

The Execution of Ground Anchor Works: The European Standard prEN1537

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DEVELOPMENT OF THE STANDARD

With the development of the European Market and the influences on civil engineering works it became clear that both design and construction standards should be harmonised to facilitate both the procurement of construction works and their execution.

There is now a major movement towards the production and implementation of European Standards which would ultimately replace national standards in each of the member countries. The responsibility for the production of the harmonised codes rests with the Brussels based standards drafting body, CEN (Comité Européen de Normalisation), which is funded by the European Commission and the European Free Trade Association (EFTA). The influence of CEN is beyond that of the European Community, membership extending currently to 18 European countries. The drafting of standards for the construction industry falls on the Technical Committee TC250, the secretariat for this committee being BSI.

The standard which most directly affects the geotechnical fraternity, ENV 1997-1:1995 Eurocode 7: Geotechnical Design, Part 1: General Rules (including National Application Document), has now been published in the member countries. Concern that this standard would not reflect the construction aspects of geotechnical processes prompted the initiative to draft construction standards for the execution of special geotechnical works. Through the offices of the European Federation of Foundation Contractors (EFFC), CEN was approached to establish a technical committee to undertake the drafting of appropriate Execution Standards. A technical committee (TC288) was established, reporting to CEN/BTS1, working in accordance with CEN rules and financed by EFFC.

Working Group 2 (WG2) was established to draft the Execution Standard for ground anchors, prEN 1537:1996 "Execution of special geotechnical work: Ground Anchors", addressing all those aspects of relevant technology required to ensure their successful construction. The standards adopted for the controls on construction, grouting and materials reflect current practice and enjoy general support in the industry. Whilst it was the explicit intention to omit detailed matters of design in the Execution Standards, this has been included as an Informative Annex addressing concern that it was inadequately dealt with in Eurocode 7.

For clarification the Standard now details examples of approved corrosion protection systems in two tables, for temporary and permanent anchors (Tables 2 & 3, prEN1537:1997), which allow the identification of the corrosion protection layers proven effective in each integrated system. Furthermore these tables provide the Client's Technical Representative with a better understanding of systems which are available for selection, how appropriate they might be and the implicit level of risk associated with their use.

The elimination of risk of anchor failure due to steel corrosion demands proof beyond reasonable doubt that the protective system will work and last for the 60 to 120 year designed lifespan of the anchored structure. Alternatively, the consequences of anchor failure must be fully addressed.

TESTING OF ANCHORS

Investigation of practices throughout Europe, revealed a wide range of testing methods and criteria for conformance currently in use in national standards. Whilst differing in some elements, the methods fall largely into three main groups, based on the testing practices in France, Britain and Germany. The main differences noted in the overall testing systems were:-

- a) methods used in proof loading (i.e. cycled or stepped)
- b) the data acquired to determine the creep or load loss characteristics
- c) the criteria of creep or load loss conformance
- d) the length of time required to monitor the anchor behaviour to determine the creep or load loss characteristics.
- d) the number of anchors to be tested at each test stage.
- e) the number of cycles of load to be applied at each test stage.

The current draft of EC7 (ENV 1997-1:1995) provides for two types of test, an assessment test and an acceptance test. Furthermore it gives very little guidance on the procedures to be adopted to achieve the objectives of these tests. Whilst not contradicting EC7, prEN1537 attempts to clarify the objectives of the testing and to provide guidance on how these may be achieved. The deliberations of the Working Group resulted in no consensus in the adoption of a single test system. Consequently prEN1537 defines explicitly the objectives of each category of test and provides examples of three test systems, including conformance criteria, which may be adopted to achieve the objectives.

prEN1537 defines three test stages:-

Investigation test - to establish in advance of the installation of the working ground anchors, the ultimate load resistance in relation to the ground conditions and materials used.

Suitability Test - to confirm or demonstrate either acceptable creep or load loss characteristics at proof and lock-off loads or critical creep load.

Acceptance test - to demonstrate that the proof load, depending on the test method, can be sustained by the anchor and to ensure that the lock-off load is at the designed load level.

The tests address the behaviour of the anchor at both ultimate and serviceability limit state and give explicit limits in each test method for the creep behaviour of the fixed anchor length or load loss in the anchor. The tests also allow the deduction of the apparent free anchor length to satisfy an acceptance criterion for efficiency of load transfer.

This paper highlights three aspects addressed in prEN1537 with special reference to how differences between national practices were resolved in the harmonisation process. These aspects are:-

1. The process of design, using limit state approach
2. Use of materials with special reference to corrosion protection
3. Testing procedures.

Given the different relationships between contractor and consulting engineer which exist across Europe, the Standard has also introduced the concept of a Clients Technical Representative, who is defined in the Standard as "represent(ing) the client and (being) fully acquainted with all aspects of the works related to the use of the anchors, including (having) expert knowledge of ground anchor technology". This definition facilitates the distribution of decision making and acceptance of responsibility.

NEW DESIGN PHILOSOPHY

Fundamentals of the new design philosophy for ground anchors and anchored structures

The publication of the European Prestandard ENV 1991-1 Part 1: Basis of Design introduced a completely new design concept for all civil engineering works; the Limit State Design. Ultimate Limit State (ULS) design (i.e. safety) demonstrates equilibrium of the design values of actions acting on a structure and the design resistance of the structure in every possible design situation. Design values are generally obtained by augmenting actions and reducing resistance characteristic values by partial factors. Use of the global safety factor is therefore no longer valid. Serviceability Limit State (SLS) is associated with proving that deformations and displacements of a structure using characteristic values of actions and material properties are acceptable.

The application of this design concept to concrete or steel structures does not offer any special problems. In the geotechnical field, however, it is not always easy to separate actions clearly from resistance, especially for anchored structures.

Furthermore, experience, extensive testing and research on the behaviour and the durability of ground anchors during the last 10 - 15 years lead to new approaches to the design of ground anchors. For example, the extension of the working life of an anchor by increasing the tendon steel section has been found to be inappropriate with the current state of knowledge of the rapid and localised nature of corrosion in tensioned prestressing steel.

Likewise the creeping behaviour of the ground is known to follow a logarithmic time function. Therefore, after 50 years, the pull-out resistance of the grout body of an anchor is theoretically no lower than after 2 years. Long-term consolidation adjacent to the ground-grout interface may even result in it being markedly higher.

For these two reasons the requirement for a larger steel section and greater pull-out resistance for permanent anchors than for temporary anchors, is redundant. The challenge lies in guaranteeing the durability of permanent anchors by an effective corrosion protection system.

The catastrophic collapse of a structure should be presaged by progressive deformation (no brittle rupture). The contribution of the free length to overall anchor deformation during loading from working load to failure is about 8 to 10 times greater than that for the fixed length. The steel tendon, the straining of which in the free length largely dictates the

magnitude of deformation in the anchor system, is the element upon which the design is based.

Since the tendon of a prestressed anchor extends freely through the whole free anchor length it is not necessary to relate the safety factor to the yield stress of the steel as is the case for prestressed concrete structures with bonded tendons (i.e. there is no local confinement in crack areas).

Design of the single anchor

A prestressed anchor is defined by the determination of the following properties:

- characteristic internal anchor resistance R_{ik} , i.e. failing of the tendon, etc.
- characteristic external anchor resistance R_{ak} , i.e. failure at grout-ground interface
- anchor lock-off load P_o
- free anchor length L_{free}

By considering the behaviour of the steel tendon in the anchor system;-

$$R_{ik} = P_{tk} = A_t * f_{pk}; \quad \text{where } A_t \text{ is the area of steel tendon and } f_{pk} \text{ is the characteristic tensile strength of the tendon}$$

R_{ak} is the characteristic pull out resistance of the grout body and should be equal to or higher than R_{ik} , which is usually equal to P_{tk} , the characteristic strength of the tendon.

If the anchor complies with this recommendation which is to be proved by testing, then the characteristic anchor resistance is R_k , where;-

$$R_k = R_{ik} = P_{tk} = A_t * f_{pk} \leq R_{ak}.$$

This design concept, together with the fact that every single anchor is tested with a proof load P_p which is at least 25% higher than the lock-off load P_o using conservative creep or load loss criteria, allows the introduction of one overall partial factor of anchor resistance $\gamma_R \geq 1.35$ for temporary and for permanent anchors to determine the maximum value of the design resistance of an anchor, $R_d = R_k / \gamma_R$.

In order to limit the relaxation characteristics of the tendon the anchor load during the design working life shall be lower or equal to $0.65 * P_{tk}$. Limiting the lock-off load to $0.60 * P_{tk}$ a modest increasing of the anchor load during working life of maximum 7.7% is possible which is in many cases reasonable. This limitation allows a proof load P_p in the acceptance test of $1.25 P_o$ ($0.75 * P_{tk}$ which conforms to ENV 1992-1). Furthermore, as with the described design concept the design resistance of the anchor, R_d , where;-

$$R_d = R_k / \gamma_R \leq P_{tk} / 1.35 = 0.74 * P_{tk}$$

The proof load of every anchor is about equal to or even slightly higher than its design resistance. Therefore, if the durability of the anchor may be guaranteed by an efficient corrosion protection a prestressed anchor may be considered as one of the most secure parts of a structure.

The minimum free anchor length and the necessary anchor lock-off load are derived from the design of the anchored structure.

Design of anchored structures

The design of anchored structures is executed in accordance with the requirements of ENVs 1991-1999. ENV 1997-1 (EC7), however, in the opinion of WG2, must be amended in two clauses. First, Clause 8.8: "Anchorages" is not acceptable and must be replaced by Annex D of prEN1537 "Design of ground anchors". Secondly, Clause 2.4.2 (17) should treat the passive earth pressure beneath the excavation level of a retaining wall as a reaction and consequently to be considered as a resistance.

The procedure to design an anchorage for three typical design situations of anchored structures is described. It should be noted that the value of the design resistance R_d of the anchor to be considered depends on the manner in which the anchor is being stressed in the limit mode under consideration.

Anchored Wall For the verification of the ultimate limit state of an anchored wall (see Fig. 1) the necessary design resistance of the anchors R_d per metre is calculated for each row (i.e. R_{d1} , R_{d2}) by using values for active earth pressure and passive earth pressure increased ($E_a \cdot \gamma$) and reduced (E_p / γ) respectively by a partial factor γ determined from EC7. As the anchors in this limit mode are stressed predominantly by tension the necessary steel section of the anchor tendon is obtained directly with the calculated values R_d in accordance with the described design concept by adopting the spacing, a , of the anchors and the load capacity of the tendon steel:

$$R_{ik} = P_{ik} = \gamma_R \cdot (R_d / \text{metre}) \cdot a, \quad A_t = P_{ik} / f_{pk}, \quad \text{if } R_{ak} \geq R_{ik} \quad (\text{see fig. 1}).$$

In this limit mode the anchors are predominantly stressed by tension, hence there is no need to apply a variation factor for the anchor load.

The anchor lock-off load is to be derived from the verification of the serviceability limit state. When determining $P_o = 0.55$ to $0.60 P_{ik}$, this verification usually is not necessary.

Ultimate Limit State due to Buoyancy The verification of the ultimate limit state of an anchored structure subjected to buoyancy is executed in accordance with the procedure in the following example (see fig. 2).

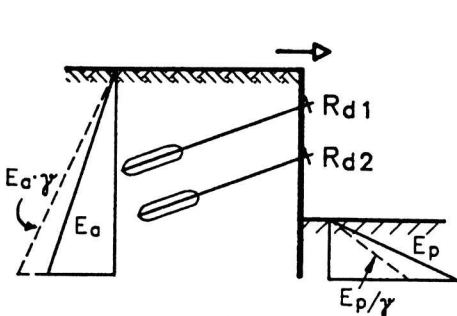


Fig.1: Anchorage of a retaining wall

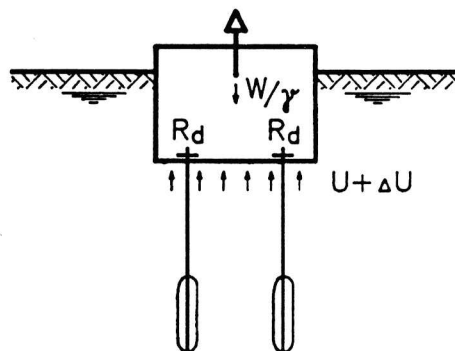


Fig.2: Anchorage against buoyancy

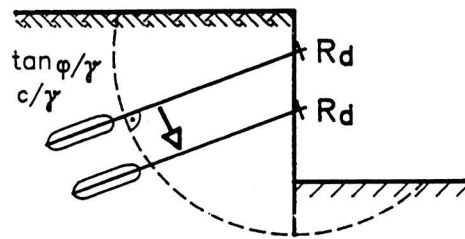
The anchors are directly stressed, therefore calculation of the two state are;-

ULS: $R_{ik} = P_{uk(1)} = \gamma_R * R_d = 1.35 * R_d$
 therefore;- $A_{t(1)} = P_{ik(1)} / f_{pk} \quad (R_{ak} \geq R_{ik})$

SLS: $P_{min} \geq U_{max} - W_{min}$, hence P_o
 Where U_{max} = maximum buoyancy force and W_{min} = minimum weight of structure both factored in accordance with EC7,
 The Standard requires that; $P_{ik(2)} \geq P_o / 0.60$, hence $A_{t(2)} = P_{uk(2)} / f_{pk}$
 This may give rise to $P_{uk(2)} \geq P_{uk(1)}$

In this case the serviceability limit state is very important and can dominate the design of the anchorage. It must be verified that the minimum anchor load P_{min} acting during working life of the structure is greater than the maximum possible resulting up-lift force. The necessary lock-off load P_o is derived from P_{min} required taking account of possible load losses due to relaxation, creeping and settlements. In order to ensure the condition $P_{ik} \geq P_o / 0.60$ a greater steel section may be required for the tendon resulting in a greater anchor resistance $R_k = R_{ik} = P_{ik}$ than that from the verification of the ultimate limit state.

Overall Stability Failure of an Anchored Wall In the verification of the overall stability failure of an anchored wall the design resistance R_d of the anchorage is equal to the factored anchor load $\gamma_q * P_o$ in this limit mode, where usually $0.9 < \gamma_q < 1.1$. As the anchors are not directly stressed by the movement of the earth body, gross displacement of the structure occurs before the anchors can mobilise their full tension strength (see fig. 3).



For values of partial factor γ , refer to EC7. ($1 < \gamma < 1.6$)

Fig.3: Overall stability failure.

Movement does not stress the anchors directly.

$$R_d = P = \gamma_q * P_o \rightarrow P_o \geq R_d / \gamma_q \rightarrow R_{ik} = P_{ik} \geq P_o / 0.60$$

($R_{ak} \geq R_{ik}$)

In this design mode the value of R_d is markedly lower than the maximum design resistance of the anchor i.e. $R_d = R_k / \gamma_R = R_k / 1.35$. The variation factor for the anchor load, γ_q , considers the changes of the anchor load after lock-off due to relaxation, creep, displacements of the anchor head and displacements of the structure as a rigid body in the limit mode considered. With the necessary anchor lock-off load $P_o = R_d / \gamma_q$ the necessary anchor resistance results in $R_k = P_{ik} = P_o / 0.60 = R_{ik} \leq R_{ak}$.

In this case the actual anchor load is used for the verification of the ultimate limit state. Normally it is used for the verification of the serviceability limit state. This at first sight appears paradoxical and is often misunderstood by engineers. It shows, however, that for the design of ground anchors a sound knowledge of the geotechnical behaviour of a structure is absolutely essential.

CORROSION PROTECTION

In many instances the consequences of failure of one or a number of anchors could have extremely severe effects on the stability of a structure. However, owing to the severity of ground anchor proof testing, complemented by load or creep monitoring prior to acceptance of each anchor, the risk of failure of a working anchor due to interfacial bonding is extremely small. But the need to take account of the risk of failure due to corrosion of steel components, must be tackled. An essential requirement in any system developed to eliminate this risk is that it must be compatible with the demands of load testing, either by proving the isolation of the tendon steel of each individual in-situ anchor, or by fully demonstrating the effectiveness of a robust protective system prior to use.

To date it is believed that only a single world wide study of the corrosion of anchors has been carried out and the report published. A working group under the FIP (Fédération Internationale de la Précontrainte) collected 35 case histories of anchor failure by tendon corrosion (Littlejohn, 1987) and their conclusions are extremely relevant when establishing the corrosion protection requirement for a standard:-

"While the mechanisms of corrosion are understood, the aggressivity of the ground and general environment are seldom quantified at the site investigation stage. In the absence of aggressivity data it is unlikely the case histories involving tendon corrosion will provide reliable information for the prediction of corrosion rates in service.

Case histories of tendon corrosion indicate that failure can occur after service of only a few weeks or many years. Invariably corrosion is localised and in such circumstances no tendon type (bar, wire or strand) appears to have a special immunity.

Since there is no certain way of predicting localised corrosion rates, where aggressivity is recognised, albeit qualitatively, some degree of protection should be provided by the designer. In this regard, the anchor head is particularly susceptible to attack, and early protection of this component is recommended for both temporary and permanent anchorages.

Choice of degree of protection should be the responsibility of the designer (usually the Client's Engineer) and such choice depends on such factors as consequences of failure, aggressivity of environment and cost of protection. In current practice the design solution normally ranges from double protection (implying two physical barriers) to simple grout cover.

Out of millions of prestressed ground anchorages which have been installed around the world, 35 case histories of failure by tendon corrosion have been recorded. With the passage of time, lessons have been learned and standards improved which augers well for the future. There is no room for complacency, however, and engineers must rigorously apply high standards both in design and construction in order to ensure satisfactory performance during service."

Although the record of failure is yet limited, it is probable that in the next decade the frequency of individual and group anchor failures will increase as anchors installed prior to the implementation of rigorous protective requirements suffer from corrosive attack and their reduced capacities no longer ensure the fulfilment of their intended role. Similar instances to those of the Thames wall failure (Barley, 1997A), and the tidal barrier wall failure (Chamley & Barley, 1997), with structural collapse or partial collapse, will occur. Many permanent anchors installed in the UK prior to the guidelines of DD81 (pre 1982), with the exception of anchors associated with the Thames Bank Raising Scheme, contained only limited protection against corrosion and are unlikely to withstand aggressive conditions, particularly those in a marine environment.

From the known vulnerability of anchors in aggressive environments, does it follow that all permanent anchors should carry the same degree of protection against corrosion despite the knowledge that corrosion in certain environments may be mild? Based on the FIP report statements, Working Group 2, with general support from the National Mirror Groups, concluded:-

"There is no certain way of identifying corrosion circumstance with sufficient precision to predict corrosion rates of steel in the ground. All steel components which are stressed shall be protected against corrosion for their design life."

and recommended that for permanent anchors:-

"The minimum corrosion protection surrounding the tendon(s) of the anchor shall be a single continuous layer of corrosion preventive material which does not degrade during the lifetime of the anchor."

This recommendation was initially supported by two requirements:-

"The tendon of a permanent ground anchor shall be provided with either:

- a) a single protective barrier to corrosion, the integrity of which shall be proven by testing each anchor insitu."
- b) two protective barriers to corrosion such that if one barrier is damaged during installation or anchor loading, the second barrier remains intact."

The method of substantiating the former requirement involves the insitu testing of the total isolation of the steel tendon from the surrounding environment. This can be established by electrical resistance measurement as illustrated in Fig.4, but clearly the efficiency of the test system itself must be established to ensure that a defective protective layer can be positively identified to satisfy the mandatory test requirements. Anchors not tested insitu must contain two protective barriers and must comply with further requirements that:-

"All corrosion protection systems shall have been subjected to at least one system test to verify the competence of the system. The results of all tests shall be documented."

Examples of methods of establishing the integrity of protective barriers during or after loading conditions, are illustrated in Fig.5, and reported by Barley (1997B). Protected tendons are loaded in a grouted gun barrel, which can allow splitting and inspection after use, or alternatively unrestrained encapsulation can be loaded and inspected whilst under

load.

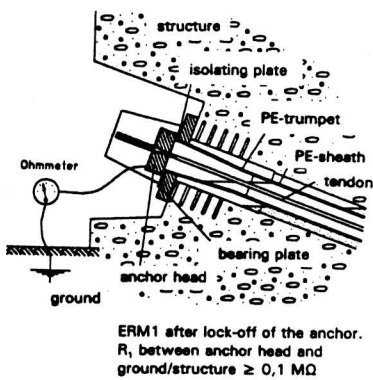
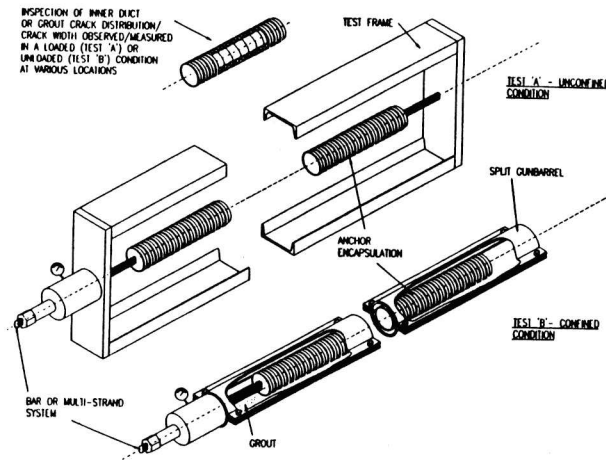


Fig.4 Investigation testing insitu by electrical resistance measurement (VonMatt, 1994)

Fig.5 Investigation testing of corrosion protection barriers (Barley, 1994)



The basic requirements outlined above, supplemented by definitive statements with regard to materials acceptable as corrosion barriers, formed the first draft completed in 1994.

Towards completion of this first draft, however, it became apparent that certain anchor systems, which allowed enhancement of anchor capacity by either pre- or post-grouting operations, would not comply with the Standard's protection requirements, owing to the utilisation of a stressed steel tube as a protective barrier, or the presence of grouting valves within a protective barrier.

Clarification from CEN/TC288 committee to overcome this impasse highlighted the obligation to accommodate any anchor systems that were extensively used on a national basis.

As a consequence the Standard has adopted a more compliant approach to contributory corrosion protective barriers. This was opposed by a number of national experts on WG2 based on their reluctance to accept any steel components in the ground forming a protective barrier, particularly when the steel itself is stressed and is required to transfer the entire load of the anchor from the tendon to the ground. Here durability depends entirely on the non-corrosive nature of the ground, or on the integrity of a potentially cracked annulus of grout.

It should be noted that no attempt has been made to achieve parity in the outcomes of each of the test methods provided. It has been accepted that at this stage the test methods cannot be compared nor can their acceptance criteria be calibrated one with the other. Insufficient data exist currently to allow this. The adoption of this approach is in accordance with the spirit of harmonisation and is based on practices in existing standards. Each method, however, is adequately demanding in the reduction or removal of risk of failure at the serviceability limit state.

CONCLUSION

The development of prEN1537:1997 has resulted in the articulation for the first time of a coherent and simple limit state design approach for ground anchors which may be adopted throughout Europe. Within current practice considerable consistency was found in the basic demand to prove the ability of every anchor to achieve a proof load and to sustain load in the serviceability state. The Standard presents three acceptable loading procedures representing current European practice, whilst not identical in method of execution, nor in outcomes, they are reasonably rigorous in achieving an acceptably low level of risk of failure. On the other hand, recognising the existence of disparate practices of corrosion protection across Europe, the Standard presents cogently and simply the alternative courses of action which the Client's Technical representative may take, on the clear understanding that there is no suggestion of parity between the corrosion protection systems.

Whilst providing a balanced standard of reasonable prescription and sensible recommendation prEN1537, however, underlines the responsibility of the industry to make decisions on performance and durability based on evidence currently available.

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