DESIGN OF SHEET PILING FOR THE PRAGUE METRO LINE C

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This paper describes the sheet pile design for the Line C extension from Ládví station to the North of Prague. The first part of the paper describes the geological conditions and structural configuration of the project. Typical cross sections, the description of the construction stages, and monitoring are detailed.

The second part of the paper focuses on the sheeting design method which uses the GEO5 software. It describes the method of dependent pressures, that is, how the pressures acting upon a structure depend on the deformation. The design process and verification methodology are described in detail with comparison of the results with in-situ monitoring.

1. Introduction

The Prague urban mass transit network including the subway was developed by The Capital City of Prague, in collaboration with Dopravní podnik hl. m. Prahy, the Prague Passenger Transport Authority. Operational section IV. C of the Metro line C – 2nd phase provides a link to the developing regions of Prosek and Letňany in the northern part of Prague. The construction operations started in May 2004 and the the line was opened to the public in May 2008. The project owner was Dopravní podnik hl. m. Prahy a. s., represented by Inženýring dopravních staveb a. s., providing construction management and supervision for the owner. METROPROJEKT Praha a. s. developed the final design.

Operational section IV. C– 2nd phase has 4.6km of tunnels ; mined tunnels make up a length of 2.36 km (mostly double-track) and contain three cut-and-cover stations, i.e. Střížkov, Prosek and Letňany. The project was divided into seven sections (construction lots) according to the construction's progress. Construction lot 11 covers cut-and-cover tunnels between the Střížkov and Prosek stations – Fig. 1. The total length of this lot is 772 m. The cut-and-cover Prosek station (construction lot 12) starts behind the cut-and-cover tunnels (CL 11) next to the Billa department store, and ends at the cut-and-cover tunnels belonging to the next construction lot 13, behind Prosecká Street. Construction lot 12 is 205 m long in total. The magnitude of the earthwork operations on the Operational section IV. C of the Metro line C – 2nd phase corresponds to the size of the project.

About 1,138,000 m^3 of spoil were transported from the open pit excavations and tunnels. Out of that, the volume of muck from the mined sections amounts to 190,000 m^3. About 306,000 m^3 of the material were used for backfilling. We are focused on the Construction lot 12 – cut and cover Prosek station (see Fig. 2). This station was built in the construction trench supported by sheet pile walls.

For the design of the sheet piling the GEO5 Sheeting Check program developed by FINE Ltd was used. This software offers the use of the dependent pressure method. The structure of the station proper is designed from cast-in-situ reinforced concrete, forming three basic levels, i.e. the under platform, platform and concourse levels (underground). The structure is designed with steel columns between the tracks. Pedestrian subways under Prosecká and Vysočanská Streets are also parts of the station.

2. Brief description of geological conditions

A 3 to 5 m thick layer of loess, loess loam (class F6) and diluvial-eluvial loams (class F4) covers an 11 m thick layer of considerably fractured and weathered sandy marlstones (cretaceous marls, class R3). There is a continuous layer of virtually impervious clay stone (class R5) 4 to 5 m thick under the undulated cretaceous marl layer. A continuous layer of glauconitic sandstone (class R6) about 1 m thick is under the clay stone layer, sitting on a several meters thick layer of weathered clay stones overlaying a competent sandstone bed. The water table is about 11 m under the ground surface, in the sandy marlstone layer. In addition to this upper level of the water table, there is another water table level in the sandstone inter beds, above the grey-black clay stone layer. The yield of this (lower) aquifer is low.

Fig. 1 Open pit for the cut-and-cover tunnels between the Střížkov and Prosek stations

Fig. 2 Aerial view of the finished Prosek station

3. Calculation Assumptions

The sheet pile construction was analyzed with the different heights of the excavations and the number of the anchoring levels including the cases necessary for the metro station structure building. 22 anchor types were reviewed altogether. Types 1 to 4 (multi-level anchoring) were calculated for two geological profiles (occurring in the open pit space). Ground water level was assumed to be 11 m below ground surface. During the excavations it was observed that GWL was approximately 1 m lower (Bartoň V., Kutil J. 2005).

4. Description of the open pit

This station was built in the open pit supported by sheet pile walls. – Fig. 3. This open pit was irregularly-shaped - 205 m long, 7 to 31.5 m the width and 6 to 20 m height – see Fig. 4. A temporary ramp was situated on the longer side of the open pit during the construction – Fig. 5.

Fig. 3 Prosek station - open pit

Fig. 5 Temporary ramp

5. Structural configuration

We are focused on the calculation of the sheeting type 2, geological profile 1 due to large amount of calculation types in the design of the sheeting pile for Prosek station open pit. Table 1 shows the soil parameters

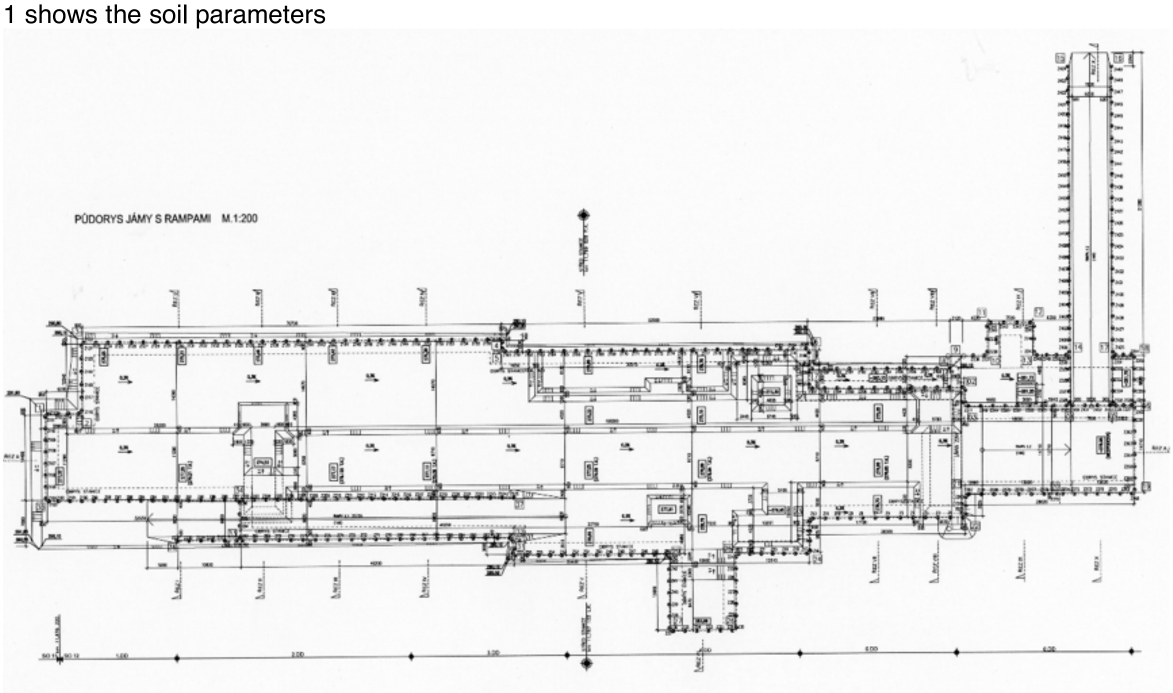

Fig. 4 Ground plan

used in the calculation. The construction length is 19 m – see Fig. 6. The rider is made from steel I section type HE 400 B (steel 37) and the longitudinal space of rider sections is 2 m. No pressure reduction was assumed in front of the wall. The modulus of subsoil reaction was assumed constant along the structure. Parameters of the anchors are summarized in the Table 2.

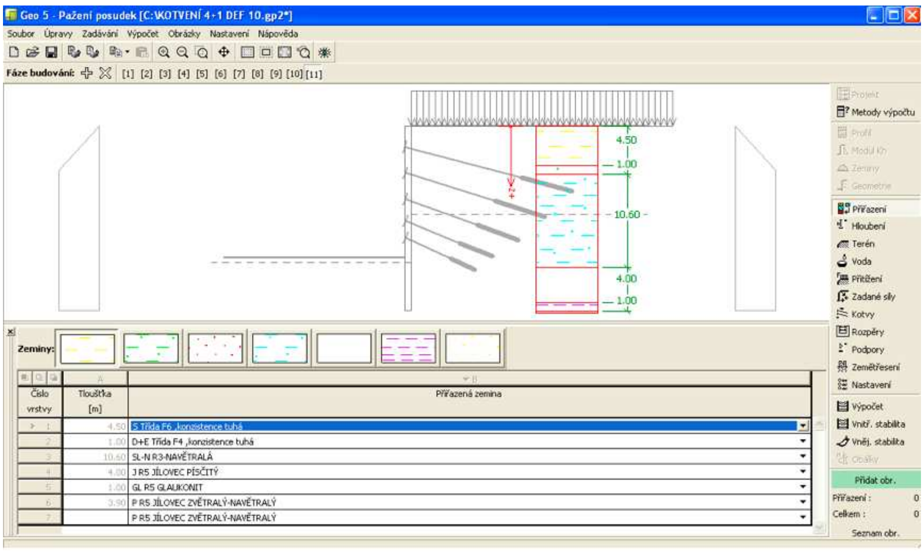

Fig. 6 Construction geometry – sheeting type 2

Table 1 Soil parameters

Stratum No / Thickness	Stratum Description	Total Unit Weight [kN/m^3]	Friction Angle [^{O}]	Poisson number [-]	Deformation Modulus [MPa]	Cohesion [kPa]
1 /4.5	F6 loess loam	19.5	20	0.40	6	16
2/1.0	F4 diluvial-eluvial loams	19.5	22	0.35	7	14
3/10.6	R3 weathered sandy marlstones	22.0	40	0.25	50	100
4/4.0	R5 impervious clay stone	19.0	24	0.30	40	20
5/1.0	R5 glauconitic sandstone	21.0	30	0.25	55	35
6/3.9	R5 weathered clay stones	21.0	40	0.20	400	100

Remarks: 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

Table 2 Parameters of the anchors

Depth [m]	Length [m]	Slope [^{O}]	Longitudinal Spacing [m]	Diameter [mm]	Deformation Modulus [MPa]	Anchor Force [kN]	Restrained
2.5	19.0	15.0	4.0	32	200000	400	No
5.5	16.0	17.5	4.0	32	200000	350	No
8.5	13.0	20.0	4.0	32	200000	400	No
11.0	10.0	22.5	4.0	32	200000	500	No
13.0	8.0	25.0	4.0	32	200000	550	Yes

5.1 Construction sequence

The following stages were considered for design of sheet piling (see Figure 7 for details):

1: Excavate to EL 3.0 m
2: Install 1st level anchors 2.5 m
3: Excavate to EL 6.5 m
4: Install 2nd level anchors 5.5 m
5: Excavate to EL 9.0 m
6: Install 3rd level anchors 8.5 m
7: Excavate to EL 11.5 m
8: Install 4th level anchors 11.0 m
9: Excavate to EL 13.5 m
10: Install 5th level anchors 13.0 m
11: Excavate to EL 15.0 m

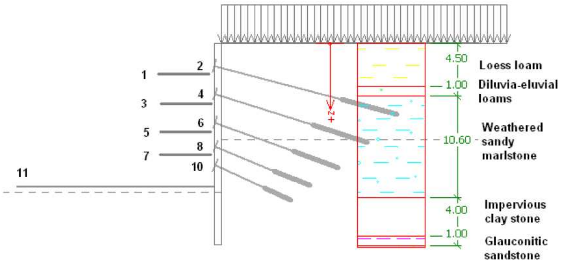

Fig. 7 Construction Sequence and Geological profile

6. Results of the calculations

Static results obtained from the GEO5 Sheeting Check were summarized into tabular form for cases covering 22 anchor types and two geologic profiles (including all working process - construction phases). Each table includes individual excavation levels, anchor levels, anchor length, anchor slope and anchor longitudinal spacing. The values of the bending moment, shear forces in the riders and rider deflections are obtained from the executed calculations. The tables contain the value of the internal stability for each construction phase as well. The rider type I400 has a loading capacity on the bending moment Q_{ult}= 150 kNm/m (with consideration of steel profile plasticity Q_{ult} = 180 kNm/m). This value is always greater than any value obtained from calculated bending moment in all cases in particular calculations. Table 3 shows the results of the analysis for geological profile 1 and sheeting type 2. The internal forces distribution is presented in Figure 8 (the same profile).

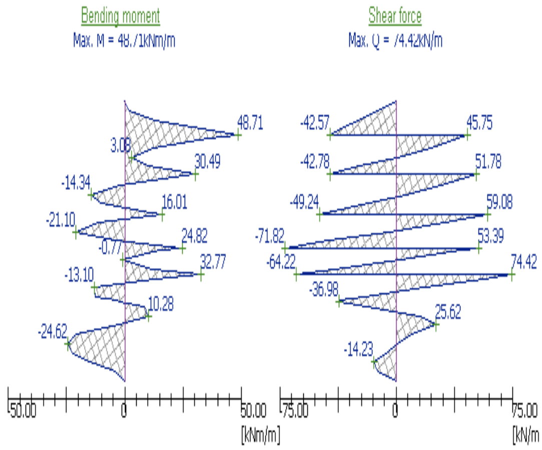

Fig. 8 Internal forces

Table 3 Results of the analysis for geological profile 1 and sheeting type 2.

Type 1	M	Q	w	Excavation	Depth of Anchors	ANCHOR FORCE					Length of Anchor	Length of Root	Anchor Slope	Spacing	INTERNAL STABILITY				
GEO-1	[kNm/m]	[kNm/m]	[mm]	[m]	[m]	1. LA[1)] [kN]	2. LA[1)] [kN]	3. LA[1)] [kN]	4.LA[)] [kN]	5. LA[1)] [kN]	[m]	[m]	[°]	[m]	1. LA[1)] [-]	2. LA[)] [-]	3. LA[1)] [-]	4. LA[1)] [-]	5. LA[1)] [-]
1.EL[2)]	65.8	36.1	33.0	3.0	-	-													
2.EL[2)]	56.3	55.8	25.9	3.0	2.5	300.0					19.0	6.0	15	4.0	13.56				
3.EL[2)]	50.0	53.4	25.0	6.5	2.5	379.7									29.0				
4.EL[2)]	43.4	55.6	25.7	6.5	5.5	371.6	350.0				16.0	6.0	17.5	4.0	28.67	34.95			
5.EL[2)]	49.5	57.9	24.0	9.0	5.5	365.6	404.5								27.14	26.57			
6.EL[2)]	48.3	69.1	24.2	9.0	8.5	367.8	396.8	400.0			13.0	6.0	20	4.0	26.28	26.06	29.84		
7.EL[2)]	48.8	69.8	24.3	11.5	8.5	365.2	396.1	478.5							24.73	22.43	19.65		
8.EL[2)]	48.8	82.0	24.2	11.5	11.0	365.6	397.9	461.1	500.0		10.0	4.0	22.5	4.0	23.38	21.11	19.30	18.81	
9.EL	48.6	68.9	24.3	13.5	11.0	365.7	395.8	462.5	568.6						22.03	18.84	15.94	12.65	
10.EL[2)]	48.8	81.0	24.2	13.5	13.0	365.6	396.8	463.8	535.2	550.0	8.0	3.0	25	4.0	20.65	17.50	14.72	12.40	13.84
11.EL[2)]	48.7	74.4	24.2	15.0	13.0	365.7	396.6	461.1	542.1	611.9					14.28	9.93	6.16	3.23	1.71

Remarks: [1)] LA = Level Anchors. [2)]EL = Construction stage

7. Monitoring

The structure deformation (horizontal movements) was measured on the anchor heads in one selected profile (sheeting type 2) during the construction. This profile was choosen in the deepest part of the open pit in geometry type 1. Figure 8 shows the calculated horizontal movements. Table 4 contains the results of the comparison between calculated and monitored displacement. No significant variation of displacement was found.

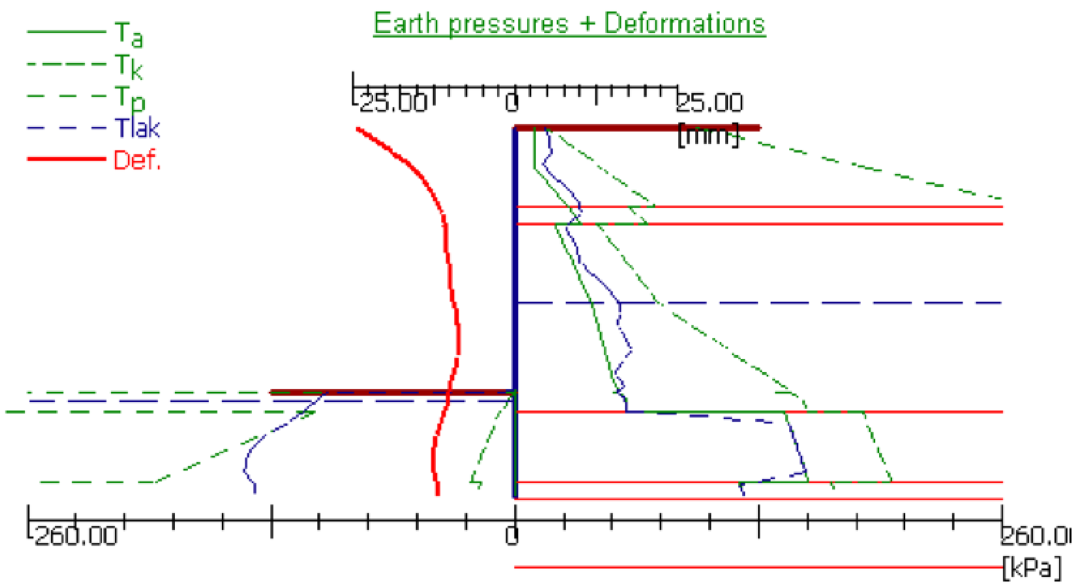

Fig 9 Calculated deformations and Earth pressures

Table 4 Structure deformation

Anchor Head No.	Calculated movement [mm]	Measured movement [mm]
1	-15.1	-17.0
2	-10.7	-11.1
3	-9.8	-10.5
4	-8.7	-7.1
5	-8.7	-6.3

8. Method of dependent pressures

8.1 General principles of the method of dependent pressures

The basic assumptions of the method are that the soil or rock in the vicinity of wall behaves as ideally elastic-plastic Winkler material. This material is determined by the modulus of subsoil reaction k_h which characterizes the deformation in the elastic region and by additional limiting deformations. When exceeding these deformations the material behaves as ideally plastic. The method of dependent pressures uses the differential equation describing the flexural line of the sheeting structure for the mathematical model. The limit values of the lateral earth pressures and earth pressure at rest are given by the equation:

$$\sigma_{(a,r,p)} = K_{(a,r,p)} \cdot \left(\sigma_z + \frac{c}{tg\varphi} \right) - c \cdot tg\varphi \quad (1)$$

where indexes a,r,p denote the type of earth pressure
(a – active, r – rest, p – passive),

σ - lateral pressure,
K - coefficient,
c - soil cohesion.
φ - angle of internal soil fiction.

The above equation describes all types of the lateral earth pressures in the Rankine state (including cohesion influence). The lateral pressure σ is a function of the depth z and the horizontal movement y (thus $\sigma = \sigma(y,z)$) it is imperative that the coefficient K in the equation (1) be variable with the deflection or deformation of structure y ($K=K(y,z)$). The other variables are independent of the curvature in the equation (1).

From above follows the general form of the equation (1) – see Fig. 10:

$$\sigma(y,z) = K(y,z)\left[\sigma_z(z) + \frac{c(z)}{tg\varphi(z)}\right] - \frac{c(z)}{tg\varphi(z)} \quad (2)$$

with derived function

$$\frac{\partial\sigma(y,z)}{\partial y} = \frac{\partial K(y,z)}{\partial y}\left[\sigma_z(z) + \frac{c(z)}{tg\varphi(z)}\right] \quad (3)$$

where σ - lateral pressure,
K - coefficient,
c - soil cohesion,
φ - angle of internal soil fiction,
y - deflection (deformation of structure),
z - depth.

The following limit is valid for the function *K*=*K*(*y,z*)

$$K_a \leq K(y,z) \leq K_p$$
$$K(0,z) = K_p$$

where K_a active earth pressure coefficient
K_p passive earth pressure coefficient
K_r at rest earth pressure coefficient
y deflection (deformation of structure)
z depth

The function *K*=*K*(*y,z*) has to be continuous, monotonic (without local extremes in the interval *<Ka,Kp>*) and has to have a bounded first derivative. For example, the dependency *K*(*y,z*) consist of two hyperbolas parts connected together at point $y = 0$ with common tangent and functional value $K(0,z) = Kr$ is shown in Fig. 11. The above described algorithm is so general that practically allows computation for arbitrary function $K=K(y,z)$ which accomplishes above described criteria. The last condition is the determination of the activation structure movement. This movement is necessary for the decrease of the at rest earth pressure coefficient Kr almost at value of Ka. Methods of the activation structure movement determination are described in the technical literature (e.g. Feda 1977).

The nonlinear equation of deflection line is:

$$EI\frac{d^4y}{dz^4} = \partial(y,z) \quad (4)$$

The linear form of the equation (4) can be described using Taylor series in the form:

$$\sigma(y,z) = \sigma(y,z) + \frac{\partial\sigma}{\partial y}(y_0,z)(y-y_0) + 5\frac{\partial\sigma}{\partial y}(y_0,z)(y-y_0)^2 + ... \quad (5)$$

where the derivative $\partial\sigma/\partial y$ is determined in point (y_o,z) -

The formulation for incremental approximation is obtained using substituting equation (5) to (4) :

$$EJ\frac{d^4y_{i+1}}{dz^4} - \frac{\partial\sigma}{\partial y}(y_i,z)y_{i-1} = \sigma(y,z) - \frac{\partial\sigma}{\partial y}(y_i,z)y_i \quad (6)$$

Equation (6) is the linear differential equation of the 4th order with unknown function y_{i+i}. The equation coefficients are determined on the knowledge of the function y_i. Equation (2) substitutes σ and equation (3) substitutes $\frac{\partial\sigma}{\partial y}$ in the incremental approximation (6).

The anchors are inserted into the calculation as tightened springs. The horizontal component of anchor stiffness is equal to:

$$DK_h = DK\cos\alpha^2 = \frac{E_k \cdot A_k}{L_k}\cos^2\alpha \quad (7)$$

where E_k stiffness module of the anchor steel rod
A_k cross section of the rod
L_k anchor length
α angel of the anchor slope to the Vertical

Solution of equations (6) and (7) is possible using numerical methods – transformation on the simultaneous linear algebraic equations (Barták J. 1991).

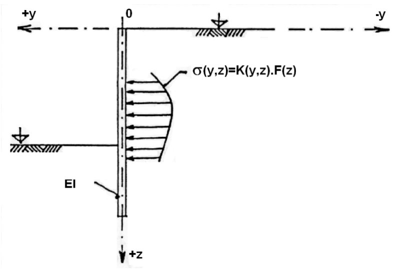

Fig. 10 Schema of the wall and load in the depend pressures method

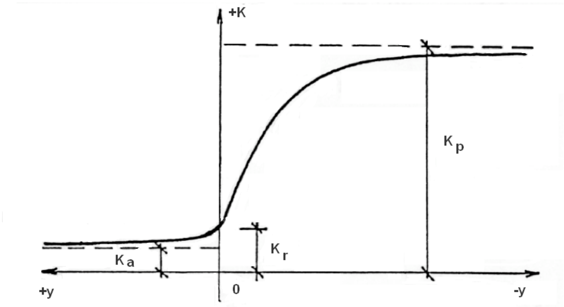

Fig. 11 Scheme of function K = K(y,z)

8.2 Application of the dependent pressure method of GEO5 Sheeting Check

The following assumptions are used in the program GEO5 Sheeting check:

- the pressure acting on a wall may attain an arbitrary value between active and passive pressure – but it cannot fall outside of these bounds,
- the pressure at rest acts on an undeformed structure (w=0).

The pressure acting on a deformed structure is given by:

$$\sigma = \sigma_r - k_h \cdot w$$
$$\sigma = \sigma_a \quad \text{for } \sigma < \sigma_a \qquad (9)$$
$$\sigma = \sigma_p \quad \text{for } \sigma > \sigma_p$$

where σ_r - pressure at rest
k_h - modulus of subsoil reaction
w - deformation of structure
σ_a - active earth pressure
σ_p - passive earth pressure

The computational procedure is as follows:

a) the modulus of subsoil reaction kh is assigned to all elements and the structure is loaded by the pressure at rest – see Figure 12.
b) 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 – see Figure 13.

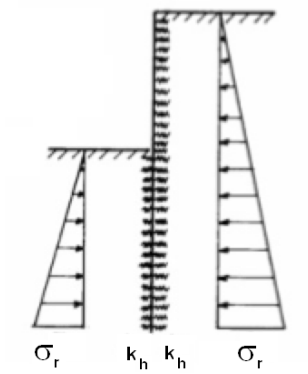

Fig. 12 Schema of the structure before the first iteration

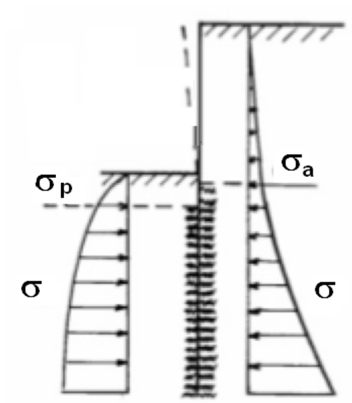

Fig. 13 Schema of the structure during the process of iteration

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

9. Conclusion

For the static calculation was used software GEO5 Sheeting check developed by FINE Ltd.

This software was selected due to following reasons:

- user friendly
- intuitiveness and transparency
- quality outputs
- easy input of the construction phases
- speed of calculations

The 22 anchor types and two geological profiles (occurring in the open pit space) were used in the design of the sheeting piling for the Prosek metro station. The results were summarized in the tables due to easy verification. All anchor types were statically evaluated according the operating procedures up to final excavation. Maximal loading capacity of the riders was not exceeded at any state. No significant variation of calculated and measured displacement has been found out.

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