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Estimation of the interaction effects of backfill on the shell in the soil-steel structure based on deformation of the shell

Abstract: A characteristic feature of the soil-steel structure, in contrast to conventional bridges, is a greatly influence of the backfill ground and the road surface as a load-bearing elements. In the model with soil-steel structure, there are two structural parts: steel shell with corrugated plates and backfilling ground with road surface. The interaction between them is modelled as a contact interaction (interface), which is a normal and tangential force to the surface of the shell. These normal interactions are variable during the construction phase as well as during operation. In this paper, the collocation condition is use to determine these interactions, based on the fact that the calculation result obtained from the model of the geometry of the shell is to be consistent with the result of the measurement of the movement of the collocation point in the real structure. The physical characteristics of the soil in layers of backfill and especially the technology of laying and compacting is taken into account. This is the advantage of this algorithm. The results of these analyses can be the basis for comparing the effectiveness of conventional geotechnical models.

Keywords: soil-steel structures; the backfilling ground impact on the shell; changes during operation; calculation model.

Introduction

A characteristic feature of the soil-steel structure, in contrast to conventional bridges, is a great influenced of the backfill ground and the road surface as load-bearing elements [5]. The stiffness of the steel shell with corrugated plates is small. It is subject to significant deformation when backfill is placed because it is the geometric form limiting the embankment from the top and from sides of a build bridge. For this reason, the shell takes the ground pressure like a retaining wall (but susceptible). The shell only in surroundings of the backfill ground becomes an effective construction element which allows for the transfer of substantial traffic load, as shown in Figure 1. The stiffness of soil-steel objects is comparable with conventional steel bridges, of course, the greatest stiffness occur in the brick bridges [8].

1. Load of railway vaulted and soil-steel objects

Three types of measurements are used in mapping work of construction soil-steel objects in FEM models:

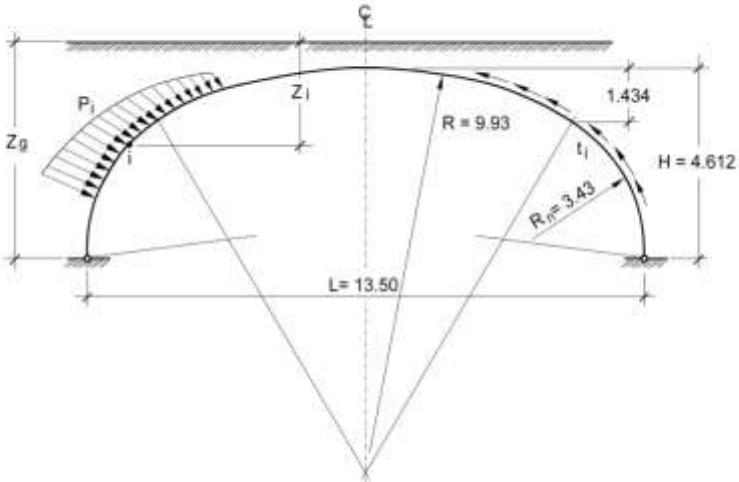
- displacement, defining the deformation of the shell immersed in ground;
- deformation of the corrugated sheets, used to determine the internal forces in the shell;
- ground pressure, giving a view on the structure behaviour.

In each of these measurement groups, different methodology research is carried out, which as a result, gives various information about the efforts of the object. This paper presents a method for determining the impact of ground on the shell, which is determined based on its deformation. The results of these analyses can be used to check the safety of buildings as well as assess the accuracy of the classic geotechnical models [11], [1], [3].

In the object models of soil-steel, there are two structural subsystems: a steel shell with corrugated plates, and the rest part in the form of backfill ground and pavement with the substructure of the road. The interaction between them is modelled as a contact interaction (interface) in the form of surface forces, divided into two components: normal p_i and tangential t_i, as in Fig. 2. Knowledge of these effects allows for separate analysis of each of the subsystems as in the case of overtime parameters (hyperstatic) in the method of forces commonly applied in rod systems. In the paper, the result of influence of p_i and t_i is a deformation of the shell determined by the displacement of the measuring points in the form of vertical w and horizontal u components. They are measured using geodetic techniques, which are sufficiently precise due to the high value of displacement. Figure 2 shows a schematic cross-section of the analysed shell and impact of the ground. The study examines the construction phase, when the level of the backfill is z_g and its use at full level with the road surface.

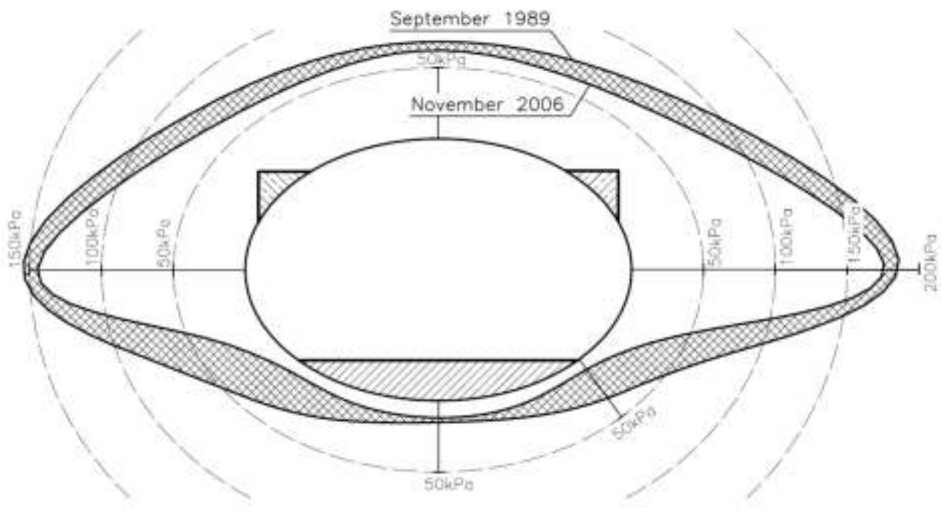
Analysis of internal forces and displacements of the second sub-system is difficult to identify because of its complex layered structure and physical characteristics of each individual layer. The determining displacement of ground based on the deformation of the shell is very difficult due to the potential slippage in the contact of sheet and ground during loading. Hence it is necessary to track the force values t_i involved with p_i. It occurs between the subsystems as a constant principle of reciprocal forces.

Impact of ground on the shell is variable during construction as well as during operation of object. The main influence on the contact forces has the position of the analysed point in the relation to the level of backfill z_i as in Fig. 2. However, the physical characteristics of ground resulting from the compaction of backfill technology, its thickness on both sides of the shell, used equipment, climatic conditions, waiting time are also important [5]. These effects of random features are mapped in the deformation of the shell. They are a record of the process of object construction. On the basis of displacements, after finishing building quality of works is assessed. In the case of shells with outstanding geometry is prepared forecast of movements, like in the programs of compression of concrete bridges.



2. Scheme of interaction ground forces on the shell

After the building of the object and during its operation, changes in interactions between the ground and the shell are observed. Figure 3 shows one example of test results of the object in Dovre (Norway). The shell was made as a horizontal oval with the span of L = 10.78 m and height H = 7.13 m with ground cover thickness of 4.2 m. The shell was formed of corrugated plates with a typical profile MP 200×55×7. The corners of the concrete shell have stiffening ribs in the shape with the triangular cross-section shown in Figure 3. They cause significant disturbance of the interaction between the ground and the shell [11], [1]. The highest values of the normal component of the impact p_i were obtained at a depth of 7.8 m from the ground level (depth of cover). It was approximately 180 kPa. The impact of ground on the shell in its key is about 75 kPa with the thickness of ground cover 4.2 m and thus with the minimal impact of the phenomena overvaulting. In summary, the results of research [11] it was noticed 30% reduction in the pressure on the shell after twenty-one year exploitation of the object.



3. Change in the impact of ground on the shell in the period of seventeen years of object exploitation [3]

Model of ground impact on the shell

The division of the object into two construction subsystems allows for independent analysis of the shell subjected to external load in the form of forces p and t in the soil-steel object. They are mutual interaction of backfill ground from the second sub-system. The shell from the corrugated plates is an ideal model of the elastic bending stiffness *EI*/*a* and axial forces *EA/a* (where *a* is wavelength in the plate with a typical symbol, e.g. MP a×f×t.

In the work to determine the interaction of the subsystems, we used the collocation condition based on the fact that the result of measurement of point displacement in the collocation object, designated as *s*, should be in agreement with the calculation obtained in the model of geometry of the shell as in equation

$$s = \boldsymbol{f}_{sp} \cdot \boldsymbol{p}. \tag{1}$$

Thus, the left-hand side of equation (1) are used measures and displacement state of the object, whereas on the right side (1), the deformation effect calculated using the phenomenological model. In the formula (1) $\boldsymbol{p}$ is evenly distributed force vector (the normal component of the impact on the ground on the shell) on a peripheral band of the shell specified in the nodes of shell division into components as in Figures 2 and 4, in the form of

$$\boldsymbol{p} = \mathrm{col}\{p_1 , p_2 , p_3 ,\ldots\ldots p_i ,\ldots\ldots\ldots p_n\}. \tag{2}$$

The vector $\boldsymbol{f}_{sp}$ is a function of the displacement impact *s* from influence of normal component $\boldsymbol{p}$

$$\boldsymbol{f}_{sp} = \{f_1 , f_2 , f_3 ,\ldots\ldots f_i ,\ldots\ldots f_n\}. \tag{3}$$

Components of the impact, tangential *t* and normal *p* are mutually entangled by a coefficient of friction. In the work and results of the measurement, as shown in Figure 3, the impact of the tangential component on displacement is omitted.

In equation (1) and the formulas (2) and (3), is visible a fault of presented methodology referred as the ambiguity of solution. It consists in the fact that a significant number of designated parameters p_i obtained based on one value *s* using the collocation condition (1). Therefore, to estimate the impact of the function *p* may be useful Coulomb solution [3] presented in the form of static ground pressure

$$p_i = \gamma_g \cdot K_a \cdot z_i - 2c\sqrt{K_a} , \tag{4}$$

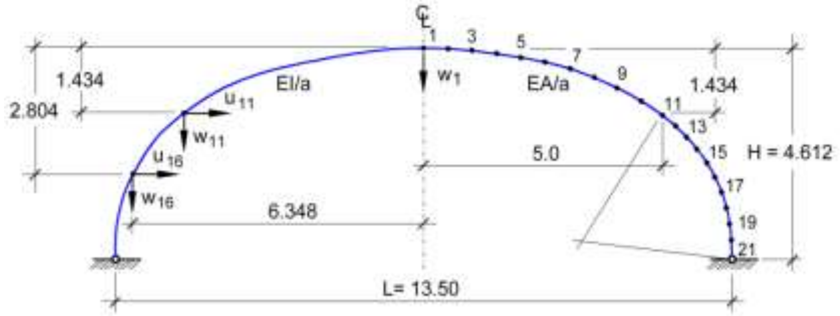
where: γ_g – volume weight of ground, *c* – cohesion coefficient. Distribution of pressure in (4) is a linear dependence on the thickness of the backfill z_i (Distance of the analysed point from the level of ground cover, as shown in Figure 2). In the function of many variables $K_a(\alpha,\beta,\varphi,\delta)$ it is considered the shape of the shell and ground parameters [5]. It should be remembered that the relationship (4) applies to ground pressure for massive retaining walls but not on the loose shell of corrugated plate as in the paper.

The discrepancy between the calculation results and the values p_i from (4) can be considerable. That is why, because in the calculation using (1) and in the values of impact p_i it is considered the actual physical parameters of the backfill ground, its layer system with different physical characteristics resulting from the degree of compaction and sometime different types of ground. An important effect has the technology of stacking backfill. The built object are essential the remaining elements of the second sub-system, e.g. pavement. A solid basis of the relationships (3) are static characteristics of the first sub-system, such as the shape and distribution of the stiffness of corrugated steel plate reflected in parameters of the displacement impact vector f_i [mm/kPa].

To obtain reliable estimates of interaction function *p* from (1) the methodology of successive approximations is used. Accuracy of elements of vector p_i is greater when several collocation conditions, i.e. displacement points s are used as in the example presented in the paper.

Studied object

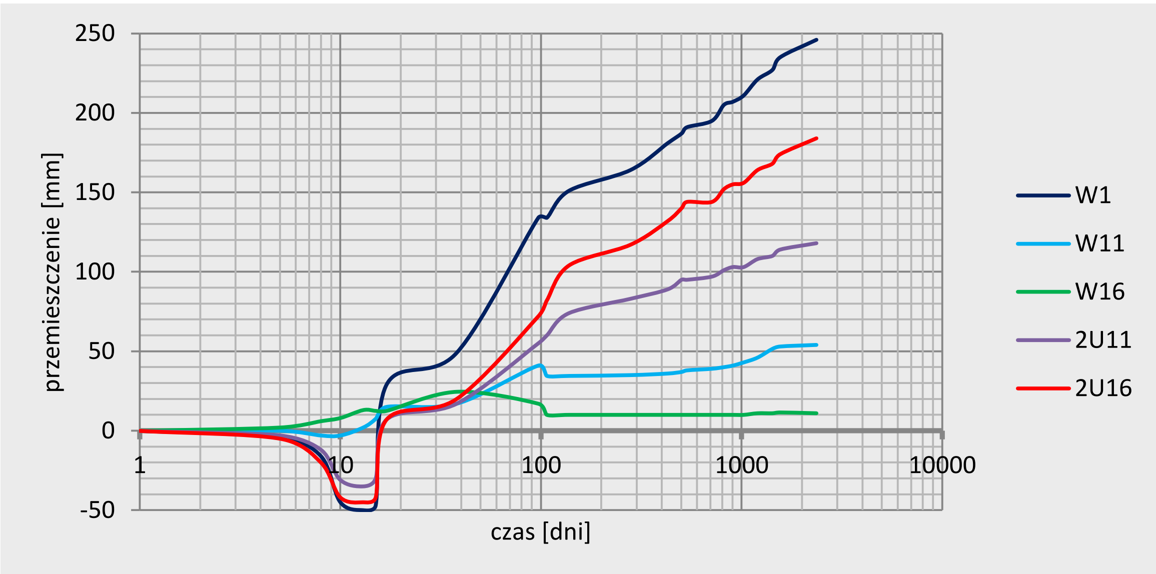
Figures 2 and 4 show the cross-sectional shape of a typical object with symbol SC-15NA [9]. Its shell has a parabolic from with the span of L = 13,50 m and height H = 4,68 m with ground cover with the thickness of 3.72 m. The shell is formed from corrugated steel plate with the profile SC 381 × 130 × 7. It is apparent from the measurements of deformation during building and exploitation that it is close to the symmetric from, which was used in the calculation model given in Figure 4. For estimating the impact of backfill to the shell, measurements of point displacements are used, as it is shown on the left side in Figure 4. These points with the same number are distributed on the shell with two radii of curvature. Among these points, measuring points were identified: in the shell key and two points on its side surface [9].



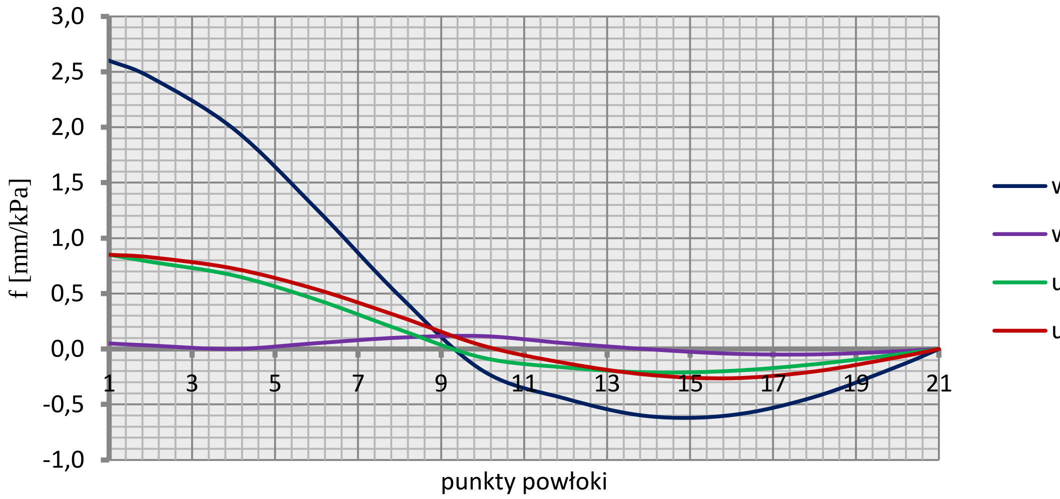
4. The computational model of the shell and displacement of collocation points

Changes in displacement of measurement points recorded during the construction period (1-67 days) and using this object for over six years are shown in Figure 5. These diagrams demonstrate that the dominant values of displacements concern w_1, u_{11} i u_{16} and these functions are proportional to time. In the study, we used the movement as a value *s* in the colocation condition (1).

Figure 6 shows the effect of selected functions of displacement when the load is evenly distributed force over the reporting point *i*, on two sections between the points i-1, i, i+1. These diagrams indicate that to determine the effects of p_i are useful displacements w_1, u_{11} and u_{16}. The influence function $f(w_1)$ is important to determine the impact on the shell key p_i. Therefore, it can be taken as the basic. It is visible form plots of $f(u_{11})$ and $f(w_{16})$ that small changes in p_i substantially affect the horizontal displacements in the shell groin. Options to use the function $f(w_{11})$ as a condition for co-location are limited, which is also reflected in the values given in Figure 5. The sections between the points 1-11 are longer than between points 11-21. Hence discontinuities of influence function are noticeable in the point 11.



5. Changes in displacements points of shell during building and exbploitation of object



6. Impact functions of shell displacement

Impact of ground on the shell

The normal components of ground forces influencing on the shell p_i were determined in three phases of building (1-107 days), and three periods of the object exploitation (107 - 2364 days). In Table 1, the measured displacements of measuring points are presented as in Fig. 6. They were used in the calculation of p_i. The last column shows the values of ground pressure at the support point 21 (the vertical concrete wall supporting the shell) calculated from the formula (4) after assumption of $c = 0$ and as constant:

$$\gamma_g \cdot K_a = 12 \ kN/m^3, \tag{5}$$

hence

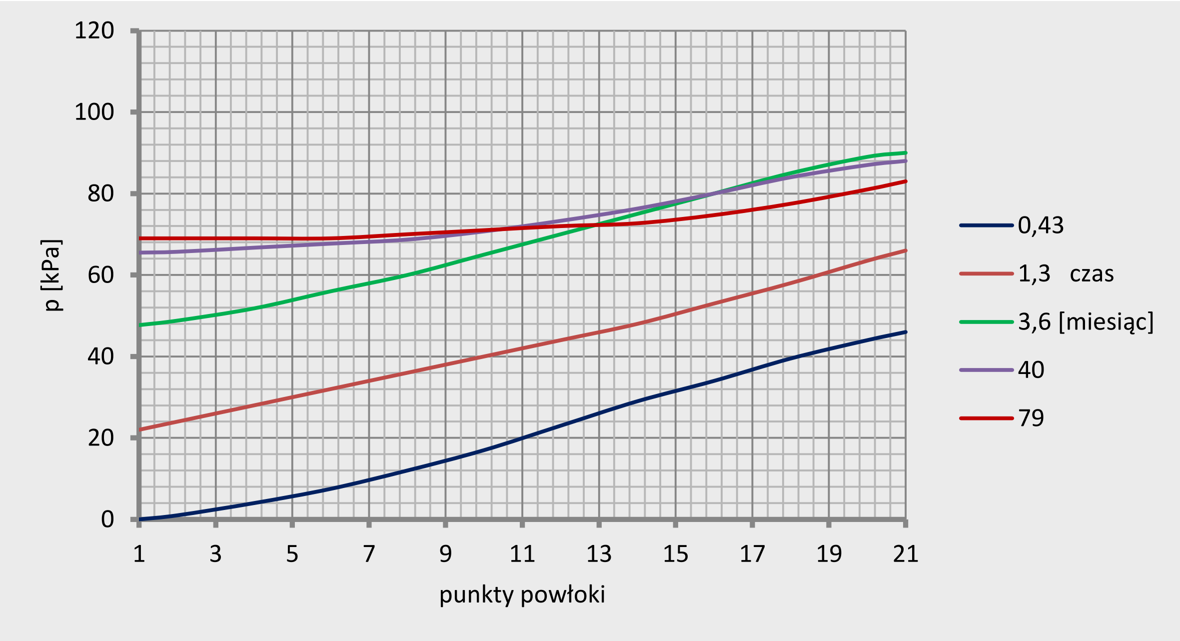
$$p_{21} = 12 \cdot z_g . \tag{6}$$

In studies of ground backfill of the object, an extremely high value γ_g = 23.5 kN/m^3 was obtained. Thus, from (5) the high value K_a = 0.51 was estimated obtained from the simplified formula (4), i.e. without inclusion of cohesion parameter c.

Tab. 1. Changes in movements and impacts during building and exploitation of object

Time [days]	Point displacements [6] [mm]			Influence	
	w_1	u_{11}	u_{16}	z_g [m]	p_{21} [kPa]
13	-50	-17,5	-22,5	4,7	56,4
38	49	8,5	10	6,5	78,0
107	134	30	41	8,4	100,8
1200	221	54	82		
2364	246	59	92		

Figure 7 shows results of calculation of the impact of p_i found from (1), when $s = w_1$, i.e. based on the deflection of the shell key. Plots in Figure 8 were obtained in a similar manner but using the horizontal displacement u_{11}. In the case of Figure 9, as a colocation condition (1) assumed a horizontal movement of the side wall of the shell u_{16}. Since each of the collocation conditions is considered independently, slightly different distributions of forces are obtained $p(s)$ as shown in Figures **7-9**. To check the efficiency of the estimated interaction equation (1) is used but in application to other measuring points of the shell. Of course, the full agreement by definition is achieved in the measurement points in the collocation condition. Displacement calculated in this way is presented in Table 2.

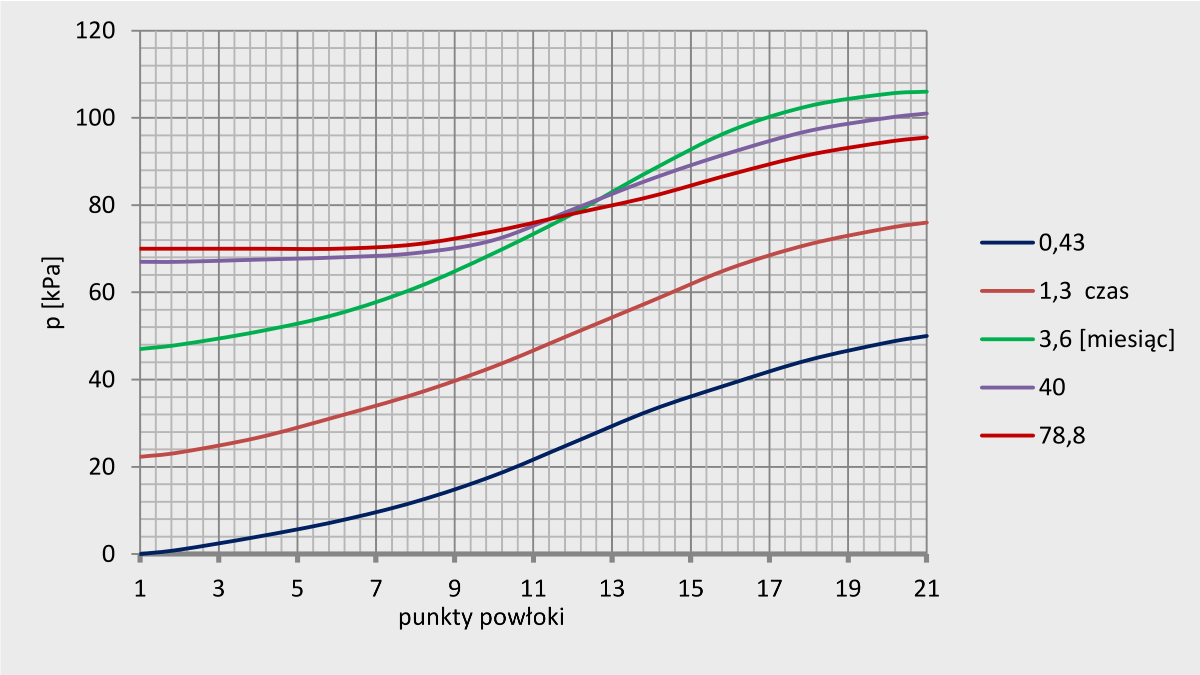


7. Changes in the influence of $p(w_1)$ calculated from the colocation condition $s = w_1$

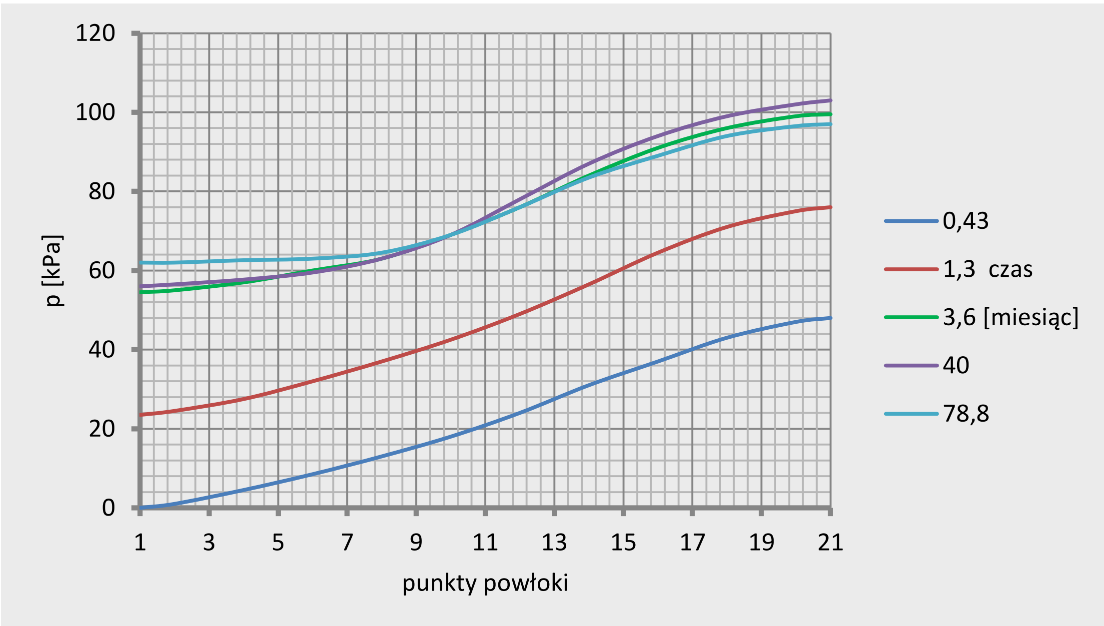
Tab. 2. Results of displacement calculations of measuring points of shell

Time [days]	Point displacements [mm]		
	w_1	u_{11}	u_{16}
13		-16,70	-18,16
	-52,72		-19,25
	-59,41	-20,09	
38		15,84	21,84
	27,34		13,12
	19,81	6,09	
107		26,22	56,20
	144,12		59,51
	96,98	13,80	
1200		81,08	89,62
	142,0		58,41
	203,0	74,93	
2364		80,69	99,28
	179,64		72,65
	227,50	74,55	

By comparison of the plots shown in Figures 7-9, for the same time periods, there is visible a small difference despite the change in the collocation condition which can be considered a good estimate of the influence *p(s)*. The analysis of the movements given in Table 2 indicates substantial differences in spite of minor changes of *p*(s) which can be regarded as an support of the previous conclusion. The applied simplification in the symmetry of the model had an influence on the divergence of results shown in Figures 7-9 and Table 2. It was the basis for the research methodology of the studied object [9]. Previously, the effects of tangential forces t_i were neglected. Plots shown in Figures 7-9 are important in the estimation of the influence of the ground on the shell in the absence of stabilizing movements of the shell (propagation of deformation during exploitation), which is shown in Figure 5.



8. Changes in the influence of $p(u_{11})$ calculated from the colocation condition $s = u_{11}$



9. Changes in the influence of $p(u_{16})$ calculated from the colocation condition $s = u_{16}$

Summary
Mapping structure to work the soil and the coating properties in models of FEM [2], [10] and assessing their safety during construction and operation of [5], [9], [6] uses three kinds of measurements:
• movement of the coating with surveying techniques [5], [9], [6];
• deformation of the corrugated plate coatings using extensometer [5], [6], [7];
• pressure of the backfill ground on the shell using pressuremeters [11], [1], [4].

In each of these groups, different research methodology is carried out and as a result, various results are obtained about the object. In the example given in this paper, the ground pressure on the

shell is achieved on the basis of the displacement of the shell like in pressuremetric measurements. On the base of the deformation of the shell, there are also obtained tensions in the corrugated plate as shown e.g., in [5], [8], [6], [7] and thus with the use of tensometric measurements. Therefore, the results of displacement measurements give a more general view on the construction than the previously mentioned methods of measurement. Geodetic measurements of shell deformation during the building are also made to other works while a specialized staff and equipment are necessary to the tensometric and prssuremetric measurements.

Determining the impact of ground on the shell is a traditional geotechnical task. When ground cover is loaded with a concentrated force it is Bousinesqu's task. In the case of the self-weight of backfill ground (with distributed load of ground cover) are in force the classic solutions of: Coulomb, Müller-Breslau, Rankin. In the case of steel shells with corrugated plates, the following methods were used: Duncan's, Spangler's, Wite's and Layer's, Meyerhof's and Baike's or Klöpel's - Glöck's [4] and many others. Numerous studies such as [11], [1], [6], [4] tried to determine the ground pressure on the shell using various research methods.

In this work, we are show the opportunity to obtain the impact of p_i based on deformation of the shell. This is achieved by the method of successive approximations, and the estimates depend on the assumed collocation point. The advantage of such algorithm is taking into account the physical characteristics of the ground in backfill layers and especially the technology of its laying and compacting. The results of these analyses can be the basis for comparing the effectiveness of classical geotechnical models mentioned above. Measurements of ground impacts on the shell are performed sporadically.

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