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EN1997 *Eurocode 7: Geotechnical design*

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Geotechnical engineers have long stood out from the other professional disciplines within civil and structural engineering—not least for their approach to design. Geotechnical calculations have traditionally relied on highly subjective assessments of design parameters whereas everything above the ground uses a more explicit and codified approach. Eurocode 7 aims to bridge the gap. It presents a comprehensive list of conditions which geotechnical designers need to consider and places much greater emphasis on serviceability and how this may be satisfied through ultimate-limit-state design. With four different design methods and three different approaches to limit-state design, it offers great flexibility at the same time as increased rigour.

In 1980 the European Commission asked the International Society of Soil Mechanics and Foundation Engineering to survey existing geotechnical codes of design practice within European Community member states and to draft a model code which could be adopted as Eurocode 7.

Following many consultations and international meetings, the Society produced a draft geotechnical code in 1987. The Commission then sponsored three more years' work on the draft, after which the document was transferred in 1990 for development, issue and maintenance to Comité Européen de Normalisation (CEN)—the European standardisation body.

Part 1 of Eurocode 7 was published as an ENV (EuroNorm Vornorm) pre-standard in October 1994 and by BSI the following year.[1] Two years later, the ENV was subjected to voting and accepted in July 1997 for further development into an EN (EuroNorm) standard. The status of the latest, unpublished, draft is as a provisional standard (prEN).

In 1998 a commentary[2] on the ENV was published in the UK to assist engineers better to understand the novel aspects of the Eurocode and to give worked examples showing its application using the British national application document in the BSI version. Further explanation of the ENV, with worked examples, was published in 1999.[3]

Harmonising with other Eurocodes

The positive vote to proceed from ENV to EN was achieved on the understanding that some member states reserved the right to propose changes to the ENV text. Particularly, this concerned the basis of geotechnical design section that is required to conform with EN1990 *Eurocode—Basis of structural design*.[4] Consequently, the technical content of several sections of the ENV was amended between 1998 and 1999. During this period and subsequently, a number of important negotiations with the project team producing EN1990 took place in which both Eurocodes were amended to enable EN1997-1 to conform with EN1990.

Part 1 of Eurocode 7, EN1997-1, provides in outline all the requirements for design of geotechnical structures. It provides little assistance or information,

Table 1: Contents of part 1 of Eurocode 7

Subjects	Sections
Overall approach	1. General 2. Basis of geotechnical design
Ground investigation	3. Geotechnical data
Design aspects of construction activities	4. Supervision of construction, monitoring and maintenance
Design of specific elements	5. Fill, dewatering, ground improvement and reinforcement, 6. Spread foundations 7. Pile foundations 8. Anchorages 9. Retaining structures 10. Hydraulic failure 11. Overall stability 12. Embankments

"Eurocode 7 recognises four fundamental ways of carrying out geotechnical design"

which the designer must therefore seek from other texts. It relies on other Eurocodes and CEN documents.

The code provides extensive checklists of conditions to be investigated, assessed and designed for and places greater emphasis on the serviceability requirement for geotechnical design than is found in many national codes. Table 1 shows the contents of part 1.

The code strongly emphasises the importance of geotechnical investigations. It requires that the final design be accompanied by formal reports, both factual and interpretative, of the investigations on which it is based.

EN1997-1 is supported by two other parts: ENV1997-2 and ENV1997-3, design assisted by laboratory and field testing respectively. Conversion of these parts into ENs is expected to begin in late 2001.

Five ultimate limit states to be considered

In common with all the Eurocodes, Eurocode 7 is based on the principles of limit-state design. ENV1997-1 required the designer to consider three ultimate limit-state design cases A, B and C, which were sets of partial factors for both actions and material strengths (or resistances, in the case of piles). This design system complied with the then draft of EN1990. Case A dealt with loss of static equilibrium, in which actions were largely in balance with little if any contribution from material strengths. The factors of case B were derived from structural codes and those of case C from an earlier draft of Eurocode 7. In order to provide consistent and safe design of structures involving ground behaviour, the ENV required that all designs should comply with all three cases in all respects, both geotechnical and structural; that is, complete designs of the geometry and structural strength were to be checked separately for all three sets of partial factors. It was noted that in many situations the critical case might be obvious by inspection, in which event it would not be necessary to produce formal calculations for all three cases.

Fig. 1. The GEO limit state is often critical in the sizing of retaining structures

The present prEN1997-1 text defines five ultimate limit states as follows

- loss of equilibrium of the structure or the ground, considered as a rigid body, in which the strengths of structural materials and the ground are insignificant in providing resistance (EQU)
- internal failure or excessive deformation of the structure or structural elements—including footings, piles and basement walls—in which the strength of structural materials is significant in providing resistance (STR)
- failure or excessive deformation of the ground, in which the strength of soil or rock is significant in providing resistance (GEO)
- loss of equilibrium of the structure or the ground due to uplift by water pressure (bouyancy) or other vertical actions (UPL)
- hydraulic heave, internal erosion and piping in the ground caused by hydraulic gradients (HYD).

Limit state GEO is often critical to the sizing of structural elements involved in foundations or retaining structures (Fig. 1) and sometimes to the strength of structural elements.

A comparison with prEN1990 clause 6.4.1 shows that definitions of the ultimate limit states common to both codes, EQU, STR and GEO, are broadly in agreement, with only minor textual differences and that specific geotechnical limit states UPL and HYD have been added to prEN1997-1. The limit state of fatigue (FAT) in prEN1990 is absent from prEN1997-1.

The ultimate limit state UPL involves failure by hydraulic uplift and occurs when, for example, the shear strength of the ground acting on the periphery of a buried structure plays only a very minor role (compared to the self-weight of the structure) in providing resistance against uplift (buoyancy) forces. Problems of failure in the ground caused by pressure and flow of groundwater due to hydraulic gradients (HYD) are considered in a special and separate geotechnical limit state that is closely related to GEO in that it involves loss of strength of the ground.

Four ways of carrying out geotechnical design

Eurocode 7 recognises four fundamental ways of carrying out geotechnical design

- using calculations based on an analytical, semi-empirical or numerical model
- adopting prescriptive measures involving conventional and generally conservative, nationally determined rules or approaches in design and specification, and in the control of materials, workmanship, protection and maintenance procedures
- using experimental models and load tests carried out on a sample of the actual construction or on full scale or smaller scale models
- using the observational method,[5] in which the design is continuously reviewed during construction.

Historically, the limit-state method became popular at about the time that partial factors began to be adopted. The two are therefore often linked though there is no fundamental connection between them. A calculation using global factors or directly assessing pessimistic design values could be sufficient to demonstrate that limit states will not occur. Limit-state calculations are usually carried out by showing that the design properties of materials are sufficient to withstand the design values of all applied actions. The design values generally incorporate all the required safety elements, with no further overall factor of safety. Calculations are principally to be carried out by applying partial factors to characteristic values of soil parameters. The code generally does not specify the precise form of calculations but states what criteria are to be checked by the calculations.

Prescriptive methods may be used when comparable experiences make calculations unnecessary or calculation models are not available. Examples in the UK would be the minimum foundation depth of 450 mm to avoid frost heave, or of 1000 mm to avoid seasonal movements in highly plastic clays.

A UK example of the experimental/load-test approach would be the application of an α factor in the range 0·4–0·6 to the undrained shear strength of London clay when calculating the shaft resistance of a pile (Fig. 2)

With regard to the observation method, it is a principle of EN1997 that the limits of acceptable behaviour are established together with the range of possible behaviour and a plan of the monitoring regime. A plan of contingency actions must also be devised, to be adopted should monitoring reveal behaviour outside acceptable limits.

The four approaches may be used in combination. Simplified design procedures may be adopted depending on the complexity of the geotechnical design and risk considerations.

Three new approaches to limit-state design

The application of limit-state design in geotechnics (as formulated using partial factors) has been under debate for several decades. Although the approach has some obvious, and generally accepted, benefits, it has proved very difficult to reach agreement on where in the calculation processes partial factors should be applied.

Fig. 2. The experimental and load test approach can be used to determine the α factor on the ground strength when calculating shaft resistance of piles

Although some engineers would still argue for single global factors of safety, the main alternative views now relate to applying factors either to primary variables—material properties and actions, or to some variable obtained part way through the calculation—resistances and action effects. A related question is the application of factors to models, both resistance and action effect models.

It has long been argued by the supporters of the ENV cases A, B and C that, where possible, factors should be applied to the uncertainties themselves so that their effects on derived quantities may result from the calculation, rather than being assumed by code drafters. In the drafting committee, two broad groups emerged: one generally supporting factoring of materials and actions and another supporting factoring of resistances and action effects. To accommodate the latter group particularly, new design approaches have been introduced, with corresponding changes to EN1990 for conformity.

The intentions of the proponents of the new approaches have been

- to reduce the perceived number of geotechnical calculations required by the ENV
- generally to introduce factors on resistances and action effects rather than on material properties and actions
- to introduce model factors.

Their introduction resulted in far greater complexity in the document than was found in cases A, B and C of the ENV. The Appendix sets out how prEN1997-1 states the approaches should be used to avoid ultimate limit states.

Alternative sets of partial factors were needed for the different design approaches for the different geotechnical structures, such as bored and driven piles, with much repetition in order that each set was separately consistent. This complexity was heavily criticised by BSI and recent simplifications have been adopted which reduce the number of partial factor values from more than 200 to around 60! These simplifications are summarised in Table 2 in which the terms A ('action'), M ('material') and R ('resistance') refer to sets of partial factors given in tables in annex A of EN1997-1; some of the partial factors and their recommended values are reproduced in Table 3.

The values of the partial factors recommended in annex A of the code are subject to national determination, in common with all the Eurocodes.

Gravity retaining wall example

The way in which different combinations of factors are applied, for the different design approaches, may be seen in Table 4, for the example of a gravity retaining wall founded on sand.

For design approach 1 it can be seen that two cases must be considered

- combination 1 in which partial factors on actions exceed 1·0, with factors on material strengths set to 1·0 (the STR limit state)
- combination 2 in which factors > 1·0 are applied to geotechnical material strengths with factors on actions set to 1·0 (the GEO limit state).

In design approach 1, for all designs, checks are required in principle for two sets of partial factors, applied in two separate calculations. This is akin to the cases B and C of the ENV. Where it is obvious that one of these sets governs the design, it will not be necessary to carry out calculations for the other set. Generally, factors are applied to actions, rather than to the effects of actions, though with one noted exception.

> In some design situations, the application of partial factors to representative values of actions coming from or through the soil (such as earth or water pressures) could lead to design values which are unreasonable or even physically impossible. In these situations, the factors may be applied directly to the effects of actions derived from representative values of the actions.

This exception applies specifically to the design of piles and anchors.

In design approaches 2 and 3, a single calculation is required for each part of a design, and the way in which the factors are applied is varied according to the calculation considered. In design approach 2,

Table 2. The three design approaches

Design approach DA1	DA2	DA3
- Except for the design of axially loaded piles and anchors, it shall be verified that a limit state of rupture or excessive deformation will not occur with either of the following combinations of sets of partial factors: Combination 1: A1 + M1 + R1 Combination 2: A2 + M2 + R1 - For the design of axially loaded piles and anchors, it shall be verified that a limit state of rupture or excessive deformation will not occur with either of the following combinations of sets of partial factors: Combination 1: A1 + M1 + R1 Combination 2: A2 + (M1* or M2†) + R4 * when calculating the resistance of the piles or anchors; † when calculating unfavourable actions on the pile owing to negative skin friction or lateral loading. - Where it is obvious that one of these combinations governs the design, it will not be necessary to carry out calculations for the other combinations. However, different combinations may be critical to different aspects of the same design. NOTE: In this approach, the design is checked for two sets of partial factors separately.	- It shall be verified that a limit state of rupture or excessive deformation will not occur with the following combination of sets of partial factors: Combination: A1 + M1 + R2 NOTE 1: In this approach, partial factors are applied to actions or to the effects of actions and to ground resistances. NOTE 2: If this approach is used for slopes and overall stability analyses, the resulting effect of the actions on the failure surface is multiplied by γ_E and the shear resistance along the failure surface is divided by $\gamma_{R;e}$	- It shall be verified that a limit state of rupture or excessive deformation will not occur with the following combination of sets of partial factors: Combination: (A1* or A2†) + M2 + R3 * on structural actions † on geotechnical actions. NOTE 1: In this approach, partial factors are applied to actions or the effects of actions from the structure and to ground strength parameters. NOTE 2: For slope and overall stability analyses, actions on the soil (e.g. structural actions, 'traffic' loads etc.) are treated as geotechnical actions by using the set of load factors A.2 Key • A = partial factors applied to actions • M = partial factors applied to material properties • R = partial factors applied to ground or foundation resistances • += in combination with.

factors are applied to either actions or effects of actions and to resistances. Design approach 2 is an action (effect) and resistance factor approach. In design approach 3, factors are applied to actions or effects of actions from the structure and to ground strength parameters. Design approach 3 is an action (effect) and material factor approach.

Table 3. Selected sets of partial factors for limit states STR and GEO, and their recommended values

(1) Partial factors on actions (γ_F) or the effects of actions (γ_E)

Action: Duration	Condition	Symbol	Set A1	Set A2
Permanent	Unfavourable	γ_G	1·35	1·0
	Favourable		1·0	1·0
Variable	Unfavourable	γ_Q	1·5	1·3
	Favourable		0	0

(2) Partial material factors (γ_M)

Material property	Symbol	Set M1	Set M2
Shearing resistance	γ_ϕ	1·0	1·25
Effective cohesion	γ_c	1·0	1·25
Undrained strength	γ_{Cu}	1·0	1·4
Unconfined strength	γ_{qu}	1·0	1·4
Weight density	γ_σ	1·0	1·0

(3) Partial resistance factors (γ_R) Spread foundations

Resistance	Symbol	Set R1	Set R2	Set R3
Bearing	γ_{Rv}	1·0	1·4	1·0
Sliding	γ_{Rh}	1·0	1·1	1·0

Pile foundations (driven)

Resistance	Symbol	Set R1	Set R2	Set R3	Set R4
Base	γ_b	1·0	1·1	1·0	1.3
Shaft (compression)	γ_s	1·0	1·1	1·0	1.3
Total/combined (compression)	γ_t	1·0	1·1	1·0	1.3
Shaft in tension	$\gamma_{s,t}$	1·25	1·15	1·1	1.6

Implications for practice in the UK

Design calculations include many sources of uncertainty

- actions
- derivation of action effects by an action effect model
- material strengths
- resistances of structural sections or zones of ground, derived using a resistance model.

The effect, later in a calculation, of an uncertainty at one point in a calculation is not easily foreseen and may be highly disproportionate.

It is important, however, that the number of factors be kept as small as possible, in order to minimise the risk of confusion, which could cause mistakes in calculation. In this case it is important that the principal uncertainties are directly factored, especially any which might have disproportionate, or non-linear effects elsewhere, with the intention of giving a sufficient margin to cover those not factored. In geotechnical design, material strength is often the principal uncertainty, suggesting that the strength of the ground should be factored at source.

EN1990 *Eurocode—Basis of structural design* notes an important point in relation to actions.

For non-linear analysis (i.e. when the relationship between actions and their effects is not linear), the

Table 4. Partial factors for a gravity retaining wall founded on sand

Design approach	Combination	Actions A: Permanent unfavourable	Actions A: Variable unfavourable	Materials M: tan Ø	Materials M: Weight density	Resistances R: Bearing	Resistances R: Sliding	Comments
1	1 (A1 + M1 + R1)	1·35	1·5	1·0	1·0	1·0	1·0	Like ENV case B
	2 (A2 + M2 + R1)	1·0	1·3	1·25	1·0	1·0	1·0	Like ENV case C
2	'Rupture' (A1 + M1 + R2)	1·35	1·5	1·0	1·0	1·4	1·1	
3	Rupture (A1 or A2) + M2 + R3	Structural 1·35 Geotechnical 1·0	Structural 1·5 Geotechnical 1·3	1·25	1·0	1·0	1·0	

following simplified rules may be considered in the case of a single predominant action.

(a) When the action effect increases more than the action, the partial factor γ_F should be applied to the representative value of the action.
(b) When the action effect increases less than the action, the partial factor γ_F should be applied to the action effect of the representative value of the action.

In other words, the factor should be applied to the basic variable, or to a quantity derived later in the calculation, according to where its effect will be most severe. If the same approach is applied to materials, particularly that of non-linear, frictional materials, it will generally require that factors be applied to material strength, rather than to calculated material resistances. For example, bearing capacity increases more, in proportion, than the angle of shearing resistance (or tan ϕ) from which it is calculated, so it is appropriate in this case to apply the factor to the material property, tan ϕ, rather than to bearing resistance itself.

Another example arises in the design of embedded retaining walls, where the magnitude of the maximum bending moment increases more than linearly with the applied earth pressures, which themselves change more than linearly with soil strength, expressed as tan ϕ. The prEN1990 rule would here imply that factors should be applied directly to earth pressures, or better still to tan ϕ, rather than to the action effect, bending moment.

It is for these reasons, primarily, that the UK national annex that will be a part of the BS EN1997-1 will require designs in the UK to follow design approach 1 exclusively. Additionally, in the long run-up to the completion of the ENV, extensive calibration studies were performed to demonstrate that the use of cases A, B and C, with the partial factor values recommended in the ENV (these have not changed in prEN1997-1) would deliver safe foundations and geotechnical constructions that were sometimes cheaper than traditional practice using national codes.

There are published examples covering flexible retaining structures (Fig. 3), piles and spread footings.[2] Also published is further discussion[6] and a demonstration of how use of design approach 2 may lead to an anomalous result in which the application of the factors provides no safety.[7]

Defining characteristic values

In addition to the application of partial factors in a limit state design methodology, another contentious aspect of the adoption of Eurocode 7 has concerned the definition and determination of the characteristic value of a variable in the design, especially for ground properties. EN1997-1 discusses characteristic value in 12 clauses, in all, and states that.

> The characteristic value of a geotechnical parameter shall be selected as a cautious estimate of the value affecting the occurrence of the limit state.

The surrounding clauses make it clear that the characteristic value is to incorporate the designer's assessment of relevant ground conditions, based both on test results and other information, especially published information, including the effects of construction processes that might change the strength of the ground. This is clearly somewhat different from the statistical analysis of test results, which defines characteristic values in structural design. The code goes on to state.

> If statistical methods are used, the characteristic value should be derived such that the calculated probability of a worse value governing the occurrence of the limit state under consideration is not greater than 5%. In this respect, a cautious estimate of the mean value is a selection of the mean value of the limited set of geotechnical parameter values, with a confidence level of 95%; a cautious estimate of the low value is a 5% fractile.

There has been much debate in the UK (and elsewhere) about the determination of characteristic values of ground properties. The authors feel that many geotech-

Fig. 3. Many types of geotechnical structures have been calibrated against the pre-standard version of Eurocode 7. Published examples are available[2]

nical engineers instinctively select values that lie close to that determined using the definition given above.[2]

Conclusions

In all the intense debate and criticism, from some quarters, that has accompanied the development of Eurocode 7, sight has often been lost of the fact that, for the first time, civil and structural engineers have a geotechnical code based upon a methodology common to both the ground and the superstructure; the uncomfortable discontinuity in logic that existed between geotechnical calculations based upon highly subjective assessments of design parameters and the far more explicit, codified structural calculations has been significantly bridged in the package of structural Eurocodes.

Eurocode 7 presents a comprehensive list of conditions to be considered in all aspects of those circumstances commonly encountered in geotechnics and places greater emphasis than hitherto on the serviceability condition and how this may be satisfied through ultimate-limit-state design methods. It offers great flexibility in the choice of design methodology yet introduces greater discipline in having to think more explicitly about the many sources of uncertainty in geotechnical design.

Very few British geotechnical engineers have yet tried to use the ENV and it is earnestly to be hoped that the arrival of the BSEN will encourage them to do so.

Appendix—avoiding ultimate limit states

The following discussion concerns the latest prEN1997-1 text being finalised at September 2001, which, although unlikely, could still change before formal voting in June 2002.

In designing by calculation to avoid the occurrence of ultimate limit states, cases A, B and C have been replaced by a system that has three design approaches. It is clearly stated that the particular design approach to be used shall be according to national determination. The occurrence of an ultimate limit state shall be avoided as follows.

When considering a limit state of rupture or excessive deformation of a structural element or the ground (STR or GEO), it shall be verified that

$$E_d \leq R_d \qquad (1)$$

where E_d is the design effects of actions and R_d is the design resistance. The design effects of actions shall be derived from the following equation

$$E_d = E\{F_d, X_d, a_d\} \qquad (2)$$

where F_d is the design value of an action, X_d is the design value of a material property and a_d are design values of geometrical data. At this point, one of the three different design approaches enters the calculation. Partial factors on actions may be applied either to the actions themselves (F_{rep}) or to their effects (E), according to national determination

$$E_d = E\{\gamma_F F_{rep}, X_k/\gamma_M, a_d\} \qquad (3)$$

or

$$E_d = \gamma_E E\{F_{rep}, X_k/\gamma_M, a_d\} \qquad (4)$$

where F_{rep} is the representative value of an action, γ_F is a partial factor for an action which takes account of the possibility of unfavourable deviations from the representative value, γ_E is a partial factor for an effect of actions which takes account of the possibility of unfavourable deviations from the representative value, X_k is the characteristic value of a material property and γ_M is a partial factor for a material property, also accounting for dimensional variations.

Equations (3) and (4) include X_k/γ_M in the calculation of actions because ground material properties may affect the values of geotechnical actions in some cases.

EN 1990 states that γ_f is a partial factor for an action and takes account of the possibility of unfavourable deviations of the action value from its characteristic value. Likewise γ_{Sd} is a partial factor taking account of uncertainties in modelling the actions and in modelling the effects of actions. EN 1990 allows γ_{Sd} and γ_f to be combined into one factor multiplying F_{rep}

$$\gamma_F = \gamma_{Sd} \cdot \gamma_f$$

It can be seen that γ_F is applied to the action itself in equation (3) while γ_E is applied to the effect of the action in equation (4). In both cases, γ_M is applied directly to the characteristic material strength, X_k.

Similarly, choices of design approach are introduced into calculations of the design resistance, R_d, as follows. The design resistance shall be derived from the following equation

$$R_d = R\{F_d, X_d, a_d\}/\gamma_R \qquad (5)$$

where γ_R is a partial factor on resistance. Partial factors may be applied either to material properties (X_k) or resistances (R) or to both, according to national determination

$$R_d = R\{\gamma_F F_{rep}, X_k/\gamma_M, a_d\} \qquad (6a)$$

or

$$R_d = R\{\gamma_F F_{rep}, X_k, a_d\}/\gamma_R \qquad (6b)$$

or

$$R_d = R\{\gamma_F F_{rep}, X_k/\gamma_M, a_d\}/\gamma_R \qquad (6c)$$

The three design approaches in effect adopt different combinations of equations (3), (4), (6a), (6b) and (6c).

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