Foundation design reliability issues

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Overview

The New Zealand Building Code through Verification Method VM4 permits the use of very low factors of safety for the design of building foundations under certain earthquake load cases (as low as FS = 1.1). The use of such low factors of safety for vertically loaded foundations is questioned because it implies a high probability of foundation failure during the design earthquake. Even where the designer may wish to limit forces within the structure and perhaps encourage system damping by permitting soil yielding, the results are likely to be unpredictable because of the uncertainty in predicting foundation performance and variability in performance among individual foundation elements. The desired structural behaviour pattern may not develop, with unintended consequences such as excessive ductility demands on some parts of the structure. Excessive foundation deformations may develop prematurely resulting in significant damage, even for lesser earthquakes.

Background

The procedure for designing building foundations in NZ may be described as a "Load and Resistance Factor Design" procedure (LRFD). In this procedure, the uncertainty and variability in the loads and design actions on foundation elements are considered separately from the uncertainty and variability in the resistance of the foundations, according to the design inequality:

$$\sum \gamma_i Q_i \leq \sum \phi_i R_i \tag{1}$$

In which;

γ_i = load factor for load type i (e.g. 1.2 for dead loads, 1.7 for live loads, 1.0 for EQ loads, for the "ultimate" limit state in NZS 1170)

Q_i = nominal value of load type i

ϕ_i = resistance factor for component of resistance i

R_i = nominal value of computed resistance for component i

The above inequality must be satisfied for several limit states which are defined in relevant codes. For *strength* limit states (e.g. the *ultimate* limit state in NZS 1170, or ULS) load and resistance factors are chosen to provide a high level of reliability that the foundation will have sufficient strength to prevent collapse.

For *service* limit states (e.g. the *serviceability* limit state in NZS 1170), generally checking for excessive deformations, load and resistance factors are often taken to be at or near 1.0 reflecting a philosophy that a lower level of reliability can be accepted for serviceability issues not involving safety. (It should be noted that for the case where the load factor and the resistance factor are both taken as 1.0, the probability of exceedance is nominally 50 percent)

In some jurisdictions, *extreme event* limit states are also considered (e.g. maximum considered earthquake or MCE) but not in NZS 1170. A lower level of reliability is often accepted for *extreme* events.

Figure 1 illustrates how the design inequality of Equation (1) operates: Both the nominal loads (Q_m) and the nominal resistance (R_m) have a certain inherent variability illustrated as "bell" shaped distribution curves. Generally, the variability in foundation resistance will be much greater than for the loads, and so the "bell" is shown to be "fatter". The probability of failure (i.e. load being greater than resistance) may be computed as the area of overlap of the two "bell" curves, shown shaded. To maintain the probability of failure at a low level it is necessary to ensure that the nominal resistance is larger than the nominal loads ($R_m>Q_m$) by applying load factors greater than 1 and resistance factors less than 1. The appropriate values of these factors depends on the shape (width) of the respective "bell" curves and the desired level of reliability.

History of geotechnical resistance factors in NZ

Prior to the adoption of the LRFD design procedure with NZS 4203 in 1976, the variability and uncertainty in both the load and resistance sides of the design equation were lumped together as a single *factor of safety* (FS) being the ratio of nominal resistance over nominal load (FS = R_m/Q_m). Traditionally, for foundations, the minimum factor of safety was taken to be 3 for static loads and 2 for seismic loads (e.g. NZS 1900 of 1965), based largely on precedent.

With the introduction of LRFD with NZS 4203:1976, it was intended to maintain the overall factor of safety for foundations at similar levels as previously but there was a new complication of a load factor that varied from 1.0 to 1.7. Strength reduction factors were not given in NZS 4203:1976 as these were intended to be provided in the respective material codes as they were updated. For foundation design, NZS 4203:1976 recommended (in the commentary) that *pending revision of NZS4205* [Code of Practice for Foundation Design] *a factor of safety of 1.8 should be applied* (equivalent to a strength reduction factor of $\phi = 0.56$) in addition to the load factors for all load combinations, including those with seismic actions.

Capacity design was in its infancy at the time of the introduction of NZS4203 and the code suggested that for certain ductile structure types where …*design loadings on the foundation system are determined by the yield capacity of other parts of the structure, a factor of safety of 1.1 for soil pressures is suggested, pending revision of the foundation code, because at this extreme condition partial yielding of the subsoil might not be significantly damaging and it provides an additional energy dissipating mechanism.* (i.e. a strength reduction factor of $\phi =$ 0.9). Effectively, this recommendation reduced the traditional all-up factor of safety for foundations with seismic loading from 2.0 down to 1.1 for buildings designed using *capacity design* - with seismic load levels already reduced because of allowance for ductility - and from 2.0 down to 1.8 for other buildings.

Capacity design considerations

The introduction of such a low factor of safety for the foundations of *capacity designed* buildings is surprising given the contemporary published views of the main proponent of *capacity design*, Professor Tom Paulay (Binney & Paulay, 1980). Discussing the design of foundations for shear wall structures, Binney and Paulay recommended that for ductile shear wall structures…*the foundations must be capable of transmitting the largest feasible actions to the supporting soil, otherwise the intended response of the superstructure cannot eventuate*. Further, that: *Bearing areas of footings, piles, or caissons should be such that negligible* *inelastic deformations, if any, are developed in the supporting soil under actions corresponding to overstrength of the superstructure*.

The writers of NZS4203:1976 seemed to agree by stipulating that …*foundation systems shall be designed to preclude foundation failure, or uplift of an entire foundation element, at loadings corresponding to yielding of the earthquake energy dissipating elements, taking concurrency effects into account where applicable.* Fulfilment of this code requirement would require a much higher factor of safety than the value of 1.1 suggested in the code commentary.

Binney and Paulay acknowledged that in some cases, the dimensions and locations of shear walls within a building might be such that the overturning moments would be difficult or impossible to resist at the foundations. They recommended that rocking (i.e. uplift of the foundation) might be permissible but that design should be by special study including "dynamic analyses" and that …*bearing areas within the foundation structure be so proportioned as to protect the soil against excessive plastic deformations that would be difficult to predict, and which might result in premature misalignment of the otherwise undamaged shear wall or the entire building*.

To provide the implied level of foundation performance, reliably, requires the use of much higher factors of safety (or lower strength reduction factors in LRFD design).

<u>Current code</u>
Since 1976, the loading code has been revised three times and the previous references to foundation design have been removed. Instead, Verification Method VM4 was introduced to the Building Code documents to provide guidance on foundation design including the strength reduction factors to be applied.

The earlier reliance on traditional factors of safety (e.g. FS = 3 for foundation design) has been replaced by a more rational approach that accounts for specific causes of uncertainty and variability in the computation of foundation resistance including the thoroughness of the site investigation, the way in which soil properties are assessed, the design procedure used, the extent of on-site verification by load testing, and the degree of construction control.

In VM4 strength reduction factors range from 0.40 to 0.65 depending on the method of computing the foundation capacity and the designers qualitative assessment of the above sources of uncertainty, for all load combinations *not involving earthquake over-strength.* Typically, in practice, values range from 0.45 to 0.5 for shallow foundations and from 0.5 to 0.65 for pile foundations.

Values higher than 0.65 may be used where static load testing of foundations is carried out – up to 0.85 where a significant percentage of the foundations are load tested statically to failure at suitable sites.

However, for load combinations *including earthquake over-strength*, the strength reduction factor is between 0.8 and 0.9 irrespective of the design methodology and not requiring static load testing. The use of such high values is inappropriate in most cases given the high level of uncertainty and variability in foundation behaviour and the requirement, identified by Binney and Paulay, for reliable foundation performance in the event of over-strength being developed in capacity designed structures.

The meaning of the words in VM4 *including earthquake over-strength* may not be well understood by some engineers, especially those unfamiliar with capacity design, and the high values of strength reduction factor may be being routinely applied to all load combinations with seismic actions.

Since the introduction of VM4, there have been further developments in assessing suitable strength reduction factors for geotechnical design. For example, the Australian piling code AS2159-2009 has introduced a much more thorough risk based approach where individual risk factors are assessed including geological complexity of the site, extent of ground investigation, amount and quality of ground data, experience in similar conditions, method of assessing soil properties, design methodology, in-situ testing and testing during pile installation, level of construction control, level of performance monitoring after construction, and the level of redundancy in the foundation system. Resulting strength reduction factors range from 0.40 for high risk, low redundancy cases to 0.76 for low risk, high redundancy cases.

Recommendations

The use of very high strength reduction factors (as high as 0.9 equivalent to FS = 1.1) for capacity designed structures is inappropriate. Many foundations so designed will receive over-strength loads during earthquakes exceeding their capacity and leading to excessive plastic deformation. The high variability of soil properties and foundation performance ensures that the overall behaviour of the structure will be unpredictable and, most likely, undesirable. Premature failure of some foundations is likely.

I recommend that for the case of the "ultimate" limit state of NZS1170, the selection of strength reduction factors for foundation design in all cases be based on a risk assessment procedure such as that used in AS2159-2009. The objective being to ensure reliable foundation performance under all load combinations. There seems to be no basis for treating capacity designed buildings as a special case where unreliable foundation performance is acceptable. The present provision appears to have arisen from a historical misunderstanding.

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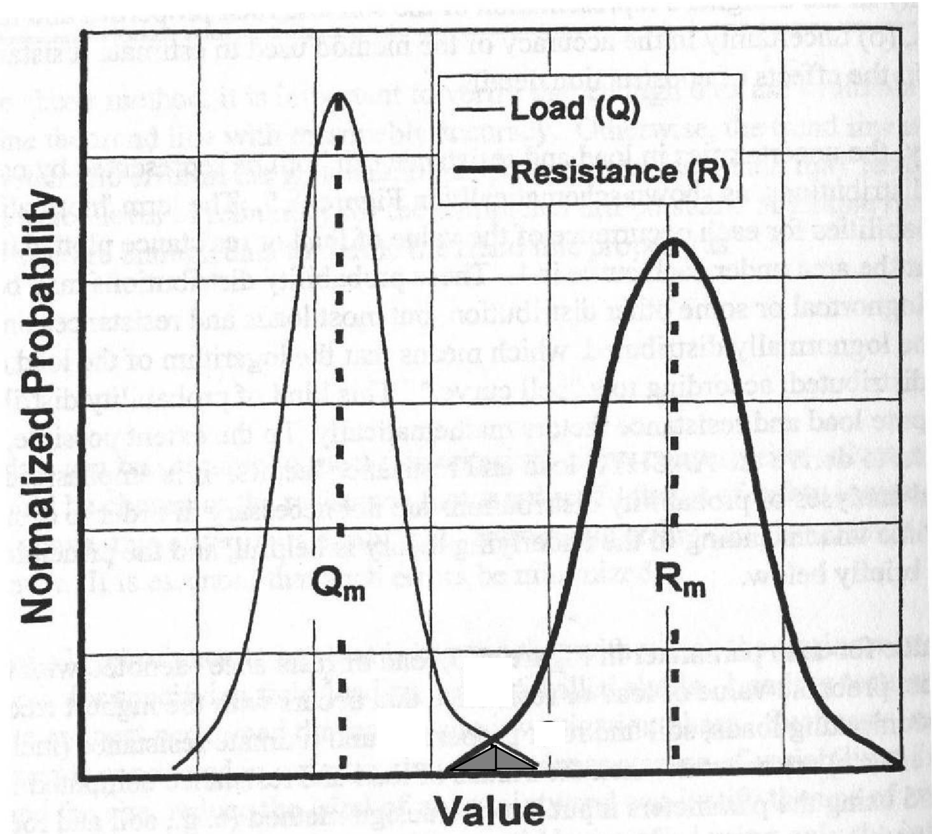

Figure 1. Idealised probability distributions of load and resistance on a foundation [Source: O'Neill and Reese, 1999]

References:

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Standards Association of New Zealand (1976) Code of Practice for General Structural Design and Design Loadings for Buildings, *NZS 4203:1976*, Wellington, New Zealand.