Sheeting Wall Analysis by the Method of Dependent Pressures

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ABSTRACT: This paper describes the dependent pressures method with its basic assumptions as well as practical application. The method is evaluated by the real life example of the anchored sheeting wall in the open pit of Metro station Prosek in Prague. The sheeting construction is built in several construction stages with various anchoring levels. Each construction stage is analysed numerically by the dependent pressures method. The results of the numerical analysis show internal forces in the soldier beam, its deformation and internal stability of anchors for each construction stage. The values of deformation obtained from the dependent pressures analysis are compared with measured values from the in-situ monitoring.

1 INTRODUCTION

The sheeting walls are used in many constructions sites where the open pit is built. The deformation of the sheeting wall is a serious issue which has to be addressed in each construction. The in-situ measurements are expensive and time consuming. The realistic model of the behavior of the sheeting walls would be therefore beneficial. We are proposing method of dependent pressures which is realistic model where loading is dependent on the deformation of the wall. This method is based on elastic-plastic Winkler model of soil using modulus of subsoil reaction.

Numerical analysis by the method of dependent pressures is shown on design of sheeting wall in the open pit of Metro station Prosek. The results from proposed model are compared to real data.

2 THE METHOD OF DEPENDENT PRESSURES

The first part of this paper describes the method of dependent pressures in details by showing its general principles, basic assumptions and practical application in GEO5 Sheeting Check program.

The loading applied to the structure is derived from its deformation, which allows for the realistic modeling of structure behavior. The analysis correctly accounts for the construction process such as individual stages of progressive construction including gradual evolution of deformations and post-stressing of anchors.

The above mentioned analysis is carried out using the deformation variant of finite element method. The structure is divided into finite elements by placing nodes into all topological points of the structure (starting and end points, points of anchors location, points of soil removal, points of changes of cross-sectional parameters) and then calculating the remaining nodes so that all elements attain approximately the same size.

The soil or rock in the vicinity of the wall behaves as ideally elastic-plastic Winkler material. This basic assumption requires the determination of subsoil reaction modulus k_h, which characterizes material deformation in the elastic region. Modulus k_h may have linear or nonlinear distribution along soldier beams. The value of modulus of subsoil reaction is assigned to each finite element.

Supports are placed onto already deformed structure – each support then represents a forced displacement applied to the structure.

Anchors, in the construction stage at which they were introduced or post-stressed, are considered as forces (variant I. in Figure 1). In later construction stages, the anchors are modeled as forces and springs of stiffness k (variant II. in Figure 1). Change of the anchor force ΔF due to deformation is provided by Eq. (1):

$$\Delta F = \frac{k \cdot v \cdot \Delta w}{\cos \alpha} \qquad (1)$$

where k = anchor stiffness; v = horizontal distance between anchors; Δw = deformation of structure; and α = anchor inclination.

The pressure acting on the deformed structure is given by Eq. (2):

$$\sigma = \sigma_r - k_h \cdot w \qquad (2)$$

where σ_r = pressure at rest; k_h = modulus of subsoil reaction; and w = deformation of structure. The value of the pressure σ may vary in the range $\sigma_a < \sigma < \sigma_p$, where σ_a = active earth pressure and σ_p = passive earth pressure. When exceeding these limits the pressure value is equal to the limiting value: $\sigma = \sigma_a$ for $\sigma < \sigma_a$ or $\sigma = \sigma_p$ for $\sigma > \sigma_p$. Another assumption used in the program is that the pressure at rest acts on the undeformed structure ($w = 0$).

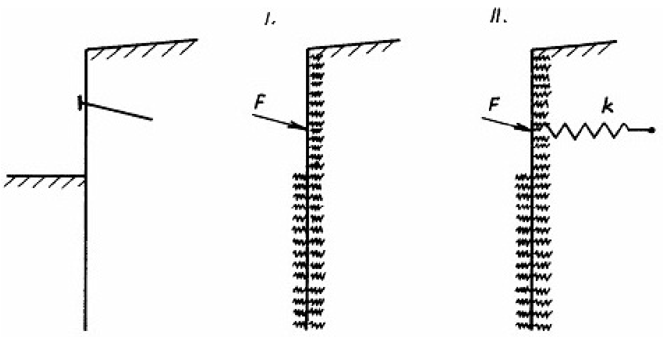

Figure 1 Anchors considered: I.) as forces and II.) as forces and springs (F – anchor force, k - anchor stiffness)

The computational procedure starts by its first step where the modulus of subsoil reaction k_h is assigned to all elements and the structure is loaded by the pressure at rest (Figure 2).

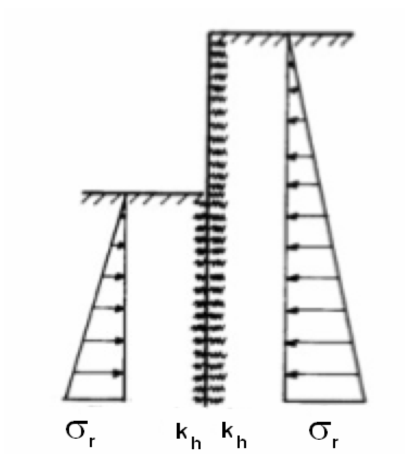

Figure 2 Scheme of the structure before the first iteration (σ_r - pressure at rest, k_h - modulus of subsoil reaction)

In the second step the analysis is carried out and the condition for allowable magnitudes of pressures acting on the wall is checked. In locations at which these conditions are violated, the program assigns the value of k_h = 0 and the wall is loaded by active or passive pressure, respectively (Figure 3). When exceeding the limiting deformations, the material behaves as ideally plastic.

The above iteration procedure continues until all required conditions are satisfied. In analysis of subsequent construction stages the program accounts for plastic deformation of the wall. This is also the reason for specifying the individual construction stages that comply with the real construction process.

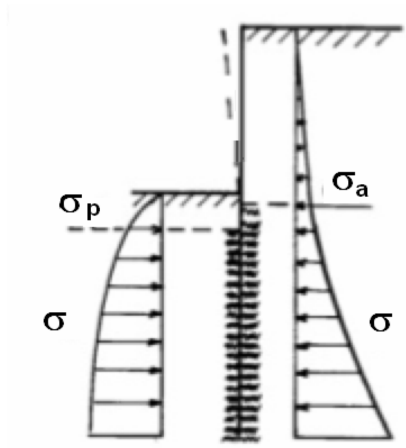

Figure 3 Scheme of the structure during the iteration process (σ_a - active earth pressure, σ_p - passive earth pressure)

The results (displacements, internal forces and the modulus of subsoil reaction) are evaluated at individual nodes.

The internal stability of an anchorage system of sheeting is determined for each anchor independently. The verification analysis determines the anchor force, which equilibrates the system of the forces acting on a block of soil. The block *ABCD* is outlined by sheeting, terrain, line connecting the heel of sheeting with anchor root and by vertical line passing through the center of anchor root and terrain as shown in Figure 4.

The theoretical footing of sheeting construction is the point where the sum of horizontal forces under the bottom of the construction pit equals zero. If this point lies under the footing of the sheeting wall, the theoretical point is the footing of this wall.

The force equilibrium of the i^{th} block *ABCD* (i^{th} anchor) is being determined. The forces entering the equilibrium of the i^{th} block are shown in Figure 4, but some of the anchor forces are not taken into account. Only "shorter" anchors (comparing with the i^{th} anchor) will contribute. Following principle is used to decide whether the given anchor (the m^{th}) is included or excluded from equilibrium of the i^{th} block. At first the lower anchor is selected (the m^{th} or the i^{th}). Then a plane slip surface is placed from the root center of the selected lower anchor. This plane is inclined 45° - $\varphi_n/2$ from vertical line (line *ab* or *Bc* in Figure 4). φ_n is an average value of the angle of internal friction above the root of the lower anchor. If the i^{th} root is found above the m^{th} one and the higher located root (the i^{th}) is outside the area cut by the plane slip surface, then the m^{th} anchor is included into analysis. The same example of including the m^{th} anchor is when the i^{th} root lies under the m^{th} one and the m^{th} root is located inside the area cut by the slip surface. Two opposite cases determine excluded anchors from analysis. First is the i^{th} root above the m^{th} one and the i^{th} inside the area, second is when the i^{th} root lies under the m^{th} one and the m^{th} is outside the area. From above definition resulting that "shorter" anchor F_k is included into analysis and "longer" anchor F_j is excluded from analysis (Figure 4).

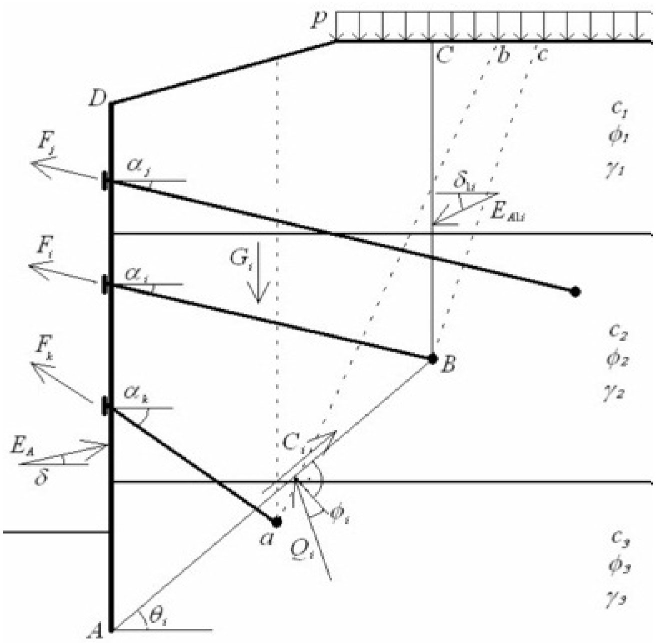

Figure 4 Internal stability of the i^{th} anchor – equilibrium of forces acting on the i^{th} block *ABCD* (Forces: G_i – weight of block, E_a – resultant of active earth pressure acting on sheeting (line *AD*), E_{ai} – resultant of active earth pressure above the root of verified anchor (on line *BC*), C_i – resultant of soil cohesion on slip surface *AB*, Q_i – reaction on slip surface *AB*, F_i – force in the analysed anchor, F_j, F_k – forces developed in other anchors included (F_k) or excluded (F_j) from equilibrium analysis; Properties of soil layers: φ_i – angle of internal friction, c_i – cohesion, γ_i – unit weight)

The weight of the soil block G_i incorporates possible ground surface surcharge *p*.

The solution of equilibrium problem for a given block requires writing down vertical and horizontal force equations of equilibrium. These represent a system of two equations to be solved for the unknown subsoil reaction Q_i and the maximum allowable magnitude of the anchor force F_i.

As the result the program provides the maximum allowable anchor forces for each row of anchors. These are then compared with those prescribed in the anchors and resulting factor of safety *FS* of internal stability.

3 PRAGUE METRO LINE C EXTENSION

The extension of Prague Metro Line C provides a link between station Ládví and significantly developed areas Prosek and Letňany in the North part of the city. This part of Prague urban mass transit network (Operational section IV, 2nd phase) was built from May 2004 to May 2008 by the Capital City of Prague, in collaboration with The Prague Public Transit Co. Inc. (PPT). Inženýring dopravních staveb Co. provided construction management and supervision for the owner (PPT) and Metroprojekt Praha Co. developed the final design.

Operational section IV with its total length of tunnels 4.6 km (Figure 5) includes 2.36 km of mined tunnels, mostly double-track and contains three cut-and-cover stations, i.e. Střížkov, Prosek and Letňany.

The paper focuses on Prosek station built in the irregularly-shaped open pit (Figure 6). The sheeting construction of this pit is placed sequentially in several construction stages (Figure 9).

This sheeting wall in Prosek open pit is analysed numerically for each construction stage, i.e. in all excavation and anchor levels, with the help of the dependent pressures method using GEO5 Sheeting Check program. The results of numerical analysis show soldier beam internal forces and displacements and anchor internal stability in all construction stages. The soldier beam deformations are compared with measured values obtained during in-situ monitoring.

Figure 5 Anchored sheeting walls in the open pit for the cut-and-cover tunnel between Střížkov and Prosek

Table 1 Soil parameters (Class: F6 – USCS classification of low to intermediate plasticity clay, F4 - USCS classification of clayey sand, R3 – Rock Mass Rating of intermediate strength rock, R5 – Rock Mass Rating of very weak rock; Soil properties: γ – unit weight, φ – angle of internal friction, ν – Poisson's ratio, E_{def} – deformation modulus, c - cohesion)

Layer	Thickness [m]	Soil	Class	γ [kN/m^3]	φ [°]	ν [-]	E_{def} [MPa]	c [kPa]
1	4.5	loess loam	F6	19.5	20	0.40	6	16
2	1.0	diluvial-eluvial loam	F4	19.5	22	0.35	7	14
3	10.6	weathered sandy marlstone	R3	22.0	40	0.25	50	100
4	4.0	impervious clay stone	R5	19.0	24	0.30	40	20
5	1.0	glauconitic sandstone	R5	21.0	30	0.25	55	35
6	3.9	weathered clay stones	R5	21.0	40	0.20	400	100

3.1 Geological conditions

Geological profile and soil parameters of the calculated cross section are shown in Table 1 and Figure 8. Loess and diluvial-eluvial loams cover a layer of considerably fractured and weathered sandy marlstones (cretaceous marls). Under the undulated basis of cretaceous marls, there are found two continuous layers of virtually impervious clay stone and glauconitic sandstone. These layers are sitting on weathered clay stones and next mighty sandstone bed.

The groundwater table lies about 10 m under the terrain surface, in the weathered sandy marlstones layer.

3.2 Prosek open pit

The subway station Prosek is built in an irregular-shaped open pit with the total length of 205 m, width from 7 to 31.5 m and height from 6 to 20 m. The open pit walls are supported by an anchored sheeting structure (Figure 6).

Figure 6 Prosek station – irregularly-shaped open pit

A temporary ramp is set up on the longer side of the open pit during the construction (Figure 7).

3.3 Sheeting wall configuration

The sheeting wall design in Prosek open pit requires verification of more than 20 various types of wall (cross sections) and of 2 geological profiles. This paper is focused on one of these types which is shown in Figure 8. The construction of this selected type of wall is 21 m long. The sheeting soldier beams are made from steel (modulus of elasticity E = 210000 MPa, shear modulus G = 81000 MPa) and cross section type I 400. The longitudinal distance of these I-profiles is 2 m.

Figure 7 Temporary ramp in the open pit Prosek

The modulus of subsoil reaction k_h is assumed to be different in upper and lower soil layers. The modulus k_h grows linearly from the terrain level (k_h = 0 MN/m^3) to the depth 5 m where it reaches its maximum value (k_h = 10 MN/m^3). In the lower layers below the depth 5 m the constant value k_h = 10 MN/m^3 is assumed .

The earth pressure below ditch bottom is not reduced by any coefficient.

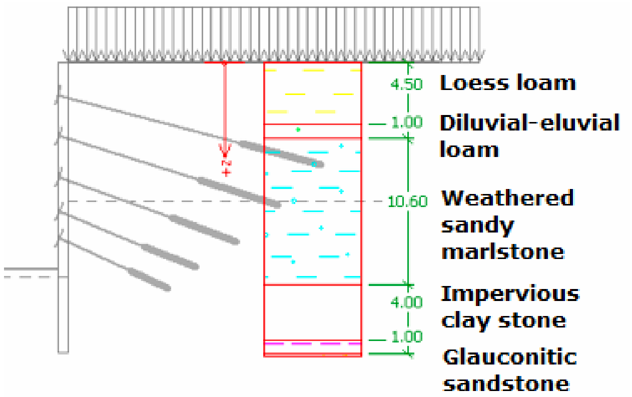

Figure 8 Construction geometry and geological profile

Table 2 Parameters of the anchors (d – diameter, E – modulus of elasticity, F – anchor pre-stress force)

Depth [m]	**Total length** [m]	**Root length** [m]	**Slope** [°]	**Spacing** [m]	***d*** [mm]	***E*** [MPa]	***F*** [kN]
2.5	19.0	6.0	15.0	4.0	32	210000	300
5.5	16.0	6.0	17.5	4.0	32	210000	350
8.5	13.0	6.0	20.0	4.0	32	210000	400
11.0	10.0	4.0	22.5	4.0	32	210000	500
13.0	8.0	3.0	25.0	4.0	32	210000	550

The surcharge of permanent character with its magnitude 25 kN/m^2 acts on the whole surface area at the terrain level.

The structure is supported by 5 levels of anchors, whose parameters are summarized in Table 2.

3.4 Construction stages of the wall

The sheeting wall is built sequentially by alternating excavations of soil and installation of anchors in various levels (Figure 9). The sequence of construction stages is following: excavation to the depth 3.0 m, installation of 1st level of anchors at the depth 2.5 m, excavation to the depth 6.5 m, installation of 2nd level of anchors at the depth 5.5 m, excavation to the depth 9.0 m, installation of 3rd level of anchors at the depth 8.5 m, excavation to the depth 11.5 m, installation of 4th level of anchors at the depth 11.0 m, excavation to the depth 13.5 m, installation of 5th level of anchors at the depth 13.0 m and excavation to the depth 15.0 m.

3.5 Calculated results

The selected type of the sheeting wall is verified using the method of dependent pressures. Table 3 summarizes the results for all construction stages obtained from GEO5 Sheeting Check program. This table shows maximum values on the soldier beam (bending moment *M*, shear force *Q* and displacement w), anchor forces and values of factor of safety *FS* (internal stability of anchors).

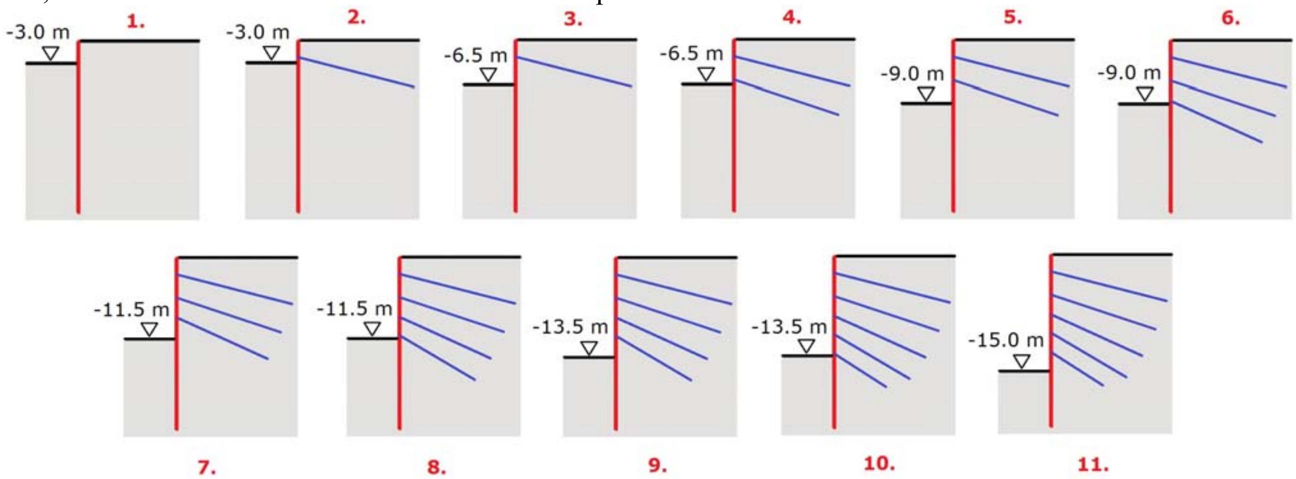

Figure 9 Sequence of the construction stages – excavation and anchor levels

Table 3 Results of the analysis for the selected type of the sheeting wall (M –bending moment, Q – shear force, w – displacement)

Stage	**M** [kNm/m]	**Q** [kN/m]	**w** [mm]	Anchor force **1.** [kN]	**2.** [kN]	**3.** [kN]	**4.** [kN]	**5.** [kN]	Internal stability (FS) **1.** [-]	**2.** [-]	**3.** [-]	**4.** [-]	**5.** [-]
1	66	36	33										
2	56	56	26	**300**					13.6				
3	50	53	25	380					29.0				
4	43	56	26	372	**350**				28.7	35.0			
5	50	58	24	366	405				27.5	26.6			
6	48	69	24	368	397	**400**			26.3	26.1	29.8		
7	49	70	24	365	396	478			24.7	22.4	19.7		
8	49	82	24	366	398	461	**500**		23.4	21.1	19.3	18.8	
9	49	69	24	366	396	463	569		22.0	18.8	15.9	12.7	
10	49	81	24	366	397	464	535	**550**	20.6	17.5	14.8	12.4	13.8
11	49	74	24	366	397	461	542	612	14.3	9.9	6.2	3.2	1.7

Maximal loading capacity of the selected soldier beam type I 400 is M_{ult} = 150 kNm/m‘, if steel profile plasticity is included then M_{ult} = 180 kNm/m‘. This allowable capacity M_{ult} is greater than all calculated values of the bending moment (in all construction stages).

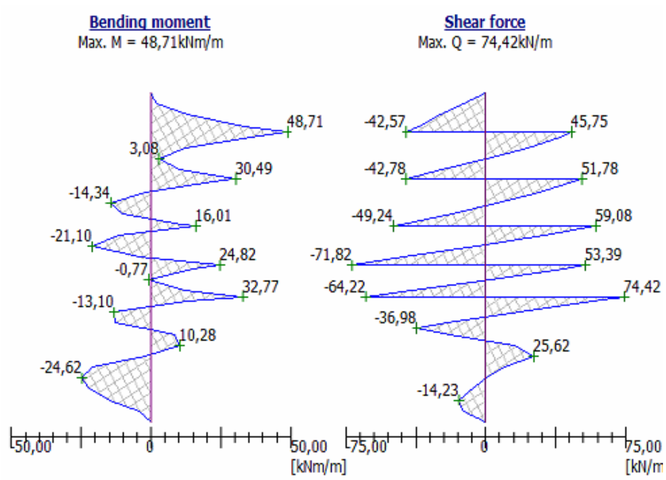

Figure 10 Distribution of the internal forces on the soldier beam – bending moment *M* and shear force *Q*

The distribution of internal forces on the soldier beam (bending moment and shear force) is shown in Figure 10, the distribution of earth pressures and the displacements in Figure 11.

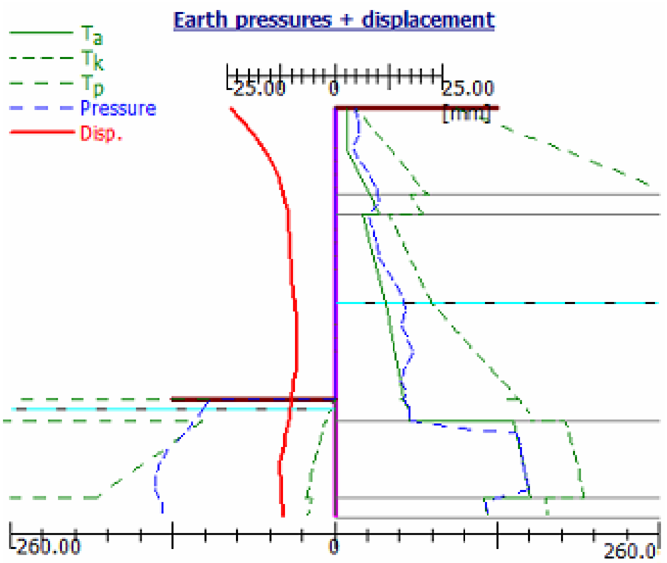

Figure 11 Distribution of the earth pressures and the displacements on the soldier beam

3.6 Monitoring

The selected type of sheeting wall was monitored. The horizontal deformations of the structure were measured on the anchor heads during the building. These measured values were compared with the calculated displacements from the program shown in Figure 11.

Table 4 and Figure 12 show no significant differences between the calculated and the monitored displacements.

Table 4 Displacements - comparison of calculated and measured values

Anchor Head Nr.	Deformation Calculated [mm]	Deformation Measured [mm]
1	-15	-17
2	-11	-11
3	-10	-11
4	-9	-7
5	-9	-6

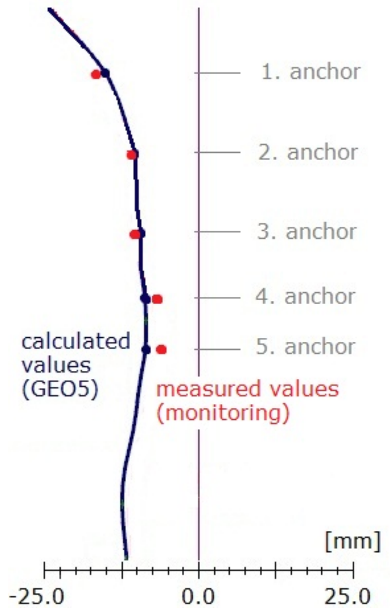

Figure 12 Calculated (blue) and measured (red) deformation of soldier beam

4 CONCLUSION

Sheeting wall at the subway station Prosek was analysed by the method of dependent pressures. Loading applied to the structure is directly dependent on its deformation and thus the method allows for realistic modelling of sheeting behavior and provides cost effective designs. The method also makes it possible to model gradual building of individual construction stages and thus including gradual evolution of deformations and post-stressing of anchors.

Maximal loading capacity of the soldier beams was not exceeded at any construction stage and the sheeting wall was verified against failure.

No significant variation of calculated and measured displacement shows reasonable applicability of dependent pressures method.

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