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Influence of the Seismic Intensity of the Area on the Assessment of Dynamic Resistance of Bridge Structures

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Abstract. The paper presents the results of the studies assessing the resistance of the existing bridge structures located in areas of varying seismic intensity. The basis for the analysis was an exemplary reinforced concrete road flyover of a slab span structure. Numerical calculations by the Finite Element Method were carried out, using the response spectrum approach in the dynamic analysis, with the use of the standard response spectra according to the Eurocode 1998 and the standard acceleration response spectra for the Upper Silesian Coal Basin and the Legnica-Głogów Copper District. For each individual analyzed case, the structure response to the assigned kinematic excitation was compared with the effects of load combinations adopted at the design stage, setting the limit values of the design horizontal ground acceleration in the horizontal plane ($a_{g,H}{}^{max}$) and the vertical plane ($a_{g,V}{}^{max}$). This allowed to assess the effect of seismicity of a specific area on the design dynamic resistance of the studied object. The paper discusses the manner of interpretation and the scope of applicability of the obtained results.

1. Introduction

The field of engineering issues dealing with the assessment of threats associated with mining exploitation which building structures are exposed to, includes the assessment of resistance of the existing objects to additional loads which occur during their use, and which were not included at the design stage. In mining areas, these impacts mostly include the effects of continuous surface deformation [1,2,3] and mining tremors [4,5,6,7,8,9]. The literature widely describes the methodology for assessing the resistance of building structures, including bridges and flyovers, to the impacts of continuous deformation [10,11,12]. The problem of assessing the resistance of buildings to the dynamic impacts caused by mining tremors is much less frequently discussed [13,14,15,16].

In most scientific studies, empirical seismic intensity scales are used to assess the resistance of building structures. Unfortunately, they do not have a universal character, because their intensity levels result from symptomatic recognition of the effects of a given tremor, and can be applied to a rather limited group of objects [17]. Therefore, the field of research related to the assessment of resistance of the existing building structures to the dynamic impacts caused by mining tremors is still open.

Assessment of the resistance of the existing bridge structures must be consistent with the guidelines regarding standard load combinations. It is therefore necessary to refer the assumptions adopted at the design stage, and subject to the directives of the obsolete standards, to the current criteria set out in the Eurocodes [18]. On the other hand, the comparison of the effects of the load combinations acting on the structure, adopted at the design stage, with the effects of the seismic combination dictated by [19],

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enables to identify some reserve in the load-bearing capacity, allowing for the structure being additionally loaded with a mining tremor. Knowing this value, it is possible to define limit values of the parameters describing tremors occurring in the specific area, which can be carried by a given object without any threat to its safety. A detailed description of the procedures for determining such resistance for bridge structures was presented in [16].

The paper demonstrates the results of the studies on the resistance of a typical flyover of a reinforced concrete slab span structure for the areas of varying seismic activity. Standard acceleration response spectra contained in [20], spectra resulting from the adaptation of the provisions contained in the Eurocode 8 to the design requirements for the seismically active areas in Poland [9], predetermined standard acceleration spectra for the Legnica-Głogów Copper District [8,17] and the Upper Silesian Coal Basin [21] were used for this purpose. Such a wide range of potential excitations adopted for the study aimed to illustrate the effect of the seismic intensity of a given area on the dynamic resistance of the structure located there. On the other hand, the adoption of five different response spectra for the Legnica-Głogów Copper District results from the local amplification of ground vibrations occurring in this area which, in accordance with the adopted research methodology [16], may consequently reduce the resistance of the structure [8,17,22].

The additional difficulty in this case is the uncertainty in relation to the material parameters adopted at the design stage. With respect to the reinforced concrete bridge structures, this problem often refers to the actual degree of reinforcement of its load-bearing components, compressive strength of concrete and the actual load-bearing capacity of the bearings. The study implemented the methodology for determining dynamic resistance, which is based on the criteria specified in [16]. According to these criteria, it is possible to analyze the structure, with respect to which the information on the above-mentioned parameters is uncertain.

Ground vibrations, characteristic for a specific area, caused by mining tremors or natural earthquakes, may be presented as a set of maximum values of acceleration, velocity or displacements, assigned to the corresponding natural frequency of the oscillator with one degree of dynamic freedom. Therefore, it is possible to create a representation of the seismic signal, together with determination of its effect on the structure, and to present it in the frequency domain (or period of oscillations). Such a representation of the seismic signal is the so-called response spectrum [7,23]. In practice, the so-called standard response spectra, which characterize the seismic activity of a specific area, are used for the designs of structures located in seismic areas. They constitute a set of separate maximum values of acceleration, velocity or displacements of vibrations, assigned to the frequency domain. During the performed calculations, not one, but all the maximum values of the analyzed frequency range are taken into account. The contribution of each of them to the structure response is determined by the resonance effect depending on the dynamic characteristics of the analyzed object, i.e. the normal mode and the corresponding frequencies. The final response of the structure is therefore the sum of all normal modes subject to excitation. This results in the determination of the permissible characteristics of ground vibrations being a problem entangled, due to the safety of the existing building structure.

The complexity characterizing both the representative seismic signal for a specific area in the form of a response spectrum, and the reaction of the structure to the dynamic load, make it impossible to express the dynamic resistance of a structure as a single peak acceleration, velocity or displacement, which that structure can carry without any threat to its safety.

In the case of the existing objects, in the context of resistance, the standard response spectrum and the permissible value of the parameter a_g are representative. The parameter a_g, which defines the design ground acceleration according to [9,17,20,24], for the newly designed structures for seismic impacts is taken arbitrarily and it expresses the predicted ground vibrations at the location of the object. In the case of the resistance of the existing building structures which were not designed for seismic impacts, it may be determined according to the procedure described in [16]. Then, it is the scaling factor for the standard response spectrum adopted for the dynamic analysis and describing the seismicity of the specific area. Determination of the limit value for the parameter a_g with a

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predetermined shape of the standardized spectrum model, in fact provides the shape of the permissible response spectrum which the structure may carry without any threat to its security in the specific area.

In this study, for each of the analyzed cases, the limit values of the design ground acceleration in the vertical and horizontal planes ($a_{g,H}^{\ max}$ and $a_{g,V}^{\ max}$) were determined, which the existing structure could carry without a safety hazard.

2. Research methodology

The subject of the research is a two-span road flyover of a reinforced concrete slab structure. It is composed of two spans with the length of 11.5 m, the width of 8.0 m and the height of the slab of 0.65 m. In addition, on both sides of the structure, there are side overhangs forming an integral part of the spans. The length of the overhangs is 4.0 m on each side. The overhangs are pin-supported on the abutments. The three reinforced concrete frames consisting of four pillars with the dimensions of 0.8m x 0.7m x 7.0m, and the transom with the function of the bridge seat with the dimensions of 0.8m x 0,8m x 8,0m, are the intermediate supports. Figure 1 illustrates the construction scheme of the flyover.

The static and dynamic analyses were performed in ABAQUS using the interface (ASI-Abaqus Scripting Interface [25]), constituting an extension of the Python language. The slab-and-girder numerical model of the structure was created (cf. Figure 2).

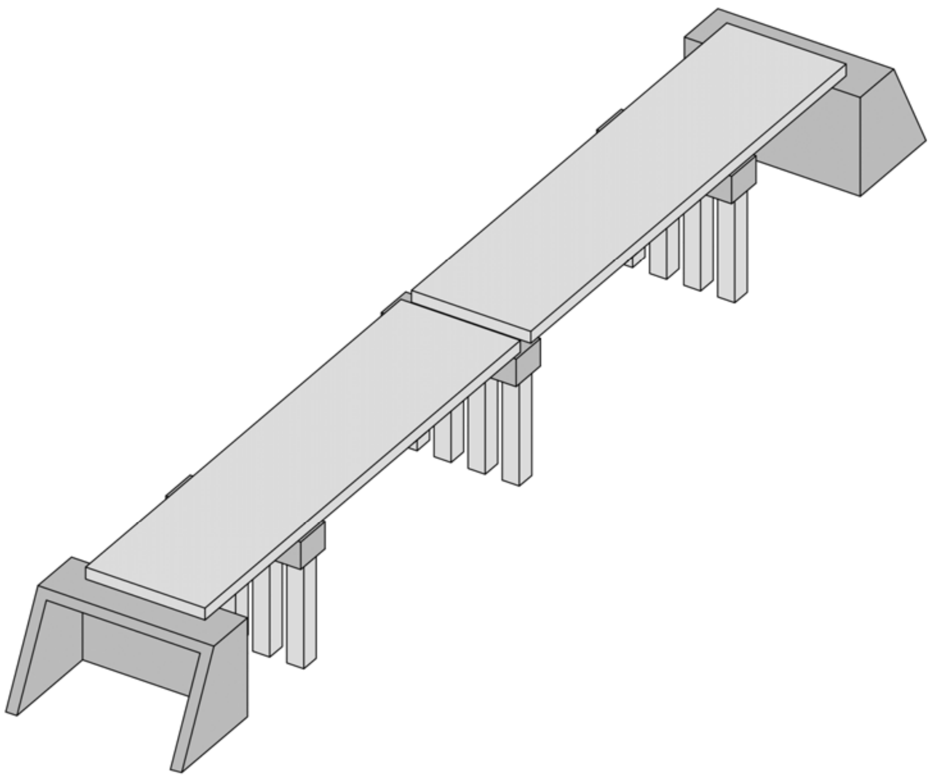

Figure 1. Diagram demonstrating the geometry of the structure

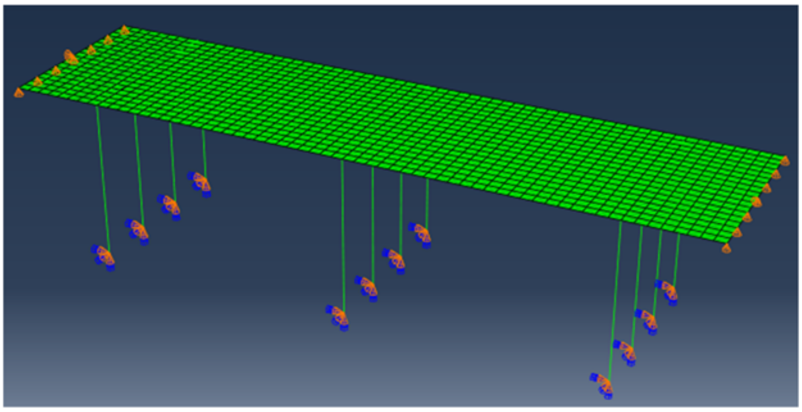

Figure 2. Numerical model of the flyover

The dynamic analysis was performed by the response spectrum method [14,23]. The normalized elastic response spectra for all ground types according to the Eurocode 8 [20], as well as the standard acceleration response spectra for the Upper Silesian Coal Basin and the Legnica-Głogów Copper District were adopted as a dynamic excitation – cf. Table 2, Figure 3 and Figue 4. The spectra representing the seismic activity of the mining areas of the Upper Silesian Coal Basin and the Legnica-Głogów Copper District are the result of the performed research studies described in [7,8,9,21]. The spectra labeled as EC-8-A-LGOM, EC-8-B-LGOM and EC-8-C-LGOM constitute an adaptation of the Eurocode 8 to the seismic conditions prevailing in the Legnica-Głogów Copper District [9]. The curves denoted as LGOM(a), LGOM(b) and GWZ are the results of the research which mainly involved the record of the tremors occurring in the mining areas of the Upper Silesian Coal Basin and the Legnica-Głogów Copper District [7,8,21]. A clear difference is the extent of these curves. In the case of the curves LGOM(a) and GWZ, this range is twice narrower than in the case of the other spectra describing the seismicity of the Legnica-Głogów Copper District (cf. Figure 4). This difference may have effect on obtaining other values of the parameters adopted for the description of the structure response. This, in turn, may lead to other limit values of ground acceleration a_g defining the resistance of the structure, obtained from the calculations.

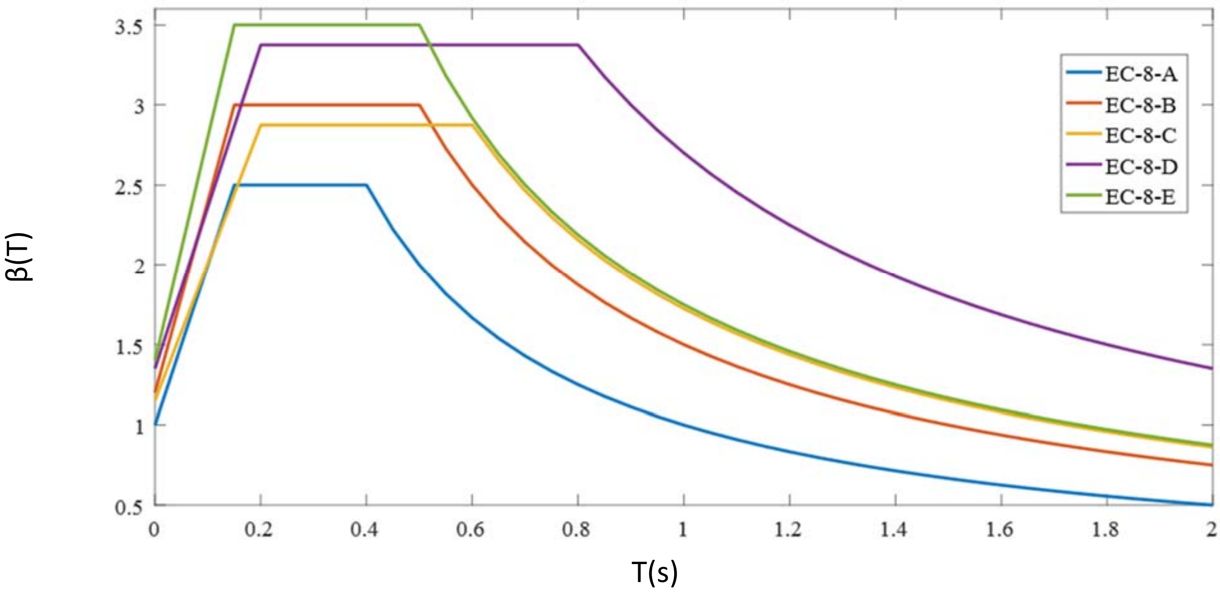

Figure 3. Curves of the standardized acceleration response spectra adopted for the dynamic calculations according to [20]

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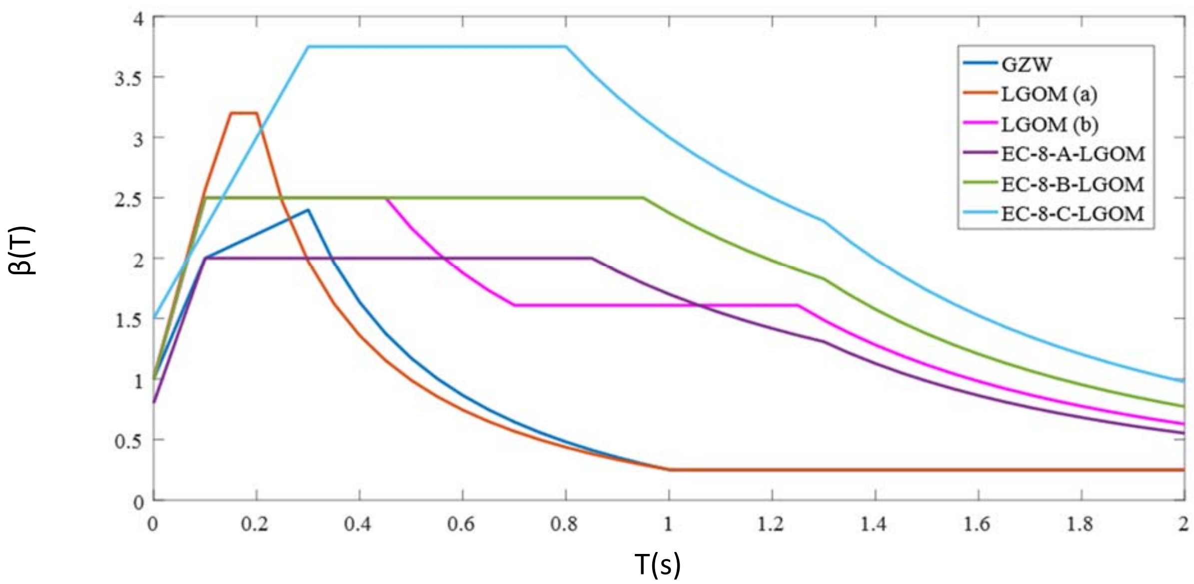

Figure 4. Curves of the standardized acceleration response spectra for the areas of LGOM and GZW according to [7,8,9,21]

In the calculations, according to [20], the damping factor ξ = 0.05 was used. According to [13,16,24], the conditions of the dynamic resistance were formulated in relation to the two directions of a potential kinematic excitation induced by a mining tremor. The longitudinal direction was considered (relative to the length of the structure) – x, and transverse direction - y. The excitation on the vertical direction - z was treated individually. The effects of excitation on individual directions in the horizontal plane were defined in accordance with the requirements contained in [24]. Ultimately, the least favourable effect of all possible combinations dependent on the direction of a seismic wave was taken for the calculations, according to [24]:

$$E_d^{SE} = \max \begin{cases} \sqrt{E\left(a_{g,x}\right)^2 + E\left(a_{g,y}\right)^2} \\ \pm E\left(a_{g,x}\right) \pm 0,3 \cdot E\left(a_{g,y}\right) \\ \pm 0,3 \cdot E\left(a_{g,x}\right) \pm E\left(a_{g,y}\right) \end{cases} \tag{1}$$

where:

E_d^{SE} – the least favourable design value of the failure effect of seismic impacts,

$E(a_{g,x})$, $E(a_{g,y})$ – failure effects of the structural components resulting from tremor impact in the direction *x* and *y*, respectively,

$a_{g,x}$, $a_{g,y}$ – values of the horizontal ground acceleration in the longitudinal direction (*x*) and in the transverse direction (*y*), having the function of the scaling factors of the response spectrum curve taken for the calculations [24].

The summation of the contributions from the individual modes of vibrations was performed according to [20] using the CQC method (Complete Quadratic Combination [23]). The performed analyses, taking into account the resistance assessment criteria defined in [16], resulted in the limit values of the vector components of the design ground acceleration ($a_{g,H}^{max}$ and $a_{g,V}^{max}$). Table 1 demonstrates the obtained periods of natural vibrations of the structure. On the other hand, the obtained results of the resistance for all the adopted seismic excitations are contained in Table 2 and illustrated in Figure 5.

Table 1. Summary of the periods and natural frequencies of the analyzed structure

No. of the natural mode of vibrations	Corresponding period of natural vibrations [s]	Corresponding natural frequencies [Hz]
1	1.18	0.85
2	0.55	1.83
3	0.38	2.65
4	0.34	2.98
5	0.22	4.45
6	0.19	5.26
7	0.18	6.74
8	0.15	7.65
9	0.13	8.32
10	0.12	9.33

Table. 2. Summary of the results of assessing the resistance of the analyzed structure for specific areas with different seismic activity

Spectrum curve	Adopted denotation	Values of limit design components of ground acceleration [m/s²]	
		$a_{g,\mathrm{V}}^{\max}$	$a_{g,\mathrm{H}}^{\max}$
GZW - [21]	GZW	0.31	1.05
LGOM (a) - [7]	LGOM (a)	0.38	1.15
LGOM (b) – [8]	LGOM (b)	0.26	0.20
Type A – [9]	EC-8-A-LGOM	0.32	0.22
Type B – [9]	EC-8-B-LGOM	0.26	0.16
Type C – [9]	EC-8-C-LGOM	0.17	0.12
Type A – [20]	EC-8-A	0.26	0.37
Type B – [20]	EC-8-B	0.22	0.25
Type C – [20]	EC-8-C	0.23	0.21
Type D – [20]	EC-8-D	0.19	0.14
Type E – [20]	EC-8-E	0.19	0.21

Having analyzed the obtained results it can be concluded that:

- resistance of the structure determined for the Legnica-Głogów Copper District, the intensity of which was described by the spectral curve LGOM(a) is similar to the resistance determined with adopting the standard spectrum for the Upper Silesian Coal Basin,
- the determined limit values ($a_{g,V}{}^{max}$ and $a_{g,V}{}^{max}$), only in the case of using the calibration curves LGOM(a) and GZW, reach the values exceeding 1.0 m/s^2. However, this applies to the horizontal plane only. Analysing all used standard response spectra curves, the curves LGOM(a) and GZW reach relatively high values in a fairly narrow band of the periods of natural frequencies (Figure 4). On the other hand, the first two normal modes, determined for the analyzed structure, occur precisely in the horizontal plane, with the periods of natural frequencies equal to T_1=1.18 s and T_2=0.55 s (Table 1). As demonstrated in Figure 5, they are located in the diminishing zone of the spectrum curve, and therefore they were not taken into account when determining the response of the structure to such an extent as e.g. the LGOM

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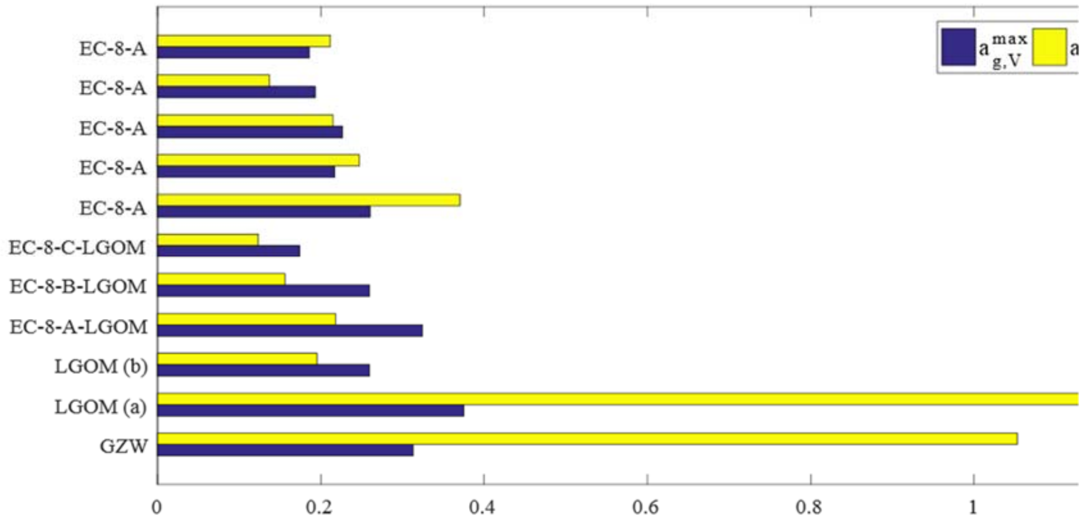
(b). This may be the reason why the resistance of the structure determined using standard response spectra curves LGOM(a) and GZW is overvalued relative to the other results,



$a_{g,V}^{max}$ *and* $a_{g,H}^{max}$ **[m/s²]**

Figure 5. Distribution of the values of limit design components of ground acceleration $a_{g,V}^{max}$ and $a_{g,V}^{max}$

- the proposed standard response spectrum curve for the Legnica-Głogów Copper District expressed by the curve LGOM(b) results in the decreased limit values of the ground vibration components, which determine its dynamic resistance relative to the results obtained for this area using the response spectrum LGOM(a). According to [8], it may be due to the phenomenon of amplification used in the response spectrum,
- the use of the spectrum curves resulting from the adaptation of the Eurocode 8 to the seismic conditions prevailing in the Legnica-Głogów Copper District [9] produces resistance values very similar to those obtained under the original directives of the Eurocode 8. The difference is visible in a noticeable decrease in the resistance of the analyzed structure when the curves denoted as: EC-8-(A,B,C)-LGOM are used relative to the corresponding original curves EC-8-(A,B,C),
- if the spectrum curves EC-8-A,B,C and LGOM(b) are used, there is a decrease in the resistance in the horizontal plane relative to the limit values of acceleration in the vertical plane,
- the determined limit values of the ground acceleration ($a_{g,V}^{max}$ and $a_{g,V}^{max}$), except for the cases of LGOM(a) and GZW, demonstrate that the resistance of the analyzed bridge structure, determined both in the vertical and horizontal planes, is comparable. This is a significant difference comparing to cubic structures, where dynamic excitations in the horizontal plane have the greatest impact.

3. Results and discussions

The study results presented in this work confirm a noticeable effect of seismic intensity of a given area on determining dynamic resistance of building structures. This is due to the adoption of the response spectrum method for the calculations, and thus the representative standard spectral curves, defining the seismicity of the area. Although the subject of the study was a bridge (road flyover), the relativity of assessing the resistance of the existing structures to dynamic impacts caused by mining tremors applies to all types of structures. The obtained results are not representative for the whole group of bridges, because its diversity both in terms of geometry and material is too large to formulate general

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conclusions. Bearing this in mind, it is planned to build a database of dynamic resistance of bridges to the impacts of mining tremors. The analysis of such a database will allow for the generalization of knowledge regarding the assessment of resistance of bridges and sensitivity of individual structural components to dynamic excitation induced by mining tremors. Such information may form the basis to build decision systems using machine learning techniques [26], and therefore streamline the process of assessing the resistance of bridge structures in the event of the occurrence of tremors in mining areas.

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