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Lateral loading of shallow foundations under seismic loads

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ABSTRACT

Seismic actions can impose high lateral loads on shallow foundations. The effect of this lateral load can be to significantly reduce the ability of the shallow foundations to support vertical loads.

This paper demonstrates the significance of this effect and sets out the steps and methods that geotechnical engineers can follow, in collaboration with structural engineers, to allow for this effect in design of new and assessment of existing shallow foundations. These steps/ methods described include understanding the lateral load paths from structure to ground, the available ground resistance mechanisms, and the available methods for calculating soil vertical bearing capacity in conjunction with lateral loading. Available ground resistance includes; passive resistance on the sides of embedded structures (foundations, ground beams, etc.) frictional resistance on the underside of floor slabs on grade and friction on the base shallow foundations. The latter has the effect of reducing the foundations vertical capacity which must be considered in design and assessment.

1 INTRODUCTION

Earthquake shaking can be expected to impose lateral loads on building foundations. Mechanisms available to resist this lateral load include; floor slab base friction, passive resistance of embedded elements and shallow foundation base friction. Mobilising the latter has the effect of reducing the foundations vertical capacity which must be considered in design and assessment. NZGS Module 4, 2016 includes some general guidance on this topic. This paper aims to provide further guidance by demonstrating the effect of mobilising foundation base friction on bearing capacity and by proposing steps/ methods for assessing the lateral load paths available from structure to ground, and for calculating soil vertical bearing capacity in conjunction with lateral loading. It is intended that these steps/methods be undertaken collaboratively by structural and geotechnical engineers.

If lateral loads from earthquake shaking exceeds the available foundation lateral resistance the consequence could be some lateral displacement (sliding) of the building. If the building is well tied together this

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displacement may be tolerable. However, a consequence of this sliding could be to reduce the vertical bearing capacity of shallow foundations which could result in differential vertical displacements of foundations which may not be tolerable.

In addition to lateral loads seismic actions can impose moment loading on foundations, which may also reduce the bearing capacity of foundations. This effect is not discussed further in this paper but needs to be considered in assessment and design of shallow and deep foundations. Ground beams between foundations are often designed to resist this moment and thus mitigate the effect on foundations.

2 SHALLOW FOUNDATION BEARING CAPACITY ALLOWING FOR LATERAL LOAD

The ability of a shallow foundation to resist vertical load (vertical bearing capacity) is reduced if horizontal loading is also applied to the base of the foundation.

This effect is well explained using a bearing strength surface (Pender 2017), where the bearing strength of foundation is presented as a combination of horizontal, moment and vertical loads where the action path intersects the bearing strength surface.

The reduction in vertical bearing capacity when a horizontal load is applied is due to the change in length of failure surface. When the foundation base starts to slide as the lateral load exceeds all other available passive resistance mechanisms, the failure surface starts to get shorter and shallower as demonstrated by Figure 1 below. In Figure 1 the combination of vertical and horizontal load is represented by a single inclined load vector.

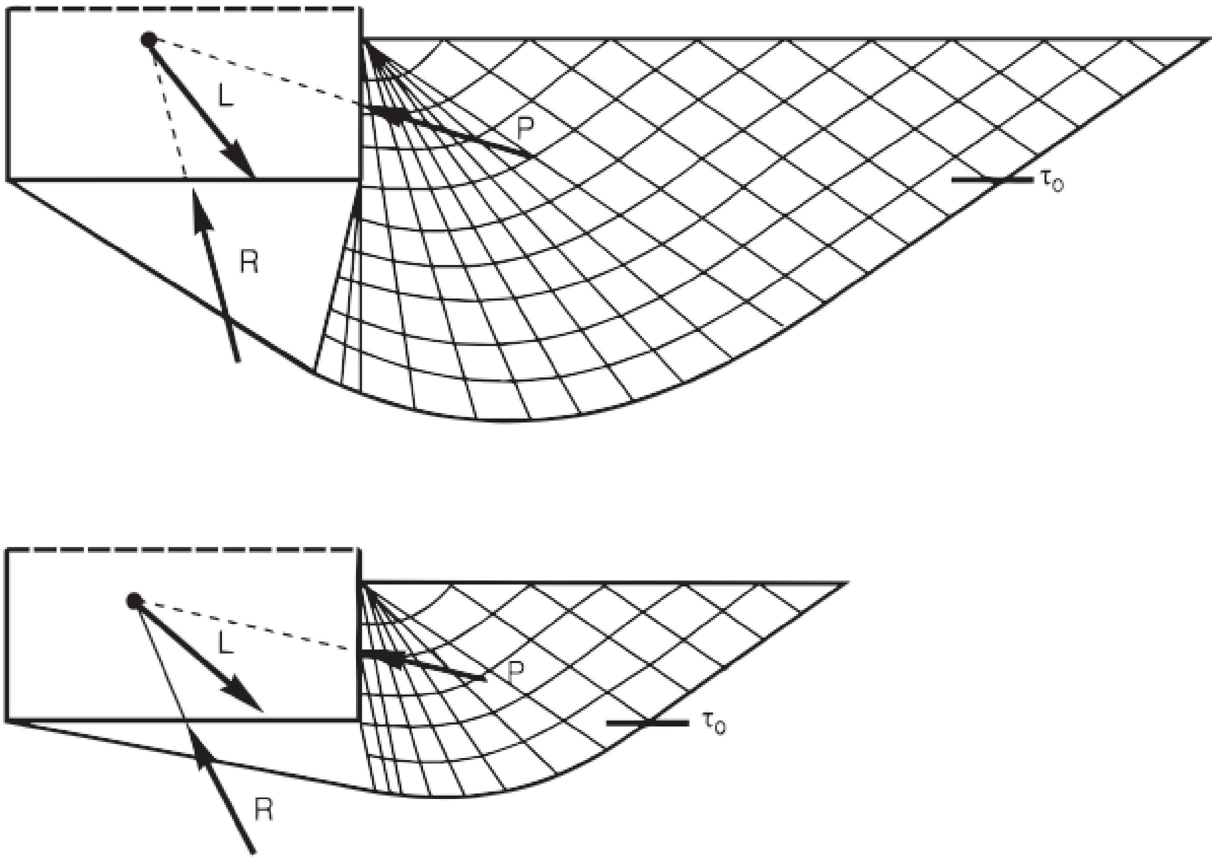

Figure 1: Rupture surfaces of inclined footing loads. (Source: Hansen 1970)

Cyclic shaking tests conducted on shallow foundations on granular soil resulted in failure through a wedge type failure mechanism (McManus & Burdon 2001). This confirms the change in rupture surface depths demonstrated in Figure 1.

The reduction in vertical bearing capacity as a result of applied horizontal load is observed for both cohesive and granular soils, although the effect is less marked for cohesive soils. Figure 2 presents the calculated vertical bearing capacity of a 1 m x 1m x 0.3 m deep foundation with varying ratio of horizontal / vertical loading (H/V). The vertical bearing capacity is reported as a proportion of that without horizontal loading ($Qv_{-H/V}/Qv_{-H=0}$). Results for cohesive and granular soils are presented. The results are for the specific foundation geometry and soil parameters assumed. The results will vary depending on the foundation geometry and the soil parameters and therefore Figure 2 reports results for an example foundation. Specific calculation is required allowing for actual foundation details.

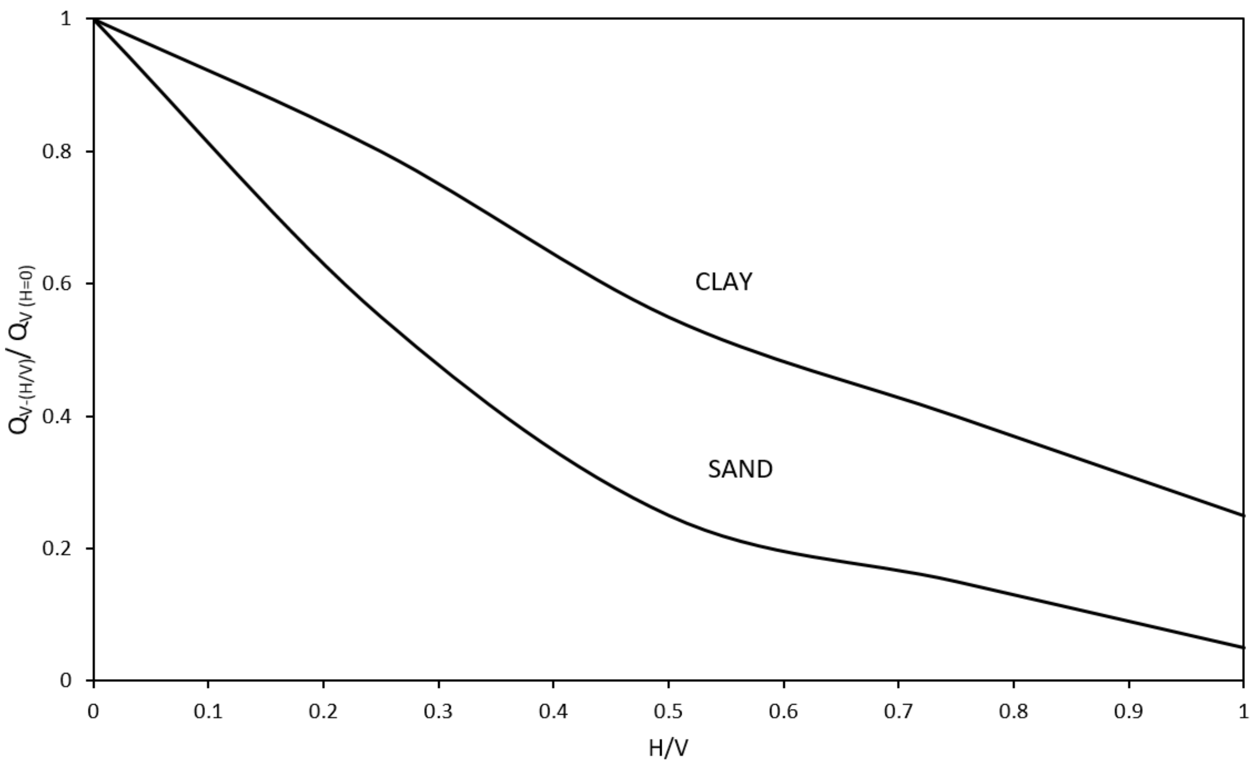

Figure 2: An example of effect of horizontal loading on vertical bearing capacity (Based on Hansen, 1970)

With reference to Figure 2, for this example foundation on granular soil, application of a lateral load of 40% of the vertical load reduces the vertical bearing capacity by more than 60%.

3 MECHANISM TO RESIST LATERAL LOAD AND CONSEQUENCES OF ALLOWING SLIDING

The various mechanisms available to resist the horizontal loading are presented in Table 1 below.

Table 1: Summary of available lateral load resistance mechanism

No	Lateral load resisting mechanisms	Calculation of the ultimate geotechnical lateral load capacity	Comments
1	Slab base friction	$F = N * \tan\delta A$ N = unit weight of floor slab δ = angle of friction between soil and underside of slab A= area of floor slab	Suspended floor slabs will not provide any friction resistance. Consider the effects of damp proof or vapour membrane. This may result in 30% reduction in resistance.
2	Embedded elements Includes sides of shallow foundations, embedded ground beams, basement walls, sides of deep foundations and other embedded elements	$F = 1/2\gamma D_f^2 * K_p L$ γ= unit weight of soil D_f = depth of embedded element; K_p = coefficient of passive earth pressure L = length of embedded element	Consider the full embedded depth from ground surface Consider the confining effect of floor slab; both its self-weight and its structural strength to resist passive heave. Structural capacity of the embedded element must also be considered, which may govern over the geotechnical capacity
3	Shallow foundation base friction	$F = N * \tan\delta$ N = foundation bearing load δ = angle of friction between soil and underside of foundation	Mobilising this frictional resistance decreases the vertical bearing capacity of the foundation.

Things to consider:

- Lateral load resistance of an element will be the lesser of the structural capacity and the geotechnical capacity.
- For simplicity, foundation base friction is assumed to be mobilised after all other passive load resistance mechanisms have been exhausted i.e. the limiting equilibrium case for vertical bearing
- The available lateral load paths are dependent on the ability of the structure to transfer loads from the superstructure to the resisting foundation elements
- Total available lateral load resistance in the direction of least resistance must be considered for design. Geotechnical and structural engineers must consider the spatial distribution of embedded elements and identify the critical direction for lateral load resistance.

- Consider the effects of ground conditions and ground water level on the passive resistance of embedded elements

4 STEPS OF LATERAL AND VERTICAL CAPACITY ASSESSMENT

In design of new foundations, or assessment of existing foundations, to resist a combination of vertical and lateral loading (ie inclined loading) the following steps are proposed:

1. Identify available load path to resist lateral load.
2. Evaluate the "residual lateral load" to be resisted by the foundation base.
3. Check bearing capacity allowing for the vertical loading and the "residual lateral load".

These three steps are discussed in the following sub sections

1. **Load path:**
   Assessment of the lateral load path from the structure to the ground requires collaboration between the structural and geotechnical engineers. The geotechnical engineer identifies the available lateral load path from foundations to ground. These could include:
   a. Friction beneath a floor slab on grade
   b. Passive resistance against buried elements including; basement walls, ground beams and foundations.
   c. Friction beneath the foundations.

   The structural engineer assesses the ability of the structure and sub-structure to transfer lateral loads from columns and shear walls to the identified areas of foundation lateral resistance. The objective is for the structural and geotechnical engineers to evaluate the maximum load which can be transferred along each available path. This maximum resistance will be the lesser of the geotechnical and structural capacity along that load path. Longitudinal and lateral loading must be separately considered.

2. **"Residual lateral load" resisted by the base of foundations:**
   In this ultimate limit state assessment of available load paths, limiting equilibrium conditions are considered, i.e. sufficient displacement is assumed to have occurred to mobilise all available lateral load paths. The objective is to investigate what alternative load paths to foundation base friction are available so that in the limiting equilibrium condition the inclination of load on the foundations is reduced improving the foundations ability to support vertical load. To this end the "residual lateral load" on the base of the foundation is calculated as the total lateral load less that which can be resisted via load paths other than base friction of the foundations. This "residual lateral load" (which in many cases may be zero) is applied in conjunction with the vertical load to check the bearing capacity of each foundation.

3. **Check bearing capacity.**
   The bearing capacity of the foundation is checked allowing for the vertical load in conjunction with the "residual lateral load". This can be undertaken in a rigorous fashion considering each foundation in turn, but this level of detail is rarely necessary. As a simplification the "residual lateral load" (H) for the entire building (or part of it) is divided by the vertical load (V) imposed by the entire building (or part of it) giving H/V. The vertical component of the bearing capacity of each foundation is calculated allowing for the inclination of loading H/V. This vertical component of bearing capacity, reduced by an appropriate strength reduction factor, (refer section 6) is checked against the applied vertical load. Part of the building rather than the entire building would be considered where the structure can only be relied on to transfer lateral loads to part of the foundation system. Lateral and longitudinal lateral loading need to be separately considered.

5 CALCULATING BEARING CAPACITY OF LATERALLY LOADED SHALLOW FOUNDATIONS

Once the "residual lateral load" has been assessed the effect of this on vertical bearing capacity is to be calculated.

5.1 Calculation methods

Methods available for calculating the bearing capacity of laterally loaded shallow foundations take different approaches. Some commonly used methods are provided in Table 1 below.

Table 2: Bearing capacity methods

Bearing capacity method	Consideration of lateral load	Comment
Terzaghi (1943)	None	Does not consider shear strength of failure surface above base of foundation (no depth factors)
Meyerhof (1963)	Inclination factors	Considers shear strength of failure surface above base of foundation within depth factors
Hansen (1970)/Vesić (1973, 1975)	Inclination factors	Do not consider shear strength of failure surface above base of foundation within depth factors. Can consider ground slope near foundation and inclined foundations

5.2 Conclusions

1. If the assessed load path for base shear resistance utilises passive resistance of the foundation then this resistance should not be double counted when calculating bearing capacity. In this case, use depth factors of unity for Meyerhof, Hansen and Vesic methods.
2. The Terzaghi method is not appropriate for foundations with a lateral load. Meyerhof, Hansen and Vesic methods can be used for foundations with a lateral load, however Hansen and Vesic are more versatile for complex conditions.
3. Calculate bearing capacity using at least two different methods and apply engineering judgement

5.3 Additional considerations

The following should also be considered when calculating of bearing capacity involving an applied 'residual lateral load':

- Inclination factors are calculated differently for cohesive and non-cohesive soils. Consider carrying out a drained and undrained analysis to understand the sensitivity of the calculation to this.
- Tension and compression loading cycles can reduce bearing capacity. Be aware that bearing capacity calculation methods may not be applicable for foundations subject to tension and compression loading cycles.
- Displacement of the foundation is required to mobilise the ULS capacity. Structural and geotechnical engineers to consider tolerance of structure to estimated displacements.
- Layered soil profiles, foundations near a slope or non-standard foundation shapes can all have a significant impact on bearing capacity. Consider these factors in the assessment.
- Moment loading will decrease the bearing capacity of the foundation. Consider this accordingly in bearing capacity calculations.
- Liquefaction of material beneath a shallow crust can significantly reduce bearing capacity. If liquefaction has been identified as an issue then use an appropriate method to determine punching bearing capacity.

- If foundation loading, shape or ground condition is complex, consider analysis by finite element or finite difference method and compare with traditional methods.

6 STRENGTH REDUCTION FACTORS

Either design of a new building foundations or assessment of existing foundations can be undertaken by applying the steps presented in sections 4 and 5. The exception to this is in the way strength reduction factors (SRF) are applied. For assessment in accordance with The Seismic Assessment of Existing Buildings (the Guidelines) MBIE 2017, strength reduction factors are not applied.

Module 4: Earthquake resistant foundation design MBIE 2016, provides guidance on selection of SRF to be applied to the bearing capacity of new shallow foundations, but is silent on the SRF to be applied to lateral load resistance. Clause B1/VM4 of the New Zealand Building Code proposes that a SRF of 0.5 be applied to passive resistance and 0.8 to frictional resistance. As highlighted in Module 4 MBIE 2016, lateral resistance is not necessarily critical to the safe seismic performance of a building and lateral seismic deformations are "self-limiting". Considering the potential impact on vertical bearing capacity, the authors propose that a SRF of 0.8 be applied to both frictional and passive resistances in calculating the "residual lateral load".

For load combinations including overstrength factors (capacity design) Module 4 MBIE 2016 provides no specific guidance. For this loading combination Clause B1/VM4 of the New Zealand Building Code allows the higher SRF of 0.8 to 0.9 to be applied to bearing capacity of shallow foundations. Palmer (2013) cautions against use of this high SRF and provides guidance.

7 CONCLUSION

The ability of foundations to resist earthquake induced lateral loads needs to be considered in assessment of existing buildings or design of new buildings. If lateral loads from earthquake shaking exceeds the available foundation lateral resistance the consequence could be some lateral displacement (sliding) of the building. If the building is well tied together this displacement may be tolerable. However, a consequence of this sliding could be to reduce the vertical bearing capacity of shallow foundations which could result in differential vertical displacements of foundations which may not be tolerable.

Mechanisms available to resist this lateral load include; floor slab base friction, passive resistance of embedded elements and shallow foundation base friction. Mobilising the latter has the effect of reducing the foundations vertical capacity which must be considered in design and assessment.

Hansen, Vesic and Meyerhof methods are recommended for calculating bearing capacity of foundations subjected to lateral loading.

A Strength reduction factor of 0.8 is recommended to be applied to both frictional and passive resistances in calculating the "residual lateral load".

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