CHARACTERISTICS OF PARASEISMIC LOADS FROM THE VIEWPOINT OF THE RANGE OF BUILDING ANALYSIS

Zbigniew LIPSKI*

* Faculty of Civil Engineering, The Silesian University of Technology, Akademicka 5, 44-100 Gliwice, Poland
E-mail address: : *zbigniew.lipski@polsl.pl*

Received: 22.09.2008; Revised: 30.10.2008; Accepted: 12.11.2008

Abstract
The paper presents a way of estimating the intensity of dynamic loads due to mining quakes, with the purpose of assessing the possibility of generating extreme dynamic reactions of buildings caused by paraseismic kinematic excitations. The suggested method may be applied in numerical analyses of the effort of structures by means of the load history method in the course of selecting representative causes of paraseismic loads. From among many mining quakes only a few are selected, provoking an extreme and similar dynamic responses of the structure. Such a classification allows to restrict the range of the numerical analysis of the structure, thus leading to a rationalization of time and work amount required for calculations. This method is based on time – and – spectral properties of kinematic excitations observed in the region of Polkowice in the Copper Mining Area of Legnica and Głogów. They have been characterized by two parameters, viz. Arias's intensity and the average power. A distinct stochastic relation has been noted between the parameters of excitations and the dynamic responses of the buildings.

Streszczenie
W pracy przedstawiono sposób oszacowania intensywności obciążeń dynamicznych związanych z wstrząsami górniczymi, przeznaczonej do oceny zdolności do generowania ekstremalnych odpowiedzi dynamicznych budynków przez parasejsmiczne wymuszenia kinematyczne. Sposób przydatny jest w trakcie prowadzenia numerycznej analizy wytężenia konstrukcji nośnych metodą historii odpowiedzi na etapie doboru reprezentatywnych przypadków obciążeń parasejsmicznych. Spośród wielu zaistniałych wstrząsów górniczych wybiera się tylko nieliczne, które wywołają ekstremalną i zbliżoną do niej odpowiedzi dynamiczne konstrukcji. Klasyfikacja taka umożliwia ograniczenie zakresu analizy numerycznej konstrukcji, a więc prowadzi do racjonalizacji nakładów czasu i pracy związanej z obliczeniami. Sposób bazuje na własnościach czasowo -widmowych kinematycznych wymuszeń parasejsmicznych z rejonu Polkowic w Legnicko-Głogowskim Okręgu Miedziowym. Scharakteryzowano je za pomocą dwóch parametrów: intensywności Arias'a i mocy średniej. Stwierdzono istnienie wyraźnej zależności stochastycznej pomiędzy parametrami wymuszeń a odpowiedzią dynamiczną budynków.

Keywords: **Mining quakes; Numerical analysis of building; Load history method; Representative kinematic excitations; Time-spectral properties.**

1. INTRODUCTION

The level of the dynamic response of various buildings exposed to the influence of intensive mining quakes has been the subject of investigations for many years. These searches consisted among others, in a numerical analysis of the dynamic response of various kinds of structures exposed to paraseismic loads, making use of the response spectrum or the load history method [1-4]. Usually the sets of results were rather scarce. The great majority of analyses dealing with the effect of paraseismic loads exerted on building concerned the region of Polkowice, where the magnitudes of shocks have not exceeded so far the value of M = 4.5, and the seismic energy did not exceed 10 GJ. Peak accelerations of vibrations of soil surface attained approximately the value of 2.5 m/s^2 for the horizontal components and 3 m/s^2 for the vertical ones. In analyses of the dynamic response of the buildings, carried out in compliance with the load history method, making use of the kinematic excitations, the expansion of its range is hampered by the time – consuming computer calculations and the expenditure of work in analyzing the results. Difficulties are also encountered in the choice of representative kinematic excitations of the analyzed buildings. Frequently some number of excitations generated by various quakes exerted on the building structure are available. It is usually impossible to take all of them into consideration, because this would be too toilsome. At most several representative cases of paraseismic loads must be selected, which we know to have caused in the analyzed buildings dynamic responses with an extreme intensity. The present paper suggests a way of assessing a priori, i.e. previous to numerical calculations, the intensity of numerous excitations, which have to be taken into account in the numerical analysis of the selected building. In this method the results of the analysis of the time-spectral properties of the kinematic excitations generated by quakes in Polkowice and criterial parameters: Arias's intensity and average power of acceleration have been applied. The assessment of these intensities permits to reduce the range of inevitable numerical analyses of the building, i.e. to speed up the realization basing on the acceptable expenditure of time and work.

2. THEORETICAL FUNDAMENTALS

The discrete accelerations connected with the horizontal vibrations of the soil, recorded at the seismologic station in Polkowice have been analyzed. The process of generating mining quakes and their effects on the environment are stochastic in their character. Therefore, induced kinematic excitations are considered to be random processes. As data concerning such phenomena are rather scarce, it has been assumed that realizations of processes of that kind are deterministic functions. They have been analyzed independently one signal after another, taking into account the fact that the excitations are not stationary [5-7], which is evident in the disconnection of the spectra of two subsequent segments of them: No. 1, i.e. the initial segment with high-frequency characteristic, and No. 2, so-called fundamental one, with properties of a low-frequency signal. Basing on the analysis of autocorrelation and the mean value, the marked segments may be considered as stationary signals in the broader meaning. The differentiation of the segments results also from dynamic calculation of the structure [4] that the extreme dynamic response of the buildings due to mining quakes occurred principally in the second segment. The accelerograms were divided into segments by applying the short–time spectral power density, which was calculated by means of the moving window method. Basing on this function, the border dividing both segments has been found, because spectral properties of the segments were distinctly diverse. For the purpose of characterizing the properties of kinematic excitations criterial parameters were applied viz. Arias's intensity [8] and the average power. Their values were jointly analyzed for the orthogonal components of horizontal forces. Arias's intensity was calculated making use of the following equation

$$I_{Ak} = \sum_{j=0}^{N_s-1} \left(a_{xj}^2 + a_{yj}^2\right)\Delta t \ , \ \ k = 1, 2, 3 \ , \tag{1}$$

where: a_{xj} , a_{yj} – the values of the horizontal components of kinematic excitations in the directions X and Y in the j-th points on the time axis,

N_s – the number of samples of the excitations component,

Δt – the period of digitizing of the signal.

The average power of the kinematic excitations was calculated by means of the formula

$$P_k = \sum_{j=0}^{N_s-1} \left(a_{xj}^2 + a_{yj}^2\right) \Big/ N_s \tag{2}$$

in which the denominations are the same as in the previous formula.

The values of the criterial parameters were calculated in selected frequency bands of excitations. The prerequisite of this operation was the need to separate those spectral components of the excitations, which might resonance affect a considered building. For this purpose the accelerograms were filtered in the bands whose boundary frequency were dependent on the natural frequency Ω of the analyzed building, according to the relation

$$\mathbf{F} = \{[f_{b1}; f_{b2}],[f_{b2}; f_{b3}],[f_{b3}; f_{b4}]\} \ , \tag{3}$$

where:

$f_{b1} = f_1 - 0{,}7$, $f_{b2} = (f_3 + f_4)/2$, $f_{b3} = (f_6 + f_7)/2$, $f_{b4} = 20\ \mathrm{Hz}$,

$\Omega = [f_1 \quad f_2 \quad \cdots \quad f_N]$.

The frequency bands were determined based on the results of analyses concerning four buildings [1, 4]. The sensitivity of dynamic responses of the buildings generated by paraseismic loads to the modification of frequency bands of the excitations was tested. It has been found, that the level of responses depended decidedly on components with frequencies approximating the lowest natural frequencies. Correlation of the first band (3) and level of dynamic responses was distinctly higher than second and third band.

In order to assess the responses of two low buildings, the results of a numerical analysis were used [4], making use of the method of finite elements and the software package Ansys. Basing on these calculations it has been found that the extreme stress fields, responsible for the level of the dynamic effort of the walls of the structure, occur almost simultaneously with the maximum dynamic horizontal displacements at their selected points. Taking this into account concerning the other two buildings for the purpose of assessing the dynamic response, the orthogonal horizontal components of the accelerograms recorded during the quakes were utilized. The horizontal components of displacements of the buildings were obtained after a twofold integration in the time domain. The calculations were carried out in compliance with standard procedures of the software Matlab v. 7. For the assessment of the maximum dynamic response in all the buildings, the horizontal dynamic displacements of the highest storey versus the foundations were taken into according to the formula

$$u_{\max}(t_0) = \sqrt{\left[u_{x2}(t_0) - u_{x1}(t_0)\right]^2 + \left[u_{y2}(t_0) - u_{y1}(t_0)\right]^2}, \quad (4)$$

where: $u_{x2}(t)$, $u_{y2}(t)$ – horizontal components of displacements of the building highest storey,

$u_{x1}(t)$, $u_{y1}(t)$ – horizontal components of displacements in the foundation of the building,

t_0 – position of the maximum relative displacement of the building on the time axis.

In order to determine the relation between the criterial parameters and the corresponding dynamic responses of the buildings, the regression was investigated, in which the independent random variable is successively the parameter according to (1) and (2), and the dependent variable – the dynamic displacement of the structure according to (4). The empirical regression function was assumed to be power (surd), concerning the variables transformed by taking the logarithm

$$y = ax^b, \quad (5)$$

where: a, b – coefficients of the regression function.

The values of the coefficients were calculated making use of the standard procedure of the Matlab v. 7. As a measure of the stochastic relation of the analyzed random variables the correlation coefficient was applied, and the matching of the regression function was assessed by the root mean square deviation. Both of these parameters concern sets of logarithmic data. Due to the application of their typical estimators the respective formulae have not been quoted. The quality of matching the regression function is also characterized by the confidence limits at a significance level of 10 % corresponding to the typical procedure.

3. CHARACTERISTICS OF THE INPUT DATA

The applied accelerograms have been obtained from the seismic stations localized in the following streets: Akacjowa, Sosnowa, 3 Maja and Miedziana. In each one of them the vibrations of the soil adjacent to the given building have been measured. In case of the third measuring station the accelerograms were placed also in the foundation and at the roof of the fourth storey. At the fourth station acceleration transducers were applied on the foundation of the building as well on the fourth and twelfth storey of the structure. Essential information concerning the applied accelerograms has been gathered in Table 1.

Table 1.
Characteristics of the quake taken into consideration in the analysis and maximum values of relative dynamic displacement of the building structures

No.	Date of quake	Measurement point	Maximum acceleration of component [m/s²]		Maximum dynamic displacement in building [mm]			
			X	Y	1	2	3	4
1	25.02.2000	3 Maja	0.68	1.02	0.82	1.20	-	-
2	1.03.2000	Miedziana	0.60	0.72	-	-	-	0.69
3	15.03.2000	3 Maja	1.02	1.02	1.62	1.91	-	-
4	30.06.2000	Miedziana	0.13	0.36	-	-	-	4.4
5		Akacjowa	0.19	0.52	0.97	1.51	-	-
6		Sosnowa	0.50	0.45	0.86	0.88	-	-
7	18.07.2000	Sosnowa	0.42	0.56	2.27	3.11	-	-
8		3 Maja	0.21	0.41	1.54	1.43	-	-
9	14.09.2000	Miedziana	0.63	1.03	1.26	1.36	-	1.74
10		3 Maja	0.70	1.02	0.73	0.90	-	-
11	7.01.2001	Miedziana	0.13	0.30	-	-	-	1.09
12	27.01.2001	Miedziana	0.37	0.95	-	-	-	2.82
13	13.02.2001	Miedziana	0.19	0.57	-	-	-	4.25
14	22.02.2001	Miedziana	0.15	0.39	-	-	-	1.94
15	2.02.2002	Miedziana	0.28	0.95			-	1.43
16		Akacjowa	1.02	0.79	0.88	1.27		-
17	20.02.2002	Sosnowa	~2.0	~2.0	5.87	-		-
18		Miedziana	1.63	0.97	3.08	-	-	-
19	25.02.2004	3 Maja	0.19	0.38	-	-	0.51	-
20	3.03.2004	3 Maja	0.19	0.36	-	-	0.66	-
21	13.03.2004	3 Maja	0.27	0.53	-	-	0.46	-

22	3.04.2004	3 Maja	0.21	0.42	-	-	0.74	-
23	13.04.2004	3 Maja	0.11	0.31	-	-	0.10	-
24	17.04.2004	3 Maja	0.33	0.79	-	-	1.88	-
25	1.05.2004	3 Maja	0.18	0.43	-	-	0.87	-
26	9.05.2004	3 Maja	0.41	0.57	-	-	1.56	-
27	16.05.2004	3 Maja	0.92	1.04	-	-	4.93	-
28	16.05.2004	3 Maja	0.82	0.93	-	-	3.44	-
29	25.05.2004	3 Maja	0.28	0.48	-	-	1.72	-
30	7.06.2004	3 Maja	0.30	0.63	-	-	1.46	-
31	19.07.2004	3 Maja	0.17	0.41	-	-	1.17	-
32	25.08.2004	3 Maja	0.19	0.25	-	-	0.24	-
33	4.11.2004	3 Maja	0.15	0.38	-	-	0.21	-
34	6.11.2004	3 Maja	0.29	0.54	-	-	3.67	-
35	31.12.2004	3 Maja	0.20	0.47	-	-	0.15	-
36	18.03.2005	3 Maja	0.25	0.42	-	-	1.93	-
37	19.07.2005	3 Maja	0.23	0.24	-	-	1.36	-
38	5.08.2005	3 Maja	0.62	0.67	-	-	3.21	-
39	28.09.2005	3 Maja	1.96	1.78	-	-	0.85	-

The quakes were chosen from among 640 which occurred in Polkowice and the adjacent region within the years 2000-2002 and 2004-2005. These were characterized by peak acceleration exceeding 0.25 m/s^2. Table 1 quotes also the values of maximum dynamic displacements according to (4) of the analyzed buildings. The buildings Nos. 1 and 2 have two storeys and a brick-wall structure with horizontal dimensions of 8.7*9.3 and 7.8*8.4 m, respectively. The building No. 3 has five storeys with a large-size block structure and transversely bracing wall. The building No. 4 has twelve storeys and a prefabricated wall structure with transversely bracing wall. Table 2 presents the frequencies of natural vibrations as well as the boundary frequencies of the bands of these buildings according to (3).

Table 2.
Natural frequencies and boundary frequencies of the bands corresponding to the given buildings

No of build-ing	Natural frequencies [Hz]					Boundary frequencies of the bands [Hz]		
						1	2	3
1	4.8	5.3	6.4	11.2	11.8	4.0	8.8	12.7
2	3.7	4.3	5.3	9.4	10.6	3.0	7.3	11.5
3	3.2	3.4	4.2	5.2	7.2	2.5	4.7	9.1
4	1.8	2.0	3.1	3.9	4.4	1.1	3.5	5.8

4. RESULTS OF ANALYSIS

The correlation between Arias's intensity or average power and the maximum dynamic displacement was checked successively in case of the buildings 1 to 4, assuming that the results of calculations for each of them constitutes statistic samples concerning various populations. Correspondingly 11, 9, 21 and 8 kinematic excitations loading these buildings were analyzed. A correlation was also checked assuming that the available values of random variables were provided by a population comprising all these buildings. Table 3 contains the values of the correlation coefficients as well as the root mean square deviations, characterizing the stochastic relations of logarithmic sets of Arias's intensity and maximum displacements.

Table 3.
Correlation coefficients and square deviations of the regression functions of logarithmic variables: Arias's intensities and dynamic displacement of the buildings

No.	No. of segment	No. of band	Correlation coefficients of buildings				Square deviation of buildings			
			1	2	3	4	1	2	3	4
1	1	1	0.75	0.66	0.79	0.21	0.45	0.27	0.69	0.68
2		2	0.62	0.62	0.82	0.04	0.54	0.29	0.64	0.70
3		3	-0.02	0.05	0.66	0.01	0.69	0.37	0.84	0.70
4	2	1	0.93	0.82	0.98	0.98	0.26	0.21	0.21	0.15
5		2	0.55	0.23	0.88	0.74	0.57	0.36	0.52	0.47
6		3	0.40	0.08	0.82	0.14	0.63	0.37	0.64	0.69

Exemplary diagrams of the regression function of the quoted variables in the segment No. 2, including the confidence limits, are shown in Fig. 1a-2a (band No.1) and in Fig. 1b-2b (band No.2). They refer to the buildings No. 1 and No. 4.

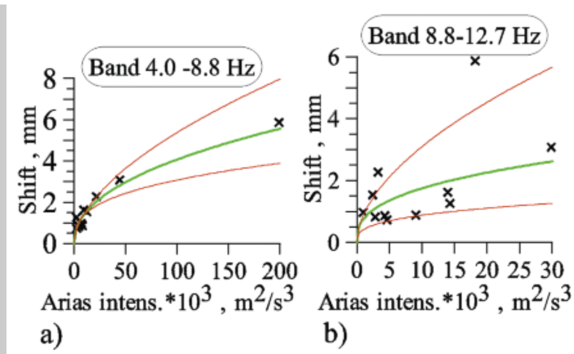

Figure 1.
Diagrams of the regression function of Arias's intensities and maximum dynamic displacements of the building No. 1, in the segment No. 2 a) band No. 1 b) band No. 2

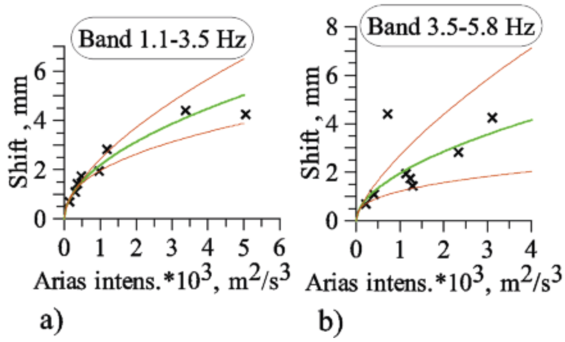

Figure 2.
Diagrams of the regression function of Arias's intensities and maximum dynamic displacements of the building No. 4, in the segment No. 2 a) band No. 1 b) band No. 2

The results concerning the first segment or highest frequency band have been neglected because of the distinctly worse correlation of the random variables and the insufficient matching of the regression function with the data. The symbol "x" in the diagrams denotes the position of the points corresponding to the analyzed data. The red curves denote confidence limits of 10 %. The correlation coefficients concerning the investigated stochastic relation in the segment No. 2 and the band No.1 are contained within the interval 0.82-0.98 and between 0.23 and 0.88 in the band No. 2. In this segment as well as in the band No. 3 the correlation coefficients are still smaller. In the segment No. 1 the values of the correlation coefficients are generally lower than their corresponding values in the segment No. 2. The root mean square deviation in the segment No. 2 amounts to 0.15-0.26 in the band No. 1 and increases in the subsequent bands. Analogically, the results of calculations of the correlation and regression function between the average power and the maximum dynamic displacements. The values of the correlation coefficients and root mean square deviation of the regression function concerning these logarithmic random variables have been gathered in Table 4.

Table 4.
Correlation coefficients and square deviations of the regression functions of logarithmic variables: the mean average power and dynamic displacement of the buildings

No.	No. of segment	No. of band	Correlation coefficients of buildings				Square deviation of buildings			
			1	2	3	4	1	2	3	4
1	1	1	0.77	0.67	0.80	0.04	0.44	0.27	0.67	0.70
2		2	0.62	0.62	0.81	0.02	0.54	0.29	0.65	0.70
3		3	0.07	0.04	0.66	0.00	0.68	0.37	0.83	0.70
4	2	1	0.89	0.84	0.98	0.98	0.31	0.20	0.21	0.13
5		2	0.45	0.40	0.86	0.72	0.61	0.34	0.57	0.48
6		3	0.29	0.04	0.72	0.18	0.66	0.37	0.78	0.69

Figs. 3a-4a and 3b-4b present diagrams of regression functions of the variables in segment No. 2 as well as the confidence limits in the bands Nos. 1 and 2 for the buildings Nos. 1 and 4, respectively.

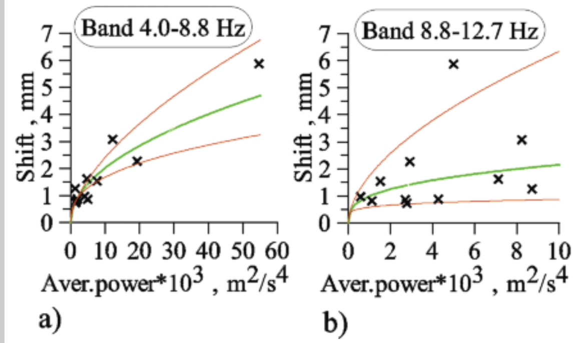

Figure 3.
Diagrams of the regression function of average power and maximum dynamic displacements of the buildings No. 1, in the segment No. 2 a) band No. 1 b) band No. 2

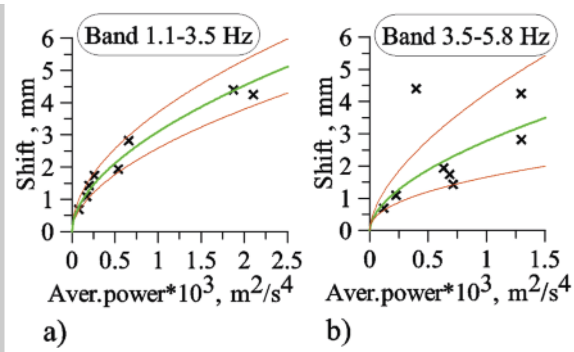

Figure 4.
Diagrams of the regression function of average power and maximum dynamic displacements of the buildings No. 4, in the segment No. 2 a) band No. 1 b) band No. 2

These diagrams have been plotted in compliance with the remarks quoted in Fig. 1. The correlation coefficients in the segment No. 2 and the band No. 1 are contained within the interval 0.84-0.98 and within the limits 0.40-0.86 in the band No. 2. The root mean square deviation in the segment No.2 and the band No. 1 is contained within the limits 0.13-0.31. It may be stated that the quality of matching the regression function with the random variables deteriorates distinctly in calculations concerning higher and higher frequency bands and that it is worse in the segment No.1 than in the segment No. 2. This is the case in all the analyzed buildings. The results of the correlative analysis of one combined statistic sample, comprising data of all the four buildings have not been quoted here, because the correlation coefficients and the root-mean-square error are in this case distinctly worse than those calculated for each building separately. Probably the type of the building influences the quality of matching the regression function, and its form is an individual characteristic of reacting to the kinematic force by the building.

5. CONCLUSIONS

For the purpose of testing the efficacy of the presented method, a set of 36 kinematic forces was analyzed [9], loading the tested building. This was a brick structure four storey high. The preliminary selection was carried out as described above, selecting six cases as representative ones. In numerical analysis of the structure the load history method was applied, making use of these excitations. The fields of extreme dynamic stresses in the structural elements were compared, confirming the correctness of the preliminary choice of representative loads and their arrangement from the most intensive to the least essential. Thus, the conclusion that the presented method permits to assess the intensity of kinematic forces reliably in the search for the maximum response of a building seems to be justified. It may prove to be useful for the restriction and rationalization of the scope of numerical calculations of the dynamic response of the structure by means of the load history method. This concerns, for instance, untypical building structures as well as detailed multi-variant analyses of constructions etc.

ACKNOWLEDGEMENTS

The investigations presented in this paper have been carried out within the frame of the grant KBN No. 1505/T07/2005/28, basing on the results of seismological and dynamic measurements carried out by the *Mining Plant "Rudna" KGHM "Polska Miedź"* in Polkowice.

REFERENCES

[1] *Ajdukiewicz A., Kliszczewicz A., Lipski Z., Porembski G.*: Analysis of Existing Large-Panel Concrete Buildings Subjected to Para-Seismic Influences in Mining Region, Proceedings of FIB-Symposium, Concrete Structures in Seismic Regions, Athens, 2003, p. 328-330

[2] *Maciąg E.*: Ocena szkodliwości drgań budynków od wstrząsów górniczych na podstawie drgań ich fundamentów czy drgań gruntu? (An assessment of harmfulness of buildings vibrations due to mining quakes on the basis of foundation vibrations or soil vibrations?). Inżynieria i Budownictwo, 12/2005, p. 670-677 (in Polish)

[3] *Tatara T.*, Działanie drgań powierzchniowych wywołanych wstrząsami górniczymi na niską tradycyjną zabudowę mieszkalną. (Action of surface vibrations generated by mining quakes on low, traditional, residential development). Zeszyty Nauk. Pol. Krakowskiej, seria Inżynieria Lądowa nr 74, Kraków, 2002 (in Polish)

[4] *Wawrzynek A., Lipski Z., Pilśniak J.*:, Ocena zagrożenia niskiej zabudowy mieszkalnej w rejonie Polkowic oddziaływaniami parasejsmicznymi. (An assessment of hazards for low apartment houses in the region of Polkowice due to paraseismic phenomena). Inżynieria i Budownictwo, nr 10/2003, p. 570-573 (in Polish)

[5] *Maciąg E.*: Interakcja układu budynek-podłoże gruntowe w świetle doświadczalnego badania drgań parasejsmicznych. (Building-subsoil interaction in the light of empirical research of paraseismic vibrations). Inżynieria Morska i Geotechnika, 4/2006, p. 240-250 (in Polish)

[6] *Lipski Z.*: Statistical characteristics of some selected parameters of paraseismic kinematic excitations in buildings. Slovak Journal of Civil Engineering, Bratislava, 3/2006, p. 10-13.

[7] *Maciąg E., Chełmecki J.*: Stopień interakcji układu wysoki budynek – podłoże gruntowe podlegającego wstrząsom górniczym. (Degree of the interaction of the high structure – foundation system subject to rockbursts). Zeszyty Naukowe Politechniki Śląskiej, Seria Górnictwo z. 278, Gliwice, 2007. s. 273-282 (in Polish)

[8] *Arias A.*: A measure of earthquake intensity. Hansen R.I. editor, Seismic design of nuclear power plants, Cambridge, MA, MIT Press, 1970

[9] *Lipski Z.*: Klasyfikacja obciążeń parasejsmicznych budynku w aspekcie minimalizacji zakresu analizy numerycznej. (Rating of paraseismical loads of building from angle of reduction of numerical analysis scope). LIV Konferencja Naukowa KIL i W PAN i Komitetu Nauki PZITB „Krynica 2008" Problemy Naukowo-Badawcze Budownictwa, Białystok-Krynica 2008, Referaty t. II, p. 65-72 (in Polish)