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Dynamic Response of Frame Structure Railway Viaduct Subjected to Spatially Varying Mining Tremor

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Abstract: The paper presents the dynamic analysis of a reinforced concrete viaduct of stiff frame structure subjected to a mining tremor registered in the Upper Silesian Coal Basin, which is one of the major mining activity region in Poland. Two methods of evaluation of the dynamic response were used: the time history analysis (THA) taking into account spatial variability of ground motion and the response spectrum analysis (RSA) with the elastic response spectrum recommended in Eurocode 8. The analysis highlights that the simplifying assumption of uniform kinematic excitation is not recommended for viaducts of a stiff frame structure. The non-uniformity kinematic excitation is essential for the accurate assessment of the dynamic response of these structures subjected to mining tremors of high variability in space. Also the response spectrum analysis may lead to underestimation of the dynamic response.

Keywords: *Dynamic response of bridge, Mining tremors, Non-uniform kinematic excitation, reinforced concrete viaduct, ABAQUS.*

1. Introduction

An extraction of minerals, like copper and coal, is often performed close to urban areas with high population density where industrial or municipal infrastructure facilities are located. More often there are also requirements to protect structures from induced seismic shocks of mining origin [6]. Therefore, the problem of the impact of mining tremors on surface infrastructure is crucial in areas of mining activity. Mining tremors differ from natural earthquakes in many aspects. The differences are mainly related to mechanisms of forming, range of the predominant frequencies, and duration of the phenomena, intensity and repetition of the occurrence. Despite these differences methods of dynamic analysis of structures under mining shocks are the same as in earthquake engineering.

Spatial variability of ground motion during seismic shocks or mining tremors is commonly neglected in calculations of the dynamic response of simple engineering structures, like buildings. But in case of long structures, like bridges or dams this simplification is not always recommended [2, 4]. These multiple-support structures are exposed to non-uniform kinematic excitation. Due to the length of the structure, which is comparable with the seismic wavelength, different motions act on particular supports of the bridge. The influence of spatial variety of excitation on the dynamic response of bridges may be significant especially in case of mining shocks, which present high variability in space.

The influence of the non-uniform seismic excitation on the dynamic response of large dimensional multiple-support structures was considered by many researchers, e.g. [3, 5, 7]. Generally authors claim that dynamic response to non-uniform kinematic excitation is smaller than dynamic response to uniform excitation. The decrease of the dynamic response is caused by reduction of average amplitudes of kinematic excitation. On the other hand, the authors mention that occurrence of quasi-static effects that result from differences in excitation in particular points of foundations may lead to an increased global response.

Railway viaducts often consist of a primary structural system made a reinforced concrete frame. The integrity of the superstructure and the piers significantly increases the stiffness of the whole structure. Hence, the non-uniformity of seismic excitation may lead to great quasi-static effects resulting in a further increase of global dynamic response.

The paper presents the dynamic analysis of a reinforced concrete viaduct of stiff frame structure subjected to a mining tremor registered in the Upper Silesian Coal Basin, which is one of the major mining activity region in Poland.

Two methods of evaluation of the dynamic response were used: the time history analysis (*THA*) taking into account spatial variability of ground motion and the response spectrum analysis (*RSA*) with the elastic response spectrum recommended in Eurocode 8.

2. Data of Registered Mining Tremor

Figure 1 represents time histories (three components) of a representative mining shock registered in the Upper Silesian Coal Basin [6]. The energy of the tremor was about $1 \cdot 10^7$ J, so the tremor belonged to the strongest events ever measured in this region. The dominant frequencies of the shock are located in the range from 1.6 to 4.8 Hz with a noticeable peak at 3.5 Hz.

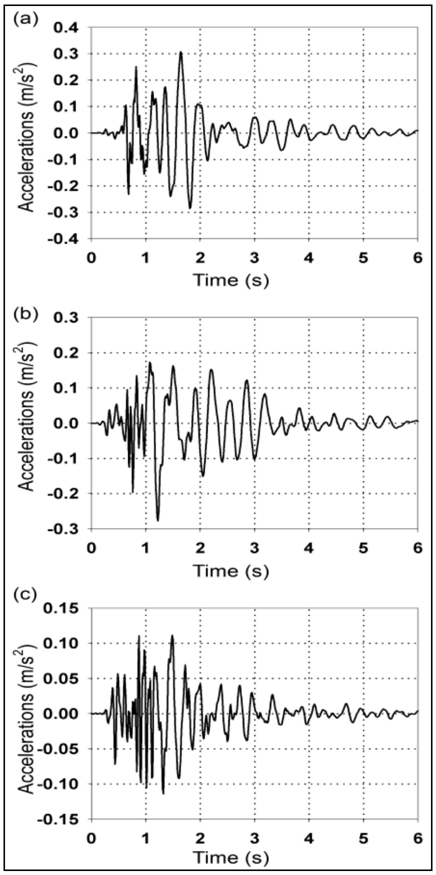

Figure 1 *Ground accelerations of the registered mining shock: a) in horizontal direction NS, b) in horizontal directions Y, c) in vertical direction Z*

3. Geometry and Material Data of the Viaduct

The dynamic response to spatially varying mining shock was calculated for a three-span railway viaduct.

The structure made of reinforced concrete is typical in Central Europe as far as geometry and mechanical data of materials of viaducts are concerned. The viaduct consisted of a reinforced concrete superstructure and piers. The length of the viaduct was 40 m (the central span - 20.0 m). The abutments were situated 10 m away from the piers. The reinforced concrete deck of the viaduct was 7.62 m wide and 1.10 m high (1.6% of reinforcement was applied). The viaduct was equipped with elastomeric bearings as linking elements between the superstructure and the abutments. The fixed boundary conditions reflected the high rigidity of the foundation rock. Linear elastic behavior of the structure was assumed since the level of dynamic impact of the mining tremor was not as high as in case of a seismic shock. The elasticity modules were taken as 3.9 and 3.2 GPa for the superstructure and the abutments, respectively.

It is worth noticing that the whole structure is very stiff due to the rigid frame constituting a primary structural system. This can result in substantial internal forces occurring in the frame while subjected to the different motions imposing on the consecutive supports. Figure 2 presents the main dimensions of the cross section of the deck, whereas Figure 3 shows the longitudinal view of the viaduct.

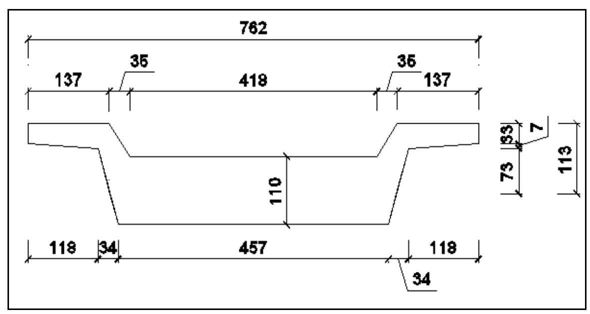

Figure 2 *Dimensions of the cross section of the viaduct deck in the middle of the main span*

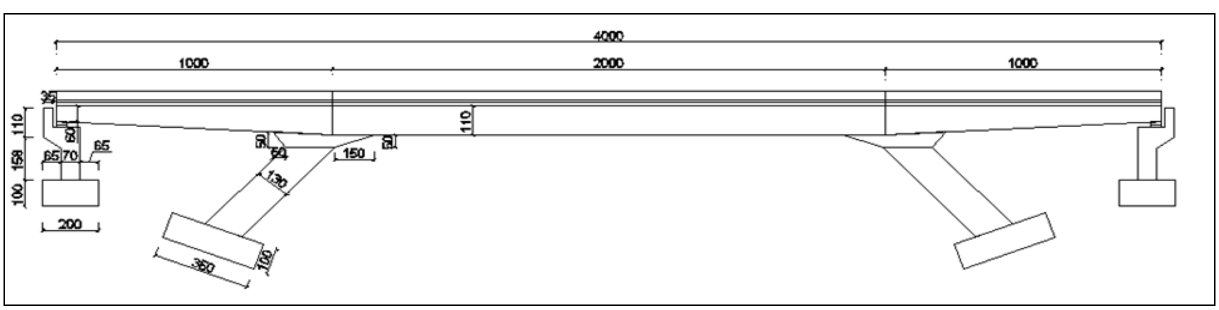

Figure 3 *Longitudinal view of the viaduct*

4. Three-Dimensional Numerical Model of the Viaduct

A 3D finite element model of the structure was developed using the ABAQUS software [1]. The whole structure was discretized by circa 44000 brick 10-node elements. The dynamic response of the viaduct, in terms of maximal principal stresses, was analyzed at selected points located at the deck of the viaduct. The FE mesh as well as the selected points is presented in Figure 4.

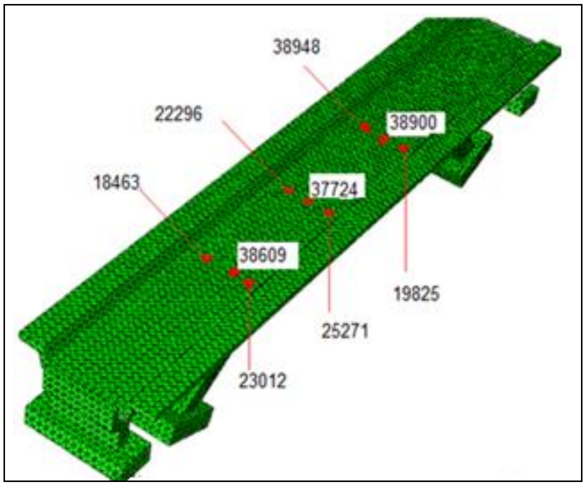

Figure 4 *FE mesh along with the location of points selected for dynamic analysis*

5. Assessment of the Dynamic Response of Viaduct to Mining Tremor Obtained with *THA* Method (Uniform and Non-Uniform Kinematic Excitation)

Fragments of time histories of maximal principal stresses at selected points in the main deck calculated for both, the uniform and non-uniform kinematic excitations are shown in Figures 5-7.

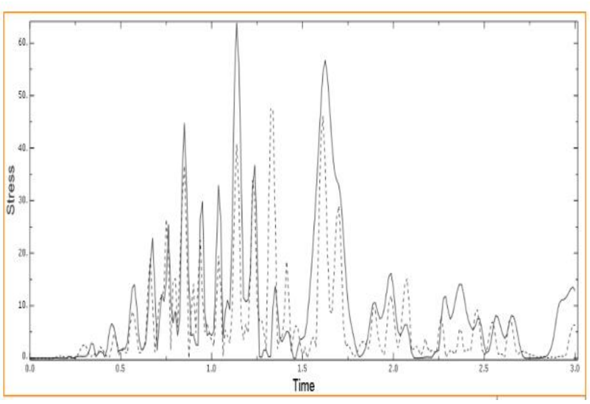

Figure 5 *Comparison of maximal principal stress obtained for: uniform (dashed line), non-uniform kinematic excitation (continuous line) at selected point 38609 (see Fig. 4)*

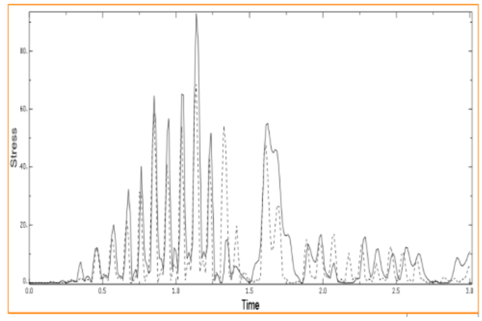

Figure 6 *Comparison of maximal principal stress obtained for: uniform (dashed line), non-uniform kinematic excitation (continuous line) at selected point 37724 (see Fig. 4)*

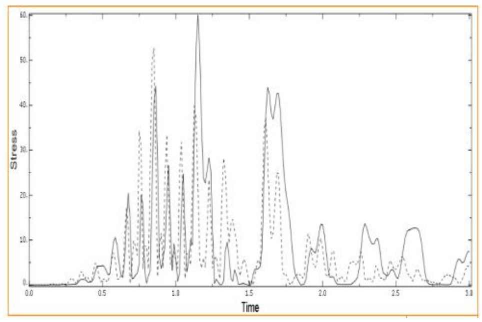

Figure 7 *Comparison of maximal principal stress obtained for: uniform (dashed line), non-uniform kinematic excitation (continuous line) at selected point 38900 (see Fig. 4)*

Time histories of the registered mining tremor in three directions were taken into consideration the as kinematic excitation. The model of non-uniform excitation, taking into account the wave passage effect, was applied for the dynamic calculations of the viaduct. It assumed that subsequent points of the ground in the direction of wave propagation repeat the same motions with a time delay dependent on the wave velocity. The wave velocity of 1200 m/s was considered. For comparison the model of uniform kinematic excitation, corresponding to the assumption of the infinite velocity of wave propagation in the ground, was taken into account.

The time history analysis (THA) was carried out with the Hilber-Hughes-Taylor time integration algorithm provided in the ABAQUS software for a direct step-by-step solution. For the dynamic analysis the Rayleigh model of mass and stiffness proportional damping was applied. The damping coefficients (α and β) were determined for damping ratios 5% referring to the first and second natural frequency of the viaduct, respectively.

Table 1 summarizes maximal principal stresses obtained at representative points of the deck in case of uniform and non-uniform kinematic excitation. The differences obtained for both cases of excitation models are evaluated and shown in Table 1 as well.

Table 1: *Maximal principal stresses obtained at selected points for uniform and non-uniform kinematic excitation*

Element number	Maximal principal stress [kPa]		Difference [%]
	Uniform excitation	Non-uniform excitation	
38609	47.5	62.7	22
37724	68.5	93.0	26
38900	52.5	60.1	13

It could be noticed from Figs 5-7 and Table 1 that the increase of the dynamic response of the viaduct was observed at analysed points in case of non-uniform model of excitation with respect to uniform excitation. Similar results, i.e. the increase of the dynamic response, were observed at all selected points (see Fig. 4). Significant differences of the dynamic responses obtained for both models of excitation (up to 40%) were specified at points located in the middle of the central span.

6. Assessment of the Dynamic Response of Viaduct to Mining Tremor Obtained with *RSA* Method

The evaluation of the dynamic response of viaduct with the RSA method was also carried out. The method is only approximate, but it estimates the peak response of a structure to a particular base motion. The elastic response spectrum recommended by Eurocode 8 (ground type A, damping 5%) was implemented.

Figures 8-9 present maximal principal stresses obtained with uniform and non-uniform excitation along with the value of stress obtained with RSA analysis (red line) at points 38609 and 37724, respectively.

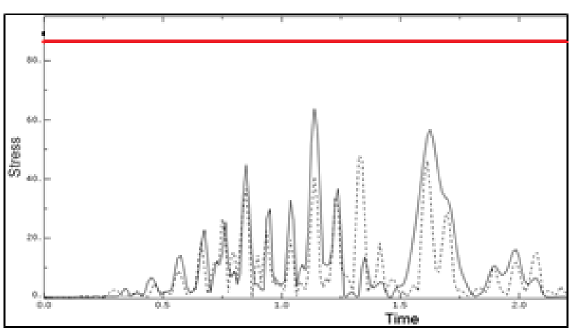

Figure 8 *Maximal principal stress obtained with THA method for uniform (dashed line) and non-uniform excitation (continuous line) as well as with the RSA method (red line) at point 38609*

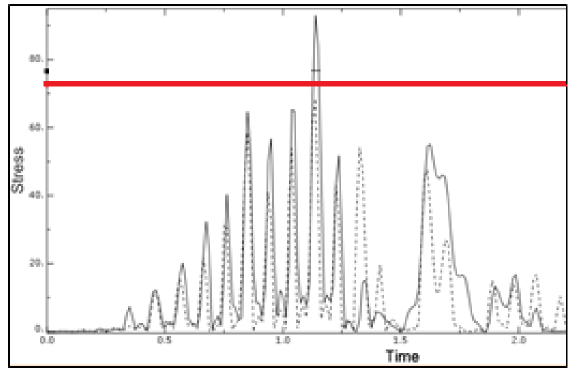

Figure 9 *Maximal principal stress obtained with THA method for uniform (dashed line) and non-uniform excitation (continuous line) as well as with the RSA method (red line) at point 37724*

The comparison of maximal principal stresses shown in Figs 8-9 indicates two options. It happen that the results obtained from the THA method with both models of excitation, uniform and non-uniform, are smaller than the results obtained from the RSA method (see Fig. 8, point 38609). However, the conclusion may be different: the results obtained from the THA method with the non-uniform model of excitation are greater than the results obtained with the RSA method (see Fig. 9, point 37724).

Hence, the dynamic behavior of the stiff frame viaduct may be underestimated by the approximate RSA method if the non-uniformity of the mining tremor is taken into consideration.

7. Conclusions

The dynamic response of the railway viaduct of a stiff frame structure to the registered mining tremor was evaluated. Two models of kinematic excitation, typical for multiple-support structures, were applied: uniform and non-uniform excitation. Also the response spectrum analysis was carried out to obtained approximate results of the dynamic analysis. On the basis of the calculations and dynamic analyses the following conclusions could be formulated:

1. The dynamic response of the viaduct to the mining shock is strongly determined by the model of kinematic excitation. If the model of non-uniform kinematic excitation is applied the response can be greater even up to 40% in relation to the response obtained for the model of uniform excitation.
2. The increase of the dynamic response of the viaduct obtained in case of non-uniform excitation can be attributed to the fact, that the reduction of average amplitudes occurring in case of non-uniform excitation does not play the central role in case of the dynamic behavior of stiff frame viaduct. The occurrence of strong quasi-static effects caused by

changes in the geometry of the subsoil seems to have more substantial impact that enlarges the global dynamic response of the viaduct.

3. The comparative analysis of results obtained from the THA and RSA method revealed that the RSA method may lead to non-conservative assessment of the dynamic response of the stiff frame bridges under mining tremors if non-uniformity of kinematic excitation is taken into consideration.

The analysis highlights that the simplifying assumption of uniform kinematic excitation is not recommended for bridges or viaducts of a stiff frame structure. No doubts, including the model of non-uniform kinematic excitation is essential for the accurate assessment of the dynamic response of these structures subjected to mining tremors of high variability in space. Moreover, the approximate response spectrum analysis may lead to underestimation of the dynamic response.

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