THE INFLUENCE OF BACKFILL QUALITY ON SOIL-STEEL ARCH BRIDGE DEFORMATION

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SUMMARY

Subject of the article is a three-dimensional numerical analysis of the impact of backfill quality on the deformation of soil-steel arch bridges. Three different backfill types were taken into consideration in numerical analysis. Calculations were performed with the use of Abaqus programme based on finite element method (FEM). A steel arch shell was modelled with the use of theory of orthotropic plates, and backfill with the use of elastic-perfectly plastic Drucker-Prager model. Numerical calculations were made for the soil-steel arch bridge with a span of 12.315 m and height of shell of 3.555 m. Soil cover over the shell crown is equal to 1.0 m. The main aim of this paper is to present the impact of quality of backfill (internal friction angle, unit weight, Young's modulus) on the effort of the steel arch shell. The obtained FEM results were compared with the results of experiments. Conclusions relate mainly to evaluation of the impact of backfill quality on the effort of steel arch shell and giving parameters that are of utmost importance.

Keywords: *Soil-steel arch bridge, backfill, displacement, stress, load.*

1. INTRODUCTION

Structures from corrugated steel plates (CSP) have recently gained popularity in the transport engineering as an alternative for typical bridge solutions. These structures are called also the soil-steel bridges. The main reasons for usage of these structures are relatively low costs and short construction period [1]. The bearing element of these structures is the soil-steel composite system which uses arching of the load in soil and interaction between flexible steel shell and backfill [2].

Backfill is the key element in these structural solutions. Therefore, it was decided to analyse the impact of the chosen backfill parameters on deformations (displacement and stresses) of soil-steel bridge. Selection of soil (backfill), which have proper characteristics and its appropriate arrangement and compaction play a key role in achievement of required load carrying capacity of that type of bridges. In general, the used soil should be water-permeable, free from grittiness and frozen ground, with uneven graining, well compactable, non-aggressive, and free of organic elements.

Experimental studies and numerical analyses of soil-steel bridges under static and dynamic live loads [3], [4], [5], [6], [7] were carried out repeatedly. Numerical analysis were also conducted and many problems were noticed, mostly in the range of modelling of backfill and steel shell.

Generally, the calculation results obtained by use of the computational models in comparison with the experimental results are insufficiently satisfactory, therefore further numerical analyses of soil-steel bridges are needed. In addition, the role of backfill quality seems to be an important element for the soil-steel bridges safety therefore the analyses in that regard should be also conducted.

The main aim of this paper is to present the influence of backfill quality (internal friction angle, unit weight, Young's modulus) on the effort of the shell in soil-steel bridge. Calculations were performed with the use of Abaqus program based on FEM. Static live loads according to three various scenarios were applied during numerical analysis like during experimental tests [8]. A steel shell was modelled with the use of theory of orthotropic plates. This approach was caused a decrease in complexity of steel shell model, because the main aim of this paper is to assess the influence of the backfill quality on the bridge deformations. Backfill was modelled with the use of elastic-perfectly plastic Drucker-Prager model. The obtained results were compared with the experiments results. Final conclusions relate mainly to evaluation of the impact of backfill quality on the effort of shell and giving parameters that are of utmost importance. Also reasons for the differences in calculation and experimental results were given.

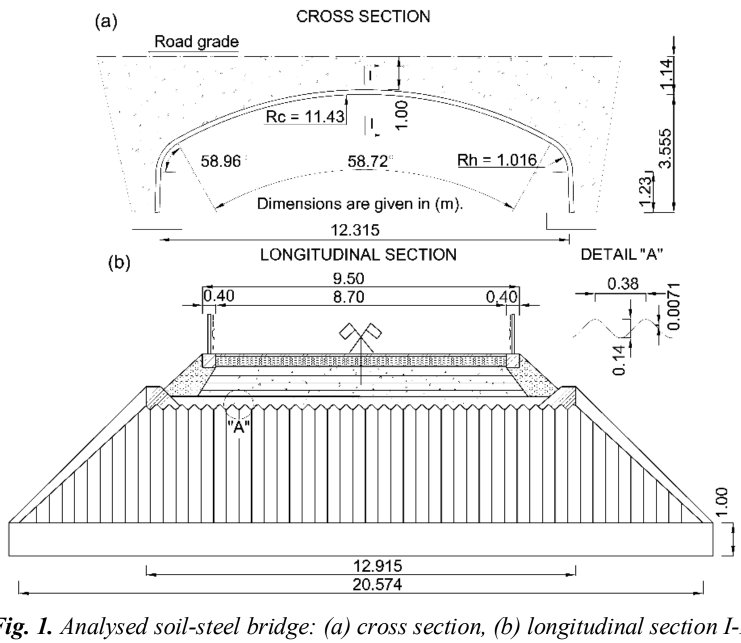

Fig. 1. *Analysed soil-steel bridge: (a) cross section, (b) longitudinal section I-I.*

2. DESCRIPTION OF SOIL-STEEL ARCH BRIDGE

Analysed structure is an arch bridge composed of shell with corrugated steel plates backfilled with soil. The road bridge has a single shell span with effective length of 12.315 m connected rigidly with a RC continuous footing (Fig. 1). The width of the shell at the top is 12.915 m, and at the bottom is 20.574 m. Radiuses of curvature of shell are as follows R_c = 11.43 m for crown and R_h = 1.016 m for haunches. In the plan view, the object is situated perpendicularly to the river current, and the vertical rise of bridge shell amounts to 3.555 m. The shell was covered with the layers of water-permeable soil (0.20–0.30 m thick and graining of 10–32 mm) properly compacted (to reach density index 0.95 for the soil connected directly with the steel structure and 0.98 for the remaining part of the backfill), allowing pavement to be laid on broken stone base. The thickness of the soil cover in the crown (backfill, road foundation and asphalt) is equal to 1.0 m. The load bearing structure was constructed as a shell assembled from the sheets of corrugation of 0.14×0.38 m and plate thickness of 0.0071 m, connected together using high strength bolts M20 (class 8.8) tightened with twisting moment of 350–400 Nm. The bridge has been designed to transfer loads in accordance with [9], what compared with the Polish Bridge Standard [10] corresponds to a Class A. Structural steel with strength corresponding to that of Polish steel S315MC (the guaranteed yield strength of the steel used to manufacture corrugated plates was 314 MPa) was used. A detailed description the bridge is shown in [8].

3. NUMERICAL MODEL DESCRIPTION

For computations of soil-steel bridge, the Abaqus/CEA ver. 6.11 [11] was used, based on the FEM [12]. In the numerical model efforts were made to reflect the actual geometry of the analysed bridge, while not taking into account the secondary elements that may affect the increasing complexity of model and considerably extended time for computation. Three numerical models of soil-steel bridge with different parameters of backfill were developed. Other parts of the bridge were all the same in each numerical models. Due to the complex shaped structure, a numerical models were slightly simplified, although main parameters of the bridge (height and span of steel shell, top shell length, various radiuses of shell, soil cover in shell crown) were maintained. Elements, such as slopes, RC collars reinforcing inlet and outlet of the shell and guardrails were neglected in the model.

Soil-steel bridge calculations under static live loads were performed in 3D. Non-linearity in computational models has been addressed by using incremental analysis – the Full Newton method [11]. Soil-steel bridge models are parts of the 3D space, which are in the dimensions of 16.32×9.50×4.70 m. In each calculation models, nodes have six degrees of freedom (U1, U2, U3 – displacement directions on the axes OX, OY, OZ, and UR1, UR2, UR3 – rotation directions relative to the axis OX, OY, OZ, respectively), wherein nodes of elements with their edges laying on external surfaces of the numerical model are blocked at all degrees of freedom – rotations and displacements (total restraint).

3D shell tetrahedral elements (S4R) were used to model a steel shell. The remaining units (backfill and roadway layers) are defined as elements with properties of a solid (C3DR8). The material parameters were chosen based on available technical data (the bridge elements and asphalt properties obtained from the producers of such materials and the backfill obtained from the project of this bridge) and material characteristics included in the Abaqus software, that are:

- CSP shell was modelled as a flat with appropriate parameters of orthotropic shell using the following Eqs. (1)-(4):
  - equivalent thickness of plate:

$$t_{equ.} = \sqrt{12\frac{I}{A}} \tag{1}$$

where I – moment of inertia (2.416e-8 m^4/m); A – cross-sectional area (9.81e-6 m^2/m),

- equivalent elastic modulus of material (Young modulus) in circumferential direction of bridge shell:

$$E_{x\,equ.} = 12\frac{EI}{t_{equ.}^{3}}, \tag{2}$$

where E – a Young modulus of steel structure assumed as 210 GPa,

- equivalent Young modulus in longitudinal direction of the bridge shell:

$$E_{y\,equ.} = E\left(\frac{t}{t_{equ.}}\right)^{3} \tag{3}$$

where t – a plate thickness (0.007 m),

- shear modulus for the corrugated steel plates is different in different directions. In this paper, an average value for the equivalent shear modulus is used based on the below Eq. (4):

$$G_{equ.} = \frac{\sqrt{E_{x\,equ.}\,E_{y\,equ.}}}{2\,(1+\nu)} \tag{4}$$

where ν – Poisson ratio ($\nu = 0.3$).

Table 1 presents the equivalent parameters of corrugated plate used in the numerical analysis. Plate elements were defined as an elastic-plastic material with a density γ = 78.5 kN/m^3 and yield strength σ = 314 MPa. In this case, adopted curvature control accuracy was 0.01 m, due to the complexity of shell itself and its curvilinear shape. The bolt connections between the steel plate elements were omitted during modelling. Parameters of steel shell were the same in all analysed computational models.

Table 1. *Orthotropic properties of the corrugated steel plate shell.*

Element	**Equivalent thickness of plate**	**Equivalent Young modulus in direction:**		**Equivalent shear modulus**
		circumferential	**longitudinal**	
	$t_{equ.}$ **[m]**	$E_{x\,equ.}$ **[GPa]**	$E_{y\,equ.}$ **[GPa]**	$G_{equ.}$ **[GPa]**
Shell structure	0.172	11.94	0.0142	0.158

Table 2. *Variables of backfill parameters used for numerical calculation of soil-steel bridge.*

Numerical model	**Angle of internal friction [°]**	**Unit weight [kN/m³]**	**Young modulus [MPa]**	**Soil condition [density index according to [13]]**
I	45	19	80	Dense (0.98)
II	40	18	70	Medium dense (0.90)
III	35	21	90	Loose (0.80)

- backfill (medium size sand) with thickness of 0.50 m (over the crown shell) was defined as elastic-plastic material with the hyperbolic Drucker-Prager yield criterion with parameters presented in Table 2 for three numerical models. In addition, dilation angle α = 5°, cohesion and initial tension equal to 0 MPa were taken into consideration. Furthermore, application of the Drucker-Prager model required determining the size of soil reinforcement, due to the fact that the effect of cohesion on the soil behaviour was eliminated. For this purpose, a parameter describing the soil reinforcement in compression was used, by fixing its size to 5 MPa.
- road structure (crushed stone) with thickness of 0.36 m was defined as elastic-plastic material (solid-type element) with the hyperbolic Drucker-Prager yield criterion with density γ = 18.0 kN/m^3, Young's modulus E = 60 MPa, angle of internal friction ϕ = 40°, dilation angle α = 10°, and initial tension equal to 0 MPa. As in the case of basic backfill model, Drucker-Prager model-type reinforcement was applied, determining soil reinforcement parameter under compression equal to 5 MPa.
- roadway layer (asphalt with thickness of 0.14 m) was modelled as an elastic material (solid-type element) with density γ = 21.0 kN/m^3, Young's modulus E = 6.9 GPa and Poisson's ratio ν = 0.41.
- boundary conditions: total restraint was applied, namely rotations and displacements along each axis of the shell's sides and base were blocked. The soil-steel bridge was modelled as a structure firmly embedded in the environment. This is because, that the lateral earth pressure phenomenon at each direction of displacements and the rigid support of the shell on massive foundations were occurred.
- calculation step was defined as $T = t + \Delta t$, where t is the initial time equal to t = 0 s, while Δt is time increment, during which the set static live load is applied, according to the three schemas used during experimental tests [8]. Accordingly, Δt equals to the time in which load in applied, and it is usually adopted in the value of 1 s. In calculation step (T = 1 s), successive iterations for increments caused by load being applied at that time, and their effect on the soil-steel bridge behaviour are computed.
- interactions at the interface of materials being interconnected (steel shell–backfill, backfill–crushed stone, crushed stone–asphalt) were modelled as rigid elements of the beam transferring their specific types of interactions from master to slave surfaces. These elements analyse phenomena occurring in the time of interaction between two materials, that is normal forces (rigidity) and friction forces (friction coefficient). The dependency of master and slave contact surfaces were determined based on the modulus of elasticity of materials being in contact with each other (interaction) and the nature of the soil-steel bridge behaviour. Slave was a surface build of the material with lower modulus of elasticity (Young's modulus), and the surface with higher modulus of elasticity was described as master. In numerical model, three types of contact areas (asphalt–crushed stone, crushed stone–backfill and backfill–CSP) were identified. Crucial element, distinguishing this type of interactions from others, is the smooth surface of the shell, which implies lower friction coefficient. Therefore, following friction coefficients were adopted: for backfill–CSP shell contact surface in the value of 0.3 and for other surfaces of

0.6. However, connection rigidity was established at the level of 2 GN/m – for backfill–CSP shell contact surface and 2 GN/m – for other surfaces.

4. 3D ANALYSIS OF THE ARCH BRIDGE

4.1. Results of numerical calculations

During numerical calculations of the soil-steel arch bridge the same loads were used (concentrated forces coming from the vehicle with a weight of 255 kN), which were used during the experimental study of bridge under static live loads [8]. Selected results of numerical calculations were presented in the form of maps of displacements and stresses (Fig. 2). Maximum displacement values were 3.02 mm and were obtained in the shell crown of bridge for numerical model III (static live-load scheme C). In case of numerical models I and II (load scheme C), the maximum displacements of soil-steel bridge were equal to 2.91 mm and 2.59 mm, respectively. Maximum displacements occur at the location where the load from the rear wheels of the vehicle has been applied (in those places there are much greater displacements than in other parts of the bridge structures). In load schemes A and B the largest displacements of the culvert were also obtained for the numerical model III.

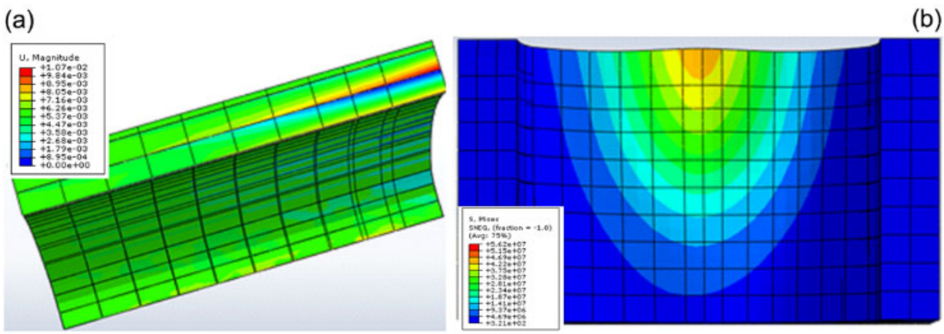

Fig. 2. *Calculation results from live-load scheme C for numerical model III: (a) displacements distribution and (b) stresses in bridge shell.*

Maximum stresses (about 10.3 MPa), as in the case of displacements, were obtained for the numerical model III from the static live-load scheme A and C. In numerical models I and II, the highest stresses in the steel shell of the bridge amounted to 9.03 MPa and 9.88 MPa, respectively. Maps of stresses show clearly that the greatest values were obtained in application points of rear wheels (axes) of the loading vehicle, i.e. in the shell crown of bridge. This is also reflected in the results of experimental studies [8].

4.2. Analysis and discussion of results

Comparison of the calculated displacements and stresses for individual numerical models (types of backfills) is shown in Fig. 3 and 4. Figures also show course of the experimental curves (maximum displacements and stresses). The impact of backfills used to effort of the steel shell can be observed on them.

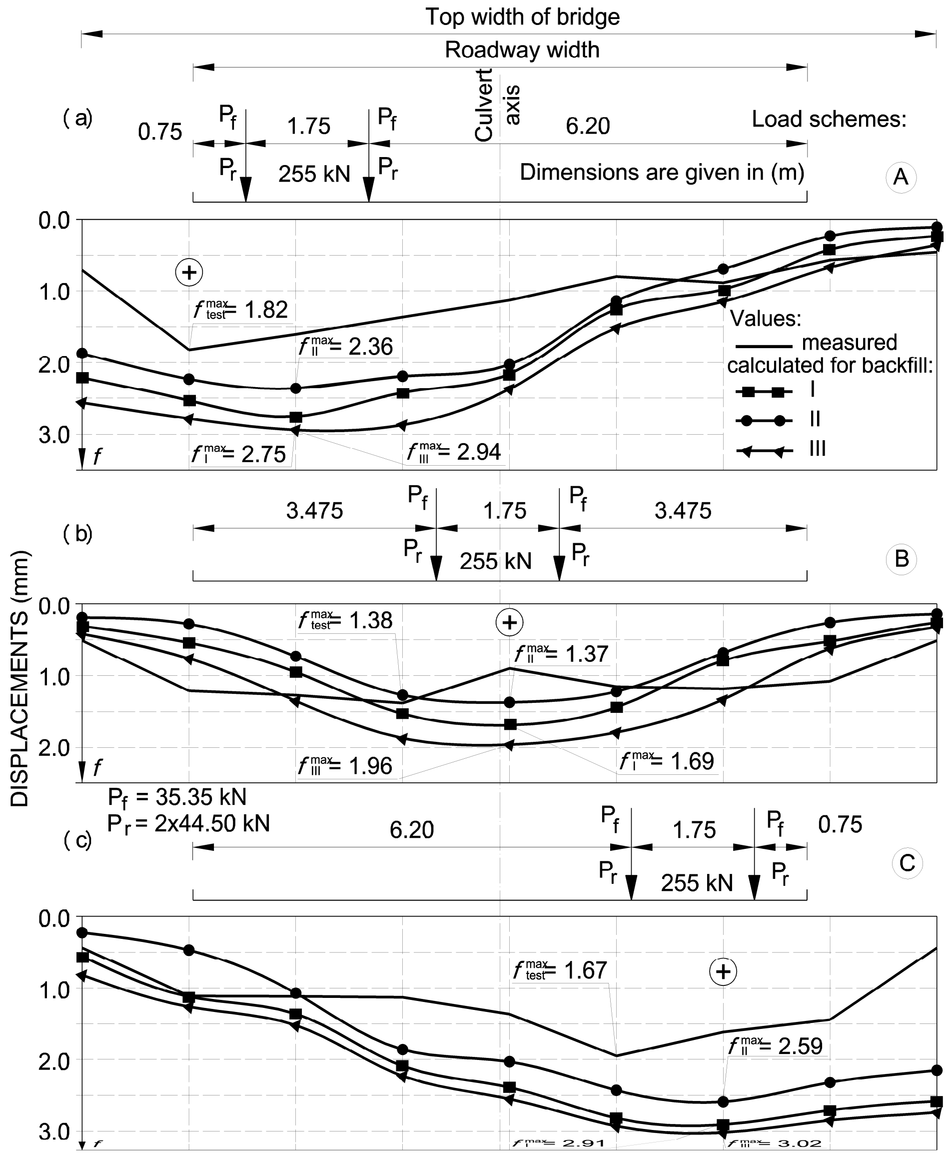

***Fig. 3.** Displacement courses at the bridge crown for three backfill types and three static live-load schemes.*

As visible in Fig. 3, the calculated displacements of soil-steel bridge with the use of Abaqus program for three types of backfills are similar to each other (shape of the curves is similar). However, they are generally higher than the measured values. It's an evidence of similar behaviour of structure and method of distributing loads by different but similar backfill parameters. It has been noted that the maximum displacement from the experimental studies was obtained at other points than in case of numerical calculations. This may indicate some heterogeneity in the actual bridge, e.g. in the backfill and at the joints of sheets of corrugated plates (possible gaps). Additionally, in numerical calculations, the existence of a uniform backfill and no connections between the sheets have been assumed. Relative differences between calculated and measured displacements for different numerical models were in the range: I (18–43%), II (1–36%) and III (30–45%). It should be noted that the best compliance of calculated and measured values was obtained for numerical model II and live-load scheme B.

Results and shape of displacement curves from live-load schemes A and C are generally similar. In case of load scheme B (vehicle positioned in the centre of the road) much smaller displacement values can be observed (54-89%) than for schemes A and C (despite the use of the same loading vehicle). In this case it has been noted that the course of displacements is more uniform across the width of the bridge (no sudden leaps of value). Behaviour of the soil-steel bridge caused by the schemes A and C clearly shows that side parts of the shell structure of the bridge have much higher deformations than in case of effect of a vehicle positioned according to the load scheme B. This indicates the lower rigidity and interaction backfill-shell at the ends of the bridge, and at the same time, a better load distribution in the soil in the middle of the bridge (load scheme B). Therefore, it seems logical and justified to use additional reinforcements at the beginning and end of the bridge. The most similar values of calculated displacements to the measured were obtained with the use of numerical model II. Thus, the relative differences of calculated displacements with the use of numerical models I and III in relation to the model II were accordingly in the range (11-23%) and (14-30%).

Fig. 4 shows values of stresses in characteristic points of the structure (in which measurements were also taken) for three types of backfill calculated in Abaqus program. In this case the influence of backfill parameters on the effort of shell of soil-steel bridge is also visible (similar shapes of courses). It was noted especially that maximum calculated stresses in the bridge shell crown are smaller than the measured values, but it should be noted that the width of the bridge - y-axis (beyond the immediate range of the load action) measured values are lower than the calculated ones (particularly for scheme A and load C – Figs 3 and 4). The greatest stresses occurred directly beneath the concentrated forces constituting pressures of the tires. Fig. 4 also shows that the maximum stresses were obtained from asymmetrical live-load schemes A and C. This may be caused by some heterogeneity and lower rigidity at the ends of the bridge (similar tendencies were obtained in case of displacements). Furthermore it is visible that vehicle position according to the scheme B (in the middle of the road) results in a rather uniform load distribution. This indicated involvement of a greater width of the soil-steel bridge into interaction in the transfer of a given live load.

Additionally, it can be seen (like displacement) that the distribution of calculated stresses is gentler (no sharp bends) than in case of measured values. Relative differences between calculated and measured stresses for different numerical models were in the range: I (27–37%), II (33–47%) and III (21–34%). The most similar values of calculated stresses to the measured were obtained with the use of numerical model III (for maximum values). However, taking the entire width of the bridge into account (Fig. 4), the numerical model II appears to be the most favourable. Thus, the relative differences of calculated stresses with the use of numerical models I and III in relation to the model II were accordingly in the range (8-15%) and (12-19%) for the benefit of model II.

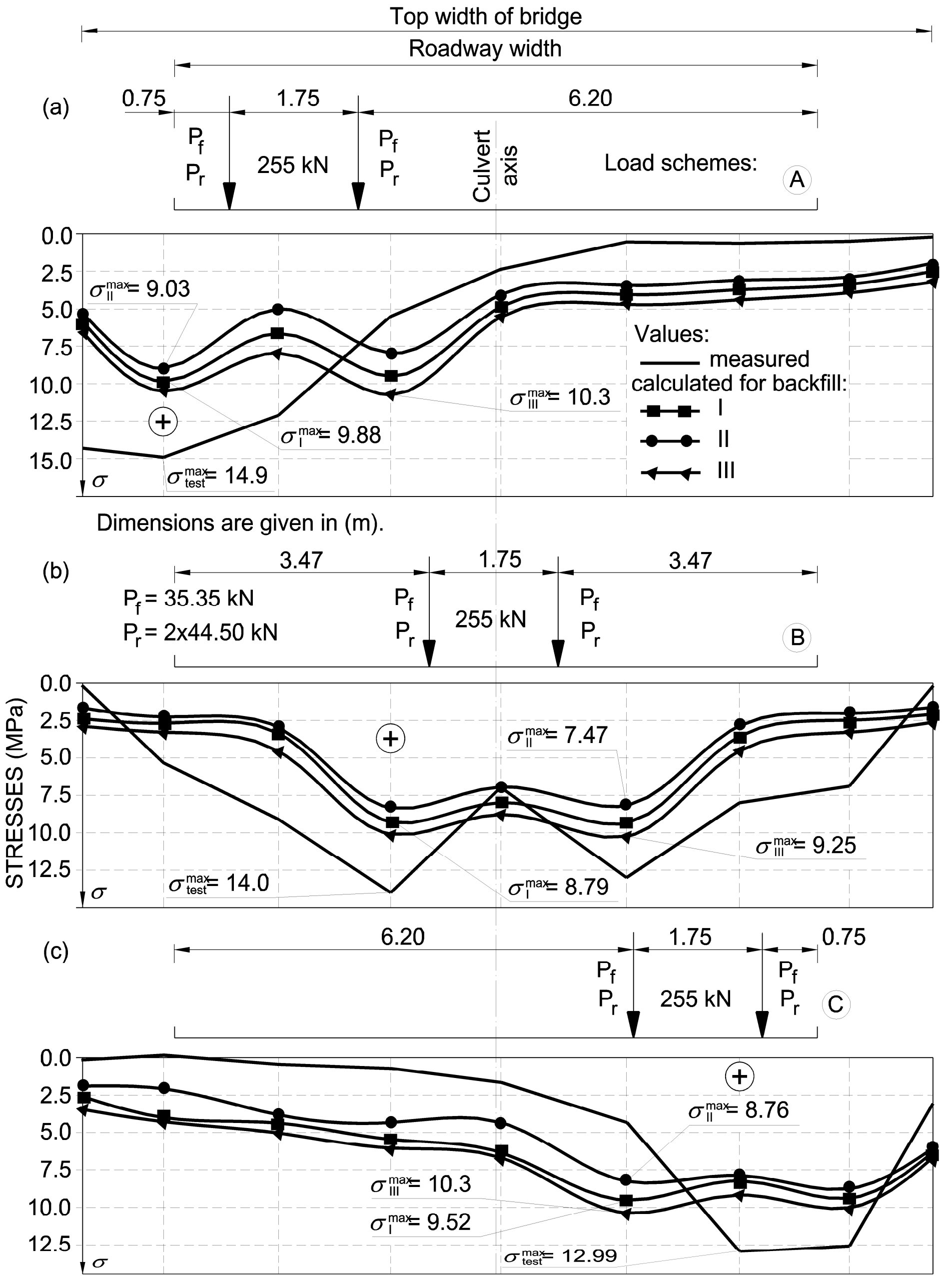

Fig. 4. Stresses courses at the crown of bridge shell for three backfill types and 3 static live-load schemes.

The smallest displacements and stresses in the shell of soil-steel bridge were obtained for the numerical model II (Fig. 5). In this model the backfill parameters were as follows: angle of internal friction 40°, unit weight 18 kN/m^3 and a Young's modulus 70 MPa. It was noted that among the selected parameters of backfills in all analysed numerical models, the angle of internal friction seems to have the greatest influence on the size of displacements and stresses of the bridge. This shows that for the considered parameter ranges of backfill, the effect of the Young's modulus is not a key parameter to reduce the deformation of the bridge. However, it can be assumed that there is a limit of Young's modulus values, below which deformations of the bridge would increase significantly. It also follows that the compaction degree of backfill (directly dependent on the angle of internal friction) is an important parameter. Although for the angle of internal friction equal to 45° the smallest values were not obtained, at the value of 35° the greatest deformations of the bridge have been noted. In addition, it should be noted that the angle of internal friction is a parameter of shear strength of the soil. It was also observed that, together with decreasing of angle of internal friction and increasing, the unit weight and Young's modulus of the backfill (Table 2) displacement and stress of the bridge are growing. Increasing the Young's modulus and unit weight of the backfill in numerical models does not reduce the deformation of the bridge.

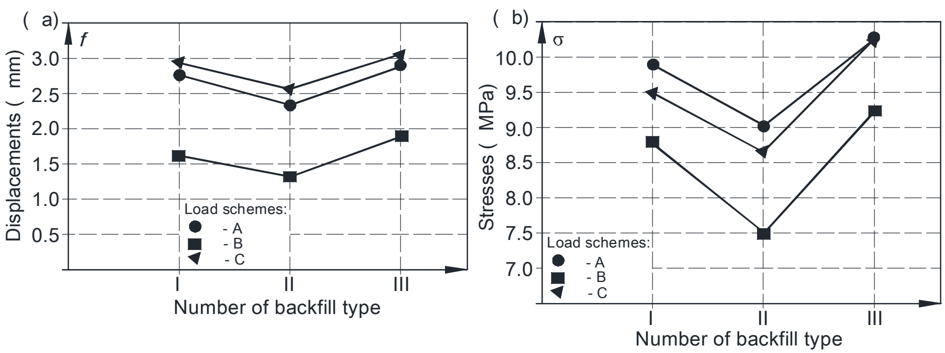

Fig. 5. *Maximum displacements (a) and stresses (b) of bridge shell for three backfill type in relation to static live-load schemes.*

In order to draw a more detailed dependence of impact of backfill quality to deformation of this type of bridge additional numerical simulations for a larger range of parameters of backfill should be carried out. It is difficult to conclude that a parameter has a decisive influence on the level of deformation of soil-steel bridge, because they are directly related. Summarizing and bearing in mind the relatively small range of variability of backfill parameters, it can be stated that the angle of internal friction plays a key role in the behaviour of soil-steel bridge.

5. CONCLUSIONS

As a result of numerical calculations of soil-steel arch bridge for selected backfills and comparison of these results with experimental values, the following conclusions can be drawn out:

1) Parametric analysis shows that the angle of internal friction is a key element in soil-steel bridge. The greatest deformations of bridge were obtained for the smallest internal friction angle (35°). It has been noted that, particularly when increasing the unit weight and decreasing in the angle of internal friction, deformation in a steel shell are growing. Increasing the Young's modulus of the backfill does not reduce the deformation of the bridge.

2) Considering the entire width of the bridge, the calculation model II was most favourable. Relative differences of the obtained values with the use of models I and III in relation to the model II were accordingly in the range (8-15%) and (12-19%) for stresses and (11-23%) and (14-30%) for displacements for the benefit of model II.

3) Calculated displacements are generally higher than measured (taking the entire width of the bridge into account), and the maximum calculated stresses are smaller than in experiments. This may be a result of the increased rigidity of calculation models of the analysed bridge than is apparent from its actual structure (e.g. the occurrence of gaps at the junctions of steel sheets and heterogeneity in the backfill). However, taking the entire width of the bridge into account (the area outside the immediate range of the load acting), measured stresses are less than the calculated (especially for live-load scheme A and C).

4) Maximum stresses (10.3 MPa) and displacements (3.02 mm) from numerical calculations were obtained in the shell crown of bridge from asymmetrical live-load schemes A and C. This shows lower rigidity and interaction backfill-shell at the ends of the bridge. Furthermore, it can be seen that the position of vehicle with the same weight according to the scheme B (in the middle of the road) results in a rather uniform load distribution. This indicates involvement of a greater width of the soil-steel bridge into interaction in the transfer of a given live load.

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