Analysis of Mining Influences on a Small Frame Railway Viaduct

Piotr Betkowski

1 Silesian University of Technology, 44-100 Gliwice, ul. Akademicka 5, Poland

piotr.betkowski@polsl.pl

Abstract. In the article, the example of the rebuilding of the real bridge object shows, how to take into account the impact of mining area deformations on small frame railway viaducts integrated with the embankment. General principles are given, how to determine additional forces induced in the construction, such forces arise as a result of mining deformations on the surface of the area. It is discussed, how to shape the geometry of the bridge structure, so that in the future it will be possible to raise the level of the railway track even by several meters (in order to eliminate the local mining hollow), without rebuilding of the viaduct. Attention is paid to the necessity of shaping the foundations so that the impact on the subsoil tension under the embankment and under the viaduct is the same, so that the viaduct can settle in the same way as the adjacent railway embankment. In addition, technological aspects related to the adjustment of the viaduct to ground conditions (shallow, thin layers of cohesive-plastic soil typical for post-glacial areas in Poland on Silesia Upland) and protection of railway traffic continuity through a bridge type relieving construction are shown. The article is supplemented by the results of 8-years measurements of subsidence and displacements of the viaduct on the deforming mining ground and conclusions from observations. This method of analysis and conclusions may be used in further studies of the interaction between the embankment and the viaduct embedded in the embankment in the situation of active mining deformations of the area.

1. Introduction

In Poland mining exploitation has been carried out in the vicinity of railway lines for over 150 years, hence there is undoubtedly a lot of practical experience here. Therefore, the article briefly discusses the impact of mining operations also on other types of bridge structures (general review), there are links to open access publications (mainly English-language) showing interesting examples and containing valuable research results. Such a general introduction is needed to better understand the specificity of mining interactions on the framework railway viaducts integrated with the embankment, where it is necessary to assess the interaction of the soil-ground with the bridge structure.

The principles contain in the Polish technical conditions and design standards, obligatory when we design or rebuild railway bridges on mining areas, will be briefly discussed. The main items from Polish technical literature devote to bridge objects on mining areas also will be described.

Such a general overview may help researchers from other countries familiarize themselves with the Polish approach to protecting bridge structures on mining areas, e.g. for purposes comparative research.
2. The impact of mining exploitation on bridge objects. Polish experience

Mining exploitation currently is conducted in Poland mainly by the "infarct" system, i.e. the emptiness after the excavated coal seam is not filled with any backfill [1]. Such an excavation system results in a noticeable appearance of the effects of mining exploitation on the surface in the form of area deformation. In general, a mining hollow of subsidence is created over the exploited seam. The mining hollow is described not only by subsidence \( w \), but also shortening/elongation (compression/stretching) of area \( \epsilon \), radii of terrain curvature \( R \), slope of terrain \( T \), horizontal displacements of points locate in terrain \( u \). Changing the slope of the area has a negative impact on the geometry of the railway track, it is necessary to limit the speed, and sometimes it is necessary to use a second locomotive (to push the wagons) to prevent the wagons from "breaking up".

Despite many practical implementations, repairs, reinforcements or preventive protections on bridge objects, Polish technical literature (concerning mining impacts on bridge objects) is relatively poor and concentrate mainly on single-span structures with a static scheme of a simply supported beam [2, 3]. In such objects, at least three rigid solids (bridge span and two abutments) can be distinguished, which can move independently [3]. As a result of shortening/elongation of area, changes of the inclination of bridge supports and the turnovers of the pillars (with the mining front slanted to the object) the bridge abutments are approaching/moving away from each other. The width of the expansion joints is changing. The span may become jammed [4], there is real threat of cutting of the backwall and deformation of the railway track (e.g. [4]), the permanent bearings break (e.g. [5]), the bearing damage due to excessive displacement (e.g. [5]), bridge span can fall from bearings (e.g. [5]). Practical analytical formulas for calculating displacements and rotations along with geometric diagrams are given in the book of professor Rosikoń [2], which is popular among Polish engineers.

In the case of hyper-static objects, additional internal forces arise due to mining area deformations. In such statically indeterminate constructions, scratches (e.g. [6, 7, 8]), deep cracks (e.g. [7, 8]) and even destruction of structural elements [8] occur. Particularly important is the effect of surface deformation \( \epsilon \) (shortening/elongation of area) and changes in the radius of curvature \( R \) (e.g. [2-7]). Interesting technical and research examples of non-standard protection of bridge structures are described in Polish literature [4-8] (open access publications), e.g. a multi-span frame subjects to very high ground compression [6].

The description of damages of bridge objects located on mining areas is made according to various classifications including loss of material continuity (e.g. cracks), deformations of structural elements, surface deformations of roads/railway lines, technical condition of bridge bearings, width of expansion joints, etc. Classifications enable the standardization of damage description, which is very important in the context of long-term observation. Classification of damages given in the book of professor Bień [9] is very popular in Poland.

Both in previous [10] and current [11] Polish technical regulations, there are only general information, how to take into account the impacts of mining terrain deformations on bridge objects, i.e. in structures with a static schematic of a freely supported beam by providing freedom to deform supports against spans by determining expansion joints of appropriate width and assembly of bridge bearings with appropriate displacement ranges. Statically indeterminate bridge objects are admitted in exceptional cases (according to [10, 11]), it is necessary to calculate additional internal forces resulting from mining area deformations, perform strength calculations and demonstrate that the structure can be used safely despite terrain deformations.

Damages to railway bridges create serious communication problems (according to [12]). It is impossible to set detours in a manner known from road speciality. Damages reduce the static and dynamic resistance of bridges to mining influences. Repair actions must always be individually matched to damages (e.g. [13]). Upper Silesia is an urbanized area, there are many important national railway lines here, but also there are many internal mine railway lines. There are many small frame viaducts integrated with the embankments here. The analysis of such frame bridge object is more difficult than object with a static scheme of a simply supported beam (e.g. [2]) - an interesting practical example is presented in this article.
3. Theoretical basis of calculations
In the analysis of statically indeterminate bridge constructions, FEM programs are primarily used, the frame construction model is spatial (3D). It is necessary to consider the general distribution of the stiffness of structural elements, the interaction of the concrete structure with the ground subsoil and mining influences. It is very important to properly identify the soil substrate parameters. The ground subsoil should be modelled as susceptible, flexible. It is necessary to carry out geotechnical tests in advance so that the soil parameters in the FEM model can be properly identified.

It is necessary to take into account the possibility of changing values of the parameters of the soil medium as a result of mining stretching/compressing of the substrate [15]. For example, during creep (stretching) of mining ground, the degree of compaction of non-cohesive soil \( \nu'_g \) decreases even about 10%. As a result of mining subsidence, the level of groundwater may change, the water may be found directly under the foundation, which should also be included in the analyses. Collaboration is needed between bridge designers and geo-technicians. It is important, that the stresses under the bridge foundation of the viaduct are similar as under the adjacent embankment. In case of much higher stresses under the foundation than under the embankment, during the approaching of the next mining walls to the object, the viaduct will settle faster than the embankment (e.g. [15]). In such cases, the railway track will be deformed. Another threat (danger) is to design too rigid foundation (ground subsoil under the foundation) - the viaduct will settle more slowly than the embankment.

Additional active pressure resulting from mining surface deformations \( \varepsilon \) for typical bridgeheads, surround by non-cohesive soil, can be estimated by formula (1) (more accurate formulas and analyzes are e.g. in the publication [1]), where:
- \( p \) – active pressure from surface deformation \( \varepsilon \),
- \( E \) – soil compressibility module,
- \( \varepsilon \) – surface deformation, e.g. mining shortening of the area,
- \( l \) – distance of front walls of supports (so-called horizontal light of bridge),
- \( b \) – height of the support (from the foundation level to the bottom of bridge span).

\[
p = 0,4 \cdot \varepsilon \cdot E \cdot \left(1 + \frac{l}{2\cdot b}\right) \tag{1}
\]

In general, after taking into account the additional influences and principles describe above, the same methods of analysis are used as in bridges outside mining areas (e.g. [14]).

4. Practical example - railway frame bridge integrated with the embankment
4.1. Description of the damaged viaduct (before rebuilding)
Until July 2011, i.e. until the beginning of works on rebuilding, the bridge object consisted of two parts, which were separate constructions. These constructions were assigned to individual railway tracks: under the track No. 1 there was a damaged brick arch, while reinforced concrete frame object was located under the track No. 2. The railway line is electrified. Under the viaduct is a municipal road, which is access to the properties, houses and fields.

Until the rebuilding, the bridge object under track No. 1 was a single-span railway viaduct with arched and vaulted construction. The construction materials in its entirety were full bricks. From the inlet side, triangular standing bridgehead wings were placed obliquely to the longitudinal axis of the object (track). The construction of the wings was a brick wall connected to the front wall of the bridge tunnel (Fig. 1). Object geometry: horizontal light: 4.60 m, vertical light: 3.60 m (inside mining enclosure), length of the tunnel under the viaduct: 5.90 m, overall length of oblique wings: 5.90 m.

The arched viaduct under the No. 1 track was irreparably damaged. There were numerous cracks, streaks and efflorescence on the arch girder. The construction of the viaduct was cracked in many places. These were cracks passing through the entire thickness of brick structural elements (Fig.2). Cracks divided the arched structure into series of loosely connected solids - the displacements of these solids (and the width of the scratches) were influenced by mining deformations of the area and vibrations coming from the railway rolling stock.
In 2004, the bridge structure was provisionally protected with a steel mining enclosure with concrete blocks filling the space between it and the vault or walls (Fig. 2). The wings of the viaduct were also severely cracked; the bricks were loose in many places (Fig. 3). The crisp brick viaduct was not adapted to transferring influences from mining deformations of the area. Damages were typical for brick walls [9, 13]. This viaduct practically lost its load capacity.

Figure 1. Brick arch viaduct under railway track nr 1

Figure 2. Mining enclosure with concrete blocks filling the space between the steel enclosure and the brick wall

Figure 3. Brick viaduct - damaged bridge wings

Figure 4. View on the railway track No. 1 on viaduct and relieving construction

Damaged viaduct under track No. 1 was, for a short time in 2004, excluded from railway use. The railway line "running" on the viaduct is an important communication route (over 40 freight trains for each day), it was necessary to restore the continuity of railway traffic. In November 2004, a temporary relieving structure type KO-21/73 was built above the viaduct (Fig. 4). The theoretical length span of the relieving structure was 21 m, total length 21.60 m. The steel relieving construction (bridge type) was supported at both ends on prefabricated reinforced concrete slabs by means of wooden railway sleepers. Relieving construction - the cost of renting it was several thousand zlotys each month (the cost for the local mine) and problems of integration with the track in the conditions of mining area deformation. Therefore it was decided to rebuild the viaduct.
4.2. Mining exploitation: made (in the past) and predicted (in the future)
On the basis of the opinion obtained from the relevant District Mining Office and mining information obtained for the local mine, data for the rebuilding project were established (information from mid-October 2009):

- Mining exploitation in the area of the viaduct was carried out in the years 1981÷2009: w=2.61 m, T=14.7 mm/m, ε = 2.7 mm/m, R=-25.7 km.
- Both current and predicted (planned until the end of the current mine concession, i.e. until 2020), mining exploitation qualifies the area for the third category of mining damage. Predicted values of area deformation indicators by 2020: w=4.55 m, T=3.0 mm/m, ε = -3.3 mm/m, R=24.8 km.
- Further mining exploitation is planned in the years 2021 ÷ 2040. Predicted values of mining area deformation indicators (from October 2009 to December 2040): w=5.32 m, T=4.4 mm/m, ε = -3.4 mm/m, R=22.6 km.
- Temporarily there may be ground creep up (stretching) up to ε = 1.5 mm/m.
- Mining shocks can cause ground vibrations with acceleration up to a=200 mm/s².
- It is possible to raise the level of groundwater to the terrain surface.

4.3. Rebuilding of the railway viaduct. New frame viaduct integrated with the embankment
The new viaduct under the No. 1 track is designed in the form of a single-span reinforced, concrete frame. It is closed frame with a bottom plate. This new frame bridge in the cross-section has a rectangular shape, adapted to the reinforced viaduct existing under track No. 2. Reinforced concrete wings of the abutments are dilated from the frame (due to mining influences). These wings are placed on a common foundation slab which plays the role of the bowstring (tie-beam) or strut - depending on the nature of the mining deformation.

Geometry of the new viaduct: horizontal light: 4.95 m; vertical utility light: 3.95 m; operational length (tunnel): 8.00 m; overall length (with abutment wings): 15.5 m.

The new bridge object has been adapted to work on the third category of mining damage (according to [1]). The construction of the bridge should safely transfer additional loads relate to mining deformations of the area and ground pressure after raising the level of the track about 5.5 m (the railway track should be raised in order to eliminate the adverse influence of the mining subsidence hollow which will be created).

![Figure 5. Model of frame - mining stretching of bottom plate and graph of bending moments from ground pressure](image-url)
New viaduct is designed as the reinforced concrete frame with rectangular cross-section. The thickness of the bottom plate is 0.80 m. The thickness of the upper plate is variable (due to inclination associated with dehydration) and amounts: 0.65 ÷ 0.68 m. The vertical walls of the frame have thickness: 0.60 m. The corners are strengthened by making slants. In the upper part of the frame (from the inlet) on the entire width of the frame a reinforced concrete front wall with thickness of 0.6 m and height of 2.2 m is made. This front wall is connected monolithically with the bridge frame.

The calculations take into account the impact of mining operations, including: horizontal deformation of the area, additional active mining pressure of the ground, changes in the curvature of the area. In order to properly take into account the effect of construction twisting and uneven settlements, the spatial 3D model of the frame is made (Fig. 5). The wings of the new viaduct are designed as reinforced concrete, trapezoidal, oblique to the viaduct (and railway track). These wings are completely dilated from the frame (also at the level of the foundation slab). The foundation of the wings is direct, as well as the foundation of bridge frame. The wings are connected to each other at the bottom by means of a reinforced concrete foundation slab with thickness of 0.8 m. Under this bottom plate, 0.5 m thick sandbag is provided. The length of the wings is 7.50 m (7.35 m measured on the axis of the municipal road), the thickness of the wings: 0.60 m. The corners joining the vertical walls with the bottom plate have been reinforced by giving slants. To take into account the influence of mining area deformations, series of complicated analysis in Finite Element Method (FEM) has been performed (for example Fig. 6).

![Figure 6](image-url)  
**Figure 6.** Model of bridge wings – modelling of mining curvature and graph of bending moments from ground pressure

The bridge object under the track No. 1 (new frame viaduct) is adapted to transfer the influence of mining exploitation. The schematic of static rectangular frame closed fully monolithic is used. This frame is stiffer than the surrounding soil-ground medium; hence the mining deformations in the embankment-bridge contact layer mainly concern the susceptible ground. Both wings of the bridge are based on a common foundation slab and are placed on the same level as the bottom plate of the viaduct frame. The foundation slab of the wings is dilated from the bottom plate of the frame (the frame and wings have separate foundation slabs).

Due to the significant predicted settlement of the area, it will be necessary to lift the railway track (embankment) over the object (the object is embedded in the embankment). The possibility of raising the embankment (superstructure) over the object by 5.5 m is assumed in the future (settlement prediction for 2040) and the possibility of raising the wing and front wall extension about 3 m; additional loads are included in the load statement and these additional loads are analyzed in
calculation of reinforcement. Such action, taking into account the correction of the railway track top at the design stage, is important, because subsequent interference (intervention) in the bridge structure, which is integrated with the embankment, requires closing the railway line and is always costly.

The foundations of the frame and wings are designed as direct. Structural susceptibility (wings and frame) to take over the deformations of the ground caused by mining exploitation is ensured by placing construction on 0.5 m thick sand cushion (sandbag), make of medium-compacted sand with $I_d = 0.9$ and make an additional concrete bottom plate (0.5 m thick) under this sand cushion. Due to the weak soft cohesive-plastic ground found at a depth of 3 ÷ 4 m below the ground level, this soil was replaced (on a non-cohesive ground). To compensate for the stress acting on the ground from the embankment and from the viaduct, the reinforced concrete slab is made: 0.5 m thick and approx. 1 m wider than the frame. Above the slab stabilizing the foundation and under the bottom plate of the bridge, the sandbag described above is made. It is important to design the foundation of the bridge so that it does not settle more than the terrain and less than the embankment. It is necessary to equalize the ground stresses under the viaduct and under the embankment in the foundation level.

In static calculations, when determining the extreme internal forces in the frame and wings of the bridge, additional active ground pressure and deformations (displacements) from the impact of third category mining exploitation are taken into account. For the FEM (Finite Element Method) analysis, extreme values of deformation indicators are adopted, using the prediction provided by the Mine until 2040 (values of mining area deformation indicators are given in section 4.2).

4.4. Rebuilding of the railway viaduct. Realization

![Figure 7. Making the sand cushion](image7)

![Figure 8. Relieving construction in track No. 1](image8)

![Figure 9. Viaduct under railway track No. 1 after rebuilding](image9)

![Figure 10. View on railway tracks after rebuilding](image10)
Fig. 7 shows the execution of the sand cushion under the new viaduct.

Ensuring the continuity of railway traffic is a very expensive problem (renting, transporting and assembling relieving construction - it is the cost of several hundred thousand Polish zlotys). Fig. 8 shows view of track No. 1 in the final phase of the rebuilding of the viaduct, steel relieving construction in track No. 1 is visible.

Fig. 9 shows side view of a viaduct after rebuilding.

Fig. 10 shows view on railroad tracks on the rebuilt viaduct.

4.5. Geodetic measurements, maintenance, monitoring, BIM

On the bridge object, there are stabilized measurements points (benchmarks) made of stainless steel, deliberate for surveying measurements - 14 pieces (Fig. 11).

Points 1a, 2a, 3, 4 are located on top of side walls. Points number d1 ÷ d12 are located at the bottom of bridge wings and side walls of frames (under both railway tracks). Geodetic height measurements are made on all benchmarks. The width of the expansion joints is also measured (between points): d1-d2, d3-d4, d5-d6, d7-d8. Geodetic measurements are usually performed once a month. These measurements are made manually, by minimum three-person team of surveyors.

![Figure 11. Location of measuring points (benchmarks)](image)

In the period from December 2011 to June 2019, the viaduct settled approximately 2.2 m. In the ground substrate initially there was small creep (stretching), and then small crawls (compression), practically insignificant to the structure of the bridge. The width of the expansion joints has changed from -3 mm to + 5 mm depending on the location of the exploited mining walls in relative to the viaduct.

The viaduct is regularly observed. Local visits are carried out on the bridge at least once a month or even more often in the case of revealing the impact of mining exploitation in the vicinity of the object. In the period from December 2011 to June 2019, no emergency dangerous situation was observed for the viaduct. This object safely took over the previous impacts of mining operations. It is worth noting that there are no differences in subsidence on the adjacent railway embankment, on the viaduct and on the municipal road under the viaduct, which proves the correct balance of stresses in the ground substrate from the railway embankment and from the frame bridge.

Undoubtedly, regular frequent geodetic measurements (sometimes even once a week), the need for frequent visits to the bridge, making repetitive analyzes are large cost of expensive human labour. The observations and measurements carried out by various teams may not be accurate (comparable) - according to the author of the article, the individual subjective experiences of the researchers influence on the assessment of the results.
Remote methods of measuring the width of expansion joints (by extensometers) and changes in the slope of bridge spans and supports (by inclinometers) are possible (e.g. [16, 17]). Strain gauges can be used to measure stress changes. Nearly all modern remote measurement methods can be implemented (e.g. [18]). The monitoring system should always be designed individually, taking into account predict mining influences. In the viaduct which is described in this article, geodetic measurements are carried out manually (so far) several times a year, and each time an individual assessment of the resistance of the viaduct to mining influences is necessary. It is planned to use the BIM (Building Information Modeling) method to automate measurements and link measurements with the construction model and mining prediction [19]. In the case of bridge structures subject to significant mining influences, the assessment of safety and maintaining railway traffic continuity is costly - railway track control is currently being conducted every week and at least once a month a visual inspection of the viaduct together with control geodetic measurements is performed. Adaptation of modern techniques based on the BIM method (e.g. [20]) can bring real financial savings, increase the level of safety on the railway line and improve the cooperation of the local mine with the owner of the railway line (e.g. [19]).

5. Conclusions
The article discusses, first of all, issues related to the impact of mining exploitation on small railway viaducts integrated with the embankment. Practical example of rebuilding is shown. Many such bridge objects are located in Poland on mining areas. These are usually reinforced concrete frames with bottom plates. Such objects are built into the embankment, over such objects there are layers of soil and the railway backfill along with the tracks.

The principles of analysis of mining interaction between frame viaduct integrated with the embankment and this embankment are described. These principles are developed individually by this article's author. The practical example is illustrated with images (screens) from FEM calculations and photo documentation, which illustrates well the practical aspects of the applied method of analysis.

Integrating the viaduct with the embankment in the case of small frame railway bridges is advantageous, because it is possible to cheaply and quickly raise the gradeline (level) of railway line by conquering the railway track with break stone. The construction of the viaduct should enable subsequent lifting of the track (level, gradeline) both in terms of geometry, stabilization of the embankment and the need to carry additional ground loads. Appropriate structural solutions should be provided at the design stage. All subsequent interventions (interferences) in the bridge structure are extremely expensive due to the active, intensively used railway line.

The article draws attention to the nuisance and large amount of work associated with geodetic measurements and observations of the viaduct, which is subject to significant mining deformation of the area. The advantages of the BIM method and automatic measurement methods (monitoring) in safe maintenance of the viaduct are pointed out.

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