Adapting of bridges at mining area to the lowered bed of rivers

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Abstract. This article describes technical problems concerning bridges, dangers that arise when the bottom of the river bed is lowered during the liquidation of the floodplains. These floodplains arise as a result of terrain subsidence caused by mining exploitation. In urban areas with developed building and road infrastructure, bayous can cause significant social and material damages. One of manners of the floodplain liquidation or long-lasting lowering the water table is lowering the bottom of river channel on the leakage from bayou. Lowering the river channel can concern the section of few kilometres even long. Lowering the riverbed by dredging or considerable deepening generally does not cause important problems. Significant technical problems are generated by bridge objects. In the case of bridges, it is necessary to ensure the stability of bridgeheads, protect foundations from washing away and undermining. It is necessary to design channel reinforcement so that significant horizontal forces do not occur due to removing the part of the soil-ground from the riverbed (lack of passive ground pressure). Several technical solutions of adapting existing bridges to the lowered river bed for different structures are described.

Keywords: bridge, mining, hydrology, foundation, river bed lowering

1 Introduction

As a result of mining exploitation local hollows of mining subsidence are formed. This problem is particularly important in the case of rivers and streams because there is a constant inflow of water into the hollow. In Polish realities, mining areas are upland, post-glacial areas, rich in numerous watercourses with complex hydrological situation.

The best way to liquidate the bayou or to permanently lower the water level is often lowering the bottom of channel of the watercourse at the outlet of the floodplain. The regulation of the river bed, made in advance, can reduce the area of the floodplain, allow for reducing the area and height of the necessary embankments, and sometimes even preventing the creation of the bayou.

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Lowering the bottom of the river may concern a section of several kilometres long. Adjustment, dredging or considerable deepening of the river channel generally does not cause technical problems, and costs can be estimated with high accuracy.

Lowering the bottom of the river bed under an existing bridge requires proper technical analysis. A reckless lowering of the river bed under the bridge may lead to the loss of stability of bridgeheads and piers, washing away and undermining foundations, weakening of the load-bearing capacity of structural elements. Many technical problems have to be solved, such as the presence of bottom plates under the river bed for some frame objects.

The article gives examples of adaptation of bridge objects to the reduced bed of rivers and streams and discusses the basic technical problems. Special attention is paid to the susceptibility of the applied solutions to mining influences.

Adjusting the existing bridge to a reduced level of the riverbed is much cheaper than replacing this object with a new one. Time-consuming and cumbersome formal-legal arrangements and official decisions, such as building permits, are generally not required. Such arrangements and decisions, temporary traffic organization projects and industry projects for protection the technical infrastructure attached to the bridge (cables, pipelines) are additional non-material costs associated with demolition and building the new object.

The problem is important for mines, because more and more restrictive regulations on environmental protection cause that more attention should be paid to water relations. Mine must, therefore, choose the actions to regulate water relations in its mining area.

2. Technical remarks

The beginning of activities regarding the adaptation of bridges to the lowered riverbed is the assessment of the current technical condition of bridges [1] and the determination of further mine plans related to mining exploitation (e.g. [2], [3]). It is advisable to obtain data wider than the standard information about mining area category (e.g. [4], [5], [6], [7]). Indicators describing mining influences should be determined in the directions of the object's axis and the axis of the watercourse.

It should be decided, taking into account further plans of the mine, whether the lowering of the riverbed is a one-off operation or similar action will be repeated in the future, so that the current choice of specific solutions does not complicate other activities in the field of hydrology in the future. It is also advisable to coordinate hydrology activities between individual mines in the event that mining areas are located in the same catchment [2]. In order to evaluate the technical and economic aspects of different solutions and proper coordination of hydrological activities with mine plans, it is necessary to make variant analyzes and calculate the costs of individual solutions in advance.

Protecting bridges for lowering the riverbed should ensure stability of supports, take over horizontal forces from under the foundations or top plate of piles and stabilize the ground under the foundation (e.g. [2], [8]). At the same time, hydrological requirements referring to the channel shape should be met [8]. It is also necessary to prevent the supports from washing, scouring and dilapidating (the lowered riverbed in many cases is below the bottom level of supports) [2].

Lack of archival documentation in the case of many old bridge objects often requires making test holes in order to discover the method of foundation of bridge structures. Execution of openings generally enforces interference in the existing strengthening of the river bed - this is a necessary action in cases where the new bottom of the channel will be below the level of direct foundation or below the top plate of piles or foundation wells. Geotechnical research is an additional cost that must be taken into account by the mining and bridge designer.

Below, in a few examples, selected solutions are presented and the necessary analytical conditions are discussed in the comments. Attention is paid to the differences in solutions applied in active mining areas and beyond mining areas. There are two possible situations: the bridge is located on the area of active mining deformations or outside the deformation area, but it is necessary to lower the bottom of river/stream under the object to get rid of the bayou, which is formed many kilometres ahead of the bridge.

3 Examples of technical solutions

3.1 Bridges with free span, indirect foundations

Many older bridges have foundations on stilts or wells. This is due non-bearing and plastic ground in river channels. Stilts are very weakly reinforced. Wells consist of rings lying on top of each other, not connected monolithically. In both solutions, these elements work similarly - they are practically unable to transfer horizontal forces.

Fig. 1 shows a two-support structure, the span is separated from supports, based on bridge bearings. This is a construction scheme popular in the 50-60's of the 20th century, willingly implemented in the case of small bridges in mining areas ([6], [7]).

Another popular constructional solution for bridges at mining areas is the static scheme of a freely supported beam ([5], [6], [7]).

The examples given below apply to the two-support structure, but similar solutions can also be used in the case of bridges with a freely supported beam scheme and classic reinforced concrete abutments.

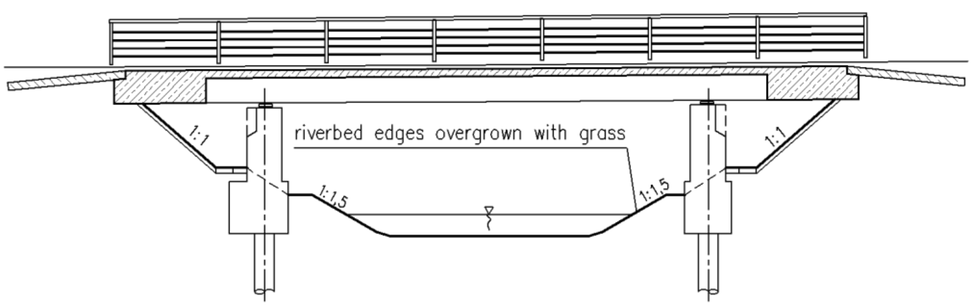

Fig. 1. Two-support bridge based on foundation stilts – state before lowering the bottom of riverbed

Lowering the riverbed means removing part of the ground between the supports.
This action does not change the limit states regarding the bearing capacity of the ground substrate and subsidence of supports. However, the distribution of horizontal forces in the ground is changed. The removed part of the ground gives resistance, so-called passive pressure, described in Poland for many years by the formula (1). It is advisable to use such construction solutions that ensure the transfer of this additional horizontal force. Failure to transfer this additional force may lead to the destruction of stilts or foundation wells and loss of stability of the support for horizontal displacement. Significant stiffening and lowering of the edge of the ground resistance from the side of the river bed, e.g. as a result of building rigid strut of supports, reduces so-called "axes of rotation" of abutment and may lead to uncontrolled rotation/inclination of the support towards the river as a result of loss of stability of the support for rotation. The stability of the supports for horizontal displacement and rotation is described in formulas (2), (3), where:
$e_p(z)$ – ground passive pressure (ground resistance)
K_p – coefficient of horizontal ground resistance,

$\gamma^{(r)}$ – volume load of native soil,
z_p – minimum working height of the ground in front of the wall,
Q_{tr} – design value of the horizontal force in the slide plane,
Q_{tf} – sum of projections on slip plane of all forces counteracting displacement of support,
T_w – friction force, ($T_w \approx 0{,}45 * N$; N: wall load + vertical ground pressure on foundation),
M_o – moment of all design forces causing wall rotation (active ground pressure)
M_u – moment of all design forces counteracting wall rotation

$$e_p(z) = \gamma^{(r)} \cdot z_p \cdot K_p \quad (1)$$

$$Q_{tr} \leq 1{,}2 \cdot (Q_{tf} + T_w) \quad (2)$$

$$M_o \leq 1{,}3 \cdot M_u \quad (3)$$

In the case of a slight lowering of the river bed, for example mesh-stone mattresses can be used to protect the soil-ground against washing away.

In the case of considerable lowering, when it is necessary to descend with the bottom of riverbed below the stilts or foundation wells, the bridge supports can be protected by an additional rigid reinforced concrete kinetics which transfers horizontal forces and secures the foundations from being washed away and undermined (Fig. 2).

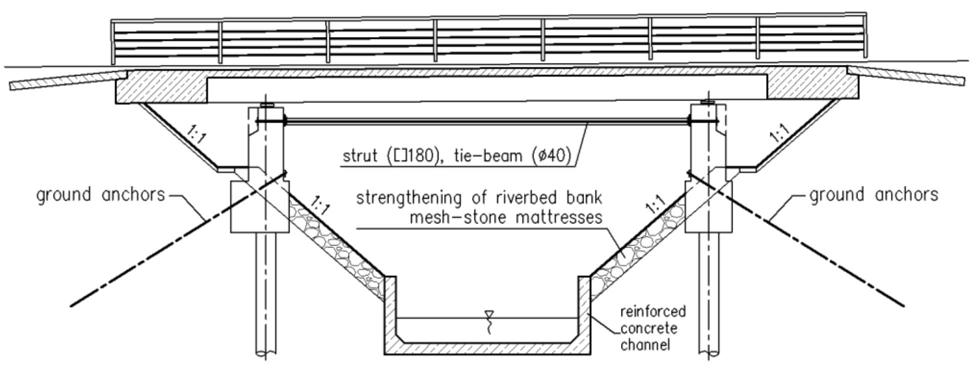

Fig. 2. Bridge based on stilts. Considerable lowering the bottom of the channel

In order to protect the stability of supports, struts are often used. The strut may be, for example, a steel pipe or two welded C-beams (Fig. 2). The strut absorbs the forces from ground pressure on abutment wall, ensuring adequate stability for horizontal displacement. The compressive force in the strut is equal to the pressure of the passive part of the soil removed from the riverbed. In addition, the strut force applied high relative to the axis of support rotation provides stability to the support for rotation/inclination.

In the case of mining areas, as a result of mining stretching, the strut may stop working. In this case, tie-beam (pre-tensioned: tie rod or steel bar) should be making inside the strut to ensure constant pressure of strut to the support surface. Tie-beam can be anchored in the support. Such construction blocks the displacement of supports on the both directions of the bridge axis. During the design of the strut and tie-beam, on the mining areas, additional forces due to the active pressure resulting from mining surface deformations ε, i.e. mining compression/stretching, must be taken into account. Additional active pressure resulting from surface deformations ε for typical bridgeheads, surrounded by non-cohesive soil, can be estimated by formula (4) (more accurate formulas and analyzes are e.g. in the publication [4], [5]), where:
p – active pressure from surface deformationε,

E – soil compressibility module,
ε – 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 (i.e. foot, top plate of piles) to the span.

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

As an alternative for strut and tie-beam, ground anchors can be used. A significant force is applied in the anchorage, which forces the anchored element to the ground. On mining areas, ground anchors should be designed taking into account shortening/lengthening of the area ε. As a result of mining stretching, the soil-ground behind the bridge abutment loosens, the anchorage of the ground anchor may not be effective. In the case of compression of mining area, the soil-ground behind the bridgehead is also compressed, the distance of the anchor from the abutment wall decreases and the anchoring force decreases.

The above problems can be avoided by designing the reinforcement of the channel so that the passive resistance from the ground in the riverbed does not change. It is necessary to make a heavy, massive reinforced concrete channel (Fig. 3). Such a reinforced concrete channel is usually made of prefabricated elements, so the large mass and size of prefabricated elements is a significant hindrance. Additionally, a temporary strut is needed, which takes over horizontal forces during construction works. Such strut reduces the work space. In the solution shown in Figure 2, the temporary strut is not necessary if the final target strut or ground anchors are made before the lowering of riverbed bottom.

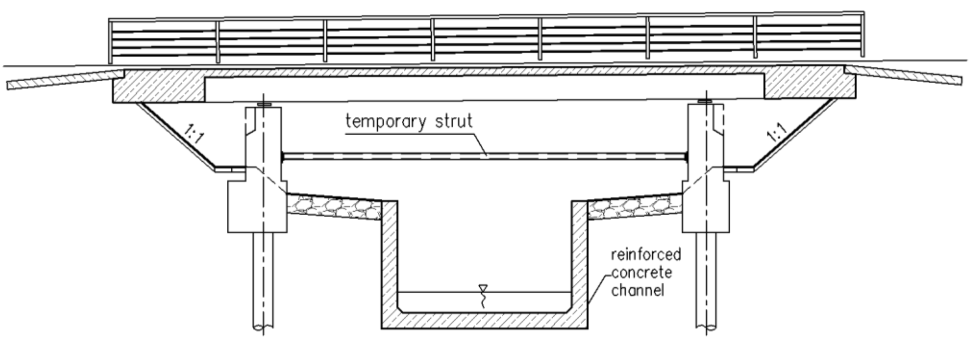

Fig. 3. Bridge on stilts. Considerable lowering and full reinforcement of the bottom of the channel

3.2 Bridges with direct foundations, open frames

Smaller bridges have often foundations set directly on the ground. Bridges up to a length of about 14 m are often rectangular frames. This solution was popular especially in the 1950s and 1960s because it significantly limited the consumption of reinforcing steel and concrete, which was important due to the shortage of materials and rapid post-war development of Poland. The structure with a static schematic of a rectangular frame additionally allowed to get rid of, among others bridge bearings and in a simple way stabilize abutments (e.g. [9], [10]). Frame bridges reinforced with a small number of steel bars have low resistance to mining influences (e.g. [5], [6], [9], [10]). Such objects are often located in Silesia outside the mining area, on watercourses flowing from the mining area.

As in the case of bridges with intermediate foundations (stilts, wells) in the case of a slight lowering of the riverbed bottom, horizontal force equivalent to the resistance (passive pressure) of the removed part of the ground may be taken over by ground anchors. In the case when it is necessary to lower the bottom of the riverbed below the footing level, the use of mesh-stone mattresses, such as shown in Figure 2, may lead to extrusion of soil from under the foundation. Analogous to bridges with freely-supported spans, frame object is protected by making a rigid reinforced concrete channel transferring horizontal forces and protecting foundations against washing away and undermining (Fig. 3). Alternatively, using a solution similar to that shown in Fig. 4, it is possible to design a high, massive reinforced concrete channel, so that the passive resistance from the ground does not change.

Framework structures (especially the old bridge with a very small number of reinforcing bars) are easier to damage than freely-supported spans. In the case of ineffective transfer of horizontal forces, caused by lack of resistance (passive pressure) from the removed soil, the frame may crack and become irreparably damaged. (Bridges with free-supported spans can also be damaged, expansion joints can be jammed, but dilatation can be reproduced, e.g. by moving the backwall of the abutment, e.g. [11]).

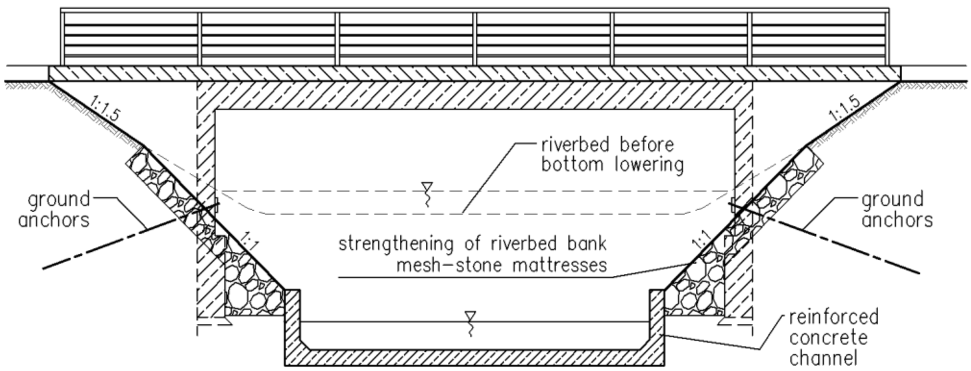

Fig. 4. Bridge based directly. Considerable lowering the bottom of the channel

3.2 Frame with bottom plate

Bottom plates in the case of frame bridges greatly hinder deepening of the riverbed. Bridges with a bottom plate are reinforced concrete structures with a span length of 6÷10 m. Such bridges were popular before the Second World War and in the 1950s, 60s and 70s of the last century. Considerable surface of the bottom plate had a positive effect on the value of stresses in the foundation level, which allowed on shallow, direct foundation of such structures and significantly reduced the requirements for soil-ground parameters.

The bottom of the channel can not be lowered without removing the fragment of the bottom plate, but this bottom plate is an important structural element of the bridge. It is technically possible to cut out a fragment of a bottom plate, but it requires a reliable computational analysis, because the distribution and values of internal forces in the structure change considerably, and the bridgeheads become independent elements/solid which can move relative to each other [2]. It is necessary to make a rigid concrete strut that will take over the horizontal forces resulting from the pressure of the ground on the face walls of the abutments (Fig. 5). This strut should be designed to protect abutments from washing away and undermining.

The cut out of fragment of bottom plate changes the distribution of bending moments in the structure, the bridgeheads are able to rotate with respect to the plate edge (the axis of rotation is created), generally the stability of the abutments per revolution is insufficient in such situations. The ground anchors are an effective solution - the horizontal force applied above the level of foundation on a certain arm in relation to the axis of rotation located on the edge of the cut bottom plate should ensure for bridgehead suitable receiving moment, thus ensure stability for rotation [2].

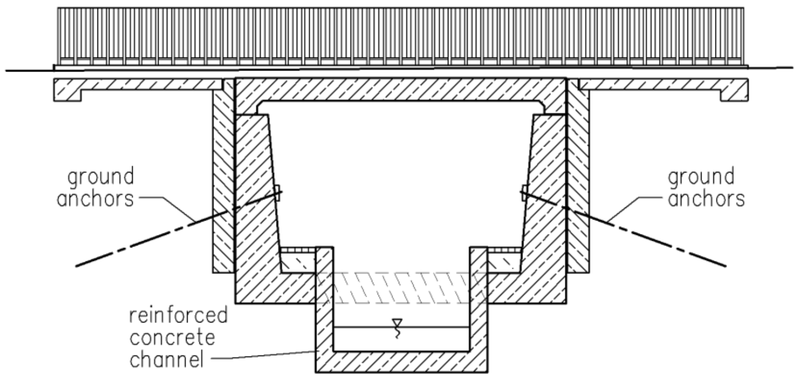

Fig. 5. Bridge with reinforced concrete channel cut out in the floor bedplate

The surface of the foundation is reduced as result of removal of a part of the plate - so the bearing capacity of the ground should be checked and, if necessary, the micropiles should be used under the remaining part of the bottom plate. Micropiles can be made by drilling holes through the bottom plate, which minimizes the interference in the foundation (e.g. there are no excavations). Micropiles can be made directly in the riverbed. The apply of light equipment allows implement of this technology in places where it is impossible to use classic stilts or sheet pilings due to difficult access or limited space under the bridge.

4 Summary and additional remarks

Several examples of technical solutions regarding the adjustment of bridges to the lowered bed of rivers and streams are described in this article.

Particular attention is paid to the problem of ensuring adequate stability of supports and protection of supports against washing away and undermining. It should be noted that the level of the bottom of the watercourse after lowering it can be considerably below the level of foundation footings or top plate of piles.

The adaptation of the existing bridge requires identification of the foundation as well as ground conditions and reliable analysis, because incorrect solutions can lead to damage of bridge and construction failure. Current technical condition assessment of the bridge structure is always necessary. The specificity of mining areas should also be taken into account, i.e. ε - shortening/lengthening (compression/stretching) of the area.

In the case of complicated technical solutions, significant forecast mining deformations, difficult ground and hydrological conditions, a good solution is continuous, remote monitoring of the riverbed condition (e.g. [12]) and displacements of selected bridge elements (e.g. [13], [14]). Displacements associated with the loss of stability or washing away of the riverbed in the initial phase increase slowly, monitoring allows identifying the displacements and rotations of the bridge elements before the bridge will be damaged.

Adaptation of existing bridge structures to a reduced river bed is economically appropriate, the cost is many times smaller than the replacement of the object with a new one. It is easier and faster to obtain the necessary permits and formal and legal decisions, there are no problems arising from the closure of the bridge for traffic, because the object can be normally used during conducting adaptation work.

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