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CORRUGATED SHELL DISPLACEMENTS DURING THE PASSAGE OF A VEHICLE ALONG A SOIL-STEEL STRUCTURE

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Abstract: Corrugated steel plates are highly rigid and as the constructions can be immersed in soil, they can be used as soil-steel structures. With an increase of cover depth, the effectiveness of operating loads decreases. A substantial reduction of the impacts of vehicles takes place as a road or rail surface with its substructure is crucial. The scope of load's impact greatly exceeds the span L of a shell. This article presents the analysis of deformations of the upper part of a shell caused by a live load. One of the assumptions used in calculations performed in Plaxis software was the circle-shaped shell and the circumferential segment of the building structure in the 2D model. The influence lines of the components of vertical and horizontal displacements of points located at the highest place on the shell were used as a basis of analysis. These results are helpful in assessing the results of measurements carried out for the railway structure during the passage of two locomotives along the track. This type of load is characterized by a steady pressure onto wheels with a regular wheel base. The results of measurements confirmed the regularity of displacement changes during the passage of this load.

Key words: *corrugated shell, displacements, soil-steel structure*

1. INTRODUCTION

Steel corrugated plates of soil-steel structures are formed from metal shell that provides complex cross-sectional shapes in the form of circle sections. Their common geometrical feature is the presence of a circle segment with a radius of curvature R in their crowns. Due to the shape of a shell, two basic groups of its structure are distinguished: box and arc-shaped. This division is due to the characteristic deformation of plates during the construction of a structure and therefore when laying the backfill layer [7]. Under a service load, deformations of all shells are similar, regardless of their cross-sectional shape. During construction, the deformation and displacement of corrugated shell, resulting from the impact of backfill, is many times greater than during the exploitation of the structure [7].

Corrugated plates are characterized by high rigidity [2], but only as structures submerged in soil and therefore when being used as soil-steel structures. With an increase of cover depth thickness, the effectiveness of service loads decreases. Thus, there is a substantial reduction in the impacts of vehicles, because a road or railway surface with its substructure has a crucial influence. The range of the impact of loads changing their position on a cover depth greatly exceeds the span of a plate L.

Fig. 1. The passage of a train along a soil-steel structure in a dynamic test [4]

Research of building structures under a live load is focused on dynamic analysis, e.g., [1], [4], as in Fig. 1. An important matter, in order to determine the mechanics of soil-steel building objects as elastic plates immersed in soil, is also static research, e.g., [2], [5], [8]. Influence functions used in the models of bridges, e.g., [3], can be useful in such analysis. They can also be determined on the basis of results of measurements on operated objects under loads in the form of concentrated forces coming from the wheels of a vehicle [2]. Then, the interaction of all structural elements, including a surface that is treated in conventional bridges as equipment, is considered.

2. THE METHOD OF ANALYZING THE EFFECTIVENESS OF LOADS ON A COVER DEPTH

In a soil-steel structure, loads in the form of the impact of vehicle wheels on a road are transferred onto the steel plate through the backfill layer. While analysing the steel plate deformations, it is seen as a displacement of measuring points at a predetermined position of a road loading. In Fig. 2, the analyzed measuring point is point C and the measured value is the horizontal component of the displacement u_c. Its change in relation to the concentrated force moving along the road axis x is defined by the influence function $\eta(x)$. It is defined as the result obtained from the force P with a unit value moving along a predetermined trajectory – in this case along the x-axis. The definition of the influence function indicates that

$$u_c = P \cdot \eta(x). \quad (1)$$

In the case of road and rail vehicles, and therefore the group of concentrated forces, the displacement caused by the n number of wheels with pressures P_i is calculated from the formula

$$u_c = \sum_{i=1}^{n} \eta(x_i) \cdot P_i \quad (2)$$

where η_i are the ordinates of the influence function of deflection as shown in Fig. 2. It can be concluded from formula (2) that the effects of loads arising from individual forces in a vehicle are added together as in the case of a complex construction (multi-layered or composite), but with elastic characteristics.

Figure 2 shows the characteristic parameters of the geometry of the circumferential segment of a simple building structure with a circular shaped shell, a radius of curvature R and span L at a height h. The thickness of the cover depth on which the load is moving is designated as H. A model of the geometry of the circumferential segment of the structure with a unit width (1 m) and discretization of soil and the corrugated shell is used in order to determine the influence function of the displacement $\eta(x)$. A plane computational FEM model (i.e., in 2D space) is used in Plaxis software as shown in Fig. 3.

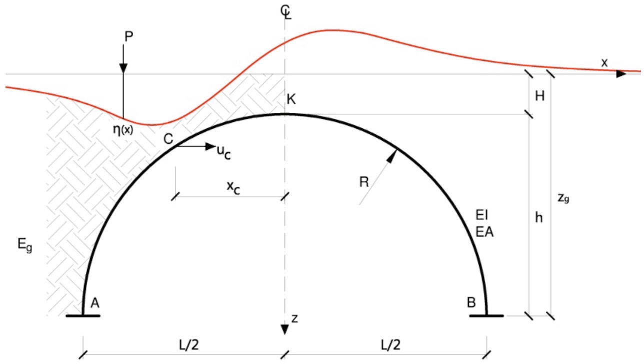

Fig. 2. Geometrical characteristics of a circumferential segment of a soil-steel structure and the influence function of shell horizontal displacement

In order to determine the influence function of a shell displacement, both the principle of reciprocity of reactions and also Rayleigh displacements are used. According to this principle, as a result of a unit horizontal force applied to a shell immersed in soil, the influence function of this displacement occurs at the place and in the direction of the analysed displacement. In the example given in Fig. 2, the analysed horizontal displacement of the shell is u_c and the loads acting on the building structure are vertical forces P moving along the cover layer. According to this principle, the function of horizontal displacement (x) (in accordance with the direction of the force P) occurs as a result of loading a steel shell with a unit horizontal force at point C. The deflection function $w(x)$ is, at the same time, an influence function of the displacement u_c as there is a $w(x) = \eta(x)$ relation when the line of the load movement is located on the x-axis, as shown in Fig. 2.

Plaxis 2D software is a tool for two-dimensional calculations of finite elements, designed for analysis of deformation, ground stability and underground water flow in geo-technological engineering. The analysis performed assumes geometric non-linearity of the material. Software makes it possible to setup step-by-step soil backfill and automatically increases load in each design phase to achieve best projection of real world conditions. Load from the ground is passed on to corrugated shell through pressure, taking into account the glide between the shell and the ground with fraction coefficient equal to 0.1.

In the analysis of examples examined in the paper, simple geometry of a shell in the form of a half-circle segment with a radius R = 5 m, span L = 10 m and height h = 5 m, and also cover depth thickness H = 1 m, were assumed and shown in Fig. 4. The shell was made of a corrugated steel plate with a profile MP of 200 × 55 × 7, typically applicable in such building structures. The physical parameters of soil were as follows: compression modulus E_g = 10 MPa, unit weight γ_g = 21 kN/m^3 and cohesive factor c = 0.1.

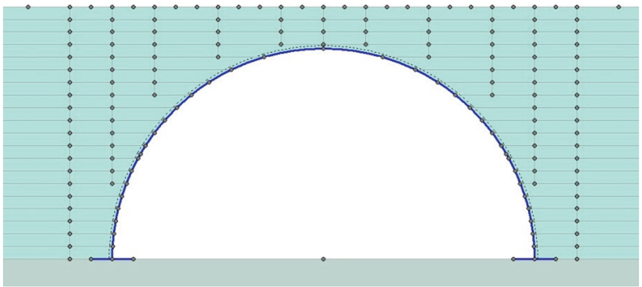

Fig. 3. Model of the soil-steel structure created in Plaxis software

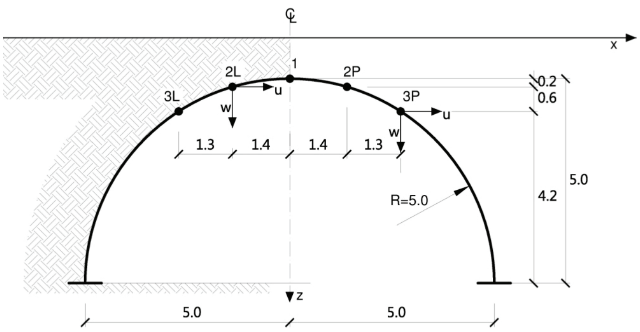

Fig. 4. Scheme of the circumferential segment of the soil-steel structure and the location of the point analysed

3. THE INFLUENCE LINES OF DISPLACEMENTS

Figure 5 shows the influence lines of deflection counted for points on the left side of the shell, which are shown in Fig. 4. These diagrams are similar and extreme values are situated over the analysed point. The highest value of $\eta(x)$ occurs in the shell crown and smaller values in the side parts of the plate in accordance with the increase of distance from the crown. The area of the impact of load greatly exceeds the span L. Along the length of the building structure, positive and negative areas $\eta(x)$ occur during the movement of the load. This firstly results in the deflection of the analysed point up, then down and then up again.

In the case of horizontal displacements, the diagrams shown in Fig. 6 are similar, regardless of the location of the analysed shell point that was shown in Fig. 4. When analysing twin points, e.g., 3L and 3P, the influence lines are similar but offset from each other – as shown in Fig. 7. Therefore, during the passage of a vehicle across the building structure, extreme values of displacements occur initially in the first point (3L) and then in the second point (3P). The comparison of both functions $\eta_{3L}(x)$ and $\eta_{3P}(x)$ indicates that there is a lack of symmetry. Even when

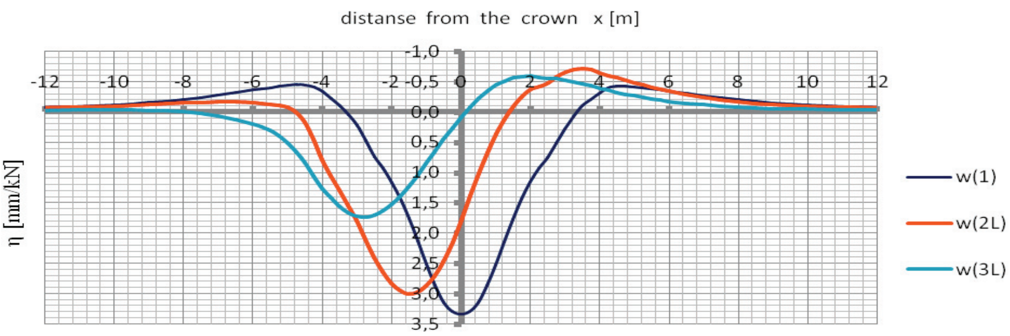

Fig. 5. Influence functions of deflection of the analysed shell points shown in Fig. 4

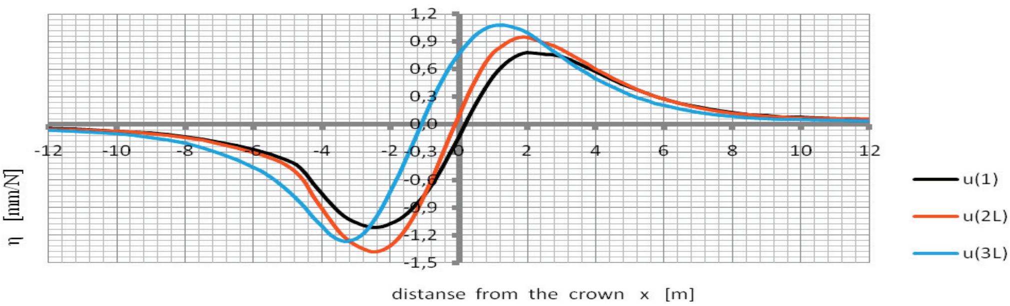

Fig. 6. Influence functions of horizontal displacements of points on the left side of the shell which are shown in Fig. 4

$x = 0$, therefore under asymmetric load, there is no equality of displacements u_{3L} and u_{3P}. This is in the first case due to the direction of the displacement from the soil to the centre of the shell and in the second case the other way round, as shown in Fig. 4. This is a specific feature of soil-steel structures.

In the case of shell immersed in soil, the direction of the displacement of the corrugated plate in relation to the soil is crucial. Due to the physical characteristics of soil, the displacement directed from the soil towards the shell, as shown in Fig. 4 and caused by earth pressure, will have a different course than in the reverse situation, namely under rest earth pressure. Figure 8 presents a comparison of these diagrams for points 3L and 3P. Therefore, there are two influence lines. When a concentrated force moving along the *x*-axis from left to right is the load, effective diagrams can be distinguished and are indicated by lines – depending on the direction of the displacement.

The main objective of the results shown in Figs. 5 to 8 is an illustration of the shape of the influence function (line) of the analysed displacements of the shell due to concentrated loads of cover depth rather than the values of the ordinates of these diagrams. The

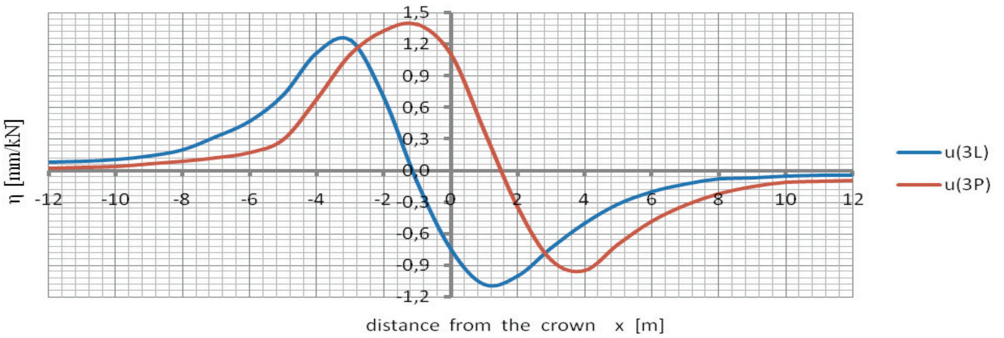

Fig. 7. Influence functions of the horizontal displacement of point 3 located on the left and right side of the shell

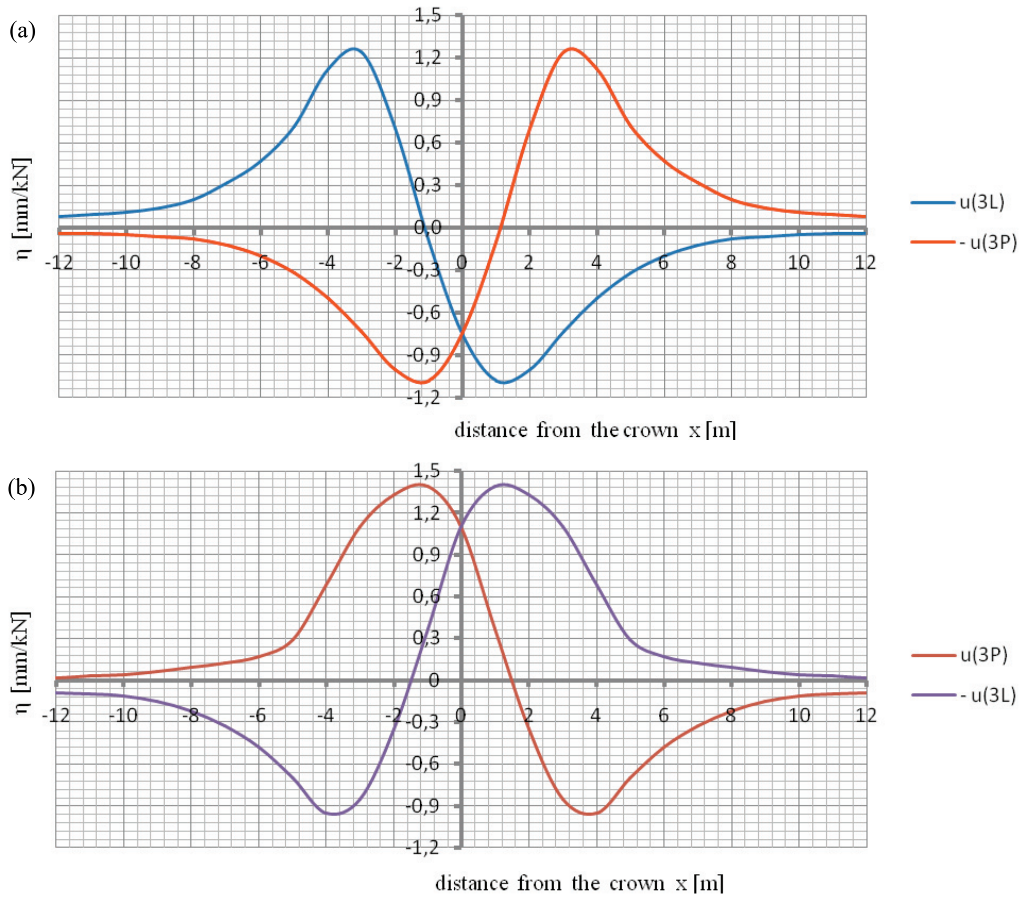

Fig. 8. Double influence functions of the horizontal displacement of points 3 located on the left and right side of the shell: a) displacement in direction from the ground, b) displacement in direction towards the ground

numerical values of these ordinates depend on many factors such as the rigidity of the corrugated plate (*EI* and *EA*), the physical characteristics of soil, as well as the geometry of the shell (*L*, *h*, *R*) and also the thickness of the backfill layer above the plate, namely the cover depth *H*. The result of calculations is affected by the complex shape of the steel shell with multiple radii of curvature and also the width of the structure (the length of the culvert). The road (asphalt) or rail surface with its substructure is crucial. Due to the above reasons, the simplest geometry of the steel shell without a surface, as shown in Fig. 2, i.e., such as ones that occur during construction, was assumed for the calculations.

4. DISPLACEMENTS OF THE STEEL SHELL AS A RESULT OF MEASUREMENTS

Figure 9 shows an example of analysis of the deformation of the shell of the existing rail soil-steel structure located in Krosnowice near Kłodzko. The twin structures [6] were made of a pipe-arch shaped shell (closed) with the following geometrical parameters: L = 4.40 m and h = 2.80 m. They were made of a corrugated steel plate with a low profile of MP 150 × 50 × 4.75. In the studies, a service load, in the form of two ST43 type locomotives, was assumed. The load is characterized by a uniform pressure on axes P = 192.9 kN. Important in this case is the identical spacing of locomotive trucks *d*. It results from the geometry of locomotive axes: a_1 = 1.95 m, a_2 = 2.15 m and c = 4.2 m (shown in Fig. 11). Therefore, the spacing between the trucks inside the locomotive amounts to $d = c + 2a_1$ = 8.5 m, and between two locomotives also $d = 2(b + a_2)$ = 8.5 m. During the analysis, the locomotives changed their location along the track with velocity v = 2.6 m/s and on their way back with velocity v = 4.2 m/s. It can be concluded that it was a quasi-static passage.

Fig. 9. The passage of two locomotives along the building structure analysed

A diagram of the shell crown deflection $w(t)$ shown in Fig. 10 was made using the results of measurements performed automatically [6]. This diagram is analogous to the other, resulting from tests carried out for building structures with both curved and vaulted shapes [2]. The maximum value of the deflection amounted to w = 0.40 mm, which is an indicator with a very small value of $\omega = w/L$ = 1/11 000. The impacts of four consecutive locomotive trucks, which repeat in regular time intervals Δt that result from the value *d*, are visible in the diagram of the deflection of the steel shell crown during the passage of locomotives as shown in Fig. 10 and are described by the following formula

$$\Delta t = \frac{d}{v} = \frac{8.5}{2.6} = 3.27\ \text{sec}. \quad (3)$$

Thus, the extreme values $w(t)$ occur when t is equal to 12, 15.3, 18.5 and 21.8 seconds, under equal forces *P*. This indicates the elastic deformation of the steel shell. The disappearance of deflections after the

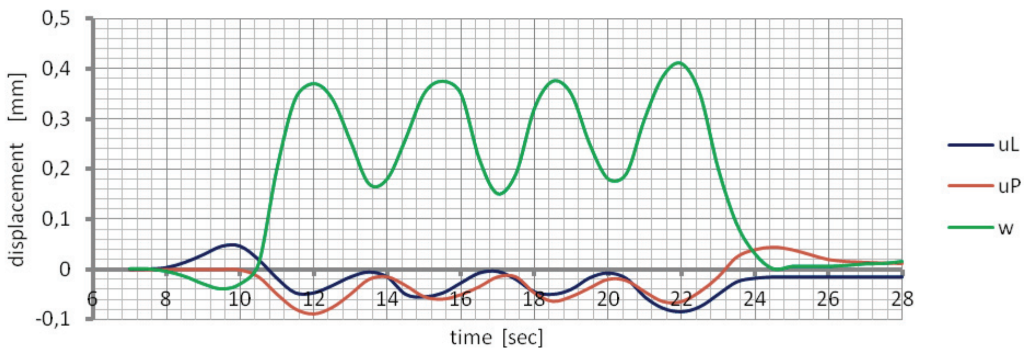

Fig. 10. Deflections of the shell crown during the passage of two locomotives

passage of the load is important in this analysis. Identical results, but reversed symmetrically to that shown in Fig. 10, were obtained on the return passage.

Horizontal displacements measured on the left "L" and right "P" side of the shell at a distance $z = 1.9$ m from the crown, as shown in Fig. 11, are interesting in this case. Diagrams of horizontal displacements given in [6] as a function of time $u(t)$ were converted into a function of the location of load $u(x)$ assuming the central axis of the front locomotive truck as a reference force position. Thus, when $x = x_1 = 0$, the central axis is above the shell crown – in such a position, the first extreme value of the deflection shown in Fig. 9, occurs. Due to the same values of $d = 8.5$ m, the consecutive three middle axes of the two locomotives trucks are offset by the following coordinate values: $x_2 = d = 8.5$ m, $x_3 = 2d = 17.0$ m, $x_4 = 3d = 25.5$ m.

The result of measurements for the passage of locomotives from the left side to the right is shown in Fig. 11a and the return passage in Fig. 11b. Repeatability of results with specific diagrams during the entry and exit of the load is seen in the displacement diagrams. During the passage from the left side to the right, the sensor on the left indicates the displacement in accordance with the direction of the passage. During the return passage, the diagrams are analogously reversed. Such regularity indicates a negligible effect of the twin construction of the culvert, as shown in Fig. 9, despite its small distance of 5.90 m between axes (similar to the span L) and 1.5 m from the side walls of the shell. A regular wave of the displacement in the middle of the diagrams results from the similar values of $2L$ (span) and $d/2$ (spacing between the trucks) and also the shapes of the influence lines shown in Figs. 5 to 8.

Figure 12 shows selected characteristic positions of axes of locomotives that occur during passage. In positions "a" to "f", the position of the reference axis (the one in the middle of the locomotive truck) was distinguished. In the locomotive position "a", the sensor on the left side indicates the highest positive displacement while the sensor on the right shows no activity. In position "c" of the locomotives, the symmetry of the load and extreme values of $u(x)$ occur but there is a lack of symmetry of displacements (values) of the shell. Both the values of displacements close to zero and the symmetrical loads also occur in position "d".

In "e" and "f" locomotive positions, extreme values of displacements occur on the left or right side of the shell. A full symmetry in loading the structure with locomotives is in position "g". There are also similar u_L and u_P. In position "h" there is an asymmetric location of the load in relation to "c". Therefore, readings of u_L and u_P are reversed regarding the value. A similar situation occurs in position "i" with respect to "b" and "j" with respect to "a". Diagrams of displacements indicate regular behaviour of the structure during the outbound and inbound passage of the locomotives.

The maximum values given in Fig. 11 are several times smaller than the deflection presented in Fig. 10. However, the regularity and consistency of displacements obtained during the analysis and the position of axes of locomotives during the passage in both directions is crucial. The end of the passage is analogous to

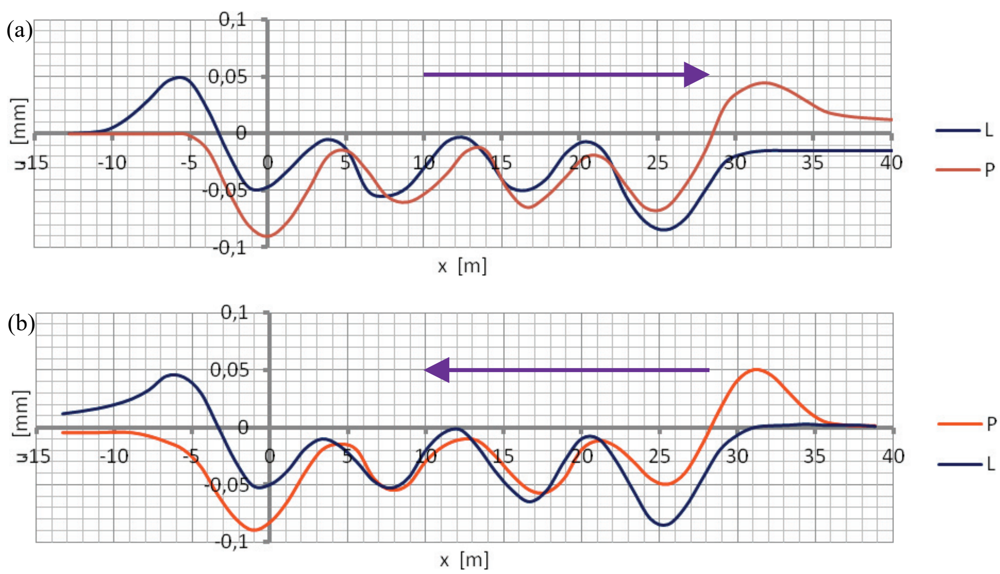

Fig. 11. Horizontal displacements of the shell during the passage of two locomotives:
a) from the left side to the right, b) return passage

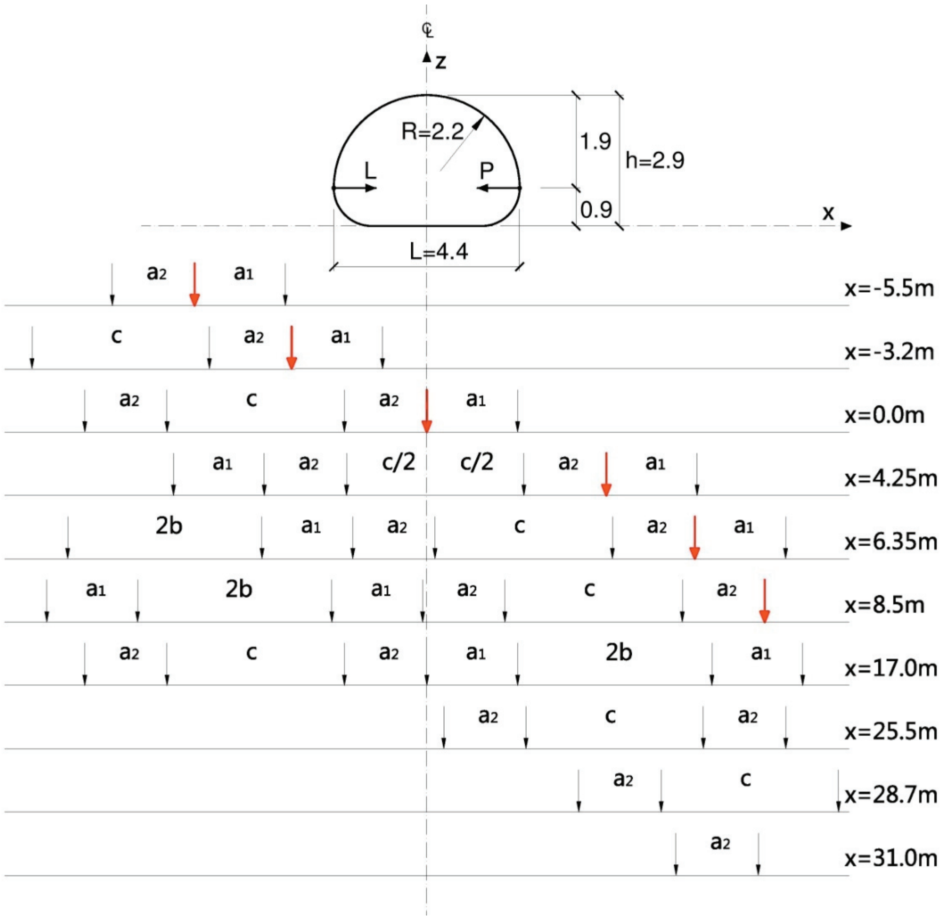

Fig. 12. Positions of locomotives axes above the shell during the passage

the start with the registration of the remaining values (residual), but with low values in relation to the accuracy of sensors and the maximum values of deflections.

5. INFLUENCE LINES OF THE DISPLACEMENT OF THE SHELL AS A RESULT OF THE MEASUREMENTS

In the case of measurements of displacements on the real object, the influence lines of these values can also be created and will be analogous to those shown in Figs. 5 to 8, and thus from a single concentrated force moving along the x-axis. Figure 13 shows such diagrams, obtained from the displacements shown in Fig. 11a. Loads from the first locomotive truck defined in schemes "a" to "d" and shown in Fig. 12 were assumed in the calculations. The ordinate values of the influence lines were multiplied by the pressures on the axes of locomotives $P = 192.9$ kN. Due to this, the functions of horizontal displacements $u(x)$ (obtained from the system of concentrated forces P) with ordinates of influence lines $\eta(x)$ received from a single force P can be compared.

From the comparison of both diagrams for points "L" and "P", their apparent similarity with respect to the vertical axis ($x = 0$) and the assumption of the symmetrical directions of displacements as shown in Fig. 12, can be seen. The diagram denoted as "L", within the interval of $-3.5 < x < 0$, looks similar to the diagram "P" within the interval of $3.5 > x > 0$. However, the ordinate values are in a ratio of 0.054/0.040 (calculated for $x = 0$). A significant difference of function $\eta(x)$ refers primarily to the interval of $-4 < x$ of the diagram "L" in relation to the interval of $x > 4$ of the diagram "P". A lack of symmetry in relation to the vertical axis can be seen in the analysis of results given in Fig. 13. In this case, the reason for this is not the twin construction of the structures but the particularly short distance between them. The scope of the influence line "L", which is shown in Fig. 13 and begins from the $-x = 2L$, greatly exceeds the area above the steel plate ($L/2$).Thus, the impact of live loads on a structure with a considerable height of cover depth and surface occurs at a considerable distance from the structure.

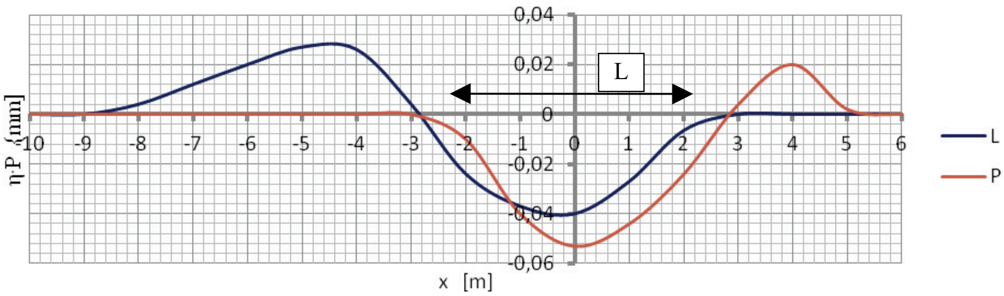

Fig. 13. Influence lines of the horizontal displacement of the "L" and "P" side of the shell determined on the basis of measurements

6. SUMMARY

The impact of loads changing their location, and therefore live loads but with static characteristics, on the deformation of shell of soil-steel structures has been analyzed in the paper. The influence functions of displacements of the elastic shell immersed in soil have been used for this purpose. The physical characteristics of soil have been determined in Plaxis software, which is used for parametric analysis. In the model of a building structure and in 2D space, a circumferential segment of the construction with an example of a simple shell in the form of a circle section has been executed. Examples presented in the paper provide the basis for assessing the behavior of steel corrugated plates of operating building structures subjected to traffic loads.

The results of measurements from the analysis of the twin railway structure were the purpose of the study. The procedure regarding loads that change their position during in bound and out bound passage has been used in the analysis [2]. It gives an opportunity to evaluate the behavior of a twin structure in relation to a single structure – with the assumption that the building structure is symmetrical with respect to the vertical axis passing through the crown of the shell. The measurement results, with the use of this procedure, indicated an egligible impact of the twin shell in this building structure.

An analysis based on the use of influence lines of displacements is preferred as a universal approach. It gives an objective view of the range of impact coming from the loads of a road in the form of a group of concentrated forces that occur in a vehicle. The shape of these lines indicates the unfavorable position of vehicles. It is helpful in assessing the impacts of live loads which are dangerous for a shell. It is convenient to use the method of kinematic extortion [3] in order to determine the influence functions (line and area of influence) of the internal forces and displacements in a shell of soil-steel structures using any MES software.

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