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Shallow foundations on liquefiable soils with a non-liquefiable crust: Overview of assessment methods

E.B. Stocks & S.J. Palmer

Tonkin & Taylor Ltd, Wellington.

ABSTRACT

Assessing bearing capacity and settlement of shallow foundations on a non-liquefiable crust overlying liquefiable soils is a complex problem. The type of shallow foundations this applies to includes, but is not limited to, building footings and rafts, retaining walls and embankments. Understanding how shallow foundations perform during and after an earthquake is a subject of continuous research. However, there are a number of existing approaches available to design shallow foundations on liquefiable soils - from simplified empirical methods based on observations from past earthquakes, to numerical analysis with complicated soil profiles and soil-structure interactions. These methods vary in complexity, inputs and assumptions, and therefore give a wide range of results. This paper provides an overview of the available methods and suggestions for strength reduction factors while assessing a bearing capacity for existing and new foundations. It is important to consider multiple methods while looking at bearing capacity and settlement of shallow foundations on liquefiable soils with non-liquefiable crust and applying engineering judgment in selecting conclusions for design.

1 INTRODUCTION

Geotechnical engineers in New Zealand often face the problem of shallow foundations being founded within a non-liquefiable crust overlaying liquefiable soils. The type of shallow foundations this applies to includes, but is not limited to, building footings and rafts, retaining walls and embankments. This problem is often very complex and the current available methods and techniques for assessment give a wide range of results as they vary in complexity, input and assumptions. This paper provides an overview of the available methods and lists a number of aspects to be considered during design (Section 2). It is important to consider multiple methods while looking at bearing capacity and settlement of shallow foundations on liquefiable soils with non-liquefiable crust and applying engineering judgment in selecting conclusions for design. Furthermore, this paper presents the results of a sensitivity assessment of methods available and input parameters (Section 3) and provides a summary of a possible strength reduction factors (Section 4).

While deep foundations or ground improvement would appear to be better a solution to overcome the challenges of the shallow liquefiable layers, there are a number of limitations of these alternatives such as existing buildings with limited headroom, limited lateral spread resistance of piles and cost.

2 LITERATURE REVIEW

A number of theoretical and experimental studies have been completed over the years considering the ultimate bearing capacity and settlement of shallow foundations on liquefiable soils. Conclusions from a literature review of studies are summarised in this paper.

2.1 Settlement of shallow foundations

For many projects, foundation settlement may be more critical than their bearing capacity. Researchers to date have used techniques including numerical analysis, back analysis of field case histories, shaking table and centrifuge tests to assess the ground and structure responses to earthquake induced liquefaction. Bray & Macedo 2017 has provided a comprehensive overview of the state-of-the-practice for estimating liquefaction-induced building settlement. Based on a sensitivity analysis and results from soil structure interaction (SSI) nonlinear stress dynamic analyses they developed a simplified procedure to estimate liquefaction-induced building settlement. In this procedure they capture the key shear-induced deformation mechanism that was not incorporated in any of the current methods developed based on empirical studies. Bray & Macedo applied this simplified procedure to several field case histories and showed that the calculated settlement was consistent with those observed. A summary of the steps proposed for the simplified procedure is presented in Table 1. In their paper they stress the importance of using engineering judgment and considering case histories and previous experience. For significant and complex projects the recommendation is to perform nonlinear dynamic SSI analysis in addition to these simpler approaches.

Table 1: Post-liquefaction settlement assessment procedure by Bray & Macedo (2017).

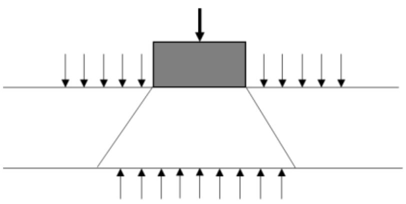
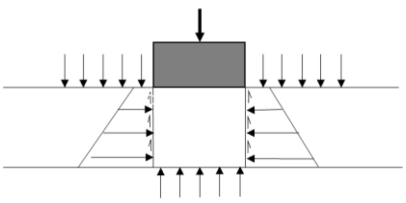
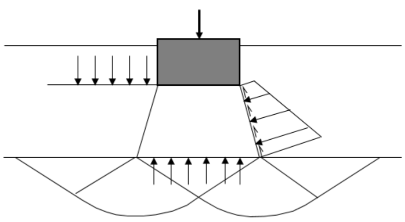
Step		Available methods
1	Undertake liquefaction assessment using available methods	Boulanger & Idriss (2016)
2	Calculate post-liquefaction bearing capacity. Bray & Macedo 2017 stress that the following steps for calculating settlement are only valid if bearing capacity failure is not expected	Hanna & Meyerhof (1980) Refer this paper
3	Assess the likelihood of liquefaction manifestation at the surface	van Ballegooy et al. (2014), Iwasaki et al. (1982), Ishihara (1985), Bowen & Jacka (2013)
4	Estimate building settlement as a direct result of loss of ground due to ejecta (De), if the likelihood of surface manifestation at the surface is high	Relevant case history; refer Bray & Macedo (2017)
5	Estimate volumetric-induced building settlement (Dv) using available methods	Zhang et al. (2002)
6	Estimate shear-induced building settlement (Ds)	Bray & Macedo (2017)

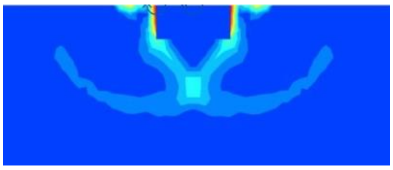
Step		Available methods
7	Estimate the total liquefaction induced building settlement (Dt)	Dt = De + Dv + Ds
8	Use engineering judgment	Previous experience

2.2 Bearing capacity of shallow foundations

Punching through a non-liquefiable crust is a common problem for shallow foundations on liquefiable soils. Conventional analysis of the punching failure uses limit equilibrium techniques. Some of these techniques are briefly described in Table 2. It is becoming common practice for researchers and practitioners to undertake finite element analysis for assessing bearing capacity for complex projects. It is important to consider multiple methods while looking at bearing capacity and settlement of shallow foundations and applying engineering judgment in selecting conclusions for design.

Table 2: Available bearing capacity analysis methods for liquefiable soils.

Failure mechanism	Method description
	**Projected area method (Yamaguchi 1963)** This method looks at a load spread through the crust providing an increased bearing area on the underling liquefied soil. The side angle of the block is typically 30°. The resistance of the side shear within the crust layer is ignored. The bearing capacity is determined from the ultimate bearing load acting on the base area of the projected block. The strength of the overlaying layer and the underlying layer is analysed in terms of effective and total stress, respectively.
	**Side friction method (Hanna & Meyerhof 1980)** This method consists of a block beneath the foundation footprint being pushed through the crust into the underling layer. The bearing capacity of the shallow foundation is calculated as the sum of the bearing capacity of the liquefiable layer and the side friction of the failing block through the crust. The strength of the crust and the underlying layer is analysed in terms of effective and total stress, respectively. **Side friction method (SNEME 2002)** This method uses the Hanna & Meyerhof 1980 method with punching shear coefficient K_S and $tan\phi'$ related to shear strength s_u of the underlying layer.
	**Projected area and side friction method (Okumura 1998)** Okamura proposed an alternative method based on the experimental observations from well-conditioned centrifuge tests. The Okumura method combines the concept of both the projected method and the side friction method. This method adopts Rankin's passive coefficient K_P using a normalised angle of the side α_c.

Failure mechanism	Method description
	**Finite element analysis (2D or 3D)** Various researches and practitioners use finite element methods (e.g. FLAC, PLAXIS) to validate post-liquefaction bearing capacity initially assessed by the methods described above (e.g. Karamitros 2013, Bowen & Jacka 2013, Dimitriadi 2017).

While assessing the bearing capacity the following should also be considered:

1. **Crust thickness.** Meyerhof (1974) and Karamitros (2013) concluded that if the non-liquefiable crust is more than a critical thickness the liquefied layer will generally have little effect on bearing capacity.
2. **Shear strength of the liquefiable layer.** There are several empirical relationships available for estimating the residual shear strength of liquefied soils (e.g. Seed & Harder 1990, Olson & Stark 2002, Idriss & Boulanger 2007).
3. **Upward pore water flow.** With a permeable non-cohesive crust there is a potential for significant vertical upward flow of liquefied pore water. This could cause an increase in groundwater level and reduction in effective stresses within the crust. Strength reduction of the crust layer due to the upward flow is discussed by Dimitriadi (2017). Furthermore, a consideration should be given to a void ratio redistribution and water film effects as indicated by Dobry & Liu (1992) and Kokusho (1999), respectively.
4. **Transition zone.** Dimitriadi (2017) discusses the possibility of transition zone development below the base of a permeable crust and into the liquefiable layer. Due to the relatively low excess pore pressures, this zone could preserve significant shear strength contributing positively to the overall degraded bearing capacity. It should be noted that the development of a transition zone is highly dependent on the permeability of the crust and thickness and density of the liquefiable layer. Transition zone could also develop within partially saturated soils, which are below nominal water table level (e.g. seasonal fluctuation). The transition zone and the beneficial effects it can offer should be considered with caution.
5. **Liquefaction of intermediate layers.** Thin medium dense non-cohesive layers assessed as too dense to be triggered for liquefaction could liquefy if sandwiched between relatively thick liquefiable layers. This is as a result of excess pore water pressure redistribution.

2.3 Strength Reduction Factor

Load and resistance factored design (LRFD) has been standard practice in New Zealand since the mid-1970s. Historically, factors of safety (FoS) have been applied to ensure safe design; typically > 3 for gravity case and > 2 for seismic case. LRFD applies strength reduction factors (SRF) in combination with load factors (NZS1170.0:2002) to provide an overall factor of safety. Summary of a literature review of recommended SRF for design on liquefiable soils is presented below. The authors' suggested guidance for assessment of appropriate SRF is presented in Section 4 of this paper.

- Bouckovalas and in their paper indicated that the selection of design value of FoS will depend on the severity of shaking and the importance of the structure (Bouckovalas, Dakoulas, 2007). The paper points out that liquefiable soils impacting on the shallow foundation performance is a short term hazard and therefore they suggest that FoS value be below a conventional value for static design i.e. FoS of 1.0 to 1.5 (equivalent SRF of 0.67 to 1.0).
- New Zealand Geotechnical Society Guidance - Module 4 (NZGS, 2016) provides a guidance on typical values for SRF of 0.45 to 0.6 for seismic foundation design. However, it does not provide specific

guidance for foundation on liquefiable soils. This guidance stresses the importance of SRF selection considering knowledge of the site, the scope of investigations undertaken, conservatism in selection of geotechnical parameters and the controls during construction.

- Bray & Macedo in their paper suggest the use of FoS of 1.0 and 1.5 (SRF of 1.0 and 0.67) for light and low buildings and for heavy and tall buildings, respectively (Bray & Macedo, 2017).

3 SENSITIVITY ANALYSIS

Several bearing capacity methods for shallow foundations on liquefiable soils are discussed in this paper. These methods vary in complexity, inputs and assumptions, and therefore give a wide range of results. The variation in results was explored by the means of a sensitivity analysis using a simple example of a strip footing on liquefiable soil. The assumed model for the sensitivity analysis is presented in Figure 1. The sensitivity analysis considered various analysis methods (refer Table 2) and input design parameters applied (refer Table 3). The results of the analysis are presented in Figure 2.

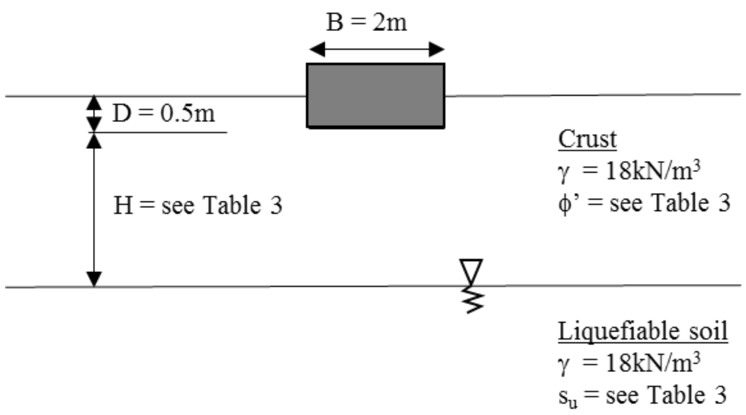


Figure 1: Assumed model and parameters for analysis

Table 3: Available bearing capacity methods for liquefiable soils.

Parameters	Moderately conservative	Reduced by 20%
s_u (kPa)*	8.0	6.4
ϕ' (deg)**	35	28
$D + H$ (m)**	2.5	2.0

* Parameter based on Olson and Stark (2002)

** Assumed

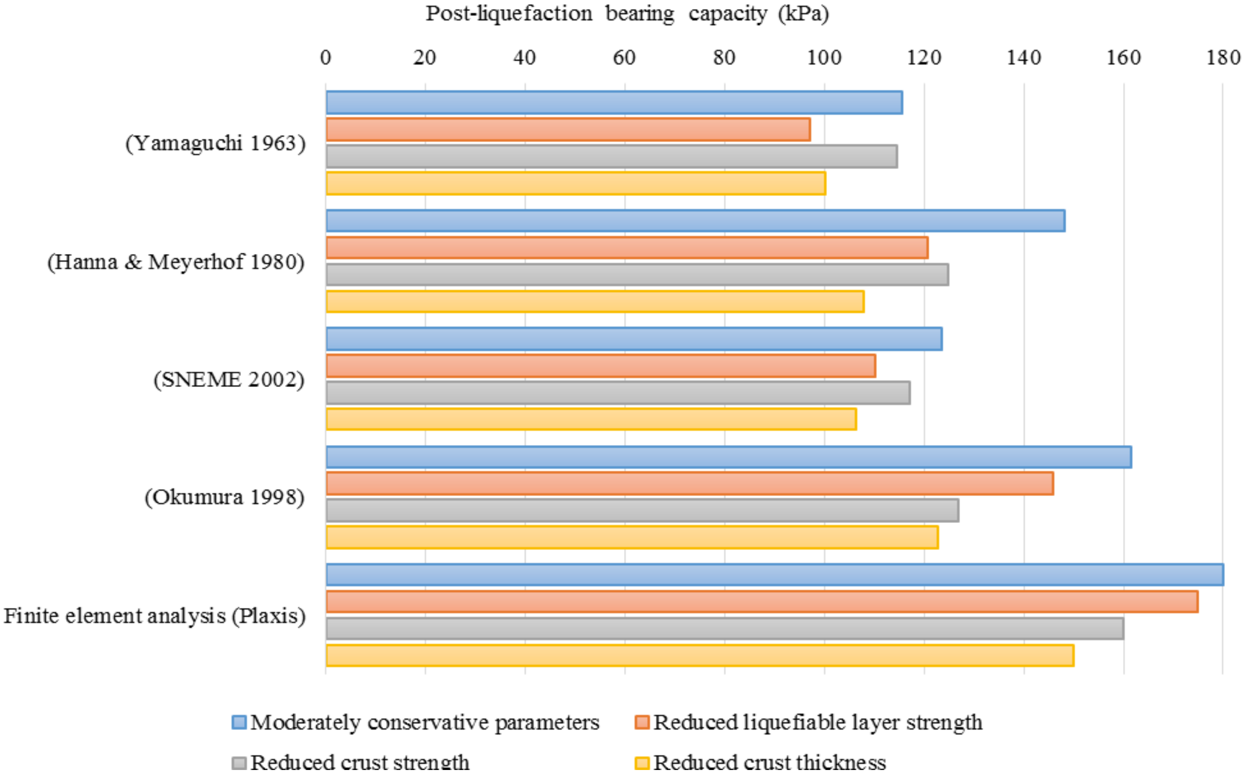


Figure 2: Sensitivity analysis results

From the sensitivity analysis it was noted that for the specific example there was up to 35% difference in results between these five methods. The sensitivity analysis of the input design parameters indicated 15% to 25% difference in results within each method. The variation in the results was considered to develop an appropriate SRF for design as presented in Table 4.

4 SUGGESTION FOR DESIGN

Bearing capacity seismic design should consider load and resistance factored design (LRFD) for the seismic design cases presented in Table 4. The assessment should consider at least two of the methods presented in Table 2 and engineering judgement applied to select the design value. Soil parameters applied in the assessment of bearing capacity should be moderately conservative and sensitivity analysis should be undertaken. The sensitivity analysis should consider parameters which are less well known and to which the output is likely to be sensitive to. This is likely to include the residual shear strength of the liquefied soil. Figure 2 presents a simple example of such a sensitivity analysis. In addition to the LRFD, the sensitivity analysis should be applied to check that with more conservative (unfavourable) but possible parameters a margin of safety against bearing capacity failure exists.

The suggested strength reduction factors for design case 2 in Table 4 include higher values than those suggested for other design cases and in NZGS Module 4 guidance. Use of these higher strength reduction factors should be applied with caution. The justification for suggesting the possibility of higher SRF is that liquefaction effects may not be fully developed at the time during the earthquake when the design seismic loads are applied. This would not hold, and the higher SRF should not be used, in instances where the trigger for liquefaction is low relative to the intensity of the design earthquake.

Table 4: Seismic design cases.

Design case	Load combination	Geotechnical SRF	Comments
1 **Early in the earthquake** Design seismic loads Assume no liquefaction effects	G+Q+E	0.4 to 0.6	Refer NZGS Module 4 Table 5.1 for SRF
2 **During shaking** Assume design seismic loads Assume liquefaction effects	G+Q+E	0.4 to 0.9 Light weight structures of up to 2 levels	The higher proposed SRF aligns with (Bray & Macedo 2017) recommendation of FoS > 1 for light buildings
		0.4 to 0.7 Heavier or tall structures	The higher proposed SRF aligns with (Bray & Mocedo 2017) recommendation of FoS > 1.5 for heavy buildings
3 **After shaking** Assume gravity loads only Assume liquefaction effects	G+Q*	0.4 to 0.6	Refer NZGS Module 4 Table 5.1 for SRF

* Unfactored gravity loads because this is a short term seismic case.

Items to consider in selecting the SRF include:

- Trigger level for liquefaction relative to the intensity of the design earthquake (lower trigger; lower SRF)
- Number of cycles to be required to trigger liquefaction (lower number of cycles; lower SRF)
- Deviatoric stresses induced by foundation loading encouraging liquefaction triggering (more heavily loaded foundations; lower SRF)
- Consequences of bearing failure (tall slender structures or structures with low tolerance to differential settlement; lower SRF)
- Scope of investigations, level of conservatism in selecting parameters, level of construction control (refer Note 1 of Table 5.1 NZGS Module 4)

The above SRF selection suggestions are for design purposes. In accordance with Section C4 of The Seismic Assessment of Existing Buildings guidelines (MBIE 2017) strength reduction factors are not applied in the assessment of existing buildings.

5 CONCLUSIONS

On the basis of published information and the sensitivity analysis the following is proposed:

- It is important to consider multiple methods while looking at bearing capacity and settlement of shallow foundations on liquefiable soils with non-liquefiable crust and applying engineering judgment in selecting conclusions for design.
- While estimating bearing capacity at developed design stage consider using finite element analysis.
- Use site specific parameters and consider multiple methods while estimating shear strength of the liquefiable layer.
- Undertake sensitivity analysis with the methods and the input design parameters applied.

- Consider potential change of conditions (e.g. increase of groundwater level due to upward pore water flow) while assessing the thickness and parameters of crust and liquefiable layer for design.
- Follow simplified procedures for assessing total liquefaction induced building settlement, if the assessed bearing capacity FoS/SRF requirements are met (Bray & Macedo, 2017).

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