

SEISMIC BEARING CAPACITY – RECENT ADVANCEMENTS IN CODE AND PRACTICE

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Abstract: A structural model with soil springs representing a superstructure supported on rectangular embedded foundations was considered to capture soil-structure interaction (SSI) under static and seismic loading. The aim of this work is to demonstrate an improved withstand capability for a defence building infrastructure. Initially, output obtained from the structural model was incorporated into the analyses considering the general bearing capacity formula included in EN 1997-1 (2004). Subsequently, checks were undertaken to further evaluate potential overturning issues in accordance with EN 1998-5 (2004), which includes a methodology for the seismic assessment of foundations based on interaction diagrams. The limitation for the available formulation of strip footings in Annex F of EN 1998-5 (2004) which would neglect the potential influence of seismic shear forces acting along the foundation length and the significant values of bending moments observed about the transversal axis was evaluated. The proposed methodology had to be adapted for the case of rectangular embedded foundations by the calculation of the ultimate bearing capacity under a vertical centred load as per BS EN 1997-1 (2004). Then the combined effects of all the shear forces and bending moments in both perpendicular dimensions were accounted for, following guidance from the proposals by M. J. Pender (2017). CEN TC250 has issued the draft Eurocodes (prEN 1997-3:2022 & prEN 1998-5:2022, 2nd generation) to its members for comments and ballot at the time of writing this paper. The method considered for this project aligns with the proposals included in Annex E of the draft prEN 1998-5:2022 for shallow embedded rectangular foundations.

Introduction

This article focuses on comparisons carried out between different bearing failure criteria proposed in BS EN 1997-1 (2004) and BS EN 1998-1:2004 for static and seismic cases. The comparisons are based on results obtained from a soil-structure interaction (SSI) seismic assessment undertaken for foundations of an existing defence building infrastructure in the UK.

The basic principles of the methodology of bearing strength surfaces or interaction diagrams included in BS EN 1998-1:2004 for seismic analyses are frequently incorporated in offshore static design (e.g. ISO 19901-4), although due to the different loading conditions generally expected, this method is neither often considered for the static design of onshore shallow foundations nor even included in BS EN 1997-1 (2004) as an alternative design methodology for specific cases in which significant values of eccentricities are obtained using classic bearing failure formulae.

A series of discussions on the adequacy of the factors of safety obtained through the different methodologies considered in the analyses are presented in this article, raising awareness on the potential applications of the bearing strength surfaces to complement results obtained through classic bearing capacity methods recommended in BS EN 1997-1 (2004).

Foundation Seismic Withstand Assessment

A structural software model representing a superstructure supported on elastic soil springs was considered to capture SSI under both static and seismic loading conditions. A set of static and seismic values for equivalent spring constants taking into account non-linear soil behaviour based on the methodology recommended in ASCE 4-16 (2017) were included as input to the structural model.

Several load cases applicable to STR and GEO as per BS EN 1990:2002 were calculated for all Persistent, Transient, Accidental and Seismic Design Situations accounting for the effect of permutations of wind directions, temperatures, crane loadings, etc., with several thousand Vertical Load, Horizontal Load and Moment (VHM) combinations being considered.

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Output from the evaluation of a significant number of load cases for static and seismic situations in the structural software model were assessed using the methodologies proposed in BS EN 1997-1:2004 and BS EN 1998-1:2004.

It is worth noting that BS EN 1997-1:2004 states that the standard does not cover the special requirements for seismic design, whereas BS EN 1998-1:2004 provides additional rules for geotechnical seismic design, completing or adapting the proposals included in BS EN 1997-1:2004. Nevertheless, the initial stage of the foundation assessment was undertaken for all load cases following the classic bearing capacity methods recommended in BS EN 1997-1:2004. For the seismic design cases, the effective section area due to eccentric loading was used to calculate the representative pressures on the base of the foundations to be compared against the values estimated during the design stage.

Subsequently, checks based on interaction diagrams included in BS EN 1998-1:2004 were also undertaken. These checks were particularly interesting, as they could be used to further evaluate potential overturning issues with different criteria for those results obtained from the most onerous seismic situations with resultant eccentricities outside 1/3 of the length of the foundation.

Assessment considering BS EN 1997-1:2004

The calculations applied the general bearing capacity formula included in BS EN 1997-1:2004 for non-cohesive soils to a rectangular foundation (11.5m long, 5.5m wide and 2.0m thick) embedded in Hydraulic Fill. This representation modelled conditions for a confidential project, and therefore, additional details of the project and site cannot be provided.

The design friction angle was assumed equal to the design value of the effective critical state angle of bearing resistance for cast-in-situ concrete foundations based on available site characterisation information. Groundwater level for the project is located at a distance of less than one foundation width below the base of the foundation.

Output of static and seismic vertical and bidirectional horizontal loads and bending moments from the SSI model were included as input to the BS EN 1997-1:2004 assessment. The adequacy factor for bearing capacity of each load case was calculated as the ratio between the net ultimate bearing capacity of the foundation and the value of the corresponding representative pressure.

Assessment considering BS EN 1998-1:2004

Annex F in Part V of BS EN 1998-1:2004 includes a calculation approach for the failure criteria involving seismic design cases. The basis of this approach involves transforming the resultant applied load with its corresponding inclination and eccentricity considered in the classic bearing capacity formula into equivalent components of VHM to investigate overall margins of safety through a series of interaction diagrams. This method was originally proposed by Butterfield and Ticof (1979).

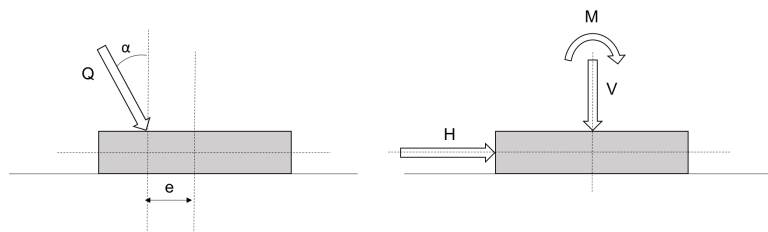


Figure 1 Equivalent components (V, H, M) of the resultant applied load Q

In this approach, the bearing strength of the foundation is not estimated as a unique value for the ultimate limit pressure but as the combination of the vertical load, horizontal shear force and moment where the action path or *locus* of all possible combinations of these actions applied to the foundation intersects a bounding surface or bearing strength surface. Pender (2017) distinguishes between bearing capacity in units of pressure when vertical actions are applied to the foundation and bearing strength in units of force when the vertical load is accompanied by shear and moment.

These bearing strength surfaces were developed through limit-analysis methods and expressed in terms of adimensional variables related to the loading parameters. Any combination of loads within the envelope implies an elastic behaviour and a stable state of forces, whilst those combinations falling outside the bearing strength surface will violate the failure criterion and initiate a bearing failure with perfectly-plastic behaviour (Pecker, 1997; Pecker and Pender, 2000; Toh and Pender, 2010; Pender, 2018). Figure 2 provides a three-dimensional diagram showing a representative section of a bearing strength surface.

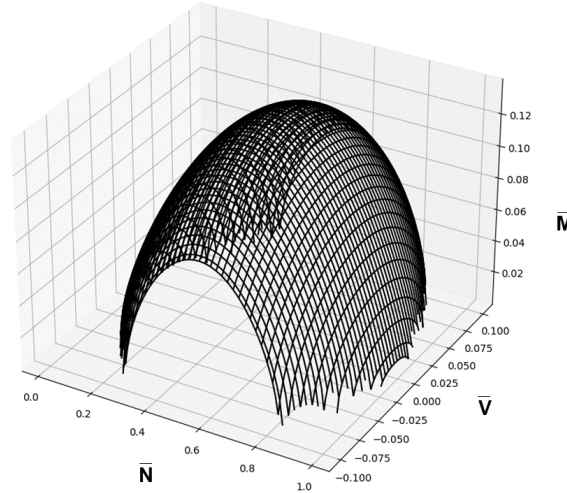


Figure 2 Representative central section of a bounding surface or bearing strength surface

The bearing strength as per BS EN 1998-1:2004 is checked using a pseudo-static approach, in which only the maximum loads acting on the foundations are considered (Pecker, 1998). The general expression proposed in BS EN 1998-1:2004 for the assessment of the stability against failure of a shallow strip footing has two considerations:

- 1) The first relates the soil strength, the design action effects at the foundation level (N_{Ed} , V_{Ed} , M_{Ed}), a parameter representing the effect of the inertia forces in the soil (\bar{F}) and a series of adimensional parameters (a , b , c , d , e , f , m , k , k' , c_T , c_M , c'_M , β and γ) depending on the type of soil:

$$\frac{(1 - e\bar{F})^{c_T} (\beta\bar{V})^{c_T}}{(\bar{N})^a [(1 - m\bar{F}^k)^{k'} - \bar{N}]^b} + \frac{(1 - f\bar{F})^{c'_M} (\gamma\bar{M})^{c_M}}{(\bar{N})^c [(1 - m\bar{F}^k)^{k'} - \bar{N}]^d} - 1 \leq 0 \quad (1)$$

where:

$$\bar{N} = \frac{\gamma_{Rd} N_{Ed}}{N_{max}} \quad \bar{V} = \frac{\gamma_{Rd} V_{Ed}}{N_{max}} \quad \bar{M} = \frac{\gamma_{Rd} M_{Ed}}{B N_{max}} \quad (2)$$

- 2) The design action effects are normalised with respect to the ultimate strength of the foundation subject to vertical load only (N_{max}) and affected by a model partial factor (γ_{Rd}) depending on the type of soil. Although this factor is in theory included to account for the potential uncertainty in the theoretical model as the bearing strength surface was derived from upper bound mathematical solutions (see Pecker and Pender, 2000), it is an essential parameter which has a series of additional implications, also intended to allow for the development of small permanent displacements in potentially stable materials, such as medium dense to dense sands or non-sensitive clays.

This allowance for small permanent displacements is based on accounting for the difference between seismic loading compared with a static loading case. As forces vary with time, if any load combination intersects the bearing strength surface at any time during a seismic event, bearing failure will be initiated but probably only for a short period of time.

The value of the model partial factor (γ_{Rd}) should be larger than 1.0 if it is only introduced to reflect uncertainties in the theoretical model, although it should be smaller than 1.0 in order to allow for limited foundation displacements. The model partial factor values proposed in Annex F in Part V of BS EN 1998-1:2004 are intended to combine both effects, proposing that for the most sensitive soils (loose saturated sands) the value of the model factor should be higher than for stable soils (medium-dense to dense sands or non-sensitive clays). For this project, the Hydraulic Fill was assessed as a *medium-dense to dense sand* in terms of the value proposed for the model partial factor.

Toh and Pender (2010) state that a design approach that allows shallow foundations to yield during an earthquake is suggested as a way to optimise system efficiency and performance, by minimising foundation size and potentially reducing foundation and superstructure actions. This is opposed to the traditional design approach, which prevents yielding of the foundation by providing a generous reserve of bearing strength during the design earthquake and can result in foundations being significantly larger than required under static loading only, especially for tall slender buildings. May (2015) notes that there is a substantial body of evidence that indicates that small permanent displacements of shallow foundations can be safely accommodated in structures and also that designing for such displacements may increase the resilience of the supported structure. The bearing strength surfaces as recommended in BS EN 1998-1:2004 provide useful insight about the likelihood of brief bearing strength failures during an earthquake and an initial appreciation of the effect of earthquake accelerations in the ground beneath the foundation (see Pender, 2018).

Although an input value for the dimensionless soil inertia force (\bar{F}) is also required as input in the general expression, Paolucci and Pecker (1997) conclude that the effect of the soil inertia is negligible with respect to the seismic actions transmitted by the structure and can be disregarded for low seismic coefficients at least in cohesionless soils, which is consistent with the approach suggested in BS EN 1998-1:2004. However, when the effect of the soil inertia needs to be incorporated, Pender (2015a; 2018) demonstrated based on a series of plots of drained sections of the bounding surfaces for different values of the inertia force that shallow foundations on cohesionless soils may be sensitive to earthquake acceleration in the soil beneath the foundation. Conversely, shallow foundations on clay are unlikely to be affected by earthquake acceleration due to their adequate static reserve of bearing strength. The lack of sensitivity of shallow foundations on clay is confirmed by post-earthquake reconnaissance observations (Pender, 2015b)

If the inertia force (\bar{F}) is considered as zero, the general expression (1) provides bearing strength surfaces with static upper bound combinations of vertical load, horizontal shear and moment which will induce bearing failure and can therefore be applied to the estimation of factors of safety for static cases.

When applying this methodology to the project, the effect of the inertia force (\bar{F}) was incorporated into the general expression by considering the value for the design horizontal ground acceleration (a_g) proposed in the site-specific hazard assessment for the structure, which already accounted for the corresponding *importance factor*. To this end, the following formula given in BS EN 1998-1:2004 for *pure cohesionless soil* (3) was considered in terms of the design angle of shearing resistance for the soil affected by the required partial factor for material property:

$$\bar{F} = \frac{a_g}{g \tan \varphi'_d} \quad (3)$$

The Hydraulic Fill was assessed as a *purely cohesionless soil* for the remainder of the numerical parameters required in the general expression (a , b , c , d , e , f , m , k , k' , c_T , c_M , c'_M , β and γ).

The following constraint (4) involving the soil inertia forces applies when the general expression (1) is applied to *purely cohesionless soil*:

$$0 < \bar{N} \leq (1 - m\bar{F})^{k'} \quad (4)$$

It is worth noting that if the formulation intended for strip footings is applied to embedded rectangular foundations, it would neglect the influence of the shear forces acting perpendicular to the foundation width (F_y) and bending moments about the transversal axis (M_x), only considering

the shear forces acting along the width of the foundation (F_x as V_{Ed}) and the bending moments about the longitudinal axis (M_y as M_{Ed}). Understanding this limitation, two modifications or departures from Annex F (Informative) in Part V of BS EN 1998-1:2004 had to be considered for calculations carried out using the proposed general expression (1):

- 1) Instead of considering the formula to obtain the ultimate bearing capacity of a surface strip foundation (N_{max}) for *purely cohesionless soils* in terms of the value of the vertical ground acceleration and the bearing capacity factor (N_γ) proposed in BS EN 1998-1:2004, both the bearing capacity factor and the ultimate vertical capacity of the embedded foundation in the absence of shear and moment were calculated for a drained case with no cohesion by directly using the methodology included in BS EN 1997-1:2004.
- 2) To account for the additional effect of the shear forces and moments in the longitudinal direction (F_y and M_x), a scaling factor Ω had to be applied to the corresponding shear forces and bending moments in the transversal direction (F_x and M_y).

Pender's (2017) study comparing the shape of the bearing strength surface for a surface strip foundation on sand with that from embedded rectangular foundation, covering a range of friction angles between 25° and 45° , length-to-breadth ratios between 1 and 5 and embedment ratios between 0 and 1, proposes that the values of Ω are in the range 1.2 to 1.7 and that Ω decreases as the friction angle and the length-to-breadth ratio increases and increases as the depth-to-breadth ratio increases. Therefore, for a friction angle of 36° , a length-to-breadth ratio of 2.1 and a depth-to-breadth ratio of 0.36, a factor of $\Omega = 1.3$ was determined and applied to F_x as V_{Ed} and to M_y as M_{Ed} so that the bearing strength surface for the embedded rectangular foundation could be described using the bearing strength surface for the surface strip foundation.

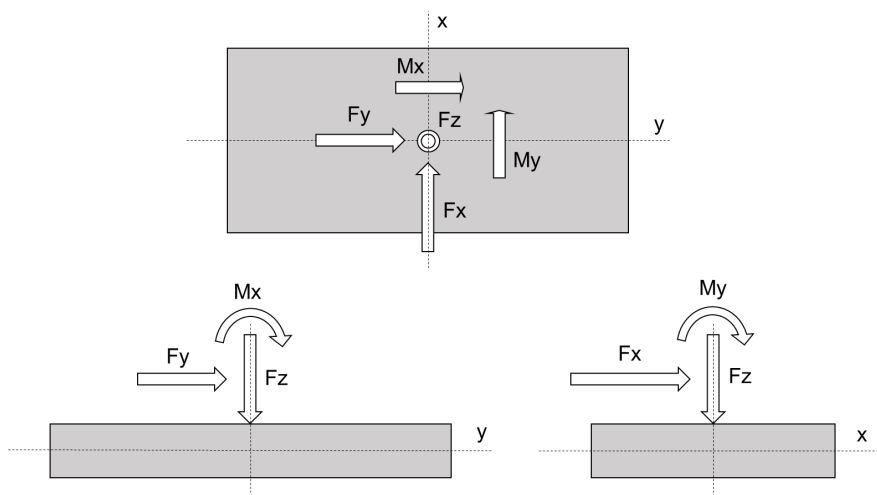


Figure 3 Diagram showing the distribution of shear forces, bending moments and vertical loads for rectangular foundations considered in the analyses

The method considered aligns with the proposals included in Annex E of the draft prEN 1998-5:2022 for *shallow embedded rectangular foundations on coarse-grained soils*. The only differences observed are the inclusion of the global resistance factor (γ_{Rd}) in the calculation of the soil inertia force (\bar{F}) and the proposal for a unique value of the scaling factor $\Omega = 1.3$ to be representative for all ranges of length-to-breadth ratios, friction angles (25° to 45°) and embedment ratios.

Assessment Results

The results of the calculations showed that all cases under seismic loading with resultant eccentricities outside $1/3$ of the length of the foundation, as per the methodology based on BS EN 1997-1:2004 considered for the calculation of the effective section areas, were compliant with the methodology by adopting interaction diagrams included in BS EN 1998-1:2004 with the corresponding adjustments implemented (Set of Analyses A).

Sensitivity checks (Set of Analyses B) were undertaken considering the general expression (1) proposed in BS EN 1998-1:2004 adapted for static situations with no effect of the inertia force (\bar{F}) for a reduced number of cases from the analyses with resultant eccentricities outside 1/3 of the length of the foundation but compliant with BS EN 1997-1:2004. The results obtained showed that the combinations of the vertical load, horizontal shear force and moment applied to the foundation were located within the bearing strength surface and therefore the foundations could also be considered as safe under this approach. In theory, these checks would not be deemed necessary by Section 6.5.4 in BS EN 1997-1:2004, as it states that special precautions are required including a careful review of the design values where the eccentricity of loading exceeds 1/3 of the width of the foundation, with no reference to cases with larger eccentricities along the foundation length, as those observed in this assessment.

This situation was observed in the analyses when additional sensitivity checks were carried out (Set of Analyses C) considering an increased design ground acceleration combined with a reduced degradation of the soil stiffness in the calculation of the spring coefficients. In this case, some of the seismic design cases with resultant eccentricities outside 1/3 of the width of the foundation were not compliant with the formulae proposed in BS EN 1998-1:2004, although they provided acceptable values for the adequacy factor on bearing capacity as per the methodology included in BS EN 1997-1:2004.

Discussions

The classic bearing capacity theory focuses on the estimation of a value for the vertical load limit through the coupling of solutions using inclination and eccentricity factors which gives bearing failure whilst the effective area of the foundation remains constant. Although this would be acceptable for those cases when either the vertical load is the only action applied to the foundation or only minor influence from additional actions is envisaged, if the foundation was also required to sustain significant values of shear forces and bending moments driving instability as expected during earthquake loading conditions, the vertical load would normally have a stabilising effect.

In these situations, the standard estimation of the available reserve of bearing strength can be quite misleading and fails to indicate how rapidly the reserve of bearing strength diminishes with increasing moments and shear forces, as at constant vertical load there are multiple combinations of shear and moment which could induce bearing failure (Pender, 2015a). Therefore, when these combinations dominate the loading behaviour, the concept of allowable bearing pressure to estimate the factor of safety during the design stage of the foundations is not recommended in the design and evaluation process. The bearing strength surfaces are an important tool in understanding the bearing strength of shallow foundations under complex loadings which has been gradually recognised in the geotechnical community. For offshore geotechnics, the representation of the ultimate limit states as a failure envelope is particularly useful, as it allows a more direct evaluation of the factor of safety against failure with respect to changes in the individual load components (Randolph and Gourvenec, 2011).

Nevertheless, the difficulty with bearing strength assessment based only on the value obtained from the general expression (1) is simply that the result alone provides no real sense of the action path leading to the initiation of bearing failure (Pender, 2018). Therefore, plotting sections of the surface is a significant aid towards understanding the estimated safety factors based on this methodology.

An example extracted from the static project calculations (Set of Analyses B) is included for clarification purposes in Figure 4. The point shown in the graph represents a combination of design-action effects located in the $\bar{N} - \bar{M}$ plane or projection of the boundary strength surface which provides an acceptable value for the adequacy factor on bearing capacity as per the methodology included in BS EN 1997-1:2004. The boundary has already been modified to account for the effect of the normalised value of the horizontal shear force in the $\bar{V} - \bar{M}$ plane; as shown in Figure 2, the section within the envelope reduces with the increase in horizontal shear forces at either side of the central section of the bearing strength surface, where the maximum extension of the envelope is obtained, as no shear forces are considered to be present along this plane.

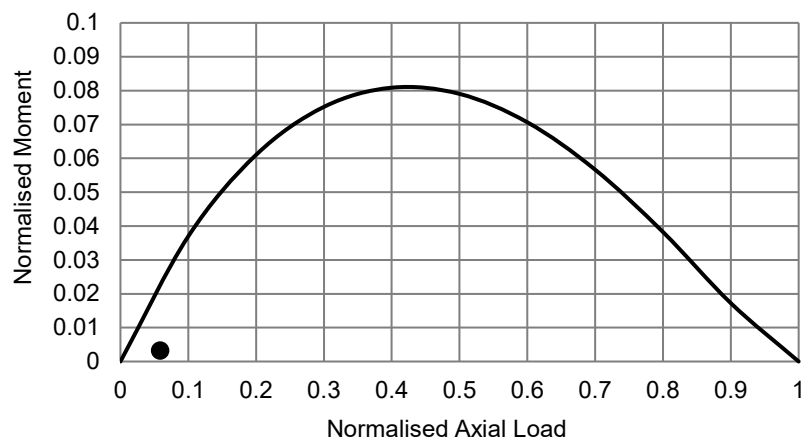


Figure 4 Representation of a $\bar{N} - \bar{M}$ Section of the bearing strength surface considering the effect of the normalised horizontal shear force (Drained Case)

For low values of normalised vertical loads, only small values of horizontal shear forces and bending moments are allowed to keep the load combination within the envelope, whereas the highest values of shear and moment can be sustained when the normalised values of vertical loads are between 0.4 and 0.5. As the combination represented in Figure 4 is showing a relatively small effect of the vertical loading on the foundation, an increase in vertical loading would contribute towards an increase in the overall safety factor of the foundation, whereas a reduction in the vertical load or an increase in bending moment would reduce its value provided that the remainder of the actions are kept constant and assuming that the effective section does not change either.

Pender (2015a; 2015b; 2018) also provide examples showing the calculation of the factor of safety with respect to foundation moment and shear based on the strength envelope in the $\bar{V} - \bar{M}$ plane, if the vertical loads acting on the foundations remain constant. For wind turbines or structures subject to extreme accidental cases or earthquake loadings supported on shallow foundations, the vertical load will frequently remain constant whilst the moment and shear increase, with shear and moment usually related as the shear applied some distance above foundation level generates the moment. Madabhushi et al. (2009) proposed that the ultimate capacity of the foundation is significantly influenced by dynamic loadings, with transient horizontal loads and moments acting to reduce the ultimate vertical capacity.

For the above reasons, it is noted by Randolph and Gourvenec (2011) that the classic bearing capacity theory under combined loading is not generally considered in static offshore shallow foundation design; interaction diagrams or failure envelopes are used instead to represent ultimate limit states due to the large components of horizontal load and moment arising from environmental conditions.

Conclusion

A structural model representing a superstructure supported on elastic soil springs was considered to capture soil-structure interaction. The output results from the evaluation of a significant number of load cases for static and seismic situations were assessed using the methodologies proposed in BS EN 1997-1:2004 and BS EN 1998-1:2004. Based on the assessment results obtained, the following conclusions are reached:

- The modifications incorporated in this seismic withstand study for embedded rectangular foundations align with the draft text included in Annex E of the draft EN 1998-5 (2022) for *shallow embedded rectangular foundations on coarse-grained soils*.
- Due to the characteristics of the structure, it was observed that the use of the classic bearing capacity method proposed in BS EN 1997-1:2004 for static cases provides misleading estimations of the available reserve of bearing strength for those cases where significant values of horizontal shear forces and bending moments are obtained as output from the structural model.

- Although BS EN 1997-1:2004 recommends a careful review of the design loadings when the results of the calculated eccentricity exceed 1/3 of the width of the foundation, the BS EN 1997-1:2004 requirement does not include any additional or alternative methodology for a quantification of the factor of safety for these cases, which would be particularly useful when large moments and shear forces are imposed on the foundation.
- The methodology based on the bearing strength surfaces or interaction diagrams, which is extensively used in offshore industry, represents an additional verification method or even an alternative to the classic calculation methods of bearing capacity for static situations currently proposed in BS EN 1997-1:2004 for specific loading conditions, provided that the adequate factors of safety to account for the different characteristics of the static loads are considered.
- For shallow foundations under seismic loading, there are common engineering issues to be considered in both onshore and offshore projects. Therefore, it would be useful to develop a pragmatic approach by considering the recommendations given in the draft prEN 1998-5:2022 and ISO 19901-4.

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