of curves, frequency and amplitudes of local maximums. For a frequency of 5 Hz, the TF_{NS} has a first local minimum and simultaneously the TF_{EW} has a first local maximum. The position of the next two local curves' maximums is similar (around 6.2 Hz and 7.5 Hz) but the amplitude difference is more than 3. This shows that measurements in both horizontal directions are significantly different. At the same time, the values of TH_{NS} are rather greater than TF_{EW} , which corresponds well with the calculated amplification factors in time domain (table 1). That result only shows the differences for NE-SW orientation. Therefore more detailed analysis should be performed in the future to check whether this effect is caused by anisotropy or other phenomena. The SR variability for the Imielin site is less than for the Miechowice site. That could be effect of site characteristic or the number of analysed data (no of events registered by the Imielin site is 273 and the Miechowice only 57). Therefore this analysis should be repeated in the future when more usefully data from the Miechowice site will be available.

The surface-downhole SR of the vertical component for station Imielin also varies from the Miechowice one. In a frequency range up to 10 Hz, the values of TF_Z are smaller than 2.5 but greater than 1 for the Imielin site. For a frequency up to 20 Hz, the amplitudes are greater than 3. The vertical component of TF for the Miechowice site, up to 4.5 Hz, is equal to almost 1 and then has a peak for a frequency of 9.2 with amplitude 4.8. Thus, the vertical component could be amplified by surface layers, so it depends on local conditions.

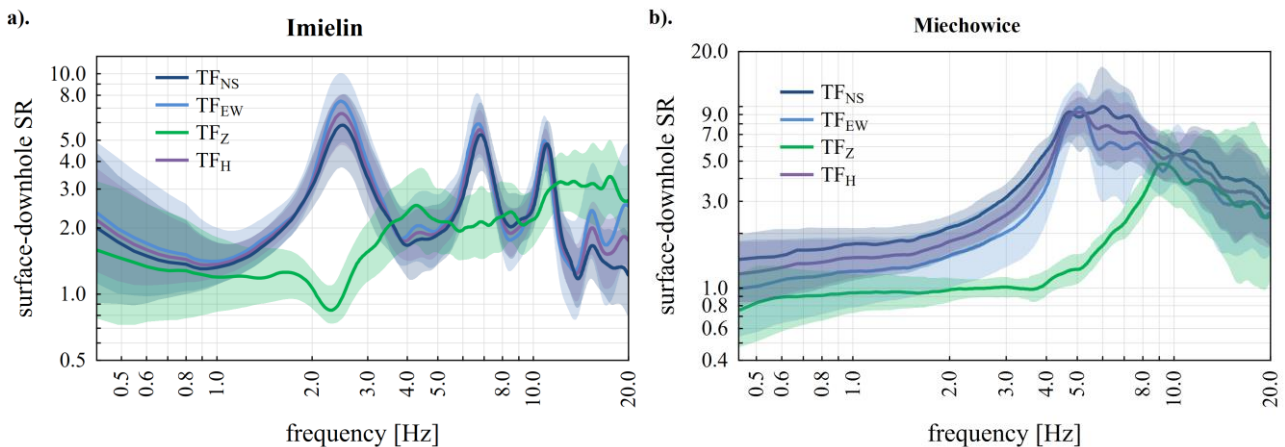


Figure 6. Surface-downhole spectral ratio of horizontal and vertical components at Imielin (a) and Miechowice (b) stations.

The next part of the analysis was to compare the average surface-downhole (SR) curves depending on the event size (M_L), epicentral distance and level of ground motion (parameterised by surface PHA). As was mention before, the type of the recorded waves depends on the epicentral distance – e.g. the surface waves are registered at a longer epicentral distance than the body waves. Thus, the observed amplification could vary significantly in size if waves are amplified in a different way. The average and standard deviation TR of the merged horizontal and vertical component for different classes of magnitude, epicentral distance and PHA were calculated for both sites. The results obtained from that part of the analysis are shown in Fig. 7 (Imielin site) and Fig. 8 (Miechowice site).

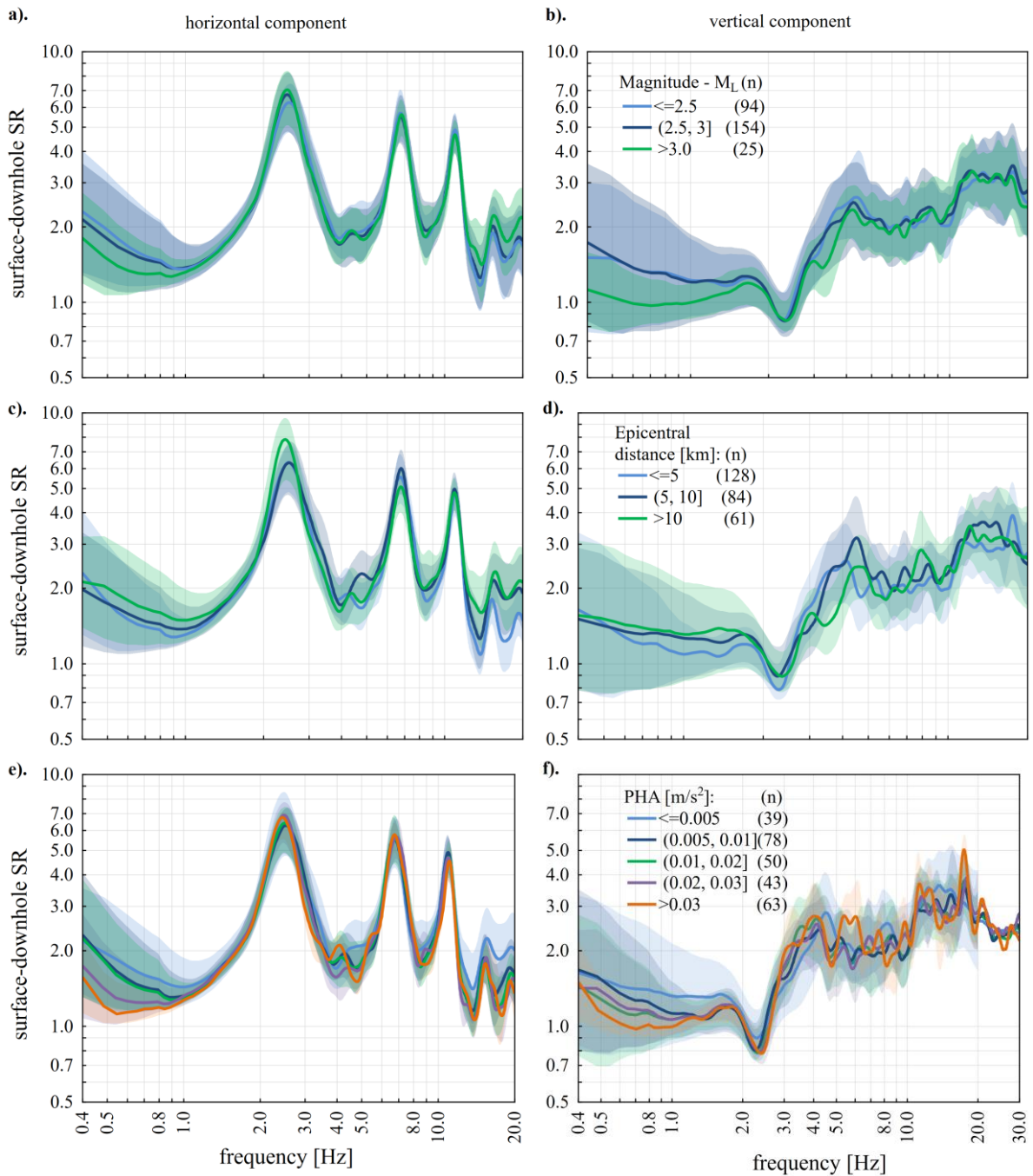


Figure 7. Surface-downhole spectral ratio of horizontal and vertical components with respect to source magnitude (a,b), source-receiver epicentral distance (c, d) and surface PHA (e f) at Imielin station. Numbers in brackets shows the number of data analysed in every groups.

As can be seen from Fig. 7 a, c, e, the TF of horizontal components for the chosen class of parameters differ slightly at the Imielin site. Greater differences are observed for vertical component (Fig 7 b, d, f), particularly in the case of the epicentral distance and PHA. However, those fluctuations are rather not significant. By contrast, the differences of TH for the Miechowice site are significant for the epicentral distance and PHA (Fig. 8). The records caused by events with epicentral distance smaller than 2.2 km in the same time had the greatest surface PHA (red dots in Fig. 2b). These measurements, due to the surface distribution of seismic events, can be easily divided into two groups. As mentioned before, seismic recordings over such a short distance consist of only body waves. Thus, the TF characteristic is so different in this case. The greatest peak is for different frequency and its amplitude is almost double.

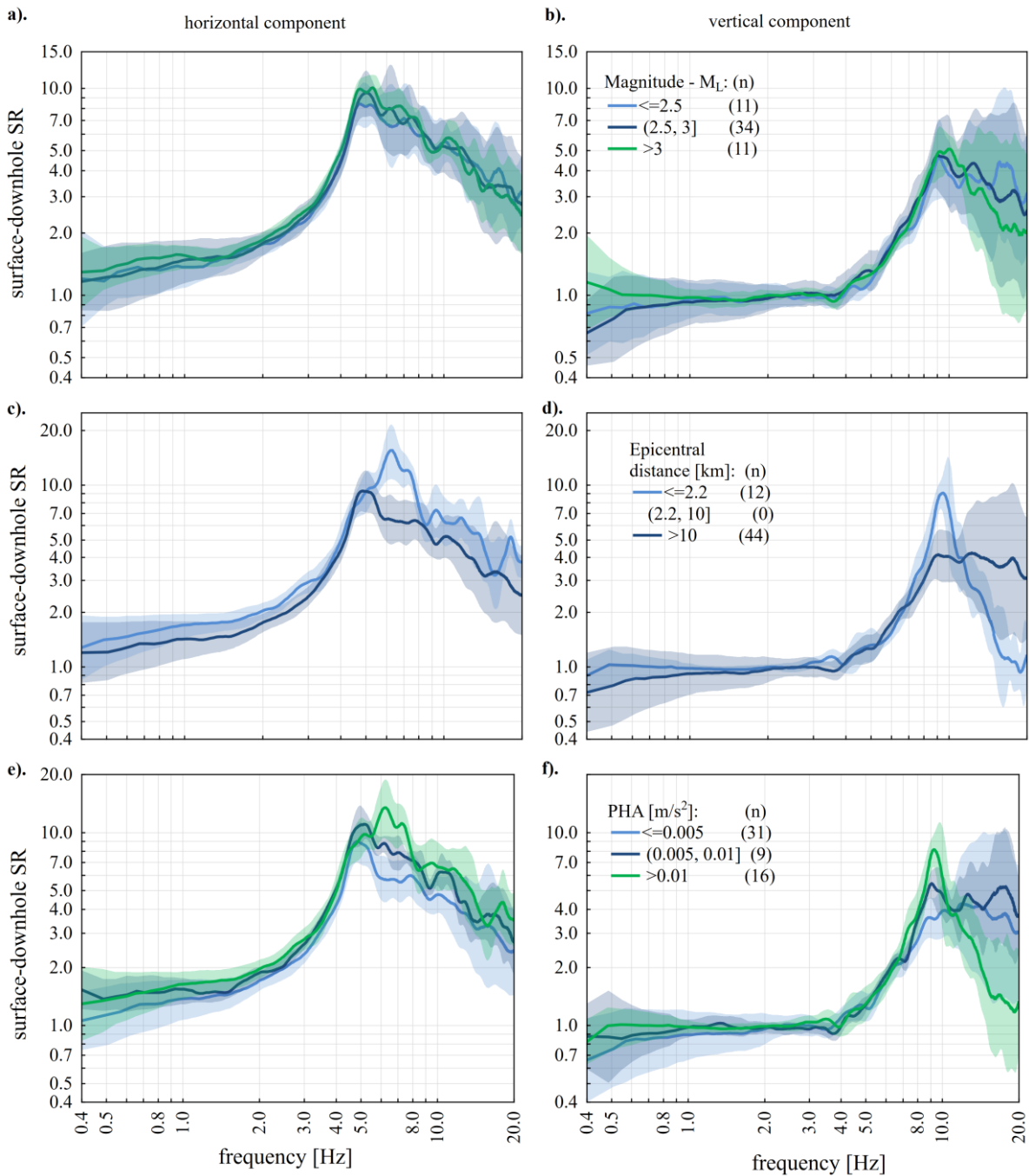


Figure 8. Surface-downhole spectral ratio of horizontal and vertical components with respect to source magnitude (a,b), source-receiver epicentral distance (c, d) and surface PHA (e f) at Miechowice station. Numbers in brackets shows the number of data analysed in every group.

HVSR was used for estimating the amplification for the Miechowice and Imielin sites. This method is based on surface measurements only. Thus, records from surface stations are used in this part of the analysis. Fig. 9 compares the TF obtained from the above analysis and the HVSR curves. The merged horizontal components (surface and downhole) were used for this comparison – HHSR (Horizontal to Horizontal Spectral Ratio). As can be seen from that figure, there is a satisfactory compatibility between the graphs for the Imielin site, compared to Miechowice site. The Imielin HVSR curve has also three main local maximums found in the same frequency as the HHSR curve. The amplitudes of the HVSR peaks is almost too times smaller than the HHSR peaks. Taking into account the Miechowice site, the HVSR and HHSR curves vary in the numbers of local maximums and their frequencies. From the graph above we can see that more comparable to the HVSR curve is the HHSR curve calculated for an epicentral distance above 10 km (dark blue line in Fig. 8c) or for the

smallest PHA. This means that the HVSR result is more comparable when data with only body waves are excluded.

Moreover, the values of the amplification factor shown in Table 1 correspond well with the amplitudes of HVSR peaks for the Imielin site.

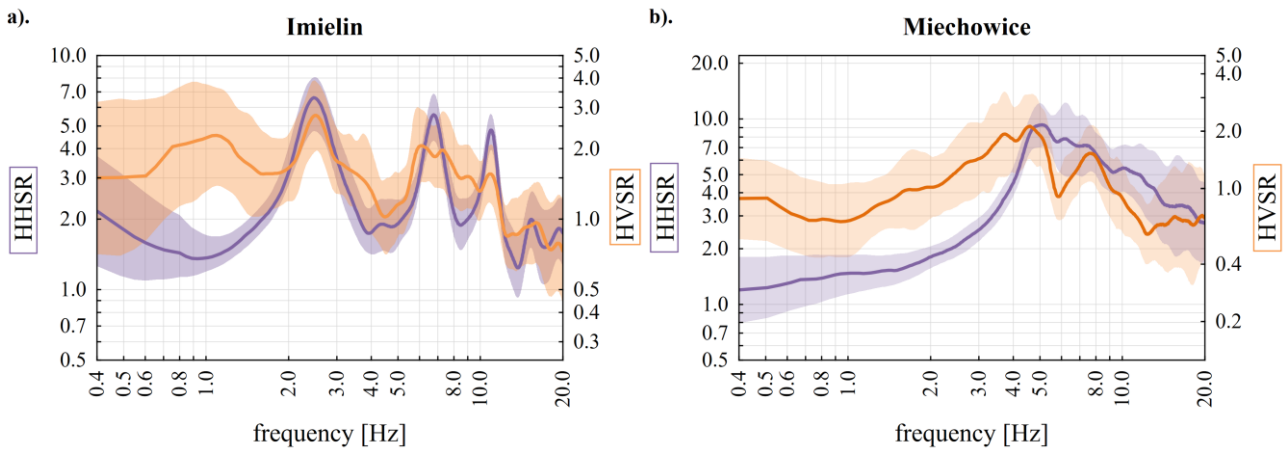


Figure 9. A HHSR and HVSR at Imielin (a) and Miechowice (b) stations.

5. CONCLUSIONS

In this paper, the amplification factors were calculated for the Imielin and Miechowice sites. Thanks to a comparison of the obtained results and profiles of shear waves up to 30 m. characteristic of both site were examined. The presented result shows that the surface layer can play an important role in the amplification of ground motion. The geological structure and therefore a shear mean velocity up to 30 m is correlated with the amplification factor.

Transfer functions of both components were calculated using surface and downhole data. We expected that the amplification behaviour of these surface waves by the surface layer may differ from the corresponding body wave amplification. In the case of induced seismicity, the body waves are mostly recorded – the epicentral distances are too small that surface waves could be observed. However, surface waves could also be observed, in the case of events with greater magnitudes, at a depth of up to 1 km and an epicentral distance to the stations greater than 3 km. The obtained result shows that the distance between the event and the station is important in the case of induced events. The amplification factor is significantly different for shorter distances than for longer ones. Additionally, the characteristics of transfer function calculated for registration caused for short distances differ from those that are longer. Nevertheless, additionally study are needed to confirm that the main reason for such a situation is the fact that for such short distances, surface waves are not registered. This phenomena could be also caused by incidence angle or back-azimuth.

The HVSR curves were calculated and the results were compared with suitable transfer functions. Those results shows that the HVSR method could be used for estimating site effect in case of induced seismicity.

6. ACKNOWLEDGMENTS

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