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FINITE ELEMENT ANALYSIS OF LATERAL EARTH PRESSURE ON A LAGGING IN SOLDIER PILE WALLS

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A b s t r a c t

The main aim of this article is to show how different ways of modelling a construction process of soldier pile walls influence the development of the computational lateral earth pressure in this type of structure. Moreover, the paper includes an analysis of soldier pile systems designed in both traditional (Coulomb, Rankine etc.) and numerical approaches. In order to analyse the above problems, several numerical models of soldier pile walls were built and the results obtained were then compared.

Keywords: excavation, soldier pile wall, FEM

S t r e s z c z e n i e

Głównym celem artykułu jest odpowiedź na pytanie, w jaki sposób różne sposoby modelowania technologii realizacji ścianek berlińskich wpływają na rozwój obliczeniowego parcia czynnego w tego typu konstrukcjach oporowych. Ponadto praca zawiera analizę porównawczą projektowania ścianek berlińskich zarówno w ujęciu tradycyjnym, jak i numerycznym. W celu analizy powyższych problemów zbudowano kilka modeli numerycznych, a uzyskane z nich wyniki porównywano.

Słowa kluczowe: wykop, ścianka berlińska, MES

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1. Introduction

Soldier pile and lagging walls are commonly used systems for supporting excavations in urban environments, where property lines or roads prohibit sloped or benched excavations. The soldier pile and lagging walls can be more economical and faster to construct than many other secure systems of excavations. In the past, they were used as elements of military fortifications.

The main components of the considered systems are steel H-piles placed vertically with spacing ranging from 1.2 m to 3.0 m, with the lagging placed between the piling to retain the soil. The lagging may be rough sawn timber, metal decking or even precast concrete planks. H-piles can be installed by driving, vibrating or by drilling a hole and wet-setting the pile in a grout column at the bottom of the excavation. Figure 1 shows the sort of the soldier pile walls which are discussed in this paper [1], [4].

The paper discusses only non-anchored soldier pile wall systems, which are used for a limited excavation depth, (in practice, $h < \sim 4.0$m). For these systems, correct evaluation of the earth pressure is of particular importance.
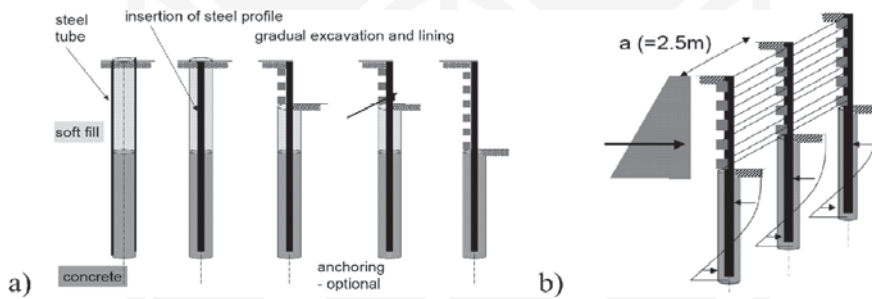

Fig. 1. Soldier pile wall („Berlin" type): a) phases of construction, b) load action

In continuous rigid earth retention systems, such as sheet pile walls, the lateral earth pressure and the displacement are generally assumed to be constant along the length of the wall (this is the one of the basic rules of analysis in the plane strains – PS). In the soldier pile and lagging systems, the lagging is often significantly less stiff than the steel soldier piles. As the lagging deflects, the soil tends to bridge between the stiffer elements resulting in a lower pressure on the lagging [2, 4].

The main aim of this article is to show how different ways of modelling the construction process of soldier pile walls influence the development of the computational lateral earth pressure in this type of structure. Moreover, the paper also discusses an analysis of the soldier pile systems designed in both traditional (Coulomb, Rankine, etc.) and numerical approaches. In order to analyse these problems, several numerical 3D models of the soldier pile walls from Figure 1 were built.

The article is the first part of wider research work devoted to creating a design algorithm for soldier wall systems based on computer modelling. However, the main subject of this research are problems regarding the bearing capacity of the underground part of the structure, and the recognition of lateral loads such as earth pressure will also be an important issue.

2. Geometry, material and load model of the soldier pile wall

A detailed geometric model of the soldier pile wall used in this case study is shown in Figure 2. The structure of the wall consists of:
– steel profiles IPE 360, length 8.0 m placed vertically at 2.5 m, $E = 210$ GPa, $\nu = 0.3$,
– concrete piles $\varnothing$ 0.5 m, length 4.0 m, $E = 30$ GPa, $\nu = 0.2$ (under the bottom of the excavation),
– timber lagging 0.25 m × 0.10 m, $E = 11$ GPa, $\nu = 0.25$.
    The described secure system of excavation represents the case of a cantilever wall where anchoring is not required.
    Two classes of soils were used in the analysis: cohesive soils and cohesionless soils. No additional load is assumed above the wall.
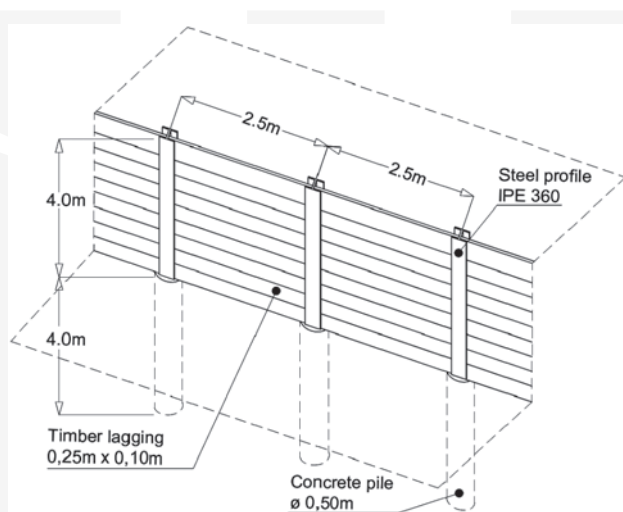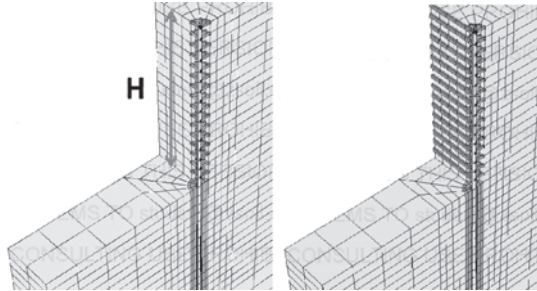

Fig. 2. Geometric model of the soldier pile wall

Four modelling scenarios of the construction process of a soldier pile wall were analysed. The process consists of two first steps which are common in all scenarios: 1 – drilling the hole, 2 – pouring the concrete and placing the steel profile. For the further phase of the construction, different scenarios are as follows (see Figure 3):
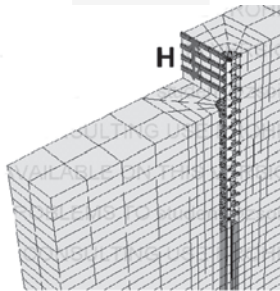– first modelling scenario (in one stage): 3 – excavation to the required level (–4.0 m), 4 – placing the lagging with use of a controlled unloading algorithm,
– second modelling scenario (in four stages – lagging immediately after the excavation): 3, 4, 5, 6 – simultaneous excavation and placing the lagging,
– third modelling scenario (in four stages – excavation then lagging in next step): steps 3, 5, 7, 9 – excavation, steps 4, 6, 8, 9, 10 – placing the lagging,
– fourth modelling scenario (in sixteen stages): steps 3 to 31 – excavation, steps 4 to 32 – placing the lagging.
    Deactivation of a certain part of the numerical model (corresponding to the excavation zone) is required in order to model the process of excavation. For this purpose, Zsoil 2012 Student v12.19 software was used. This allows instability problems occurring in the numerical solution due to unbalanced internal forces to be avoided by applying the partial relaxation technique.
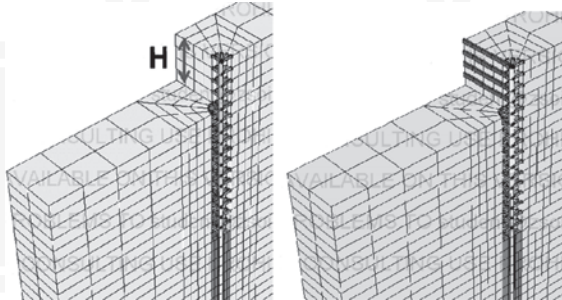
First modelling scenario (in one stage)

Second modelling scenario (in four stages – lagging immediately after excavation)

Third modelling scenario (in four stages – excavation then lagging in next step)

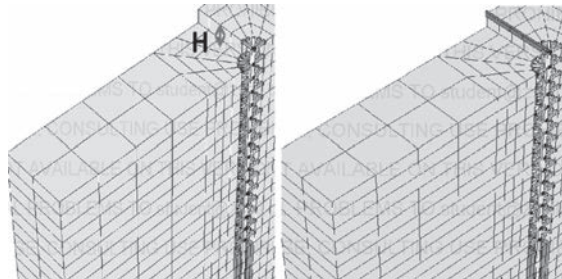Fourth modelling scenario (in sixteen stages)

Fig. 3. Considered modelling scenarios of the construction process of the soldier pile wall – step of the excavation and lagging placement

The principle of operation is based on the deactivation of the elements (its stiffness) at the part of the numerical model corresponding to the excavation zone while the resultant internal forces (equivalent to stresses) are preserved in the deleted elements. These forces are in the following incremental steps gradually reduced to zero. At the edge of the remaining area, the difference between internal forces at the deleted and remaining elements is a load (tending to zero), which facilitates the convergence of the iterative process. Figure 4 shows the process of controlled unloading by using the LTF function (Load Time Function).

Fig. 4. The process of controlled unloading:
a) equilibrium state before excavation, b) forces after excavation without controlled unloading,
c) forces after excavation with controlled unloading, d) the final state of equilibrium after unloading

3. FE models of the soldier pile wall

For analysing the problem of lateral earth pressure on the lagging in a soldier pile wall, 3D FE models were built (see Figure 5), and named as follows:
– "shell model",
– "beam-shell model",
– "beam model".
Detailed description of each of the FE models can be found below.

Fig. 5. FE models of the soldier pile wall: a) "shell model", b) "beam-shell model", c) "beam model", d) detail of the "beam model"
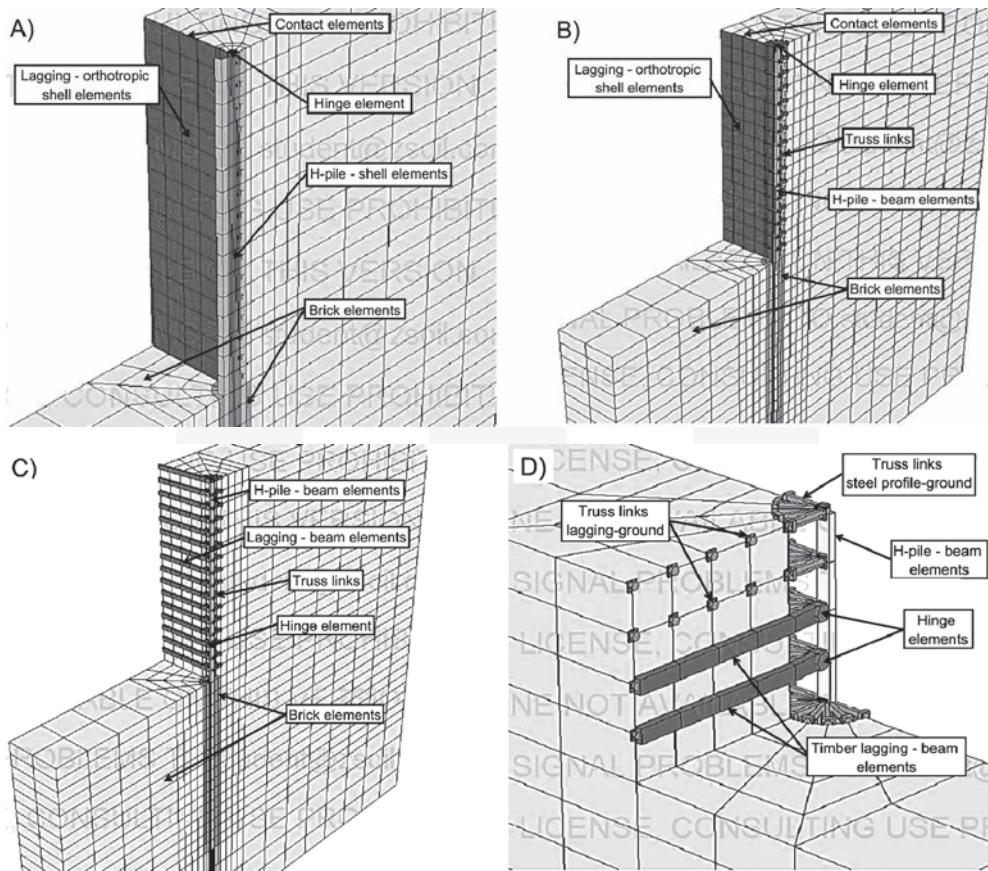
As can be seen in Fig. 5, the FE models were built based on the symmetry of the analysed problem. The elastic-plastic Mohr-Coulomb model of soil with the following parameters: $E = 100$ MPa/20 MPa, $\nu = 0.3$, $\psi = 0°$ (there is only one layer of soil) was applied in each of the cases. Structural elements of the wall were made of elastic materials. The results are compared for cohesive and cohesionless soils.

Figure 5a shows the model where the steel profile and the lagging were described as shell and orthotropic shell elements (Q4 plane elements), respectively – "shell model". The concrete part of the pile was modelled as B8 brick elements. In order to diversify vertical displacements of the soldier pile wall and the adjacent soil, interface (contact) elements were applied between these parts of the model.

The "beam-shell model" is shown in Figure 5b. The main difference between this model and the model described earlier is in the use of beam elements for the steel profile and truss elements for its connection with the soil. The truss links have a compressive strength ($f_c \neq 0$) and no tensile strength ($f_t = 0$). The lagging and the concrete pile have the same numerical structures as in the "shell model".

The "beam model" is shown in Fig. 5c and 5d. In this situation, both the steel profile and the lagging are the beam elements connected with the soil by truss links. The truss links were divided at the links connecting steel profile – soil and links connecting the lagging – soil (see Fig. 5d). These truss links have different parameters of strength and stiffness [1, 3].

In this way, unilateral constraints between the soil and the lagging were modelled in two equivalent fashions:

– in the "shell-beam model" and the "shell model" by frictionless contact interface elements,
– in the "beam model" by no tension truss links.

4. Results of the numerical analysis

While comparing the displacements and forms of deformation among the "shell model", "beam" and "beam-shell model", a good agreement of these was noticed. Therefore, this section describes only the results from numerical analysis of the "beam" and "beam-shell model". These two models are easier and faster to visualise the numerical results and to compare with the traditional approach. The first results are shown for the second modelling scenario of the construction process of the soldier pile wall (in four stages – lagging immediately after the excavation).

4.1. Cohesionless soils

The subject of the analysis were cohesionless soils with a variable value of friction angle from 24º to 46º with an increment of 2º. The values of cohesion and a Young's modulus were adopted: ~0 kPa and 100 MPa, respectively. Fig. 6 shows the results for both the "beam model" and the "beam-shell model" for the soil with $\phi = 36º$. Fig. 7 shows a comparison of an active pressure for numerical and traditional approaches. Good agreement between the computations was reported.

4.2. Cohesive soils

The subject of the analysis were cohesive soils with variable values of the friction angle ranging from 6º to 22º with an increment of 2º and cohesion ranging from 15 kPa to 31 kPa with an increment of 2 kPa. The value of Young's modulus $E = 20$ MPa was adopted. Fig. 8 shows the results for both the "beam model" and the "beam-shell model" for the soil with $\phi = 16º$ and $c = 25$ kPa. Fig. 9 shows a comparison of an active pressure for the numerical and the traditional approaches.

The non-physical phenomena could be seen when analysing the results for cohesive soils from Fig. 8. The Fig. 8c, 8e, 8g and 8h show the bending moments in the steel profile from the excavation site and in the lagging from the ground site while the soldier pile walls are not anchored. Besides this, Fig. 8h shows the arching effect well. Active pressure resultants E_a in the numerical and the traditional approaches are different as shown in Fig. 9 [5].

Results for the "beam model"

A)

Ux=2.75e-002m

B)

Results for the "beam-shell model"

Ux=2.92e-002m

C)

Mz=60kNm

D)

Qy=37kN

E)

Mz=61kNm

F)

Qy=36.5kN

G)

kNm

H)

kNm/m

Fig. 6. Comparison of the numerical results for the "beam model" and the "beam-shell model", the cohesionless soil $\phi = 36^\circ$: a), b) displacements and forms of deformation, c), e) bending moment for the steel profile, d), f) shear force for the steel profile, g), h) bending moment for the lagging
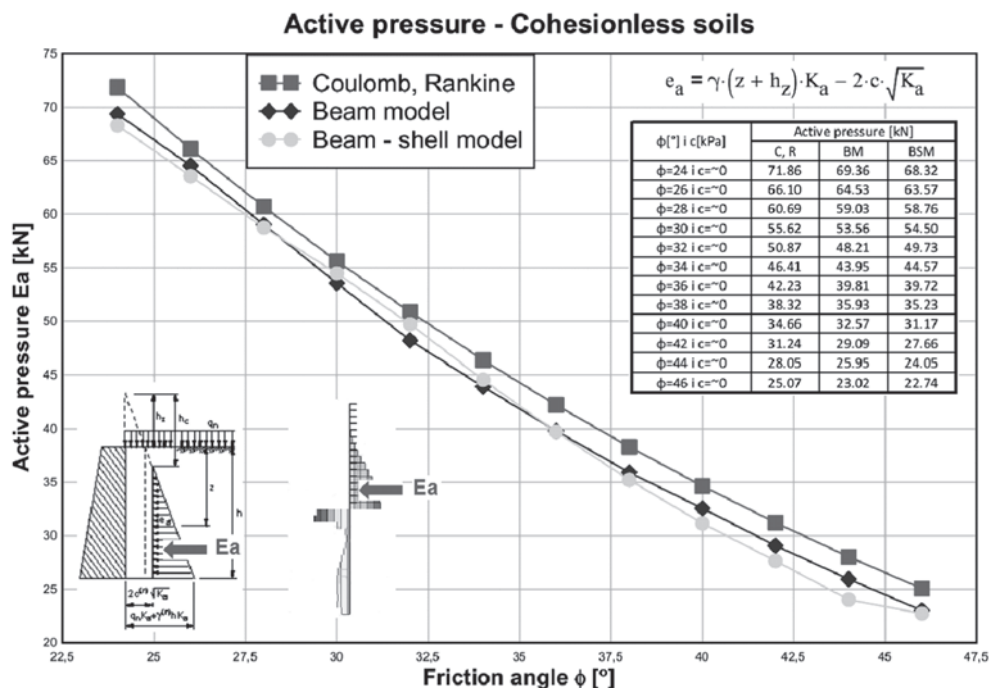
Active pressure - Cohesionless soils

Fig. 7. Comparison of an active pressure for the "beam model", the "beam-shell model" and the traditional approach, cohesionless soils

5. Results of the numerical analysis after upgrade

Non-physical bending moments in the soldier pile wall are related to the poor way of describing the unloading of the ground in the Mohr-Coulomb soil model, resulting in too large a displacement (vertical and horizontal) on the excavated side. Figure 10 shows the influence of the excavation on the development of the bending moments in the wall. It can be seen that, in modelling, the effect of beam curvature due to excavation prevails on effects of lateral loads.

In order to remove the non-physical bending moments from the steel profile and the lagging, the parameters of the truss links were changed (reduced values of stiffness). Additionally, a third class of truss links (see Fig. 11) was introduced. These links separate the adjacent ground from the steel profile (in reality, bentonite is between the adjacent soil and the steel profile). Besides these treatments, the other ways of modelling the construction process of the soldier pile wall were analysed: the first modelling scenario (in one stage), the third modelling scenario (in four stages – excavation then lagging in next step) and the fourth modelling scenario (in sixteen stages). The detailed results below are shown for the "beam model" only and for the example of soil with the following parameters: $\phi = 16º$ and c 25 kPa (see Fig. 12, 13, 14).

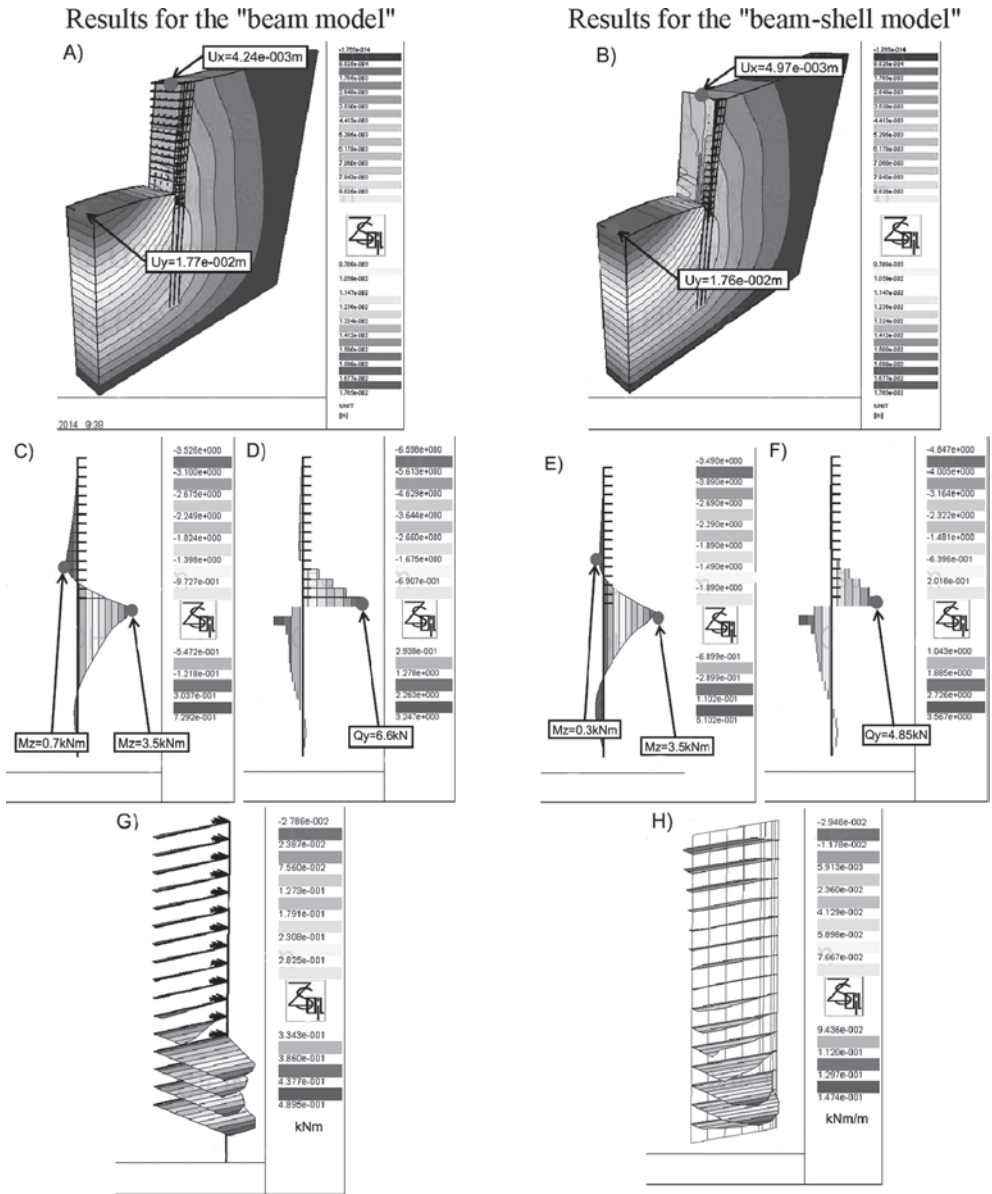Results for the "beam model"

Results for the "beam-shell model"

Fig. 8. Comparison of the numerical results for the "beam model" and the "beam-shell model", the cohesive soil $\phi = 16°$ and $c = 25$ kPa: a), b) displacements and forms of deformation, c), e) bending moment for the steel profile, d), f) shear force for the steel profile, g), h) bending moment for the lagging
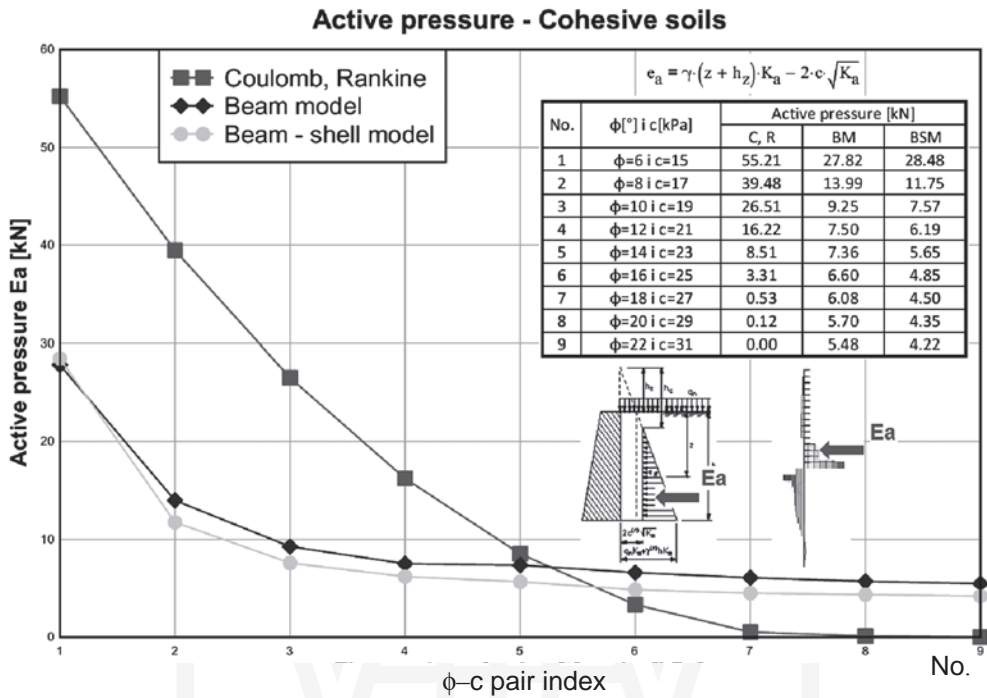
Active pressure - Cohesive soils

$$e_a = \gamma \cdot (z + h_z) \cdot K_a - 2 \cdot c \cdot \sqrt{K_a}$$

No.	$\phi[°]$ i c[kPa]	Active pressure [kN]		
		C, R	BM	BSM
1	$\phi=6$ i c=15	55.21	27.82	28.48
2	$\phi=8$ i c=17	39.48	13.99	11.75
3	$\phi=10$ i c=19	26.51	9.25	7.57
4	$\phi=12$ i c=21	16.22	7.50	6.19
5	$\phi=14$ i c=23	8.51	7.36	5.65
6	$\phi=16$ i c=25	3.31	6.60	4.85
7	$\phi=18$ i c=27	0.53	6.08	4.50
8	$\phi=20$ i c=29	0.12	5.70	4.35
9	$\phi=22$ i c=31	0.00	5.48	4.22

Fig. 9. Comparison of an active pressure for the "beam model", the "beam-shell model" and the traditional approach, cohesive soils
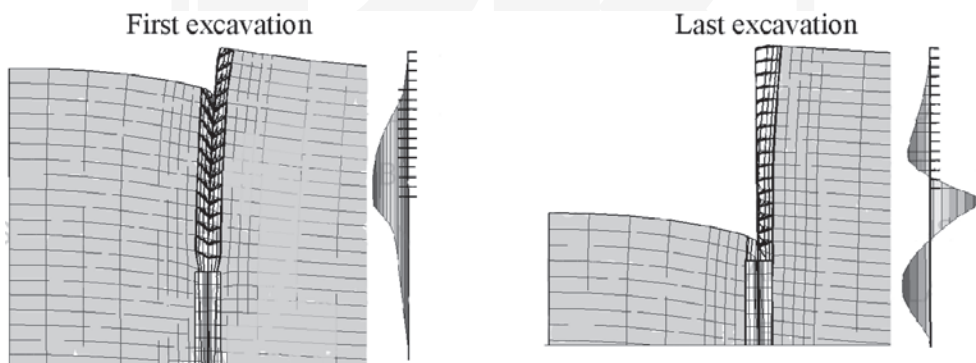

Fig. 10. Influence of the relaxation of the ground on the bending moments in the soldier pile wall
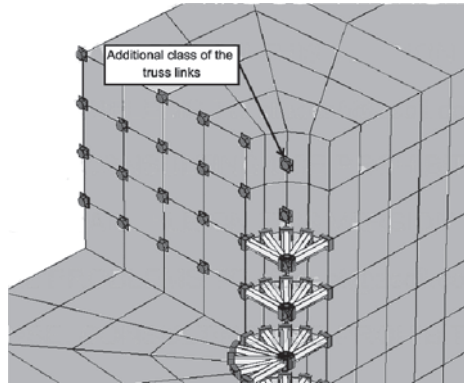
Fig. 11. An additional class of the truss links

As can it be seen in Fig. 12a, the bending moments in the steel profile from the excavation site still exist. In the case of the third and the fourth modelling scenarios of the construction process, the correct moment graphs for the cantilever wall can be seen (see Fig. 13a, 14a). Furthermore, it seems that the bending moment in the lagging for the fourth modelling scenario best reflects the real distribution of the lateral earth pressure in the lagging (see [5]). In reality, the single timber lagging is placed one after another during digging (Fig. 14c). The influence of cohesion on the lateral earth pressure in the soldier pile wall can be seen in Fig. 15.
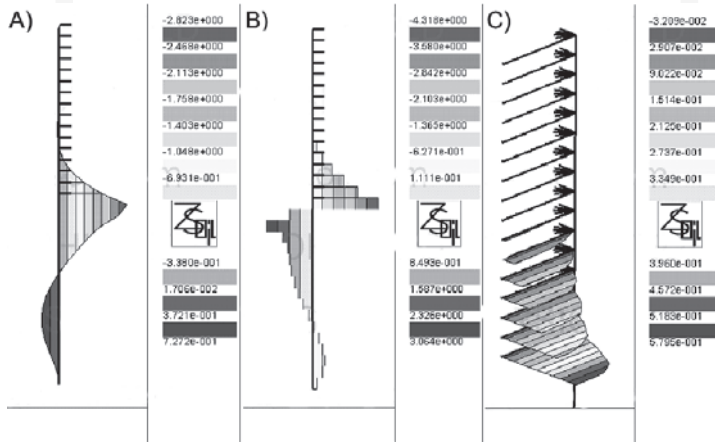

Fig. 12. The results for the first modelling scenario (in one stage) of the construction process of the soldier pile wall, the "beam model", the cohesive soil $\phi = 16°$ and $c = 25$ kPa: a) bending moment for the steel profile, b) shear force for the steel profile, c) bending moment for the timber lagging
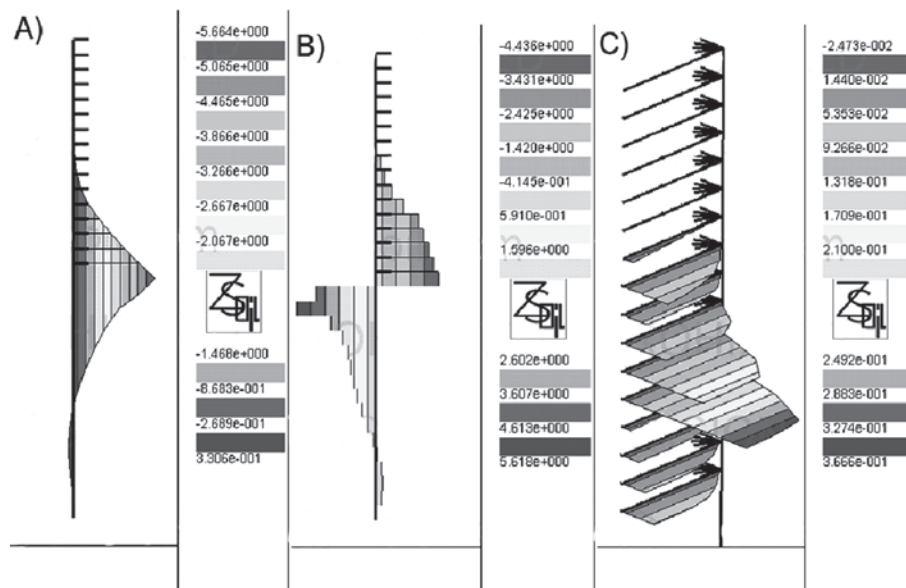
Fig. 13. The results for the third modelling scenario (in four stages – excavation then lagging in next step) of the construction process of the soldier pile wall, the "beam model", the cohesive soil $\phi = 16°$ and $c = 25$ kPa: a) bending moment for the steel profile, b) shear force for the steel profile, c) bending moment for the timber lagging
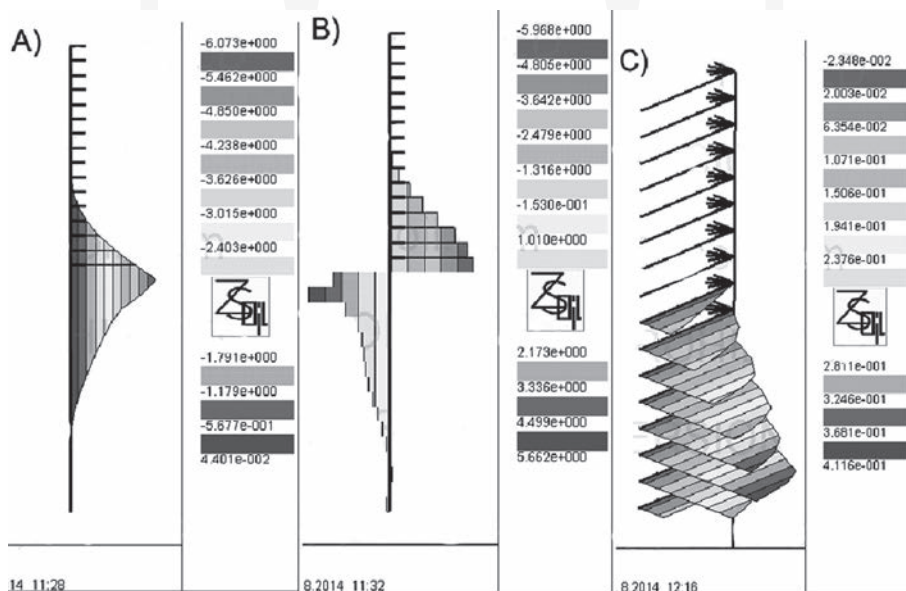

Fig. 14. The results for the fourth modelling scenario (in sixteen stages) of the construction process of the soldier pile wall, the "beam model", the cohesive soil $\phi = 16°$ and $c = 25$ kPa: a) bending moment for the steel profile, b) shear force for the steel profile, c) bending moment for the timber lagging
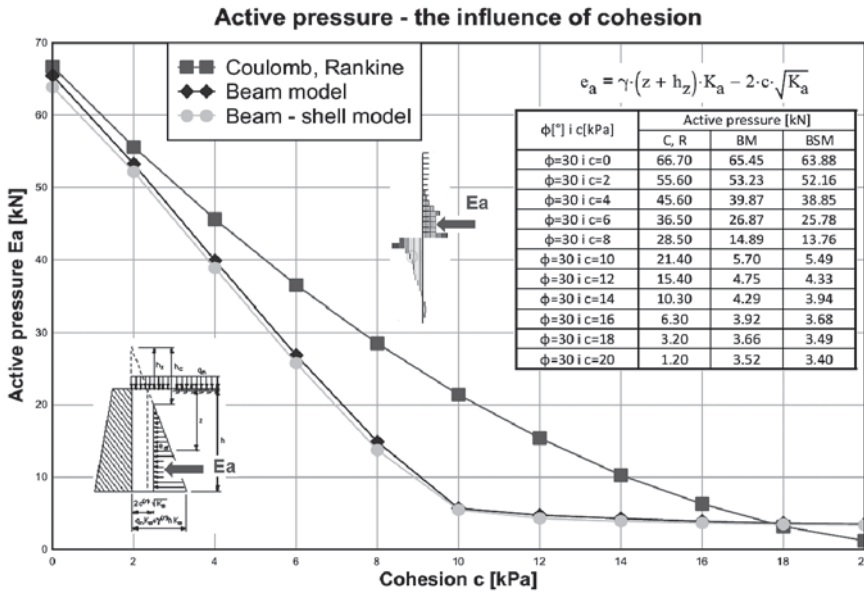
Active pressure - the influence of cohesion

Legend:
- Coulomb, Rankine
- Beam model
- Beam - shell model

$$e_a = \gamma \cdot (z + h_z) \cdot K_a - 2 \cdot c \cdot \sqrt{K_a}$$

$\phi[°]$ i c[kPa]	Active pressure [kN]		
	C, R	BM	BSM
$\phi=30$ i c=0	66.70	65.45	63.88
$\phi=30$ i c=2	55.60	53.23	52.16
$\phi=30$ i c=4	45.60	39.87	38.85
$\phi=30$ i c=6	36.50	26.87	25.78
$\phi=30$ i c=8	28.50	14.89	13.76
$\phi=30$ i c=10	21.40	5.70	5.49
$\phi=30$ i c=12	15.40	4.75	4.33
$\phi=30$ i c=14	10.30	4.29	3.94
$\phi=30$ i c=16	6.30	3.92	3.68
$\phi=30$ i c=18	3.20	3.66	3.49
$\phi=30$ i c=20	1.20	3.52	3.40

Fig. 15. Comparison of an active pressure for the "beam model", the "beam-shell model" and the traditional approach, the influence of cohesion

6. Conclusions

The article discusses the issue how development of the lateral earth pressure in the soldier pile walls depends on: the type of soil, and the modelling scenario of the construction process of the excavation. In addition, its dependence on the parameters of the numerical model was analysed. Internal forces for the "beam" and the "beam-shell model" were compared in this article. The paper also contains an analysis of the soldier pile systems designed in both the traditional (Coulomb, Rankine etc.) and the numerical approach.

As was shown, the so called "beam model" of the soldier pile wall is easier and faster in visualisation and analysis of the internal forces. They can be used directly for the design of the wall. The correct choice of the parameters of the truss links, which are defined in the "beam model", is of crucial importance. Incorrectly assumed parameters (stiffness) of these truss links may cause non-physical phenomena such as the bending moments in the steel profile from the excavation and in the lagging from the ground.

The modelling scenario of the excavation in the soldier pile wall should be focused on the distribution of the lateral earth pressure in the lagging. The presented modelling scenarios of the excavation clearly show the differences in the internal forces of the soldier pile wall (mainly in the lagging). It seems that the bending moment in the lagging for the fourth modelling scenario (in sixteen stages) best reflects the real distribution of the lateral earth pressure in these elements of the wall – in practice, the single timber lagging is placed one after another during digging.

The added truss links in the "beam model" easily allow a comparison of the lateral earth pressure with the traditional approach. For cohesionless soils, good agreement between computations was observed. In the case of cohesive soils, deeper analysis is necessary.

The paper also shows how different ways of modelling and their details may have an influence on important results in soil structure interaction problems.

Recognition and establishment of a way to realistically describe load action on the soldier pile wall (cantilever schema) was an introductory part of a wider research project devoted to practically deriving design formulae based on FEM analysis of these geo-structures. Its main issue, i.e. analysis of the underground part of the soldier pile wall, will be the subject of the future studies.

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