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Research paper

Influence of soil backfill parameters on culvert load capacity with accordance to Eurocodes and Sundquist-Pettersson calculating method

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Abstract: The paper presents analysis of effect of structural soil backfill parameters on load capacity of culvert made as buried flexible steel structure. The work is divided into two parts. The first part is devoted to the assumptions of the Sundquist-Pettersson method. The principles of the analysis of the structure in terms of ultimate limit strength, serviceability and fatigue in permanent and temporary calculation situations are described. The second part presents a design example of a soil steel composite bridge in the form of a closed profile culvert made of MulitiPlate-type corrugated sheet. The static and strength calculations were conducted according to the Sundquist-Pettersson method and the guidelines presented in the Eurocodes. According to the guidelines, the value of the backfill tangent modulus was determined using the simplified (A) and precise (B) methods. It was found that the modulus values determined by the simplified method were about three times lower than for the exact method, leading to very conservative, uneconomical results. The structural calculations using the tangent modulus determined by the simplified method, indicated that the load capacity of the structure was exceeded, regardless of the thickness of the backfill used (in the range from 0.5 to 5 m). The use of the tangent modulus determined using the precise method resulted in a significant reduction in stress to bearing capacity ratio of analysed parameters. Similar reduction was observed with the increase in the thickness of the backfill.

Keywords: corrugated sheet, road engineering structures, soil–steel structures, culvert

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1. Introduction

The load capacity of steel and ground composite structures is determined with the assumption of interaction between the shell and the surrounding backfill. The result of this interaction is the phenomenon of soil arching, i.e. the reduction of soil pressure on the shell surface [1]. The importance of backfill in the load transfer process has been demonstrated by tests conducted at the Road and Bridge Research Institute in Żmigród. The authors, on the basis of the test results presented in their works [2–4], on full scale elements, concluded that the soil is the main load-bearing element, and the shell essentially has a shielding function. The decisive parameter describing the load capacity of the soil is the tangent modulus.

Incorrectly made backfill results in a number of failures or catastrophes, mostly occurring at the execution stage. The issues of executive errors, their consequences and aspects affecting the durability of structures in use are discussed in [5, 6]. A special role in the quality assessment of a structure plays the observation of the shell displacement at the construction and operation stage [7–9].

The methodology of structural design of deformable structures has evolved over recent years, resulting in a number of proprietary procedures ranging from simple methods that ignore the soil and shell interaction, modern methods [10] that are based on it, such as the Swedish method [11], to calculations based on the finite element method, using commercial software. Still despite the growing popularity of soil-shell structures, European standards do not provide guidelines for the design of such structures. Therefore, recommendations on the type of material from which a structure was made are important – standards relating to geotechnical design [12, 13], as well as steel structures and their connections. In Poland, there are several studies which contain a comprehensive description of these issues, in the form of compact publications [14–16] and a series of thematic publications [17].

The following is an analysis of the calculation of a VR closed elliptical structure, conducted according to the Swedish method and the corresponding Eurocodes.

2. Sundquist-Pettersson Method

The Sundquist-Pettersson method, also known as the Swedish method, is currently the leading method for designing flexible structures [11]. It was developed on the basis of studies of real engineering structures [18]. The latest fifth edition of the manual by H. Sundquist and L. Pettersson, published in 2014, has been fully adapted to the requirements of the Eurocodes.

When designing culverts, it is assumed that the shell cross-section is the same along the longitudinal axis of the structure. Therefore, the design model consists of a one-metre long section which is loaded perpendicular to its longitudinal axis. Where the cover height, backfill material or cross-section varies over its length, each section should be considered separately. The structural design involves checks in the following range [11]:

a) serviceability limit states (SLS): plasticisation of the structural wall due to the subsidence of the structure;
b) ultimate limit states (ULS): verification of plastic hinge or kinematic chain mechanism formation possibility in the upper part of the structure, verification of the possibility of transforming the structure into a kinematic chain, verification of the load-bearing capacity of bolt connections, verification of the load-bearing capacity in the lower part of the structure, verification of safety due to soil pressure on structural corners of the underpasses, verification of the load-bearing capacity of reinforced concrete foundations;
c) during the assembly stage: checking the stiffness of the structure during the assembly stage, checking the structure with the backfill at zero cover depth, checking the structure during temporary assembly stages, and
d) structural fatigue checks: due to fatigue of corrugated sheet metal, due to fatigue of bolted connections.

2.1. Serviceability Limit States

Verification for structural wall plasticisation at the serviceability limit state involves proving that the stresses in the culvert coping do not exceed the yield strength of the material. The maximum stress in the structural walls is calculated for the absolute value of the section forces from the Navier's equation:

$$\sigma = \frac{|N_{d,SLS}|}{A} + \frac{|M_{d,SLS}|}{W} \leq f_{yd} \tag{2.1}$$

where:

$N_{d,SLS}$ – normal force at serviceability limit state, $M_{d,SLS}$ – bending moment at serviceability limit state, A – culvert wall cross section area, W– culvert wall section modulus, and f_{yd} – design value of the yield strength.

2.2. Ultimate Limit States

2.2.1. Local Buckling

The selected profile made of corrugated sheet must be checked due to the risk of local buckling from the condition:

$$M_{u,cr} < M_u \tag{2.2}$$

where:
$M_{u,cr}$ – critical sectional moment, M_u – plastic moment capacity.

This condition does not have to be met, as the risk of local buckling, as assumed by this method, is acceptable. However, when it occurs, this ratio, interpreted as the ratio of the critical sectional moment to the plastic moment capacity, should be used to reduce the load-bearing capacity in structural design in ultimate limit states when checking the possibility of a plastic hinge mechanism formation.

2.2.2. Plastic Hinge Mechanism Formation

The check shall be performed according to a simplified formula [20]. Assuming that the sheet is not subjected to torsional deformation, therefore $M_{z,Ed} = \Delta M_{z,Ed} = 0$; $\chi_{LT} = 1.0$and $\chi_z = 1.0$. In addition, since the cross-section of a component is usually class 1 or 2, there is no additional bending moment due to the shift of the neutral axis. The formula shall then take the following form [19]:

$$\frac{N_{Ed}}{\frac{\chi_y N_{Rk}}{\gamma_{M1,steel}}} + k_{yy} \frac{M_{y,Ed}}{\frac{M_{y,Rk}}{\gamma_{M1,steel}}} \leq 1.0 \tag{2.3}$$

where:
$N_{Ed}, M_{y,Ed}$ – design values of normal force and bending moment relative to the *y*–*y* axis, χ_y– flexural buckling coefficient according to [19], k_{yy} – interaction factor according to

[19], N_{Rk}, $M_{y,Rk}$ – compression and bending strength of the cross-section, $\gamma_{M1,steel}$ – material factor for steel, recommended value is 1.0.

This procedure is described in detail in paper [20].

2.2.3. Converting the Structure Into a Kinematic Chain

The verification for the possibility of converting the structure into a kinematic chain shall be carried out without the exception of the formula of the component taking into account the bending moment effect. This simplification reduces the formula to the form [11]:

$$\left(\frac{N_{d,ULS}}{\omega f_{yd} A}\right)^{a_c} \leq 1.0 \tag{2.4}$$

where:

$N_{d,ULS}$ – design normal force for ultimate limit state, $\omega = \frac{N_{cr}}{A}$, $a_c = \eta^2 \cdot \omega \geq 0.8$, $\eta = \frac{Z}{W}$, N_{cr} – critical force for the structural wall placed in the ground (buckling load), Z – culvert wall plastic section modulus, A, W, f_{yd} - according to Eq. (2.1).

2.2.4. Load Bearing Capacity at the Bottom of the Culvert

The load-bearing capacity condition of the lower part of the culvert should be considered for sections with a fixed radius. The check is to show that the estimated normal force for the most unfavourable ultimate limit state system is less than the critical force for the culvert walls. The critical force is determined according to second order theory, based on Klöppel and Glock's formulas [11]. The load-bearing capacity condition can therefore be written as follows:

$$N_{d,ULS} \leq N_{cr} \tag{2.5}$$

2.2.5. Load Capacity of Bolted Connections

The load capacity of bolted connections is checked for shear, tension and shear-tension interaction. In addition, the spacing between parallel bolt rows is checked for the required bending strength of the connection. The design is conducted in accordance with the applicable standard [21].

2.3. Assembly Stage

The basic element necessary to verify the structure during the assembly stage is its stiffness. The structural stiffness is determined by the formula [11]:

$$\eta/(m/kN) = \frac{D^2}{(EI)_{steel}} \tag{2.6}$$

where:

$\eta/(m/kN)$ – steel pipe's stiffness, D – diameter or span in unloaded condition,$(EI)_{steel}$ – the bending stiffness of the pipe per unit length.

The value determined from Eq. (2.6) should meet the following conditions:
$\eta/(m/kN) < 0{,}13$ for circular sections, and
$\eta/(m/kN) < 0{,}20$ for arch shape sections and low profile sections.

In addition, account should be taken of temporary design situations where the cover height is different from its target value. The check should be performed when the backfill is at the level of the crown segment, using the Navier's formula mentioned above for serviceability limit state analysis.

2.4. Structural Fatigue

Fatigue of steel structural components, such as corrugated sheet metal and bolted connections can be checked using the simplified method known as the lambda coefficient method or the damage summation method, i.e the Palmgren-Miner method. The first one was developed for railway bridges and is recommended for such structures. However, it should be borne in mind that it is permissible to apply to road engineering structures. The calculations should be made in accordance with the guidelines of the standards [22–24].

3. Design Example Analysis

3.1. Design Assumptions

The subject of the analysis is a VR closed elliptical culvert made of MultiPlate corrugated sheet metal – S235J2G3 MultiPlate steel class [25]. The geometry and materials of the tested structure and its surroundings are presented in Fig. 1.

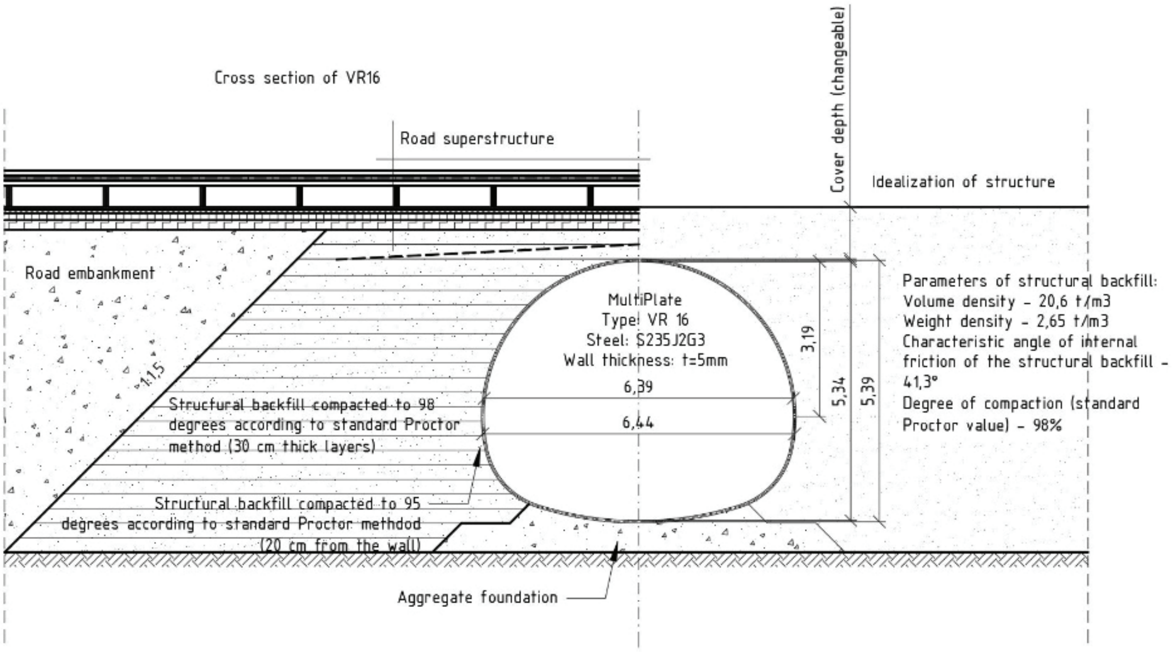

Fig. 1. Cross section of VR16 closed culvert

The scope of the analysis included functions dependent on the cover height and the tangent modulus of the soil, describing stress to bearing capacity ratio of selected parameters:

- In the ultimate limit states: the mechanism of plastic hinge formation, the conversion of the structure into a kinematic chain, the load capacity of the structure in the lower part and the load capacity of the bolted connections due to: shear, tension, shear and tensile interaction;
- Serviceability limit states: plasticisation of the structural wall during the operation, and
- In fatigue limit states: corrugated sheet metal, bolted connections, due to shear, tension and their interaction.

The analysis was conducted using Excel and MathCad.

The structural load during the operation phase of the facility was a permanent load caused by the deadweight of the backfill (density level according to the Proctor test – 98%) and the service load caused by the movement of vehicles according to the LM1 model for the ultimate and serviceability limit state and the fatigue model 3 for fatigue checking according to the standard [23]. Vertical forces of operating loads have been replaced by a load distributed linearly on the road surface. The internal forces in the culvert wall were determined according to [11]. In a temporary design situation (assembly stage of the structure) only the weight of the backfill treated as an alternating load is taken into account. The interaction combinations and partial factors for checking the ultimate and serviceability limit states have been adopted in accordance with [26]. Partial factor for fatigue loads as recommended in [24].

The structural fatigue was estimated on the basis of a simplified method of so-called lambda coefficients. The range of stress variation from a single run of a simplified fatigue load model was determined from the formulae given in the manual [11]. The range was then modified according to [23], summing the tensile component and 60% of the compressive component. The damage equivalence factor for road bridges was determined on the assumption that [22, 23]: the category of traffic on the site is the main road with a small share of the lorry traffic; the bridge service life is assumed to be 100 years as for the structure class S5. As the share of the lorry traffic increases, the fatigue intensity will increase, but the very shape of these parameters will be constant.

The soil tangent modulus was determined by two methods according to [11]: simplified (method A) and accurate (method B). In the simplified method, the value of the tangent modulus is determined from the relationship based on Duncan's equation, in which, apart from the relative degree of compaction (RP), the only parameters required are h_c (cover height) and H (vertical distance between the crown center of gravity line of the pipe and the height at which the culvert has its greatest width). The degree of compaction RP is the standard Proctor value. The simplicity of this method makes the soil tangent modulus values low – a conservative approach. Method A can be used for sand – and gravel – type soils.

The application of the exact method (B) requires detailed information about the backfill parameters, including particle size distribution, degree of compaction, and stress level in the surrounding fill. The parameters of the backfill adopted at the design stage are subjected to detailed control during construction. The procedure of tangent modulus determination involves calculation of void ratio e_0, uniformity coefficient C_u, modulus ratio m, stress exponent β and characteristic angle of internal friction φ_k.

For the purposes of calculations, the space above the crown segment was converted into a continuum with parameters corresponding to the backfill, thus omitting the road construction layers. Due to the fact that one of the analysed parameters was the backfill height, the possibility of using a variable cover height resulting from changes in density of individual layers was not used.

3.2. Results

The results of the analysis are presented graphically in Figs 2 and 3. The elements of the diagram are stress to bearing capacity ratio function curves depending on the backfill height for particular conditions in serviceability, ultimate and fatigue limit states of steel elements.

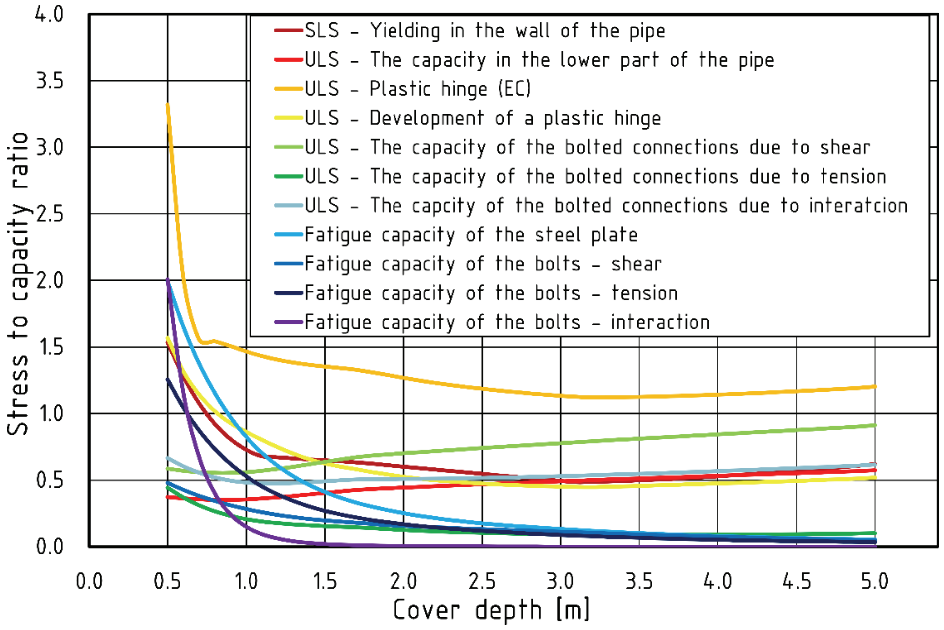

Fig. 2. Stress to bearing capacity curves for analysed parameters (backfill parameters determined according to the method A)

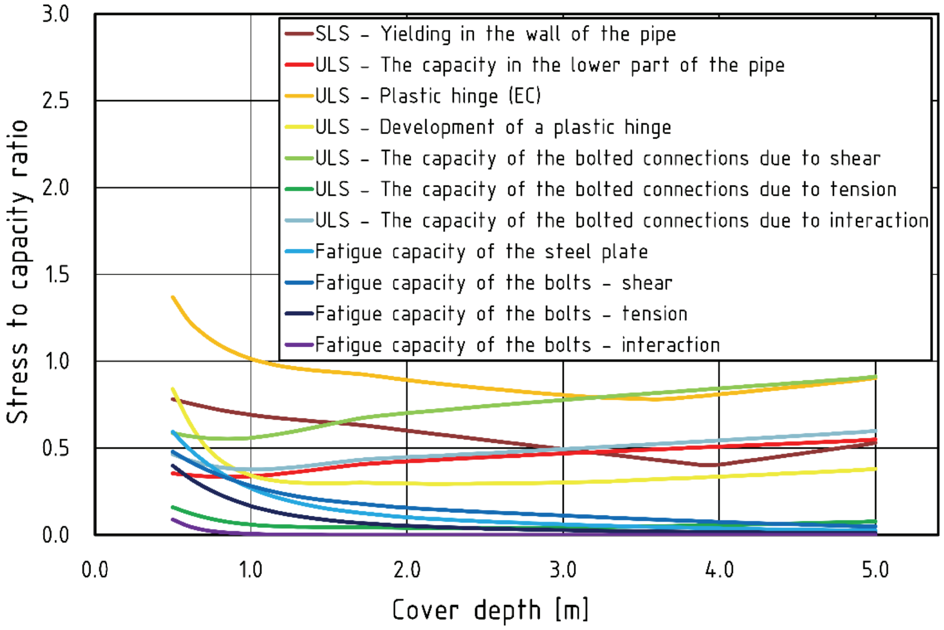

Fig. 3. Stress to bearing capacity curves for analysed parameters (backfill parameters determined according to the method B)

The structural stiffness condition during the assembly stage as well as the check for the local buckling risk of the structural walls have been omitted as they are values that depend only on the material characteristics of the tested profile.

In the ultimate limit states for the structure under analysis, the key elements affecting the load capacity of the culvert are the conditions taking into account the possibility of the plastic hinge mechanism formation in the most stressed section and converting the structure into a kinematic chain. The plasticisation of the structural wall at the serviceability limit state became important when the soil tangent modulus had been determined using the simplified method. In addition, for small cover thickness, the fatigue condition of corrugated sheet metal and the fatigue of the bolted connectors due to the interaction of shear and tension of the bolts should be checked.

The differences between the stress to bearing capacity ratio values for the cases under consideration are caused by the differences in the characteristic value of the soil tangent modulus. Using the simplified method marked with the letter A, the load capacity of the structure in the most heavily loaded section was exceeded over the whole range of cover height changes considered. Precise calculations of the backfill parameters with the B method allowed for a significant reduction of the previously mentioned ratio. The structure is designed correctly even for cover thicknesses slightly exceeding 1 m. The analysis of the stress to bearing capacity ratio changes for the mechanism of the plastic hinge formation as a function of the cover height change and the soil tangent modulus value is presented in Fig. 4.

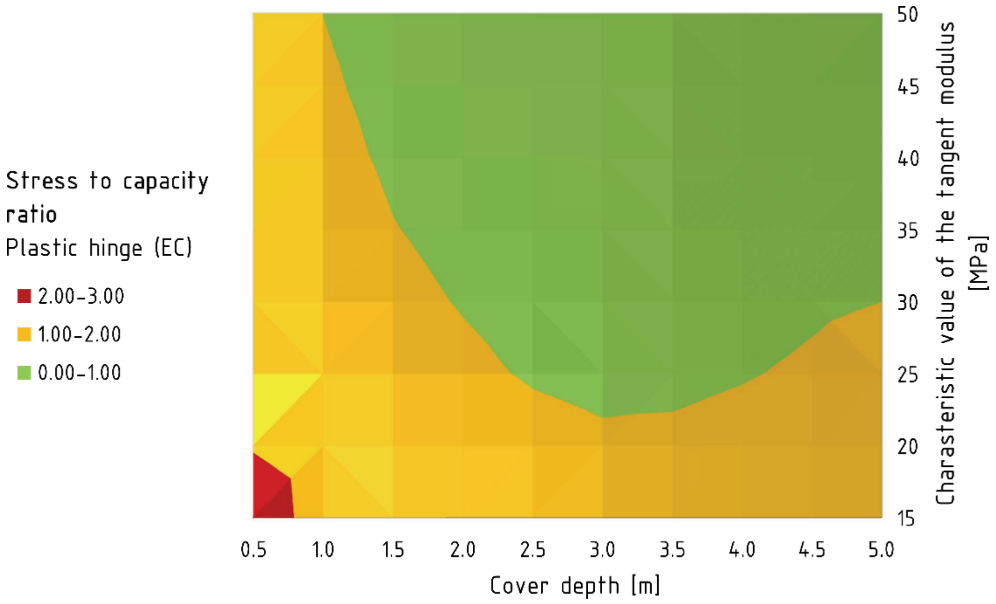

Fig. 4. The value of stress to bearing capacity ratio for the mechanism of plastic hinge, depending on the value of the tangent modulus of the ground and the height of the cover

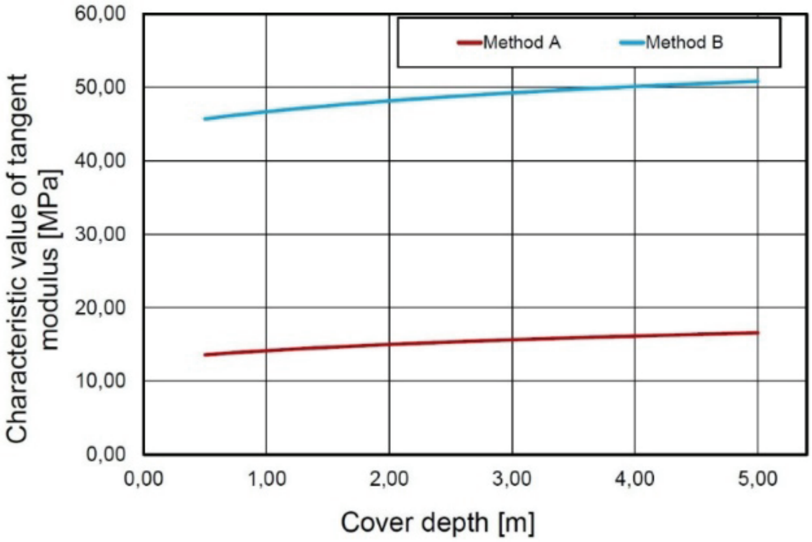

Fig. 5. Changes in the ground tangent modulus for the analysed case

The soil tangent modulus determined according to the simplified method is about three times lower than in the case of a thorough analysis (Fig. 5).

4. Discussion

Results of analysis of design example show that increasing thickness of the backfill usually resulted in a decrease in stress to bearing capacity ratio – due to decreasing values of bending moments from moving loads of all evaluated parameters. An exception is made for the load capacity of the lower part of the structure and the capacity of the bolted connections due to shear and interaction, the values of which are largely dependent on the normal force. It should also be noted that for some curves, an initial decline in stress to bearing capacity ratio is followed by their growth. The reason for this behaviour is the change in the maximum bending moment, the value of which was increasingly dependent on the weight of the soil layers lying above the crown segment.

Preliminary design stage could be limited to plastic hinge check in ultimate limit stage which indicate highest values of stress to bearing capacity ratio regardless to the cover depth value. In analysed example increasing the thickness of the corrugated sheet or steel class would reduce up to 30% previously mentioned ratio without changing the cover height values. The selected values of ULS – plastic hinge parameter for different values of steel class, sheet thickness and cover height are shown in Table 1.

Table 1. Selected values of ULS – plastic hinge parameter for different values of steel class, sheet thickness and cover height

Steel class	Sheet thickness [mm]	Cover height [m]		
		0.5	1.0	1.5
235	5	1.369	1.014	0.940
	6	1.283	0.895	0.820
	7	1.219	0.806	0.732
	8	1.168	0.737	0.663
355	5	1.205	0.817	0.737
	6	1.129	0.729	0.650
	7	1.071	0.663	0.586
	8	1.024	0.611	0.536

5. Summary and conclusions

The article presents an analysis of the impact of selected parameters of the backfill on the ultimate, serviceability and fatigue limit states of the VR closed elliptical culvert. The analysed parameters were the backfill height and the change in the method of determining the soil tangent modulus. The static and strength calculations were conducted according to the Sundquist-Pettersson method and the guidelines presented in the Eurocodes. The results obtained lead to the following conclusions:

- From the point of view of designing this type of structure, the parameters of the backfill have a decisive impact on the load capacity of the structure;
- Determining the soil tangent modulus value in a precise manner allows to limit the calculated stress to bearing capacity ratio of the evaluated parameters to a large extent in relation to the simplified method;
- As the soil deadweight increases, the bending moment due to the operating load decreases, and
- Analysis of the impact of the backfill height on the values of internal forces and the strength of structural elements is an important issue when checking structures with low cover height values, as for most of the key parameters checked, the course of their curves could be described as quasi-logarithmic.

At the end it should be emphasized that estimating the current load-carrying capacity of structures existing in overload conditions is extremely important [27]. For steel structural elements it seems that methods based on the damage mechanics [28–32] have got considerable potential in this regard. Thanks to the analysis the stress and strain state in critical parts of the structure it is possible to estimate the current load-carrying capacity as well as to predict the time to failure.

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Wpływ wybranych parametrów zasypki inżynierskiej na nośność przepustu według Eurokodów i metody Sundquista-Petterssona

Słowa kluczowe: blacha falista, drogowe obiekty inżynierskie, konstrukcje gruntowo-powłokowe, przepusty

Streszczenie:

Nośność konstrukcji zespolonych stalowo-gruntowych określana jest przy założeniu współpracy powłoki z otaczającą ją zasypką inżynierską. Wynikiem tej współpracy jest powstanie zjawiska przesklepienia, czyli redukcji nacisku gruntu na powierzchnię ścianki. Aktualnie wiodącą metodą obliczania i wymiarowania tego typu konstrukcji jest metoda Sundquista-Petterssona, w pełni przystosowana do wymagań stawianych przez Eurokody.

Przedmiotem pracy jest wykorzystanie metody Sundquista-Petterssona do oceny nośności przepustu o konstrukcji zamkniętej, wykonanego z blachy falistej typu MultiPlate, ze stali gatunku S235J2G3. Określono wpływ wysokości zasypki inżynierskiej oraz modułu stycznego gruntu na wytężenie konstrukcji. Analizie poddano:

- w stanach granicznych nośności: mechanizm powstania przegubu plastycznego, przekształcenia konstrukcji w łańcuch kinematyczny, nośność konstrukcji w dolnej części oraz nośność złączy śrubowych ze względu na: ścinanie, rozciąganie, interakcję ścinania i rozciągania;
- w stanach granicznych użytkowalności: uplastycznienie ścianki konstrukcji w fazie eksploatacji obiektu;
- w stanach granicznych zmęczenia: blachy falistej, złączy śrubowych, ze względu na ścinanie, rozciąganie i ich interakcję.

Obliczenia przeprowadzono z wykorzystaniem programów Excel i MathCad.

Analiza zmęczenia konstrukcji została przeprowadzona na podstawie uproszczonej metody tzw. współczynników lambda. Zakres zmienności naprężeń od pojedynczego przejazdu uproszczonego modelu obciążenia zmęczeniowego wyznaczono na podstawie metody Sundquista-Petterssona. Następnie zakres ten został zmodyfikowany, poprzez sumowanie składowej rozciągającej oraz 60% składowej ściskającej. Współczynnik równoważności uszkodzeń dla mostów drogowych wyznaczono przy założeniu, że: kategoria ruchu na obiekcie to droga główna z małym udziałem potoku samochodów ciężarowych; czas użytkowania mostu przyjęto jak dla klasy konstrukcji S5 równy 100 lat.

Zgodnie z wytycznymi wyznaczono wartość stycznego modułu sztywności zasypki metodą uproszczoną (A) i dokładną (B). Stwierdzono, że wartości modułu wyznaczone metodą uproszczoną były około trzykrotnie niższe niż w przypadku metody dokładnej, prowadząc do bardzo konserwatywnych, nieekonomicznych wyników wymiarowania. W analizowanym przypadku wyniki wymiarowania z zastosowaniem modułu wyznaczonego zgodnie z metodą uproszczoną każdorazowo wskazywały na przekroczenie nośności konstrukcji, niezależnie od zastosowanej grubości zasypki (w zakresie od 0.5 do 5m). Wykorzystanie do wymiarowania modułu stycznego, określonego za pomocą metody dokładnej, powodowało znaczne ograniczenie obliczonego wytężenia konstrukcji. Przepust już dla grubości naziomu nieznacznie przekraczającej 1 m został zaprojektowany poprawnie.

Zwiększająca się grubość zasypki inżynierskiej powodowała zazwyczaj zmniejszenie wytężenia – na skutek zmniejszania wartości momentów zginających od obciążeń ruchomych. Wyjątek stanowią warunek nośności dolnej

części konstrukcji i nośność na ścinanie złączy śrubowych, których wartości w dużej mierze zależne są od wielkości siły normalnej. Zauważyć należy również, że dla niektórych krzywych po początkowym spadku wytężenia następuje jego wzrost. Przyczyną takiego zachowania jest zmiana znaku maksymalnego momentu zginającego, którego wartość była coraz bardziej zależna od ciężaru warstw gruntu zalegających powyżej klucza konstrukcji.

W stanach granicznych nośności dla analizowanego obiektu kluczowymi elementami wpływającymi na zapewnienie nośności przepustu są warunki uwzględniające możliwości powstania mechanizmu przegubu plastycznego w przekroju najbardziej wytężonym oraz przekształcenia konstrukcji w łańcuch kinematyczny. Uplastycznienie ścianki konstrukcji w stanie granicznym użytkowalności stało się istotne w przypadku, gdy moduł styczny gruntu wyznaczono za pomocą metody uproszczonej.

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