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CHARACTERISTICS OF NONSTATIONARY PARASEISMIC KINEMATIC EXCITATIONS IN THE REGION OF POLKOWICE

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Abstract

The paper presents the results of an analysis of nonstationary kinematic excitations generated by quakes due to mining activities in Polkowice in the Copper-Mining District of Legnica and Głogów, affecting dynamically building structures in the town. Their time-and-spectral properties decide about the intensity of dynamic response of the supporting structure of buildings. In the analysis Gabor's transformation was applied, based on which the values of eighteen random variables were calculated, characterizing time-and-spectral properties of these excitations. In every one of them two segments were discerned, the initial and the fundamental one, which were characterized with respect to the durability of the segments, the boundary frequencies of the evolving bands and extreme values of acceleration. In the coordinate system time-frequency those areas have been separated, and extreme transient harmonious components of excitations did occur. Sixty-four mining quakes which occurred in the region of Polkowice have been analyzed, for which horizontal, orthogonal components of the accelerograms were recorded with an extreme value of acceleration of at least 0.25 m/s^2. A synthetic specification of obtained results characterizing the time-and-spectral properties of kinematic excitations has been presented.

Streszczenie

W pracy przedstawiono wyniki analizy niestacjonarności wymuszeń kinematycznych generowanych przez wstrząsy górnicze w Polkowicach w Legnicko-Głogowskim Okręgu Miedziowym. Stanowią one obciążenia dynamiczne zabudowy miejskiej i ich własności czasowo-widmowe decydują o poziomie odpowiedzi dynamicznej konstrukcji nośnych budynków. W analizie wykorzystano transformację Gabora. Na jej podstawie obliczono wartości osiemnastu zmiennych losowych, za pomocą których scharakteryzowane zostały własności czasowo-widmowe wymuszeń. W każdym z nich wyróżniono dwa segmenty: początkowy i podstawowy. Niestacjonarności wymuszeń scharakteryzowano za pomocą: czasów trwania segmentów, częstotliwości granicznych ewoluujących pasm oraz ekstremalnych wartości przyspieszeń. Wydzielono także obszary w układzie współrzędnych czas – częstotliwość, w których pojawiają się ekstremalne, krótkotrwałe składowe harmoniczne wymuszeń. Analizowano 64 wstrząsy górnicze z terenu Polkowic, dla których zarejestrowano poziome, ortogonalne składowe akcelerogramów o ekstremalnej wartości przyspieszenia co najmniej 0.25 m/s^2. Podano syntetyczne zestawienie uzyskanych wyników charakteryzujących czasowo-widmowe własności wymuszeń kinematycznych.

Keywords: **Mining quakes; Kinematic excitations; Time-spectral properties, Gabor's representation.**

1. INTRODUCTION

The accelerograms and seismograms recorded in regions affected, among others, by quakes due to mining activities provide an image of elastic waves propagated in the lithosphere. Geophysical investigations indicate that in these waves are fragments connected with longitudinal waves to be distinguished [1] denoted as P, transverse waves, denoted as S, and Rayleigh's waves, i.e. surface waves, which subsequently reach the measuring stations. In special cases the images of these waves are distinctly recognizable [2-4]. The question arises, what effect do delays of the respective groups of waves exert on the dynamic reaction of the supporting structures of the buildings exposed to such quakes. Basing on dynamic analyses carried out so far [5-7] concerning buildings situated in the Copper-Mining Region of Legnica and Głogów it may be stated that the dynamic response of these structures in the initial stage of excitations is usually rather small, but increases in the course of further excitations, reaching eventually the occurrence of extreme fields of stresses and dynamic displacements, after which they again fade out. In case of kinematic excitations with low or high dominating frequency bands [2,4] the structural dynamic responses depend on their spectral properties. These qualitative regularities are connected with nonstationary state of these kinematic excitations [8], because their time-spectral properties change due to various kinds of elastic waves propagating in the laminar rocky medium and their sequential approach to the buildings. Thus we may say that the problem of nonstationary excitations generated by mining quakes has from the viewpoint of the dynamics of the construction of buildings two aspects, a general and an applicable one. The former one consists in the recognition of the spectral properties evolving in the course of each kinematic excitation together with their numerical characteristics. The latter aspect comprises the way and instruments applied in the analysis, taking into account the nonstationarity and consequences concerning a numerical analysis basing on the history loads method affecting the structures exposed to paraseismic excitations.

The present paper provides results of nonstationary kinematic excitations analysis recorded in Polkowice. The aim of this analysis was to recognize and to characterize numerically described phenomenon in form of an accessible specification of representative excitations. It may be an underlie of analysis of their dynamic effect on various kinds of building structures.

2. THEORETICAL FUNDAMENTALS AND MEASUREMENT DATA

The paper analyzes the signals which are discrete accelerations in time, connected with vibrations in the subsoil generated by quakes due to mining activities. It has been assumed that the respective excitations are the result of certain random processes. The set of their values at the moment t comprises samples of random variables $\mathbf{x}_t$, i.e. the values of accelerograms at this moment t. Their variances (1a) in the set of the realization of the processes and the values of the correlation function (1b) depend on time in compliance with the formulae [9]:

$$\sigma_{x_t}^2 = E[(\mathbf{x_t} - E[\mathbf{x_t}])^2] = \mathrm{var}\,, \tag{1a}$$

$$R_{x_t x_{t+\tau}} = \mathrm{E}[\mathbf{x}_t \mathbf{x}_{t+\tau}] = \mathrm{var} \tag{1b}$$

where: E[.] – the averaging operator in the set of all the realizations of the process at a steady value of t.

The assumptions (1a) and (1b) determine the nonstationary character of the accelerograms in a wider sense [9]. So-called time-frequency representation of signals was applied in the analysis of the nonstationary state. The general aim of its application was a highly accurate joint amplitudinal-frequency decomposition of signals as functions of time, i.e. a representation of the variability of the amplitudes, frequency and phases of their components. Usually, however, the evolution of the function of spectral power density is determined in time [9]. For this purpose Gabor's transformation was used, owing, first of all, to its sufficient accuracy, comparatively simple algorithm of numerical calculations and facile realization in the computer system Matlab 7.5. Generally Gabor's transformation may be defined [9] as the representation of a nonstationary signal as the sum of basic function, resulting from an assumed prototype function due to shifting it along the axes of time and frequency by multiplying it with the complex harmonic signals. Gabor's time-frequency transformation of a continuous signal $x(t)$ is defined by the formula

$$\begin{gathered} x(t) = \sum_{m,n=-\infty}^{+\infty} c_{m,n} g_{m,n}(t) \\ g_{m,n}(t) = g(t - m\cdot\Delta t) e^{j2\pi n \Delta f \cdot t}, \quad \Delta t \cdot \Delta f \le 1 \\ c_{m,n} = \int_{-\infty}^{+\infty} x(t) \gamma_{m,n}^{*}(t - m\cdot\Delta t) e^{j2\pi n\,\Delta f \cdot t} \end{gathered} \tag{2}$$

where:

$g_{m,n}(t)$ - window function of the synthesis $g(t)$ with an energy equal to 1, shifted in time by $m\cdot\Delta t$ and frequency by $n\cdot\Delta f$,

$c_{m,n}$ – coefficients of decomposition,

$\gamma(t)$ – window function of the analysis, biorthogonal to the window function of the synthesis $g(t)$, (the asterisk denotes a conjugate complex function),

Δt, Δf – shift in the domain of time and frequency, respectively.

The function of the synthesis ought to characterize concentration of energy in the domain of time and frequency. This condition ensures an adequate resolution of the transformotion in both domains. The modules of Gabor's transformotion, i.e. the resulting Gabor's time-frequency representations were calculated by means of the formula

$$S_x(m\cdot\Delta t, n\cdot\Delta f) = \left| c_{m,n} \right|^2 \tag{3}$$

Analogically to Fourier's transformotion, the function $S_x(m\Delta t,n\Delta f)$ may be compared with the spectral power density rating. The formulae (2) have also a discrete version, not quoted here. It was realized by means of a program taken down in the Matlab 7.5. As the window of the synthesis Chebyshev polynomials were applied, indicating concentration of energy around the central frequency, as well as inconsiderable errors. The window functions of the analysis were calculated numerically making use of an adequate algorithm [9].

For practical reasons the results of the analysis of the accelerograms, i.e. the values of Gabor's representations, have been visualized by means of maps in the decibel scale. As a reference level a harmonic signal with an amplitude of a_{ref} = 0.01 m/s^2 was assumed, adapted to the currently analyzed component frequency of the accelerogram and the window length of the analysis $\gamma(t)$. These maps were applied particularly for the purpose of assessing the duration and boundary frequencies of the evolving spectrum bands of the Gabor's representations. All the parameters characterizing the nonstationarity of kinematic excitations are considered to be random variables with an unknown distribution of probability. In the course of analyzing their empirical densities of probability, considerable irregularities have been detected in the form of two local extremes, asymmetry etc. Therefore, their distribution functions were applied, basing on which the quantiles of the random variables orders of 0.1; 0.5 and 0.9 were calculated.

The set of the analyzed kinematic excitations, i.e. accelerograms, comprised 64 pairs of signals in the form of horizontal, orthogonal components of acceleration of the vibrations in the soil, caused by mining quakes in the region of Polkowice. They resulted from four measuring stations situated in various parts of the town. The quakes were selected from about 640, occurring in the years 2000-2002 and 2004-2005 in Polkowice and its neighborhood. They were characterized by peak accelerations exceeding 0.25 m/s^2. Their entire duration comprised a point on the time axis of the arrival of signal at the measuring station, ending beyond the last local extremum amounting to a_e = 0.1 m/s^2 . The specification of these quakes was published in [10] and will not be quoted here again.

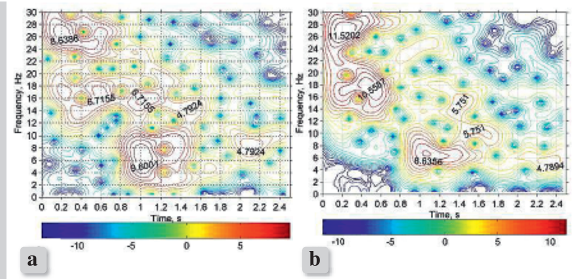

Figure 1.
Maps of Gabor's time-frequency representations of the accelerograms a) component X, b) component Y

3. RESULTS OF THE ANALYSIS

The maps of Gabor's representations permitted a synthetical visualization of the time-frequency evolution of the spectral power density of these signals. Exemplary diagrams for both horizontal components of the acceleration of the vibrations occurring on January 25th, 2000 have been presented in Fig. 1, together with the decibel scales.

The distribution of the representation, particularly their local extremes indicates a distinct evolution of the spectrum in the course of excitation. Their initial part is located in a band whose boundaries are distinctly higher than those of the subsequent fragment of the signal. Also both components of the diagrams are similar, because they are images of the same progress of vibrations generated in the lithosphere and have been recorded synchronically in selected orthogonal directions. It ought to be stressed that this characteristic image of the time-frequency representation of excitations concerned 56 shocks recorded at various measuring stations. The remaining eight shocks displayed a different distribution of representations along the time axis, they required apart and individual time-frequency analysis.

The evolution of the spectrum of kinematic excitations is still more distinctly visible in Figs. 2a-b. Here the peak values of accelerations are localized in those points in which Gabor's representations achieve local extremes. These diagrams have been plotted independently for the components X and Y of set of kinematic excitations, excluding untypical ones.

Fig. 2 sets off the effect of the evolution of the peak values of accelerations, taking into account their dependence on the frequency. Two zones can be distinguished, viz. the first segment characterized by peak values of accelerations localized in the higher band in contradistinction to the second segment, in which these values appear in the lower band. It is also evident that the peak values wane with the passage of the time of excitations.

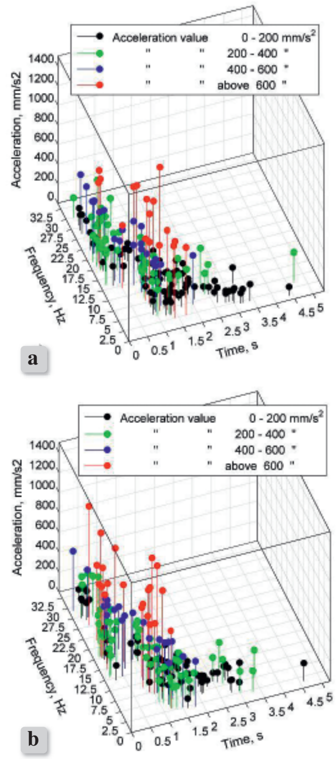

Figure 2.
Diagrams of the local extremes of kinematic excitations, a) components X, b) components Y.

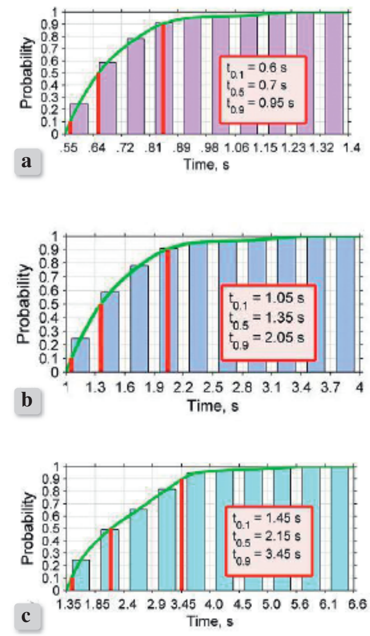

Figure 3.
Localization of the ends of segments No. 1 a), No. 2a b), No. 2b c) at the time axis

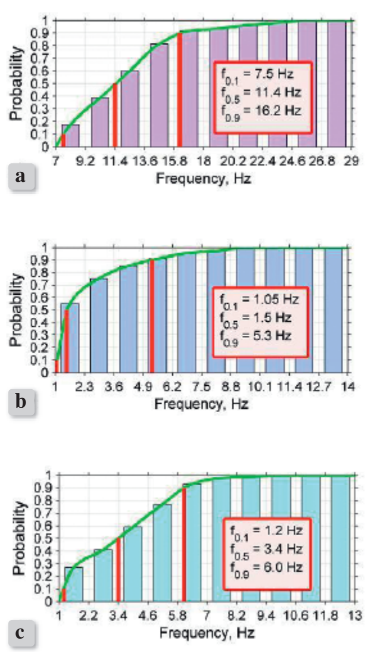

Figure 4.
Frequencies in the lower bands of segments: a) No. 1, b) No. 2a, c) No. 2b

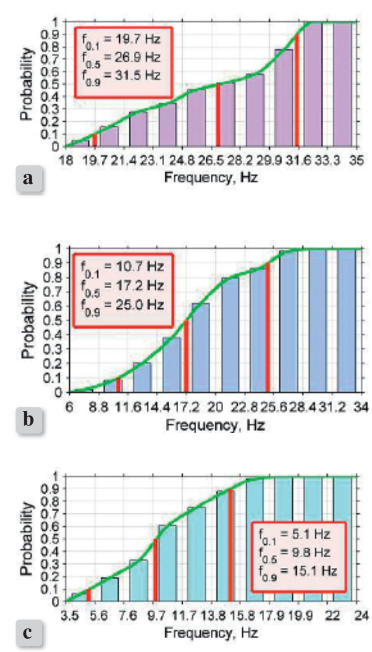

Figure 5.
Frequencies in the upper bands of segments: a) No. 1, b) No. 2a, c) No. 2b

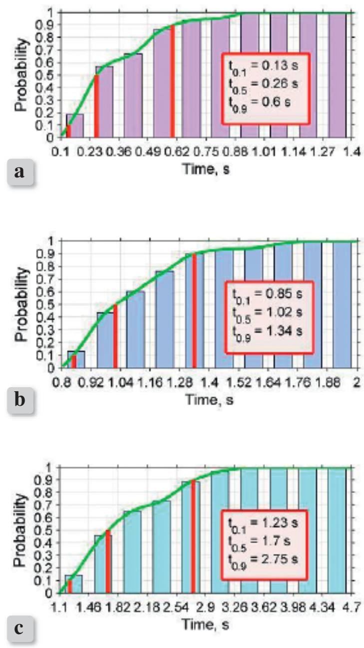

Figure 6.
Localization of the local extremes of Gabor's representations on the time axis in segments: a) No. 1, b) No. 2a, c) No. 2b

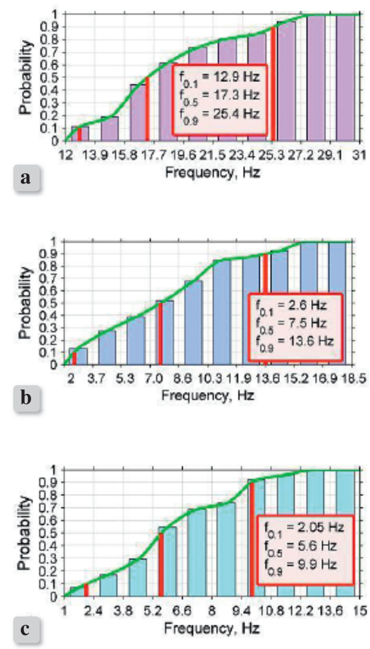

Figure 7.
Localization of the local extremes of Gabor's representations on the frequency axis in segments: a) No. 1, b) No. 2a, c) No. 2b

Gabor's representations concerning a set of 56 mining concussions were analyzed in detail basing on the assumptions quoted below. The components X and Y were analyzed jointly due to the similarity of the maps of values of the representations and because they constitute the image of one resultant excitation. For each kinematic excitation two fundamental segments have been distinguished, the initial one No. 1 and the basic one, No. 2, the latter have been divided additionally into two parts – subsegments "a" and "b". The duration and dominating frequency bands of the respective segments of kinematic excitations have been assessed basing on maps analogical to those presented in Fig. 1 where the level of 7 dB in Gabor's representation is conspicuous, corresponding to the ratio of the peak values of accelerations of the components of excitation to the peak value of the reference signal a_{ref} = 0.01 m/s^2 amounting to 5. The isoline of the values 7 dB permitted to read off in the maps the mentioned parameters of the excitations segments. In the analysis use was also made of the values and position of the local extremes of Gabor's representation in the segments 1 and 2a, b. In the zones determined by them the local extremes of acceleration of the components of kinematic excitation have been calculated. Altogether 18 random variables were analyzed, characterizing the nonstationarity of kinematic excitations. The classified distribution functions of the mentioned random variables have been presented in Figs. 3-7. The respective colors concern the respective segments. The values of quantiles of the order 0.1; 0.5 (median) i 0.9 have denoted, as well as their localization. These were applied to determine the boundaries in the domain of time and frequency of the selected segments of kinematic excitations.

The values of the quantiles of random variables calculated basing on empirical distribution functions have been gathered in Table 1.

Fig. 8 visualizes the time-frequency properties of kinematic excitations, taking into account the assessed parameters. Denoted time boundaries of the segments are: the first one is commenced by a quantile of order 0.1, segments No. 1 and No. 2a divide the medians and the last one is completed by a quantile of order 0.9. The boundaries of segments bands have been plotted too: the upper one as a quantile of order 0.9, the bottom one as a quantile of order 0.1, approximated by means of spline functions. Inside the segments bands those areas have been marked in which the maximum of Gabor's representations, being the image of the local components dominating in the segments of excitations are localized. Their lower and upper boundaries have been depicted, whereas the

Table 1.
Values of the parameters characterizing random variables

No.	Random variable	Value of quantile			Peak value
		0.1	0.5	0.9	
1	End time, segment No.1 [s]	0.6	0.7	0.81	-
2	End time, segm. No.2a [s]	1.05	1.35	2.05	-
3	End time, segm. No.2b [s]	1.45	2.16	3.45	-
4	Lower frequency, segm. No.1 [Hz]	7.5	11.4	16.2	-
5	Lower frequency, segm. No.2a [Hz]	1.05	1.5	5.3	-
6	Lower frequency, segm. No.2b [Hz]	1.2	3.4	6.0	-
7	Upper frequency, segm. No.1 [Hz]	19.7	26.9	31.5	-
8	Upper frequency, segm. No.2a [Hz]	10.7	17.2	25.0	-
9	Upper frequency, segm. No.2b [Hz]	5.1	9.8	15.1	-
10	Time coordinate of Gabor's representation maximum, segm. No.1 [s]	0.13	0.26	0.60	-
11	Time coordinate of Gabor's representation maximum, segm. No.2a [s]	0.85	1.02	1.34	-
12	Time coordinate of Gabor's representation maximum, segm. No.2b [s]	1.23	1.7	2.75	-
13	Frequency coordinate of Gabor's representation maximum, segm. No.1 [Hz]	12.9	17.3	25.4	-
14	Frequency coordinate of Gabor's representation maximum, segm. No.2a [Hz]	2.6	7.5	13.6	-
15	Frequency coordinate of Gabor's representation maximum, segm. No.2b [Hz]	2.05	5.6	9.9	-
16	Peak value of acceleration, segm. No. 1 [m/s^2]	-	-	0.59	1.24
17	Peak value of acceleration, segm. No. 2a [m/s^2]	-	-	0.72	1.015
18	Peak value of acceleration, segm. No. 2b [m/s^2]	-	-	0.19	0.385

boundary points on the time axis correspond to quantiles of order 0.1 (segment No. 1) or order 0.9 (segment No. 2b). The immediate points are identical with the boundaries of segments.

The assumption of indicated boundaries of the segments means that inside the area denoted by them there were 80% of the results concerning the analyzed excitations in the domain of time and as many in the domain of frequencies. Beyond this area there were results concerning samples of random variables, which were rather improbable. The evolution diagram in Fig. 8 illustrates the variation of the properties of kinematic excitations, which in their initial phase constitute high-frequency signals with a band of 7.5-31.5 Hz, dominating in band 12.9-25.4 Hz. The duration of this segment amounts to about 0.7 s and may include peak accelerations reaching 0.59 m/s^2 with probability of 90% and extreme observed values not exceeding 1.24 m/s^2 .The basic segment No. 2 lasts from about 0.7 s to about 3.45 s. Beyond this limit in about 10% of cases the kinematic excitations are longer. Two subsegments may be distinguished, their boundary being the point on the time axis t_2 = 1.35 s. The bands of these subsegments are defined by the boundaries 1.05-25.0 Hz and 1.2-15.1 Hz. The lower boundaries are in their case much lower than in the initial segment. The dominant areas of the segment 2 are comprised within bands 2.6-13.55 Hz and 2.1-9.9 Hz, they are distinctly shifted towards lower frequencies in relation to the initial segment. Dominating zones of segment No. 2 correspond with accelerations of 0.72 or 0.19 m/s^2 with a probability of being exceeded amounting to 10%. The extreme measured values did not exceed 1.015 and 0.385 m/s^2, respectively. Changes of the bottom boundaries of bands inside segment No. 2 are rather small in contradistinction to the upper bound-

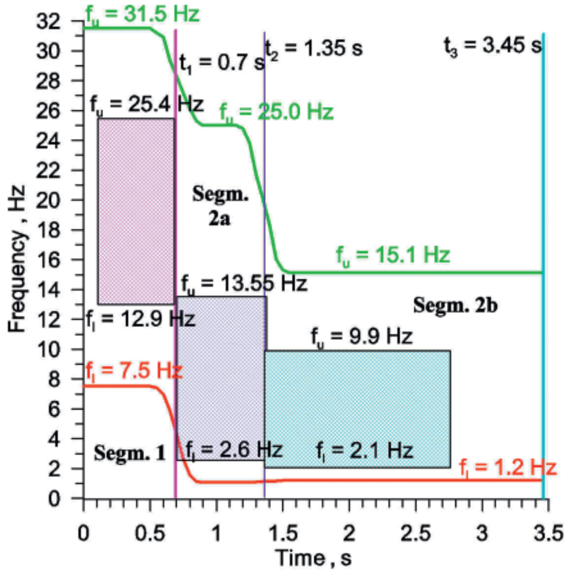

Figure 8.
Time-frequency characteristics of kinematic excitations segments

ary. Values of the peak values of acceleration fade quickly in the course of their duration. In subsegment No. 2b they are at least about 2.5 times lower than in part No. 2a.

6. CONCLUSIONS

Presented analysis of the nonstationarity of kinematic excitations permitted to expose the time-frequency properties and express them by means of the assumed parameters. Their nonstationarity is quite evident and may not be disregarded by assuming stationarity of accelerograms based on measurements of quakes due to mining activities. Mentioned properties of excitations are of essential importance from the viewpoint of the effects of these quakes on building structures. The initial segments of excitations, being high-frequency signals, do not affect considerably buildings with low basic frequencies of their natural spectrum [2, 4, 8]. It is only the basic segments which intensify this effect markedly. The latter is, however, comparatively short and quickly fades out in the course of its duration. It may be said that this constitutes a general and qualitative justification of the frequently described regularity, maintaining that mining quakes in spite of high peak values of acceleration affect the building development of towns only to a small degree, without causing larger damages in the structures of the buildings.

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