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Dynamic Response of a Road Viaduct to a Mining Tremor Using Multiple Support Response Spectrum Method

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Abstract. In this study the dynamic response analysis of a concrete road viaduct subjected to a mining shock is presented. The dynamic analysis was performed using different methods of analysis, i.e. the Time History Analysis (THA), the Response Spectrum Analysis (RSA) and the Multiple Support Response Spectrum Analysis (MSRS). On the basis of analyses, the effectiveness and the suitability of these methods in case of non-uniform kinematic excitation were determined. For the analysis of dynamic response, a real road structure was chosen. The object is a three-span bridge, 40 m long. The structure was subjected to a real, representative mining shock as a kinematic excitation. The typical shock from Upper Silesian Coal Basin was taking into account. The dynamic calculation of the viaduct to the mining shock were performed using the THA, RSA and MSRS methods. For the THA method two kinds of ground motion models were used: the uniform and non-uniform model. For the non-uniform excitation model two wave velocities were taken into account: 500 and 1000 m/s. For the RSA and MSRS analysis the spectral curves, created on the basis of the mining shock acceleration, were used. In the RSA method, the same spectra were used at each supports. In the MSRS method, the response spectra were modified, due to the occurring non-uniformity of excitation effects. For the MSRS analysis the wave passage effect, the attenuation effect and the incoherence effect were taken into account. As the results of the analysis, principal stresses in representative points were determined. To compare the obtained solutions, the results of each analysis were correlated. This comparison clearly presents the significant influence of the non-uniformity effects. On the basis of the results obtained for chosen elements it was easy to notice that the non-uniform excitation model results in much greater values of stresses than the uniform excitation model. The presented results also prove that the MSRS analysis led to significantly greater values of stresses than the RSA method. The conducted response spectrum analysis has shown that the RSA method may lead to underestimation of the dynamic response of structures, whereas the MSRS method provides the proper quasi-static way to estimate the stress level in a structure subjected to a non-uniform kinematical excitation. The key conclusion of this studies is that the non-uniformity effects has important influence on the dynamic behaviour of multiple-support structures. Neglecting of these effects may results in underestimation the maximum response of a structure. In addition, the comparison of results obtained by different methods shows that the MSRS method may be used in estimation of the dynamic response of large-dimensional structure subjected to non-uniform mining shock.

1. Introduction

The dynamic response of engineering structures to seismic shocks is one of the main task of earthquake engineering. In some region of the world seismic excitation is a primary load which affect an object. Many different types of dynamic analysis are used by engineers to determine the response of an object to an earthquake. The most common calculation methods are time history analysis (THA) and response spectrum analysis (RSA). Both methods allow to calculate the stress level in structural elements. From the THA method solution is obtained directly from equation of motion. The equation of motion is solved for each step of time according to the current excitation level. This method is very precise and obtained results are in the form of time history. The RSA is much faster method. Calculated results are approximation of maximum response of a structure. The results are based on the modal characteristics of a structure and a maximum value of excitation (e.g. ground motion acceleration). On the basis of literature [1, 2] it can be proved that the RSA method can be used as safe assessment of the maximum dynamic response of a structure.

Both of described above methods are prefect for the analysis of small, compact structures, especially for the analysis with uniform excitation models. However, in case of long objects (like bridges) where non-uniformity of kinematic excitation plays a significant role, the RSA method may lead to incorrect results. This phenomenon was shown in papers [3, 4]. The presented observations suggest that methods taking into account the non-uniform effects of excitation should be used for large-dimensional structures. In engineering practise, except for THA, there is another method which fill the requirements - the Multiple Support Response Spectrum Analysis (MSRS) [5]. The MSRS method is similar to the RSA method, but the non-uniform effects of ground motion can be taken into consideration.

Many authors demonstrate that the MSRS analysis is a very helpful method in estimating the maximum dynamic response of a large object subjected to non-uniform seismic excitation [6,7]. However, there is no studies concern the dynamic analysis of a structure exposed to non-uniform excitation of mining origin using the MSRS method. In some regions of the world mining tremors represent much more dangerous phenomenon than the earthquakes. For example, in mining areas of Poland, which is located in low seismicity zone, shocks happen quite often and bring a lot of energy.

In this paper, the dynamic response of a road viaduct to a mining shock is presented. For the analysis non-uniform aspects of excitation (like wave passage or incoherency effect) were taken into account. The analysis was performed using different types of the dynamic analysis: the THA, RSA and MSRS methods. The results obtained from each of methods allowed to determine the effectiveness and the suitability of these methods in case of non-uniform kinematic excitation.

2. Description of the Multiple Support Response Spectrum Method

To estimate the dynamic response of the bridge under non-uniform mining excitation the Multiple Support Response Spectrum Method was used [5]. The analysis using MSRS method takes into consideration the main reasons of the kinematic excitation non-uniformity: wave passage effect (effect associated with non-infinity wave velocity), site effect (different foundation conditions), attenuation effect (decrease of amplitude along with the distance) and incoherence effect (changes of the frequency spectrum of excitation). The accuracy of results depends on implemented parameters of kinematic excitation non-uniformity. As a result of calculation the maximum structural displacements can be obtained. The maximum value of nodal displacement z can be determined on the basis of equation (1):

$$z_{\max} = (b^T \cdot l_{uu} \cdot b + b^T \cdot l_{uz} \cdot \Phi_{BD} + \Phi_{BD}{}^T \cdot l_{zz} \cdot \Phi_{BD} + \Phi_{BD}{}^T \cdot l_{zu} \cdot b)^{0.5} \tag{1}$$

where:

$l_{u_i u_j}$ - correlation matrix between the displacement of the supports;

$l_{u_i z_j}$ - correlation matrix between the displacement at the support and modal displacement;

$l_{z_i z_j}$ - correlation matrix between the modal displacements;

$$b = [a_i \cdot u_{pi}] \tag{2}$$

$$\Phi_{BD} = [\Phi_1 \cdot \beta_{11} \cdot D_{11} \ldots \Phi_m \cdot \beta_{sm} \cdot D_{sm}] \tag{3}$$

Parameter *b*, described by equation (2), represents the response of the system to the ground motion applied at the *i*th support only. In this equation a_i is the value of the displacement for unit ground motion and the u_{pi} is the maximum ground displacement in support *i*.

Parameter Φ_{BD}, shown in equation (3), presents the response of the system in the *m*th mode, to the spectrum curve assumed for the support *s*th. The Φ_{BD} matrix consists of three components. The first one, the Φ_m, is the *m*th mode shape of structure. Next, parameter D_{sm} is the value of the displacement response spectrum for the ground motion at support *s* corresponding to *m*th natural frequency of object. The last parameters, β_{sm} is the well-known from the classical response spectrum theory, modal shape coefficient.

Development of the MSRS method from the random vibration analysis has been presented in detail by Der Kiureghian and Neuenhofer [5]. In this paper only the selected steps of derivation of formula (1) are presented. For better understanding of the derivation of equation (1), the start form of the equation of motion (4) is needed.

$$M \cdot \ddot{x} + C \cdot \dot{x} + K \cdot x = -M \cdot \ddot{x}_g \tag{4}$$

where:

M, C, K - mass, damping, stiffness matrix of structure respectively;
x - total displacement of structure node;
x_g - displacement of the ground (support).

In general, the total displacement of a structure node can be presented as a sum of the static and dynamic component. The relation of the total displacement and the description of the static and dynamic component, are given by equations (5)-(7).

$$x = x^s + x^d \tag{5}$$

$$x^s = -R \cdot x_g \tag{6}$$

$$x^d = \Phi \cdot \beta_{ki} \cdot S_{ki} \tag{7}$$

where:

x^s, x^d - static and dynamic component of displacement of structure node;
R - the influence coefficient matrix;
S_{ki} - power spectral density function (PSDF) of a mining shock.

On the basis of formula (6), it is clearly seen, that the static component of the structural displacement, depends only on the ground motion amplitude and the structural stiffness. The dynamic component of displacement, presented by equation (7), depends on the modal characteristics of structure as well as on the excitation parameters (represented by the PSDF). As the random vibration theory shows, the PSDF and the ground motion acceleration can be related in the fallowing way:

$$\ddot{S}_{ki} + 2 \cdot \xi_i \cdot \omega_i \cdot \dot{S}_{ki} + \omega_i \cdot 2 \cdot S_{ki} = \ddot{x}_g \tag{8}$$

It can be noticed from equation (8) that the relation between the PSDF and the ground acceleration, is strongly non-linear and depends also on the dynamic characteristics of system, like: damping coefficients ζ_i and natural frequencies ω_i. After solving and simplifying the above expressions, the total displacement of a structure may be presented as follows:

$$z(t) = \sum a_k \cdot x_{kg} + \sum b_{ki} \cdot S_{ki} \tag{9}$$

The response spectrum analysis should lead to a conservative estimation of the dynamic response of an object. In case of the spectral analysis the maximum value of a structural displacement is demanded. Hence, the assumptions given by equations (10)-(13) are needed:

$$D_k(\omega,\xi) = E[\max(S_{ki})] \quad (10)$$

$$u_{k\max} = E[(\max(x_g)] \quad (11)$$

$$D_k(0,\xi) = u_{k\max} \quad (12)$$

$$\lim_{\omega\to\infty} \omega^2 \cdot D_k(\omega,\xi) = \ddot{u}_{k\max} \quad (13)$$

where:

D – displacement response spectral function on a mining shock;
a, b - static and dynamic coefficient, respectively;
$u_{k\max}$ - the maximum displacement of *k*th support.

The first and the second of assumption - equations (10) and (11) - allow to simplify the notation. Another two assumptions involve the function *D* (the response spectrum function). Equation (12) concerns the quasi-static body motion (with no frequency), whereas formula (13) the rigid body motion resulting from ground excitation. Finally, formula (9) can be presented as follows:

$$z(t) = \sum a_k \cdot u_{k\max} + \sum b_{ki} \cdot D_{ki} \quad (14)$$

Due to the fact that the maximum peak of ground (and the supports) accelerations appeared in different times, maximum displacements of structural elements, generated by this situation, also appeared in some lag of time. In this case, the peak response of the structure can be estimated by the Complete Quadratic Combination (CQC) rules (equation (15)). After all, the maximum response of a structure subjected to the ground motion excitation is expressed by the formula (16):

$$z_{\max} = \sqrt{\sum z(t)_i^{\,2} + \sum\sum \rho i_j \cdot z(t)_i \cdot z(t)_j} \quad (15)$$

$$z_{\max}^{\;2} = \sum\sum a_k \cdot a_l \cdot u_k \cdot u_l + 2\sum\sum a_k \cdot b_{lj} \cdot \rho_{ukSki} \cdot u_k \cdot D_i + \sum\sum\sum\sum b_{ki} \cdot b_{lj} \cdot D_k \cdot D_l \quad (16)$$

Equation (16) can be also represented using integral equation. The simplification of notation, leads to the final formula, presented by equation (1).

3. Data of an analysed structure

For the analysis of dynamic response to a mining shock a road viaduct was chosen. The viaduct is a real structures located in Southern Poland. The object is a continuum, three-span bridge (figure 1). Total length of the structure is 40 m: the middle span is 20 m long, the left and right spans - 10 m. The bridge supports are built of concrete and the deck of the bridge is a pre-stressed concrete structure. The object is designed as a rigid, monolithic frame. The intermediate supports are created as double columns, angled 45 ° to the ground level. The bridge slab is supported on the abutments by elastomeric bearings. The object is founded on a homogenous earthen sub-base.

Figure 1. The structure chosen to the dynamic analysis [8]

To conduct the dynamic analysis, the numerical model was created with the ANSYS 18.1 software [9]. The chosen software allows to carry out each kind of the dynamic analysis: the THA, RSA and MSRS analysis. The finite element method was used in the linear dynamic analysis. The density of the finite element mesh was fitted basing on the analysis of the results convergence. The final numerical model is presented in figure 2.

Figure 2. Numerical model of the viaduct

The material characteristics of the numerical model were taken from the technical documentation of the bridge. Due to the linear character of the conducted analysis, the linear material parameters were taking into account. In the numerical model the pre-stressing tendons are neglected. However, the additional stiffness from the pre-stressed forces has been considered by the modification of the Young modulus of the slab material [10]. The Rayleigh model of mass and stiffness proportional damping is applied. The damping coefficients α=1.284 and β=0.00116 were used. The parameters were calculated on the basis of the damping ratios of 5% and first and second natural frequencies.

4. Kinematical excitation

To calculate the dynamic response of the viaduct to a mining shock the real tremor was used. The typical shock from the Upper Silesian Coal Basin (one of the main mining activity zones in Poland) was taking into account. In figure 3 the recorded time histories of accelerations of this shock are presented. The shock was registered in three directions - two horizontal and vertical. The maximum acceleration in horizontal directions reach 0.3 m/s^2 and in vertical direction - 0.1 m/s^2. The horizontal peak ground acceleration (PGA) equal 0.42 m/s^2.

For the THA method the mining tremor was implemented as the accelerations of the supports in three directions. The following two kinds of the excitation model were used: the uniform and non-uniform ground motion model. For the non-uniform ground motion model two different wave velocities were taken into account: 500 and 1000 m/s. In non-uniform model the amplitude reduction phenomenon was also assumed.

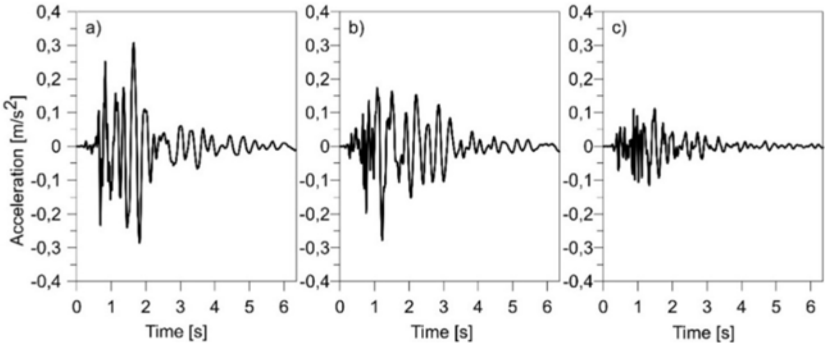

Figure 3. The time histories of accelerations of the mining shock in three directions: (a) horizontal NE, (b) horizontal WS, (c) vertical

For the RSA and MSRS analyses the spectral curves were needed. The spectral curves were created on the basis of the mining shock acceleration records. The spectrum in three directions were defined. For the RSA method, the same spectra were used at each supports. In the MSRS method, the response spectra were modified, due to the occurring non-uniform effects. In the MSRS analysis the wave passage effect, the attenuation effect and the incoherence effect were taken into account. Because of the homogenous ground conditions, the side effect might be neglected. The non-uniform effects were taken into consideration by scaling the origin spectral function and multiplying it by the coherency function. In this paper the simply coherency function described by Hindy and Novak [11] was used. The coherency function is given by equation (17):

$$coh(d,\omega) = e^{-c\cdot(\frac{d\cdot\omega}{2\cdot\pi\cdot V_s})} \tag{17}$$

in which:

d - a distance between the structure supports;
V_s - the wave velocity (in the analysis assumed value 500 m/s);
c - ground parameters (in the analysis assumed value 1.0).

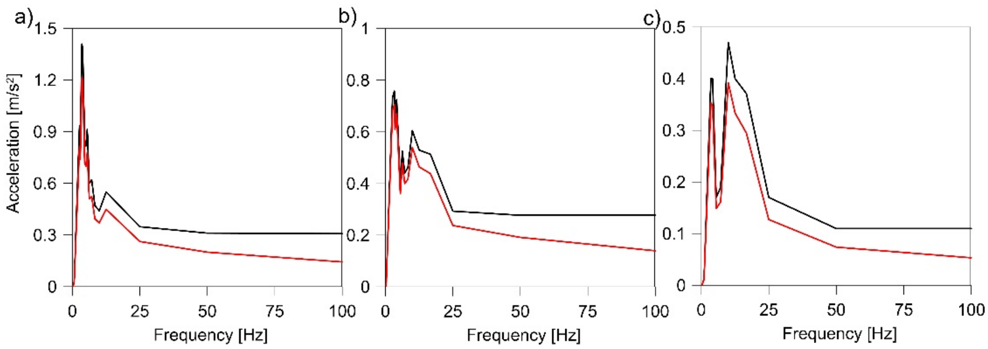

Figure 4. The functions of response spectra in three directions: (a) horizontal NE, (b) horizontal WS, (c) vertical

The original and modified spectral curves are presented in figure 4. The original functions are signed by the black lined, and the modified by the red one. For the MSRS analysis the primary spectral functions were implemented on the one side of the bridge, whereas the transformed functions were applied to the other side.

5. Results

5.1. An elements chosen to analysis

The dynamic response of viaduct to the representative mining shock were performed using the THA, RSA and MSRS analysis. The principal stresses were calculated for all kinds of analysis. To compare the results obtained from different methods four elements were taking into account. The locations of the chosen elements are presented in figure 5. The elements P1 and P2 are located in the middle of the span (P1 on the right side, P2 in the middle of cross-section). The others elements (P3 and P4) are situated in the section of the bridge over the interior column. In chosen parts of the structure the stress intensification is predicted.

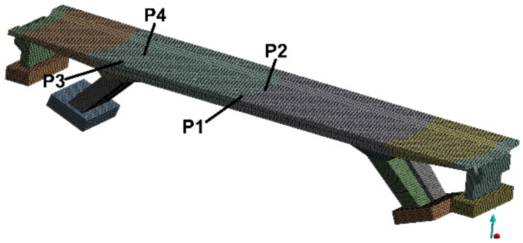

Figure 5. Location of elements chosen to the dynamic analysis

5.2. Comparison of the results obtained for different calculation methods

Firstly, the results of the dynamic analysis obtained for elements P1 and P2 were compared. The stresses in elements P1 and P2 are presented in figures 6. In figure 6 the time histories of stresses obtained from THA and the value of stresses from the RSA and MSRS method are shown. The results of the THA method in case of uniform excitation are signed by the black line. The green and red lines show the time histories of stresses obtained from the THA method with non-uniform model of excitation (for velocities 1000 and 500 m/s, respectively). The stress level obtained for the RSA and MSRS analysis are marked by the blue and violet line. In the graphs only the first 2.5 s of the dynamic responses are presented. It this range of time the maximum excitation level appeared and out of this range the response level is irrelevant.

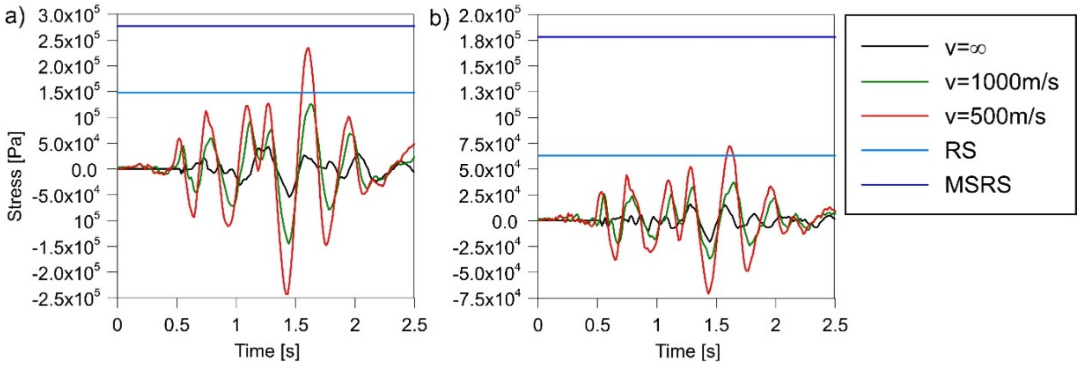

Figure 6. The stress distribution in element: (a) P1, (b) P2

On the basis of the results obtained for element P1 (figure 6a) it is easy to notice that the non-uniform excitation model resulted in much greater values of stresses than the uniform excitation model. The maximum value of stresses obtained from the uniform model of excitation reached about 50 kPa, whereas for the non-uniform model of ground motion the peak stress was over 2-5 times greater. The maximum stress, in case of the analyses with wave velocities of 1000 and 500 m/s equalled 150 kPa and 250 kPa, respectively. Hence, it can be noticed that slower the wave velocity was, the greater value of stress were obtained. This comparison clearly presents the significant influence of the non-uniformity effects. It is worth mentioning that the stress variability in time were similar for each velocity level. The peak value of stresses appeared at about 1.5 s of the time of shock for both analysed wave velocities. At this moment the maximum ground accelerations appeared. The influence of the non-uniformity effects is also visible in the results of the Response Spectrum Analysis. In the RSA method the stresses in elements were calculated on the basis of the uniform spectral function. The obtained stress level reached 150 kPa. These value was greater than the maximum stress resulted from the THA method with the model of the uniform kinematic excitation. So, the RSA method led to the conservative estimation of stresses in case of uniform excitation model. But in case of the non-uniform excitation model, the THA resulted in a higher value of stress than the RSA method. This phenomenon can be observed for the wave velocity of 500 m/s. The maximum peak of stress obtained from the THA method was over 100 kPa greater than the stress calculated from the RSA method. This comparison prove that the RSA method cannot be regarded as a conservative method of the stress estimation in case of the non-uniform excitation analysis. In this case, the MSRS method gave satisfying results. The maximum stress obtained from MSRS analysis was greater than the maximum stress from the THA. The difference equalled about 50 kPa and, what is important, the peak stress obtained from the MSRS analysis was 20 % higher than the result from the THA method. Since the MSRS method led to the higher results it could be regarded as a conservative and safe way of calculation.

The similar dependence can be observed in element P2 (figure 6b). The maximum stress was obtained for the smaller wave velocity (500 m/s). The difference between the peak value of stresses for the uniform and non-uniform excitation models reached 50 kPa. The stresses obtained for the non-uniform model of excitation were over 3 times greater than the results calculated for the uniform excitation. In element P2 the stress obtained in RSA equalled 65 kPa. It was a safe estimation of the dynamic response of structure to a uniform mining excitation, but it was also less than the maximum stress derived from the non-uniform THA. For element P2 the stresses from the MSRS analysis were also calculated. The maximum dynamic response equalled 180 kPa. This value was much higher than the maximum stress appearing in the time history of stresses for the non-uniform excitation. On the basis of the presented comparisons, it can be stated that the MSRS method properly specify the upper limit of stress in structures subjected to mining tremors.

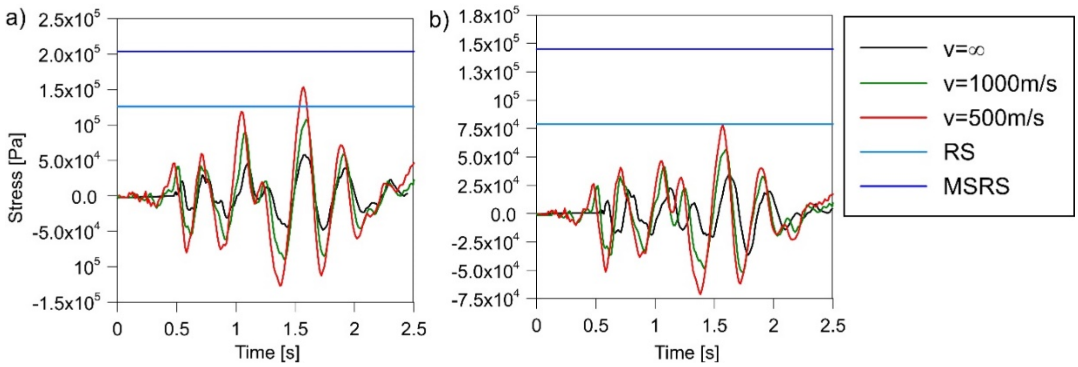

Figure 7. The stress distribution in element: (a) P3, (b) P4

The results of stress analysis conducted in the section above the inner column are presented in figure 7. Figure 7a and 7b show the time-stress distribution obtained from the THA method for elements P3 and P4, respectively. The resemblance of time-stress histories for both elements is easy to notice. The maximum stress in both elements were observed for the slower ground motion (i.e. for the wave velocity of 500 m/s). The maximum stress for the uniform and non-uniform models of excitation occurred in the same time (1.5 s of the shock). The stress obtained for the uniform excitation were significantly smaller than the stress calculated for the non-uniform model. The differences reached 100 kPa and 50 kPa for element P3 and P4, respectively. The impact of the non-uniformity effects was undeniable.

In figure 7 the stresses obtained in elements P3 and P4 from the response spectrum analyses, both the RSA and MSRS, are also shown. The presented results clearly prove that the MSRS analysis led to significantly greater values of stresses than the RSA method. The stress level estimated for the non-uniform mining excitation was over 1.5-2 times greater than the level received in case of the uniform excitation. It is worth mentioning that in element P3, the RSA method led to underestimation of the peak stress of around 30 % in comparison with the results of the THA analysis. In the other hand, the stress derived from the MSRS analysis led to the stress reserve equalled 50 kPa. So, it can be stated that the MSRS method provides the proper quasi-static way to estimate the stress level in a structure subjected to a non-uniform kinematical excitation.

6. Conclusions

The analysis of dynamic response of the road viaduct to the mining shock carried out with different methods of the dynamic analyses (i.e. the THA, RSA and MSRS method) allow to formulate some important general conclusions:

- The analysis of time histories of stresses in structural elements shows significant differences for uniform and non-uniform excitation models. Stresses obtained for non-uniform excitation were several times greater than stresses derived for uniform excitation model. It is proven that the non-uniformity effects have an important influence on the dynamic behaviour of multi-support structures, like bridges. The neglecting of some effects may results in underestimation the maximum response of an object. The conducted study also indicated that the wave velocity plays a central role as far as of the stress level is concerned.
- In case of the uniform excitation the Response Spectrum Analysis allows to estimate the maximum stress with a safety reserve. However, the RSA analysis does not take into account the effects of excitation non-uniformity. As a result, the obtained stresses were lower than the results predicted for the Time History Analysis in which non-uniform model of kinematic excitation was included. The conducted response spectrum analysis has shown that the RSA method may leads to underestimation of the dynamic response of structures.
- The Multiple Support Response Spectrum Method much better estimates the behaviour of structure subjected to non-uniform excitation than the RSA method. Since in the MSRS method the effects of excitation non-uniformity are taken into account, the proper estimation of stress level in a structure is possible. The peak value of stresses that results from the THA, in which non-uniform model of kinematic excitation was included, does not exceed the stress value obtained from the MSRS analysis. In each element, the MSRS method leads to more conservative (safer) results. Hence, the MSRS method may be used in estimation of the dynamic response of a large-dimensional structure subjected to mining shocks.

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