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THE ACCELERATION RESPONSE SPECTRA FOR LEGNICA-GLOGOW COPPER DISTRICT

RZYSPIESZENIOWE SPEKTRA ODPOWIEDZI DLA REJONU LEGNICKO-GŁOGOWSKIEGO OKRĘGU MIEDZIOWEGO

Abstract

This paper presents average normalised acceleration response spectra calculated for mining induced seismic events which were recorded by twenty-one stations located in the area of Legnica-Glogow Copper District (LGCD). In this paper, 5246 ground motion signals with peak ground acceleration (PGA) over 0.03 m/s^2 were analysed. The ground motions were caused by 1886 mining events with M_L greater than 2 (energy $> 10^5 \text{ J}$), which occurred from 2004 to 2015. The design response spectra were estimated based on average normalised acceleration response spectra. Further analysis of results shows that the shape and amplitude of response spectra are strongly dependent on the event magnitude, the epicentral distance and the location of the stations. The obtained response spectra could be used for computing seismic forces which have impact on buildings response to ground motions caused by mining events in LGCD.

Keywords: Response spectra, induced seismicity, local amplification

Streszczenie

W pracy wyznaczono średnie znormalizowane przyspieszeniowe spektra odpowiedzi na podstawie zapisów drgań wstrząsów górniczych, zarejestrowanych przez 21 stanowisk akcelerometrycznych znajdujących się, na terenie Legnicko Głogowskiego Okręgu Miedziowego (LGOM). Do analizy wykorzystano 5246 rejestracje drgań gruntu o wartościach szczytowych powyżej 0.03 m/s^2 , wywołane 1886 wstrząsami górniczymi, o M_L powyżej 2 (energia od 10^5 J), które miały miejsce od 2004 do 2015 roku. Na podstawie wyznaczonych znormalizowanych przyspieszeniowych spektrów odpowiedzi wyznaczono wzorcowe spektrum odpowiedzi dla tego rejonu. Pokazano także, że kształt i amplituda spektrów odpowiedzi zależy od wielkości zjawiska, odległości epicentralnej oraz od miejsca. Otrzymane wzorcowe spektrum odpowiedzi może być wykorzystywane do obliczania sił sejsmicznych oddziałujących na budowle w wyniku drgań podłoża wywołanych wstrząsami górniczymi w tym rejonie.

Słowa kluczowe: Spektra odpowiedzi, sejsmiczność indukowana, lokalna amplifikacja

1. Introduction

Earthquakes and anthropogenic-induced seismic events (e.g. mining events, seismicity connected with oil and gas exploitation, water reservoirs impoundment) are sources of ground motions, which could have considerable impacts on the Earth's surface, particularly on buildings. The infrastructures affected by these strong forces may be damaged or even destroyed. The areas which are subjected to the influence of seismic events are monitored in order to assess the influence of ground motions on the structural buildings properties. The results of those measurements are interpreted and ground motion parameters are estimated. Consequently, special norms for observing, forecasting and modelling seismic impact in regions where tectonic earthquakes occur is needed. Therefore, seismic hazard studies are one of the fundamental methods of seismic risk analysis providing seismic hazard maps, showing e.g. the 10% PGA exceedance probability in 50 years at particular sites. (e.g. <http://www.share-eu.org> [Europe], <https://earthquake.usgs.gov/hazards/hazmaps/> [USA] and the references therein). Engineers use these maps and associated tools for earthquake resistant design of buildings and other infrastructures. Special rules and regulations in this field are covered by, among others, European Standard 'Eurocode 8: Design of structures for earthquake resistance (Part1)'.

Induced seismicity areas are characterised with lower intensity shocks than natural ones, however, the magnitudes of such anthropogenic events are often large enough ($M > 5.0$ and up to 7.9, [4, p. 171–185] and references therein) to provoke hazard and cause local or regional devastation [e.g. 5; 25, p. 4–19]. The issues related to induced seismicity are known and remain valid [7; 17, p. 385–396 and the references therein]; therefore, a wide range of specialised analyses [e.g. 24, p. 1766–782; 22, p. 1011–1026; 12, p. 2592–2608; 13, p. 7085–7101; 2, p. 158–173; 11, p. 5–15; 28, p. 1517–1537] have been conducted on such areas, in particular, Probabilistic Seismic Hazard Analysis (PSHA) [e.g. 30, p. 105–121; 15, p. 28–37]. Recently, the impact of induced seismicity has been a source of rising scientific and public concern, taking into account the growing needs to develop new methods for the exploration and exploitation of georesources, e.g. Shale Gas. These activities are often carried out on so far aseismic, yet populated areas. As expected, the infrastructure of aseismic areas is not adequately prepared for even relatively weak seismic effects. Because these areas are not affected by tectonic earthquakes, the expected PGA values, based on seismic hazard maps, are too low to have an impact on the infrastructure. This situation changes significantly if exploration of resources starts on the close vicinity of such areas, e.g. in the USA [8, p. 618–626]. Therefore, it is necessary to develop appropriate analyses for such areas in order to be able to assess the effects of seismic impact and to provide adequate resistance measures against them. Thus, the recent US Seismic Hazard Maps has been updated to include areas exposed to induced seismicity [23, p. 772–783]. The design response spectra proposed by the European Seismic Code, Eurocode 8, are inadequate for low intensity induced seismicity; however, due to its apparent impact, the spectra should be adapted to take these conditions into account [1; 33, p. 81–90]. This is especially true when the suitable database of ground motion catalogue is available.

The growing importance of seismic-induced issues is also evident by the development of research infrastructures (RI) for the purpose of addressing them. An example of such RI is the Thematic Core Service – Anthropogenic Hazard (TCS-AH) 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), and will be integrated with other thematic core services by EPOS Integrated Core Services (ICS). The main TCS-AH service is the IS-EPOS platform which contains special data sets related to induced seismicity – episodes, dedicated applications, and a rich document repository (tcs.ah-epos.eu). The platform is open to accommodate data integrated with other research projects and it is continuously being updated and improved through both the enhancement of current features and the implementation of new features.

In terms of buildings resilience, the amplitudes of the ground motions are less important than the oscillations caused by the abovementioned events. It can be assumed that the oscillations of buildings may be approximated by the movement of the oscillator with a single degree of freedom. Therefore, it is essential to identify the distribution of the maximum amplitudes of the oscillator with known damping and natural frequencies in response to ground motions – this distribution is called “response spectra” [10, p. 1097–1125]. On the basis of the estimated response spectra, the frequency band for the expected largest influences can be assessed – this corresponds to the dominant frequencies of the ground motions. Additionally, the response spectra are closely related to the local conditions; thus, the response spectra are assessed in relation to the ground type [9] – this is because the local amplification of ground motions varies with different ground types; this has connotations for the effects of the events observed on the surface. The response spectra are used in construction to assess seismic forces acting on the structures of the building which are caused by seismic events followed by ground motions [e.g. 3].

The knowledge of parameters of potential ground motions and their possible influence on the construction of building is useful at the stage of project works. Based on previous observations of ground motions and spectral amplitudes, ground motion prediction equations can be estimated – this enables the assessment of ground motion amplitudes induced by hypothetical earthquakes [e.g. 6, p. 43–104]. The average response spectra, representing rockburst seismic loading, are also useful for these kinds of analyses as they allow the dynamic verification of existing buildings and help in the designing of new objects [26].

Legnica-Glogow Copper District (LGCD), as an area where seismicity is induced by the mining exploitation of copper ore, is one of the regions of Poland where seismicity is relatively substantial. Thus, various researches have been conducted to assess the influence of ground motions on this area and on the surrounding building infrastructures. Examples of such research are: the estimation of the ground motion prediction equations (GMPE) for peak ground acceleration [e.g 19; 14, p. 1130–1155]; peak ground velocity and spectral amplitudes [19]; Probabilistic Seismic Hazard Assessment [15, p. 28–37]. A site effect which has an important impact on the value of the peak ground motion is also examined. The area is considered to have a uniform ground type because the actual area of the mine activity is rather small and the velocity wave in the surface layer is relatively uniform [18; 21]. Nevertheless,



the analysis of the HVSR (Horizontal to Vertical Spectral Ratio) curves [20] and also the residuals of the GMPE [19; 14, p. 1130–115] indicate that the local effect depends on location. The analysis of the ground motion shows also that there are two types of events in this area [31, p. 11–23].

- ▶ Records of type I occur rather often (return period of 3–6 months) with very short durations (1–2 s) and Fourier spectra shifted to higher frequencies (about 20–40 Hz). Despite this fact, these records have high values of peak ground accelerations ($PGA = 1.5\text{--}2 \text{ m/s}^2$) characterised by their low intensity in reference to the buildings and low peak ground velocity ($PGV < 2\text{--}3 \text{ cm/s}$).
- ▶ Records of type II occur rarely (return period 1-2 years) with longer durations than type I (about 5 s or more) and with the dominant part of the Fourier spectra below 5 Hz – similar to recordings of a weak, shallow earthquake. These records are characterised by their higher values of peak ground velocity ($PGV = 6\text{--}18 \text{ cm/s}$) and their significant, unfavourable influence on building infrastructure.

Type I ground motion has high PGA which corresponds to higher dominant frequencies (about 20–40 Hz); thus, its impact on the building is negligible – this is because, the frequency bands of the natural oscillations of the buildings is up to 10 Hz [29]. Therefore, the standard procedure for processing ground motion data from that area is parametrizes registration in frequency range of up to 10 Hz. This results in PGA which could have a significant impact on buildings by eliminating the influence of higher frequencies of type I ground motions. So this is ‘standardisation’ of PGA for the engineering purposes in that area. More detailed analyses of the impact of ground motion on building infrastructure are also prepared for that area [e.g. 32, p. 1403–1416; 27, p. 442–458; 16, p. 1769–1791; 33, p. 81–90]. One of them is the calculation of the average response spectra representing seismic rockburst loading for that region [26; 19; 32, p. 1403–1416] and also estimation of the design spectra for various ground types according to Eurocode 8 [33, p. 81–90]. Nevertheless, the latest proposed design spectra are based only on eighteen registration-intensive, type II ground recordings (with lower dominant frequencies) caused by two events.

The paper proposes new response spectra for horizontal and vertical components for LGCD area; thus, a seismic load can be defined for civil engineering purposes. The main advantages of these spectra are greater accuracy and unification in the frequency domain. These were achieved by using a large amount of data (5.246 ground motion records) and by avoiding negligible high frequencies, from structural point of view, which only concerns a part of the ground motion (10 Hz low pass filtration of input data). Further studies of the obtained spectra, possibly due to the substantial amount of available data, included analysis in relation to the scale of the event, the distance between epicentre and the stations and the division of response spectra due to the nature of the spectral curve.

2. Characteristics of the LGCD mining region

In Poland, induced seismicity is mainly related to mining activities. LGCD, located in north-central part of the Lower Silesia voivodeship, is an area where seismicity induced by underground mining is relatively substantial. There are three copper mines in the area – Lubin, Polkowice-Sieroszowice and Rudna; all of these are part of KGHM Polska Miedź S.A.

Strongground motions caused by underground mining operations have a negative influence on the surface and might even damage the nearby infrastructure. Considering the importance of the building infrastructure in the area, mines and local communities conduct continuous monitoring of ground motions caused by seismic events, which provides a wide range of data for scientific research. Seismic networks belonging to the Polkowice commune and KGHM Polska Miedź S.A and seismic network LUMINEOS (LUBin Mining INduced Earthquake Observation System) belonging to the Institute of Geophysics Polish Academy of Science (IG PAS) provided the data for further analysis. All the data are stored in a seismometric database, which is owned and governed by IG PAS. All stations within the above mentioned networks have 3 component sensors measuring ground motion acceleration. Currently, about 20.000 accelerograms, registered since January 2000 by a total number of 51 stations, are stored in this database. All records have explicitly assigned parameters of events that triggered ground motions as energy or local magnitude, event coordinates, epicentral distance to stations (if event was located by seismic network).

Ground motion recordings with peak ground acceleration of at least 0.03 m/s^2 for any component, caused by events with $M_L \geq 2$ (energy $\geq 10^5 \text{ J}$), were chosen for further analysis; these recordings were restricted to those made from 2004 to the end of 2015.

Table 1. The basic parameters of measured units selected for analysis

No. of unit	Stations	Coordinates		Amount of data	Period of time	
		X2000	Y2000		Start	End
1	2	3	4	5	6	7
20	3-go Maja	5 708 549	5 574 411	458	Jan. 2004	Dec. 2015
21	Akacyjowa	5 707 965	5 574 751	317	Jan. 2004	Dec. 2015
22	Biedzychowa	5 705 205	5 576 367	572	Jan. 2004	Oct. 2015
23	Fiołkowa	5 708 265	5 573 378	150	Aug. 2005	Dec. 2015
24	Miedziana	5 708 285	5 574 628	357	Jan. 2004	Dec. 2015
25	Moskorzyn	5 712 545	5 575 201	321	Jan. 2004	Jan. 2015
26	Pieszkowice	5 705 930	5 579 069	87	Sep. 2004-wrz	Jul. 2015
27	Sosnowa	5 707 950	5 575 589	461	Jan. 2004	Aug. 2015
28	Żuków	5 712 765	5 579 667	146	May 2006	Dec. 2014
29	Guzice	5 711 184	5 576 599	334	Jan. 2004	Aug. 2014
30	Trzebucz 31	5 710 090	5 577 152	91	Jan. 2004	Jul. 2005
32	Trzebucz	5 710 160	5 577 259	275	Aug. 2005	Nov. 2014

Table 1 cont.

1	2	3	4	5	6	7
33	Guzice_n	5 711 164	5 576 590	52	Oct. 2014	Dec. 2015
42	Tarnówek	5 709 620	5 580 770	82	Apr. 2010	Jun. 2014
50	Grodowiec	5 712 811	5 581 318	170	Jan. 2004	Dec. 2015
51	Komorniki	5 710 871	5 579 539	329	Jan. 2004	Dec. 2015
80	Hotel	5 707 919	5 574 388	226	Jan. 2004	Jan. 2015
81	Spółdzielnia	5 708 289	5 574 818	275	Jan. 2004	Dec. 2015
82	Tarnówek-gmina	5 709 719	5 580 918	39	Apr. 2010	Feb. 2014
83	Skalników	5 708 859	5 574 548	350	Jan. 2004	Dec. 2015
84	Polkowice Dolne	5 708 199	5 573 438	154	Nov. 2004	Mar. 2014

Very weak events and recordings at the noise level were eliminated from the analysed data due to the aforementioned criteria. Stations located on the Żelazny Most repository embankment and Stations with less than thirty-five records were also discarded from the analysis. After the selection process, 5,246 ground motion records remained – these were recorded by twenty-one stations. Table 1 presents basic information about all chosen data: number; full name and coordinates of stations; total number of ground motion record for each station; period of registration.

The selected records are associated with 1,886 seismic events. The surface distribution of these events along with locations of measurement stations is presented in Fig. 1.

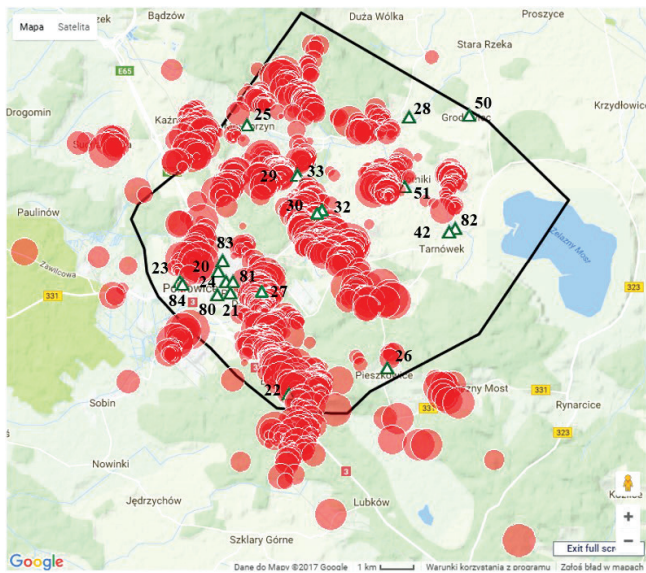


Fig. 1. Locations of stations and seismic events, Green triangles are the seismic stations and red circles are the seismic events

3. The average normalised response spectra

Oscillators with a single-degree of dynamic freedom and subjected to kinematic forces as a result of ground motions, have maximum amplitudes of oscillations related to their own known damping and natural frequencies – these relationships are called response spectra. Response spectra have a wide range of applications in regions which have notable seismicity [10, p. 1097–1125].

The movement of an oscillator with known damping, D , and natural angular frequency of oscillations, ω , forced by ground motions, can be described by the following formula:

$$\ddot{x} + 2D\omega\dot{x} + \omega^2 x = -a(t) \quad (1)$$

where:

- x – mass displacement in relation to the surface;
- D – fraction of critical damping;
- ω – angular frequency of oscillator;
- $a(t)$ – ground motion (accelerations).

The solution to this equation is Duhamel's integral:

$$x(t, \omega, D) = \frac{-1}{\omega\sqrt{1-D^2}} \int_0^{t_{end}} a(\tau) e^{-\omega D(t-\tau)} \sin\omega\sqrt{1-D^2}(t-\tau) d\tau \quad (2)$$

This equation describes the convolution of the seismometric signal with sinusoidal and exponential functions. The solution of equation (1) for discrete signals is given by the convolution of series; this is a time series connected with angular frequency (ω) and damping (D). Angular frequency ($\omega = 2\pi f$ or $\omega = 2\pi/T$) can be easily calculated to frequency f (Hz) or period T (s); thus, the solution to equation (1) is presented as a function of one of these parameters. Response spectra corresponds to maximum amplitudes of oscillator in the function of natural period of oscillation, considering constant damping factor (e.g. $D = 0.05$). Spectral acceleration, SA, is relevant to maximum absolute accelerations of masses within oscillators, which have the same values of damping, in the function of natural period of oscillations (which are response to ground motions).

$$SA(\omega, D) = \max_{t \in [0, t_k]} |\ddot{x}(t, \omega, D) + a(t)| \quad (3)$$

If the natural frequency of oscillations is close to zero, then the acceleration response spectra will also have values close to zero; however, when the natural frequency of oscillations is heading to infinity, the acceleration response spectra reaches peak values of ground acceleration. Normalised acceleration response spectra is useful tool for comparing the acceleration response spectra of various signals. The calculated values of spectral amplitudes are divided by the peak ground acceleration; thus, the amplitude for the maximum natural frequency of oscillations is equal to 1. The normalised response spectra are non-dimensional and show how many times the vibration of the oscillator are larger than the ground vibrations amplitudes.

For all considered signals, acceleration response spectra were calculated for damping at a level of 5% and a natural frequency of oscillations between 1 and 100 Hz. The larger of x and y components was chosen as horizontal component for further calculations. As was mentioned before, the rockburst-induced ground motion for that area can be divided into two groups [31, p. 11–23]. Briefly, the first group is characterised by high PGA which corresponds to dominant frequencies over 20 Hz and the second group relates to dominant frequencies of about 5 Hz. The impact of the type I ground recording on the building is negligible but the impact of the type II ground recording could be significant taking into account interesting frequency band in respect to the natural building oscillation (up to 10 Hz). Therefore, the analysis of ground motion measurement in the frequency band of up to 10 Hz is the standard procedure for that area. Thus, the response spectra were also calculated for records in the frequency band of up to 10 Hz. Next, a case study was conducted to explain the advantages of such a solution. Weak events ($M < 3$), occurring in the vicinity (within 1–2 km) of the stations, have weak records but with a large contribution of high frequencies. These frequencies are dominant in the spectra; however, their influence on the infrastructure is minor. As a result of this, response spectra estimated for signals before and after filtration were compared. This comparison was particularly important in the case of records with dominant frequencies over 10 Hz (Fig. 2). Acceleration response spectra and normalised response spectra, calculated from the filtered signal (Fig. 3a, b; green curve), do not have local maximum for frequencies of above 12 Hz. They were removed from the signal as a result of the process of low-pass filtration. The response spectra before and after filtration have rather similar shapes (Fig. 3a) for frequency ranges up to 10 Hz; however, local maximum amplitudes of normalised spectra before and after filtration differ significantly (Fig. 3b). The value of response spectra for 9 Hz is 1.7 in the case of spectra obtained with signals without frequency modification, and 2.6 in the case of spectra obtained for signals in frequency ranges up to 10 Hz. This difference is an effect of calculating normalised response spectra through dividing spectral amplitudes by appropriate values of peak ground accelerations – these are 0.117 m/s² and 0.057 m/s². According to this, if we calculate response spectra for single ground records, there is no significant difference between assessing oscillator response based on record across the full range of frequencies or in selected frequency bands. When comparing multiple curves of normalised response spectra, calculated for ground motions with various dominant frequencies (especially in the frequency band interesting from our point of view), the situation is more complicated. The average estimated from normalised response spectra would be reduced in f band important for us (e.g. up to 10 Hz) if there will be much more records with dominant frequencies beyond the interest f band (e.g. > 10 Hz) (Fig. 3). Considering the fact that the majority of analysed ground motion records are caused by weak events (which obviously occur more frequently), there is a necessity to narrow the frequency band of ground motions down to 10 Hz, before calculating normalised response spectra. As was mentioned before, such a type of low-pass filtering is commonly used for ground motion analysis in LGCD area, as ‘standardisation’ of PGA for engineering purposes in that area. After the application of a low-pass filter with a frequency range of up to 10 Hz, records were unified in the frequency domain. This was done to demonstrate the impact of seismic loading on the buildings in the frequency band

essential for infrastructure. This can be also done by only choosing intensive, type II ground recordings which have dominant frequencies of around 5 Hz for analysis. Zembaty *et al.* [33, p. 81–90] select only eighteen, intensive, type II ground records from that area and based on them calculated an average response spectra representing rockburst seismic loading. There are two weaknesses to this approach – suitable records have to be chosen and the average values are biased due to a lack of data.

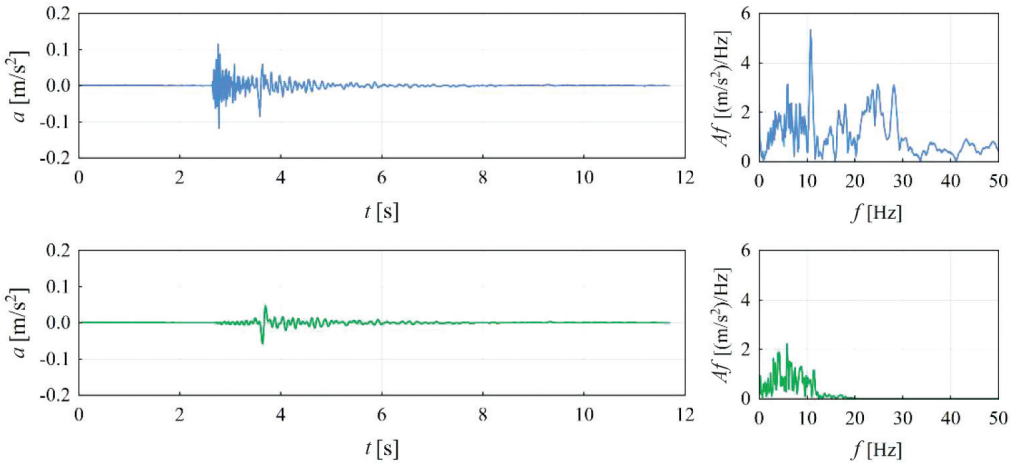


Fig. 2. An example registration of the ground motion x component with an amplitude FFT spectrum of the LGCD region (station 21) (blue curve), and in the frequency range of up to 10 Hz (green curve)

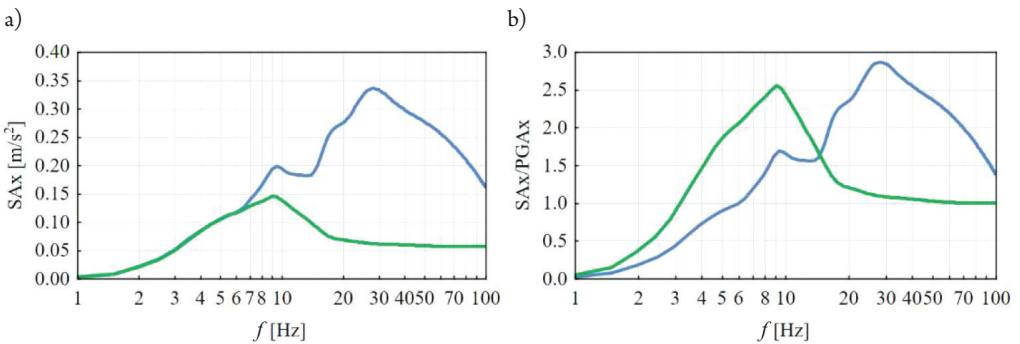


Fig. 3. x component of acceleration response spectra for the example registration across the whole frequency range (blue curve) and in the frequency range of up to 10 Hz (green curve); a) normalised acceleration response spectra, b) normalised acceleration response spectra

Fig. 4. Averages of normalised acceleration response spectra for station 21 based on ground motion across the whole frequency range (blue curve) and in the frequency range of up to 10 Hz (green curve); dashed lines show standard deviation of mean

In the next step, the average normalised acceleration response spectra for the horizontal and vertical components of each station were calculated (Figs. 7 & 8). Larger events possess lower dominant frequencies ($\sim 4\text{--}5$ Hz); therefore, the average normalised response spectra

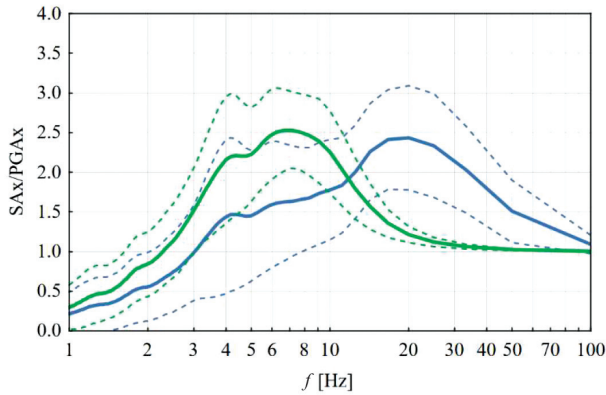


Fig. 4. Average normalised acceleration response spectra dependent upon the local magnitude of events which caused the analysed ground motion at station 21

were calculated according to the values of magnitude and the epicentral distance (Figs. 5 & 6 – example spectra for station no. 21). Those figures show that magnitudes and epicentral distances are factors that affect the values of spectral amplitudes and dominant frequencies of oscillators, for which the largest amplification of ground motions occurs. The larger the magnitude and epicentral distance, the lower the dominant frequency of oscillator (for which the largest amplification of ground motions occurs). Moreover, spectral amplitudes are slightly larger when these two parameters increase. As previously mentioned, weak events ($M < 3$) possess higher dominant frequencies than stronger events. The distributions of spectral amplitudes in the function of epicentral distances and in the function of magnitudes are similar due to the fact that the distribution of events according to the above mentioned parameters are correlated. Recorded signals caused by events occurring at distances greater than 2 km from the station (Fig. 6, red and orange curves) are also caused by events with $M > 3$ (67% of analysed data in the mentioned range of epicentral distances). Recorded signals, caused by events occurring in a distance smaller than 2 km from the station (Fig. 6, green and blue curves), are at the same time caused by events with $M < 3$ in 84% of cases.

The design average response spectra were estimated based on the averaged normalised acceleration response spectra for the horizontal and vertical components of each station. Firstly, the weighted arithmetic mean was calculated from the averages of spectra for each station and for both component separately. Smoothing of the averaged acceleration response spectra was then performed [26], resulting in the design acceleration response spectra for the vertical and horizontal components (Fig. 7):

$$SAh(f) = \begin{cases} -0.24 + 0.5 \cdot f, & f \in [1, 6] \\ 3.00, & f \in [6, 9] \\ 0.95 + \frac{10.40}{f - 5.0}, & f > 10.1 \end{cases} \quad (4)$$

$$SAv(f) = \begin{cases} -0.19 + 0.41 \cdot f, & f \in [1, 7.8] \\ 3.00, & f \in (7.8, 10.1] \\ 0.95 + \frac{10.40}{f - 5.00}, & f > 10.1 \end{cases} \quad (5)$$

The new design response spectra for the horizontal component, in comparison to the previous one made by the author, differ in the value of the constant spectral branch and with range of them. The new spectra has a higher value of the constant part and the upper frequency limit is smaller, it does not contain frequencies higher than 10 Hz. This is the effect of calculating response spectra for records in the frequency range of up to 10 Hz. The response spectra proposed by Tataru [26] has lower the constant branch with an even more narrow range of frequencies. This probably depends on input data, but there is not enough detailed information about the used recordings for calculating response spectra in the Tataru [26] monography. The significant differences are in relation to the response spectra estimated by Zembaty *et al.* [33, p. 81–90]. The response spectra for the different ground types are estimated using fully stochastic ground response analysis and for overall eighteen signals were used as a input data. The frequency ranges of the constant branch of the Zembaty response spectra are wider and also comprise frequencies below 5 Hz. Only individual response

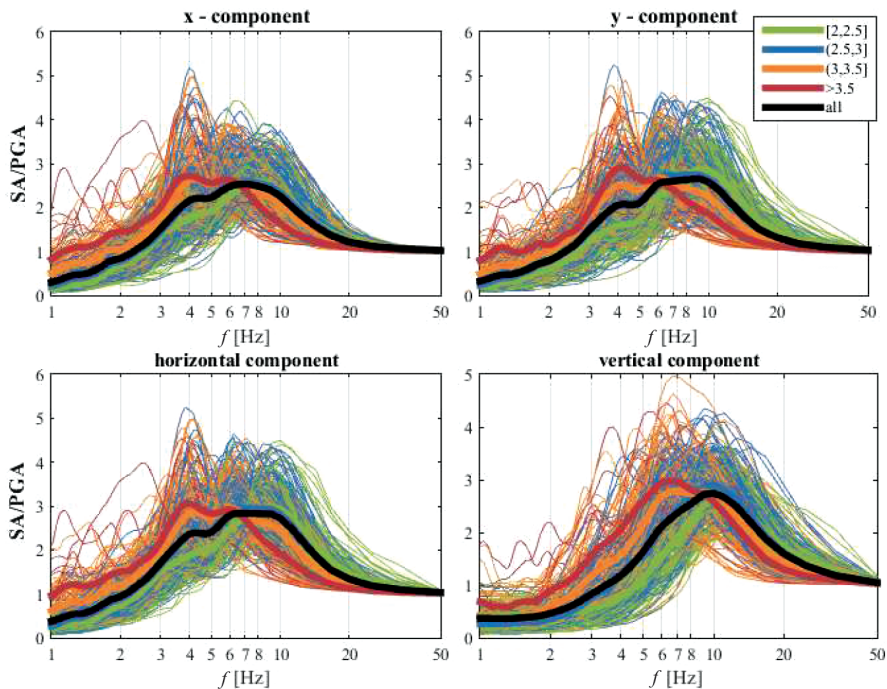


Fig. 5. Average normalised acceleration response spectra dependent upon the epicentral distance of events which caused the analysed ground motion at station 21

spectra have local maximum in that range of frequencies (Fig. 5). Thus, such high values of response spectra are probably biased by data input. Zembaty *et al.* [33, p. 81–90] used only one of the most intensive seismic events in that area which was really rare and unique. This is why a thorough comparison of response spectra should be done for different ground class separately and for representative input data. Therefore, because of the overall number of pieces of data, the new average response spectra can be treated as global for that area and should definitely be estimated according to different ground types in the future.

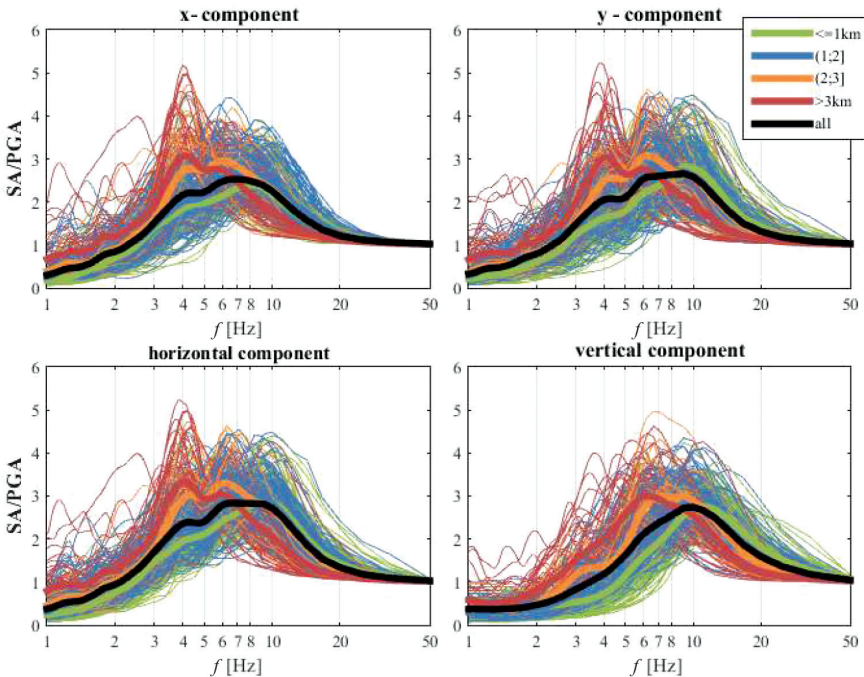


Fig. 6. Comparison of average response spectra for the horizontal component prepared for the LGCD area

The average response spectra for all stations and for both components were compared with adequate design response spectra. Three groups were separated according locations of local maximum of the stations response spectra and design spectra (Fig. 8, Fig. 9). For the horizontal component, the division of the three groups was performed in the manner stated below:

- ▶ the first group consisted of averaged spectra which had maximum in the lower frequencies than the frequency of the design spectra, that is to 5 Hz (Fig. 8a),
- ▶ the second group comprised averaged spectra which had maximum in a similar frequency band to the design spectra (6–9 Hz); however, their curves are slightly higher than the design spectra in frequency range of up to 6 Hz (Fig. 8b),
- ▶ the third group consisted of average spectra which had maximum located in the design spectra frequency band or higher (> 7 Hz), and their spectral amplitudes are mostly equal to amplitudes of the design spectra in the frequency range up to 6 Hz (Fig. 8c).

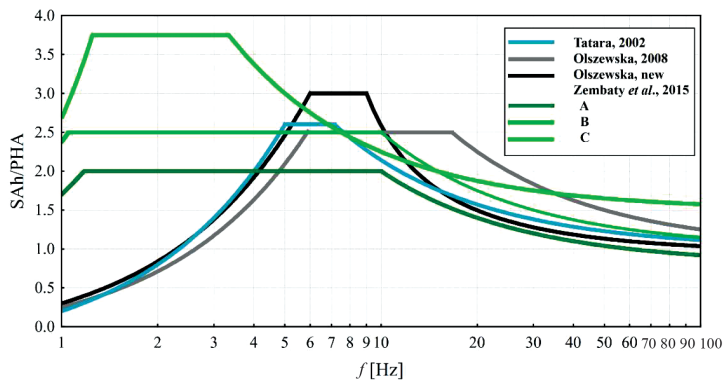


Fig. 7. Average normalised acceleration response spectra of horizontal component for the stations from the LGCD region with the design response spectra (black line)

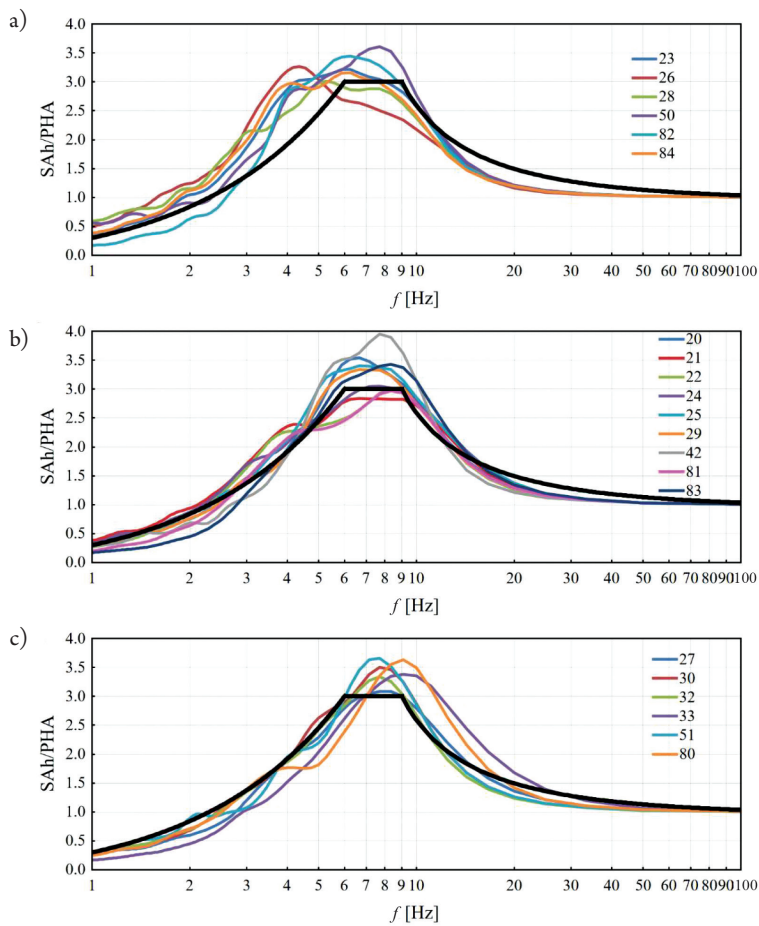


Fig. 8. Average normalised acceleration response spectra of the vertical component for the stations from the LGCD region with the design response spectra (black line)

For the vertical component, the classification of averaged spectra for the three subgroups was similar, with two small differences – the frequency band for the first group was up to 6 Hz (Fig. 9a) and the frequency band for the third group was above 8 Hz (Fig. 9c). Variations of average acceleration response spectra are *closely related* to the underlying ground conditions at the site of measurement (Eurocode-8). The lower the type of ground, the higher the amplification of the ground motions that occur; thus, ground motions are amplified and the maximal spectral amplitudes occur for lower frequencies. According to this, the aforementioned classification of the response spectra generally allows to distinguish local ground conditions at the LGCD area, as has been shown by Olszewska [19].

If the shape of the averaged response spectra is related to the local geological conditions and the ground motions amplifications, then the average normalised acceleration response spectra should have a compatible shape for areas with similar geological conditions and amplifications.

Further research will investigate this problem to a more detailed level. At present, it can be assumed that for close distances (100–200 m), local conditions should be similar to *each other*. Therefore, the average acceleration response spectra for nearby stations should have comparable shapes, or at least be in the same subgroup. This situation can be observed for the average response spectra for stations 23 and 84 (Fig. 8a – blue and orange curve) and for stations 21 and 81 (Fig. 8b – red and magenta curve). However, for some stations, despite being in very close proximity to each other (e.g. 22 m), the averages of response spectra differ enough for them to be classified into separate subgroups; this is the case for stations 29 and 33. This difference might be the a result of unique local conditions in that area. Factors concerning the manner of installing the sensor on the site may also be the reason for this difference.

4. Summary and conclusions

In this paper, the design acceleration response spectra for horizontal and vertical components were calculated for ground motions recorded by selected stations located in the LGCD area in order to enable seismic load to be defined for civil engineering purposes.

It was shown that for ground motions with different ranges of dominant frequencies, the average normalised response spectra should be calculated in the chosen frequency range. Thus, for the analysed area, the average normalised acceleration response spectra and the design response spectra for each station were evaluated from signals which were filtered to a frequency range of up to 10 Hz. As a consequence of this, the recordings were unified in the frequency domain – this is needed because of great part of type II recording with dominant frequencies is higher than for engineering purpose. Thus, the selection of only intensive, type II ground recording it is not necessary and uncertainties of obtain design response spectra is lower thanks to suitable number of data.

Moreover, the relationship between the response spectra and factors such as magnitude and epicentral distance has been presented. Maximal spectral amplitudes of strong events (with dominant lower frequencies) are in the lower band ($\sim 5\text{--}6$ Hz).

Response spectra are strongly dependent upon the measurement site and the underlying ground conditions. The analysed area is rather small and previous research shows that ground type is uniform for that area. Nevertheless, the average response spectra have been divided into subgroups on the basis of their shapes; hence the assumption that stations were classified regarding the similarity of local ground conditions. However, this classification requires further studies.

As a result of this paper, the design acceleration response spectra for the vertical and horizontal components of the LGCD area have been estimated [equations (5) and (6)]. These response spectra can be used for analysis of ground motion influences on building infrastructure in the LGCD area and can help with the estimation of the local ground condition.

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