Research on the interface elements in soil-steel structures based on the in situ test

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ABSTRACT: One of the characteristic features of steel-soil structures in comparison to classical bridges is the impact of the surrounding soil and the road superstructure for its bearing capacity. In this paper based on the in-situ test it is proved that the results of analysis are sensitive of the direction of live load vehicle. For this purpose, the methodology, where the vehicles change their positions was used. Both in the test and the analysis, the full load cycle was carried out, including the drive of the vehicle in two directions, i.e. from the starting position to the turning point and back. A special feature is structure tendency to reaching the primary readings after full cycle of loading. This proves an elastic behavior of soil-steel structure, which is especially important where the one of the basic structural material is the soil (in the classical arch bridges treated as a non-structural).

1 SOIL-STEEL STRUCTURE TESTING

As one of the examples of performance of tests involving strain gauge measurements, the paper presents those performed on the test structure built in Rydzyna (Poland), shown in (Figure 1). The geometrical parameters of the perimeter zone of the shell are as follows: span $L = 17.594$ m rise $H = 5.459$ and top radius $R = 13.735$ m. The geometry of the corrugated steel plate is described by its technical designations SC 380×140×7 – SuperCor type with the dimensions: $a = 380$ mm – corrugation pitch, $f = 140$ mm – its depth, $g = 7$ mm plate thickness.

The test results presented in this paper apply to a structure in 8 years after completion of the construction but without its service. Therefore, this is an example of the structure behavior taking into account the occurring processes of soil backfill consolidation. Our load consists of a loader as shown in (Figure 1), without diggings in the bucket. Axle-loads of the loader on both axles were similar: $P_1 = 114.3$ kN (reference axle) and $P_2 = 104.7$ kN. Axle base (measured along the structure) was 3.4 m. Location of the vehicle is determined on the figures with regard to the crown point of the soil-steel structure using the x_p coordinate. The loader travelled along the longitudinal axis of the bridge in a steeping way with $\Delta x_p = 1.5$ m. The vehicle wheels were located symmetrically along the structure axis.

2 HYBRID MODEL OF THE STRUCTURE

In the case of a hybrid model, as shown in (Figure 2), the structure is divided into two sub-systems: the upper part comprising the soil backfill and road surface, and the lower one made of corrugated steel plate. A specifically modelled interface elements are used in the soil-steel

Figure 1. View of the loaded structure.

Figure 2. Example of a soil-steel composite bridge.

structures between mentioned above sub-systems. Steel structure was modelled as a orthogonal isotropic grillage as shown in (Figure 2c). In comparison to the conventional bridges, a characteristic feature consists in taking the backfill, the basic material of the structure, as a structural element. For this model, mapping of the interface layer between the soil backfill and the steel structure is of particular importance. Mutual interactions in the layer in question are the basis for the analysis presented in this paper.

3 INTERNAL FORCES

In this paper the internal forces are taken directly from the strain gauge measurements. Electrical resistance strain gauges were fixed to the surface of the corrugated steel plates

(accessible from the inside) within the structure periphery. In every measurement section, the gauges were applied in pairs, in the crest and valley of the corrugation, around the structure periphery as shown in (Figure 3b). This layout of gauges and assumption of flat cross-sections makes it possible to determine the normal force according to the following formula:

$$N = EA \cdot \varepsilon = EA \frac{\varepsilon_D(f - g) + \varepsilon_g(f + g)}{2f} \quad (1)$$

The formula (1) includes the geometry of the corrugated steel plate as shown in (Figure 3b). In order to determine the curvature change κ and the structure radius ρ , geometrical relations of the steel plate can be used with ε_D and ε_g , and then the bending moment can be calculated according to the formula:

$$M = EI \cdot \kappa = EI \frac{\varepsilon_g - \varepsilon_D}{f} \quad (2)$$

Both formulas include the stiffness of the cross-section EA and EI .

Figure 3a presents the distribution of interactions $p(s)$ and $t(s)$ along the length of the analysed structure periphery. The pressure $p(s)$ is applied radially, i.e. in accordance with the radius R . The functions of internal forces $N(s)$ and $M(s)$ directly give the normal interactions:

$$p(s) = \frac{d^2 M}{ds^2} + \frac{N}{R} \quad (3)$$

and the tangential interactions, distributed along the structure periphery:

$$t(s) = \frac{dN}{ds} + \frac{dM}{ds} \frac{1}{R} \quad (4)$$

When using a differential approach to determine the normal interaction forces $p(s)$, the following formula (3) can be used:

$$p_j = \frac{1}{c^2} (M_{j-1} - 2 \cdot M_j + M_{j+1}) + \frac{N_j}{R} \quad (5)$$

Figure 3. Distribution of contact forces between two adjacent subsystems (steel structure and surrounding soil).

Figure 4. Layout of measurement points of the shell's periphery. Individual stages of loading.

Tangential interactions calculated according to the formula (4) are included in the equation:

$$t_{ij} = \frac{1}{c} \left[(N_i - N_j) + \frac{1}{R} (M_i - M_j) \right] \quad (6)$$

Due to the calculation method, this is a mean value between the measurement points around the periphery. In both formulas, c is the distance between the measurement points.

4 MEASURING BASE

The strain gauge layout along the periphery of the shell is presented in (Figure 4). Therefore, the measuring system is not regular but symmetrical in relation to the crown point. The distances between the points located near-crown are $c = 1.202$ m. When the point layout is irregular and the length of the preceding section is $c \cdot \Delta = 1.202 \cdot 2.88 = 3.462$ m, then the derivative of the bending moment is calculated according to the formula (5) in the differential approach is included in the following equation:

$$\frac{d^2 M}{ds^2} = \frac{2}{c^2(1 + \Delta)\Delta} [\Delta \cdot M_{i-1} - (1 + \Delta)M_i + M_{i+1}] \quad (7)$$

where $\Delta = 3.462/1.202 = 2.88$. The section with the length $c \cdot \Delta$ is located from the $i+1$ point, where length of the opposite section ($i-1$) is c .

5 CONTACT INTERACTIONS

Figures 5 and 6 present the changes in contact interaction components: normal p and tangential t . The horizontal axis of the diagrams specifies the value of x_p as the distance of loader axle as the force P_1 from the structure crown point. The legend to the diagrams marks the curves plotted from the loader back (W) and forth pass (P). In both passes, the location of the vehicle is exactly the same in each position marked with x_p . The measurements started and had been finished at $x_p = 21$ m. At $x_p = -9$ m the passing direction was changed. Characteristic vehicle locations are:

Figure 5. Normal interactions in the structure crown point area. a) intermediate point 4, b) structure crown, point 5.

- $x_p < L/4 = 4.4$ m, where contact interactions increase;
- $x_p = 0$, where the loader axle P_1 is above the structure crown point;
- $x_p = -1.7$ m, where the vehicle axles P_1 and P_2 are equally distanced from the structure crown point;
- $x_p = -3.4$, where the loader axle P_2 is above the structure crown point.

In order to determine the analysed shell measurement points in Figures 5 and 6, we used the marking of the location of the measurement points $x_4 = 1.2$ m $x_5 = 0$ (crown point) $x_6 = -1.2$ m.

The curves in Figure 5 are very similar in terms of their shape but show significant differences between the values during the back (W) and forth (P) passes. The similar maximum values p in the points 4, 5 mean that there is similar pressure from the loader wheels load in the crown point area. During the forth pass (P), there is no second wave with the peak value, where the second axle P_2 of the loader is just above the analysed point. Such peaks can be seen for the back pass (W). From the results of the analysis, we draw a conclusion of a significant reduction of the interaction p when the vehicle returns to its starting point. Therefore, there is a hysteresis loop for the earth pressure.

The sense of the tangential forces t_{45} is matching the direction specified in (Figure 3). The main feature of the functions $p(x_p)$ and $t(x_p)$ is that they are similar during the back and forth drive of the loader. High values of the force t , created when the vehicle returns to the starting point, are very significant. The same curves were obtained also for points located further from the crown point but on the opposite side of the symmetry axis of the shell. Therefore, there is no hysteresis loop for tangential forces.

Very high values of $t(s)$ in comparison with $p(s)$ are not here an error of the calculation algorithm (and of measurements). The relation t/p – assumed not to exceed the friction coefficient values specified in the paper – does not include the effects of interactions from the self

Figure 6. Tangential interactions in the structure crown point area. a) from the ramp side, b) in the crown point.

weight of the soil (occurring during the backfilling). In the analysed example of a structure, the maximum strain in the corrugated steel plate reached the value of:

$$\sigma = E \cdot \varepsilon = 205000 \cdot 184 \cdot 10^{-6} = 37,7 \text{ MPa} \quad (8)$$

6 CONCLUSIONS

For a hybrid structure model, it is important to determine the principle of contact interactions between the adjacent subsystems. The paper presents the results of the algorithm for determining the soil interactions onto the shell as the normal p and tangential t components based on the strain gauge measurements. The hybrid model uses the condition of consistence of contact interactions between the soil and the shell. The principle of displacement conformity is not included, i.e. slip at the interface of the two adjacent materials is allowed. This is an important advantage of the algorithm.

A characteristic feature of the soil-steel composite bridges is a significant difference of displacement, internal forces and contact interactions (as in work) between the back and forth passes of the live load vehicle. When the analysed values, after the vehicle full passage (back and forth), return to the initial, a characteristic hysteresis loop is achieved. This phenomenon in bridge structures is poorly known and concerns moving loads, i.e. ones which change their position. The outcomes of the test data evaluation presented in this study are to be used in the ongoing research for a validation of the numerical finite element hybrid model proposed by Authors in section 2.

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