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Reliability in geotechnical design – some fundamentals

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ABSTRACT: This paper is written from the point of view of practical geotechnical design. Five features of the designer's situation are noted: (a) his specific knowledge of the site, the ground conditions and their possible variability; (b) the importance of extreme variations in causing failures; (c) the large number of variables usually involved in a design situation; (d) the need for "robustness"; (e) the significance of human error. It is argued that a set of safety provisions in a code of practice should accommodate these items. The possibility of using reliability analysis rather than factors of safety is discussed in the light of these issues.

Keywords: Geotechnics; design; robustness; reliability; variability

1 INTRODUCTION

Severe failures of civil engineering structures are fairly rare, but when they occur they may have serious consequences, involving multiple deaths or injuries. Less severe failures, leading to inconvenience and some cost for repairs, are more common. Designers and code drafters aim to avoid failures of all types, across the full range of severity. This is generally achieved by demonstrating that a design would not fail, even if parameters and conditions were significantly worse than those it is thought most likely to prevail. The parameters considered may be either basic input to the design calculations (eg actions and material strengths) or values derived within the calculations (eg action effects and resistances).

As a shorthand in this paper, severe failures leading to danger or gross economic loss will be regarded as ultimate limit states (ULS). Less severe failures, leading to inconvenience, disappointment or relatively minor cost will be termed serviceability limit states (SLS). Strictly, the failure occurs when the limit state is exceeded. References to clauses or paragraphs of codes will be shown thus: {...}.

In order to ensure that severe failures (ULS) are very unlikely, recent drafting of codes has mainly used a partial factor approach in some form. The factors are applied to parameter values that are thought to be reasonably likely to occur, in order to derive parameters values that are very unlikely to occur for the calculations. This approach is widely used in structural design, and has been taken up by the geotechnical community partly to achieve compatibility in the analysis of ground and structures as they interact and rely on each other.

For serviceability (SLS), two broad approaches are in use: (a) direct calculations of displacements, crack widths and damage, and (b) limits on the mobilisation of strength allowed, with the intention that this will limit displacements and damage. In both cases, it is normal practice to base calculations on reasonably likely values of parameters. Approach (a) is ideal in principle, but may be very difficult to apply in practice. In approach (b) the proportion of strength mobilised can be limited by applying a factor to the strength which is sometimes termed a "mobilisation factor", but which in use is difficult to distinguish from a partial factor applied to material strength or resistance, as might be used for ULS calculations (Osman and Bolton 2006, BS8002).

The "reasonably likely" values may be deliberately slightly cautious ("characteristic" in Eurocodes, "conservatively assessed means" in some US publications, "moderately conservative" in some UK practice) or perhaps mean values – the most likely to occur. The writer would argue that good designers would not, by instinct, use mean values (the most probable values) in situations of significant uncertainty, except in safety formats that allow the designer to vary the factors applied as a function of his perception of variability. This latter was explicitly the case, for example, in earlier Swedish practice (Boverket, 1995).

An alternative approach, allowed by Eurocode 7 (EC7), is "direct assessment of design values", in which the designer consciously assesses a value sufficiently severe that a worse value is extremely unlikely to occur. It is not easy to define this value, and EC7 resorts to comparisons with factored values by saying "If design values of geotechnical actions are assessed directly, the values of the partial factors recommended in [the code] should be used as a guide to the required level of safety" {2.4.6.1(5)}.

A further alternative, not yet adopted in codes of practice, might be to perform a reliability calculation, in which the probability of failure is calculated, or alternatively an index to it such as the "reliability index" β. This is generally achieved by considering a stochastic spread of parameter values, including some that are very severe. Here again, therefore, the intention is to allow for a reasonable range of severe values.

2 COLLECTION AND INTERPRETATION OF GEOTECHNICAL DATA

2.1 *Specific knowledge of the site*

In structural design, it is commonly the case that drafters of codes of practice have more knowledge about the parameters of strength and loads relevant to a particular design, and their variability, than does the designer. For example, code drafters may be more knowledgeable about wind loading, floor loading, variations in dimension of cast in situ concrete, or seismic loading than is the designer, and the same applies to the variability of steel and concrete. However, in geotechnical design, the designer knows the location of the site, something of its geology and ground water conditions and the results, or paucity of results, of the ground investigation, together with their likely reliability. This information varies considerably from one design to another and could not possibly be known by the code drafter.

It is suggested, therefore, that the designer's understanding of the uncertainty of the parameters of the site is of critical value and must be included in a rational safety format.

EC7 achieves this, to some extent, by asking the designer to assess not the most likely value for a strength parameter, but "a cautious estimate of the value affecting the occurrence of the limit state" {2.4.5.2(2)}. This is essentially similar to the American "conservatively assessed mean" or British "moderately conservative" value, both discussed further by Simpson et al (2009). It is doubtful, however, whether this makes full use of the site-specific knowledge of the designer.

2.2 *Large variety of data*

Suitable geotechnical information is usually scarce. Besides requiring information gained from the site itself, good geotechnical engineering requires study of published literature, collection of comparable case histories and the assimilation of sets of data that are very diverse in both quantity and quality. This is a conceptually difficult process because it requires the combination of data that are precise (from the site) and relatively vague (from literature about similar soils), data that have obvious interpretation (eg vane tests for undrained strength) with others of more doubtful interpretation (eg penetration tests or liquidity indices), data that are plentiful (eg quick undrained triaxial tests) with those that are few (eg plate tests or triaxial stress-path tests), and so on. These all require a careful review of their relative reliability, which depends on factors such as the skill of operators, the details of equipment used, the specification followed (which may be unknown, for older information), and so on.

Assimilation of all this information to obtain parameters useful in calculations is a skilful, if inconvenient, process, not readily reduced to a computer activity. Nevertheless, it is very important that the geotechnical process does not discard any information that is potentially useful, unless careful examination shows that it is worthless.

A safety format suitable for geotechnical design must encourage this process and use it to best advantage. EC7 attempts to do this by making the designer responsible for the selection of the characteristic values of materials, avoiding mathematical prescription of their derivation. Inevitably, such a process leads to values affected by the subjective experience, knowledge and judgement of the designer. The author would contest that it is better to accept such subjectivity than to discard the valuable information it provides. An important issue for codes of practice is to encourage and facilitate communication of such subjective information, so that it can be understood and examined by others.

3 THE IMPORTANCE OF EXTREME VARIATIONS

3.1 *Reasons for geotechnical failures*

It is often observed that severe failures rarely occur as a result of the reasonably expected statistical variation of parameters. Perhaps this should not be surprising since most safety formats are designed to prevent such failures. Arguably, some earlier failures of that type led to the introduction of partial factor formats (Simpson 2007). Most often, geotechnical failures occur because (a) the ground conditions and geological features are significantly different from those expected, beyond the anticipated range of variation, (b) groundwater pressures are worse than had been expected (Simpson et al 2011), or (c) human error has led to mistakes in calculation or omission of an important factor, such as a likely extreme load or a failure mode.

3.2 *Three examples*

In their report on the public inquiry into the Nicoll Highway collapse in Singapore, Magnus et al (2005) place the main responsibility on human errors in design. The diaphragm wall was designed to extend 3m below the soft marine clay into much stronger Old Alluvium. However, Magnus et al note that at the location where the collapse started, the surface of the clay had been eroded by a buried channel. Figure 1, taken from Whittle and Davies (2006), shows that as a result, the diaphragm had far less penetration into the Old Alluvium than was intended. The Inquiry report concludes that this “inadequate appreciation of complex ground conditions” was a contributory factor in the collapse. There was also an element of human error or poor communication, since the designer’s original intention was for 3m penetration, yet the construction team were content to accept much less than this.

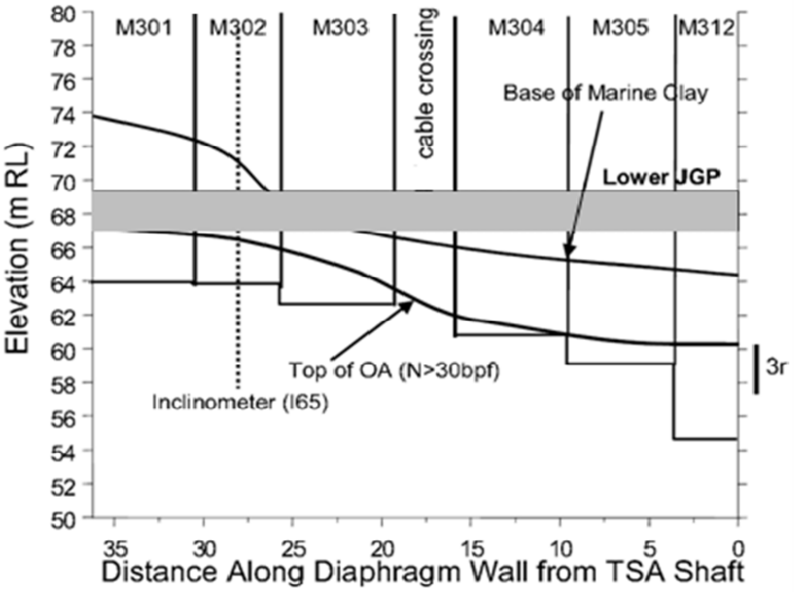

Figure 1. Lack of penetration at buried valley (after Whittle and Davies 2006)

Figure 2, taken from Potts et al (1990) shows a section through the Carsington dam embankment, which failed during construction. The cause was identified to be the presence of the “yellow clay”, a layer that had not been identified in ground investigation and which behaved in a brittle manner, allowing the development of a progressive failure.

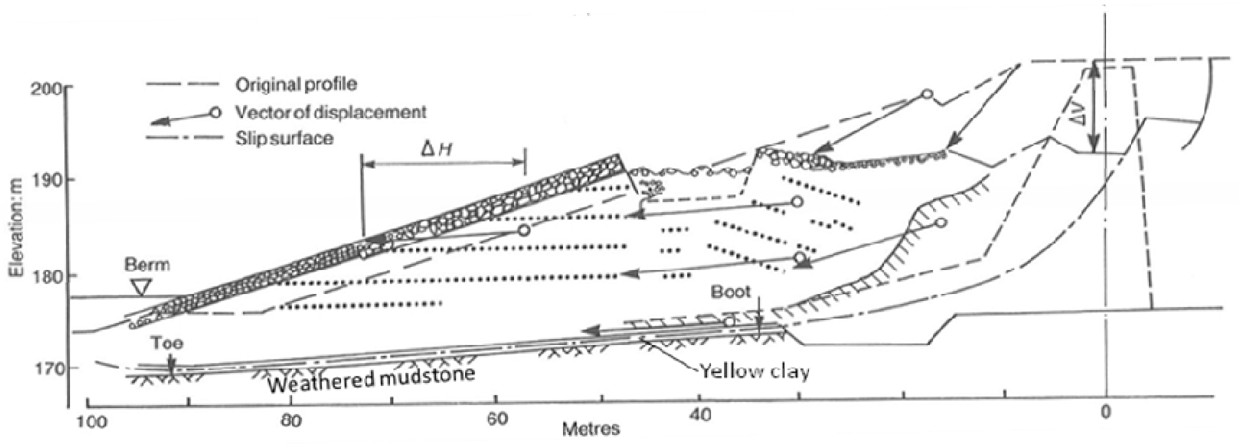

Figure 2. Cross section of Carsington dam (after Potts et al 1990)

Figure 3 shows an excavation for a small reservoir on sloping ground on Lias Clay in southern England. The "head" material was also stiff clay, but it had slipped down the slope and therefore contained pre-sheared surfaces, which also existed at the interface with the undisturbed material. The pre-sheared material exhibits a much lower angle of shearing resistance and, perhaps more important, does not dilate as it shears so its undrained strength is considerably lower. Failure to recognise these features led to the slip.

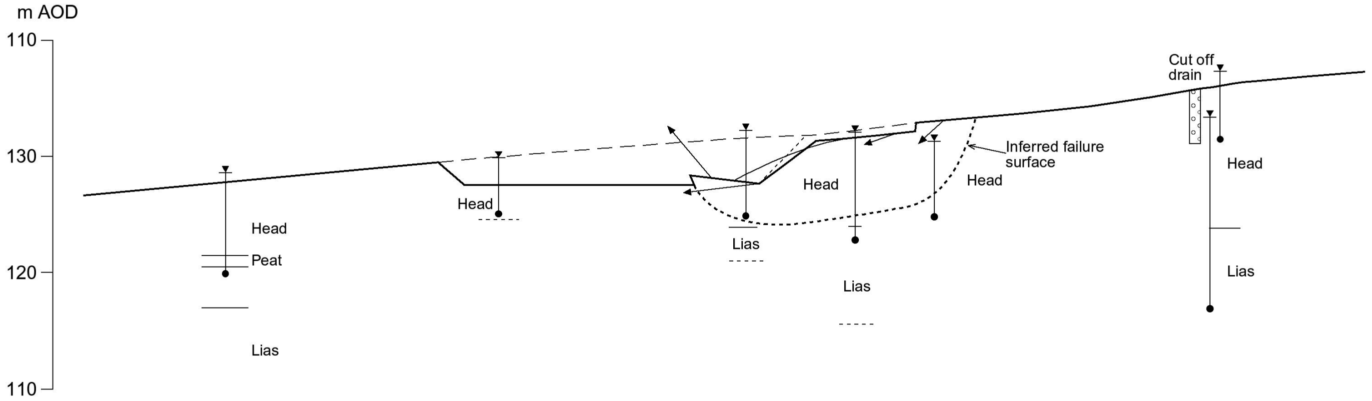

Figure 3. Slip at excavation for a small reservoir.

3.3 *Considering the "worst credible"*

In the writer's opinion, it is essential that engineering designers consciously consider the worst situations and parameter values that could be imagined on the basis of a reasonable and well informed engineering assessment. It is important that this involves and encourages "thinking outside the box", not merely extrapolating what is reasonably likely, but deliberately contemplating the effects of what is credible, even though unlikely. Simpson et al (1981) termed such a value the "worst credible" and suggested that it might be assumed to have a 1 in 1000 chance of occurrence, on the basis that designers would be unlikely to be able to believe that anything more remote might happen. The term "worst credible" will be used here with this meaning.

In contemplating the worst credible, designers need to give thorough consideration to the geological setting of the site, its history, geomorphology and hydrology. These have to be related to possible behaviour of the ground, including features such as buried channels, pre-sheared zones or slip surfaces, permeable bands within clays, etc., as illustrated by the three examples above.

None of these features are readily represented either by partial factors or in a reasonably simple reliability analysis. The danger of both these approaches is that applying prescribed factors or a more complex numerical calculation may give a false sense of security, attracting attention away from the essential tasks of geotechnical engineering discussed above.

EC7 attempts to tackle the problem of extreme conditions, to a degree, by providing extensive checklists of aspects of design and behaviour to be considered. In the writer's opinion, these are important, helping to outline the procedure to be undertaken in design, not just a numerical calculation. The writer considers that one simple addition would improve EC7: to require that the designer checks that design values of ground parameters are, in his opinion, at least as severe as the "worst credible". In other words, it should not be possible that a ULS is caused by the occurrence (in a relevant body of soil) of a value for a ground parameter that the designer considered could credibly occur.

3.4 *Parametric variations*

It is often taught that calculations in which parametric variations of parameters are considered is a valuable feature of good engineering design. However, such calculations are rarely carried out, except in terms of load combinations, especially prevalent in bridge design. Parametric studies encourage checking a design for extreme values of parameters, usually considering one parameter at a time.

Conscious of these issues, Simpson et al (1981) proposed that designers should not enter calculations mainly on the basis of a "characteristic" or moderately "cautious" value, but that the starting point should be an assessment of the "worst credible" value of a parameter. A safety system was then devised, the "λ-method", in which this worst credible was taken as a pivot point, from which design values were derived. This was achieved by requiring the designer also to assess the "most probable" value, and using the difference between worst credible and most probable as a measure of uncertainty. The important point here, however, is that conscious thought about the worst credible was required.

Many safety formats used in codes of practice generate extreme values of parameters by applying partial factors. In most cases it becomes incredible that several variables could attain very extreme values simultaneously. This underlies the principles of load combinations following the principles developed by Turkstra and Madsen (1980), and much of seismic design, in both of which the effect of one dominant variable is considered while others are given less extreme values. When load combinations are used, it may be necessary to carry out several independent calculations, each treating a different action as the lead variable. This is also the underlying principle of "Design Approach 1" in EC7, in which two independent calculations are required, one with very severe loading, and the other with a very severe view of material strengths. In both cases, the "very severe" values are probably beyond the credible range, with the intention of ensuring that failure is incredible. The approach was discussed in more detail by Simpson (2007).

4 THE NEED FOR "ROBUSTNESS"

4.1 *Large number of secondary variables*

In conventional designs using factors of safety in some form, a small number of main variables is selected for factoring, effectively performing a parametric study. Similarly, in a reliability analysis a relatively small number of variables is usually considered. Real constructions in real ground are much more complex, and practical design has to accommodate a reasonable degree of unforeseen (and unforeseeable) variations in loading and geometry, including the precise disposition of materials and layers in the ground, and deterioration of structures. This is conventionally achieved, in part, by adopting additional margins or factors on the selected primary parameters.

For example, for situations dominated by water pressure, Simpson et al (2011) note that "secondary actions" could include sedimentation around a structure in water, excavation of the ground above a structure relying on the weight of ground, minor vehicle or ship impacts, considered too small to include in calculations, or vandalism of various kinds. If these "secondary" actions are large, failure could occur but the fault may be seen to rest with the owners or maintainers of the structure, or the vandals; alternatively, the designer should have foreseen them and was wrong to omit them from the primary actions for which the structure was designed. However, if the secondary actions are small, the owner would reasonably expect the structure to be sufficiently robust to withstand them. In this context, "large" and "small" effects have to be judged in relation to the magnitude of the primary actions.

It follows that the factors or margins applied to the primary parameters should accommodate the possible secondary parameters that are not otherwise included. These variations could be applied either to the actions themselves, in deriving design values, or to the action effects. Merely considering the variation of the primary parameters within the range the designer or code drafter considers credible may not provide sufficient safety.

4.2 *Human error*

In the writer's experience of investigating failures, errors in geotechnical engineering design are depressingly common. These include arithmetic errors, lack of expected basic knowledge, failures of communication, oversight or misunderstanding of important information, etc. Although such errors sometimes cause failures, it is fortunate for society and for the engineering profession that they often do not. In part, at least, this is because adequate factors or margins of safety have been incorporated in other aspects of the design.

A significant influence of human error in the results presented for trial calculations at the Eurocode 7 conference in Dublin was noted by Simpson (2005).

If an error is made involving a factor of 10, it is likely that the design will appear inadequate "by inspection" and it will be spotted during the process of design or construction. However, an error by a factor of 2 or less may be much more difficult to spot, except in cases of very repetitive design. Quality control and checking systems aim to catch such errors, but quite frequently fail. The agreed major cause of the Nicoll Highway collapse (Magnus et al 2005) was an error in steelwork design of this magnitude. Simpson et al (2008) argue that avoidance of other errors of similar or smaller magnitude could well have prevented the failure.

Errors also occur in construction, even when designs are sound. As with design errors, many of these do not cause failures because of the protection given by adequate margins or factors of safety.

The need for an adequate margin against human error is another important feature of robustness. It is essential that safety systems make provision for this. It is also important that codes and standards are both sufficiently comprehensive and sufficiently clear, and as simple as possible, in order to avoid misunderstandings that contribute to errors.

4.3 *Calibration – extrapolating from success*

A great deal of geotechnical design and construction leads to a successful outcome. This provides the biggest possible stochastic test of design approaches. It would be unwise, therefore to adopt a system that gave design results not comparable with conventional practice, especially if they were significantly less cautious.

In view of the difficulties of secondary variables and human errors, theoretical derivation of factors of safety has eluded most developers of codes of practice. Although reliability calculations are sometimes attempted, in reality almost all partial factors and margins used in codes have been derived by engineers considering what seems reasonable and, in particular, calibrating the factors to give results similar to previous, well tried practice.

Nevertheless, the need for both economy and sustainability motivate a gradual reduction in conservatism, until it becomes clear that this leads to failures, ULS or SLS. Hence it is appropriate to reduce factors of safety gradually as codes are evolved. A secondary issue for code drafters, in countries where designers have some freedom to choose between codes, is the fact that codes that give a more economic result will usually be adopted more readily.

Existing designs that have performed successfully have been adequate in terms of both ULS and SLS. Hence, in the calibration process it may be difficult to know whether the conventional factors or margins that were adopted were governed by the needs of ULS or SLS. This means that, inevitably, some of the partial factors used for ULS in codes, derived partly by calibration exercises, are influenced by the needs of SLS. It was noted above that it may be difficult to distinguish in practical design between mobilisation factors and partial factors of safety, and this difficulty also affects the calibration process.

5 RELIABILITY ANALYSIS

In the foregoing discussion, some basic requirements of a safety format to be used in geotechnical design have been considered. These have generally been expressed in terms of factors or margins of safety, which could be specified in codes and standards of the type currently available. The use of calculations based more directly on probability theory may have the potential to provide a more rational basis for design, if used directly by designers, or for the prescription of partial factors or safety margins in codes.

The analysis of the previous sections shows that an adequate safety format ought to include proper account of the following features:

- the designer's specific knowledge of the site, the ground conditions and their possible variability. This includes taking full account of the geology, history, geomorphology and hydrology of the site;
- an appropriate assimilation and compilation of data from all available sources, including published literature, collection of comparable case histories and test results, often form several types of test, of varying number, means of interpretation and reliability;
- a parametric study, to reveal the significance of variations of the lead variables;
- in particular, a careful assessment of the worst credible values of parameters. This will often not be obtained from a study of likely values and statistical variations around a mean;
- adequate robustness. This entails providing adequate margins for secondary actions and other variations that are not related to the primary parameters, including moderate human errors;
- adequate prescription for both ULS and SLS, noting that these may be difficult to separate.
- Reliability analyses have the advantage that they provide a comprehensive parametric study. In the author's view, it is possible that advanced reliability analysis may be able to take account of all the aspects listed here, including consideration of extreme values. However, simple reliability analysis, such as based on a study of means and standard deviations, will not achieve this. Indeed, such an analytical approach is more likely to distract attention from the main issues relating to geology, history, geomorphology and hydrology.

Although reliability analysis can provide an overall control on relative safety and economy, it is likely that use of partial factors can be targeted more precisely when using the outcome of calibration exercises.

6 CONCLUDING REMARKS

The purpose of the paper has been to consider what is needed in a safety format that reflects and encourages good geotechnical engineering. These basic requirements are listed in the previous section. It is very important that the attention of design engineers is concentrated on these aspects, and that they are distracted as little as possible by calculation. Hence, in the author's view, codes of practice should strive to provide for these requirements with as little complexity of calculation as possible.

The author submits that these principles should underlie the choice of safety format, whether partial factor, reliability calculations, or other approaches.

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