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# A Concept Solution of Anchored Diaphragm Wall in Central Part of Budva Town

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**Abstract:** In this paper is presented a concept solution and acceptance test application procedure of deep pit protection structure, intended for three underground levels of residential building: A,B,C,D, block 10C, Budva, Montenegro. The anchored wall used consist of nongravity cantilevered walls with three levels of ground anchors. Nongravity cantilevered walls employ continuous walls constructed in slurry trenches (i.e., slurry (diaphragm) walls), e.g vertical elements that are drilled to depths below the finished excavation grade. For those nongravity cantilevered walls, support is provided through the shear and bending stiffness of the vertical wall elements and passive resistance from the soil below the finished excavation grade. Anchored wall support relies on these components as well as lateral resistance provided by the ground anchors to resist horizontal pressures (e.g., earth, water, external loads) acting on the wall. Anchored wall analysed and applied is temporary supporting structure necessary for the excavation and erection of the underground structure part up to ground surface level. Temporary ground anchors lifetime is up to two years. Dynamic loads are not considered.

**Key words:** Anchored retaining walls, slurry walls, deep excavation support, ground anchors.

## 1. Introduction

The concept of an anchored wall system is to create an internally stable mass of soil that will resist external failure modes at an adequate level. The design should consider the mobilization of resistance by both anchors and wall elements in response to loads applied to the wall system.

The magnitude of the total anchor force required to maintain the wall in equilibrium is based on the forces caused by soil, water, and external loads. Anchors can provide the required stabilizing forces which, in turn, are transmitted back into the soil at a suitable distance behind the active zone. This requirement generally defines the minimum distance behind the wall at which the anchor bond length is formed. The anchor bond length must extend into the ground to intersect any potentially critical failure surfaces which might pass behind the anchors and below the base of the wall. The required depth to which anchors must be installed in the soil should be determined based on the location of the deepest potential failure surfaces that have an insufficient factor of safety without any anchor force.

To provide pit protection by means of an excavation supported by an anchored wall, is necessary:

- The anchored wall should support the soil immediately adjacent to the excavation in equilibrium. This support typically governs the maximum required force in the anchors and the maximum required dimensions, strength, and bending moments in the wall section.
- The anchors should be extended sufficiently deep into the soil to beneficially affect a range of shallow and deep-seated potential failure surfaces with inadequate factors of safety. The anchor forces act on these potential slip surfaces to ensure they have an acceptable factor of safety.

## 2. Construction Procedure

The design task is to prepare solution of excavation pit protection using anchored diaphragm wall. On the site five buildings A,AB,C and D should be constructed going -11.5m below the ground surface.

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The general solution considers a separation of 25 cm between the new building structure and the inner diaphragm wall face, necessary to protect the excavation. This gap is defined as horizontal displacements analysis output by adding construction diaphragm wall vertical tolerance h/200.

The diaphragm wall composed of monolithic RC panels with dimensions: thickness d=0.6m, height (depth) h=20m, width b=2.5m.

The solution is set for preciously chosen anchor types PREN 10138 T15. The anchorage is made in three layers below the ground level with anchor length L=30m (1-st and 2-nd anchorage rows) and L=25m (3-rd anchorage row).

To install the diaphragm protection wall a special type of mechanization (for excavation) is used and the process starts before the pit excavation by setting the RC concrete guidewall with thickness 20cm to ensure the soil stability near ground level.

The construction works connected to installation of the diaphragm wall and anchors as well, is made according to following procedure:

- RC guidewall construction

The reinforced-concrete guidewalls are first set with respect to exact survey as two parallel beams with thickness 20cm, height 80cm making an opening of 65cm for the excavation of the wall.

- Excavation of the diaphragm wall

To ensure a precise excavation during the process a slurry suspension is purred in the excavated segment. The sllury material is made of bentonite with unit weight from 11kN/m3.

The excavation is set in segments over a L=2.5m as one segment width, over one segment field, later after excavating and finishing the adjacent segments the construction of mid-segment is started.

- Reinforcing and concreting of the diaphragm wall

The diaphragm wall is double side reinforced. The cover to the main reinforcement shall be 7.5cm and the minimum clear spacing between the vertical bars shall be 10cm.

The concrete used for the diaphragm wall is the type C20/25 and is made by using a tremie pipe with minimum internal diameter of 25cm to allow the continuously free flow of concrete.

- Excavation of the soil material from the pit
- Anchorage

The boring of the anchors is made by rotary drilling cased. Cased bore diameter is $d_c$=140mm. The calculated grout body(bulb) diameter $d_b$ is: $d_b$=2x$d_c$ (medium to coarse gravel), $d_b$=1.4x$d_c$ (cohesive soil); $d_b$=1.5x$d_c$ (sand and gravelly sand). The anchors are composed from two lengths, namely a free length of the anchor and bond or grouted length of the anchor Lb=(12.5÷15)m.

To ensure that the design values for the anchor force in tensions are properly sustained, acceptance test is applied for each individual anchor according to European standard prEN1537 [1, 2].

## 3. Basic Design Data

- Material data sets are presented in Tables 1-4.
- Hydrostatic pressure

In the static analysis groundwater conditions are defined by water column of -2m from ground surface level.

**Table 1 Soil data sets parameters.**

| Parameter | *Name* | *Unit* | Soil Layer 1 (Fill) | Soil Layer 2 (Brown Clay) | Soil Layer 3 (Sandy Gravel) |
|---|---|---|---|---|---|
| Material model | | | Mohr-Coulomb | Mohr-Coulomb | Mohr-Coulomb |
| Type of material behaviour | | | Drained | Drained | Drained |
| Soil unit weight above phreatic level | $g_{unsat}$ | [kN/m³] | 16 | 17 | 17 |
| Soil unit weight below phreatic level | $g_{sat}$ | [kN/m³] | 20 | 21 | 21 |
| Permeability in horizontal direction | $k_x$ | [m/day] | 0.01 | 0 | 0.1 |
| Permeability in vertical direction | $k_y$ | [m/day] | 0.01 | 0 | 0.1 |
| Young's modulus (constant) | $E_{ref}$ | [kN/m²] | 3700 | 6000 | 9000 |

Table 1 to be continued

| | | | | | |
|---|---|---|---|---|---|
| Poisson's ratio | n | [-] | 0.3 | 0.3 | 0.3 |
| Oedometer modulus | $E_{oed}$ | [kN/m²] | 5000 | 8000 | 12000 |
| Cohesion (constant) | $c_{ref}$ | [kN/m²] | 2.5 | 10 | 5 |
| Friction angle | j | [°] | 15 | 20 | 28 |

**Table 2 Material properties of diaphragm wall (plate).**

| Parameter | *Name* | *Unit* | Value |
|---|---|---|---|
| Type of material behaviour | | | Elastic |
| Normal stiffness | EA | [kN/m] | 1.80E+07 |
| Flexural rigidity | EI | [kNm²/m] | 5.40E+05 |
| Equivalent thickness | d | [m] | 0.6 |
| Weight | w | [kN/m/m] | 14.4 |
| Poisson's ratio | n | [-] | 0.2 |

**Table 3 Material properties of strand anchors (node-to-node anchor).**

| Parameter | *Name* | *Unit* | Value |
|---|---|---|---|
| Type of material behaviour | | | Elastic |
| Normal stiffness | EA | [kN] | 1.12E+05 |
| Spacing out of plane | Ls | [m] | 2.50E+00 |
| Maximum Force | $F_{max,comp}$ | [kN] | 1E+15 |
| | $F_{max,tens}$ | [kN] | 1E+15 |

**Table 4 Material properties of the grout body (geogrid).**

| Parameter | *Name* | *Unit* | Value |
|---|---|---|---|
| Normal stiffness | EA | [kN/m] | 1.85E+05 |

## 4. Static Analysis

The calculation of the excavation pit protection is performed numerically using the finite element method (FEM) by means of software package PLAXIS.

The program enables simple and efficient modeling defining different boundary conditions. Besides the multi-layered soil medium, structures can be also modeled like, diaphragm walls, anchors, geotextile using discrete beam and plane elements.

The software package PLAXIS enables a choice of wide spectra of nonlinear elasto-plastic material definitions which are used to define behavior of different types of soils.

The spatial discretization is performed using triangular plane finite elements with 15 nodes, as for the structural element a beam finite element with 3 nodes is used.

The analysis is defined to be a two-dimensional plane strain. The soil is defined using the Mohr-Coulomb material behaviour as drained continuum. Plates is used to model diaphragm wall with bending and normal stiffness.

Geogrids and node-to-node elements combination is used to model ground anchors at grout body and free length respectively. Geogrids presents a slender element with normal stiffness, while node-to-node presents spring elements used to model strands in free length of ground anchors.

### *4.1 Diaphragm Wall Design Load Calculations*

The soil excavation is simulated in 8 calculation phases as follows:

1 phase - installation of diaphragm walls

2 phase - excavation to a depth 4.0m. The pit is pumped dry.

3 phase - first row anchors PREN 10138 4T15 installation and prestress to a depth 3.0m.

4 phase - excavation to a depth 6.75m. The pit is

pumped dry.

5 phase - second row anchors PREN 10138 2x3T15 installation and prestress to a depth 5.75m.

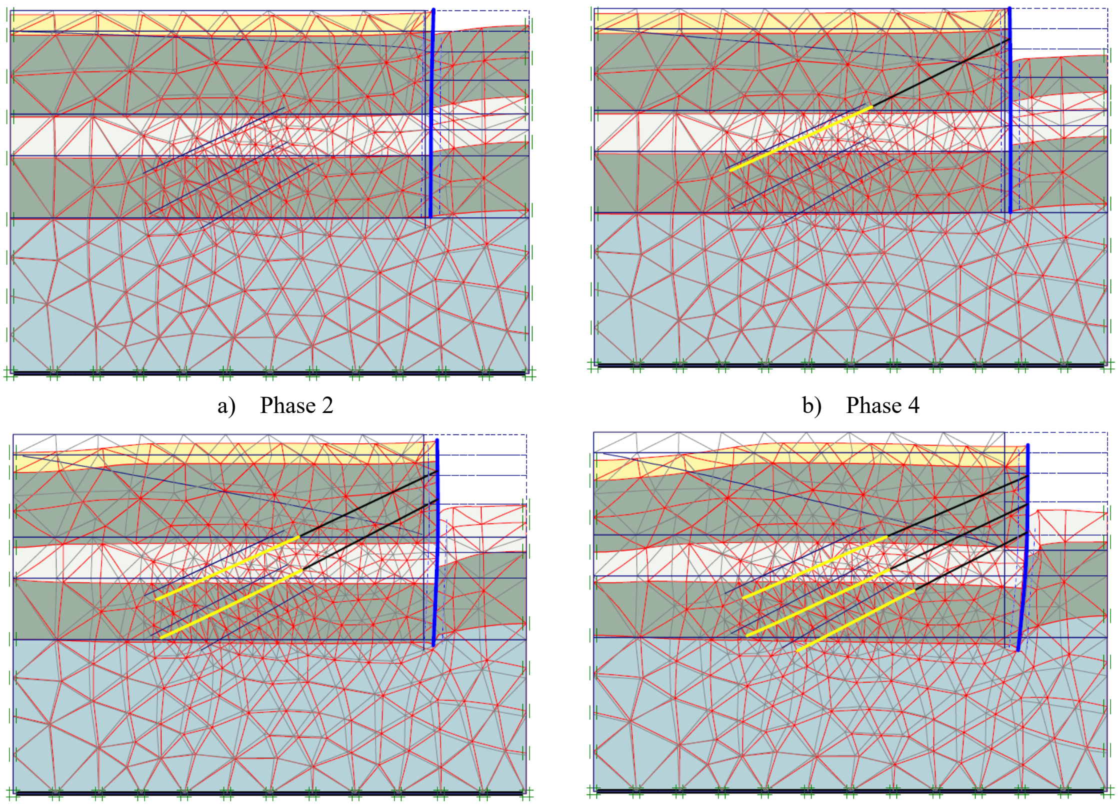
6 phase - excavation to a depth 9.5m. The pit is pumped dry.

7 phase - third row anchors PREN 10138 2x3T15 installation and prestress to a depth 8.5m

8 phase - excavation to a depth 11.5m. The pit is pumped dry.

The selected phases and respective results generated from plastic calculations are presented, Figs. 1-3.

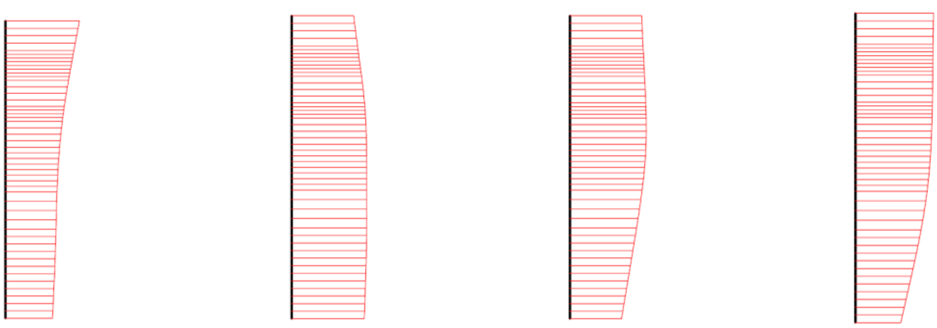
Design of diaphragm wall is made considering their maximal forces, bending moment, shear and axial forces. Anchor design Loads are presented in Table [3].



a) Phase 2 b) Phase 4

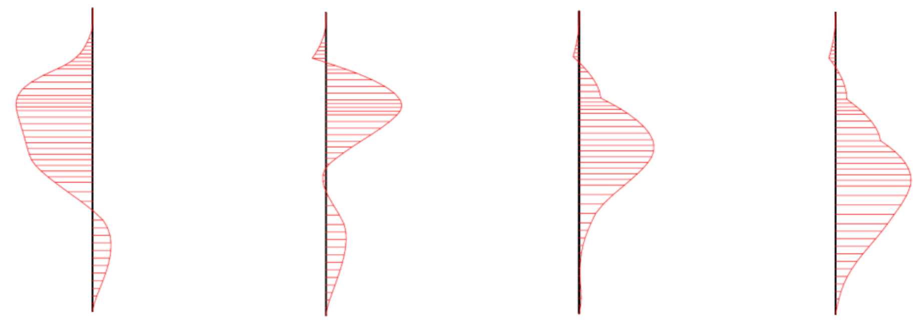
c) Phase 6 d) Phase 8

**Fig. 1 Deformed mesh phases.**



$MaxU_x$=39.64x$10^{-3}$m, a) Phase 2 $MaxU_x$=57.19x$10^{-3}$m, b) Phase 4 $MaxU_x$=140.06x$10^{-3}$m, c) Phase 6 $MaxU_x$=227.68x$10^{-3}$m d) Phase 8

**Fig. 2 Diaphragm wall horizontal displacements.**



$|M|_{max}$=99.8kNm/m, $|M|_{max}$ =211.7kNm/m, $|M|_{max}$ =556.2kNm/m, $|M|_{max}$ =714.1kNm/m

a) Phase 2 b) Phase 4 b) Phase 6 b) Phase 8

**Fig. 3 Diaphragm wall bending moments.**

**Table 5 Anchor Loads.**

| Ground anchor level (m) | Anchor Working Load, P (kN) | | | | | | Anchor Design Load, Rd (kN) | Spacing out of plane Ls(m) |
|---|---|---|---|---|---|---|---|---|
| | phase 3 | phase 4 | phase 5 | phase 6 | phase 7 | phase 8 | | |
| -3 | 375.00 | 478.74 | 358.39 | 446.78 | 397.63 | 438.38 | 478.74 | 2.5 |
| -5.75 | | | 250.00 | 302.14 | 256.46 | 283.82 | 302.14 | 1.25 |
| -8.5 | | | | | 250.00 | 289.64 | 289.64 | 1.25 |

**Table 6 Anchor type selected.**

| Ground anchor level (m) | Anchor Design Load, Rd (kN) | Anchor Proof Load, Pp (kN) | Anchor Type prEN10138 | $0.6P_{tk}$(kN) | Installation Angle (°) | Bulb Diameter (mm) | Spacing out of plane Ls(m) |
|---|---|---|---|---|---|---|---|
| -3 | 478.74 | 574.488 | 4T15 | 624 | 25 | 190 | 2.5 |
| -5.75 | 302.14 | 362.568 | 3T15 | 468 | 25 | 190 | 1.25 |
| -8.5 | 289.64 | 347.568 | 3T15 | 468 | 30 | 190 | 1.25 |

*4.2 Maximum Anchor Stressing Force*

Anchors are formed by strands in harmonic steel and sheathed and greased separately in the free length. The protection of the free length is obtained through greasing and sheathing of every single strand. The separation of the free length from the bond length is made using a sealing pad allowing a perfect tightness between the parts.

In the bond length the strands are divided by suitable spacers and, being placed in sinusoidal shape by steel strips and taping, they allow to increase their adherence with grouting body.

The temporary anchors used are partially prestressed at a lock-off force $P_0$ equal to anchor design load Rd. $P_0$= Rd.The maximum anchor stressing force according to EURO NORM EN 1537-2002 paragraph 9.8 must be limited to 0.6 Ptk. $P_{tk}$-Characteristic strand resistance to traction.

The maximum stressing force correspond to acceptance test proof load Pp. Pp=1.2Rd. The anchor type selected are presented in Table [4] for each anchors row.

*4.3 Anchor Bond Length and Load Capacity*

The length of the pressure-grouted body, known as the bonded length, varies depending on the type of soil, the diameter of the pressure-grouted body and the amount of tension.

Bond length $L_b$ is calculated to guarantee strength capacity:

- at soil/grouting body interface according to expresion:

$$L_b=N_l/ \pi d_b f \tag{1}$$

$N_l$ -ultimate soil/grouting body, load capacity

$d_b$ -bulb diameter

f - ultimate bond strength capacity at soil/grouting body interface, Geotechnical Engineering Circular No. 7 (1991).

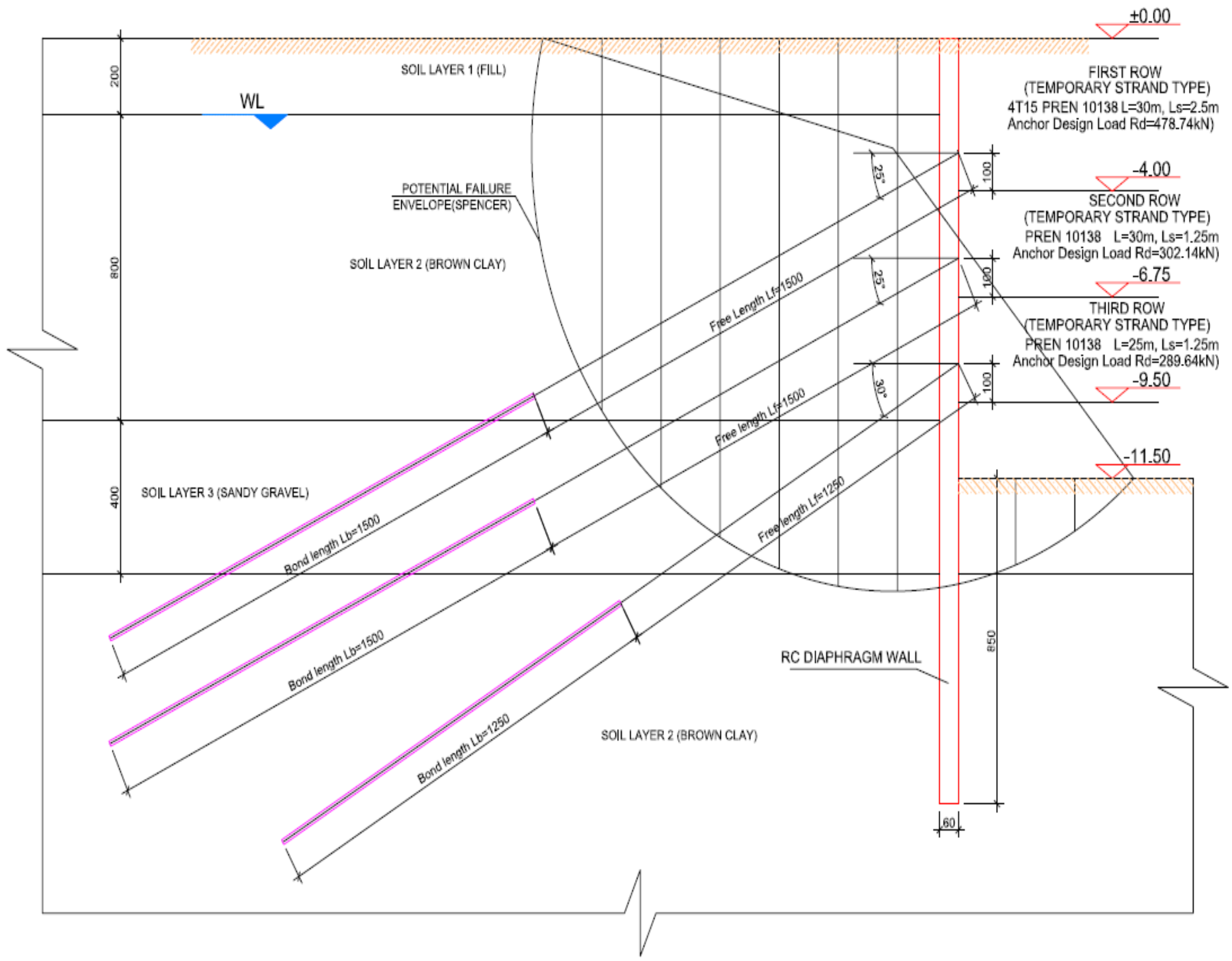



**Fig. 4 Deep pit protection structure section.**

- at strand/grouting body interface according to expresion.

$$L_b=N_2/\pi\, d\, f_{bd}\,\omega \qquad (2)$$

$N_2$ -ultimate strand/grouting body, load capacity

d- sum of strand diameters inside anchor

$f_{bd}$- ultimate adherence strength capacity at strand/grouting body interface.

ω-reduction coefficient according to number of separated strands inside anchor.

$$\omega=1-0.075(n-1) \qquad (3)$$

n-number of separated strands inside anchor

Bond length consist of maximum value, max$L_b$ derived from Eqs. (1) and (2). Considering the envelope potential failure the deep pit protection structure section is presented in Fig. 4. Anchor load capacity must comply the following relations:

$$[N]=\min((N_1,N_2)/K,\ 0.6P_{tk}),$$

$$[N]\geq Rd(\text{Anchor Design Load}); \qquad (4)$$

where K=1.5; safety coefficient for temporary anchors

## 5. Safety Analyses

Phi-c reduction procedure is used to calculate the global safety factor for different construction stages. According to this approach the soil and soil interface strength parameters tanφ and c are reduced successively up to structure failure. Strength parameter tanφ and c reduce in the same proportion:

$$c/c_r= \tan\varphi/\tan\varphi_r=\sum M_{sf} \qquad (5)$$

where: φ and c are input strength parameter, while $\varphi_r$ and $c_r$ are reduced strength parameters enough to maintain equilibrium. The safety factor defined as the value of $\sum M_{sf}$ at failure, is obtained for a number of successive load steps. In phase construction 2 safety factor $\sum M_{sf}$=2.64. In phase construction 8 safety factor $\sum M_{sf}$=1.29, which means that failure does not occur.

## 6. Anchor Testing

Acceptance test is performed to each individual anchor according to EN ISO 22477-5 [5].

The objectives of the acceptance test are as follows:

a) to demonstrate that a proof load Pp=1.2Rd, can be sustained by the anchor;

b) to determine the apparent tendon free length $L_{app}$;

c) to ensure that creep movements or load loss lies inside the allowable limits.

Acceptance test loading procedure for the first row anchorage level -3m is presented in Table [6]. A datum load, Pa=10%Pp is applied to minimise movement of the anchor test set-up upon initial loading.

The apparent tendon free length $L_{app}$ is the theoretical free length of the tendon up to the connection of the tendon to the stressing jack deduced from the test.

Apparent Tendon Free Length, $L_{app}$ is calculated according to Hooke's law:

$$L_{app} =(At\cdot Et\cdot \Delta s)/\Delta P;$$

$$\Delta Pj=(At\cdot Et\cdot \Delta s)/L_{app}\ \min,\max \qquad (6)$$

At-cross sectional area of anchor tendon. For 4T15, At=5.6cm$^2$.

ΔP- Difference between proof load and datum load $\Delta P=Nj-N_0$; $N_0$=Pa=0.1Pp; j=1÷5

Δs-Measured extension of anchor tendon under load increment ΔP

The limits of Lapp for bond anchors used are:

$$\text{Upper limit: } L_{app}\max = L_f+Le+ 0{,}5L_b \qquad (7)$$

$$\text{Lower limit:} L_{app}\min = 0.8L_f+L_e \qquad (8)$$

External length $L_e$=1m. Substituting in Eq.6, Eq.7 and Eq. 8 it is obvious that $L_{app}$ lies inside acceptable limits. $L_{app}$ min =9.0m<$L_{app}$=11.2m< $L_{app}$ max=18.5m.

The creep movements measurements are performed and evaluated in accordance to UNIN 1537 EIT, E.2.4, E.4.3. The anchor is loaded from the Datum Load, Pa to Proof Load, Pp in 5 (minimum is 4) increments, Table [7]. Then the proof load is maintained constant for at least 15 min. The increment of anchor head displacement relative to a fixed point is measured at the end of specified time intervals 3÷15minutes for Proof Load, Pp. The creep rate determined as a constant displacement rate ks is measured over two time intervals.ksj =Δsj/logΔtj; j=1÷6; α=ks6,

**Table 7 Acceptance test loading procedure.**

| Load Step Increment Nj, j=0÷5 | Hold Time | Stressing Jack pressure, Spj | Measured movement Strand 1, (Δ1) | Measured movement Strand 2, (Δ2) | Measured movement Strand 3, (Δ3) | Measured movement Strand 4, (Δ4) |
|---|---|---|---|---|---|---|
| Units | minutes | bar | mm | mm | mm | mm |
| N0=0.1Pp | Until stable | 30 | 90.0 | 102.0 | 89.0 | 89.0 |
| N1=0.2Pp | 1min, 2max | 60 | 95.0 | 110.0 | 93.0 | 93.0 |
| N2=0.4Pp | 1min, 2max | 120 | 110.0 | 122.0 | 105.0 | 108.0 |
| N3=0.6Pp | 1min, 2max | 180 | 132.0 | 142.0 | 125.0 | 129.0 |
| N4=0.8Pp | 1min, 2max | 240 | 153.0 | 163.0 | 145.0 | 150.0 |
| N5=1.0Pp | 1min, 2max | 300 | 195.0 | 207.0 | 187.0 | 197.0 |
| N5=1.0Pp | 15 | 300 | 196.0 | 208.0 | 188.0 | 199.0 |
| N4=0.8Pp | 1min, 2max | 240 | 189.0 | 197.0 | 180.0 | 190.0 |
| N3=0.6Pp | 1min, 2max | 180 | 177.0 | 185.0 | 172.0 | 181.0 |
| N2=0.4Pp | 1min, 2max | 120 | 161.0 | 170.0 | 156.0 | 165.0 |
| N1=0.2Pp | 1min, 2max | 60 | 146.0 | 154.0 | 140.0 | 148.0 |
| N0=0.1Pp | Until stable | 30 | 144.0 | 152.0 | 138.0 | 146.0 |

**Table 8 Creep test procedure.**

| Time tj, j=1÷6 | Δtj=tj-t1 | Measured movement Strand 1, (Δ1) | Measured movement Strand 2, (Δ2) | Measured movement Strand 3, (Δ3) | Measured movement Strand 4, (Δ4) | Mean movement Δj=(ΣΔi/i)j | Head displacements Δsj=sj-s1 | Displacement rate ksj, j=1÷6 |
|---|---|---|---|---|---|---|---|---|
| | minutes | mm | mm | mm | mm | mm | mm | mm |
| t1 = 3 min | 0 | 195.0 | 207.0 | 187.0 | 197.0 | 196.5 | 0.0000 | |
| t2 = 6 min | 3 | 195.5 | 207.5 | 187.0 | 197.0 | 196.8 | 0.2500 | 0.5240 |
| t3 = 8 min | 5 | 196.0 | 208.0 | 187.4 | 197.5 | 197.2 | 0.7250 | 1.0372 |
| t4 = 10 min | 7 | 196.0 | 208.0 | 187.8 | 197.8 | 197.4 | 0.9000 | 1.0650 |
| t5 = 12 min | 9 | 196.0 | 208.0 | 188.0 | 199.0 | 197.8 | 1.2500 | 1.3099 |
| t6 = 15min | 12 | 196.0 | 208.0 | 188.0 | 199.0 | 197.8 | 1.2500 | 1.1583 |

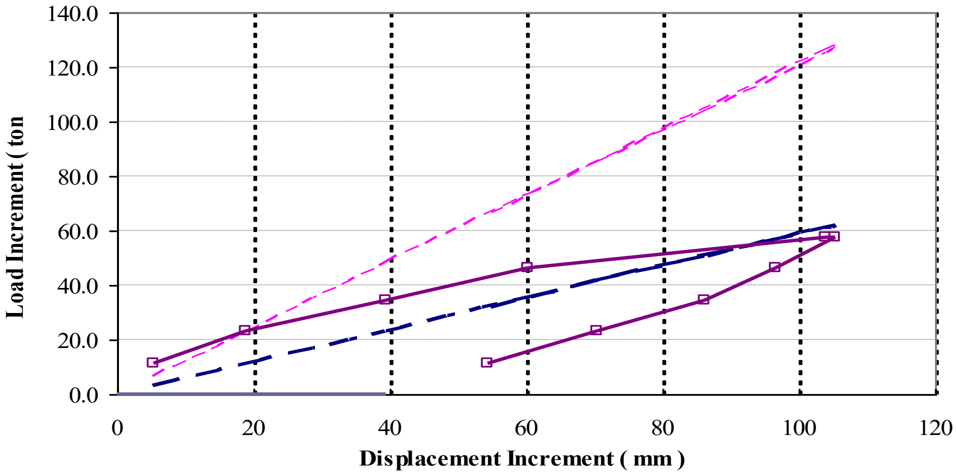



**Fig. 5 Incremental, load-displacement curve.**

The maximum creep movement: $\alpha$=ks6=1.1583mm < 1.2mm which complies with limits for temporary anchors without investigation tests (EN ISO 22477-5).

Anchor load-displacement curve is presented in Fig. 5.

After acceptance test is passed each anchor is incrementally loaded up to lock-off value $P_0$.

## 7. Conclusions

Anchored continuous diaphragm wall provide:

• rational solution in supporting open deep pit excavations of building structures mostly in urban sites where demand for space is obligatory.

• ability to withstand horizontal pressures without significant increase in wall cross section.

• protection of the excavation base from ground water effect, uplift pressures and bottom swelling.

• unobstructed workspace for excavations, clean environment and comfortable conditions inside the pit to follow easily the building erection phase.

• feasibility of combining the deep pit protection structure with the permanent structure. Diaphragm walls can easily be designed to carry loads from the permanent structure after the temporary anchors are destressed. Diaphragm walls can serve as watertight element of permanent structure.

• feasibility of combining ground anchors with horizontal struts as additional support of diaphragm wall to prevent horizontal displacements of surrounding structures.

• flexible positioning and inclination of the anchors in case of existing underground structures in vicinity of the excavation.

• construction time reduction

• flexible solution for the temporary anchors that do not satisfy acceptance criteria. Those anchors can be replaced or regrouted.

- flexible section shapes other than conventional straight section like T-section, L-section etc.
- minimum noise and vibration levels, that make it construction suitable in urban areas.

Anchored diaphragm walls however, require the use of heavy construction equipment, considerable mobilization cost. In hard and rocky grounds this type of deep pit protection is not efficient.

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