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LIVE LOAD EFFECTS ON A SOIL-STEEL BRIDGE FOUNDED ON ELASTIC SUPPORTS

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Abstract: Bridges of soil-steel structure built as traffic objects of small spans are attractive because of their architectonic values as well as technical qualities and low costs associated with them. Essential elements of such structures are: steel shell supported on a foundation, soil backfill surrounding it and the kind of roadway. In this paper, the results of measurements and the calculations for bridge construction are presented. Erection of the bridge under consideration is far different from classic structure engineering and the form of soil-steel objects. The shell was made of flat steel instead of corrugated steel and the soil backfill was put without extra assembly scaffolding. The support of the shell is of elastic construction made from steel sheet piles crowned with a steel top girt. The technology applied allows us to shorten the time of bridge construction to a necessary minimum, especially under the conditions of soil saturated with water.

In this paper, displacements and external forces in the shell made by live loads are analyzed. The results of testing the object under changing loads testify to a nature of the construction as heterogeneous system. If loads, i.e., vehicles cross from one side of the bridge to the other, the measured deflections and unit strains confirm the statement that in the carrying system the soil backfill is of a special importance. Because in this construction the backfill is a loose material, the effects of changing load depend on shell deformation before measurements. The test and calculation results indicate that the construction analyzed behaves as classic soil-steel objects.

Streszczenie: Mosty o konstrukcji gruntowo-powłokowej, budowane jako obiekty komunikacyjne o małej rozpiętości, są atrakcyjne zarówno z uwagi na walory architektoniczne, jak i na zalety technologiczne i związane z tym niskie nakłady finansowe. Zasadniczymi elementami takich konstrukcji są: stalowa powłoka podparta na fundamencie, otaczająca ją zasypka gruntowa oraz nawierzchnia jezdni. W pracy przedstawiono wyniki pomiarów i obliczeń konstrukcji mostu, który różni się od mostu budowanego według klasycznej technologii i przyjętego ukształtowania obiektów gruntowo-powłokowych. Powłokę wykonano z blachy płaskiej zamiast falowanej, a przy tym zasypkę gruntową układano bez dodatkowego rusztowania montażowego. Podparcie powłoki stanowi konstrukcja podatna, wykonana z grodzic stalowych zwieńczonych stalowym oczepem. Zastosowana technologia skraca do minimum czas realizacji budowy, szczególnie fundamentów, w uciążliwych warunkach gruntów nawodnionych.

Analizowano przemieszczenia i siły wewnętrzne w powłoce wywołane obciążeniem ruchomym. Rezultaty badań obiektu pod zmiennymi obciążeniami wskazały na właściwą naturę tych konstrukcji jako układów niejednorodnych. W przypadku obciążeń przejeżdżających po moście mierzone ugięcia i odkształcenia jednostkowe potwierdziły, że w układzie nośnym dużą rolę odgrywa zasypka gruntowa. Ponieważ jest ona w tej konstrukcji ciałem sypkim, więc efekty obciążeń zmiennych zależą od poprzedzającej pomiary deformacji powłoki. Wyniki badań i obliczeń wskazują na to, że analizowana konstrukcja zachowuje się jak klasyczne obiekty gruntowo-powłokowe.

Резюме: Мосты, характеризующиеся грунтово-настильной конструкцией, построенные как коммуникационные объекты малого пролета являются заманчивыми как из-за архитектонических, так и технологических положительных черт и низких денежных затрат. Основными элементами таких конструкций являются: стальный настил, крепленный на фундаменте, окружающая его загрузка и покрытие проезжей части дороги. В настоящей работе представлены результаты измерений и расчетов конструкции моста, который отличается от моста, построенного согласно классической технологии и принятому рельефу грунтово-настильных объектов. Настил был выполнен из плоской стали вместо волнистой, причем грунтовая загрузка была укладываемая без подлесок. Крепление настила составляет податливая конструкция, выполненная из стальных шпунтин, венченных стальной обвязкой. Примененная технология сокращает время реализации постройки, особенно фундаментов, в неблагоприятных условиях подмокших грунтов.

Был проведен анализ смещений и внутренних сил в настиле, вызванных подвижной нагрузкой. Результаты исследований объекта под влиянием переменных нагрузок показали свойственную природу этих конструкций как неоднородных систем. В случае проезжающих по мосту нагрузок измеряемые прогибы и единичные деформации подтвердили, что в несущей системе важную роль играет грунтовая загрузка. Из-за того, что в этой системе она является сыпучим телом, эффекты переменных нагрузок зависят от опережающей измерения деформации настила. Результаты исследований и расчетов показывают, что анализируемая конструкция ведет себя как классические грунтово-настильные объекты.

1. INTRODUCTION

• **Classification.** Traffic structures such as culverts or small bridges of soil-steel construction can be divided into two basic groups [11], [20], i.e., rigid constructions which are mainly made of brittle materials (omitted in this work) and elastic ones. In elastic constructions, there is a profitable collaboration between a thin shell and a soil backfill when vertical loads from the roadway are transferred. Thus during designing such objects we consider both backfill and roadway of the construction and not filling like in vaulted bridges. The carrying system of an elastic construction is very heterogeneous as it consists of a spring shell, road pavement and thickened loose material (soil backfill). The shapes of shell cross sections may be diversified [7], [8], [17], [18]. Basically they are adjusted to the kinds of obstacles like water or traffic ones. Taking account of a longitudinal section along the circumferential strip, the shells of soil-steel objects are divided into open and closed (pipe) ones. The shape of a shell is usually associated with the thickness of soil backfill over a shell in the middle of the span. The tendency to design the constructions of small height (small thickness of backfill) in these objects is because of a natural trend of gaining the largest possible area underneath the bridge at a minimum amount of soil over the construction. That is why there are shells of small height, the so-called *box culvert*. In such objects [13], [14], unlike typical bridges of this kind [4], [9], [21], i.e., with a thick layer of soil backfill over the shell, we may expect local effects under the load caused by traffic. In order to smooth the results of loads caused by vehicle wheels in the objects of small thickness of the backfill, sometimes concrete plates made over the shell and under the road are used [1].

Corrugated sheets of two kinds, being different in wavelength and height, are used as shell constructions. Their trade names are: Multi Plate (MP) and Super Core (SC). The sheets vary in thicknesses depending on predicted shell strain. In the case of specifically great values of internal forces, multilayer systems or additional ribbing reinforcement ones are used. Open shells are usually supported by the foundation most often made of reinforced concrete. The real state of the shell effort is meaningfully influenced by soil backfill setting.

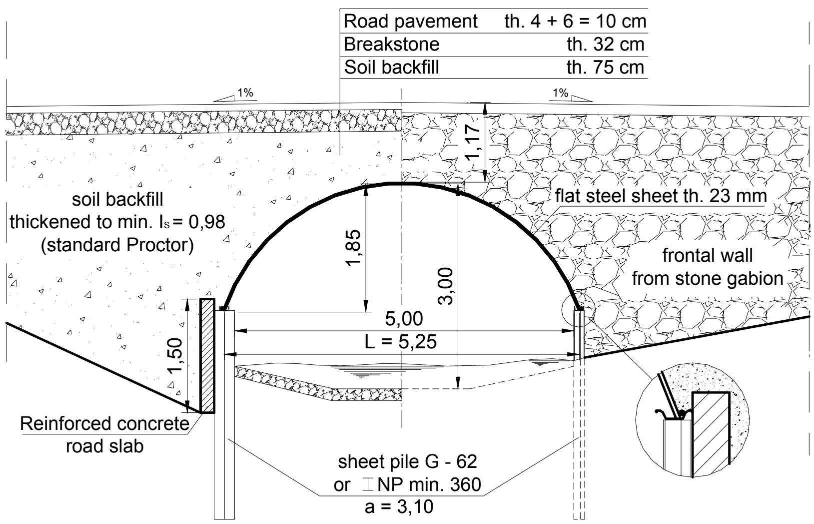

Fig. 1. Cross section of the bridge

• **Construction of the bridge analyzed.** The bridge shown in figure 1 is analyzed. It differs considerably in shape from soil-steel objects built according to classic engineering. The differences are as follows:

• the shell made of corrugated steel sheet was replaced by thin steel sheets, curved in circumferential direction, and the soil backfill was made without any additional assembly scaffold,

• the shell rings were supported by the elastic construction made from steel piles crowned with a steel top girt.

The basic construction element of this bridge is the soil backfill limited from the top by the road surface and from the bottom by the shell of a thin steel sheet supported by the elastic openwork support. The object was built and given for use as a detour (by-pass) bridge on national road no. 8, i.e., Wrocław–Kłodzko route, nearby the Niemcza village. In the longitudinal section, the bridge is a one-span circular arc of a curve radius $R = 2.75$ m and a span $L = 5.25$ m. The carrying structure of the bridge is a shell made of a thin steel sheet of the thickness $t = 23$ mm and the width $b = 1.50$ m. The bridge width $B = 15.0$ m. The steel sheets are connected in several spots of the coats contacts on the shell circuit by means of welded cover plates.

The shell coats were spaced in the cradle of a steel element which is a girt of piles. The piles were made in the form of individual sheets used to build sheet pile walls spaced every 3.10 m. The foundation serving as a steel shell support made from segments that were non-connected in a continual way was unique as the way of foundation of the bridge construction [19]. In the case of soil-steel construction, such a foundation is a considerable rationalization of work associated with setting the foundation, especially in difficult conditions in the area of water courses. The finished object was designed in the form of vertical walls made of gabions.

2. ROADWAY LOAD EFFECT TESTS

The tests on the object were carried out twice after soil backfill had been put, but before the road foundation and asphalt surface were laid, and at the time when the bridge was put to use (with the pavement). The tests conducted on the object during its construction were meant as the estimation of the road surface influence on the construction work.

• **Measuring base** was adjusted to load schemes by a vehicle and the configuration of the shell. The measuring points were set in the circumferential middle line of the shell of a selected steel sheet and on the crown line perpendicular to the roadway axis. In figure 2, there is shown the arrangement of inductive sensors and the pairs of strain gauges stuck in the circumferential direction and perpendicular to it at the bottom surface of the steel sheet. In this figure, the numbers of these measuring points are given.

• **Load of the object.** The bridge was loaded with the car of TATRA brand of the following weights per axle (according to the order starting with a front axle):

- in the tests without pavement: $P_1 = 54.0$ kN, $P_2 = 129.0$ kN and $P_3 = 102.0$ kN,
- in the tests with pavement: $P_1 = 55.6$ kN, $P_2 = 128.3$ kN and $P_3 = 124.6$ kN.

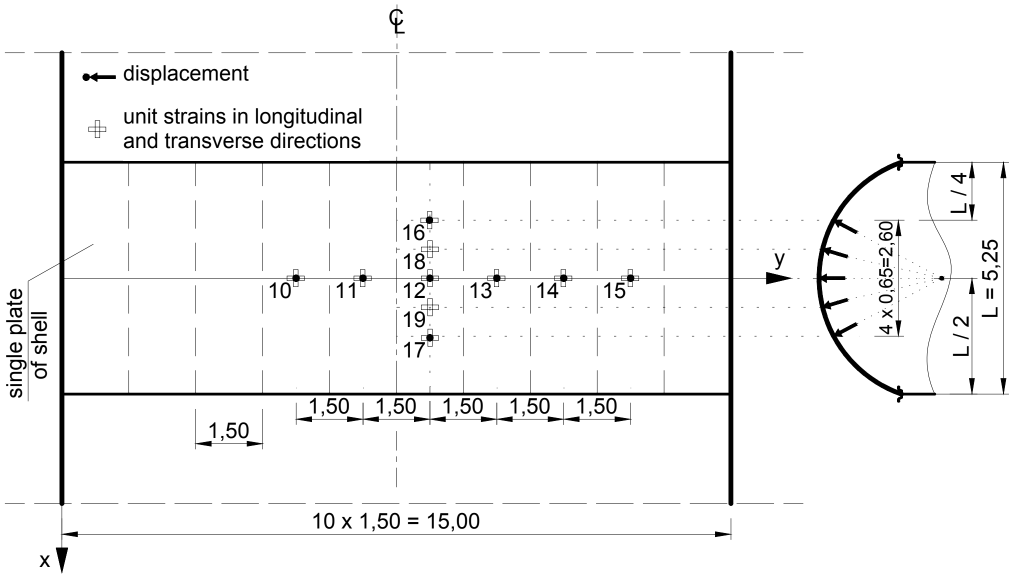

Fig. 2. Arrangement of the sensors on the bridge plan

The distances between the axles of the vehicle are: a_{12} = 3.55 m and a_{23} = 1.35 m.

The vehicle approach to the bridge was always done backwards up the travelling direction and coming back was in a proper direction like at a normal drive (forwards). One-wheel line of the moving vehicle was always lying over the measuring line. In the tests, two positions of the vehicle according to the cross section of the bridge were recognized, i.e.:

- central position when the roadway axis was between the wheels of the vehicle,
- side position when the vehicle was moving at one side of the roadway axis.

Table 1

Bridge load schemes

Vehicle positions	Phases of the bridge construction	
	Without pavement	With pavement
Central	SO	SN
Side	BO	BN

The vehicle position on the length of the bridge was related to its middle axle (P_2) and the crown of the shell, which is shown in figure 3 and represented by the following equation:

$$x_p = \frac{a_{23}}{2} \cdot i\,, \tag{1}$$

where a_{23} = 1.35 m is the rear wheel track of the vehicle. When $i = 0$ the middle axle (P_2) is situated over the crown line. The values of i are positive or negative integer numbers.

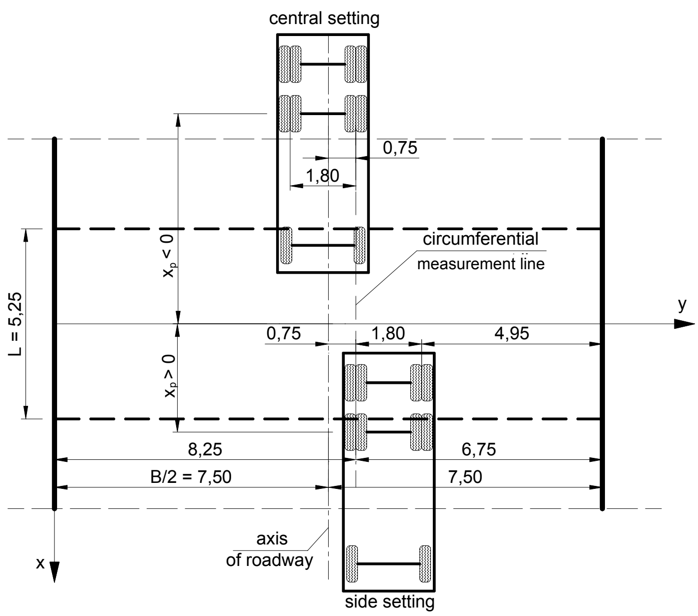

Fig. 3. Vehicle position on the roadway schemes

3. DISPLACEMENTS

Displacements were measured in the direction perpendicular to the steel sheet surface. Thus vertical displacements occur in the crown, and diagonal at the intermediate points. Figures 4–7 present the charts for selected (characteristic) measuring points. On the horizontal axis there is shown the position (i number) of the vehicle moving along an indicated movement track. The position of the vehicle is unmistakably given by the x_p-coordinate as the distance of the vehicle's middle axle from the beginning of the coordinate system (of the crown).

The first load arrangement that began the measuring cycle on the object was usually made for $i = 7$, i.e., $x_p = 4.725$ m. This means that the vehicle's rear axle (P_3) was distant from the shell support at $c = 4.725 - 1.35 - 5.25/2 = 0.75$ m. At that position the sensors indicated a minimum deflection. The vehicle was driven back in a proper direction and then stopped at the established positions to enable automatic registration of the results.

That load is taken as a static and short-term one. A final vehicle position ($i < 0$) was followed by a secondary load of the bridge at the same arrangements of the vehicle (figure 4), but in the opposite direction. The conclusion is that at each stage of the tests we deal with the pairs of the same vehicle positions, i.e., the primary ones when the vehicle was driven back considering a proper direction of driving and the secondary ones when the vehicle was driven forwards. A final vehicle position completing each stage of the test was out of the site. The movement direction of the vehicle was marked with an arrow on the charts. The measuring results were used in charts reminding the influence line of deflection for those points. They refer to the concentrated force P_2 (exactly to the vehicle's axle) moving along the established motion track.

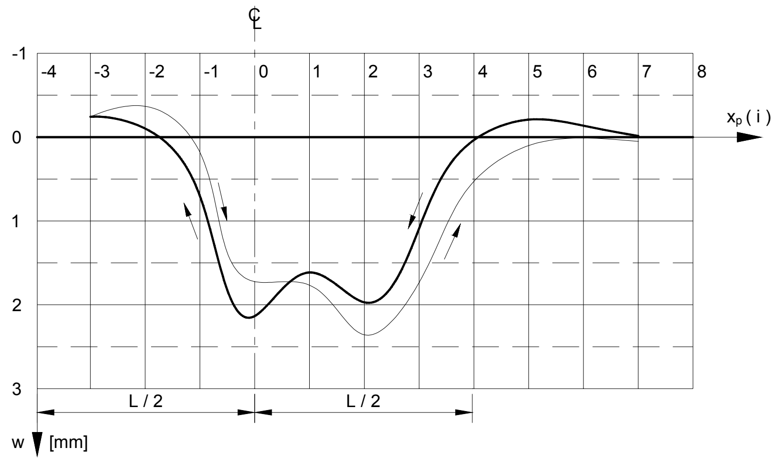

Fig. 4. Chart of the displacement of the point 12, scheme SO-3

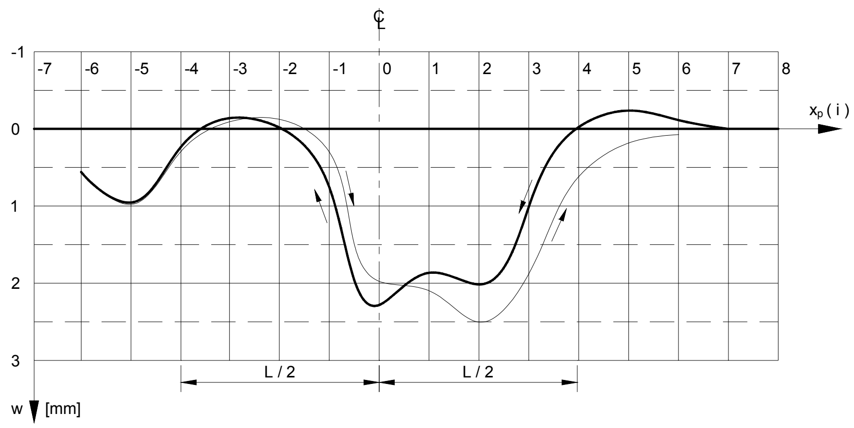

Fig. 5. Chart of the displacement of the point 12, scheme SO-1

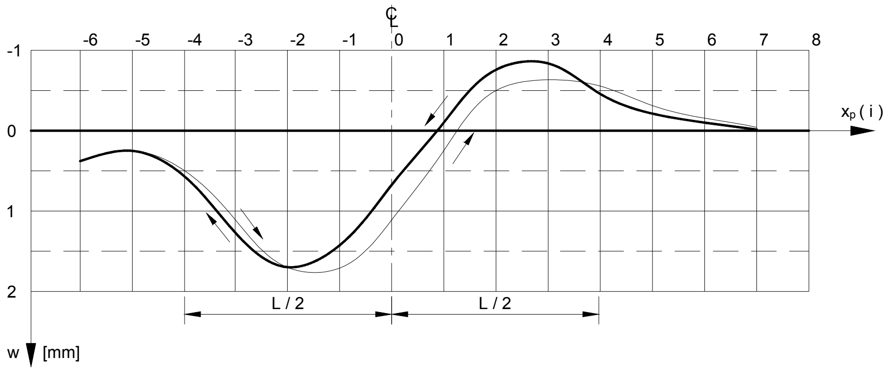

Fig. 6. Chart of the displacement of the point 16, scheme SO-1

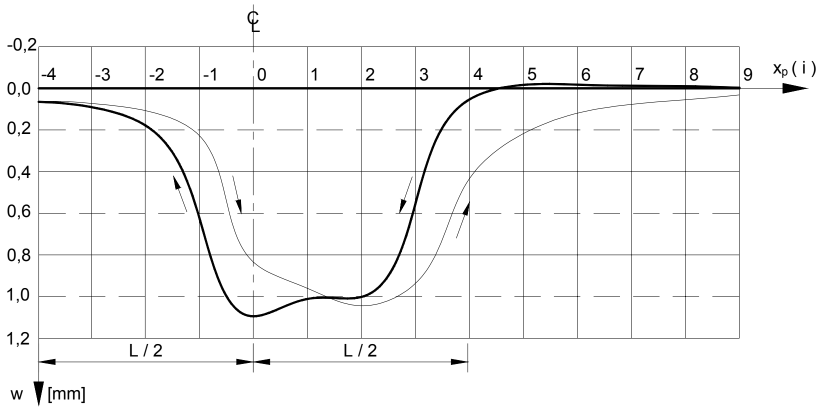

Fig. 7. Chart of the displacement of the point 12, scheme SN-1

The characteristic feature of the charts is the shift of the extreme deflection in the direction of the vehicle drive, primary drive with reference to the secondary drive. The deflection extrema are formed under the P_2 (middle) and P_3 (rear) axles when they are in the crown. In other positions of the vehicle, there are big differences in deflections. For instance, at the vehicle position $x_p = 2.025$ m (i.e., $i = 3$, figure 4), the deflection at the primary drive is $w_{13} = 1.14$ mm, but at the secondary drive $w_{13} = 1.75$ mm. It fades after the load is driven off, thus deflections appear because the load recovers a primary state. Similar phenomena can be noticed at the change of the initial point ($i > 6$) as well as the final point ($i > -4$), as shown in figure 5. The local deflection extremum in the area of $i = -5$ seen in figure 5 is associated with the appearance of the force P_1 over the measuring point. For $x_p = 2.85$ m the force P_1 takes a central position, over measuring point 12. The force P_2 at this moment is over the spot of the shell support.

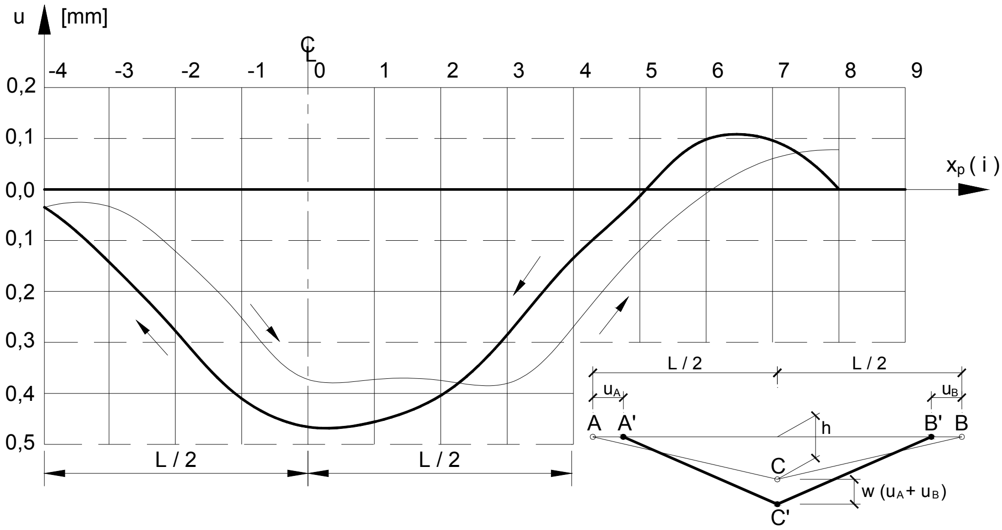

Fig. 8. Chart of the support displacement, scheme SN-1

Horizontal displacements were measured at the spot of the steel sheet support on the girt. For this reason a special measuring base was set. The base enabled multiplication of horizontal reading done as a vertical one (scheme given in figure 8). In the case of such a measuring base, the horizontal displacements of both points of support (left and right parts) are summed up. The shape of the displacement chart is similar to those of deflection. Small values of displacement testify to a big role of the soil, considering the load-carrying ability of the steel supports to be relatively slender in that construction.

The displacements of the intermediate point (figure 6), between the crown and the support, show shifts in the result of the primary and secondary drives, too. In the case of the object with pavement, all the displacements get reduced, as is shown in figure 7 (compare it to figure 4). The displacement tests were carried out several times and chart shapes were similar also when the beginning and finishing of the load cycle is at another point.

4. UNIT STRAINS AND NORMAL STRESSES

On the basis of measurements in the form of unit strains, normal stresses were calculated from the following equations:

$$\sigma_x = E(\varepsilon_x + \nu\varepsilon_y), \tag{2a}$$

$$\sigma_y = E(\varepsilon_y + \nu\varepsilon_x) , \tag{2b}$$

and the charts are shown in figures 9–11. The loads in that case were the same as when the displacements were defined.

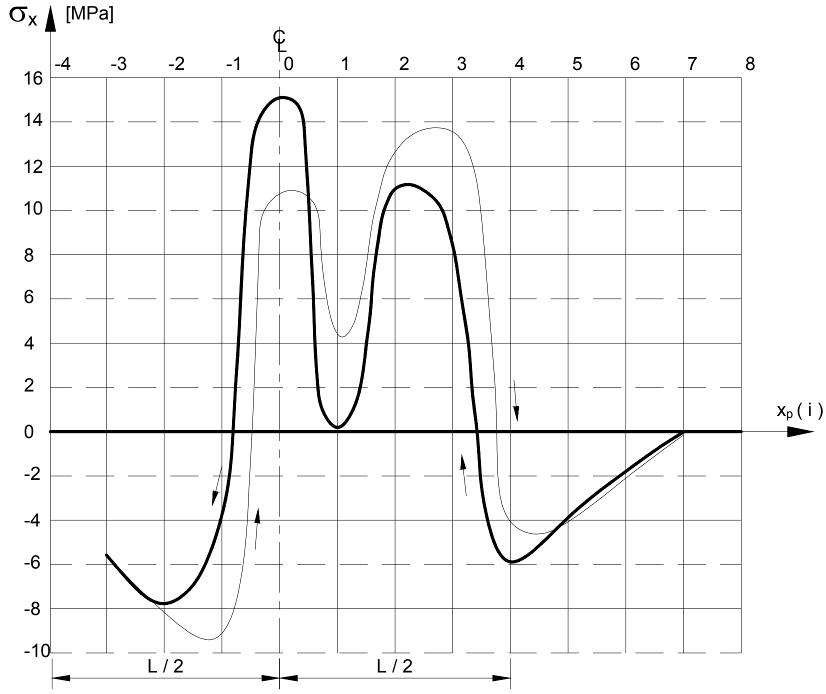

Fig. 9. Chart of the stress σ_x at the point 12, scheme SO

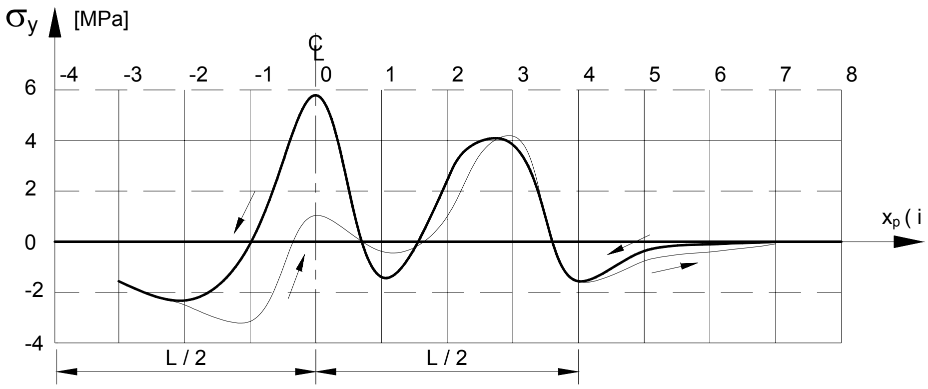

Fig. 10. Chart of the stress σ_y at the point 12, scheme SO

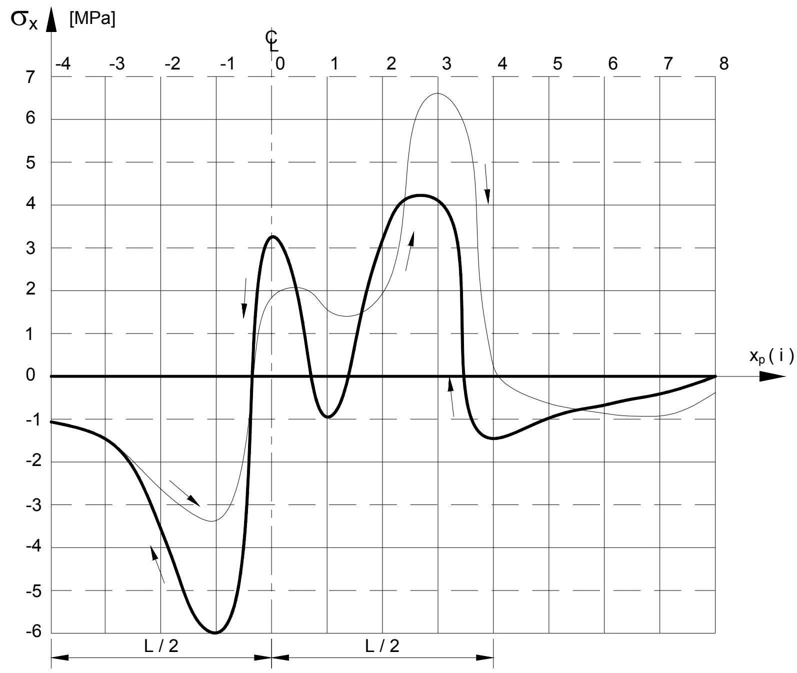

Fig. 11. Chart of the stress σ_x at the point 12, scheme SN

The charts of normal stresses show a greater variability than these of displacements which results from local deformations of the shell under the vehicle wheels. This phenomenon occurs despite a big thickness of soil backfill. The values of normal stresses are subjected to a considerable reduction after an asphalt pavement has been put onto the roadway.

5. INFLUENCE LINES OF INTERNAL FORCES

The results of numerical calculations given below make the interpretation of the test results presented in figures 9–11 easier. They allow separating the roadway load effects into an axial force and a bending moment. In a numerical model, it is also possible to sum up internal forces within one quantity which is normal stress. Because we analyze the effects of loads moving along the bridge axis, the analysis results are given in the form of influence lines. The chart of the influence line enables us to separate the load effects in the form of coupled forces, like in a vehicle, from the effects coming from individual forces connected with that system. The load effect on the whole roadway plain was analyzed in [3] and [10] based on the influence surface.

A static aspect of the bridge work in the phase of its usage, i.e., after the construction had been finished and the pavement had been laid, was analyzed. The influence functions of normal stresses at the selected point of the shell derived according to the procedure given in [2] and [12] were compared. Such a procedure allows us to compare objectively the effects of the parameter changes under consideration on internal forces in the shell. The influence functions of stress enable the calculation of normal stresses in the analyzed point of the shell on the basis of freely taken and set live loads (like real vehicles or imaginary norm vehicles).

• **Calculation model.** Based on the results of numerical tests on the shell models surrounded by soil and the results of tests on real objects, presented, for instance, in [1]–[6], [9]–[14], [16], [20] and [21], we adopted the following assumptions:
- steel sheet of the shell is a circumferential strip made from beam elements,
- soil backfill is a two-dimensional isotropic continuum,
- roadway is treated as area isotropic elements.

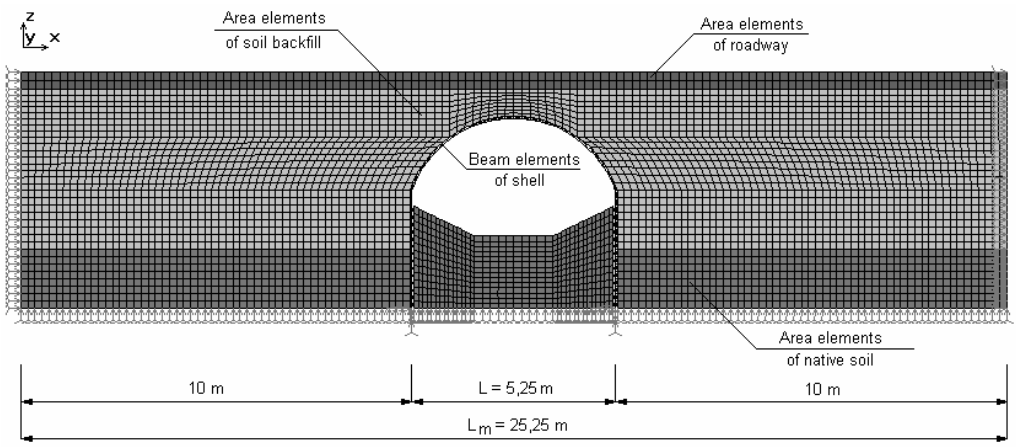

Fig. 12. Model of the soil-steel bridge

The geometry of the carrying system was designed in the 2D space, while area isotropic elements PLANE2D were used as well as beam elements of BEAM2D kind. The interface was modeled by one-dimensional elastic elements of SPRING. Physical features of the elements were taken as lineally elastic because of the short-term changing loads [3], [5], [6]. A basic calculation model is presented in figure 12. The roadway was projected by using PLANE2D elements of the following material characteristics: $E = 120$ MPa (Young's modulus) and $\nu = 0.3$ (Poisson's ratio). The thickness of the roadway together with substructure was assumed to be 42 cm. The soil surrounding the shell made of plane sheet was modelled by area isotropic elements (PLANE2D). The elements were given the following characteristics: $E = 60$ MPa and $\nu = 0.3$. The thickness of the backfill layer over the shell was taken as 75 cm. The shell was designed in the form of beam elements (BEAM2D). For the shell there were taken the following material characteristics (complying with the steel kind): E = 205 GPa and ν = 0.3.

• **Influence lines of normal stresses.** In order to obtain the influence surface of normal stresses on top and bottom edges of the steel sheet we used kinematic inputs [15] and the algorithm presented in [3] and [10]. If we assume the homogeneity of the sign of the axial force (compression), two kinematic inputs of different senses of bending moment are satisfactory. A section in the middle of the shell span (L/2), where the highest values of normal stresses on the edge of the top shell occurred, was analyzed in detail. The middle of the shell span ($x = L/2$) shown in figure 12 is at the distance of x = 12.625 m from the end of model.

The coordinates of the stresses influence lines ξ presented in the charts should be interpreted according to the following equation:

$$\sigma = P \cdot \xi \, , \tag{3}$$

where:

σ – the normal stress in the analyzed point of the shell [MPa],

ξ – the coordinate of the influence line at the point, where the force moving the roadway along the bridge axis was applied [m^{-2}],

P – the value of the concentrated force [MN].

We assumed that the thicknesses of the flat steel sheet and the corrugated steel sheet of MP 150 50 type were variable parameters.

• **Thickness of plane steel sheet.** The changes in the thickness t of plane steel sheet in the range of 5 mm < t < 30 mm influence the value of geometrical parameters given in table 2.

Table 2

Geometrical parameters of plane steel sheet

t [mm]	5	10	15	20	23	25	30
A [mm^2/mm]	5	10	15	20	23	25	30
I [mm^4/mm]	10	83.3	281.2	666.7	1013.9	1302.1	2250.0

A – the area of the cross section.
I – the moment of inertia.

The influence of the thickness of the plane steel sheet on the coordinate values $\xi(t)$ is presented in figures 13–15.

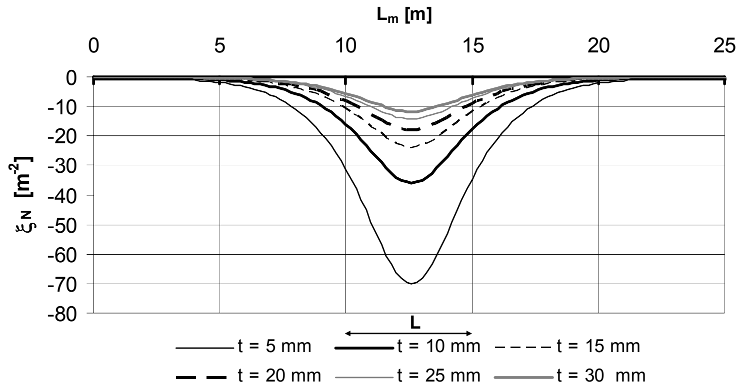

Fig. 13. Influence lines $\sigma_N(t)$ in the crown

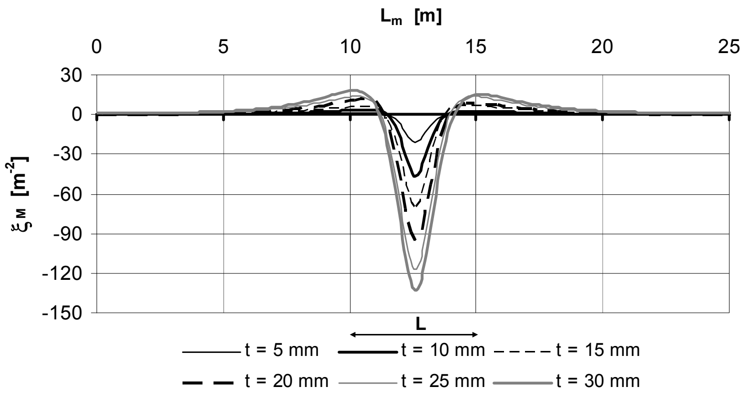

Fig. 14. Influence lines $\sigma_M(t)$ in the crown

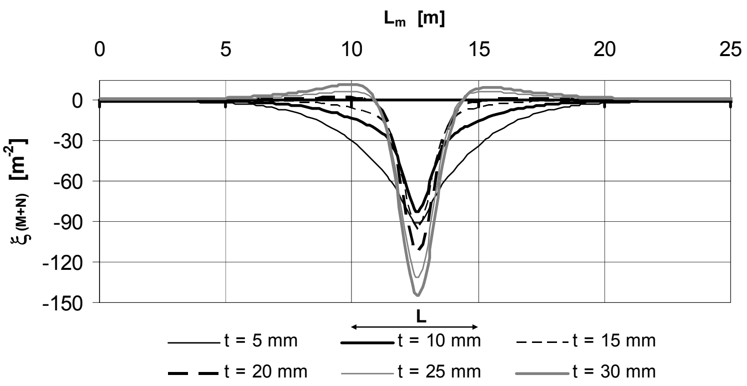

Fig. 15. Influence lines $\sigma_{(M+N)}(t)$ in the crown

Based on the analysis of partial results we can claim that along with the thickness increase the axial forces σ_N (t) decrease and the bending moments σ_M (t) increase. It is caused by an increase in the area and moment of inertia of the cross section of the steel sheet, i.e. the shell rigidity increases towards the soil backfill. Greater thickness (rigidity) of the shell steel sheet causes greater normal stresses than those due to the bending moment. An increase in the cross section area of the steel sheet is responsible for a decrease in a normal stresses due to the axial force.

From the charts presented in figure 15 we can infer that thinner steel sheets are not profitable in terms of the resistance, because in some sections of the shell great normal stresses may appear. The optimum solution seems to be the application of plane steel sheets whose thickness ranges between 15 and 25 mm.

• **Thickness of shell steel sheets of the MP 150·50 type.** The values of geometrical parameters of the shells defined on the basis of [7] are given in table 3. The changes in the thickness of the steel sheet of the MP 150·50 type in the shell of the object of the size given earlier is presented in figures 16–18.

Table 3

Geometrical parameters of the shell steel sheet of the MP 150·50 type

t	A	I	$h_c = h_f + t$
[mm]	[mm^2/mm]	[mm^4/mm]	[mm]
3.0	3.520	1057.5	53
4.0	4.828	1457.6	54
5.0	6.149	1867.1	55
6.0	7.461	2278.3	56
7.0	8.712	2675.1	57

h_f = 50 mm – the height of the steel sheet wave.
h_c – a total height of the cross section of the steel shell.

Considering the analyses of partial results, we can say that the stresses due to axial forces essentially influence the changes in the values of total normal stresses in the shell as the function of steel sheet thickness. We can arrive at the conclusion that an increase in the bending moment in the shell is proportional to an increase in its moments of inertia, thus the values of normal stresses associated with those values are roughly constant. In the case of stresses being the result of axial forces, the proportion is opposite. The axial force increase is small, but the cross section area of the shell increases more than twice as much. This causes a meaningful decrease in the value of the ordinates shown in figures 16 and 17.

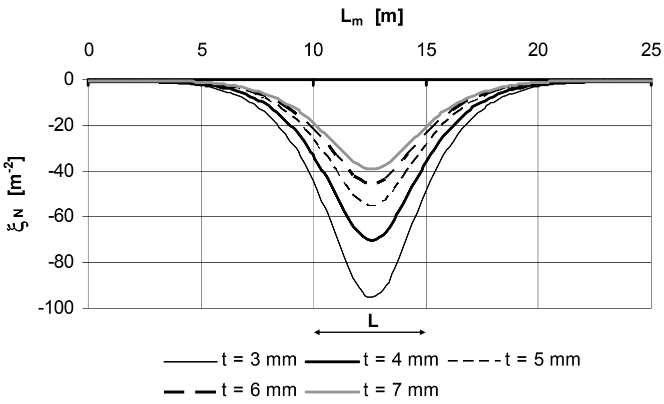

Fig. 16. Influence lines $\sigma_N(t)$ in the crown

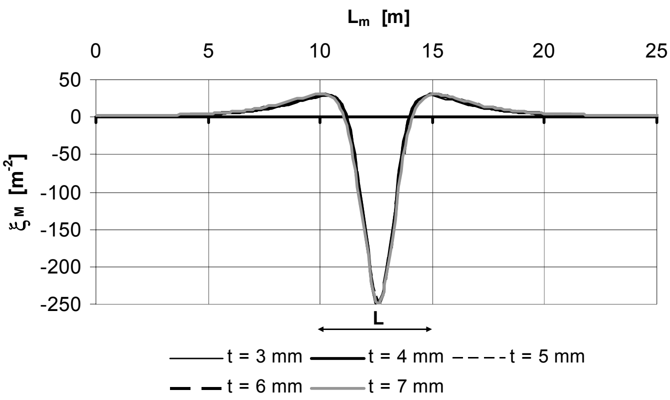

Fig. 17. Influence lines $\sigma_M(t)$ in the crown

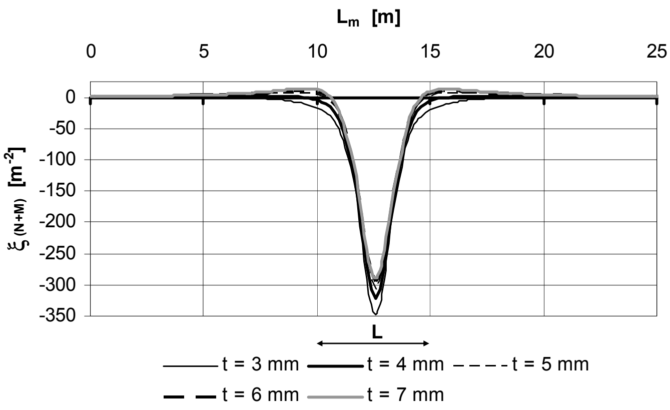

Fig. 18. Influence lines $\sigma_{(N+M)}(t)$ in the crown

The results of the resistance analysis show that it is effective to apply shell built up from of thick steel sheets. However, the thickness setting should be based on economical criteria since using steel sheets of big thickness reduces normal stresses to the level of a few MPa, because at the steel resistance of 200 MPa it results from a minimum material stress of the construction. In the case of the shells of MP 200·55, SC 380·140 and SC 400·150 types, the character of the stress in the system is similar.

6. SUMMARY

The tests on the soil-steel construction usually refer to two kinds of load reactions to the roadway:

- a stationary one when vehicles are set at a chosen place of the bridge and their effect on the object is either short-term (temporary) or long-term,
- a changeable one taking account of the position of a vehicle or its dynamical effect on the construction.

The results of the measurements of temporary loads imposed on real objects confirm that the use of FEM for calculation is justified. In the light of the test results [9], [12], [14] and [16] we can infer that under short-term loads imposed on roadways, the construction works elastically. Under long-term loads delayed effects are noticeable [10], [20]. The results of the tests carried out on the objects subjected to changing loads show a beneficial character of the construction as non-homogeneous system. In the case of loads moving along the bridge, the deflections observed indicate that in the carrying system the backfill plays an important role. Because the backfill is a loose material, the effects of changing loads depend on the shell deformation prior to measurements.

The carrying system of the object analyzed is different from that of classical soil-steel bridges because of the given support of the shell on piling support and point connections of the plane (without corrugation) steel sheet plates. However, the tests and calculations results show that the construction analyzed works in a similar way as classical soil-steel objects.

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