Analysis of Influence of Geometric and Material Properties on Dynamic Resistance of Overpasses Subjected to the Impact of Mining Tremors

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Abstract. This research paper presents the results of the analysis of the influence of geometric and material properties on the dynamic resistance of road overpasses of reinforced concrete slab span structure. The research was based on the database regarding the resistance of 3,000 structures with different geometric and material properties. The database compared the results of multiple numerical FEM simulations using the response spectrum method and a set of criteria for assessing dynamic resistance. The requirements set forth in Eurocode 8 and its adaptations to the seismic conditions prevailing in Legnica-Głogów Copper District (Poland) were applied. Reasons were given for the selection of 1,499 structures with properties which were characteristic for the existing bridges located within the range of mining impacts which took the form of continuous surface deformations. Then, the selected group of structures was subjected to a detailed analysis of dynamic resistance based on the criterion condition regarding the strength of the spans. The influence of geometric and material properties of a selected group of bridge structures on shaping the permissible values of vertical accelerations of ground vibrations ($a_{V,dop}$) was analyzed. The results of preliminary analyzes made it possible to build a statistical predictive model. It was demonstrated that this model, using only basic geometric and material properties, allowed to replace the complex dynamic analysis of the discussed criterion. This paper also outlines further research studies on the analyzed issue.

1. Introduction

Bridge structures constitute a large group of civil engineering structures located in mining areas in Poland, including Legnica-Głogów Copper District (LGCD) and Upper Silesian Coal Basin (USCB). These areas are subjected to the impacts of underground mining, which take the form of continuous surface deformations and mining tremors. In the case of the existing building structures, including bridges, located in areas where seismic activity has only become apparent in the course of their utilization, it is necessary to assess the dynamic resistance of these structures to the impacts of mining tremors. According to the methodology proposed in the research paper [1], in order to determine the dynamic resistance of a given structure, it is necessary to:

- determine the characteristic of the seismic activity of a given area in the form of a standard acceleration response spectrum,
- determine both the dynamic response of the structure and the criteria for determining the permissible values of ground vibration parameters that can be carried by the structure without any risk to its safety.
The issue of determining the dynamic resistance of an existing structure to potential seismic excitation is both different and more complex than assessing the resistance to static loads. In the paper [2], it was demonstrated that the dynamic resistance of the structure expressed by the permissible components of acceleration of ground vibrations ($a_{V,dop}$ and $a_{H,dop}$) is significantly affected by the seismicity of a given area. This is due to the fact that a structure with strictly defined and invariable dynamic properties (frequencies and normal modes of vibration) reacts differently to various types of seismic excitation of the ground. It is justified by the phenomenon of resonance [3]. Therefore, it is important to make the environment of construction engineers aware that the dynamic resistance of a given structure cannot be given as an absolute value, but depends on the seismicity of the area where it is located. This is what distinguishes the static resistance of building structures from its dynamic resistance.

Moreover, as part of the assessment of the dynamic resistance of a specific structure, besides defining the seismic characteristics of a given area, it is necessary to define the criteria allowing for additional impacts induced by mining tremors. For the existing structures that were not designed to carry accidental seismic loads, this is a complex task, which requires a detailed analysis of the behaviour of a structure when exposed to the loads from the design stage and its comparison with its response to the influence of the seismic combination.

2. Description of applied methodology for assessing dynamic resistance of existing bridge structures

The research paper [1] discusses the methodology for assessing dynamic resistance of the existing road overpasses of reinforced concrete structure. The criteria which are presented allow to determine the permissible values of the components of acceleration of ground vibrations ($a_{V,dop}$ and $a_{H,dop}$) from mining tremors, which can be carried by the structure without compromising its safety. These criteria are recorded in the form of kinematic and strength conditions. This approach can also be used to assess the dynamic resistance of other types of bridges as well as building structures, e.g. industrial portal-frame buildings of steel or reinforced concrete load-bearing structures, as demonstrated in the paper [4]. A necessary condition to be met in order to apply this type of approach, however, is that the technical condition of the structure being assessed should be at least satisfactory [5,6].

Due to the fact that it is often necessary to determine the resistance of a large number of structures of a given type in order to protect the surface against mining impacts, the analysis of each structure individually is ineffective. This is due to a large computational effort made during the assessment, which requires in general:

- building a numerical model with regard to geometric and material properties,
- establishing a combination of loads adopted at the design stage,
- establishing a combination of seismic loads,
- determining a set of normal modes of vibrations to carry out the analysis of the response spectrum,
- performing static FEM calculations for defined load cases,
- performing numerical FEM calculations for the method of the response spectrum,
- recording of the data describing effects of all defined load cases acting on the structure (values of internal forces, displacements, etc. for individual structural members),
- selecting reliable cross-sections for which extreme effects of the combination of loads from the design stage were obtained,
- comparison of extreme effects of the combination of loads from the design stage and the effects from the seismic combination,
- determining limit values of acceleration of ground vibrations $a_{V,dop}$ and $a_{H,dop}$, which balance effects of the seismic combination with reliable effects of the combination of loads from the design stage acting on the structure.
Therefore, if a large number of structures of a specific type are analyzed, it seems reasonable to look for simplified solutions which would be built on the databases of dynamic resistance for the possibly largest group of structures, taking into account the diversity of their geometric and material properties. Statistical analysis of such data may consequently allow to identify the relationships binding geometric and material properties with limit values of accelerations of ground vibrations $a_{V,dop}$ and $a_{H,dop}$.

The research paper [7] presents the adopted procedure and preliminary results for the created “simulation” database of the dynamic resistance of road overpasses of the slab span structure. This database contained information about the structure, static scheme, bearing application method and material characteristics of the analyzed bridges. The data for the analysis were each time randomly drawn from the interval of values which was consistent with the guidelines for the construction of concrete bridges [8]. For each case, the limit values of the components of acceleration of ground vibrations $a_{V,dop}$ and $a_{H,dop}$ were defined in the database. They were presented in detail for each of the analyzed criterion conditions [1], and in general for the whole structure [7]. The values of the permissible components of acceleration of ground vibrations for the whole structure were determined as the minimum values obtained from the analysis of all criterion conditions. Finally, 3,000 cases of overpasses of various structures were collected, for which dynamic resistance to seismic influences characteristic for the LGCD area was determined [7]. Then, from all the types of structures collected in the database, those that met the kinematic requirements for carrying continuous deformations were selected [9,10,11]. The final analysis covered a group of 1,499 structures which had their spans freely supported both on the abutments and on intermediate supports. In each of these cases, the arrangement of the bearings allowed for free multifaceted displacement of the spans [9,10,11]. All types of structures analyzed in the paper are illustrated in figure 1.

Linear descriptions used to define the resistance of the entire structure ($a_{V,dop}$ and $a_{H,dop}$) in the domain of all geometric and material parameters, proved insufficient due to the low accuracy of the created regression models. Therefore, analysing each criterion condition separately was considered to be necessary. The construction of separate, simple statistical models allowed for the prediction of the permissible components of ground vibrations within each criterion condition. Finally, the set of the obtained results allowed to identify the dynamic resistance of the entire structure. This solution eliminates the necessity to carry out individual numerical FEM analysis and allows to use simpler regression models. However, it requires a one-time detailed analysis of the significance of the variables required to create such models within each of the criterion conditions.

In this research paper, an attempt was made to analyze the criterion condition regarding the load-bearing capacity of the spans in great detail. According to [1], it allows to determine the limit vertical component of the ground vibrations $a_{V,dop}$, which can be carried by the span without compromising its safety.

3. Presentation of analyzed condition of dynamic resistance as statistical linear regression model

The numerically created “simulation” database of dynamic resistance of 3,000 bridge structures adapted to car transport formed the basis for the analysis. During the construction of the database, the response spectrum method was used as part of the dynamic calculations. The standard response spectrum characteristic for the mining area of Legnica-Głogów Copper District was adopted as the representative dynamic excitation [12]. Data capture was carried out based on multiple numerical FEM analyzes. These analyzes, conducted in the ABAQUS software [13], were controlled externally by a specially created set of scripts and functions written in the Python programming language [7]. A detailed description of the adopted procedure is described in the paper [7].
Figure 1. Summary and description of structural types of the group of bridge structures included in the study

Out of 3,000 types of structures, a subgroup of 1,499 objects was selected, which met the requirements of kinematic freedom regarding the span support and the method of bearing application in the support zones.

These requirements apply to all the existing bridge structures located in mining areas. If these conditions are met, it is possible to carry the impacts of continuous surface deformations without generating additional effort in structural elements [9,10,11]. The scope of the analyzed types of structures is illustrated in figure 1. Figure 2 demonstrates an example of the existing overpass that qualifies for the group of the analyzed structures.

| TYPE | Diagram | Type features | TYPE | Diagram | Type features |
|------|---------|--------------|------|---------|--------------|
| I    | ![Diagram](image) | - single-span<br>- free supported | V    | ![Diagram](image) | - multi-span<br>- free supported<br>- with overhangs<br>- intermediate supported by wall pillars |
| II   | ![Diagram](image) | - multi-span<br>- free supported<br>- without overhangs<br>- intermediate supported by wall pillars | VI   | ![Diagram](image) | - cantilever<br>- intermediate supported by pillars |
| III  | ![Diagram](image) | - multi-span<br>- free supported<br>- with overhangs<br>- intermediate supported by pillars | VII  | ![Diagram](image) | - cantilever<br>- intermediate supported by wall pillars |
| IV   | ![Diagram](image) | - multi-span<br>- free supported<br>- without overhangs<br>- intermediate supported by wall pillars |
Figure 2. Example of existing overpass representative of the group of analyzed structures (an existing overpass structure located in the Upper Silesian Coal Basin area - own source)

According to [1], the form of the strength condition of the load-bearing capacity of the span is presented in table 1, and its use is explained schematically in figure 3. The effect allowing to formulate the condition were the values of the span moments (static scheme with freely supported spans - figure 1.a) and support moments (static diagram of spans with overhangs - figure 1.b).

Table 1. Comparison of the main characteristics of the model

| Description of the condition | Mathematical description of strength criterion of the load-bearing capacity of the spans |
|------------------------------|-----------------------------------------------------------------------------------------|
| The combination of design stage by [14,15] | $\sum_{i=1}^{m} 1.2G_{k,i} + 1.3Q_{TS}$ |
| Seismic combination of loads by [16,17] | $\sum_{i=1}^{m} G_{k,i} + A_{ed}$ |
| The final form of the condition | $M^{PN} \left( \sum_{i=1}^{m} 1.2G_{k,i} + 1.3Q_{TS} \right) \geq M^{SE} \left( \sum_{i=1}^{m} G_{k,i} + A_{ed} \right)$ |

$G_{k,i}$ – self-weight structural components of the bridge and equipment

$A_{ed}$ – design value of the seismic impact

$Q_{TS}$ – value of traffic load from design stage

$M^{PN}$, $M^{SE}$ – bending moments determined for the combination of design stage $^{PN}$ and seismic combination $^{SE}$

The research was carried out in two stages. The first stage examined the relationship between the variables describing geometric and material properties, and the determined limit value of the vertical component of ground vibrations $a_{V,dop}$. Pearson's linear correlation analysis was used. These research studies were aimed at selecting a set of these properties that could be used at the stage of constructing a statistical prediction model.
In the second stage, based on the selected set of the most significant geometric and material properties, the construction of the statistical model was commenced. During this stage, the MLR (Multiple Linear Regression) method was used. The analysis involved testing various sets of input variables from the originally selected set of geometric and material properties. This allowed to obtain a statistical model for predicting the permissible value of the vertical component of acceleration $a_{V,dop}$, which may replace the deterministic condition of resistance due to the strength of the spans (c.f. table 1). Additionally, a set of input variables that increased the accuracy of the model prediction was established in the course of the performed analyzes.

4. Test results

The first stage involved the performance of the analysis of correlations between the variables describing geometric and material properties, and the permissible value of the vertical component of acceleration of ground vibrations $a_{V,dop}$, determined from the condition of the load-bearing capacity of the spans (c.f. table 1). In addition to the results of the static analysis, this condition includes the dynamic response of the structure. According to the response spectrum method, it is determined by a set of predefined frequencies and natural modes of vibration [3]. Therefore, a set of potential input variables has been extended in the analyzes to include those geometric properties that could have influenced the natural modes of vibration generated in the planes other than the loads from the design stage. The list of all geometric and material properties is demonstrated in table 2. The Table also presents the values of the linear correlation coefficient with the permissible component of acceleration of ground vibrations $a_{V,dop}$ and relevant significance levels (value of the parameter p).

As it is demonstrated in table 2, all the variables describing the geometric properties have a significant influence on the value of the permissible vertical component of ground vibrations $a_{V,dop}$. However, no significant correlations with the variables describing the material properties were identified. The highest level of the linear dependence was obtained for the variable describing the length of the potential overhang (variable $V_i$). This is justified by the values of the moments in the support zone, which definitely exceed the bending moments in the spans (c.f. table 1 and figure 1). Thus, the geometric parameters describing the length of the overhangs may become a factor determining the permissible value of the vertical component of ground vibrations $a_{V,dop}$, determined based on the load-bearing condition of the span.
Table 2. Results of linear analysis of relationship between geometric and material properties, and permissible value of vertical component of acceleration of ground vibrations $a_{V,dop}$

| Variable no. | Description of the variable                              | Correlation coefficient $R$ | $p$-value |
|--------------|-----------------------------------------------------------|-----------------------------|-----------|
| $V_1$        | Number of spans                                          | -0.053                      | 0.040     |
| $V_2$        | Length of spans                                          | 0.053                       | 0.040     |
| $V_3$        | Width of spans                                           | 0.110                       | 0.000     |
| $V_4$        | Height of span                                            | 0.096                       | 0.000     |
| $V_5$        | Length of cantilever/overhang                            | 0.690                       | 0.000     |
| $V_6$        | Number of pillars                                        | 0.191                       | 0.040     |
| $V_7$        | Width (y – perpendicular to the axis of the structure) of a single support/wall pillar | -0.142                     | 0.000     |
| $V_8$        | Width (x – parallel to the axis of the structure) of a single support/wall pillar | -0.083                     | 0.001     |
| $V_9$        | Height of supports/wall pillars                          | -0.069                      | 0.008     |
| $V_{10}$     | Height of the support frame lintel                       | 0.065                       | 0.013     |
| $V_{11}$     | Width of the support frame lintel                        | 0.091                       | 0.000     |
| $V_{12}$     | Modulus of elasticity of concrete of span slabs          | 0.036                       | 0.170     |
| $V_{13}$     | Modulus of elasticity of concrete of support frame lintels | 0.015                      | 0.565     |
| $V_{14}$     | Modulus of elasticity of concrete of supports/wall pillars | 0.016                      | 0.542     |

In the second stage of the research studies, a predefined set of variables was used to make an attempt to build a predictive model. The MLR (Multiple Linear Regression) method was used. Various combinations of the variables were analyzed to fit the model to the primary data. Each time, statistical significance of the model parameters was also assessed, which allowed to reduce the set of input variables for which a linear prediction model was created (1):

$$a_{V,dop}^{pred} = -0.370V_2 + 0.025V_3 + 0.244V_4 + 0.049V_5 - 0.013V_7 - 0.057V_8 + 0.360 \frac{m}{s^2}$$  \quad (1)

The created model (1) allows to predict the permissible value of the component of acceleration of ground vibrations $a_{V,dop}$, depending on the values of individual input variables (1). The quality of fitting the model prediction to the reference data, measured by the linear correlation coefficient, is equal to $R=0.724$.

On the other hand, the linear combination coefficients (1) determined for standardized variables are demonstrated in table 3. These values allow to determine the relative quantitative contribution of each of the variables included in the model. Based on the values summarized in table 3, it can be concluded that the variable describing the length of the overhang ($V_5$) has the greatest influence on the prediction value. This is confirmed by the preliminary results of the studies of linear relationships summarized in table 2. The influence of the remaining variables falls within the range of comparable values. However, it should be noted, that the model exhibits a significant influence of the geometry of intermediate supports (supports or wall pillars). As it was mentioned earlier, this is an artifact after the response spectrum method used at the stage of formulating the deterministic form of the span load-bearing condition.
Table 3. Values of linear combination coefficients of the model (1) for standardized variables

| Variable number - description                                                                 | Value of linear combination coefficient (1) for standardized variables |
|-----------------------------------------------------------------------------------------------|------------------------------------------------------------------------|
| $V_2$ – Length of span [-]                                                                   | -0.211                                                                 |
| $V_3$ – Width of spans [-]                                                                    | 0.163                                                                  |
| $V_4$ – Height of span [-]                                                                    | 0.137                                                                  |
| $V_5$ – Length of cantilever/overhang [-]                                                     | 0.697                                                                  |
| $V_7$ – Width (y – perpendicular to the axis of the structure) of a single support/wall pillar [-] | -0.126                                                                 |
| $V_8$ – Width (x – parallel to the axis of the structure) of a single support/wall pillar [-]  | -0.072                                                                 |

5. Conclusions
The demonstrated research results confirm the possibility of presenting the deterministic condition of dynamic resistance of bridge structures (1) in the form of a statistical model, provided that the analyzes are carried out on sufficiently numerous simulation data sets. This is a great simplification, because knowing the model parameters and having information on the geometric and material properties of its basic structural members, it is possible to assess the dynamic resistance for the considered criterion with satisfactory accuracy.

In this research paper, this criterion was the strength condition of the load-bearing capacity of the spans. It is one from the set of defined conditions that allow to determine the dynamic resistance of the whole structure. Based on the proposed approach, it is planned to continue the research, so that each of the resistance criteria proposed in the paper [1] could be transformed into a corresponding predictive model.

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References
[1] J. Rusek. A proposal for an assessment method of the dynamic resistance of concrete slab viaducts subjected to impact loads caused by mining tremors. *Journal of Civil Engineering, Environment and Architecture*. vol. 34 no. 64, pp. 469–485. 2017
[2] J. Rusek. “Influence of the seismic intensity of the area on the assessment of dynamic resistance of bridge structures”. *IOP Conference Series: Materials Science and Engineering*. vol. 245 art. no. 032019, pp. 1–9. 2017.
[3] A.K. Chopra. Dynamics of Structure. *Prentice Hall*. New York, 1995.
[4] J. Rusek, W. Kocot. “Proposed assessment of dynamic resistance of the existing industrial portal frame building structures to the impact of mining tremors”. *IOP Conference Series: Materials Science and Engineering*. vol. 245 art. no. 032020, pp. 1–10, 2017.
[5] K. Firek, A. Wodyński. “Qualitative and quantitative assessment of mining impacts influence on traditional development in the mining areas”. *Archives of Mining Sciences*; ISSN 0860-7001. vol. 56 no. 2, pp. 179–188, 2011.
[6] A. Wodyński. „Zużycie techniczne budynków na terenach górniczych. (Technical wear of buildings in mining areas)”, *AGH Publishing House*, Cracow, 2007, (in Polish).
[7] J. Rusek. “Procedure of building and analysis of the information database of the resistance of existing bridge structures to mining tremors”. *Geomatics and Environmental Engineering*. vol. 11 no. 4, pp. 111–123, 2017.
[8] A. Madaj, W. Wołowicki. Projektowanie mostów betonowych. (Designing of concrete bridges). *WKiL*. Warsaw, 2010, (in Polish).
[9] S. Barycz, W. Kocot W, A. Wodyński. „Zagrożenia dla konstrukcji mostów na terenach górniczych (Threats to the construction of bridges in mining areas)”. Bezpieczeństwo pracy i ochrona środowiska w górnictwie (Work safety and environmental protection in mining),
[10] A. Rosikoń. Budownictwo komunikacyjne na terenach objętych szkodami górniczymi. (Communication construction in areas affected by mining damage) WKiŁ, Warsaw, 1979, (in Polish).

[11] A. Rosikoń. O obrotach podpór i przęsół mostu. (About the rotations of the bridge supports and spans). Rosikon-Press. Warsaw, 2004, (in Polish).

[12] Z. Zembaty, S. Kokot. „Adaptacja sejsmicznych norm projektowania konstrukcji do ujęcia wpływu wstrząsów górniczych na budowle. (Adaptation of seismic design standards structure to include the impact of mining tremors on buildings)”. Technical Magazine: “Przegląd Górniczy”, No. 70, Katowice, 2014, (in Polish).

[13] ABAQUS, Simulia. Dassault Systemes. Providence, RI, USA, 2011.

[14] PN-B-02000:1982 Building loads - Rules for determining value, (in Polish).

[15] PN-S-10030:1985 Bridge structures. Load. (in Polish)

[16] PN-EN 1990:2004. Eurocode. Basis of structural design.

[17] PN-EN-1998-2:2006. Eurocode 8. Design of structures for earthquake resistance. Part 2: Bridges