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Classification of soil-steel structures due to shell deformation changes during backfilling

Abstract: Soil-steel structures made of corrugated sheets are divided into two groups in the paper. This division results from the critical situations caused by flexural stresses (bending stresses) in shells. One of them occurs in the stage of construction, during backfilling – index of uplift ω is then controlled. The other situation is more difficult to be identified as it occurs in the exploitation phase. The possibility of its occurrence is evident in the final stages of construction, which is indicated by the index of deflection change η. Specific examples of both shell groups are analysed in the paper. A relationship between shell crown deflection and normal stress determined in the work in a geometrical form – as a change of curvature – is used to evaluate the structural safety. Usefulness of basic surveying techniques, available during construction, is indicated in the calculation examples. They allow assessing the shell safety on the basis of the shell crown zone deformation.

Keywords: Soil-steel structure; Backfilling; Change of curvature; Safety.

Introduction

Soil-steel structures are objects for communication purposes, as shown in Figure 1, playing the role of bridge objects: flyovers, footbridges, culverts, tunnels, subways, business trips and passing for wild animals. A large group of these buildings serves as municipal buildings, usually in the shape of closed (tubular) ducts, or for transport purpose, e.g. housing of conveyors. They are built in the form of a shell and specially compacted ground surrounding the structures, on a similar basis as railways and road embankments.

Due to the construction (design) of these objects, there are two groups of soil-steel structures recognized: flexible and rigid [4]. Given the material used, the following shells are distinguished: concrete including the prefabricated components as well as plastic and metal ones. For the metallic shell, steel and aluminium corrugated sheets are used. According to the profiles of corrugated sheets, there are distinguished by the types designated by producers as HC, MP, SC NP, UC [3]. Due to the geometry of the circumferential band, there are two groups: closed with circular, elliptical, drop-like and pear shapes as well as opened: arc with high or low profile, and in the box form [2].

Flexible soil-steel structures with corrugated sheets are divided here exclusively into two groups, depending on the course of deformation and the accompanying stress changes in the shell crown during backfilling. There are considered structures with symmetrical deformation of the cross section of the shell, usually found at the horizontal overground and not in twin buildings and inclined slopes [8].

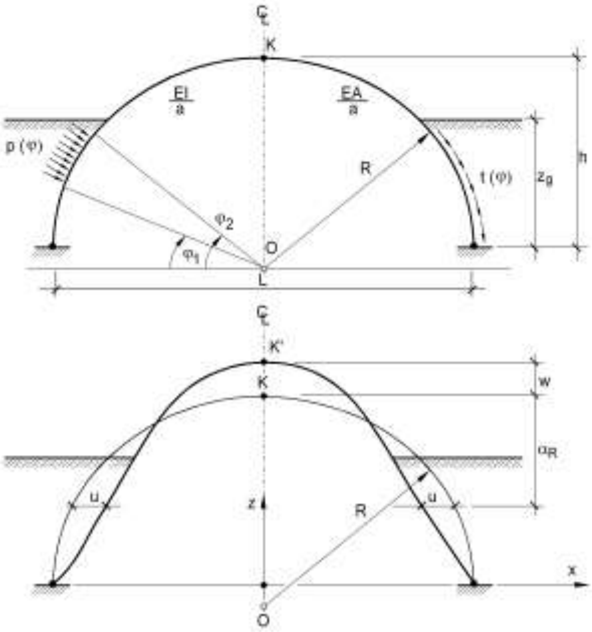
1. A view of road soil-steel structures

Uplift index of shell crown

The initial phase of construction is important in the evaluation of safety in the most cases of soil-steel structures with arc shape when the soil backfill reaches shell crown. The biggest uplift is usually in the shells with open and closed section as a result of pressure of backfill ground [3]. These deflections of corrugated sheet in the crown are directed up, as shown in Figure 2. Then, to assess the safety of structure under its construction a geometric control of the following index is sufficient:

$$\omega = \frac{w_{\max}}{L} 100\% \quad , \tag{1}$$

where: w_{max} is the maximum uplift of shell crown and L is its largest horizontal dimension (span) of the peripheral band. In the projects of constructions there are estimated values ω and in the guidelines, it is recommended the condition ω < 2%. In practice, however, larger values were observed [3, 6], even such as ω > 3%.

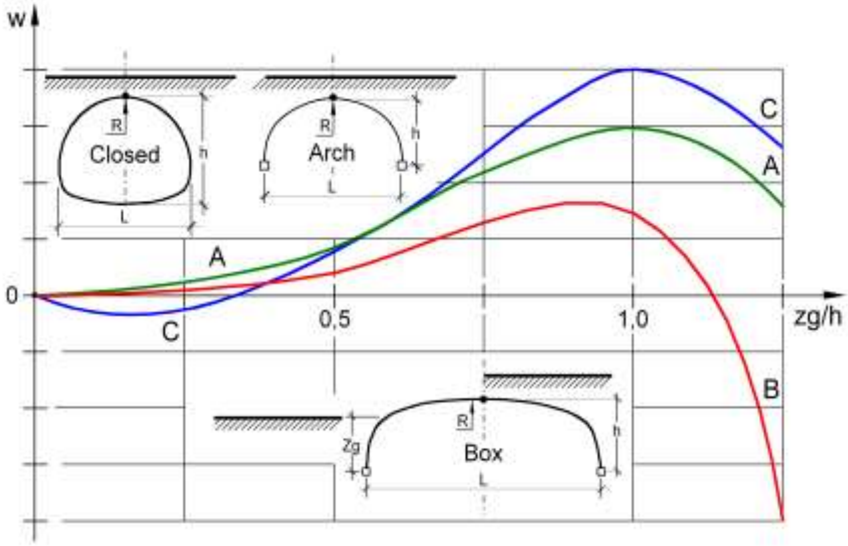


2. Impact of ground on the shell and its deformation during construction of an object

In the group of soil-steel structures with a box shape and, in special cases, in arc shells with low eminence ($\kappa = h/L$), as in the situation discussed in the paper, the operational phase is important in assessing the safety of the object. Then the uplift of the shell is smaller than the deflection (vertical displacement of crown facing downward).

Figure 3 shows the change in uplift as a function of the thickness of the backfill layer z_g (in proportion to the shell height h). When $z_g/h = 1$ backfill reaches the level of crown, and then the greatest value uplift is created w_{max}. When $z_g/h > 1$ its reduction occurs and deflection w_{min} appears in the box-shaped shells. Due to the characteristic changes of the vertical displacement of the shell, crown soil-steel structures are divided into three groups: the arc (A - arch) and box (B - box) and closed (C - closed). Open shell with arc shape (A) and closed (C) are treated, usually as a single group because of the similarity in uplift. In the shell C, there are initially negative values of crown displacement, but then the shape of the graph is similar to those in the shells A. In shell B, crown shell deflections (movement directed downward) are formed usually in the final stages of construction. The paper introduces an additional shell, referred to as AB, with A geometry and behaving as the type B.

Table 1 shows the geometric parameters of the analysed shells. In the cross-sections of all shells with steel corrugated sheet there is distinguished the radius of curvature of the peripheral band of the shell crown, designated as R, as shown in Figure 3. The width of the object is less critical issues. Due to the significant values of displacements in shells with corrugated sheet, geodesic techniques are used for the measurement. These methods are also used for construction of other buildings [3].



3. Characteristic changes in vertical displacement of shell crown during backfilling

The object with the shell was built in ViaCon Poland in Rydzyn only for research purpose [3, 5]. In the cross section of the shell, there are two curvature radii of the peripheral band in the area R = 13,735 m and many times smaller in the groin (corner) R_n = 3.45 m. In the final phase of construction, he level of ground backfill crown shell over 1.8 m is an important parameter. The shell B was built in the facility in Lidköping [1, 3] (Sweden). The object was divided longitudinally so as to form two comparative structures based on a common line foundation. The aim of the study was to evaluate the impact of additional stiffening (overlay) of shell. Measurements of displacement and unit strains were carried out on the object s for shells A and C. The object with shell C was built in Sweden only for research purposes [3, 7]. It was created with a sheet with a low profile and small thickness MP 200×55×2.93. The cross section of the shell was closed with drop shape and dimensions as in Table 1. In the object, tests were carried out with road vehicles assuming different depth of overground thickness. The results of these studies were the basis of guidelines for design of soil-steel structures. AB shell with dimensions shown in Table 1, because of its shape, is classified to the group A. The object was built in the ring road of Nowa Ruda [3, 6] and it is currently operating. It is characterized by an increased depth of overground thickness with 3.05 m.

Table 2 shows the value ω gained from measuring the uplift of shells of analysed objects. The values ω do not contain important information concerning the safety of objects of type AB and B.

Tab. 1. Geometrical characteristics of the analysed objects

Shell	L [m]	h [m]	$\kappa = h/L$
A	17,59	5,459	0,3103
AB	13,46	5,004	0,3718
B	8,00	2,370	0,2960
C	6,04	4,550	0,7533

Tab. 2. Characteristic changes in shell deformation

Shell	L [m]	Overground [m]	w_{max} [mm]	$w_{\min}$ [mm]	ω [%]	η
A	17,59	1,80	80,7	-0,6	0,459	0,993
AB	13,46	3,05	50	-134	0,372	0,272
B	8,00	1,35	12	-26	0,150	0,316
C	6,04	1,50	65	50	1,076	4,333

Index of shell deflection change

Characteristic changes in uplift (in the initial construction phase) and deflection (during the final works) as a function of the thickness of backfill z_g are shown in Figure 3. In the initial period of backfilling, charts are similar to achievement of the highest uplift value $w_{\max}$. When the backfill is placed above the crown shell, uplift decreases and reaches deflection $w_{\min}$ in the shells B in the final phase of construction. On this basis, index of deflection change is determined:

$$\eta = \frac{w_{\max}}{w_{\max} - w_{\min}} \quad . \tag{2}$$

Due to the positive and negative values $w_{\min}$ there are two ranges of results: η > 1 i η < 1. According to this principle, it was proposed in the paper a division of soil-steel structures to those in which it is sufficient to check the ω (when η > 1) and those, in which the utility phase may be important in assessing their safety (when η < 1). Table 2 shows the results obtained from the measurements of the characteristic objects. From the value η it is visible the difference between the shells A and C, and AB and B. It indicates that the shell A and C may be classified into a different group than the shell AB and B. The geometrical characteristics of the analysed properties are shown in Table 1.

Changing the curvature and stress in the shell crown

Tensometric measurements (unit strains) shall also be conducted in facilities from corrugated sheet of the experimental significance and hence the internal forces are determined (M – bending moments and N – axial forces). In this case, specialized measuring equipment is required [1, 3, 7]. Based on the deformation of the upper area of the shell the internal forces can be determined in the shell e.g. the bending moments from the change in curvature of the crown of the peripheral band of corrugated sheet. For this purpose, the geometric relationships and movements in w and u are used, as illustrated in Figure 2, whereas the calculation algorithm is discussed in [3, 5, 6].

Section of the peripheral band of the shell crown is bent in the manufacturing process, so that its radius of curvature was constant and equals R. As a result of interactions of ground backfill shown in Figure 2, the bending moment with the value M occurs in the crown. In the case of rod with the large radius R, its change to the value of R_K, caused by the moment M, is related with bending stiffness of the element (EI) by formula [3, 5]:

$$\frac{M}{EI} = \frac{1}{R_K} - \frac{1}{R}. \quad (3)$$

From the formula (3) the bending moment can be described as:

$$M = \frac{EI}{R} \cdot \frac{R - R_K}{R_K}. \quad (4)$$

In the formula (4), there is a dimensionless parameter ρ defined in the strength of materials as a change in the curvature of rod, as in formula:

$$-\rho = \frac{R - R_K}{R_K} 100\%. \quad (5)$$

When $R > R_K$ the shell is bent upwards (as shown in Figure 2), and then it is assumed that the change of curvature is negative as well as the bending moment. Of course, in the issues analysed in the work the sign of ρ and *M* are not important, because when $\rho > 0$ stress in the bottom wave of the sheet are extending, whereas in the upper wave are compressive. When $\rho < 0$, the situation is opposite but it does not affect the absolute values of the calculated stress coming from bending.

Based on ρ, i.e. changes in the radius of curvature *R* to the value of R_K the bending moment is calculated as in equation: changes in the radius of curvature:

$$M = \frac{EI}{100 \cdot R} \rho. \quad (6)$$

The value of the normal stress σ, originating from the bending can be calculated from (4) after consideration of the bending index of corrugated sheet *W*, as in the equation:

$$\sigma = \frac{M}{W} = E \frac{f + t}{200 \cdot R} \rho = \sigma_o \cdot \rho. \quad (7)$$

The factor present in (7) is a constant characteristic of the shell geometry. When the corrugated sheet is SC 380×140×7 (SC – designation of sheet profile; *a* – wavelength; *f* – wave height; *t* – sheet thickness) and its design radius of curvature *R* = 9930 mm, as in the object AB, its value is:

$$\sigma_o = E \frac{f + t}{200 \cdot R} = 205000 \frac{140 + 7}{200 \cdot 9930} = 15{,}17 \ MPa.$$

Geometrical characteristics of shells from corrugated sheets of the analysed objects are shown in Table 3.

Tab. **3**. Strength parameters of shells

Shell	Sheet type	*R* [m]	σ_o [MPa]	ρ_{max} [%]	ρ_{min} [%]
A	SC 380×140×7	13,735	10,97	-	-13,4
AB	SC 380×140×7	9,930	15,17	6,6	-3,8
B	SC 380×140×4	8,820	16,74	8,2	-2,0
C	MP 200×550×2,93	3,052	19,46	-	-9,5

Figure 4 shows a linear relationship with the normal stresses resulting from the bending shell in dependence on the change of curvature of corrugated sheets used in soil-steel structures. A significant impact of project (initial) value of the radius of curvature *R* is visible in the values σ_o, given in Table 3. Using equation (7), the maximum (limit) of curvature can be determined on the basis of the assumed allowable stress values σ_{max}, as in the formula:

$$\rho_{max} = \frac{\sigma_{max}}{\sigma_o}. \quad (8)$$

In this way, the minimum (permissible) value of the radius of curvature R_K can be also calculated on the basis of σ_{max} and σ_o using equations (5) and (7) as in the formula:

$$R_{\max} = \frac{100\sigma_o}{100\sigma_o + \sigma_{\max}} R . \quad (9)$$

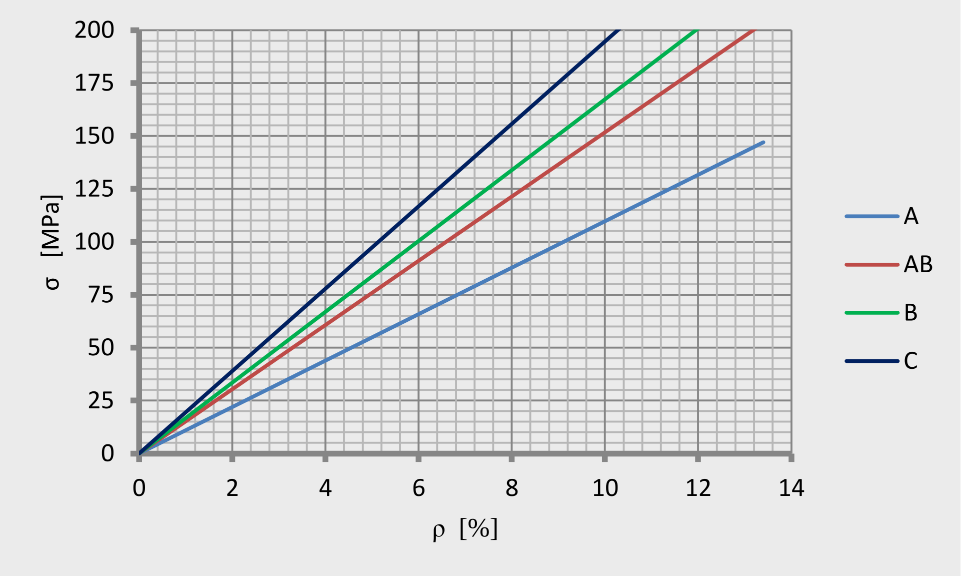
Changes in deflections and stresses in the shell crown

Changes in indices of shell deformation ω and ρ as a function of the thickness of the ground backfill z_g as in the equations:

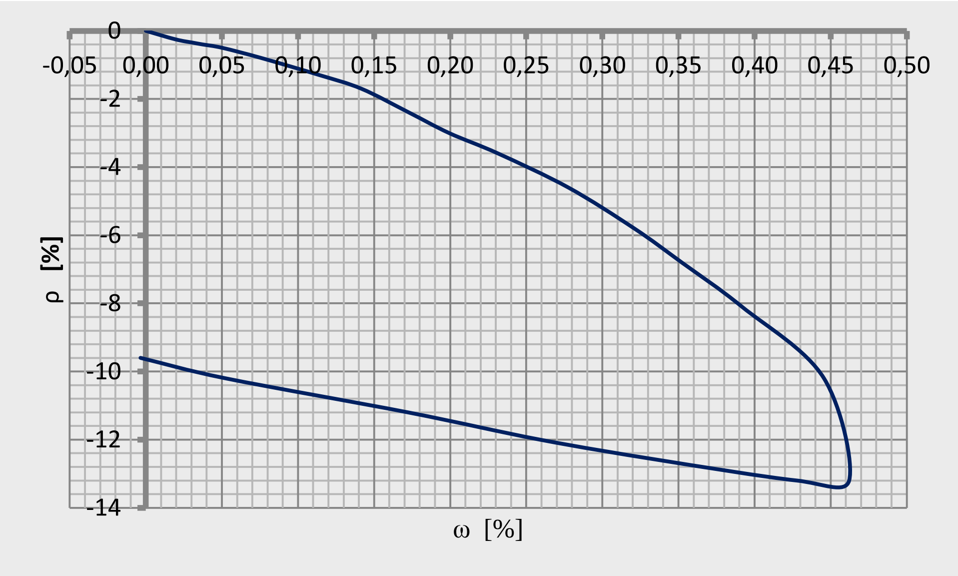
$$\omega(z_g) = \frac{w_K(z_g)}{L} 100\% , \quad (10)$$

$$-\rho(z_g) = \frac{R - R_K(z_g)}{R_K(z_g)} 100\% , \quad (11)$$

are similar to the graphs of change in the deflection of shell crown $w(z_g)$ shown in Figure 3. These diagrams show that the deformation indices are subject to growth in the first phase of backfilling, i.e. when $z_g < h$ (as shown in Figure 2), and when $z_g > h$ they are reduced. However, the characteristics differing analysed shells are only visible in the function ω(ρ), when the changes resulting from the bending are related to the crown shell deflection. They are shown in Figures 5-8, separately for each type of object.

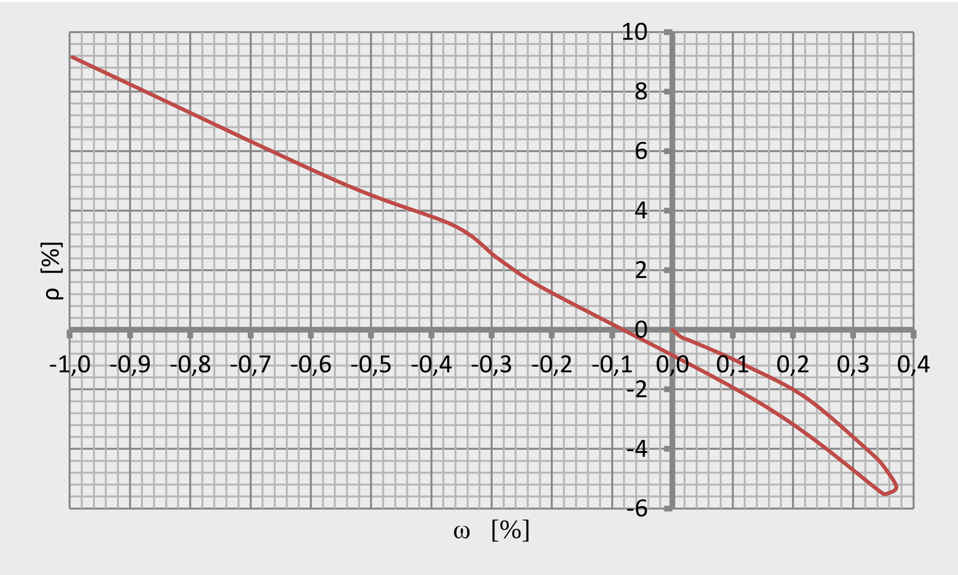


4. Normal stress dependence on the curvature change

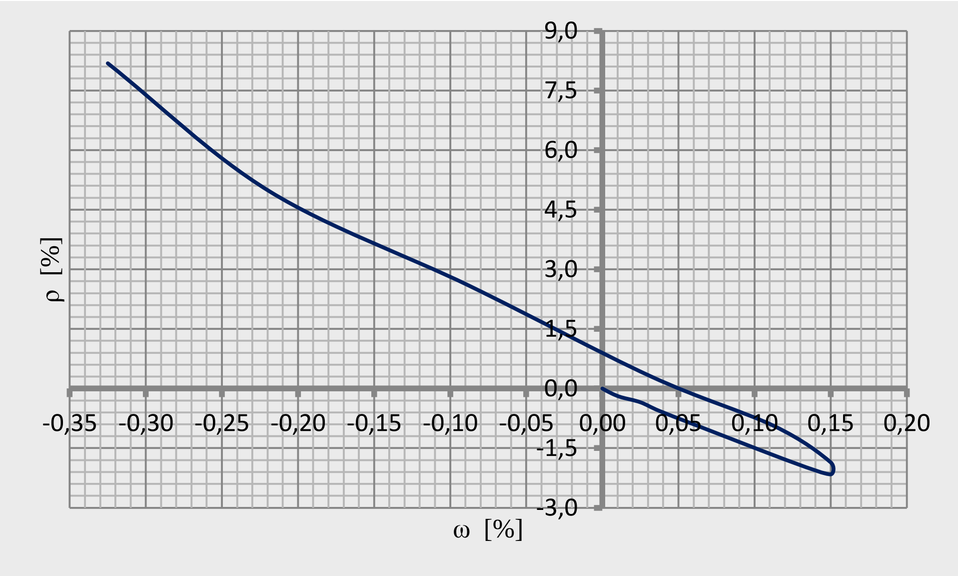


5. Changing the geometrical deformation indices ω(ρ) in the shell A

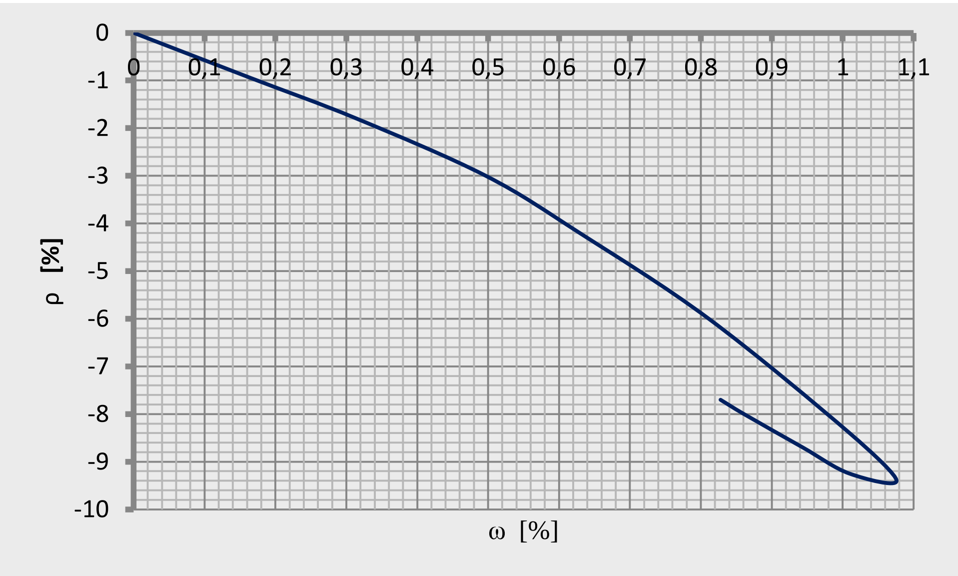
From the range of values ω, shown in Figures 5-8, it is apparent that the uplift is not normally subjected to the complete reduction after the completion of building in shells from groups A and C, hence $\eta > 1$ and $\omega(z_g) > 0$. In the B type shells, deflections ($w_{min} < 0$, stąd $\eta < 1$) often occur - usually significantly larger than the uplift (w_{max}). A comparison of the graphs in Figures 6 and 7 show that the AB shell behaves like a shell with the geometric shape of B, despite belonging to the group A.



6. Changing the geometrical deformation indices ω(ρ) in the shell AB



7. Changing the geometrical deformation indices ω(ρ) in the shell B



8. Changing the geometrical deformation indices ω(ρ) in the shell C

The analysis of changes ρ compared to ω implies that the shells A, AB and C may be classified into the same group. In the case of B shape shell, the change of the shell curvature is greater in the first phase of backfilling than during the process of overground laying ($z_g > h$). In the shells AB and B, there is a change of curvature sign in backfilling, as in the graphs shown in Figures 6 and 7. It is also interesting the special situation, when ρ = 0, and hence the bending moment is reduced to zero. Then, the radius of curvature R_K is reduced in relation to the initial value R in the first stage of construction in order to back to the original value during laying overground on the shell R. At this particular time, deflections of shells reach the following values calculated from plots ω (from Figures 6 and 7):

- shell AB

$$w_{AB} = L \cdot \omega_{AB} / 100 = 13460 \cdot (-0{,}08) / 100 = -10{,}77 \;\; mm,$$

- shell B

$$w_B = L \cdot \omega_B / 100 = 8000 \cdot 0{,}05 / 100 = 4{,}00 \;\; mm.$$

Thus the other signs of crown movements occur in both types of shells when ρ = 0.

Another special situation is the creation of identical radii of curvature $R_K(z_g=h) = R_{max}$ but with different signs, i.e. - $R_{min} = R_{max}$. Then, the calculated deflections of shells are:

- shell AB

$$w_{AB} = L \cdot \omega_{AB} / 100 = 13460 \cdot (-0{,}62) / 100 = -83{,}45 \ \ mm$$

- shell B

$$w_B = L \cdot \omega_B / 100 = 8000 \cdot (-0{,}062) / 100 = -4{,}96 \ \ mm.$$

Larger values of ρ in the final stages of construction than when $z_g = h$ indicate that the exploitation loads of the object are meaningful for the safety of shells AB and B. In the shells A and C, the opposite is true - the maximum value of the stress are generated during the construction when $z_g = h$ and during the construction, they are subject to reduction when the backfill is being laid as overground above the shell.

Changes in the radius of curvature R_K were determined according to the strength given by the formulas (3) - (5) and were referenced to the initial value of R in the index ρ. In the physical interpretation, the value σ_o is the normal stress resulting from the unit value ρ = 1%. Thus, the graphs of relationships ω(ρ) shown in Figures 5-8 you may also be treated as relationships ω(σ) using multiplier σ_o. For this purpose, charts given in Figure 4 can be used.

Summary

The sensitive soil-steel structures with the corrugated sheets can be divided into two groups, depending on the deformation during the course of backfilling. This division is exemplified by the test results of four representative objects with different geometry of the peripheral shell band. In both groups, one of two dangerous construction situations is reliable in shells with corrugated sheets soil-steel structures. One occurs when the index of the deflection change is η > 1. Then the initial phase of construction is important when laid backfill reaches crown, i.e. the value of uplift index ω is then important. The second situation is more difficult to identify because it occurs during the use of the building. The possibility of its creation can be seen in the final phase of construction, when the index of deflection change is η < 1. Then the stress analysis and calculation of the change of curvature ρ it is necessary to assess the safety of the shell.

In the example of analysed objects, we demonstrated the effectiveness of geodetic techniques available on building. It is important that there are no accurate readings - the displacement of 1% with respect to the span of the shell L. In determining the bandwidth of the peripheral deformation of the shell as shown in Figure 2, it is indicated in [3, 5, 6], the estimation of the possibility of bending moments in the crown shell and thus the normal stresses in the corrugated sheet. Therefore, using the geodetic measurements, these results can be also obtained, such as from tensometric measurements, which are much more difficult in the implementation of research.

Analysed in the paper, geometric indices ω, η and ρ are determined on the basis of the displacement in the shell crown. The paper shows that their values are related to the geometry of the peripheral band of the shell. In practice, technology of backfilling and its material is also important, as in the object AB. On the other hand, the object with the geometry from the group A acted as the construction of type B.

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