The influence of bond stress distribution on ground anchor fixed length design. Field trial results and proposal for design methodology

L'influence de la répartition des contraintes sur les tirants d'ancrage de longueur fixe. Résultats de planche d'essais et proposition de méthodologie de conception

Vukotić G.
Kellerterra, S.L.

González Galindo J., Soriano A.
Universidad Politécnica de Madrid

ABSTRACT: This paper presents a brief analysis and comparison of different recommendations for a ground anchor fixed length design and a load transfer capacity at grout-ground interface, comparing it with the full scale test results recently carried out in Spain. Simple methodology for ground anchor routine design is proposed, incorporating efficiency factor as a conceptual control of anchor capacity, and fixed length criteria to determine range of application of conventional anchors, with single fixed length unit, or Single Bore Multiple Anchors (SBMA). Ground anchors discussed in this paper are cement pressure grouted, formed by pre-stressed strand tendons that are installed in soil or rock.

RÉSUMÉ: Cet article présente une brève analyse et la comparaison des différentes recommandations pour la conception de tirant d'ancrage de longueur fixe et la capacité de transfert de charge à l'interface coulis-sol, en le comparant avec les résultats d'essais à échelle réelle obtenus en Espagne au cours des dernières années. Une méthodologie simple pour la conception de tirant d'ancrage est proposée; elle intègre le facteur d'efficacité comme un contrôle conceptuel de la capacité de l'ancrage et les critères de longueur fixe pour déterminer le champ d'application des tirant d'ancrage conventionnels, d'unique longueur fixe, ou d'ancrages multiples en un unique forage (SBMA pour ses sigles en anglais). Les tirants d'ancrage décrits dans ce document sont injectés à pression au moyen d'un coulis de ciment et sont formés par un faisceau de câbles d'acier précontraints qui sont installés dans le sol ou la roche.

KEYWORDS: anchor, fixed length, bond stress, efficiency factor.

1 INTRODUCTION

Nowadays anchors represent a key medium to sustain and strengthen slopes formed by instable soils and fractured rocks, and to ensure the stability of various types of gravity structures.

Regarding bond stress and load transfer capacity at the grout-ground interface, most procedures for anchor design are empirical values or formulas derived by local experiences, very difficult to extrapolate for different locations or execution systems. The design procedure is often simplified, considering direct proportionality between fixed anchor length and its load capacity, as it is prevailing practice in Spain and South America.

However, since late 1960s numerous authors demonstrate bond stress or skin friction distribution to be highly non-uniform at all stages of loading, with high bond stress mobilization along reduced fixed length. In the following chapters, based on presented references and analysis of the field trial results recently performed in Spain, the methodology for anchor fixed length design is proposed.

2 DESIGN OF THE FIXED ANCHOR LENGTH

2.1 *Current practice*

Design assumption of uniform load distribution along the fixed anchor length is not only limited to usual methodology and standards in Spain and South America but is internationally generally adopted. Considering this hypothesis the ultimate or capacity of the anchor is commonly expressed as follows:

$$T_{ult} = \pi \cdot d \cdot L_{fix} \cdot \tau_{ult} \qquad (1)$$

where: d = anchor diameter, L_{fix} = anchor fixed length and τ_{ult} = ultimate bond stress.

This formula differs from experimental and theoretical evidence that corroborate that there is no linear dependency of ultimate capacity on fixed anchor length.

2.2 *Non-uniform bond stress distribution*

It is fully acknowledged by numerous researchers that the distribution of stress along the fixed anchor length is non-uniform, both at low stress levels and at failure. This phenomenon results from the general incompatibility between elastic modulus and corresponding deformation of the anchor strands, cement grout and ground.

Field tests on instrumented conventional anchors, reported by Muller (1966), Berrardi (1967), Ostermayer (1974), Ostermayer and Scheele (1977), Mastrantuono and Tomillo (1977), Barley (1995) and Briaud et al. (1998), showed that when applying the initial load the bond stress is concentrated over the proximal length of the fixed anchor, leaving a significant part of the fixed length towards distal end unstressed. By the evolution of the load the bond stress concentration zone is transferred along the fixed anchor as the bond stress along either the tendon/grout or grout/ground interface is exceeded.

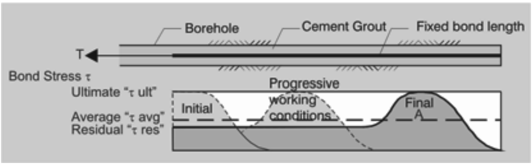

Figure 1. Development of bond stress distribution along a fully bonded fixed anchor length (Barley 1995).

Simultaneously, due to progressive debonding, stress at the proximal end reduces to residual values. The bond stress concentration zone reaches distal end of the anchor just before the failure, as it can be seen in Figure 1.

The same mechanism of a non-linear load and bond distribution was confirmed by laboratory full-scale test accomplished by Weerasinghe (1993). It is also important to mention investigation done by Coates and Yu (1970), which studied stress distribution around a cylindrical anchorage in triaxial stress field using finite element methods. The results emphasize the non-uniform bond stress distribution for the ratio of the elastic modulus of the anchor material (E_A) and the rock (E_R) less than 10 ($E_A/E_R<10$) , which is very common for wide range of rocks and soils in which anchors are usually constructed.

2.3 *Efficiency factor*

There have been a number of attempts to quantify the non-uniform load distribution and to introduce effects of progressive debonding into Formula 1. Casanovas (1989) recommended design based on definition of apparent fixed length (L_{ve}) over which the ultimate bond stress can be mobilized:

$$\mathrm{L}_{\mathrm{ve}} = \left(\frac{L_{fix}}{L_0}\right)^{\frac{1}{\log(0.1\cdot\frac{\tau_{ult}}{\tau_0})}} \cdot L_0 \tag{2}$$

where: L_{ve} = apparent fixed length over which τ_{ult} (kN/m^2) operates, L_0 = reference length of 1 m, τ_0 = reference value of 1 kN/m^2.

To understand better efficiency factor concept it is possible to analyze Figure 1 and to compare area A, that corresponds to the final and maximum load stage, with the total area below τ_{ult}.

$$f_{eff} = \frac{Area.A}{Area.below.\tau_{ult}} \tag{3}$$

Then, ultimate anchor capacity can be expressed as follows:

$$T_{ult} = \pi \cdot d \cdot L_{fix} \cdot \tau_{fix} \cdot f_{eff} \tag{4}$$

Research based on over 60 full scale tests performed on different anchor fixed lengths, installed in wide range of soil (clays, silty clays, sandy clays, boulder clay and glacial till), permitted development of the concept of the efficiency factor (Barley 1995 and 1997, Barley and Windsor 2000). Figure 2 presents the distribution of the values of the efficiency factor (f_{eff}) against anchor fixed length, and the best fit curve can be expressed by following expression:

$$f_{eff} = 1{,}6 \cdot \left(\frac{L_{fix}}{L_0}\right)^{-0{,}57} \tag{5}$$

It is important to emphasize that Barley´s efficiency factor is quite consistent with Ostermayer (1974) diagrammatic presentation of the ultimate medium skin friction against fixed length for similar soil characteristics and anchor construction process, as it can be seen in Figure 2.

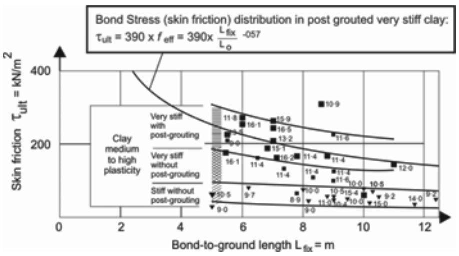

Figure 2. Ostermayer´s (1974) boundary lines vs. Barley´s (1995) efficiency factor.

Barley (1995) also suggested the efficiency factor for sands, correlating efficiency with the fixed length and the friction angle:

$$\mathrm{f}_{\mathrm{eff}} = (0{,}91)^{\frac{\mathrm{L}_{\mathrm{fix}}}{\mathrm{L}_0}\cdot\tan\varphi} \tag{6}$$

One of the most extensive attempts to model construction technique, characteristics and behaviour of anchors have been accomplished by Mecsi (1995), based on analysis of results from numerous installed and monitored anchors.

Analytical solution and simple graphical method based on the theory of expanded cylindrical cavity provide the possibility to define the approximate pull-out capacity. The Analysis of load distribution for the known anchor geometry and rigidity permits determination of the specific pull-out resistance of a 1 m anchor length (t_{ult}) and the length of the fully mobilised bond stress (L_b). Considering that only reduced percentage of maximum bond stress can be mobilised over the remaining fixed anchor length ($L_{fix} - L_b$), the ultimate anchor capacity can be expressed by the following expression:

$$\mathrm{T}_{\mathrm{ult}} = \tau_{\mathrm{ult}} \cdot \left[\mathrm{L}_0 + \frac{1}{\mathrm{k}} \cdot \mathrm{th}\left[\mathrm{k} \cdot (\mathrm{L}_{\mathrm{fix}} - \mathrm{L}_0)\right]\right] \tag{7}$$

$$k = \sqrt{\frac{\tau_{ult}}{E_{steel} \cdot A_{steel} \cdot \Delta_{ult}}} \tag{8}$$

where: k = rigidity index, E_{steel} = steel deformation modulus, A_{steel} = steel tendon area, Δ_{ult} = elongation of the shear strength length ($L_{fix} - L_0$).

Based on data from Ostermayer and Scheele (1997), Woods and Barkhordari (1997) proposed efficiency factor for its incorporation in the expression for ultimate capacity of low-pressured anchors in sand (Formula 10), recommended in BS 8081 (1989), which is a function both of fixed anchor length and friction angle:

$$f_{eff} = \exp(-0.05 \cdot \frac{L_{fix}}{L_0} \cdot \tan\varphi) \tag{9}$$

where: L_0 = reference length of 1 m.

$$T_{ult} = f_{eff} \cdot L_{fix} \cdot n \cdot \tan(\varphi) \tag{10}$$

2.4 *Single Bore Multiple Anchors - SBMA*

This system involves the installation of a multiple unit anchors into a single borehole, with enough short unit lengths to reduce or even to avoid the progressive debonding. Each unit is formed by individual tendon and is loaded with the corresponding unit stressing jack, mobilizing its own capacity independently of other unit anchors.

Application of this system permits the unlimited theoretical total fixed length, while conventional anchors formed by only one unit do not provide beneficial effects in load capacity for fixed length superior to 10 m as is stated by numerous authors and design guidelines or codes.

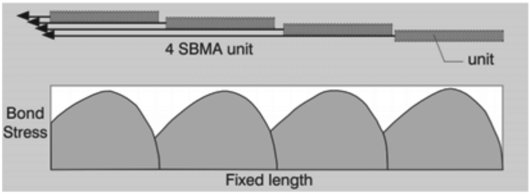

Figure 3. Development of bond stress along a four unit single bore multiple anchor (Barley, 1997).

Total fixed lengths of 10 to 20 m are frequently used in all types of soils, achieving high anchor capacities (2000 to 5000 kN) that are almost three times greater than the normal conventional anchors capacity values (Barley 1997, Barley and Windsor 2000). A comparison of load distribution between conventional and SBMA anchor is presented in Figure 3.

3 GENERAL FIELD TEST DETAILS

The results of full-scale field tests, undertaken to verify the influence of the fixed anchor length on the ultimate capacity (T_{ult}) and the average bond stresses (τ_{ault}) obtained at failure in gravelly sands, silty clays and clayey marl are presented in this chapter.

Investigation test were done according to the Test Method 1 (EN 1537), with incremental load cycles from a datum to ultimate load. The test involved very strict measurement of tendon displacement versus applied load and, at the peak of each cycle, measurement of tendon displacement versus time. Anchors subjected to investigation were high-pressure grouted, designed to fail at grout/ground interface. Field tests were carried out near previously performed boreholes to establish better correlation between obtained data and soil characteristics.

Values of efficiency factor presented in Table 1, 2, 3 and 4 are calculated comparing average bond stresses (τ_{ault}) of SBMA units and conventional anchors, considering that units that formed SBMA anchors with fixed length of 2.5 – 3.0 m were short enough to avoid progressive debonding effects. Due to that hypothesis it can be assumed that efficiency factor for individual units of SBMA anchor have the value of 1.

To avoid possible influences and collaboration of the free anchor length on pull-out capacity and bond stress distribution, fixed units of all test anchors were separated by specially designed compressible joints that prevent load transmission from fixed to free anchor length.

3.1 *Test results in gravelly sand*

The trial anchors, six SMBA with two units (in total 12 units) and two conventional anchors, were executed in dense to very dense gravelly sand, with silt content that varied from 5 to 15%, at depth of 20 to 30 m.

SBMA anchors were formed by two units of 2.5 m fixed length, while conventional anchors had fixed length of 7.5 m. Diameter of all test anchors was of 178 mm. The following table shows ranges of obtained results:

Table 1. Test results for pressure grouted 178 mm diameter anchors in gravelly sands.

Nº/Type of Anc.	L_{fix} m	T_{ult} kN	τ_{ault} kN/m^2	f_{eff}
6 SBMA (12 units)	2.5	780–960	558-687	1
2 Conventional	7.5	1880-1920	445-455	0.65-0.8

It is worthy to mention that values of the obtained ultimate load capacities are very consistent with Ostermayer and Scheele (1978) diagrammatic presentations of the load capacity against fixed length (see Figure 4).

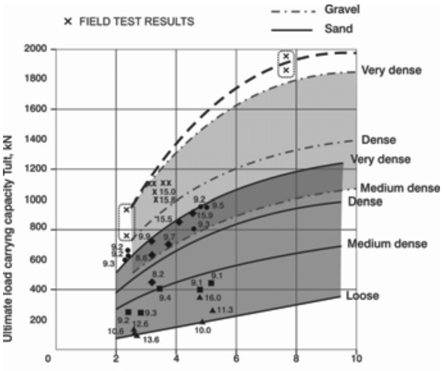

Figure 4. Ultimate load capacity obtained in field test vs. values proposed by Ostermayer and Scheele for sand and gravel (1977).

3.2 *Test results in silty clays*

Table 2 summarizes results for trial anchors, 2 SMBA with two units (in total 4 units) and two conventional anchors, performed in stiff silty clay (CL) at depth of 15 to 25 m. SBMA anchors were formed by two units of 2.5 m fixed length, and conventional anchors had fixed length of 8.0 m. Diameter of all test anchors was of 160 mm.

Table 2. Test results for pressure grouted 160 mm diameter anchors in silty clays.

Nº/Type of Anc.	L_{fix} m	T_{ult} kN	τ_{ault} kN/m^2	f_{eff}
SBMA (4 units)	2.5	400–440	318-350	1
2 Conventional	8.0	915-950	227-236	0.65-0.74

3.3 *Test results in clayey marl*

The trial anchors were carried out in two different sites with similar soil characteristics, stiff to very stiff clayey marl (CH-CI), with sand proportion less than 10%.

3.3.1 *Test site A*

The trial anchors were constructed at depth of 20 m, with diameter of 150 mm. SBMA anchors were formed by two units of 3 m fixed length, and conventional anchors had fixed length of 11 m.

Table 3. Test results for pressure grouted 150 mm diameter anchors in clayey marl – Test site A.

Nº/Type of Anc.	L_{fix} m	T_{ult} kN	τ_{ault} kN/m^2	f_{eff}
2 SBMA (4 units)	3.0	450	318	1
2 Conventional	11.0	785	110-152	0.35-0.48

Results presented in Table 3 demonstrate high inefficacy of fixed anchor lengths longer than 8 or 10 m.

Efficiency factor for 11 m long fixed length obtained comparing average bond stresses varies from 0.35 to 0.48. It is important to emphasize that results feet well with efficiency factor values proposed by Barley (1995), as it can be seen in Figure 5.

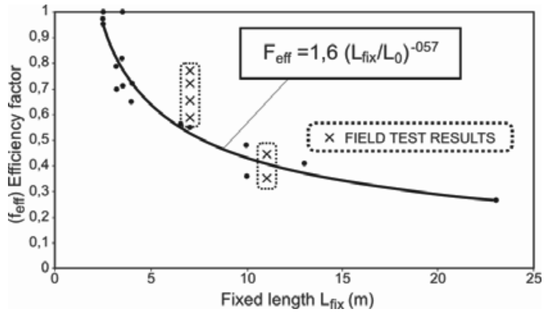

Figure 5. Efficiency factor obtained in field tests in silty clays and clayey marlvs. values proposed by Barley (1995).

3.3.2 *Test site B*

The trial anchors were executed at depth of 30 to 35 m, with diameter of 178 mm. SBMA anchors were formed by two and three units of 2.5 and 3 m, while conventional anchors had fixed length of 7.5 m.

Table 4. Test results for pressure grouted 178 mm diameter anchors in clayey marl – Test site B.

Nº/Type of Anc.	L_{fix} m	T_{ult} kN	τ_{ault} kN/m^2	f_{eff}
8 SBMA (18 units)	2.5	450–540	322-386	1
2 Conventional	7.5	960-1080	230-254	0.59-0.79

3.4 *Summary*

An extensive series of field anchor tests performed in different soils showed that:

- there is no direct proportionality between fixed anchor length and its ultimate load capacity;
- obtained values of the average ultimate bond stresses in cohesive soils fit well with Ostermayer´s (1974) diagrammatic presentation of skin friction against fixed length, while results obtained in gravelly sands fit well with Ostermayers and Scheele (1978) presentation of ultimate load capacity vs. anchor length;
- ranges of obtained efficiency factors are consistent with tendency of values proposed by Barley (1995);
- efficiency factor can be considered as a conceptual control of anchor ultimate capacity;
- fixed anchor lengths longer than 10 m do not contribute significant beneficial effects on capacity.
- SBMA anchors permits construction of high anchor capacities that approach more than two times that of the conventional anchors which utilize long inefficient fixed length.

4 PROPOSAL FOR DESIGN METHODOLOGY

Based on the information presented in previous chapters, proposal for design methodology for cement grouted anchors formed by steel tendons is presented below, considering most important parameters that define its capacity, like: soil characteristics, execution process, ultimate and average bond capacity, fixed length, type of anchors (conventional or SBMA), stress distribution and efficiency factor.

Emphasis is placed on the effects of progressive debonding that cause the non-uniform stress distribution along the fixed length, with efficiency factor as a conceptual control of anchor capacity. Due to the number of parameters that enter the analysis, recommended methodology has an iterative character, as it can be seen in Figure 6. Some of the most important steps of the flow chart are commented below.

Phase I: Evaluation of the site subsoil conditions and relevant properties of in situ soil and rock, as a factor that directly influence steps in the Phase II (construction system and skin friction estimation).

Phase II: For the skin friction estimation it is recommended to use at least two sources, taking into account the concept or formula that will be applied for the anchor design. If pre-design load tests are performed to evaluate ultimate anchor load capacity, construction process has to be exactly the same as planned for production anchors, and fixed lengths should be similar with test anchors.For the first iteration anchor length is calculated considering uniform bond stress distribution (Equation 1). If calculated fixed length is larger than 5 m, construction process can be reconsidered (Alternative A), varying anchor diameter or type of grouting, with objective to reduce fixed length up to 5 m. Other option (Alternative B) is to introduce directly the efficiency factor.

Phase III: If the fixed length obtained considering non-uniformity is in the range between 5 and 10 m, two alternatives are proposed. First alternative considers conventional type of anchor, with unique fixed length unit calculated taking into account efficiency factor (f_{eff}) – Equation 2. Another alternative is the application of SBMA. In this case fixed length of each unit that forms SBMA is calculated considering corresponding efficiency factor (f_{eff}) – Equation 3.

If the fixed length, obtained considering non-uniformity is greater than 10 m it is recommended to apply SBMA anchors.

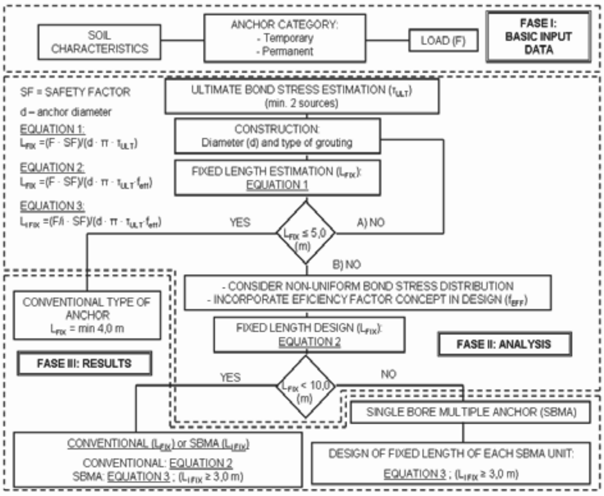

Figure 6. Flow chart for design of fixed anchor length.

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