Analysis of the geotechnical anchor load transfer mechanism

L'analyse du mécanisme de transfert de chargement d'ancre de geotechnical

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ABSTRACT: Regular assumption in everyday engineering practice is that the contact bond stresses are even along the anchor. The results of instrumented anchor show that the mentioned distribution is highly nonuniform. The numerical procedure is presented which allows a safe and quick assessment of geotechnical anchor ultimate capacity, obtaining the distribution of all important statical values along the fixed anchor length (force, bond stresses, displacements).

RESUME: La supposition régulière dans la pratique construisant de tous les jours est que les tensions de lien de contact sont même le long de l'ancre. Les résultats d'exposition d'ancre de instrumented que la distribution mentionnée est extrêmement nonuniform. La procédure numérique est présentée qui permet une évaluation sûre et rapide d'ancre de geotechnical la capacité ultime, obtenant la distribution de toutes valeurs de statical importantes le long de la longueur d'ancre fixe (la force, les tensions de lien, les déplacements).

1 INTRUDUCTION

During last ten years in the urban areas of Croatia, a diaphragm walls strenghtened by geotechnical anchors of great ultimate capacity is often used while executing deep building pits. Due to the large nearness of nearby structures it is very important to sufficiently accurate predict the ultimate capacity of geotechnical anchors, but also to anticipate the displacements of the diaphragm wall. The overload of the geotechnical anchors can cause a collapse of the bearing structure, while the unanticipated amount of displacements can result a inconvenient distribution of load on the construction and finally an overload of maximum inner forces in the construction. The initial defining (and sometimes the final) of the ultimate bearing capacity of geotechnical anchor T is lead by using the simple expression that contain the geometrical amounts of the anchorage zone length L, its unit area A and mean bond stress τ Littlejohn (1980), Canadian Foundation Engineering Manual (1992).

$$T = A \cdot L \cdot \tau \tag{1}$$

From the expression (1) it is notable that the ultimate capacity of geotechnical anchor is directly proportional to the anchorage zone length for the same conditions of anchor execution. The results of the field and laboratory tests conducted by various authors Ostermayer, Scheele (1978), Weerrasinghe, Littlejohn (1997) show that the bond stresses are nonuniform for the whole span of outer tensile forces value. That is the reason why it is necessary to determine the real mechanism of force distribution, displacement and bond stresses along the anchor in order to economically design the anchor with a large enough safety factor.

2 ANALYSIS OF THE BOND STRESSES

For the smaller force amounts the ultimate bond stress is on the proximal end, while it falls towards the distal end of the anchor. By progressively increasing the tensile force, the location of the ultimate bond stress translates toward the distal end of the anchor, which is the consequence of progressive debonding of the anchor. This behavior can be explained with the competent curve bond stress – displacement (τ-u diagram) on the contact of the anchor body and surrounding soil. At the smaller force amounts only the initial end of anchor is in the area of peak amounts of bond stresses, while the displacements and bond stresses in the end of the anchor are relatively small. By progressively increasing the outer tensile force a redistribution of stress along the anchor takes place. The edge displacements of the anchor dictate the distribution of bond stresses along the anchor Somerville (1981). The ultimate bearing capacity of the anchor is then proportional to the area under the τ-u diagram between to edge displacements. For the short anchors, due to their great stiffness, the difference of edge displacements are small, therefore almost the whole anchor length is in the area of ultimate stress. In case of longer anchors, the displacement of the point where a force is brought is big, in the area of residual stresses, while the displacement of the distal end is for the bond stress, which is between the peak and residual stresses. A qualitative distribution of edge displacements and bond stresses along the length of anchor for the long and for the short anchor for the ultimate anchor force capacity is shown on Figure 1.

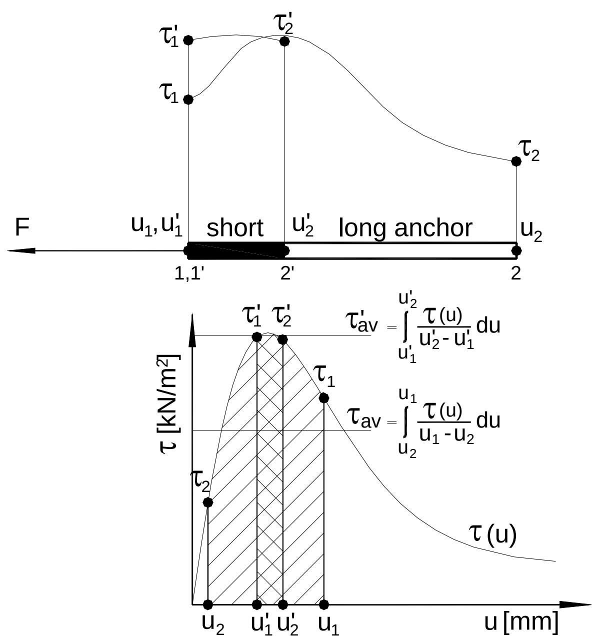

Figure 1. Displacements and bond stresses on the fixed anchor zone for short and long anchor.

The problem of calculating the distribution of bond stresses along the fixed anchor zone can be solved using the finite elements method. The so called *interface* elements on the contact part of the anchor body and the surrounding ground have in themselves embedded various constitutive relations which allow solving a wide spectre of problems Woods, Barkhordari (1997). However, such sophisticated analyses have not yet become a practical solution for problems in everyday engineering practice. The proposed process of calculating the force distribution, displacement, and bond stresses along the fixed anchor length will be presented, which can fill the void between the rough calculations, based on crude empirical knowledge, and sophisticated analyses, for which one must have the appropriate exactness of input parameters. The proposed method can be easily implemented in a spreadsheet and used to predict the distribution of all static quantities and of course the ultimate capacity of the ground anchor.

3 PROPOSED NUMERICAL PROCEDURE

The basic assumptions of the proposed procedure are the following:

- the tendon and surrounding cement injection mixture work uniquely, without relative displacements, which means the surrounding mixture deforms elastically, just like iron, with possible appearance of radial micro-cracks in the mixture, but without influencing the distribution of stresses and displacements,
- there is a defined cylindrical body of injection mixture which is in contact with surrounding intact ground,
- at the contact of the cylinder with the surrounding ground, where a normal pressure acts, the relationship τ-u is known.

The unknowns in this model are defined as three statical values: force F, displacement u, and bond stress τ along the fixed anchor zone. Based on the mutual dependency of each of the three statical values, it is possible to construct the equations to be solved by iteration in the finite number of points. It can be written for point i of anchor zone for relations between the unknown values:

$$F_i = F - \left(\frac{\tau_1}{2} + \sum_{j=2}^{j=i-1} \tau_j + \frac{\tau_i}{2} \right) d\pi\Delta x \tag{2}$$

$$u_i = \sum_{j=n}^{i} F_j \frac{\Delta x}{EA} = \frac{\tau_i}{K_i} \tag{3}$$

Equation (2) represents the magnitude of the force in point i after the bond stresses have been activated on the interface of the anchor zone to the point in question. The left part of equation (3) is the condition of deformation, while the entire equation (3) represents the condition of compatibility of the displacement of the tendon and the anchor zone envelope. Values K_i are secant modules in diagram τ-u. In the first iteration step, the values K_i are equal for all points, and meant as a tangent module for the nil-displacement on the given curve τ-u. In all the other steps, they are equal to the values reached in the previous step of the calculation. When values K_i are known the problem can be reduce to determining the force vector along the anchor zone via the relations given by (2) and (3). Using (3), the bond stresses τ_i can be expressed as a function of unknown forces Fj, where $j=n, \ldots, i$. It follows for point i:

$$\begin{aligned} F_i &= F - \left(\frac{\tau_1 + \tau_2}{2} + \frac{\tau_2 + \tau_3}{2} + \ldots + \frac{\tau_{i-1} + \tau_i}{2}\right) d\pi\Delta x \\ &= F - \left(\frac{1}{2} K_1 \sum_{j=1}^{n} F_j + K_2 \sum_{j=2}^{n} F_j + K_3 \sum_{j=3}^{n} F_j + \ldots + K_{i-1} \sum_{j=i-1}^{n} F_j + \frac{1}{2} K_i \sum_{j=i}^{n} F_j \right) \frac{d\pi\Delta x^2}{EA} \end{aligned} \tag{4}$$

The procedure analogue to the one just shown can be done for all discrete points, and the system of algebraic equations obtained by this method can then be shown as a matrix:

$$[B]\ \{p\} = \{f\} \tag{5}$$

where are:

$[B]$ is a non-dimensional matrix
$\{p\}$ is the vector of tensile forces along the anchor F_i, $i = 2, \ldots n$,
$\{f\}$ is the vector of external tensile forces.

Values for forces F_2 to F_n along the anchor are obtained by solving the system (5), which, along with the known forces $F_1 = F$ give the distribution of external force on the fixed anchor. When external forces are also known, equation (3) is used to calculate the displacement along the anchor. Knowing the displacement values allows us to calculate bond stresses via the adopted relation τ-u, and the values of new secant modules K_i, which we use for further calculations. Iteration for the increment of load force ends when the difference between two consecutive steps is smaller than that of the given criterion.

4 RESULT OF THE INSTRUMENTED ANCHOR AND BACK ANALYSIS

The results of the instrumented fixed anchor length of the diaphragm wall used for erecting the Branimir Centre in Zagreb (2001) are shown in Figure 2. It is apparent from Figure 2. that gradually increasing external tensile force brings on the change in line slope along the anchor. This means the values of bond stresses along the anchor will be changing which is shown in the Figure 3.

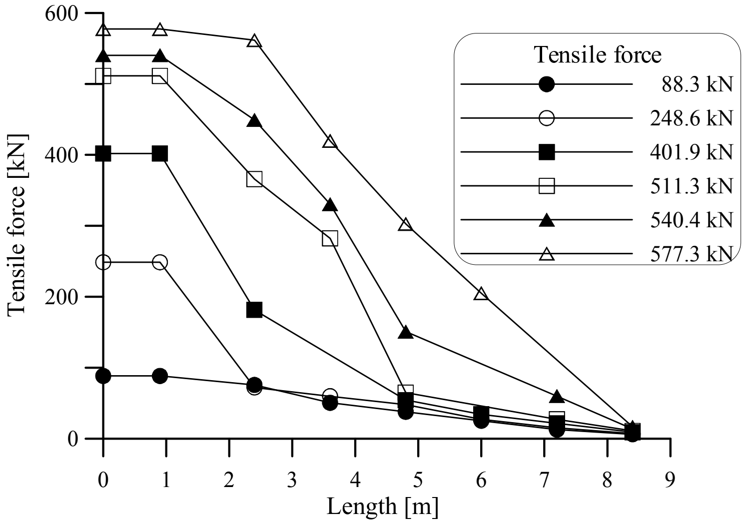

Figure 2. Distribution of the tensile force along the anchor.

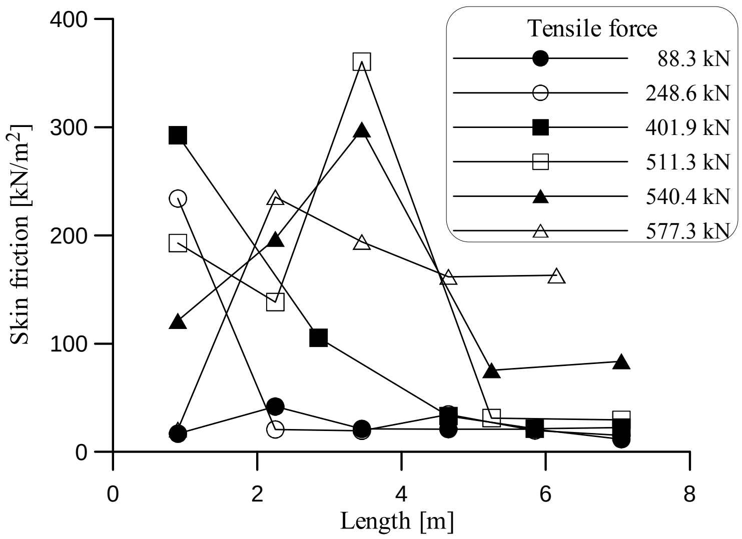

Figure 3. Distribution of the bond stresses along the anchor.

Figure 3. shows the ultimate value of bond stresses translated toward the distal end of the anchor. In this way the stronger force means a gradual widening of the zone with higher values of bond stresses along the anchor. Distribution of bond stresses is visibly nonuniform. Activation of the entire anchor length is possible at a relatively high force with value 401.9≅0.7x577.3. When using smaller value of the force, the anchor with observed length of anchor zone of 8.0 m is effectively unloaded.

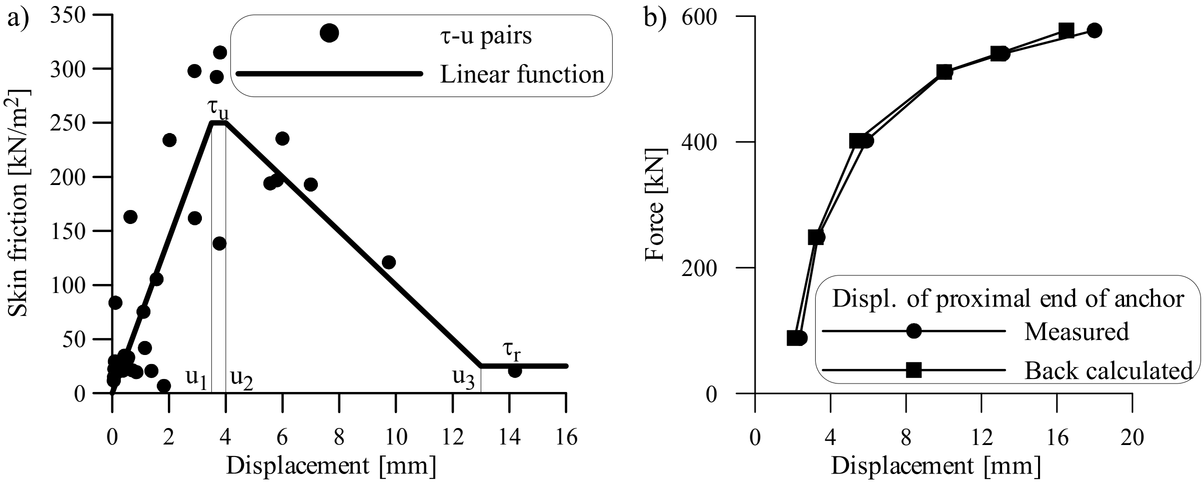

Figure 4.a) Pairs of τ-u and linear approximation and Figure 4.b) Computed and measured displacements of the proximal end of anchor.

Using Figure 2. and Figure 3. it is possible to arrange the pairs of displacements and bond stresses in observed anchor points, as is shown on Figure 4.a) At the same figure is also shown the linear approximation of these points used in further analysis. Back analysis gives the following values of curve *τ-u:* τ_u = 250 kN/m^2, τ_r = 25 kN/m^2, u_1 = 0.035 m, u_2 = 0.040 m and u_3 = 0.13 m. From Figure 4.b) it can be seen the goog agreement of the measured and back calculated displacements of the proximal end of the anchor zone.

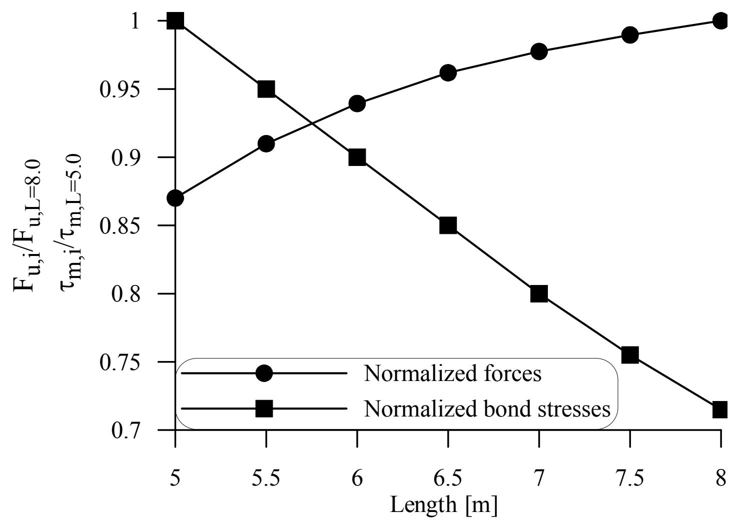

Figure 5. Parametar analysis of the influence of the fixed anchor zone length on the anchor ultimate capacity and the mean bond stress.

When the rule for activation of bond stress as a displacement function is known, the analysis of the optimal choice of anchor length can be made. By varying lengths of anchor zone, it is possible to determine the anchor ultimate capacity and give recommendations about possible changes to anchor length. In Figure 5. is shown normalized ultimate forces and normalized average values of bond stresses τ_m values of anchor for various anchor lengths. It can be seen that there is no drastic lowering of anchor ultimate capacity if the anchor gets shortened, while the average values of bond stress change considerably. This anchor behaviour is a result of numeric values of the residual and peak stresses τ_r / τ_u quotient, in this case equalling 25/250 =0.10. Shorter anchor results in higher relative ratio of anchor part with ultimate value of bond stress and total length of anchoring. For higher values of quotient τ_r / τ_u there will be a higher decrease of ultimate anchor force for equal shortening of anchoring length, because of lower average bond stresses.

5 CONCLUSIONS

Distribution of bond stresses along the anchoring section is highly nonuniform, which applies to all values of external tensile forces. Deviation from uniform distribution grows with the length of anchoring zone and the difference between peak and residual values of bond stresses in calculation curve *τ-u*. Maximum force and displacement are activated at the proximal end of anchor, and gradually decrease toward the distal end because of bond stresses having an effect on the contact of injection mass with the surrounding ground. At small external forces (in relation to the anchor ultimate capacity), force is exerted only on a part of anchoring zone. Increasing force on the limits of anchor ultimate capacity results in activation of whole anchoring section along with displacement of bond stresses toward the distal end of the anchor.

The results of back analyses made by proposed numerical procedure show the importance of correct assessment of relations *τ-u* on the contact of anchor body with surrounding ground. Using the regular assumption of uniform bond stresses along the anchoring section often leads to irrational solutions, especially when using long anchors. In such cases there is an activation of residual bond stresses along a sizable portion of the anchor, and the value of mean bond stress is lower than in the case of shorter anchoring section.

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