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Paweł Boroń orcid.org/0000-0003-4977-6574
Joanna Dulińska orcid.org/0000-0002-4140-8120
pboron@pk.edu.pl
Institute of Structural Mechanics, Faculty of Civil Engineering, Cracow University of Technology

Assessing the dynamic response of a steel pipeline to a strong vertical mining tremor using the multiple support response spectrum method

Ocena odpowiedzi dynamicznej naziemnego gazociągu na pionowy wstrząs górniczy z wykorzystaniem metody wielopodporowego spektrum odpowiedzi

Abstract

This paper presents an analysis of the dynamic response of an overground steel pipeline during a strong mining shock. The analysis was conducted using various calculation methods- a time history (THA), a response spectrum (RSA) and a multiple support response spectrum analysis (MSRS). For the THA and MSRS methods, non-uniform effects of ground excitation were taken into account. During the analyses, the bending moment was calculated. On the basis of obtained results, it can be noted that the non-uniform effects had a significant impact on the dynamic behaviour of the pipeline and it was indicated that the MSRS method led to more accurate estimation than the RSA.

Keywords: non-uniform excitations, multiple support response spectrum

Streszczenie

W artykule przedstawiona została analiza odpowiedzi dynamicznej gazociągu na rzeczywisty wstrząs górniczy. W obliczeniach zastosowano metodę całkowania równań ruchu (THA), spektrum odpowiedzi (RSA) oraz wielopodporowego spektrum odpowiedzi (MSRS). W metodzie THA i MSRS uwzględnione zostały efekty związane z nierównomiernością wymuszenia kinematycznego. W trakcie analizy obliczono momenty zginające w konstrukcji, na których podstawie zauważono, że nierównomierne wymuszenie ma wyraźny wpływ na wartość odpowiedzi dynamicznej.

Słowa kluczowe: nierównomierne wymuszenie, wielopodporowe spectrum odpowiedzi

1. Introduction

Seismic and the human-induced vibrations are examples of common dynamic loads that have an influence on structures. The most hazardous dynamic loads in the case of the stability and strength of structural elements are seismic shocks. In some regions of the world, seismic activity is low and does not constitute a threat to buildings. However, in these regions, other sources of dynamic load may occur, such as mining shocks, which have an impact on buildings which is similar to that of seismic load. Mining shocks can represent excitation energy close to that of seismic shocks. There are many studies that prove that mining tremors may cause damage or cracking to structural elements [5, 12].

The influence of mining shock to a structure strongly depends on the energy of the shock, the maximum acceleration and also the foundations. All of these parameters can be taken into account during the dynamic analysis of structures under mining shock. To determine the maximum dynamic response of a given object, many different methods of analysis are used. Common dynamic methods applied in research are time history analysis (THA) and response spectrum analysis (RSA). THA is based on the integration of the equation of motion in each time step. This method determines the full range of engineering parameters such as displacement, strain and stress at any point in time. The second methods, RSA, only allows the maximum value of a given parameter to be estimated.

Both of these methods correctly describe the behaviour of the structure under uniform excitation. Unfortunately, a uniform model of excitation (a model assuming a constant value of excitation in each structural support) may be inappropriate for some types of objects. The dynamic response for multiple support structures such as bridges or pipelines strongly depends on non-uniform effects appearing during the passage of mining shock. Non-uniformity can be taken into account using THA. In this procedure, the effect connected with the non-infinity wave velocity (wave passage effect) and the attenuation effect (decreasing amplitude along the direction of the wave propagation) can be counted. The effects related to ground conditions like site or coherence effect cannot be implemented in THA without data from field measurements. In this case, the THA method is suggested for use in the region of homogenous ground condition. The method that takes into account all of the non-uniform effects is the random vibration approach [6, 10, 13]; this method was developed on the basis of the SMART 1 array experiment in Taiwan. The results obtained during the experimental observation enabled formulation of a stochastic, spatial seismic ground-motion model. The random vibration approach allows consideration of not only the wave passage effect, but also the additional phenomena connected with local soil conditions and loss of coherency between supports. This approach is very useful in case of a lack of measurement results. The stochastic parameters used in this method enable prediction of the effects related to the ground wave passage. However, there is no possibility to implement the non-uniformity effects in RSA. In the case of the non-uniform excitation model, RSA lead to an underestimation of the maximum dynamic response of the structure [4, 8]. In some studies regarding non-uniform seismic excitation, the multiple support response spectrum (MSRS) method is used. The MSRS method is based on RSA but also takes non-uniformity into account. The authors indicated that the method allows an accurate estimation of the maximum level of dynamic response of the structure under non-uniform seismic shock [9, 11]. It is noteworthy that there has been no research using the MSRS method to calculate dynamic response under mining tremors.

In this paper, an analysis of the dynamic response of a steel pipeline under mining shock is presented. The calculation of the dynamic response is determined using the THA, RSA and MSRS methods of dynamic analysis. The chosen methods correspond with and are a continuation of the authors' field of research. The aims of the analysis are to compare the results obtained for each method and determine the usefulness of the MSRS method in the case of mining shock analysis.

2. The theoretical basis of the multiple support response spectrum method

The multiple support response spectrum method was used to determine the dynamic response of the pipeline under non-uniform mining excitation. As mentioned in section 1, the MSRS method allows the non-uniformity of the excitation to be taken into account. In this method, typical effects connected to non-uniform mining shock can be taken into consideration. These effects are: the wave passage effect (associated with non-infinity wave velocity), the site effect (different foundation conditions), the attenuation effect (decrease of amplitude with increasing distance) and the incoherence effect (changes in the frequency spectrum of excitation). The results of the MSRS analysis strongly depend on the accuracy of the implemented non-uniformity parameters of kinematic excitation. During the calculation, the maximum structural displacement can be obtained. The maximum value of nodal displacement z can be determined by following Eq. (1).

$$\mathbf{z}_{\mathbf{max}} = (\mathbf{b}^{\mathbf{T}} \cdot \mathbf{l}_{\mathbf{uu}} \cdot \mathbf{b} + \mathbf{b}^{\mathbf{T}} \cdot \mathbf{l}_{\mathbf{uz}} \cdot \mathbf{\Phi}_{\mathbf{BD}} + \mathbf{\Phi}^{\mathbf{T}}_{\mathbf{BD}} \cdot \mathbf{l}_{\mathbf{zz}} \cdot \mathbf{\Phi}_{\mathbf{BD}} + \mathbf{\Phi}^{\mathbf{T}}_{\mathbf{BD}} \cdot \mathbf{l}_{\mathbf{zu}} \cdot \mathbf{b})^{0.5} \tag{1}$$

Where $\mathbf{l}_{\mathbf{uu}}$, $\mathbf{l}_{\mathbf{uz}}$, $\mathbf{l}_{\mathbf{zz}}$ are the correlation matrix between the displacements of the supports; the displacement at the support and modal displacement, and the modal displacements, respectively. Matrix **b**, describes the response of the system to the ground motion occurring at a single support. Matrix **b** is based on the value of the displacement of the structure for unit ground motion and the maximum ground displacement in supports. Matrix $\mathbf{\Phi}_{\mathbf{BD}}$ represents the response of the system in the simple mode to the spectrum curve relating to a single support. The $\mathbf{\Phi}_{\mathbf{BD}}$ matrix consists of three components: the vector of the mode shape of the structure, the displacement response spectrum function for the ground motion at the support and the modal shape coefficient (which is well-known from the classical response spectrum theory).

The MSRS method was developed by Der Kiureghian and Neuenhofer [3]. The method comes from random vibration analysis and is based on the classical equation of motion with the influence of ground motion (Eq. (2)).

$$\mathbf{M}\cdot\ddot{\boldsymbol{x}}+\mathbf{C}\cdot\dot{\mathbf{x}}+\mathbf{K}\cdot\boldsymbol{x}=-\mathbf{M}\cdot\ddot{\boldsymbol{x}}_{g} \quad (2)$$

where:

MCK – mass, damping, stiffness matrix of the structure;
x – total displacement of the structure's node;
$\boldsymbol{x}_g$ – displacement of the ground (support).

In general, the total displacement of a structure's node can be presented as the sum of the pseudo-static and dynamic components. The pseudo-static displacement depends on both ground motion and structural stiffness. The dynamic component depends on the modal characteristics of the structures and also on the power spectral density of the excitation forces.

The utility of the response spectrum analysis causes this method to lead to a conservative estimation of the dynamic response of an object. In the case of spectral analysis, the maximum value of structural displacement is required; therefore, certain conditions are needed. The main conditions are that the value of the displacement of the structure supports is equals to the maximum ground displacement in this location (u_{kmax}). The another conditions is that the response spectrum function (D_{ki}) represents the maximum response of the mode during excitation. Following this, the formula representing the structural displacement can be presented as follows (Eq. (3)):

$$z(t)=\sum a_k\cdot u_{k\max}+\sum b_{ki}\cdot D_{ki} \quad (3)$$

Due to the fact that the maximum peak of ground accelerations appeared in different places at different times, the maximum displacements of structural elements also appeared at different times. As a consequence, the peak response of the structure can be estimated through the application of the complete quadratic combination (CQC) rules (Eq. (4)). Finally, the maximum response of a structure subjected to the ground motion excitation can be expressed by the following formula (Eq. (5)):

$$z_{\max}=\sqrt{\sum z(t)_i^2+\sum\sum\rho_{ij}\cdot z(t)_i\cdot z(t)_j} \quad (4)$$

$$z_{\max}^2=\sum\sum a_k\cdot a_l\cdot u_k\cdot u_l+2\cdot\sum\sum a_k\cdot b_{i,j}\cdot\rho_{ukSki}\cdot u_k\cdot D_i+\sum\sum\sum\sum b_{kl}\cdot b_{ij}\cdot D_k\cdot D_l \quad (5)$$

Equation (5) can also be represented using the integral version. The simplification of the notation leads to the final formula presented in Eq. (1).

3. Numerical model of the steel pipeline

In this paper, the dynamic response was calculated for an overground pipeline. The analysed pipeline consisted of a single, uncovered steel pipe. The diameter of the pipe was 60 cm and the thickness was 1.35 cm. The total length of the pipeline was 105 m (7 spans of 15 m). The length of the structure enabled it to represent the behaviour of a real length of pipeline. Supports are located at 15 m intervals along the length of the pipeline.

To evaluate the dynamic response of the chosen pipeline to a mining shock, a numerical model had to be created. The model was created in the ANSYS software application [1]. Because of the pipeline dimensions, a simple beam model was used in the analysis. The pipeline was represented as a multi-span continuous beam (Fig. 1).

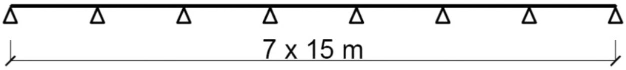

Fig. 1. Physical model of the pipeline

In the numerical model, the pinned supports and the rigid ground conditions were taken into account. This assumptions deflect on the real construction on the pipeline supports. To avoid excessive deformation of the structure, the supports of real pipeline are equipped with special bearings or sliders which allow easier displacements. The reduction of deformation leads to less stress level of structure. The pinned supports used in the numerical model limit the possibility of displacements. This caused a structural stiffness increasing and finally, may leads to the increasing the inertial forces in structure. Summarise, using the non-displaceable, pinned supports conduct to safer (overestimated) results. It also can be noticed, that this approach of modelling were effectively used in the same thematic works [10].

The finite element mesh density was chosen on the basis of the convergence of the modal analysis. Linear material characteristics and linear beam finite elements were used for the response spectrum analysis.

4. Kinematic excitation – mining shock

To calculate the dynamic response of the pipeline, data relating to an actual mining shock was applied. The mining shock in question was recorded in the Upper Silesian Coal Basin (USCB). The shock was registered as an acceleration of the ground and the displacement of the ground was determined on this basis. The value of the acceleration of the shock was scaled up to the maximum PGA appearing in the region of the USCB. During the dynamic analysis (in the case of THA analysis), the shock was applied to the numerical model as a time history of the displacement of the structural supports. Only the vertical direction of shock was considered. The vertical component of acceleration and the displacement of the mining tremor are presented in Fig. 2.

The peak value of the displacement of the shock was 2.5 mm. The dominant frequency of the shock was in the range of 3–4 Hz and this value does not coincide with the natural frequency of the pipeline.

In case of the THA, two kinds of the ground excitation model were used – uniform and non-uniform. In the uniform model of excitation, the supports of the structure repeat the same movements simultaneously. This model is a representation of infinity wave velocity. A wave velocity of 500 m/s was used in the case of the non-uniform excitation model.

Additionally, attenuation effects were taken into account. In this model, each pipeline support repeats the same moves as the previous support but to a weaker degree and with an appropriate time lag.

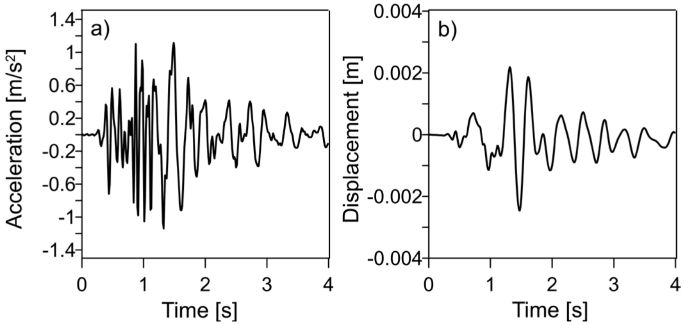

Fig. 2. A time history of the vertical component of (a) acceleration and (b) displacement of the mining shock

The other calculation methods applied in this investigation (RSA and MSRS) concern the estimation of the dynamic response of the structure under mining shock. In the case of the dynamic analysis of the structure to the mining shock, the main difficulty is the application of the appropriate kinematic excitation. The analysis may be based on shocks stored in database (historical shocks); however, the obtained results concern only the specific excitation that has been input. To define the dynamic response of the object to any mining tremors which may appear in a given zone (e.g. in the USCB) spectral curves should be used. The standard spectral curves determined for the specific region enable representation of the behaviour of ground motion during possible mining tremors. By contrast, RSA and MSRS analyses (for which spectral curves are used) are much faster than THA.

In this paper, the standard acceleration spectral curve of the vertical component of the USCB region was used [2]. During the calculation, a maximum ground acceleration of 1.1 m/s^2 was used. In the case of RSA, the spectral curve presented in Fig. 3 (denoted by the black line) was taken into account. In the MSRS method, the spectral curve needed to be modified. The spectral curves applied to the structural supports differ from each other. The differences between the values of the spectral curves are caused by the non-infinity wave velocity and the distance between the supports. The modification of the spectral curves is created by multiplying the spectral value by the coherency function. In this analysis, the simple coherency function was used [7]. The used function took into account both the distance between the supports (d) and the wave velocity of 500 m/s (v). The function is represented by Eq. (6).

$$coh(\omega,d)=e^{-\frac{d\cdot\omega}{2\cdot\pi\cdot v}} \tag{6}$$

In the numerical model, the original spectral curve (see Fig. 3 – black line) was added to the first support. The spectral curves applied to the other supports were modified by the coherency function. In Fig. 3, an example of the used spectral curves are presented; the curves for the first support (black line), fourth support (grey line) and last/eighth support (dashed line) are shown.

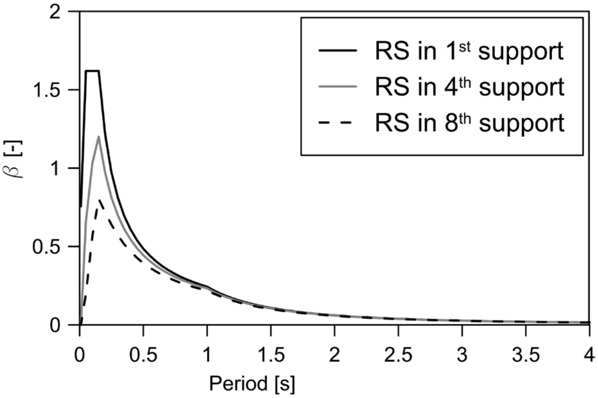

Fig. 3. Example spectral functions used in RS and MSRS analyses [2]

5. Results of the analysis

The dynamic response of the overground pipeline under mining shock excitation was calculated using the THA, RSA and MSRS methods. In each kind of analysis, the Rayleigh model of damping was used. The parameters of the damping model ($\alpha = 2.67$ and $\beta = 0.01$) were determined on the basis of the first and second natural frequency of the pipeline ($f_1 = 7.26$ Hz and $f_2 = 8.77$ Hz).

During the calculations, the bending moments at some specyfic points were determined. The results for five points are presented in this paper. Three of the chosen points (P1-P3) were located under the second, third and fourth supports and the other two points (P4-P5) were situated in the middle of the third and fourth spans. The location of these points is presented in Fig. 4.

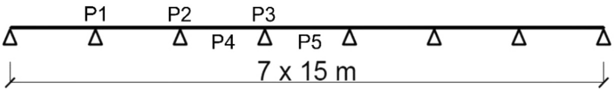

Fig. 4. The location of points chosen for analysis

The results obtained for the uniform and non-uniform THA are presented as a time history of the bending moment in mining excitation. The values of bending moment are presented in Figs. 5 and 6 by the black and grey lines for the uniform and non-uniform excitation models, respectively. The estimated values of bending moment from the RS and MSRS analyses are marked as solid lines in Figs. 5 and 6. Dashed lines for RSA and solid lines for MSRS indicate the maximum values of bending moment for the chosen finite elements.

At the beginning of the response analysis, the results obtained for the points located under the supports are presented. In Fig. 5, the bending moments at points P1 (Fig. 5a), P2 (Fig. 5b) and P3 (Fig. 5c) calculated by the THA, RSA and MSRS methods are collated. The results for each calculation method are indicated by the line styles as described above.

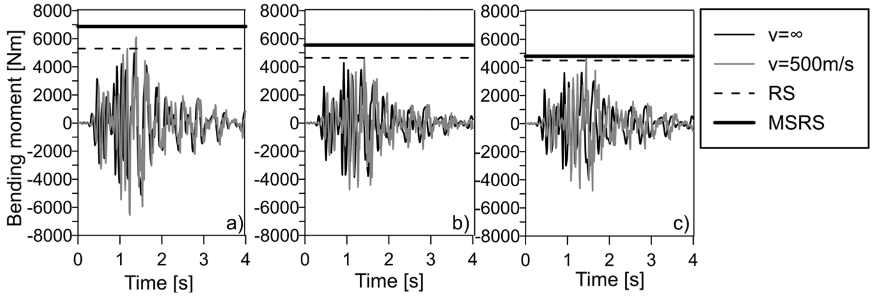

Fig. 5. Time history of bending moments at points (a) P1, (b) P2 and (c) P3

On the basis of Fig. 5, it can be seen that the bending moment strongly depends on the wave velocity. The influence of the wave velocity on the value of the bending moment can be clearly observed in THA. The bending moments obtained during THA in the case of non-uniform excitation are greater than the moments for uniform ground motion. For the uniform excitation model, the maximum value of the bending moment at point P1 reaches around 5 kNm, whereas for the non-uniform case, it is over 6.5 kNm. The difference is significant and equates to 25%. A similar dependence can be observed at the other points (P2 and P3). The peak value of bending moments determined for the uniform and non-uniform ground-motion model at point P2 differs by 10–20%, and at point P3 it is as high as around 30%. It is noteworthy that the maximum value of bending moment at each point appears between one and two seconds of excitation time (at the time when the mining excitation reaches the highest level). It is important to note the fact that the maximum peak of bending moment appears at different times in the case of uniform and non-uniform excitation. The maximum duration of time between the occurrence of extreme values of moment is observed for point P3. This delay is caused by the non-infinity velocity of the mining shock wave and the long distance between the supports.

Another part of the analysis concerns the estimation of the dynamic response using response spectrum methods. During this analysis, the maximum value of bending moment for each point was calculated. Comparing the results obtained during THA and RSA, it can be seen that the RSA leads to a safe estimation only in the uniform excitation case. In case of the uniform model of excitation, for all points (P1-P3), the value of bending moment obtained from RSA is higher than the maximum peak moment from THA. The difference between the exact (THA) and the estimated solution (RSA) reach around 150 Nm, 200 Nm and 590 Nm for points P1, P2 and P3, respectively. Based on this, it can be claimed that the safety stock is 5–15%.

The results presented in Fig. 5 indicate that RSA leads to an underestimation of the bending moment level if the non-uniformity effects are taken into account. The maximum bending moments calculated using THA including non-uniform effects are greater than the acquired through RSA. This phenomenon is clearly seen in Fig. 5. The line represents the results of the non-uniform THA is crosses by the line denoting the level of the bending moment obtained from RSA. The maximum difference is observed for point P1 and reaches over 1000 Nm. For points P2 and P3, the differentials between results are not particularly high, but it also cannot be treated as a correct estimation of dynamic response. In the case of non-uniform mining excitation, a more accurate estimation can be obtained by using the MSRS method. As is the case with THA, the MSRS method takes non-uniformity effects, such as wave velocity or the distance between the structural supports, into account. The comparison of the results obtained using the THA, RSA and MSRS methods indicate that the MSRS analysis leads to accurate estimation of structural response. The bending moments calculated using the MSRS method are greater than the moments obtained from RSA and THA. This can be observed for each analysed point. For example, for point P1, the maximum value of the bending moment obtained from THA is 6.5 kNm, whereas the moment received during the MSRS method reaches almost 6.9 kNm. For the other points, the differences are 0.7 kNm for point P2, and 0.1 kNm for point P3.

The complete results relating to the dynamic response of the pipeline during a mining shock for another two points of the structure were taken into considered. The solutions for the points located in the middle of the spans are presented in Fig. 6.

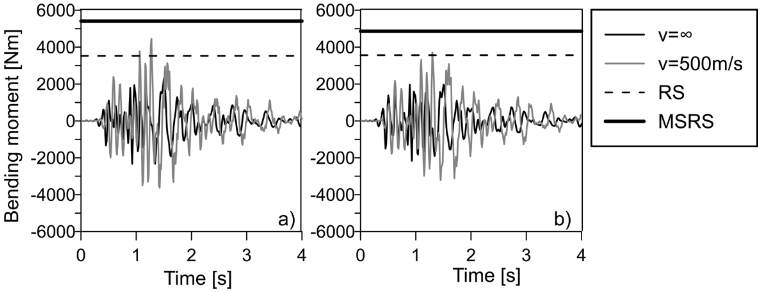

Fig. 6. Time history of bending moments at points (a) P4 and (b) P5

The results for points P4 and P5 are presented in Figs. 6(a) and 6(b), respectively. The comparison of the results obtained from the different types of analysis indicate a similar dependence for points P1-P3. The main observation is that non-uniformity effects have a strong influence on the value of bending moment. The maximum bending moment obtained from THA relating to the uniform excitation model reaches 2,300 Nm for point P4 and 2,100 Nm for point P5. In the case of THA taking into account the non-uniform effects, the results are much greater. The peak bending moment for point P4 is 4,400 Nm and for point P5, it is 3,700 Nm; this is approximately 80% more than the results from the analysis that disregards the non-uniformity. For points P1-P3, the maximum bending moments appear between one and two seconds of excitation time. The lag between the peak values of moment is also clearly visible. For points P4 and P5, a response analysis was also conducted. The bending moment obtained during RSA reaches around 3,500 Nm for both points. Additionally for both points P4 and P5, the values of moment estimated by RSA are greater than the results from THA without non-uniform effects. As with points P1-P3, RSA yields a reliable estimation of the dynamic response for points P4 and P5 in the case of uniform excitation, but simultaneously underestimates the response when the non-uniform effects are taken into account. The underestimate derived from the RSA reaches around 900 Nm for point P4 and 200 Nm for point P5. The influence of the non-infinity wave velocity is correctly represented by the MSRS method. The results obtained from the MSRS method are greater than from RSA; the difference reaches over 1000 Nm. On the basis of Fig. 6, it can also be observed that the MSRS analysis yields a higher value of bending moment than the THA (with non-uniform effects included). In the case of the MSRS method, the safety stock in points P4 and P5 reaches 20–30%.

6. Conclusions

In this paper, the dynamic response of an overground pipeline to mining shock was calculated. Based on the results obtained from a variety of dynamic analysis types, some final conclusions can be formulated.

The conducted analysis indicated that the non-uniform effects of wave passage strongly influence the dynamic response of an object. This phenomenon is especially observed for long structures. Neglecting some non-uniformity effects, such as non-infinity wave velocity or the decreasing of amplitude, leads to incorrected results. The dynamic response of the structure may be up to 80% lower than the response calculated when considering the non-uniform effects.

The comparison of results from the time history analysis and the response spectrum analysis shows that the spectrum method allows estimation of the solution in the case of the uniform excitation model only. The estimation of the results guarantees a safe level of dynamic response derived from the uniform ground-motion model. The analysis also indicated that the response spectrum analysis leads to the underestimation of the solution in the case of non-uniform excitation. The results for response spectrum analysis were lower than the results predicted for the time history analysis in which the non-uniform model of kinematic excitation was included.

To represent the behaviour of the structure under non-uniform kinematic excitation, the multiple support response spectrum method can be used. The MSRS method permits estimation of the maximum level of the bending moment in the structure when taking into account the non-uniformity effects. In each of the analysed points, the MSRS method provided more conservative results. Thus, in contrast to RSA, the MSRS method may be used in the estimation of the dynamic response of a long structure subjected to the non-uniform modelling of mining shocks.

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