Design Concept for an Anchored Diaphragm Wall in the Central Part of Budva, Montenegro

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Abstract: This paper presents a design concept and acceptance test application procedure for a deep pit protection structure. The structure is intended for use in the construction of three underground levels of a residential building: A, B, C and D, located in Block 10C, Budva, Montenegro. The anchored wall will consist of non-gravity cantilevered walls with three levels of ground anchors. Non-gravity 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 non-gravity 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 and external loads) acting on the wall. The anchored wall analyzed in this paper will be recommended for use as a temporary supporting structure necessary for the excavation and erection of the underground structure. The design life of the temporary ground anchors is two years. Dynamic loads are not considered in this analysis.

Key words: Design, pit, non-gravity, diaphragm, ground, anchor, slurry, excavation.

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 of safety. 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.

The following items are necessary to provide pit protection by means of an excavation supported by an anchored wall:

• 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 adequate factors of safety. The anchor forces act on these potential slip surfaces to ensure they have an acceptable factor of safety [1];

• Anchor acceptance testing procedure must be

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performed prior loading up to lock-off value.

2. Construction Procedure

The design task is to prepare a solution for an excavation pit protection using an anchored diaphragm wall. On the site four building parts, A, B, C and D should be constructed going 11.5 m below the ground surface.

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 displacement analysis output by adding construction diaphragm wall vertical tolerance as h (height)/200.

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

The solution is set for preciously chosen anchor Type prEN 10138 T15. The anchorage is made in three layers below the ground level with anchor length $L = 30$ m (1st and 2nd anchorage rows) and $L = 25$ m (3rd 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 begins by setting the RC guide wall with a 20-cm thickness to ensure the soil stability near ground level.

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

- RC guide wall construction: The reinforced concrete guide walls are first set with respect to exact survey as two parallel beams with a thickness of 20 cm and height of 80 cm making an opening of 65 cm for the excavation of the wall;

- Excavation of the diaphragm wall: To ensure a precise excavation during the process, a slurry suspension is poured in the excavated segment. The slurry material is made of bentonite with a unit weight of approximately 11 kN/m³. The excavation is set in

segments over a length of 2.5 m as one segment width, over one segment field, later after excavating and finishing, the adjacent segments of the construction of a mid-segment is executed;

- Reinforcing and concreting of the diaphragm wall: The diaphragm wall consists of a double reinforced mat. The cover to the main reinforcement must be 7.5 cm and the minimum clear spacing between the vertical bars must be 10 cm. 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 25 cm to allow the continuous free flow of concrete;

- Excavation of the soil material from the pit;

- Anchorage.

The boring of the anchors is made by using rotary drilling casing [2]. The cased bore diameter is $d_c = 140$ mm. The calculated grout body (bulb) diameter d_b is:

- $d_b = 2 x d_c$ (medium to coarse gravel);
- $d_b = 1.4 x d_c$ (cohesive soil);
- $d_b = 1.5 x d_c$ (sand and gravelly sand).

The anchors consist of two engaged length segments, namely a free length of the anchor and bond or grouted length of the anchor $L_b = (12.5 \div 15)$ m.

To ensure that the required design values for the anchor tension force are properly sustained, acceptance testing is applied for each individual anchor according to European Standard prEN 1537 [3].

3. Basic Design Data

Soil, RC wall and anchors properties assigned below, are basic design data to simulate interactive behavior:

- material data sets (Tables 1-4);
- hydrostatic pressure.

In the static analysis, the groundwater conditions are defined by a water column of 2 m below the ground surface level.

4. Static Analysis

The calculation of the excavation pit protection is

Table 1   Soil data sets parameters.

Parameter	Name	Unit	Soil Layer 1 (clay sand)	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	γ_{unsat}	kN/m³	16	17	17
Soil unit weight below phreatic level	γ_{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	3,700	6,000	9,000
Poisson's ratio	ν	-	0.3	0.3	0.3
Oedometer modulus	E_{oed}	kN/m²	5,000	8,000	12,000
Cohesion (constant)	c_{ref}	kN/m²	2.5	10	5
Friction angle	φ	-	15	20	28
Plasticity index	PI	-	10	16	-
Relative density	Dr	-	-	-	0.4

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	ν	-	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-compressive	$F_{max.\ comp}$	kN	1E + 15
Maximum force-tensile	$F_{max.\ tens}$	kN	1E + 15

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

Parameter	Name	Unit	Value
Normal stiffness	EA	kN/m	1.85E + 05

performed numerically using the FEM (finite element method) by means of the PLAXIS[1] software package.

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.

PLAXIS enables selection of a 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 three nodes is used in analysis.

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.

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[1]Software package PLAXIS professional version.

Geogrids and node-to-node elements combination are 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 eight calculation phases as follows:

• 1st phase: installation of diaphragm walls;

• 2nd phase: excavation to a depth of 4.0 m. The pit is pumped dry;

• 3rd phase: first row anchor prEN 10138 4T15 installation and pre-stress to a depth of 3.0 m;

• 4th phase: excavation to a depth of 6.75 m. The pit is pumped dry;

• 5th phase: second row anchor prEN 10138 2x3T15 installation and pre-stress to a depth of 5.75 m;

• 6th phase: excavation to a depth of 9.5 m. The pit is pumped dry;

• 7th phase: third row anchor prEN 10138 2x3T15 installation and pre-stress to a depth of 8.5 m;

• 8th phase: excavation to a depth of 11.5 m. The pit is pumped dry.

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

Design of the diaphragm wall is made considering the maximum forces, bending moment, shear and axial forces [4]. Anchor design loads are presented in Table 5.

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
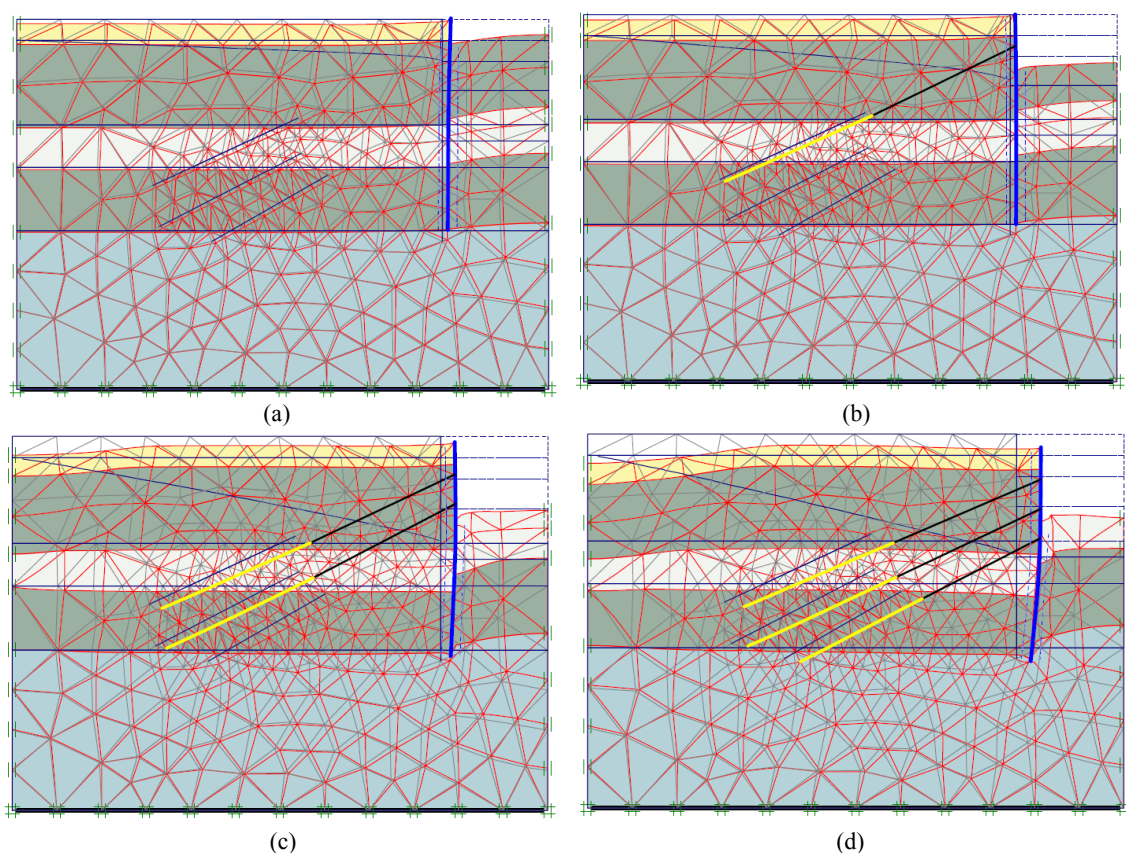

(a)	(b)
(c)	(d)

Fig. 1   Deformed mesh phases: (a) Phase 2; (b) Phase 4; (c) Phase 6; (d) Phase 8.

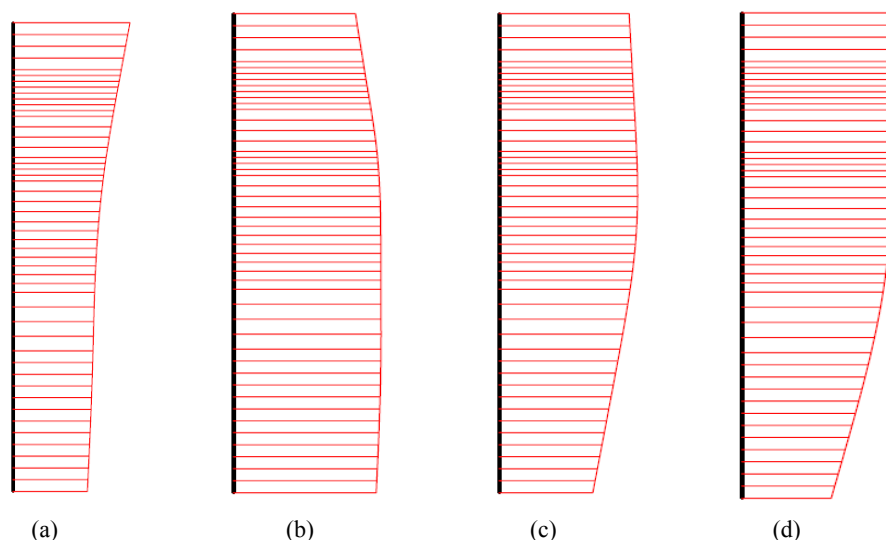(a)   (b)   (c)   (d)

Fig. 2   Diaphragm wall horizontal displacements: (a) Phase 2 (max $U_x = 39.64 \times 10^{-3}$ m); (b) Phase 4 (max $U_x = 57.19 \times 10^{-3}$ m); (c) Phase 6 (max $U_x = 140.06 \times 10^{-3}$ m); (d) Phase 8 (max $U_x = 227.68 \times 10^{-3}$ m).

(a)   (b)   (c)   (d)

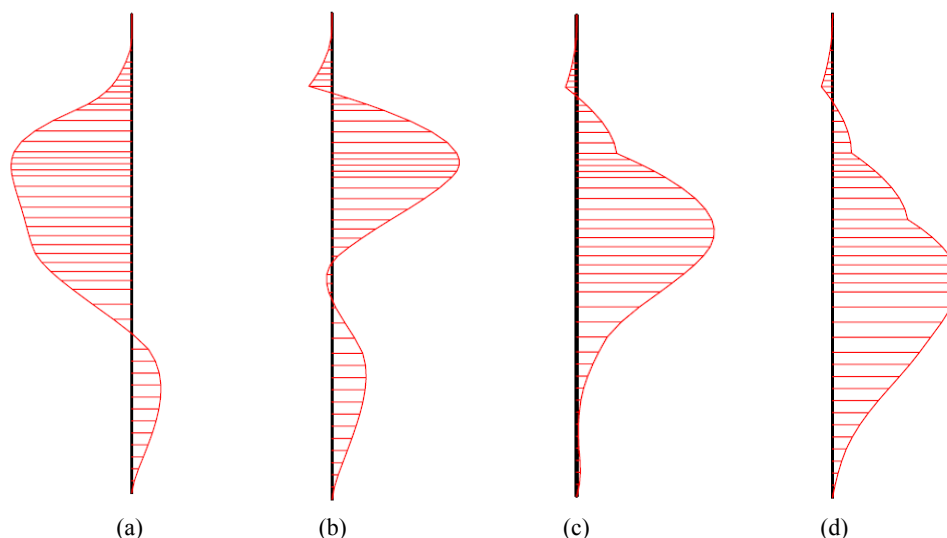**Fig. 3   Diaphragm wall bending moments: (a) Phase 2 ($|M|_{max} = 99.8$ kNm/m); (b) Phase 4 ($|M|_{max} = 211.7$ kNm/m); (c) Phase 6 ($|M|_{max} = 556.2$ kNm/m); (d) Phase 8 ($|M|_{max} = 714.1$ kNm/m).**

Table 5   Anchor loads.

Ground anchor, level (m)	Anchor working load, P (kN)						Anchor design load, R_d (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

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 R_d ($P_0 = R_d$). The maximum anchor stressing force according to EURO NORM EN 1537-2002 Paragraph 9.8 [3] must be limited to $0.6P_{tk}$ (P_{tk}—characteristic strand resistance to traction).

The maximum stressing force corresponds to acceptance test proof load Pp ($Pp = 1.2R_d$). The anchor type selected are presented in Table 6 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:

• soil/grouting body interface according to Eq. (1):

$$L_b = N_1/\pi d_b f \qquad (1)$$

where:

N_1 means ultimate soil/grouting body, load capacity;

d_b means bulb diameter;

f means ultimate bond strength capacity at soil/grouting body interface [2];

• strand/grouting body interface according to Eq. (2):

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

where:

N_2 means ultimate strand/grouting body, load capacity;

d means sum of strand diameters inside anchor;

f_{bd} means ultimate adherence strength capacity at strand/grouting body interface;

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

This coefficient is defined according to following expression:

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

where, n = number of separate strands inside the anchor.

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

$$[N] = \min((N_1, N_2)/K, 0.6P_{tk});$$
$$[N] \geq R_d \text{ (anchor design load)} \qquad (4)$$

where, $K = 1.5$ (safety coefficient for temporary anchors).

5. Safety Analyses

The Phi-c reduction procedure is used to calculate the global safety factor for different construction stages. According to this approach the soil to soil interface strength parameters $\tan\varphi$ and c are reduced successively up to structural failure. Strength parameters $\tan\varphi$ and c are reduced in the same proportion:

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

where, φ and c are input strength parameters, while φ_r and c_r are reduced strength parameters selected 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 2, the safety factor $\sum M_{sf} = 2.64$. In Phase 8, the safety factor $\sum M_{sf} = 1.29$, which means that both phases satisfy adequate factor of safety criteria.

6. Anchor Testing

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

The objective of the acceptance testing is as follows:

(1) demonstrate that a proof load $Pp = 1.2R_d$, can be sustained by the anchor;

Table 6 Anchor type selected.

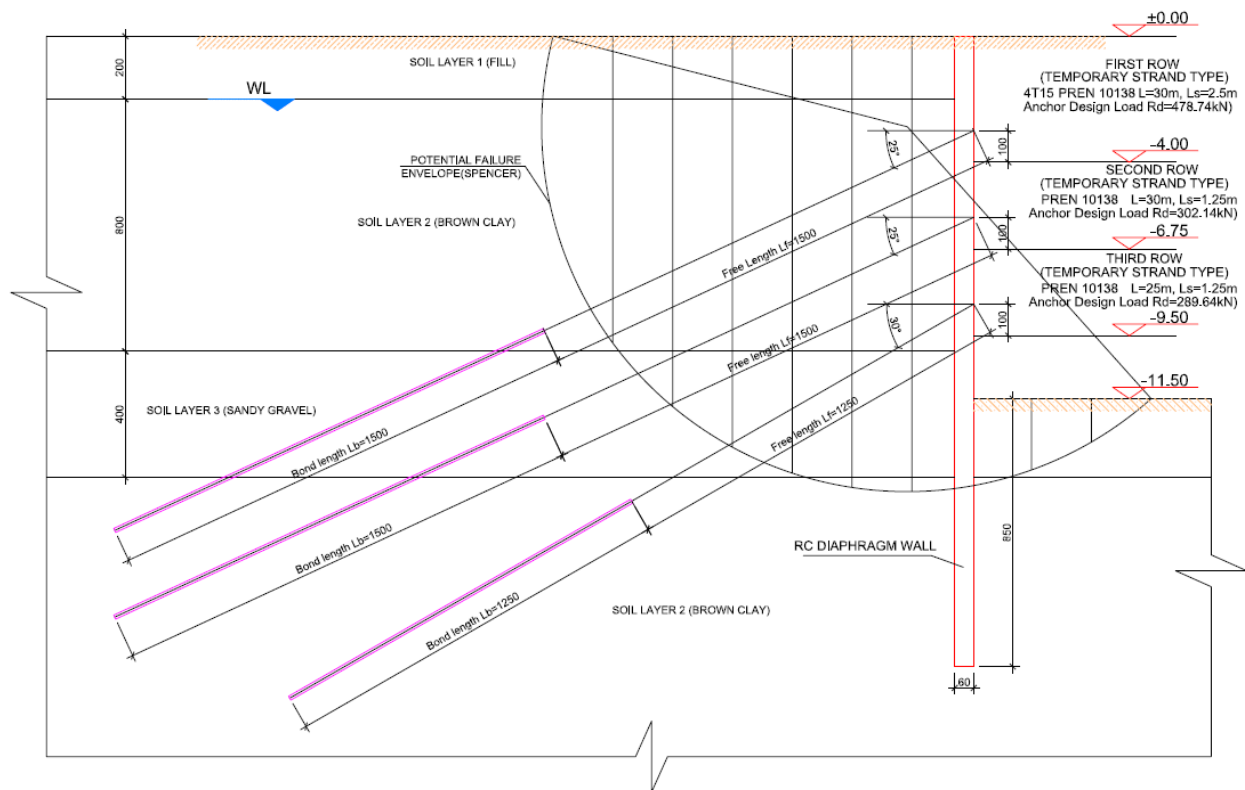| Ground anchor, level (m)	Anchor design load, R_d (kN)	Anchor proof load, Pp (kN)	Anchor type, prEN 10138	$0.6P_{tk}$ (kN)	Installation angle (°)	Bulb diameter (mm)	Spacing out of plane, Ls (m)
−3	478.74	574.488	4T15	624	25	190	2.5
−5.75	302.14	362.568	3T15	468	25	190	1.25
−8.5	289.64	347.568	3T15	468	30	190	1.25

Fig. 4   Deep pit protection structure section.

Table 7   Acceptance test loading procedure.

Load step increment N_j ($j = 0 \div 5$)	Hold time	Stressing Jack pressure S_{pj}	Measured movement Strand 1 ($\Delta 1$)	Measured movement Strand 2 ($\Delta 2$)	Measured movement Strand 3 ($\Delta 3$)	Measured movement Strand 4 ($\Delta 4$)
Unit	Minute	Bar	mm	mm	mm	mm
$N0 = 0.1Pp$	Until stable	30	90.0	102.0	89.0	89.0
$N1 = 0.2Pp$	1 min, 2 max	60	95.0	110.0	93.0	93.0
$N2 = 0.4Pp$	1 min, 2 max	120	110.0	122.0	105.0	108.0
$N3 = 0.6Pp$	1 min, 2 max	180	132.0	142.0	125.0	129.0
$N4 = 0.8Pp$	1 min, 2 max	240	153.0	163.0	145.0	150.0
$N5 = 1.0Pp$	1 min, 2 max	300	195.0	207.0	187.0	197.0
$N5 = 1.0Pp$	15	300	196.0	208.0	188.0	199.0
$N4 = 0.8Pp$	1 min, 2max	240	189.0	197.0	180.0	190.0
$N3 = 0.6Pp$	1 min, 2 max	180	177.0	185.0	172.0	181.0
$N2 = 0.4Pp$	1 min, 2 max	120	161.0	170.0	156.0	165.0
$N1 = 0.2Pp$	1 min, 2 max	60	146.0	154.0	140.0	148.0
$N0 = 0.1Pp$	Until stable	30	144.0	152.0	138.0	146.0

(2) determine the apparent tendon free length L_{app};

(3) ensure that creep movements and/or load loss lies within the allowable limits.

Acceptance test loading procedure for the first row anchorage level −3 m is presented in Table 7. A datum load, $Pa = 10\%Pp$ is applied to minimize 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:

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

where:

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

ΔP = difference between proof load and datum load ($\Delta P = Nj - N_0$ ($N_0 = Pa = 0.1Pp, j = 1 \div 5$));

Δs = measured extension of the anchor tendon under load increment ΔP.

The limits of L_{app} for bond anchors used are:

upper limit: $L_{app} \text{ max} = L_f + L_e + 0.5L_b$ \quad (7)
lower limit: $L_{app} \text{ min} = 0.8L_f + L_e$ \quad (8)

External length L_e is equal to 1 m. Substituting in Eqs. (6)-(8), it is obvious that L_{app} lies inside

acceptable limits, $L_{app} \text{ min} = 9.0$ m $< L_{app} = 11.2$ m $< L_{app} \text{ max} = 18.5$ m.

The creep movement measurements are performed and evaluated in accordance to UNIN 1537 EIT, E.2.4 and E.4.3 [6]. The anchor is loaded from the Datum load, (Pa to proof load, Pp in 5 (minimum is 4) increments) (Table 8). Then the proof load is maintained constant for at least 15 minutes. The increment of anchor head displacement relative to a fixed point is measured at the end of the specified time intervals $3 \div 15$ minutes for proof load Pp. The creep rate determined as a constant displacement rate ks is measured over two time intervals. $ksj = \Delta sj/\log\Delta t$ ($j = 1 \div 6$; $\alpha = 6ks$).

Table 8 Creep test procedure.

Time tj ($j = 1 \div 6$)	$\Delta tj = tj - t1$	Measured movement Strand 1 ($\Delta 1$)	Measured movement Strand 2 ($\Delta 2$)	Measured movement Strand 3 ($\Delta 3$)	Measured movement Strand 4 ($\Delta 4$)	Mean movement $\Delta j = (\Sigma\Delta i/i)j$	Head displacements $\Delta sj = sj - s1$	Displacement rate ksj ($j = 1 \div 6$)
Unit	Minute	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
$t6 = 15$min	12	196.0	208.0	188.0	199.0	197.8	1.2500	1.1583

- - - Upper limit, L_{app} min (min displacement, loading cycle)

— — Lower limit, L_{app} max (max displacement, loading cycle)

—□— Load-displacement curve (loading-unloading cycle)

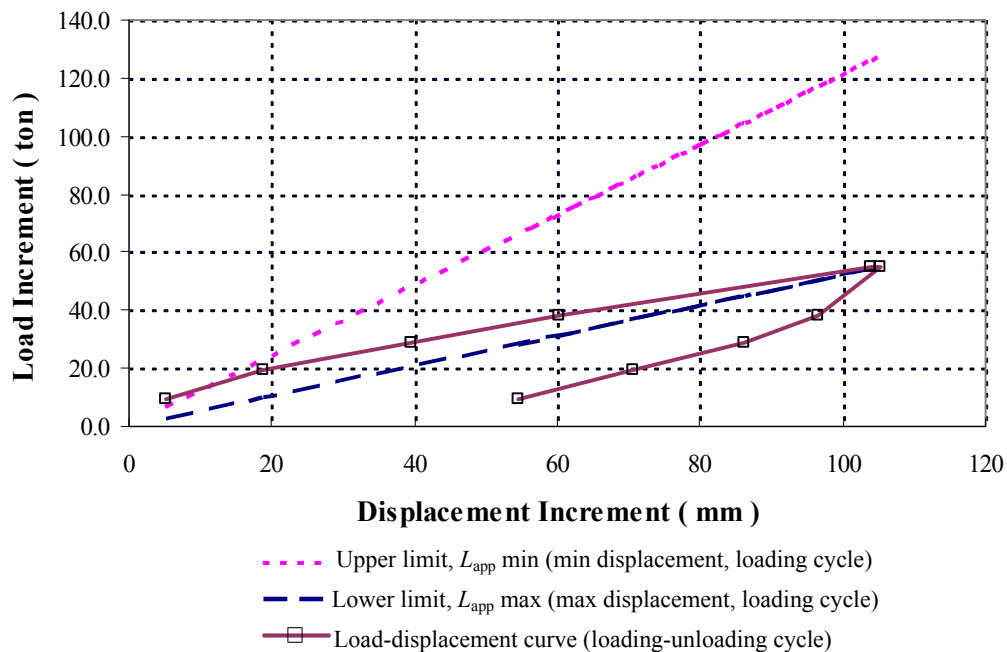**Fig.5 Incremental load-displacement curve**

The maximum creep movement $\alpha = 6ks = 1.1583$ mm < 1.2 mm complies with limits for temporary anchors without investigation tests [5].

The anchor load-displacement curve is presented in Fig. 5.

After the acceptance test is passed each anchor is incrementally loaded up to lock-off value P_0 [7].

7. Conclusions

Anchored continuous diaphragm walls provide:

• a 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, uplift pressures and bottom swelling;

• unobstructed workspace for excavations, clean environment and comfortable conditions inside the pit to expedite the building erection phase;

• feasibility of combining a deep pit protection structure with the permanent structure. Diaphragm walls can easily be designed to carry loads from the permanent structure after removing the tension in the temporary anchors. Diaphragm walls can serve as a watertight element for the permanent structure;

• feasibility of combining ground anchors with horizontal struts to serve as additional support of the diaphragm wall and prevent horizontal displacements of the surrounding structures;

• flexible positioning and inclination of the anchors to avoid existing underground structures in the vicinity of the excavation;

• reduced construction time;

• flexible solution for the temporary anchors that do not satisfy acceptance criteria. Those anchors can be replaced or re-grouted;

• flexible section shapes other than conventional straight sections like the T-section, L-section, etc.;

• minimum noise and vibration levels, which make construction suitable in urban areas.

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

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