European practice in ground anchor design related to the framework of EC7

Pratique européenne pour le dimensionnement des tirants d'ancrage en application de l'EC7

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ABSTRACT: EN 1997-1:2004 (Eurocode7, Part 1 - EC7) is the European Standard for Geotechnical Design. Ground anchors are addressed in Section 8 of this standard, EN 1537:1999 (execution)(under revision) and it is planned that testing will be covered by prEN ISO 22477-5. EC7 Section 8 has been little used and is now under revision. Discussions between European experts on ground anchors have highlighted the diversity of current design practices used in different countries. This paper explores this diversity and highlights the variations in the approaches to the design and testing of ground anchors, dealing exclusively with grouted ground anchors which are able to be tensioned. The existing practices of Denmark, France, Germany, Ireland and the UK are considered in relation to the EC7 requirements for verification of ultimate and serviceability limit states. It is shown how the draft now proposed of EC7 for the design and testing of anchors accommodates the approaches currently used in European countries within a single framework.

RESUME : L'EN 1997-1:2004 (Eurocode 7, Par 1 - EC7) est la norme pour la conception des ouvrages géotechniques. Les tirants d'ancrage sont traités dans le chapitre 8 de cette norme, dans la norme d'exécution EN 1537 :1999 en révision et dans le projet de norme d'essais pr EN ISO 22477-5 en cours de rédaction. Le chapitre 8 de l'EC7 bien qu'encore peu utilisé, est en cours de révision. Les discussions entre les experts européens sur les tirants d'ancrage ont mis en lumière la diversité des pratiques couramment appliquées dans les différents pays. Cet article présente cette diversité et montre les différences d'approche tant au niveau de la conception que des essais, en particulier avec les tirants d'ancrage scellés au terrain qui peuvent être mis en tension. Les pratiques existantes au Danemark, en France, en Allemagne, en Irlande et au Royaume-Uni sont présentées selon les exigences de l'EC7 dans le cadre d'une vérification aux états limites ultimes et de service. L'article montre comment le projet proposé pour l'EC7 concernant la conception et les essais des tirants d'ancrage prend mieux en compte et de façon simple approches actuellement utilisées dans les pays européens.

KEYWORDS: Anchors, Eurocode, Standards, Design

1 INTRODUCTION AND HISTORICAL CONTEXT

Ground anchor design as it is today has been derived from many years of field tests, performance monitoring and field scale research, resulting in an empirical approach of anchor performance linked to soil parameters. Early use of anchors included the application of rock bolts for roof stability in Poland in 1918 and later in Czechoslovakia in 1926 to support an inclined shaft. The mining industry led the field in anchoring ground at this stage. Anchors were first introduced into civil engineering in 1934 by the French engineer André Coyne who devised strand anchors in sandstone to allow the raising of the Cheurfas dam in Algeria. The first use of anchors in soil was by Karl Bauer GmbH in Munich in 1958 to tie back retaining walls. The site agent, noting the difficulty in withdrawing steel drill casing developed a system which included 20m bars with 3m bond lengths installed with working loads of 25 tonnes. Development of anchor design accelerated between 1966 and 1969 with the use of anchors in stiff clays, marl, fine to medium sand and chalk (Littlejohn, 1970).

The developing design process was based on observations from field anchor tests taken to failure and long term behaviour of prestressed anchors. Empirical design rules with realistic factors of safety were being produced relating ultimate pull-out resistance to soil properties and anchor dimensions. The relationship between soil parameters and anchor performance was the basis of extensive research between 1970 and 1980, when many of the empirical relationships were developed upon which calculation of anchor/soil bond resistance, creep and multiple interface resistance are based (Littlejohn, 2012).

The methods of designing the anchor to contribute to the overall structural stability of, say, an anchored retaining structure were based on limit equilibrium stability analyses applying linear, active and passive pressure distributions. Where the design required the minimisation of wall displacement, the same approach was adopted using different pressure distributions. With the relatively recent availability of accessible FE approaches these conditions, taking into account the effect of anchor prestress, are examined routinely today.

With the expansion of anchor use throughout Europe, individual countries developed design guides and codes of practice (BS8081, DIN 4125, SIA V 191, TA95 for example) to promote safe design. Inevitably there were variations of design practice between these standards reflecting regional practices. In 1975, the Commission of the European Community initiated an action programme to develop a set of harmonised rules for the structural design of construction works based on Article 95 of the Treaty. This was transferred to CEN in 1989 guaranteeing them the status of European standards. EC7 (EN 1997-1:2004) was subsequently published and is intended to be used as a general basis for the geotechnical aspects of the design of buildings and civil engineering works. The design of anchors is accommodated in Section 8, for which a new draft has recently been prepared, which is referenced as EN 1997-1:2004/prA1, to be published. Alongside EC7 two further standards EN 1537 and prEN ISO 22477-5 have been developed to provide rules for the execution of anchors and the testing of anchors respectively. Whilst EN 1537 has been published for some time and is now the subject of systematic review, prEN ISO 22477-5 has yet to be published.

2 DESIGN REQUIREMENTS OF EC7

The limit state framework adopted by EC7 requires that anchors are designed to ensure that:-

- Neither an ultimate limit state (ULS) nor a serviceability limit state (SLS) occur within the anchored structure or other supported structures.
- That an anchor has the required ULS and SLS resistance corresponding to these limit states.

The requirements of the new draft of Section 8 which are designed to satisfy these limit states for the anchor and structure are discussed in the following section.

2.1 *Ultimate limit state (ULS) design force*

Anchors are required to have an ULS design capacity ($R_{ULS,d}$) to resist not only the force required to prevent an ULS in the anchored structure and supported structure ($F_{ULS,d}$), but also must have the capacity to resist the maximum force that could be transferred to the anchor during its service life ($F_{serv,k}$), with an adequate margin of safety. Thus the design of the anchor must consider the prestress or lock-off force applied and also any additional force attracted to the anchor during its design life. These safety requirements are expressed as Eq. 1 to 3 where γ_{serv} is a partial factor.

$$E_{ULS;d} \leq R_{ULS;d} \quad (1)$$

where $E_{ULS;d} = Max(F_{ULS;d}; F_{Serv;d})$ (2)

$$F_{Serv;d} = \gamma_{Serv} F_{Serv;k} \quad (3)$$

2.2 *Serviceability limit state (SLS) design force*

Anchors are required to have the design capacity ($R_{SLS,d}$) to resist the $F_{serv,k}$ such that the limiting creep or load loss for a SLS are not exceeded. This requirement is not explicitly stated in all countries and may be covered in a ULS requirement. Assuming that the appropriate partial factor for this SLS is unity, this requirement is expressed as Eq. 4.

$$F_{Serv;k} \leq R_{SLS;d} \quad (4)$$

2.3 *Geotechnical ULS anchor resistance*

EC7 requires that anchor tests be carried out to confirm that they have the resistance to satisfy Eq. 1. The value of the ULS resistance, R_{ULS}, is defined as the "value of the resistance of an anchor complying with ultimate limit state criteria". This means that tests must demonstrate that an anchor can provide a certain resistance while satisfying specified criteria of creep or load loss. The pull-out resistance will be greater than the value determined from the test. The design value of $R_{ULS,d}$ and the characteristic resistance ($R_{ULS,k}$) are determined from the minimum $(R_{ULS,m})_{min}$ of measured values ($R_{ULS,m}$) in investigation and suitability tests using the partial factor ($\gamma_{a,ULS}$)and correlation factor (ξ_{ULS}) and Eqs. 5 & 6.

$$R_{ULS,k} = \frac{(R_{ULS;m})_{min}}{\xi_{ULS}} \quad (5)$$

$$R_{ULS;d} = \frac{R_{ULS;k}}{\gamma_{a;ULS}} \quad (6)$$

2.4 *Geotechnical SLS anchor resistance*

In those countries which require that SLS of the anchor resistance be considered, it is necessary to verify that the anchors have at least the capacity to satisfy Eq. 4, satisfying SLS criteria of creep or load loss. Using the same symbols as in 2.3 but with SLS replacing ULS and a correlation factor of unity, the design SLS resistance ($R_{SLS,d}$) and characteristic SLS resistance are given by Eqs. 7 & 8.

$$R_{SLS;k} = \left(R_{SLS;m}\right)_{min} \quad (7)$$

$$R_{SLS;d} = \frac{R_{SLS;k}}{\gamma_{a;SLS}} \quad (8)$$

3 CURRENT DESIGN PRACTICE

The amended Section 8 of EC7 only covers the design of anchors from load tests, hence only this aspect of anchor design is covered in this paper. Calculations using parameters derived from ground tests are considered to be for the estimation of the bond length only, and the design is then verified by load tests.

The discussion on current design practice is not as straightforward as it might appear due to the way anchor forces are determined for particular design situations in some countries and to the current lack of agreement on what precisely constitutes ULS and SLS failure criteria of an anchor. The design aspects include not only whether the SLS or ULS resistance of the anchor is verified but also whether the force used in this verification process is derived from analyses using factored ground properties or using characteristic values.

The derivation of ULS anchor forces is well developed and, for embedded walls, typically involves some type of Limit Equilibrium Analysis, although the use of finite elements is becoming more common. However the design of anchors in some countries is related to the 'working load'. This practice arose from the fact that earth pressures in the SLS condition (unfactored and considering compaction and at rest pressures) are greater than those at failure when the soil strength is fully mobilised, consequently can give rise to greater anchor force. Furthermore, as these are 'working loads', the anchor would be required to satisfy more onerous creep criteria at such loads. However, EC7 requires that in ULS design a more conservative view is taken of the ground strength and resistance, together with unexpected excavations and higher surcharges than considered for SLS and this situation must also be considered.

The methods used in the past to determine SLS forces, which are also called working forces, were very approximate for embedded walls. Typically the length required for ULS was derived by considering the wall as a beam with a length required for ULS, supported at the anchor and by passive earth pressure, on which act the active earth pressures determined using characteristic actions and soil parameters. Other approaches for simple walls were to calculate the anchor force using the characteristic actions and parameters but with the shortened pile length that is required for equilibrium. The advent of finite elements and other methods of analysis has allowed deformations to be considered more realistically thus providing a more reliable estimate of $F_{serv;k}$. The forces required to limit the movement of the structure and the supported ground are considered, including those forces attracted to the anchor after lock-off.

France has perhaps a design practice that can be most easily related to the proposed amendments of EC7 in that a $F_{ULS;d}$ is determined from an ULS analysis of the structure and a 'service load', similar to $F_{Serv;k}$, is also derived using characteristic values of actions and soil parameters. The testing is required to verify that the anchors have the required 'pull-out' resistance to satisfy the ULS requirements, including the required ULS resistance to ensure safety under $F_{ULS;d}$, and that the creep requirements are satisfied under the service load.

Germany also calculates a value of $F_{ULS;d}$, however this value is calculated from characteristic values of the effects of permanent and variable actions, which are termed F_{Gk} and F_{Qk}. The anchor force for proof testing is related to $F_{ULS;d}$ which is the maximum of $1{,}35\ F_{Gk} + 1{,}5\ F_{Qk}$, or 1,35 times the anchor force after lock-off if that is greater. The proof load has to satisfy a limiting creep criterion which is discussed in the following section. The creep criterion is selected to represent a ULS anchor resistance.

The UK currently excludes Section 8 of EC7 from use in that country in its National Annex and requires anchors to be designed to BS8081 'Ground Anchorages'. The design of anchors in that standard is based on the 'working load', T_w, which is defined as 'The safe load of the anchorage'. No guidance is given in the standard as to whether T_w is determined using a ULS calculation or using characteristic values, however the terminology would suggest that it was originally considered to be similar to $F_{Serv;k}$. In practice, it is considered that for embedded walls, T_w is taken as the higher of that obtained using either a limit equilibrium or a bending moment and displacement analysis using appropriate pressure distributions. The proof load is related to T_w, as discussed in the following section, with different creep criteria to be satisfied which can be related to a SLS and to a ULS resistance.

Section 8 has not been specifically excluded in Ireland, nevertheless the practice is generally to adopt the BS8081 testing criteria with T_w based on a calculation using characteristic actions and parameters. However, given the general lack of specific guidance in this area prior to the publication of the amended Section 8, some designers also considered the value of $F_{ULS,d}$ in the selection of T_w if that gave a greater value.

Denmark uses the present EC7, section 8. The anchor force is based on a ULS design force found from a calculation of the anchored structure with factored soil parameters. Some Danish designers compute a service load ($F_{Serv;k}$),which considers prestress/lockoff of the anchor. This force is such as to resist a ULS if $F_{Serv;k}$ is greater than $F_{ULS;d}$. This means that $E_{ULS;d} = F_{Serv;k}$ if $F_{Serv;k} > F_{ULS;d}$. The Proof load is then based on $E_{ULS;d}$ and must satisfy a limiting creep criterion. Previously Denmark used the German test method as described in DIN 4125. However, with the introduction of EN 1537:1999 Denmark has accommodated the incomplete test specifications stated in the informative annex E of EN 1537:1999. Test method 1 (TM1) is preferred because of the relationship to the former DIN 4125, but the creep rate limit measured in the acceptance test using TM1 in EN1537:1999 is so strict (0,8 mm), that often Test Method 3 (TM3) is adopted because of the more moderate creep rate limit (1,2 mm). Temporary anchors may be loaded to a lower proof load than permanent anchors, provided the consequence of failure justifies that. Similarly the effect of high or serious consequences of failure are governed by the reliability class concept as described in EC0, Annex B by introducing a K_{FI} factor applied to the partial safety factor on the load or on the resistance.

4 TESTING OF ANCHORS

Load testing of anchors has historically been an intrinsic part of the design and execution of anchors – in particular grouted ground anchors - and the mandatory acceptance testing of all grouted anchors is required in EN 1997-1:2004/prA1:2012 and in EN 1537:1999. The anchors are loaded to a proof load (P_p) to verify limit state design requirements. The tests are categorised as:

1. Investigation Tests undertaken to establish the geotechnical ultimate resistance, $R_{ULS;m}$, of the anchor at the grout/ground interface and to determine the characteristics of the anchor within the working load range.
2. Suitability tests – carried out on site on anchors identical to those to be used in the works – to investigate some characteristics of the anchor and how the anchor performs under working conditions.
3. Acceptance tests – carried out on every anchor installed in the permanent works – to ensure that each anchor will perform as designed.

For Investigation and Suitability tests P_p is derived from:

$$P_p \geq \xi_{ULS}\ x\ \gamma_{a;ULS}\ x\ E_{ULS;d} \tag{8}$$

For Acceptance tests P_p is derived from $E_{ULS;d}$ or $F_{Serv;k}$;

$$P_p \geq \gamma_{a;acc;ULS}\ x\ E_{ULS;d} \tag{9}$$
or
$$P_p \geq \gamma_{a;acc;SLS}\ x\ F_{Serv;k} \tag{10}$$

The method is to be stated in the National Annex of each country.

Table 1 - Limiting Criteria for investigation, suitability and acceptance tests for persistent and transient design situations at the ultimate and serviceability limit states (from EN 1997-1:2004/prA1:2012)

Test Method[a]	**Limiting criterion**	**Investigation and Suitability tests**	
		ULS	SLS
1	α_1	2 mm	$0.01\Delta_e$[b]
2	k_l (per log cycle of time)	2%	2%
3	α_3	5 mm	NA (use P_c)
Test Method[a]	**Limiting criterion**	**Acceptance tests**	
		ULS	SLS
1	α_1	2 mm	$0.01\Delta_e$
2	k_l (per log cycle of time)	2%	2%
3	α_3	NA	1.5 mm[c]
Note: NA = Not applicable			

[a] Test methods are in accordance with Draft EN ISO 22477-5 Geotechnical investigation and testing - Testing of geotechnical structures - Part 5: Testing of anchorages

[b] Δ_e = ($F_{serv,k}$ x tendon free length)/(area of tendon x elastic modulus of tendon)

[c] Value given is for permanent anchors; for temporary anchors, α_3 = 1.8 mm

EN 1537:1999 provides for three methods to undertake the suite of tests, essentially following the traditions in testing developed and maintained in Germany, the UK and France. As stated in section 3, these test methods are referred to as Test Method 1, 2 and 3. This approach and test designation has been implemented in EN 1997-1:2004/prA1:2012 and Draft EN ISO 22477-5 expected to be published in 2013.

The provisional limiting criteria for ULS and SLS resistance for these tests to EN 1997-1:2004/prA1:2012 are given in Table 1. The methods of execution and interpretation of the tests are to be found in Draft EN ISO 22477-5. This standard makes no specific reference to testing for either SLS or ULS stating that proof loads are to be set in accordance with EN1997-1. Not all countries have the requirement to determine the limiting criteria for SLS of the anchor as this is considered to be satisfied if the test results meet the ULS criteria.

The test methods currently adopted in Germany, Denmark, France, Ireland and the UK are summarised below. It should be noted that some countries already use partial factors whilst others still adopt a more global safety factor approach.

<u>Germany.</u>

1. Follow Test Method 1
2. For all categories of test (investigation, suitability and acceptance), proof load is:
$$P_p = 1{,}1\ x\ 1{,}35\ x\ F_{Serv;k} \tag{11}$$
or
$$P_p = 1.1\ x\ F_{ULS;d} \tag{12}$$
3. Limiting criteria based on value of α_1 for investigation, suitability and acceptance tests. Acceptance tests are required to satisfy the α_1 criterion, but the test is shorter than that required for suitability tests.

Denmark

1. Follow Test Method 1 and 3.

2. For all categories of test, proof load:

   $P_p = \xi (\gamma_a)^\alpha F_{ad}$ (13)
   where
   $F_{ad} = max(F_{ULS;d}; F_{Serv;d})$ (14)

   where all anchors are tested, $\xi = 1,1$ and $\gamma_a = 1,3$.

   α is a factor used to control reduced safety in temporary situations, provided the risk of the consequence justifies it. It may range from 0 to 1. For permanent anchors $\alpha = 1$. For temporary anchors – with small or no risk to human life or important infrastructure α is typically set to 0,5. Thus for permanent anchors:

   $P_p = 1,1 \times 1,3\, F_{ad} = 1,43\, F_{ad}$ (15)
   For temporary anchors with less severe consequence of failure:
   $P_p = 1,1 \times (1,3)^{0,5}\, F_{ad} = 1,25 \times F_{ad}$ (16)

3. Limiting criteria are based on a value of the creep rate according to (informative) values in EN 1537:1999

France

1. Follow Test Method 3

2. Proof load for Investigation and Suitability tests
   $P_p = 1,50 \times F_{serv;k}$ (17)
   where $F_{serv;k}$ is derived from calculation.

3. Suitability tests should demonstrate that the critical creep load $P_c \geq 1,2 \times F_{Serv;k}$ (for permanent anchors) and $P_c \geq 1,1 \times F_{serv;k}$ (for temporary anchors) where P_c is derived from the load corresponding to the end of the first pseudo-linear part of the creep rate versus anchor load plot found from an investigation or suitability test.

4. Proof load for Acceptance tests:

   $P_p = 1.25 \times F_{Serv;k}$ (permanent anchors) (18)
   or
   $P_p = 1.15 \times F_{Serv;k}$(temporary anchors) (19)

   Given the limits on $F_{Serv;k}$ with respect to the critical creep load, at these proof loads the ratio between test load and creep load is independent of the application of the anchor . It will be constant and approximately 1,04.

5. Limiting criteria based on the value of α_3 at Proof load P_p and the value of P_c to check that $P_c / F_{Serv;k} > 1,2$.

UK and Ireland

1. Follow Test Method 2 but also use Test Method 1.

2. Investigation tests - the anchor is normally loaded to the point where the vertical asymptote of the cumulative load loss k_l vs load relationship may be determined. An estimate of the anchor pull-out capacity may also be made.
3. Proof Load for the suitability and acceptance tests
   $Pp = 1,5 \times T_w$ (20)
   where T_w is derived from the stability and serviceability requirements of the structure.
4. In both suitability and acceptance tests the limiting criteria are based on the values of k_l at a) $P_p = 1,5 \times T_w$ and b) $P_p = T_w$

5. Where Test Method 1 is adopted the limiting criterion k_l is translated into a creep displacement as shown in Table 1, note b.

5 CONCLUSIONS

The aim in developing a new Section 8 for EC7 has been to provide a rational framework for the design of ground anchors as elements within an overall ground-structure design, while accommodating the diverse practices of different countries. In the opinion of the group responsible for the drafting, which included the authors, this has been achieved. Some of the values of factors and criteria will probably be refined during the development of national annexes, though it is likely that national practices will remain distinct for the time being. Nevertheless, as with other aspects of Eurocodes, the existence of a single agreed text gives the possibility of clearer comparisons between national approaches, and so will hopefully contribute to the development of a more unified approach in the future.

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