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MONITORING OF SOIL-STEEL STRUCTURES DURING CONSTRUCTION

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Abstract

A unique feature of soil-steel structures, unlike classical bridges, for example vaulted ones, is the very large effect of backfill and road superstructure on the bearing capacity of the bridge. In the model of a buried structures made of corrugated steel plates, two structural subsystems are distinguished: a flexible arch shell and a soil backfill with road superstructure. The interaction between these subsystems is modelled as a contact layer, i.e. forces with a normal and tangent direction to the surface of the steel shell. It is a static condition for the compatibility of mutual interactions between soil and coating. Between the sub-systems, slip is allowed, i.e. the difference of displacements. The paper presents the structure safety assessment algorithm based on the shell deformation determined on the basis of deflection measurement and change of curvature in the shell crown point. The construction phase of the structure is analysed and a also the symmetrical deformation is assumed during the backfill material placement. Usually, during the bridge construction the forces in the steel shell are several times greater than those arising from operational loads. For this reason, the results of analyses given in the paper are also important as the basis for calculation and behaviour of the soil during live loads.

Introduction

In this paper, flexible engineering structures are analysed based on the example of soil steel bridge, as shown in Fig. 1. Their unique feature, unlike classical arch bridges, is the large effect of backfill and road superstructure on the bearing capacity of the bridge [1, 2, 3]. Considered is the construction stage of the bridge where there are a variable thicknesses of overfill. Corrugated steel structures are characterizing by high stiffness [2], but if buried in surrounding soil. With the increase of the height of cover, the effectiveness of live loads in the form of concentrated forces is decreasing. There is also a significant reduction of the impact of vehicles caused by the rigidity of the road or rail bridges [2].

Fig. 1. General view of structure during construction in Ras Al Khajmah (near Dubaj)

During backfilling, the steel shell is subject to considerable deformations, because it is a geometrical form, which limiting the soil as shown in Fig. 2. The steel shell during construction takes over the soil active pressure similar as it is related to the retaining walls. When the structure is completely backfilled it starts to interact and becomes an effective element of the structure which allows the transfer of significant loads, including also the construction loads [2, 3]. The results of measurements of these objects are distinguished by two phases as shown in Fig. 2, i.e. when the backfill is up to the level of the crown ($z_g < H$) and when it cover the structure ($z_g > H$). For the paper purposes it was assumed that the deformation of the steel shell is symmetrical, just like the backfill procedure.

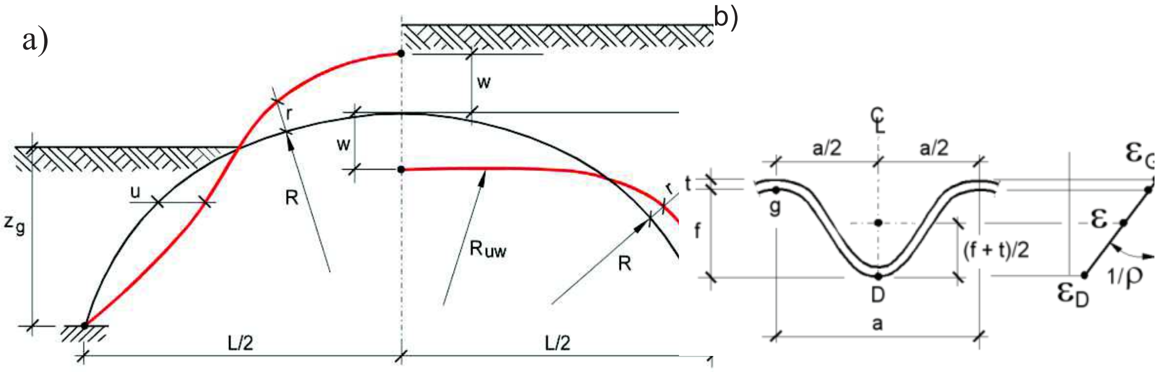

Fig. 2. Geometry of the steel shell: a) shell deformation during backfilling; b) strain distribution in the measurement point

There are two structural subsystems [1, 2, 3, 4] in the soil-steel structures models: the steel shell and the remaining part - backfill (road or railway superstructure is in backfill included). As a computational model of a soil-shell facility during construction, a perimeter portion - strip of the shell as shown in Fig. 2a. Corrugated sheets in such models are presented in the form of a beam element with a complex geometry. The geometrical characteristics of the sheet are brought to the neutral axis as shown in Fig. 2b.

During the construction of soil steel bridges, geodetic measurements of the shell geometry are made [4, 5]. In the case of structures with record spans - as in this paper, stain gauges measurements are also carried out. The paper presents selected methods of monitoring of soil-steel structures.

Effect of soil impact to the structure

During backfilling, the structure starts to deformation. Its crown point is rising reaching the maximum upward deflection when the backfill reach the crown $z_g < H$. In the second phase, when the soil is placed over the crown point ($z_g > H$) the slight reduction is observed as in Fig. 2a. During the backfilling process the displacement function in (z_g) is quite complex. It is related of the shape of the steel shell and the parameters L, H, R and the type of corrugation, determined in the dimensions a, f, t. The engineering backfill pattern also has a significant influence on the measurement results [1].

A complex function of normal stresses σ(w) in its crown point effects on the variable form of the deformation of the shell as shown in Fig. 3. The stresses obtained from the strain gauge measurements are analysed, as shown in Fig. 2b in relation to the crown point displacement, as shown in Fig. 2a. The measurement results given in this figure refer to a study object (not in service) in Rydzyna (Poland) [3]. Markings *D* and *G* refers to valley and crest of the corrugation accordingly, as shown in Fig. 2b. The difference between the σ_G - σ_D values shows the influence of axial force on stresses. It is increasing when the backfill level is rising. In the first phase ($z_g < H$) there is an increase displacements *w* and stresses σ. Then, in the second phase ($z_g > H$), a further increase of σ takes place with a decrease of displacements *w*. In the third phase, which also applies to the service of the bridge, both values are reduced.

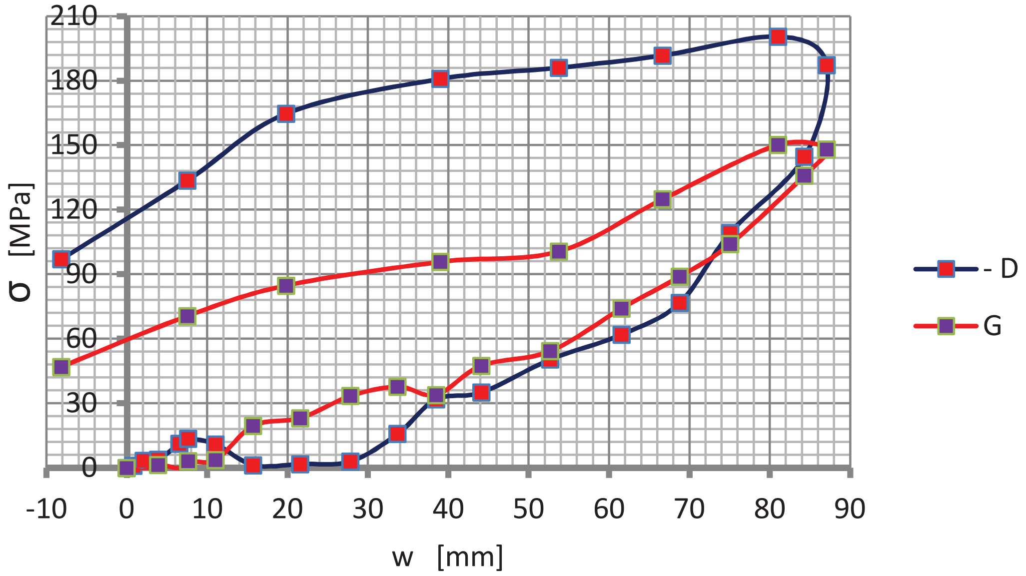

Fig. 3. Changes of the normal stresses in the steel shell during the backfilling [3].

Changes of the steel shell curvature

When placing of soil material special attention should be paid to the deformation of the shell and especially to the vertical displacement of the crown point, i.e. as shown in Fig. 2a. Geodetic techniques can be used for such measurements - also used for other purposes during the structure construction. When measurements are made at three points *i, k, j* adjacent to the crown (*k*), the change of the curvature of the shell can be determined [2].

$$\kappa_r = \frac{1}{s^2}(r_i - 2w + r_j) \tag{1}$$

In the formula (1) vertical displacements, obtained from measurements *w* and horizontal *u* at points *i* and *j* (adjacent to crown point *k*) were converted to radial displacement *r*, i.e. in the direction of the radius of curvature *R*, as in Fig. 2a. The distances between points *i* and *j* with the value of *s* are the length of a circle with radius *R*.

In case when the points *i* and *j* are far away from the crown point (*k*), the geometrical relations in the isosceles triangle are used [4]. From vertical displacements *w* and horizontal *u* of measurement points *i, k, j*, R_{uw} [3, 4] is determined as shown in Fig. 2a. By referring the calculated radius of R_{uw} curvature to the initial design value *R*, a relationship is obtained

$$\kappa_R = \frac{R - R_{uw}}{R \cdot R_{uw}} \quad . \tag{2}$$

From the formulas (1) and (2) similar values are obtained when the additional measuring points *i* and *j* are located close to the crown. To increase the accuracy of R_{uw} calculations, extrapolation and more than 3 measuring points have to be used. In the case when strain gauge measurements [2] are used, strains in the crown are used, as shown in Fig. 2b. The curvature in the analyzed section is calculated from the geometrical relation $\kappa = 1/\rho$ given by

$$\kappa_e = \frac{1}{f}(\varepsilon_g - \varepsilon_D). \tag{3}$$

Presented above three formulas for calculating κ were created assuming completely different assumptions. Formula (3) is accurate - obtained by assuming the principle of flat cross-sections. The formula (1) assumes a uniform value of κ in the range of points *i-k*, *k-j* and thus the assumption of radial displacements as a function of the second stage (parabola) of the *r*(s). In the case of formula (2), the result depends on the height of the triangle - hence extrapolation is apply [3, 4]. From comparative analysis, formula (2) is efficient [4] in the range $z_g < H$. Differences of results κ are reduced as the distance between points *i* and *j* is decreasing in relation to the shell crown point.

Shell curvature vs deflection

In the case of soil-steel structures, the relation of κ(w) is the geometric characteristic of the shell (its basic dimensions *L, H, R*) but also the technological backfill pattern. In paper compared are the deformations of three shells with large spans and similar geometry, aspresented in Table 1. Presented in Fig. 4 graphs are obtained from strain gauge measurements during backfilling. The analysed structures were built without any stiffeners. Presented charts are very similar in terms of shape, but they differs in the reduction of upward deflection during backfilling. From the comparison of the graphs σ(w) as shown in Fig. 3 and κ(w) as shown in Fig. 4, obtained from the Rydzyna structure, notice their high similarity can be observed. This indicates a high level of bending in normal stresses in the steel shell during the backfilling.

Table 1. Geometrical parameters of shells

Structure	Basic dimensions [m]			Type of the corrugation $a\times f\times t$	EI/a MNm^2/m
	L	H	R		
Rydzyna (Poland)	17,594	5,459	13,735	SC 381×140×7	4,954
Gajec near Rzepin (Poland)	20,000	7,424	13,930	SC 381×140×7 +SC/2 381×140×5,5	11,40
Ostróda (Poland)	25,724	9,110	16,632	UC 500×237×9,65	19,89
Ras Al Khajmah (UAE)	32,660	9,570	29,680	UC 500×237×12	22,80

The change of curvature is related to the stiffness of the corrugated sheet (see Table 1) in the equation of bending moments towards the peripheral strip of the shell

$$m = \frac{EI}{a}\kappa . \tag{4}$$

In the assessment of the safety of the structure during backfilling, the three construction phases given below have significant importance.

- increase of bending moments (changes of curvature and normal stresses) during reduction of upward deflection ($z_g > H$);
- when the crown point upward deflection is completely reduced ($w = 0$), significant values of bending moments still remain in the steel shell;

- the total reduction of bending moments (κ = 0) occurs with significant values of the deflection of the shell crown point.

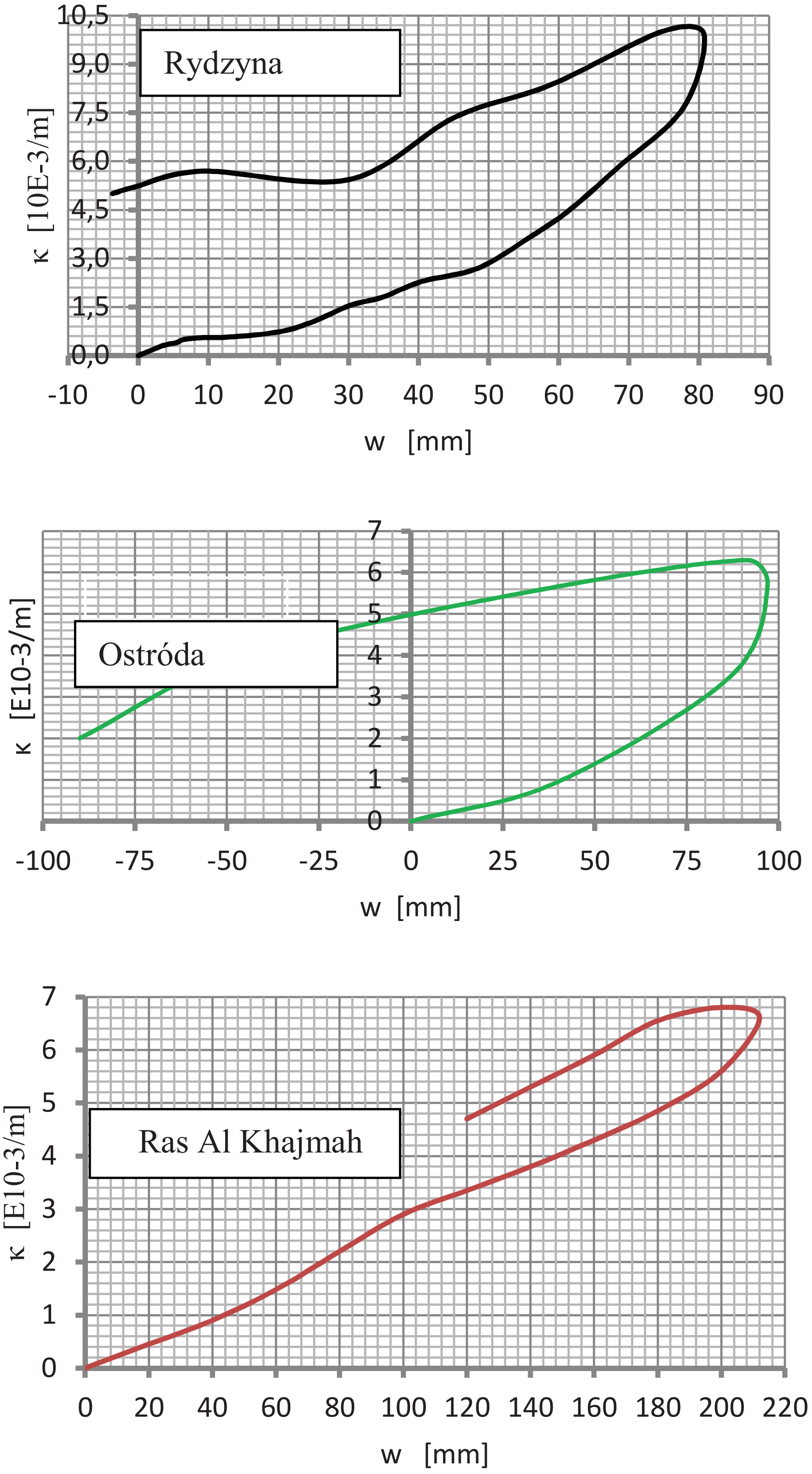

Fig. 4. Characteristic deformations of analysed structures

Therefore, the transition of the deformation of the shell from the upward to downward deflection (UAE structure) may play a positive role due to the reduction of stress values in the steel shell, as presented in Fig. 3. For the steel shell the total reduction of κ is the transition from eccentric compression to momentless state and therefore more favourable for steel shell. This trend is observed during the soil-steel structure service.

Allowable deformation of the steel structure

Based on the changes of the curvature, the normal stresses (from bending) can be determined acc. to equation

$$\sigma(m) = \frac{f+t)}{2} E \cdot \kappa . \tag{5}$$

With a constant value of E = 205000 MPa, the direct relation of the curvature of the perimeter shell strip with the geometry of the corrugated sheet is observed. Using the equation (5) and adopted as an acceptable value of σ(m), we can determine:

- maximum radius of curvature of the shell, from equation (2)

$$R_{uw} = \frac{R}{1 + \frac{2R}{f+t} \frac{\sigma(m)}{E}} \quad ; \tag{6}$$

- allowable deformations of the steel shell, from equation (1)

$$w_k = \frac{s^2}{f+t} \frac{\sigma(m)}{E} \tag{7}$$

In the formula (7), the deflections of the shell crown point were assumed to the two points adjacent to it, hence $w_k = w - (r_i + r_j)/2$.

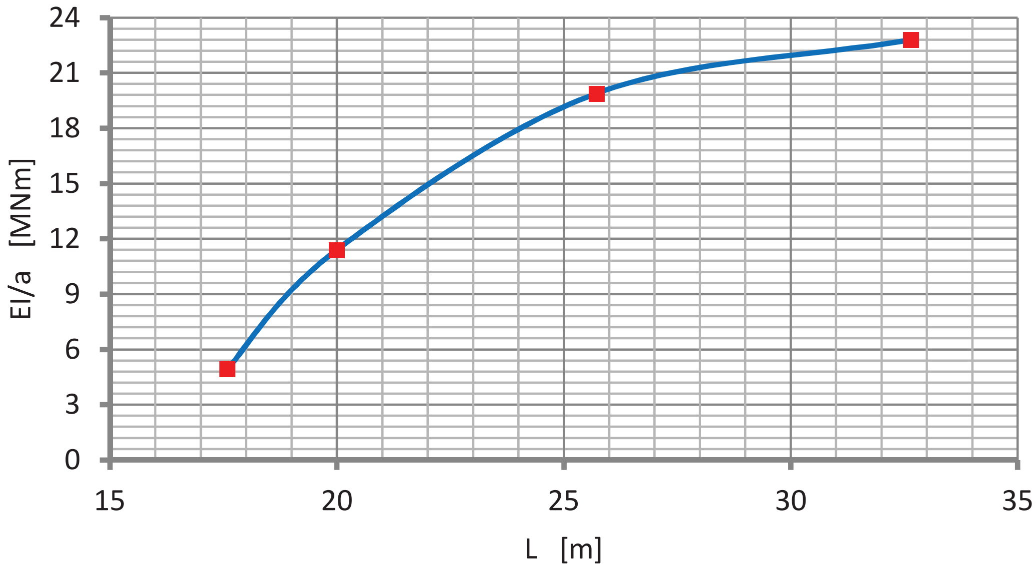

Fig. 5. Relations of stiffness of corrugated plate and spans shell

Maximum deflections of steel structure given in Fig. 4 are not related of the structure span. This is due to the proper adjustment of corrugation to the span. Fig. 5 presents the results of analysed structures, as shown in Table. 1. Graph shows, that multilayer structures i.e Barrel + Ribs SC + SC (with Super Cor corrugation) have a higher stiffness EI/a = 21.3 MNm^2/m in relation to the spans L = 20 m. Fulfilling of free spaces between two sheets with concrete such with coatings, i.e. SC + SC + EC Ribs, allow to achieve EI/a = 34.7 MNm^2/m. The graph given in Fig. 5 shows that the use of reinforcing Rib plates causes higher material consumption, i.e. it is less effective than Ultra Cor sheets - used for record span structure [1, 5, 6].

Summary

The deformation of the steel shell during backfilling is significant and require to be controlled using geodetic techniques [3, 4, 5, 6]. Usually, the displacement of the crown point is observed, which is subject to significant movements when the structure is backfilled. In the initial phase of the construction, the steel structureis upward deflected and then its reduction occurs due to the overfill. In this paper analysis of changes of the radius of curvature as a function of vertical displacement of the shell crown point. In this way, a characteristic graph is created to assess the safety of the structure during construction and during the service. With use of such relation, it has been shown that the total reduction of the upward deflection (to zero) does not cause the disappearance of the initiallyobtained bending moment. Deflection of the steel shellcan be beneficial for it, because the bending effect in the corrugated shell is reduced.

The presented method of safety analysis can be useful after observations during construction also during the service. This applies especially in the situation where significant technological deformations occur. Therefore, it is necessary to monitor mid and the large span structures.

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