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Numerical analysis of steel-soil composite (SSC) culvert under static loads

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Abstract. The paper presents a numerical analysis of a steel-soil composite (SSC) culvert in the scope of static (dead and live) loads. The Abaqus program based on the finite element method (FEM) was used for calculations. Maximum displacements were obtained in the shell crown, and the largest stresses in the haunches. Calculation results were compared with the experimental ones and previous calculations obtained from the Autodesk Robot Structural Analysis (ARSA) program. The shapes of calculated displacements and stresses are similar to those obtained with the experiment, but the absolute values were generally higher than measured ones. The relative differences of calculated and measured values were in the range of 5-23% for displacements, and 15-42% for stresses. Developed calculation model of the SSC culvert in the Abaqus program allows obtaining reasonable values of internal forces in the culvert. Using both calculation programs, the relative differences for displacements were in the range of 15-39%, and 17-44% for stresses in favour of the Abaqus program. Three design methods (Sundquist-Pettersson, Duncan and CHBDC) were used to calculate the axial thrusts and bending moments. Obtained values were compared with test results. Generally, the design methods have conservative assumptions, especially in the live loads distribution, safety factors and consideration the interaction between soil and steel structure.

Keywords: steel-soil composite culvert; FE model; displacement; stress; live loads; backfill

1. Introduction

Steel-soil composite (SSC) culverts are getting widely used as an alternative to traditional steel or concrete bridge structures (Janusz and Madaj 2009). These structures consist of the corrugated steel plates and properly compacted backfill. The corrugated profiles usually are used to the main girders in the bridges (Chen *et al.* 2016, Xu *et al.* 2015, Nie *et al.* 2016). In this case, the corrugated steel profiles are one of the elements in a little different composite (the steel-soil structure). One of the most important issue in these structures is a soil-structure interaction (Cheng and Liu 2012). The well-known advantages which justify the choice of such solution are mainly short period and relatively low cost of construction. Static (Manko and Beben 2005, Flener 2010) and dynamic (Beben 2013a, b, 2014, Mellat *et al.* 2014) experimental tests of such bridge structures were held on many occasions. However their numerical analysis causes many problems such as modelling of corrugated profiles, selection of a soil model and interaction properties (Elshimi 2011, Machelski 2008). This is why a reasonable way of numerical analysis of SSC culverts has not been elaborated so far.

Sargand *et al.* (2008) presented a culvert study which included comparing measured field performance with numerical predictions given by the FE computer program (CANDE). The initial numerical calculations of the steel culverts were also presented by Beben (2012). 2D FE program (CANDE) and a 3D finite difference program (FLAC) were applied by Yeau *et al.* (2015) to simulate the behaviour of the pipe-arch culverts. The hyperbolic soil model proposed by Duncan *et al.* (1980) and the Mohr-Coulomb linear elastic perfectly plastic model were applied for 2D and 3D, respectively. Deflections predicted from the 2D analyses were larger than the deflections measured on site. However, the experimental and calculated axial thrusts were similar. Deflections and axial thrusts predicted from the 3D analysis were similar to the experimental results. Mai *et al.* (2014) presented the 2D finite element analysis for the deteriorated corrugated steel culverts with a span of 1.8 m. All the finite element models were unable to capture non-linear behaviour of the deteriorated culvert with poor backfill as well as the culverts at high surface loading due to the use of linear elastic models. Mellat *et al.* (2014) showed the 2D and 3D continuum models for dynamic response of the railway culvert. Basing on the models, the influence of the Young's modulus of the backfill on the culvert behaviour was also investigated. The proposed 3D-model also enables estimation of load distribution, which is found to increase at higher train speeds. Kunecki (2014) presented full scale testing and three-dimensional numerical calculations of steel–soil composite tunnel. The calculation results were higher than the ones received from experimental tests. Beben and Stryczek (2016) present a numerical modelling of an arch steel culvert with reinforced concrete (RC) relieving slab. The obtained numerical results are overestimated in comparison to site test results.

Generally, as above-mentioned, the calculation results obtained with use of the computational models in comparison with the experimental results are insufficiently satisfactory, therefore further numerical analysis of SSC

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Fig. 1 Side view on the analyzed SSC culvert

culverts is needed.

Any effective method of geometrical dimensioning of such structures has not been worked out so far despite existence of numerous analytical methods. However, they do not allow determining precisely the internal forces in these bridge structures. The calculations of the SSC culverts executed with such methods are unsatisfactory in comparison with the results received from the experimental tests. This probably results from versatility of such methods as well as simplifications being too large. For the most part, current design methods for the SSC culverts are based on experience rather than a viable analytical model. This is because a reasonable analytical model is quite complicated. These complications are due to the interaction phenomena. In such composite systems, both the soil and steel structures are required to be taken into consideration as the load-carrying elements, it is not possible to simply accept only as the loads acting on the steel structure. Flener (2010) showed that the Swedish and Canadian design methods are conservative when estimating live load moments but they underestimate live load thrusts. The measured maximum thrusts are up to four times larger than the calculated design values.

Elaboration of a reasonable method of dimensioning of these structures will definitely contribute to increase in safety and to even greater savings in comparison to traditional bridge structures of medium spans. That is why experimental and theoretical research is still needed on SSC structures.

The aim of this paper is to present a numerical analysis of a SSC culvert (Fig. 1) within the scope of static loads. A method of numerical analysis of a steel shell with the orthotropic properties has been presented as well as a method of considering a soil-steel shell structure interaction phenomena. The numerical analysis of the bridge was executed in a 3D space of the Abaqus/CEA 6.11 program (Abaqus Theory Manual 2011). Calculation results (displacements and stresses) were compared to the results of experimental tests (Manko and Beben 2005) as well as to previous numerical calculations in the Autodesk Robot Structural Analysis (ARSA) program (Manko and Beben

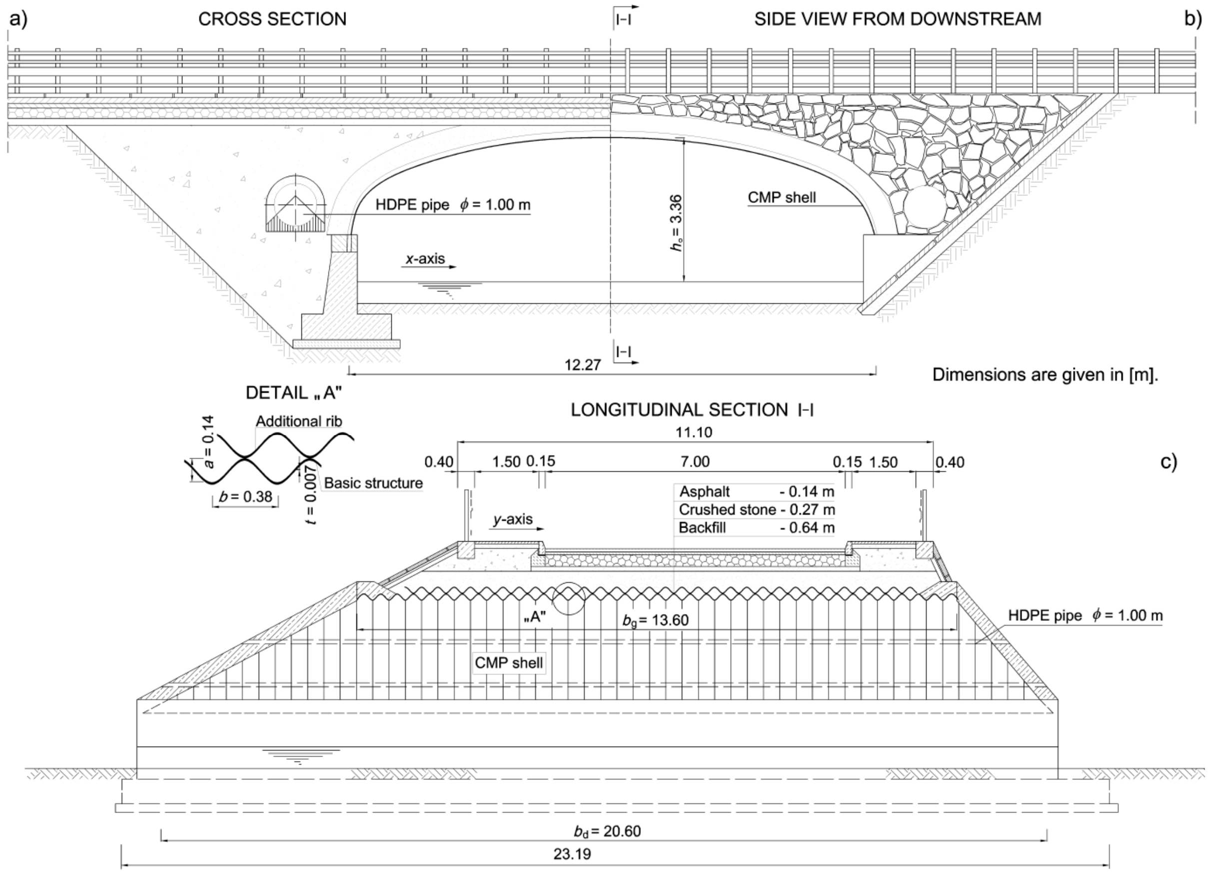


Fig. 2 Analyzed SSC culvert: (a) cross section; (b) side view; and (c) longitudinal section I–I

2005). The internal forces (axial thrust and bending moment) calculated on the basis of the following three methods, i.e., Sundquist-Pettersson (Pettersson and Sundquist 2014), Duncan (Janusz and Madaj 2009) and CHBDC (CHBDC 2006) which were compared mutually and to the results of experiments. The conclusions mainly consider accuracy of calculation results in comparison to the previous analyses (Manko and Beben 2005). The underlying reasons of the observed discre-pancies were also explained.

2. Culvert description

The subject of analysis is SSC culvert with effective span of 12.27 m and vertical height of 3.36 m (Fig. 2), which was earlier comprehensively tested (Manko and Beben 2005). The analyzed structure in the cross section constitutes a single-span steel shell structure. The shell is made of corrugated steel plate of thickness t = 0.007 m and has a corrugation depth of a = 0.14 m with pitch b = 0.38 m (detail in Fig. 2). The structure's width is b_t = 13.60 m at the top and b_b = 20.60 m at the bottom. The individual sheets of corrugated plate are connected together using high strength bolts $ø$ = 20 mm using a torque moment of 350-400 Nm. The steel shell culvert was supported, by means of steel uneven-armed channel sections, on two RC strip foundations made from B30 grade concrete. The basic metal shell of the culvert was reinforced in the crown and haunches with using additional corrugated profiles (so-called ribs) with the same plate thickness as in the basic structure.

The load-bearing structure was designed as a shell consisting of corrugated steel plates backfilled with 0.20-0.30 m thick course of permeable soil with 10-32 mm grading, compacted to I_D = 95% (on the Proctor Normal Density) for the soil being in direct contact with the shell and to I_D = 98% for the other backfill whereby a pavement could be laid on a broken stone subgrade. The backfilling process was conducted step-by-step from both sides of the shell structure. The differences in the soil layer height on both sides did not exceed 2-3 layers, i.e., ca. 0.40-0.60 m. Vibratory plates were used for soil compaction during construction. The cover thickness (backfill, road structure and asphalt) over the steel crown shell is hc = 1.05 m.

Structural steel with strength corresponding to that of Polish steel S315MC (the guaranteed yield strength of the steel used to manufacture corrugated plates was 314 MPa according to PN-EN 10149-2:2014-02 (2014)) was used. Detailed description of the SSC culvert and the stages of its construction are presented in (Manko and Beben 2005), and the basic geometrical dimensions of the culvert are shown on Fig. 2.

3. Numerical model description

3.1 General remarks

For computations of SSC culvert, the Abaqus/CEA ver. 6.11 (Abaqus Theory Manual 2011) was used, based on the FEM. In the numerical model efforts were made to reflect the actual geometry of the analyzed culvert, while not taking into account the secondary elements that may affect the increasing complexity of model and considerably extended time for computation. Therefore, due to the complex shaped structure, a numerical model was slightly simplified, although main parameters of the culvert (height and span of steel shell, top shell length, various radiuses of shell) were maintained. Elements, such as slopes, RC collars reinforcing inlet and outlet of the shell, guardrails and drainage pipes were neglected in the model. These elements should not significantly affect the computational results, because they are located outside the range of active loading, and at the same time represent only additional accessories of the culvert.

Culvert calculations were performed in three-dimensional space. Non-linearity in computational model has been addressed by using incremental analysis – the Full Newton method (Abaqus Theory Manual 2011, Skrzat 2010). Culvert model is parts of the 3D space, which are in the dimensions of 16.27 × 11.10 × 4.22 m (Fig. 3). Modelling the soils placed at distance greater than 2 m from the steel shell does not substantially affect the obtained results of computations, while in this case, boundary conditions are rather decisive, which reflect the real structure in quite approximate manner. Hence, the RC foundations, as an element of rigid support for the structure was omitted in modelling process.

In calculation model, nodes have six degrees of freedom (U1, U2, U3 – displacement directions on the axes OX, OY, OZ, and UR1, UR2, UR3 – rotation directions relative to the axis OX, OY, OZ), wherein nodes of elements with their edges laying on external surfaces of the numerical model are blocked at all degrees of freedom – rotations and displacements (total restraint).

3.2 Material characteristics

3D shell tetrahedral elements (S4R) were used to model a steel shell culvert. The remaining units (soil and roadway layers) are defined as elements with properties of a solid (C3DR8). The material parameters were chosen based on available technical data (the culvert elements and asphalt properties obtained from the producers of such materials and the backfill obtained from the project of this culvert) and material characteristics included in the Abaqus software, that are:

Corrugated steel plate shell was modelled as a flat with appropriate parameters of orthotropic shell using the following Eqs. (1)-(4):

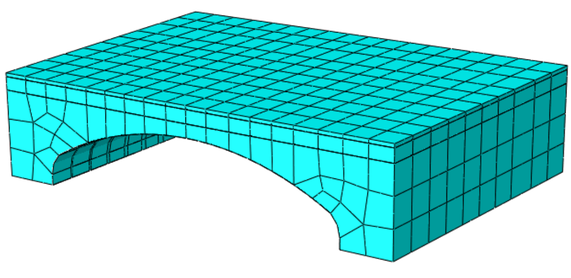


Fig. 3 Finite element model of SSC culvert

- equivalent thickness of plate:

$$t_{equ.} = \sqrt{12(1-v^2)\frac{I}{A}} \tag{1}$$

where I is moment of inertia, A is cross-sectional area, and v is Poisson ratio ($v = v_x = 0.3$),

- equivalent elastic modulus of material (Young modulus) in circumferential direction of shell:

$$E_{x\,equ.} = E\frac{A}{b\,t_{equ.}}, \tag{2}$$

where b is a pitch of corrugation,

- equivalent elastic shear modulus:

$$E_{y\,equ.} = E\left(\frac{t}{t_{equ.}}\right)^3, \tag{3}$$

- equivalent Poisson ratio:

$$v_{y\,equ.} = v\frac{E_{y\;equ.}}{E_{x\;equ.}}. \tag{4}$$

Table 1 presents the equivalent parameters of corrugated plate (basic structure and with the additional ribs) used in the numerical analysis. Plate elements were defined by shell-type elements (SR4) as an elastic-plastic material with a density $\gamma = 78.5$ kN/m^3 and yield strength $\sigma = 314$ MPa. In this case, adopted curvature control accuracy was 0.01 m, due to the complexity of shell itself and its curvilinear shape. The bolt connections between the metal plate elements were omitted during modelling.

– backfill (medium size sand) with thickness of 0.64 m (over the crown shell) was defined as elastic-plastic material (C3DR8 solid-type element) with the hyperbolic Drucker-Prager yield criterion with density $\gamma = 20.5$ kN/m^3, Young's modulus E = 100 MPa, angle of internal friction $\phi = 45°$, dilation angle $\alpha = 5°$, and initial tension equal to 0 MPa. Furthermore, application of the Drucker-Prager model required determining the size of soil reinforcement, due to the fact that the effect of cohesion on the soil behaviour was eliminated. For this purpose, a parameter describing the soil reinforcement in compression was used, by fixing its size to 5 MPa.
– road structure with thickness of 0.27 m (crushed stone) was defined as elastic-plastic material (solid-type element) with the hyperbolic Drucker-Prager yield criterion with density $\gamma = 18.0$ kN/m^3, Young's modulus $E = 60$ MPa, angle of internal friction $\phi = 40°$, dilation angle $\alpha = 10°$, and initial tension equal to 0 MPa. As in the case of basic backfill model, Drucker-Prager model-type reinforcement was applied, determining soil reinforcement parameter under compression equal to 5 MPa.
– roadway layer (asphalt with thickness of 0.14 m) was modelled as an elastic material (solid-type element) with density $\gamma = 21.0$ kN/m^3, Young's modulus E = 6.9 GPa and Poisson's ratio $v = 0.41$.
– boundary conditions: total restraint was applied, namely rotations and displacements along each axis of the shell's sides and base were blocked. The SSC culvert was modelled as a structure firmly embedded in the environment. This is because, that the lateral earth pressure phenomenon at each direction of displacements and the rigid support of the shell on massive foundations were occurred.
– calculation step was defined as $T = t + \Delta t$, where t is the initial time equal to $t = 0$ s, while Δt is time increment, during which the set static load is applied, according to the three schemas used during experimental tests (Manko and Beben 2005). Accordingly, Δt equals to the time in which load in applied, and it is usually adopted in the value of 1 s. In calculation step ($T = 1$ s), successive iterations for increments caused by load being applied at that time, and their effect on the SSC culvert behaviour are computed in the software. Thus it is necessary to define the calculation step, the assumption of geometric non-linearity of the culvert (specified also in material characteristics of various components of the structure, i.e. soil and steel shell), which has an important effect on deformations occurring in the structure, caused by the applied forces. Then, specifying the methodology for solving the system of equations, direct method of numerical analysis was assumed, while applying the Full Newton type algorithm for the solution (Abaqus Theory Manual 2011). Adopted load change in the time of performing subsequent iterations is linear during the entire calculation step, which corresponds to applied static loads. Furthermore, in order to clarify the non-linear analysis of the numerical model for subsequent initiated iterations, parabolic extrapolation from previous states of loads action on the culvert was adopted.

3.3 Properties of contact zones

SSC culvert modelling consisting of a three different

Table 1 Orthotropic properties of the corrugated steel plate structure

Element	Equivalent thickness of plate $t_{equ.}$ (m)	Equivalent Young modulus in circumferential direction $E_{x\,equ.}$ (GPa)	Equivalent Young modulus in longitudinal direction $E_{y\,equ.}$ (GPa)	Equivalent shear modulus $G_{equ.}$ (GPa)
Basic structure	0.172	11.94	0.0142	0.158
Basic structure + ribs	0.207	16.39	0.000812	0.044

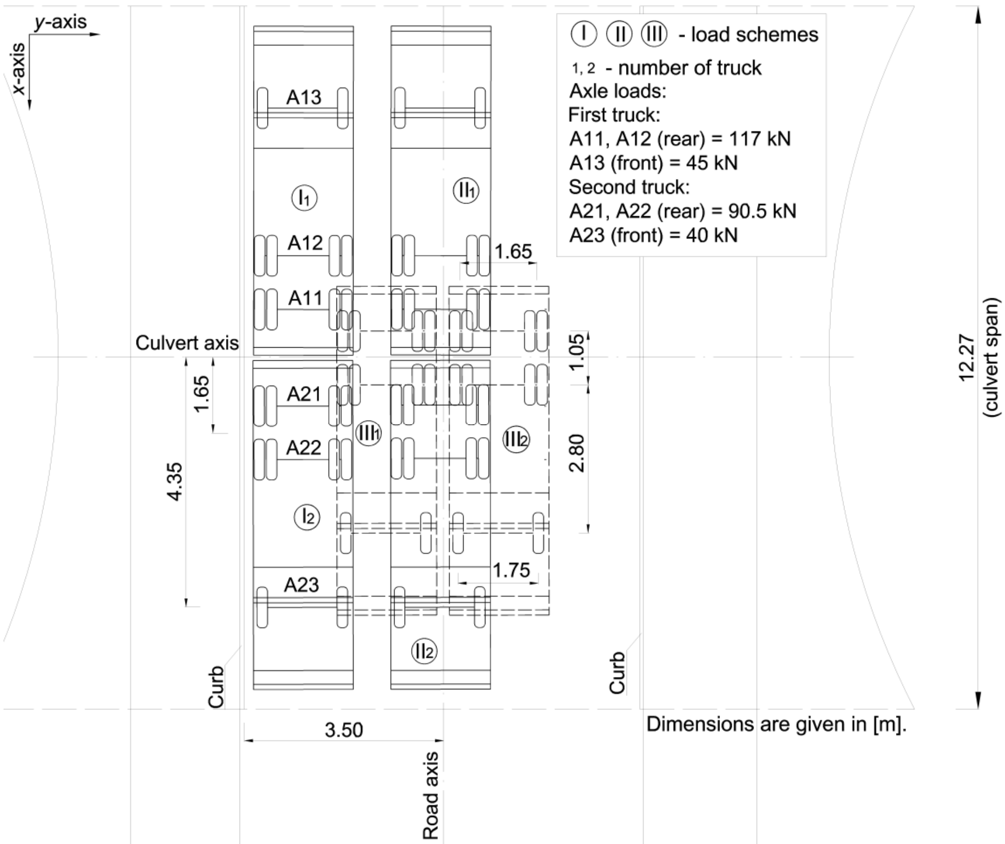


Fig. 4 Top view on the applied three static load schemes

layers (roadway elements (crushed stone and asphalt), backfill, steel shell elements) with different physical properties requires determination of their interactions. These interactions shall be determined between all layers, which are in direct contact, even if any of these have similar physical properties (backfill–crushed stone). For modelling interactions between different materials with predefined physical properties, which are incorporated into the steel culvert, contact elements, also called interfaces were used (Abaqus Theory Manual 2011). Interactions at the interface of materials being interconnected (steel shell–backfill, backfill–crushed stone, crushed stone–asphalt) were modelled as rigid elements of the beam transferring their specific types of interactions from master to slave surfaces (Abaqus Theory Manual 2011). These elements analyse phenomena occurring in the time of interaction between two materials, that is normal forces (rigidity) and friction forces (friction coefficient). Furthermore, Abaqus software allows specifying the nature of surface interactions by defining the type of slide between contacting surfaces. Due to the nature of construction and behaviour of the entire SSC culvert, which transfers loads to the last of its layers, that is corrugated plate, the type of interaction that occurs between the layers (asphalt–crushed stone, crushed stone–backfill) is defined as "finite sliding", which means not sliding. Basic argument for the establishment of this type of interaction is the fact that only in the last contact layer (steel shell–backfill) small sliding of backfill surrounded by steel plate can occur. In this case, an interaction was adopted in which small sliding is present.

The dependency of master and slave contact surfaces were determined based on the modulus of elasticity of materials being in contact with each other (interaction) and the nature of the SSC culvert behaviour. Slave was a surface build of the material with lower modulus of elasticity (Young's modulus), and the surface with higher modulus of elasticity was described as master. In numerical model, three types of contact areas (steel shell–backfill, backfill–crushed stone and crushed stone–asphalt) were identified. For individual layers, following master–slave dependencies were adopted, that is: (a) steel shell – backfill → master – slave; (b) backfill – crushed stone → slave –master; (c) crushed stone – asphalt → slave – master.

The type of surface, being in contact with one another was the basis for determining two types of interaction properties specifying friction coefficients between the layers, and surface rigidity formed by these layers. Selecting these two types of interaction properties is the result of specific nature of steel shell–backfill interaction, compared with other contact surface properties with relatively similar characteristics (asphalt–crushed stone, crushed stone–backfill). Crucial element, distinguishing this type of interactions from others, is the smooth surface of the shell, which implies lower friction coefficient. Therefore, following friction coefficients were adopted: for steel shell–backfill contact surface in the value of 0.3 and for other surfaces of 0.6. However, connection rigidity was established at the level of 2×10^9 kN/m – for steel shell–backfill contact surface and 2×10^6 kN/m – for other surfaces.

4. Analysis of calculation results and discussion

4.1 General remarks

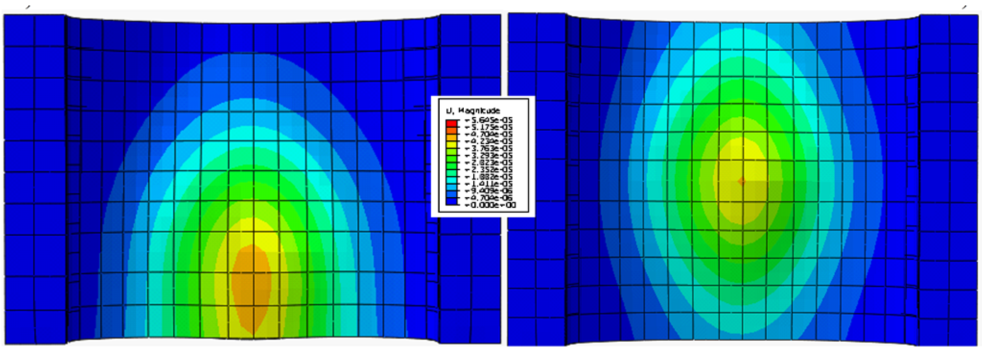
In order to compare the results of numerical analysis with measurement results, the same loads as at experimental tests under dead and live loads were used. At the time of experiments two trucks of total mass of 500 kN (Manko and Beben 2005) were used. To ensure possibility of direct comparison of calculations and measurements results, the forces from the vehicles wheels were nearly identically placed in both the numerical analysis and the experimental tests. An exact description of the three schemes in the scope of static loads is contained within paper (Manko and Beben 2005), and the sketch has been presented in Fig. 4. The numerical analysis results of the SSC culvert are presented in the form of maps of displacements and stresses.

Internal forces in the SSC culvert were additionally calculated with the use of popular design methods, i.e. Sundquist-Pettersson, Duncan and CHDBC. The same loads as in the numerical analysis and experimental tests were used.

4.2 Displacements and stresses

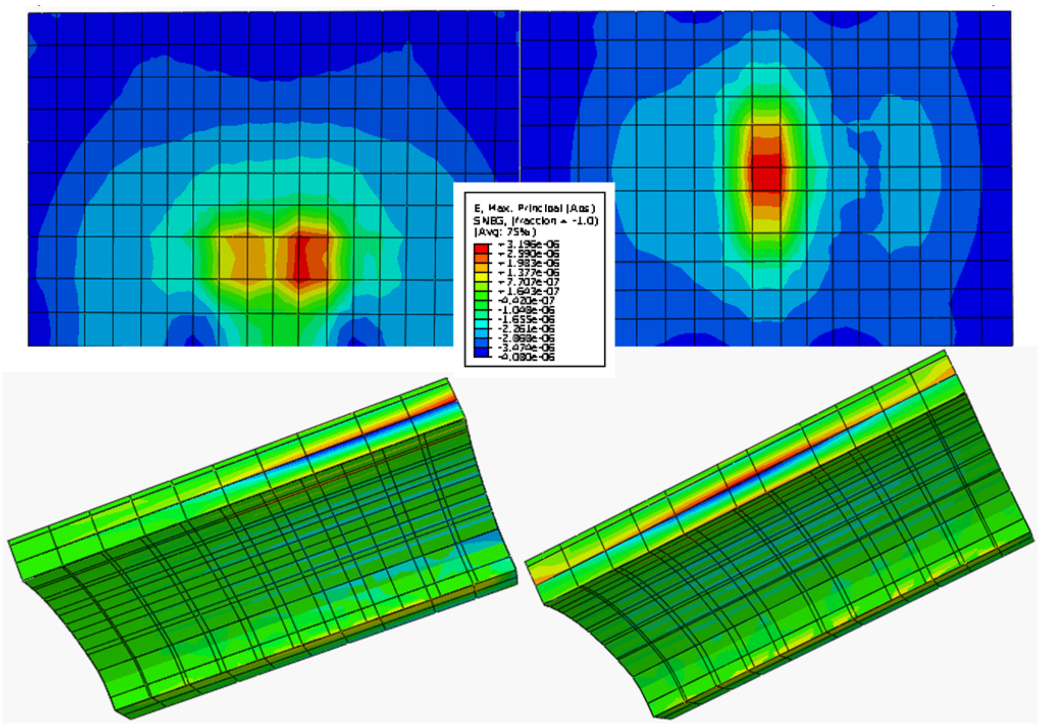
Selected calculation results of the SSC culvert are presented in Figs. 5-6 in the form of culvert section along the longitudinal axis of the shell as well as the top and bottom view in order to show load distributions in the backfill and shell.

For the three schemes of static loads under considera-tion, distribution of displacements in the calculation model indicates that the displacements are not evenly distributed but they are concentrated in the shell crown within the



(a) I – asymmetrical (b) III – symmetrical

Fig. 5 Stresses maps of SSC culvert (top view and in section) from two static load schemes



(a) Load scheme I (b) Load scheme II

Fig. 6 Displacements in the steel shell in bottom view of the culvert from two scenarios scope of the load impact (Fig. 5). The maximum displacements amounting at 3.01 mm were obtained from the scheme of loads I (asymmetric), where the loading vehicles were standing backwards to each other near the curb (Fig. 4) (Manko and Beben 2005), from scheme II (2.07 mm) and scheme III (2.54 mm).

A detailed analysis of the results indicates that the impact of loads is manifested as quite considerable local deformations in selected points of the steel shell (no even distribution of loads over the shell width observed). This is probably a result of a relatively low soil cover at the shell crown (0.87 m) and a curvilinear shape of the shell. Response of the culvert to the scheme III of load can be considered an exception (Fig. 5(b)), where the vehicles are placed side by side, which causes a relatively even distribution of load on the shell width. Moreover, the maps of displacements definitely reflect the impact of the vehicles rear axles on the shell deformations.

Distributions of stresses presented in Fig. 6 explicitly show that the loads are transferred onto the SSC culvert shell in an indirect way, which results in maximum values at the haunch and at 2/3 of the shell height. In these sections the maximum values amount at 65 MPa from load scheme I (Fig. 6(a)) and 56 MPa from scheme II (Fig. 6(b)), respectively. Whereas at the crown the observed stresses are lower (maximum 36 MPa from scheme II). The maps of stresses allow observing the way a soil-soil structure behaviour. It means, when a quasi-point load is applied (a resultant of loads from the trucks rear wheels), the stresses are moved towards the haunch and the 2/3 of the shell height where the obtained values are the most extreme. Getting the maximum stress values in these sections of the steel culvert confirms necessity to use additional reinforcement there (ribs for example).

4.3 Discussion of calculated and measured results

Figs. 7-8 show comparison of displacements and stresses obtained from experimental tests (Manko and Beben 2005) and numerical analysis from the Abaqus and ARSA programs (Manko and Beben 2005). Numerical modelling in the ARSA program includes the use of isotropic

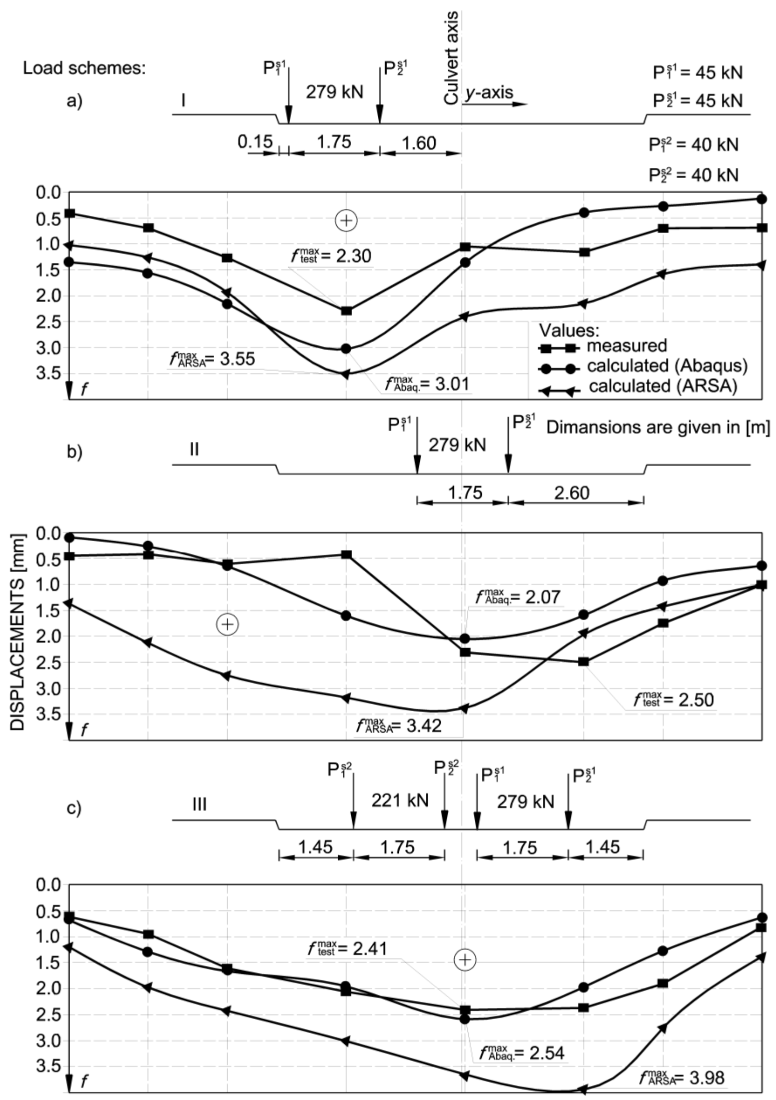


Fig. 7 Comparison of maximum displacements of the SSC culvert crown obtained with measurements and numerical calculations for three static load schemes: (a) I; (b) II; and (c) III

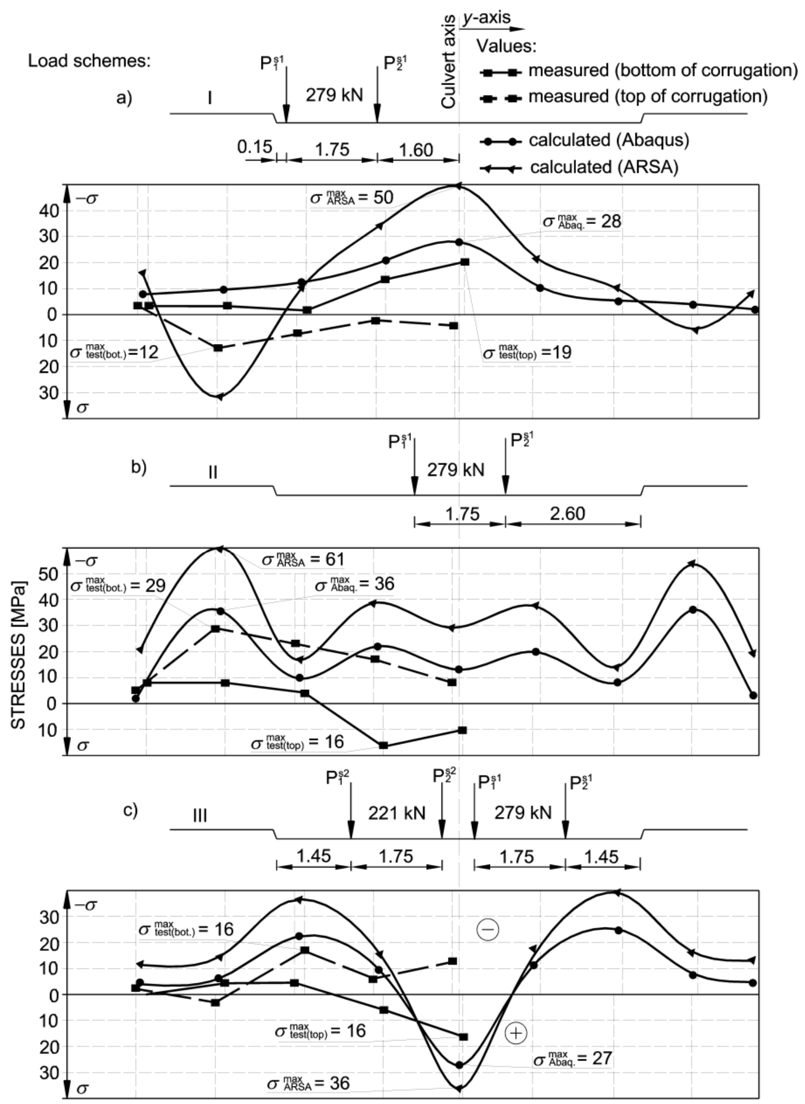


Fig. 8 Comparison of maximum stresses of the SSC culvert crown obtained with measurements and numerical calculations for three static load schemes: (a) I; (b) II; and (c) III

properties for the steel shell, the elastic, perfectly plastic Mohr-Coulomb model for soil modelling and friction coefficient to reflect interaction between SSC culvert elements. As it can be observed from these diagrams, the stresses and displacements obtained from numerical analysis by the Abaqus differ from ones obtained from experiments. However, they are more convergent to measurement results than those obtained from numerical analysis with use of the ARSA program (Manko and Beben 2005).

Comparison of the values obtained from Abaqus and the measurements is shown in Figs. 7-8 and explicitly shows that in a real SSC culvert some heterogeneities in materials are possible, for example in soil and the steel shell (for example at steel sheet joints), which can hardly be accounted for in numerical analysis. It is manifested in sudden increase in measured displacements and strains (stresses). The displacement and stress courses are similar in shape to the curves representing the actual (measured) values. Relative discrepancies of calculated and measured values were contained within the range of 5-23% for displacements, and 15-42% for stresses. It needs to be underlined that the authors did not know the exact parameters of the backfill. Moreover, the calculation model assumed the same type of soil around the shell and in other parts of the backfill and the shell was modelled as a homogenous flat surface structure (with no corrugations and screw joints between steel sheets). In a real SSC culvert some clearances at screw joints can occur. Calculation results show to some extent an idealized behaviour of the analyzed SSC culvert under static load. The maximum displacement results obtained from calculations and measurements are located exactly under the point load representing wheels of the vehicles. Whereas in the case of stresses the maximum values are relocated towards the haunch and the 2/3 of the shell height (Fig. 9).

Observing, in Fig. 8, the stresses course from experiments obtained at the top and at the bottom of corrugation, one can easily notice uneven distribution of loads over the shell width (the neutral axis is not located in the middle of corrugation). Also the diagrams of stresses on the shell circumference (Fig. 9) prove the above. As it has already

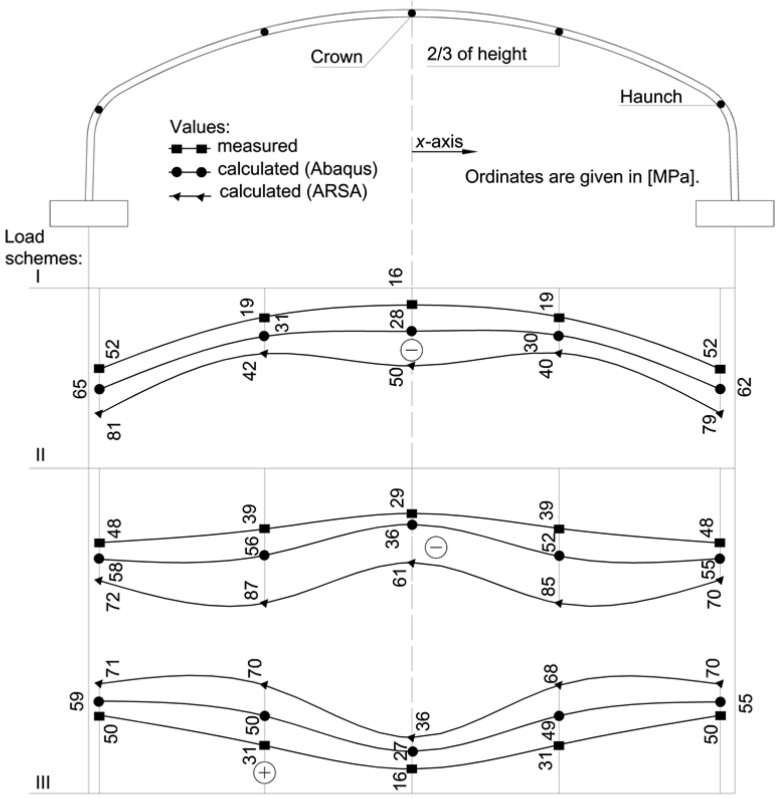


Fig. 9 Comparison of maximum stresses in the SSC culvert obtained with measurements and numerical calculations for three static load schemes

been mentioned, it results in maximum stresses in the haunch and at the 2/3 of the shell height. It should be mentioned that the presented stresses in the numerical analysis were obtained for flat shell structure at the upper fibres.

Apart from that, Fig. 9 shows that the two first applied load schemes (I and II) cause maximum compressive stresses in the shell, and the scheme of load III evokes tensile stresses. This is related to the curvilinear shape of the steel shell, the way of the load distribution by soil layers which manifests itself by increased local deformations of the shell, as well as, probably, by the fact that soil pressure is not evenly distributed.

However, when maximum displacements and stresses obtained from calculation models from two types of software, i.e.: Abaqus and ARSA (Manko and Beben 2005) are compared, it can be stated that the herein presented way of modelling of a SSC culvert allows obtaining more satisfactory results. When both calculation programs were used, relative discrepancies amounted at 15-39% for displacements and 17-44% for stresses, with advantage to the model worked out by Abaqus. These differences result from the way of modelling in ARSA program, i.e.:

- it does not apply the flat shell with the orthotropic properties,
- the soil is modelled with use of the Coulomb-Mohr criterion,
- it uses simplified contact elements (friction coefficient only) to reflect interaction between SSC culvert elements.

The elaborated calculation model of a SSC culvert in Abaqus program makes it possible to obtain reasonable values of displacements and stresses despite the fact that in most cases they exceed the measured values.

To evaluate the actual live load-carrying capacity of the steel-soil composite culverts the load rating can be used. A load rating for the evaluation of these culverts can be defined as the ratio of the actual live load-carrying capacity of the culvert to the factored design live and impact load (Yeau and Sezen 2012). So the proposed numerical model can be used to determine the actual load-carrying capacity of the steel-soil composite culverts.

The internal forces in a SSC culvert were calculated with use of three analytical methods, Sundquist-Pettersson, Duncan and CHBDC. To estimate the maximum stress in the SSC culvert using above methods, the combined effects of the bending moment and thrust (the Navier equation) can be applied

$$\sigma = \frac{N_b + N_r}{A_{s1}} + \frac{M_b + M_r}{W_{s1}} \le f_{yd}, \tag{5}$$

where: N_b, M_b = maximum axial thrust and bending moment in the basic shell structure, respectively, received from the experimental tests; N_r, M_r = maximum axial thrust and bending moment in the reinforcement ribs of shell structure, respectively, received from the experimental tests; A_{s1}, W_{s1} = area of composite cross-section and section modulus (basic shell structure and ribs), respectively; f_{yd} = yield strength of material of the steel shell structure.

Table 2 shows maximum stresses calculated on the basis

Table 2 Axial forces, bending moments and stresses calculated based on Sundquist-Pettersson, Duncan and CHBDC methods

Methods	Phase (load)	Axial thrust (kN/m)	Bending moment (kNm/m)	Maximum stresses (MPa)	% of yield strength of SSC culvert
Sundquist-Pettersson (2014)	Construction (backfill)	266.33	-90.55	266.8	85
	Serviceability (live load)	45.13	46.11	154.3	49
Duncan (Janusz and Madaj 2009)	Construction (backfill)	426.21	-66.97	174.0	55
	Serviceability (live load)	545.60	-63.47	150.5	48
CHDBC (2006)	Construction (backfill)	65.90	30.27	105.0	33
	Serviceability (live load)	107.08	54.93	189.3	60
Test (Manko and Beben 2005)	Construction (backfill)	522.87	-87.88	232.0	74
	Serviceability (live load)	365.0	5.32	52.0	17

of the three design methods and Eq. (5). As it can be seen stresses at each stage of the analysis of the culvert (construction and service state) do not exceed the allowed value (314 MPa). A maximum stresses constitute of 33-85% and 48-60% of the yield strength of the steel, respectively for the construction and service state. However the stresses (from the live loads) are considerably higher than values obtained from experiments (σ_{test} = 52 MPa) and from calculation models ($\sigma_{\text{Abaq.}}$ = 65 MPa, σ_{ARSA} = 81 MPa). In the case of stresses obtained at the construction stage, the Sundquist-Pettersson method gives overestimated results, whereas the Duncan and CHBDC methods underestimate them. This proves conservative assumptions in the analyzed design methods (too high safety factors, conservative way of load distribution by soil layers, insufficient consideration of interaction between the soil and the steel shell).

Table 2 also shows calculated axial thrusts and bending moments. The maximum axial thrusts were obtained at the steel shell crown (for all the methods), and in the case of bending moments at the crown (for Sundquist-Pettersson and Duncan methods) and at the haunch, for the CHBDC method. In the case of test results, the most extreme bending moments were observed at the steel shell crown, and the axial thrusts at the crown or around (2/3 of the shell height).

As it results from Table 2, the present analytical methods to determine internal forces in SSC culverts are generally quite conservative when compared to values obtained from experiments. In the case of axial thrusts at the construction stage, the considered methods give underestimated values (the Duncan method is the most accurate - the axial thrusts lower by 22.6%). At the service stage under live loads the axial thrusts calculated on the basis of the Sundquist-Pettersson and CHBDC methods are highly underestimated, and in the case of the Duncan method – considerably overestimated (49.5%). Whereas bending moments calculated on the basis of the Sundquist-Pettersson method (construction stage) are nearly identical with the ones obtained from experiments. The remaining methods give underestimated values of bending moments (31.2% for Duncan and 190% for CHBDC methods). Bending moments during live loads are considerably overestimated for all the methods.

The differences between the CHBDC and Sundquist-Pettersson methods can be related to the use of the Dynamic Amplification Factors (DAF). In the case of the Sundquist-Pettersson method, the DAF for a given culvert is not taken into consideration. The live loads are multiplied by the load factor that equals 1.5. Whereas the CHBDC method takes into account dynamic impacts through the dynamic load allowance (DLA), i.e., 1+DLA, which changes linearly depending on the soil cover thickness over the steel shell. Generally, differences between analytical methods and field tests may be caused by their approach to the load distribution through the soil cover. Additionally, the manner of determine the arching factor and the soil-steel structure interactions are not properly considered.

5. Conclusions

As a result of numerical analysis of the SSC culvert in the Abaqus program and comparing the results with data from prior experiments and calculations executed with use of the ARSA program, and on the basis of three design methods, the following conclusions can be drawn:

(1) The calculated displacements and stresses exceed the values obtained from experiments. The shape of the displacements and stress curves does not generally differ from the one obtained from experiments. Relative differences between the calculated and measured values ranged from 5 to 25% for displacements, and 15–42% for stresses. However the calculation results are considerably more precise than the ones obtained from the ARSA program (Manko and Beben 2005). Relative differences were contained within the scope of 15–39% for displacements, and 17–44% for stresses, with advantage to the model elaborated with use the Abaqus. It results from the fact that in the case of Abaqus program, the calculation model assumed a flat shell with orthotropic properties, the soil behaviour was better described (the Drucker-Prager model) and mutual interaction of SSC culvert elements was reflected in a more advantageous way.

(2) The most extreme displacements of SSC culvert obtained from the Abaqus program were located at the shell crown (3.01 mm) and their courses was uneven (schemes I and II) with quite considerable

local deformations. Whereas the maximum stresses amounted at 65 MPa and were observed at the haunch of the steel shell. They approximated the maximum value obtained from experiments (52 MPa), but were considerably lower than ones calculated by means of the analytical methods: Sundquist-Pettersson, Duncan and CHBDC. This proves that the methods have conservative assumptions, especially as far as load distribution, safety factors and soil-steel shell interaction.

(3) The differences in the obtained test and calculation results may be due to:

- inexact mapping of the soil in the calculation model (the exact physical and strength parameters were not known). Moreover the numerical analysis should take into consideration the influence of soil consolidation,
- neglect to take the shell slope into account in the numerical model, which diminishes the shell surface taking over loads from higher located soil layers,
- complex geometry of the SSC culvert – then numerical model does not constitute an accurate image of the existing structure, numerous details have been omitted or simplified, such as corrugation profile, reinforce concrete reinforcements of the shell at the inlet and the outlet, as well as screw joints between the steel sheets.

Bending moments and axial thrusts in the SSC culvert calculated on the basis of three design methods (Sundquist-Pettersson, Duncan and CHBDC) in most cases give overestimated values when compared to test results. Bending moments from soil loads (construction stage) for the Sundquist-Pettersson method and axial thrusts from service load for the Duncan method constitute an exception. However, it needs to be underlined that on each stage of the analysis the stresses do not exceed the acceptable value (314 MPa). A maximum stresses constitute of 33-85% and 48-60% of the yield strength of the steel, respectively for the construction and service state. The differences between analytical methods and field tests may be caused by their approach to the load distribution through the soil cover, the manner of determine the arching factor and that the soil-steel structure interactions are not properly considered.

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