The development of codes of practice for design

Le développement des normes de projet

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SYNOPSIS A new style of Design Code is described which concentrates on setting professional standards. Performance criteria are set down in terms of a list of independent "limit modes" which must be forestalled in each of a given set of "design situations" which are judged to envelope the most hazardous conditions which the facility must survive. Calculation methods are reserved to non-statutory appendices by avoiding mention of any "safety factor". Instead, engineers are guided to the direct selection of appropriate design values.

1 BACKGROUND

Codes of Practice are often written by committees of engineers who do not agree on their objectives, and who therefore leave their collective aims undefined. Their Codes may then be criticised both for failing to set proper standards and for over-specifying calculation methods and construction techniques which are soon outdated. Lawyers are in no such doubt: Codes of Practice and Design Standards are seen as offering criteria against which the actions of professional engineers may be judged.

If Codes avoided textbook topics and concentrated on defining mandatory steps, then the role of their drafters would be much clarified. Technical Reports could be produced to justify particular calculation methods, and separate Standards could be produced for new materials such as geotextiles.

A further challenge for geotechnical engineers is that design authorities are demanding codes which interface with structural codes written in limit state terms.The use in structural codes of partial factors on material properties and loads follows original work in the reliability of well-defined systems such as radio transmitters which comprise components whose individual failure rates were the subject of rigorous statistical tests on the production line. Geotechnical designers usually tolerate uncertainty - of the ground "system", soil behaviour, and future environmental influences - which is of a different order to that experienced by the electronics designer . Statistics relating to the particular job in hand will, moreover, be conspicuous by their absence: the rate of sample testing by volume of affected soil might be 10^{-7} or less. Any attempt to supplant, or even decorate, the process of foundation design by a list of approved formulae and prescribed partial factors is bound to lead to complacency, error and, ultimately, litigation. On the other hand, the essential feature of limit state design is its direct consideration of critical events: partial factors are redundant if the designer can be guided directly to safe values.

These precepts guided the author in his production for the U.K. Department of Transport (Bolton, 1988a) of a draft Code for Bridge Abutments on Spread Foundations . The Code is written in limit state terms to be compatible with the U.K. Bridge Code B.S.5400 . It is accompanied by a separate Technical Report (Bolton, 1988b) which exemplifies the calculation methods called for in the Code.

2 FUNDAMENTAL REQUIREMENTS

A code should begin by specifying the class of construction to which it applies and the education, training and experience required of the personnel who will use it. The code must aim to ensure that the facility which is being designed remains safe and serviceable during its intended life. It must also permit the designer flexibility to achieve economical solutions, taking both capital and maintenance costs into account. The code must therefore establish objective criteria against which a proposed scheme should be checked. Since the collapse of geotechnical works usually threatens life, it will be deemed necessary to adopt separate criteria to deal with collapse and serviceability. Economy may dictate levels of serviceability, whereas society should demand more rigorous standards of safety.

Should a structure fail to satisfy one of its performance requirements it will be considered to have reached a limit state. The purpose of the code should be to guide the designer through a sequence of decisions aimed at eliminating foreseeable limit states.The variety of potential limit state events which threaten any structure is, however, infinite. In order to balance the needs of safety and economy in design it is therefore necessary to reduce the consideration of limit state events to a relatively small number of trials of critical events. The minimum number of trials necessary for any particular class of structure is determined firstly by the number of independent modes of behaviour of the structure, and secondly by the diversity of situations which it will be asked to face.

The code should give details of the limit modes and the design situations which must be considered in assessing the suitability of a design. The limit modes should be representative of the modes of behaviour which are known to lead to unsatisfactory performance of structures in the class under consideration. The specified design situations should be sufficiently hostile and of sufficient variety to safely encompass all foreseeable conditions of construction and use.

Design situations will have to be defined not only in terms of critical loading incidents, but also the soil conditions which are to be assumed in the assessment. In the design of a retaining wall, for example, it is essential to know whether compaction stressses must be allowed for behind the stem, whether the fill must be assumed to be fully softened to a critical state at collapse, whether the drains are to be assumed blocked in the worst case, whether passive support in front of the base must be neglected to recognise the future possibility of a service trench etc. The design authority must decide these questions even though it has sparse information to guide it. A Code which dodges these issues is failing to act as a Standard.

Limit modes must be subdivided into collapse limit modes, concerned principally with safety, and serviceability limit modes concerned principally with loss of function or appearance. Each trial of a potential collapse should be based on the most unfavourable conditions which could reasonably be anticipated at that particular stage. The code must offer specific guidance to the designer in the selection of worst credible characteristics for the soil-structure system, and the external influences acting on it: no further safety factor will then be necessary.

The structure must separately be shown to be serviceable, in the sense that excessive deformations and cracks are avoided at certain critical stages during its construction and design life. It may be cost-effective to permit reparable deformations to take place under certain exceptional conditions if the cost of prevention exceeds the possible costs of surveillance and repair. Design values in serviceability checks may be less severe than the worst credible values used in collapse checks. In such circumstances a detailed, costed, contingency repair plan should be appended to the operation and maintenance manual for the structure.

3 LIMIT STATE CRITERIA FOR BRIDGE ABUTMENT WALLS

Reinforced concrete abutment walls with spread bases will be used to illustrate the specification of design checks in terms of limit mode and design situation. Five independent limit modes are described which cover qualitatively the whole range of possible soil-structure behaviour. Design situations are specified by reference to three critical loading incidents, and to the soil conditions to be assumed around the structure for the purposes of the evaluation.

3.1 Limit modes

Mode 1: Unserviceability through soil strain.

The magnitudes of soil strain are such as to imply unserviceability of the structure. Unserviceability due to strains in the natural soil substratum may take the form of loss of headroom under the deck, loss of clearance in joints and bearings, disruption of drains, or unfavourable load distributions between bridge supports. Compaction of loose backfill by live loads in service may also lead to a step developing behind the abutment wall which would cause extra road repair costs.

The designer must generate a list of performance criteria in terms of the actual deflection requirements of specified components. Calculated deflections may exceed permissible limits where reliable means of readjustment such as jacking points can be economically provided.

Mode 2: Unserviceability through concrete deformation.

The reinforced concrete structure develops excessive internal deformations arising from the combined actions of any bridge loads and soil stresses acting upon it. Excessive deformations include crack width criteria and permissible stresses in concrete and steel.

Mode 3: Collapse through soil failure alone.

Active failure of the backfill coupled either with sliding failure of the base or the failure of the natural soil substratum, permits an incalculably large movement of the otherwise undamaged wall, acting as a monolith.

Mode 4: Collapse with both soil and concrete failure.

The reinforced concrete structure is ruptured whether due to excessive tension, compression, shear or moment arising from the combined actions of any bridge loads and soil stresses acting on it.

Mode 5: Collapse arising without soil failure.

Structural components fail, without previous signs of distress, through brittleness or lack of continuity and without mobilizing the full strength of neighbouring soil bodies.

For example, brittle shear failure of the reinforced concrete base occurs, due to the ommission of stirrups: neighbouring soil bodies could not be assumed to be at failure at the instant of collapse, and the structure could be vulnerable to stress concentrations on the base.

Mode 5 can usually be avoided by evasive measures which ensure ductility of members and continuity of support. Collapse must then be preceded by an unserviceable condition which will have been checked under Modes 1 or 2.

3.2 Loading incidents

Incident C: Construction nearing completion.

The backfill to the structure is in place. The maximum superimposed load, whether consisting of the paving machine and the higher elevation pavement or of the machine used to compact the backfill, or some other, will be considered to act in whatever location maximises the hazard.

Deck loads appropriate to erection are to be included unless their contribution is found to be beneficial - to base sliding, for example.

Incident P: Maximum primary loading.

Superimposed loads on the carriageway over the fill shall comprise a uniform surcharge for normal traffic and a local surcharge representing an abnormally heavy vehicle, sited for maximum hazard.

Dead loads from the deck are to be applied: primary live loads will also be included unless their contribution is found to be beneficial.

Incident L: Longitudinal loading incident.

Dead loads and primary live loads from the deck, and superimposed loads on the fill, will be taken to act in conjunction with one agency of longitudinal loading, forcing out the abutment. Temperature restraint, friction at deck bearings, and the braking of vehicles on the deck, are to be considered.

3.3 Soil conditions

Two soil conditions are to be used for the evaluation of limit events. The appropriate condition to be invoked in a particular case will depend both on the limit mode under investigation and on the type of loading incident to be applied.

Condition R: Removal of base support, active fill.

A narrow service trench will be invoked in front of the base, which eliminates passive support. The lower carriageway pavement will be assumed not to be present. Active earth pressures, modified by current superimposed loads, will be taken to act in the fill.

Condition S: Support at base, enhanced lateral pressures in the fill.

The base is to be taken to be supported with the greatest credible stiffness. For this purpose, the lower level carriageway will be taken to be present and resistance is to be invoked in front of the base. Enhanced lateral stresses will be taken to be locked-in to the backfill due to the initial compaction process or to the later application of superimposed loads. Additional lateral stresses may also be generated by current superimposed loads.

Condition R is to be selectd when the failure mode would be suppressed by the presence of extra base support. This is always the case with limit modes 1,3,4 and 5.

Condition S is to be selected when the failure mode would be aggravated by the presence of extra base support. This is generally the case with limit mode 2 when locked-in lateral pressures (eg due to compaction) in the backfill could be relieved by base movement, thereby reducing the load effects in a structural serviceability calculation.

Parameters describing the strength and stiffness of the soil, and the location of the groundwater, are to be selected to be as unfavourable as they could reasonably in be in the circumstances.

4 TRIALS OF CRITICAL EVENTS FOR ABUTMENT WALLS

Table 1 displays the factors governing the critical events to be forestalled by calculation. Events 9, 10 and 12 (marked *) are not critical since they are inherently less demanding then other events in the list. Events 7,8, and 11 (marked Δ) will become non-critical if the serviceability checks of events 1 to 6 use maximum design loads together with yield stresses inferior to ulimate strengths.

In addition to the required calculations, it will also be necessary to demonstrate that Mode 5 failures will be avoided through evasive measures ensuring ductility of members and continuity at joints, taken together with the avoidance of serviceability failure Modes 1 and 2.

For every limit event, a free body diagram must be constructed which demonstrates that the complete structure is in equilibrium under the action of stresses generated in the backfill, loads transmitted through the deck, and bearing pressures created around the foundations. Depending on the limit mode being checked, the output of the free body diagram may be a demonstration that bearing stresses and associated soil strains, or structural load effects and consequential structural deformations, are admissible.

Table 1: Limit Events

Event number	Limit mode	Soil condition	Loading incident	Design Variable
1	1	R	C	foundation outline
2	1	R	P	
3	1	R	L	
4	2	S	C	concrete sections
5	2	S	P	
6	2	R	L	
7Δ	3	R	C	foundation outline
8Δ	3	R	P	
9*	3	R	L	
10*	4	R	C	concrete sections
11Δ	4	R	P	
12*	4	R	L	

The particular conditions and objectives relating to each limit event can then be set out; a few examples are given below.

Limit Event 1: (Mode 1, Condition R, Incident C)

Construction loads must not cause bearing stresses to exceed their serviceability limit. Both drained and undrained foundation conditions will be checked, if relevant.

Additional lateral stresses due to compaction need not be included since relatively small wall translations would relieve them. Soil strains need not be estimated at this stage because they will be exceeded in service if yield is substantially prevented during construction.

Limit Event 4: (Mode 2, Condition S, Incident C)

Construction load effects in the structure will be derived, and then checked in accordance with the structural concrete code.

The lateral stress distribution in the backfill will not be inferior to

(i) the largest compaction-induced stresses which could reasonably be expected to occur, account being taken of any weight limits to be imposed on contractors' plant.

(ii) stresses due to self weight and superimposed loads based on an earth pressure coefficient $K_o = 1 - \sin\varphi'_{max}$, which may be reduced to an active coefficient $K_a = (1 - \sin\varphi'_{mob})/(1 + \sin\varphi'_{mob})$ based on a mobilizeable soil strain in the case of walls designed to be correspondingly flexible; where φ'_{max} or φ'_{mob} are taken at their lowest credible value bearing in mind the projected control over compaction.

Limit Event 6: (Mode 2, Condition R, Incident L)

The calculations of Limit Event 4 will be modified for longitudinal loading, forcing out the abutment.

The lateral stresses in the backfill will be calculated using active pressures supplemented for current superimposed loads only. This takes account of the degree of wall movement necessary to produce distress being at least as large as that required to erase locked-in lateral pressures.

5 DESIGN CONSIDERATIONS FOR ABUTMENT WALLS

Having clearly established the required test conditions for design evaluation, it will be necessary to set additional standards regarding the calculations. Traditionally, Codes have either introduced safety factors in terms of resistance divided by load, or have set permissible limits to stresses. The safety factor approach suffers from several serious flaws:

- It requires "typical" parameter values but is constitutionally unable to advise on how pessimistic the selection should be; the strength and stiffness of soils can only be selected when the particular limit mode and design scenario are known.
- The definition of safety factor itself is arbitrary; in earth pressure calculations especially, loads and resistances are impossible to distinguish; furthermore equilibrium demands that resistance should always balance load so the introduction of factors may lead inadvertantly to gross design errors through lack of global or local equilibrium.
- Control of deformations should logically involve soil stiffness rather than strength. There is little doubt that the conventional factor of "safety" of 3 on bearing capacity is actually serving as a crude factor of serviceability; our knowledge of soil mechanics and our database on foundation behaviour is now sufficient to permit a more rational approach.

The proposed Code is based on a modification of the alternative permissible state methodology in which advice is given to facilitate the direct selection of design values corresponding to the "worst credible scenario". A few examples are given below.

1) Superimposed traffic loads above the fill.

The HB load defined in BS5400 Part 2 is used as a standard heavy vehicle which applies a vertical surcharge of 130 kPa over the 2 x 3.5 m plan area of a 2-axle bogey. Earth pressure calculations are expected to include this as a surcharge over a corresponding strip of carriageway. Instructions are given for the siting of the load to create maximum effects: close to the stem for structural calculations, just beyond the plane of the heel for most soil calculations.

2) Bearing stresses for serviceability.

Two requirements are to be met: large areas of yielding soil are to be avoided, and the strength demanded of the soil directly beneath the foundation must not mobilise excessive soil strains. In an undrained clay, the first condition requires a stress reduction factor of about two on collapse, noting that an ideal elasto-plastic soil would yield beneath a strip load at a pressure of πc_u. The second condition can be taken to imply that a typical footing should not displace more than 1% to 2% of its width, which is approximately equivalent to limiting the compressive strain beneath it to 1%. A suitable serviceability stress might therefore be derived from a standard bearing capacity calculation, but based on the soil strength mobilised after 1% strain in an appropriate triaxial test. The serviceability limit would be the lower of the two.

3) Soil strength at collapse.

Critical state (fully softened) soil strengths are to be used for the backfill since collapse mechanisms invariably involve localisation of shear strain along slip surfaces. The value of ϕ_{crit} for granular fill may be taken to range from 32° for round particles to 37° for angular particles. If it is intended to use any additional dilatant strength component in bearing capacity calculations, then the peak component must be safely under-estimated by taking the soil element to be as loose, and as highly stressed, as it could reasonably be.

6 IMPLEMENTATION

When a new Code is proposed, such as that described above, it is necessary to evaluate its performance in the hands of practising engineers. "Code calibration" is the term sometimes used for this process. It is important to recognise, however, that structures designed by the new method might in principle be either more or less sturdy than those designed previously, and that this could be perfectly acceptable. All that matters is that structures avoid limit states. Code validation must therefore be based solely on the evidence of structures approaching limit states. If no such evidence is available from the field it is likely that designs have been too conservative; a programme of prototype and model testing might then be prudent.

It is also necessary to check that the wording of the Code is sufficiently clear to ensure that different designers are broadly working to the same performance specification. This has by no means been the case in the past, when "typical values" for parameters in poorly defined incidents gave the designer scope to justify any desired degree of robustness.

7 CONCLUSION

The Code referred to here, with its accompanying Technical Report on methods of calculation, is presently under scrutiny by practising engineers in the U.K. Present indications are that it will be capable of offering the designer both a clearer view of design requirements and additional flexibility to achieve them. Newly designed walls happen to be similar to those previously designed in good offices.

REFERENCES

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