Proposed Safety Strategy for Soil/Rock Anchors

By
Eliezer Shamir civ. eng.
Partner, Shamir Posner Brown Cons. Eng. Ltd.
Professional member of PCI, ACI, IABSE, Prestressed concrete group at Israel Asso. of Engineers and Architects, member of several Standard Committees regarding bridge design, seismic design, reinforced concrete, and Prestressed concrete, in Israel Inst. of Standardizations

1. Introduction

Soil (or rock) anchors are used widely as a mean for stabilizing open - steep excavations adjacent to existing structures. Anchors can be either prestressed or non-prestressed, temporary of permanent, rod-type or cable - type, depending on the main task of the anchor.

The design procedure should adopt proper safety factors taking into consideration the following aspects:

* Main task of the anchor.
* Its life expectancy.
* Its pull out capacity at ultimate limit state.
* Its elastic behavior at service limit state.
* Strength of materials and anchor components at ultimate limit state.
It is suggested here that the same methodology of partial safety factors used today in all reinforced concrete standards following the EC, should be adopted in this case. This approach will contribute to better understanding of the materia, i.e.: better modeling of the interrelationship of soil/anchor/structure as one integral composite system.

As a result, a clear distinction between service and ultimate limit states, can be achieved, for global stability (external equilibrium), and strength of all various anchor components - (internal forces), as well as for anchoring capacity of the integral system (pull-out forces).

The integration of all partial safety factors, relevant to the said task of anchor, and with respect to its designed life expectancy, will compose the final and total safety factor of the system.

2. **Anchor categories with respect to their tasks**

Two main categories of anchors can be designated with respect to their main task:

* Anchors that allow some limited movement of the anchored mass - (a) ahead.
* Anchors that prevent any significant movement - (b) ahead.

(a) Anchors that enable soil or rock movements but prevent collapse, is usually the case of anchors used for slope stability, rock stability, and steep or vertical excavation stability.
In this case there is no importance whether limited lateral movements occur, as long as these do not cause local stability damages, or collapse, to the soil (or rock), as well as to the retaining (or shoring) structure itself. It is needless to say that these anticipated movements should not affect any neighboring structure, or facility, such as underground piping, system of cables, tunnels, manholes, etc.

Anchors can be either non-prestressed (using steel rods and anchor plates), or prestressed to limited extent (using steel rods or cables, and anchor plates).

(b) Anchors that prevent any possibility of lateral movement, is usually the case of anchors used in shoring or retaining walls, that are close to neighboring structures, of any kind, or to underground facilities, that can be affected and damaged by lateral movements or due vertical settlements of their subsoil or surrounding soil.

In this case the anchor provides the required confinement to the soil, as to ensure that no vertical settlement, due to lateral movement, occurs.

This is also the case of stabilizing steep excavations in rock, where large rock blocks gain their stability mainly by friction in vertical planes (cracks), rather then being directly supported, or while maintaining enough friction in horizontal planes.

In such conditions, even small sliding of the block might cause a significant loss of the mutual interlocking between neighboring blocks, and further loss of stability after stress release in the rock.

The anchor provides here a tie-back of the loose block to the stable rock mass.

In all these cases, anchors will always be fully prestressed (using either steel rods or cables, and anchor plate).
3. **Anchor categories with respect to life expectancy**

Two categories of anchors can be designated with respect to their life expectancy.

* Temporary anchors.
* Permanent anchors.

Temporary Anchors are defined as those that will act, as such, not more than 2 years, regardless if they will be removed at a later stage or remain in place afterwards.

All other anchors will be considered as Permanent Anchors.

4. **Safety factors for working loads**

Safety factors for loads should take into account the following:

(a) Uncertainties of the static analysis with respect to soil (rock) parameters, soil pressure distribution, probability of live loads and its magnitudes.

(b) Main task of the anchor (moveable or non-moveable anchoring).

The general case for the total load safety factor is:

\[ \gamma_{LT} = \gamma_L \cdot \gamma_n \]

Where \( \gamma_L \) is the net load factor, representing (a) above, and \( \gamma_n \) is a behavior factor representing (b) above. Reasonable values for \( \gamma_n \) are:

\[ 1 \leq \gamma_n \leq 1.5 \]
and should be established by the designer, taking into consideration the importance of anchor fixity in the relevant situation.

$\gamma_n = 1.0$ will be used in the case that limited movement is allowed as per clause 2 (a) above.

$\gamma_n = 1.25 - 1.5$ will be used where no movement is allowed as per clause 2 (b) above.

The maximal value of $\gamma_n = 1.5$ will be applied only in the case that major damages are anticipated due to slight movement, of the anchoring device.

Following FIP recommendations, $\gamma_L$ values for the ultimate limit state will be:

For Temporary Anchors: $\gamma_L = 1.6$
For Permanent Anchors: $\gamma_L = 2.0$

Therefore, the design load at ultimate limit conditions is:

\[ S_d = \gamma_L T \cdot S \]  \hspace{1cm} (2)

Where:

$S$ - actual calculated (or applied) load on anchoring device.

The anchor will be stressed up to its working load, which is:

\[ S_w = \gamma_n \cdot S \]  \hspace{1cm} (3)

$S_w$ is, therefore, the design load at the service limit state.
5. **Safety factors for mechanical strength of anchoring device**

The relationship between actual loads and designed strength, involve safety factors representing loads on one side, and materials properties on the other side and should be kept as:

\[
S_d = \gamma_{LT} \cdot S \leq \frac{S_k}{\gamma_m}
\]

Where:

- \(\gamma_{LT}\) - total load safety factor
- \(\gamma_m\) - material safety factor
- \(S\) - applied load on anchoring device (or one of its components)
- \(S_k\) - characteristic breaking strength of anchoring device (or one of its components)
- \(S_d\) - design value at ultimate limit state

\(\gamma_m\) factors should comply with the various national standards. In Israel \(\gamma_m = 1.15\) with respect to the 0.1% strength of the pre-stressing steel.

6. **Safety factors for anchoring capacity (pull-out capacity)**

The anchor pull-out capacity is governed mainly by the following parameters:

* Size and shape of the anchor “capsule” (length, diameter, and bulb).
* Soil parameters.
* Location of the fixed part of the anchor (“capsule”) outside the sliding soil wedge, and its depth, measured down from ground surface.
* Bond between anchor fixed part and surrounding material.

The forces applied to the anchor device, are transmitted from the fixed part of the anchor (“capsule”) to its surrounding material (rock or soil), by means of bond/friction mechanism.
Therefore, the pull-out capacity depends strongly on the grout materials, technique and performance, and soil (or rock) stability in the borehole, its cracks, porosity, shear strength and adhesion to grout material.

As long as this interconnection between ground and anchor does not fail, the overwhole stability of the anchoring device is maintained by its ability to transmit the loads to a larger stable ground mass, assumed to have a shape of an inverted cone, which serves as the anchoring block. The size of this cone should be large enough, as to provide sufficient weight, and sufficient shear strength to be able to counteract the applied load.

Pull-out capacity of an anchor will be therefore, the lower of:

(a) Bond/friction capacity between the capsule and the surrounding ground, and:

(b) Inverted cone shear failure.

Since it is common practice to execute anchorages, either vertical, or steeply inclined downwards, the bond/friction mechanism, (a) above, will determine the anchorage pull-out capacity, in most cases, of anchoring in soil, where there is no end bulb.

On the other hand, in cases of anchors in soil where an end bulb do exist, as well as the case of anchors in rock, both cases of failure should be checked.

Soil and rock mechanics methodologies will be used to determine the characteristic pull out capacities, and these are beyond the scope of this article.

But in order to demonstrate the design procedure, the case of bond/friction failure will be detailed below.
Pull-out characteristic strength of an anchor without an end bulb, can be assessed using the formula:

\[ P_K = \pi \cdot D \cdot L \cdot \tau \] (in rock)

Or:

\[ P_K = (\gamma \cdot d \cdot K \cdot \tan \phi + Ca) \cdot \pi \cdot D \cdot L \] (in soil)

Where:

- \( P_K \) - characteristic pull out strength
- \( D \) - diameter of the “capsule”
- \( L \) - length of “capsule” (bond length)
- \( \tau \) - characteristic bond between capsule grout and surrounding rock
  \( \tau = 0.3 \left( f_{ck} \right)^{\frac{1}{2}} \), where \( f_{ck} \) is the characteristic concrete strength (MPa).
- \( \gamma \) - unit weight of soil (in case of buoyancy: use \( \gamma_{sub} \))
- \( \phi \) - internal friction angle of soil (characteristic value)
- \( d \) - depth of capsule below surface
- \( K \) - lateral soil pressure constant. In case of injected grout use \( K_o \) (at rest), otherwise, use \( K_a \) (active conditions).
- \( Ca \) - soil/grout adhesion (use app. 80% of soil cohesion)

To derive the design pull-out capacity, at ultimate limit state, proper \( \gamma_m \) safety factors should be applied to the soil properties.

EC-7 calls for the following \( \gamma_m \) values:

<table>
<thead>
<tr>
<th>( \tan \phi )</th>
<th>( C )</th>
<th>( Cu )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.25</td>
<td>1.6</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Where:

- \( C \) - cohesion (characteristic value)
- \( Cu \) - untrained shear strength (characteristic value)
since bond between grout and rock will be mainly governed by the grout (concrete) properties, it is proposed here that a value of $\gamma_m = 1.85$ will be incorporated in this case.

A reasonable estimate for bond design strength at ultimate limit state is:

$$\tau_d = 0.3 \left( \frac{f_{ck}}{1.85} \right)^{\frac{1}{2}}$$

Accordingly, the design pull-out capacity of the anchor at ultimate limit state becomes:

$$P_d = \pi \cdot D \cdot L \cdot 0.3 \left( \frac{f_{ck}}{1.85} \right)^{\frac{1}{2}} \text{ (in rock).}$$

(Note: $f_{ck}$ in Mpa)

$$P_d = (\gamma \cdot d \cdot K \cdot \frac{\tan \varphi}{1.25} + \frac{Ca}{1.6}) \cdot \pi \cdot D \cdot L \text{ (in soil)}$$

To fulfill the required safety factor for bond/friction failure, one must keep

$$P_d \geq S_d = \gamma_{LT} \cdot S$$

It is clearly seen above that although soils are much less homogenic and isotropic than structural steel, or even concrete, $\gamma_m$ values for soil parameters are significantly smaller, and this calls for an explanation.

Since EC-7 uses Constant values of $\gamma_m$ as said above the characteristic values for $\varphi$, $C$ and $Cu$ above, must be clearly defined. According to EC-7 selection of the characteristic values of soil and rock properties will be based upon results of laboratory and field tests, and account be taken of possible differences between properties measured in the tests, and the properties governing the behavior of the geological structure due to the following:

(a) Geological and other background information, such as from previous projects.

(b) Variability of properties values.
(c) Extent of the zone of ground governing the behavior of the geotechnical structure at
the limit state being considered.

(b) The influence of workmanship on artificially placed or improved soils.

(e) The effect of construction activities on the properties of in-situ ground.

Special attention should be paid to (a) above, because this is the difference between
characteristic strength of soil properties, and characteristic strength or reinforced concrete
or steel structures. The latter involve only strength values that are results of standard tests,
and do not involve any personal previous experience of the designer, which is much less
objective criteria. This is the reason why values of $\gamma_m$ for soil are smaller than those of
concrete; it is because a certain part of the total $\gamma_m$ of the soil in already included in the
characteristic value due to (a) above.

One of the main objectives of this paper is to establish a common language for structural
engineers and soil consultants. Therefore, characteristic strength values of soil, as well as
steel and concrete, should be selected, based on the same grounds.

It is proposed that characteristic values of soil will be selected according to laboratory and
field tests, only, and without taking account of (a)-(e) above, while increasing the total
$\gamma_{mt}$ value up to app. 3.0.

It will be much simpler to use a total $\gamma_{mt} = 3.0$ factor for the entire characteristic relevant
strength of the soil, rather than separate values for $\tan \varphi$, $C$ and $Cu$.

This approach leads to the modified expression which is recommended here for this case:

\[
(9)^* \quad P_d = \frac{P_k}{\gamma_{mt}} = \frac{1}{3} (\gamma \cdot d \cdot k \cdot \tan \varphi + Ca) \cdot \pi \cdot D \cdot L
\]

in this expression: $k$, $\tan \varphi$, and $Ca$ are the ultimate limit state values.
7. **Proof load safety factor**

It is the common practice to check each pre-stressed anchor by over-stressing it temporarily up to a proof load.

According to Fip recommendations factors of $\gamma_p = 1.25$ and $\gamma_p = 1.5$ will be applied to the working load in case of temporary anchors and permanent anchors, respectively, to establish the appropriate proof load.

Therefore, proof load becomes:

(11) \[ S_p = \gamma_p \cdot \gamma_n \cdot S \]

where $\gamma_p$ is the appropriate proof load factor, and $\gamma_n$ is the behavior factor.

Since the proof load condition is, by definition, a temporary one, checking the ultimate limit state safety, will involve a reduced value for the $\gamma_L$ safety factor.

It is easy to show that, as long as the equilibrium condition of the mechanical strength of anchor components, at the ultimate limit state, as per (4) above, is fulfilled, a partial load safety factor of $\gamma_L = 1.33$ is guaranteed for the proof load of permanent anchors, and $\gamma_L = 1.28$ for temporary anchors, provided $\gamma_p$ will not exceed the values recommended above. Therefore, in this case, the ultimate limit state safety as per clause 5 above will suffice.
In case the $\gamma_p$ factors do exceed the recommended values, the ultimate limit state of the mechanical strength of anchor, at proof load conditions, should be checked, providing $\gamma_L = 1.30$ load safety factor using the formula:

(12) \[ S_{pd} = \gamma_L \cdot S_p \leq \frac{S_k}{\gamma_m} \]

This value will deviate by only app.2% from the guarantied safety values mentioned above.

7. **Summary**

Design of anchors using the partial safety factor methodology involves checking of several modes of failure, at the ultimate limit state.

for each mode, the equilibrium condition of the failure mechanism should be fulfilled.

Applied loads should be multiplied by the appropriate load factors $\gamma_L$, and behavior factors $\gamma_n$, while characteristic magnitudes of the resisting forces and pull-out capacities will be divided by the appropriate material factors $\gamma_m$.

(a) Pull out capacity – over-whole equilibrium at ultimate limit state:

(13) \[ \gamma_L \cdot \gamma_n \cdot S \leq P_d \]

(b) Anchor breaking strength - internal forces equilibrium of the ultimate limit state:

(14) \[ \gamma_L \cdot \gamma_n \cdot S \leq \frac{S_k}{\gamma_m} \]

(c) Proof load safety - internal forces equilibrium of the ultimate limit state:

(15) \[ \gamma_L \cdot S_p \leq \frac{S_k}{\gamma_m} \quad \text{(where} \quad S_p = \gamma_n \cdot \gamma_p \cdot S \text{)} \]

A summary of the various partial safety factors is listed in the table below.
<table>
<thead>
<tr>
<th>Safety Factor Type</th>
<th>Parameter to be Multiplied</th>
<th>Safety factor values</th>
<th>Proof Load Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Temporary Anchor</td>
<td>Permanent Anchor</td>
</tr>
<tr>
<td>( \gamma_L ) load factor</td>
<td>Actual load</td>
<td>1.6</td>
<td>2.0</td>
</tr>
<tr>
<td>( \gamma_n ) Behavior factor</td>
<td>Actual load</td>
<td>Limited movement allowed:</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>No movement allowed:</td>
<td>1.25-1.5</td>
</tr>
<tr>
<td>( \gamma_{mT} ) material factor for soil/rock</td>
<td>( P_k )</td>
<td>( \frac{1}{3} )</td>
<td>( \frac{1}{3} )</td>
</tr>
<tr>
<td>( \gamma_m ) Material factor for steel and concrete</td>
<td>( f_s )</td>
<td>( \frac{1}{1.15} )</td>
<td>( \frac{1}{1.15} )</td>
</tr>
<tr>
<td></td>
<td>( \tau ) (Bond between anchor steel and capsule concrete)</td>
<td>( \frac{1}{1.85} )</td>
<td>( \frac{1}{1.85} )</td>
</tr>
<tr>
<td>( \gamma_p ) Proof load Factor</td>
<td>Actual load</td>
<td>1.25</td>
<td>1.5</td>
</tr>
</tbody>
</table>