Design scenarios for piles in ground subject to liquefaction

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ABSTRACT

Seismic shaking and liquefaction with its associated loss of soil strength and ground movements/deformations can be damaging to buildings and their foundations. Understanding ground behaviours and soil-structure interaction during various stages of strong earthquake shaking is critical in developing a resilient foundation and building design. Ground behaviour in strong earthquake shaking cannot be reliably predicted, but we can develop scenarios of possible ground behaviour and test our foundation design against these. Four scenarios are proposed for consideration in design; 1) pre-liquefaction representing the start of an earthquake; 2) liquefaction without lateral ground movement; 3) liquefaction-induced cyclic displacements; 4) liquefaction-induced lateral spread, representing towards the end of an earthquake or post- earthquake. All or some of these scenarios would be considered in design depending on the particular site conditions. The percentage of design building inertial loads (base shear) to be considered in conjunction with each of these design scenarios depends on the natural periods of shaking of the building and of the ground, plus other factors. Various percentages of base shear are proposed in the literature and discussed in this paper.

1 INTRODUCTION

A piled building located on land prone to liquefaction can be subject to inertia loads (base shear), loss of soil strength, cyclic (transient) ground displacement (kinematic loading) and possibly permanent (cumulative) ground displacement (lateral spread) as a consequence of strong earthquake shaking. These actions individually or in combination, may damage foundation piles and compromise their performance. (Tokimatsu and Asaka 1998) identified and investigated these effects as a consequence of the 1995 Hyogoken-Nambu earthquake. Design to allow for these potential effects requires geotechnical and structural engineering collaborative input. This needs to consider: 1) how the ground will behave; 2) how the building and foundations will behave; 3) the interaction between the ground, foundations and building. It is proposed that possible scenarios of ground behaviour as a consequence of strong earthquake shaking be identified and the building and foundation design be developed to accommodate these. This paper discusses identification of these possible scenarios and their application to design of the building and foundation. Pseudo-static analysis such as that proposed by (Cubrinovski et al. 2012) is discussed.

2 GROUND BEHAVIOUR

Prior to developing a pile design, it is critical to define the site ground conditions and assess the potential for and consequences of liquefaction. This includes developing an understanding of the site's geology via a desktop study and then planning and implementing ground investigations and analysis. A ground model is created to represent the site's conditions. This ground model is normally presented on a series of cross sections, or possibly a 3D model. The ground model is developed in stages as more information becomes available including:

- Geology;
- Site development history and evidence of behaviour in historic earthquakes;
- Historic and new; borehole, penetrometer, laboratory and other investigation data;
- Groundwater level monitoring data and an understanding of factors that could affect groundwater level during the life of the structure;
- Topographical data as inputs to slope stability and lateral spread assessment;
- The results of liquefaction susceptibility analysis;
- The results of assessments of cyclic displacement and lateral spread potential;
- Assessing and nominating soil parameters with and without liquefaction effects to be applied in subsequent soil structure interaction analysis.

Ground conditions can be expected to vary across the site and the tools available to us for the assessment of liquefaction, cyclic displacement and lateral spread potential provide an indication of a range of possible behaviours rather than absolute numbers. Ground behaviour cannot be reliably predicted. The designer must therefore identify scenarios to represent possible ground behaviour which are to be considered in the design. Moderately conservative design scenarios should be selected in line with guidance in Module 4 (MBIE/NZGS 2016).

An example and common outcome of this development of a ground model and design scenarios for a site prone to liquefaction is as follows:

- A soil profile comprising a liquefied layer sandwiched between a non-liquefied crust layer at the ground surface and non-liquefiable base. An intensity of shaking to trigger that liquefaction and an understanding if that liquefaction is continuous/widespread across the site and beyond, or discontinuous.
- If liquefaction is assessed to be widespread, cyclic displacement is modelled. A profile of cyclic displacement with depth is identified. That displacement profile would normally be zero at the base of the liquefied layer and increase approximately linearly to a peak at the top of the layer. and
- If liquefaction is assessed to be widespread and the site is sloping or adjoins a free edge (e.g. a river or coast) lateral spread could be expected and is modelled. A profile of lateral spread displacement with depth is modelled. A model of how the magnitude of this lateral spread could vary across the site is defined (e.g. reducing with distance from a free edge).

Where a potential for lateral spread is identified, design should separately consider cyclic displacement and lateral spread scenarios because predictions of which mechanism will occur may not be reliable and it is possible that cyclic displacement could develop early in the earthquake and lateral spread later or after the shaking.

In selection of soil strength and stiffness parameters to be applied in soil-structure interaction analysis lower estimate values should be selected when soil is providing resistance to piles (beneficial to the design) and upper estimate values should be applied where soil displacement is applying kinematic loads to the piles (adverse to the design).

3 BUILDING BEHAVIOUR

The selection of the concept design for the building's foundations and structure needs to consider the assessed ground behaviour and the performance brief for the design. The performance brief will include building code minimum requirements plus specific expectations of the client. These specific client expectations could include a level of life safety greater than code and/or low damage. This concept design should be undertaken collaboratively by the structural and geotechnical engineers in liaison with the client.

Important aspects of this concept design which influence the soil structure interaction will include:

- Pile type, diameter, flexural stiffness and capacity. Degree of pile head fixity.
- Embedment depth of any basement or substructure.
- The ability of the structure to tie all pile heads together.

Preliminary and subsequent design including consideration of soil-structure interaction could dictate modification of some of these aspects of the concept.

4 SOIL-STRUCTURE INTERACTION

The interaction between the soil and piles and buried substructure will be dictated by the relative stiffness of these two components; i.e. will the piles bend with ground displacement (a flexible pile) or will the soil displace past the piles (a stiff pile)? An example of a flexible pile could be a screw pile, and an example of a stiff pile could be a large diameter bored pile. Further insight on this aspect is provided by (Cubrinovski et al. 2006).

Another important aspect of this interaction is: will the shaking of the building (base shear loading) be in-phase or out-of-phase with the shaking of the ground (kinematic loading due to cyclic displacement); or somewhere between these two extremes. Further insight on this aspect and its relation to the natural periods of shaking of the building and the ground, and pile loading is provided by (Tokimatsu et al. 2005) and (Tamura and Tokimatsu 2005).

These factors are considered with reference to a number of design scenarios in the following sub-sections. As discussed in Section 2, it is not possible to reliably predict ground behaviour as a consequence of liquefaction and therefore the designer needs to develop possible scenarios of ground behaviour on which to base the design. In the following sub-sections, four generic scenarios are presented and discussed. For a specific design some or all of these scenarios can be expected to be relevant, depending on the site conditions.

4.1 Design Scenario 1: Pre-liquefaction

The first scenario represents early in the earthquake before liquefaction develops, or tests the possibility that liquefaction is not triggered by the shaking, as indicated by Figure 1. Base shear loads from the structure are resisted by pile bending and passive resistance of the soil against the piles and buried substructure.

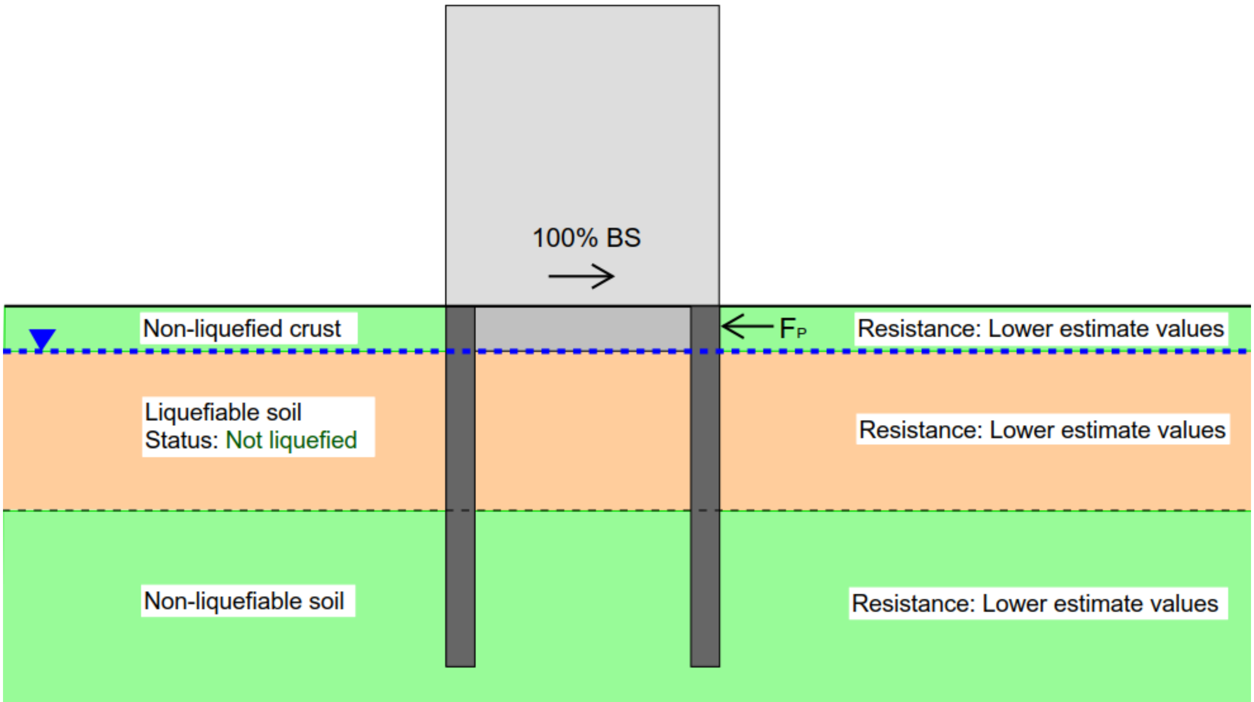

Figure 1: No liquefaction & 100% BS

BS: Base shear from building inertia.
F_P: Passive soil resistance against buried elements including substructure and basement.

<u>Analysis model</u>

The analysis can be undertaken within the structural engineering computer model or separately as a pseudo-static analysis in a geotechnical computer model such as LPile. Both analyses are recommended to provide a check on the assessed pile actions (bending moments, shear forces and displacements). Structural properties of the piles and their head fixity details are modelled. The soil resistance against the piles can be modelled as non-linear springs. (Cubrinovski et al. 2006) provides some guidance on selection of these parameters. The base shear (BS) load from the building inertia can be modelled as a point load.

<u>Soil strength/stiffness parameters</u>

The passive resistance of the soil against the buried substructure or basement (F_p) can be modelled as a non-linear spring or as a point load. If a point load is assumed an assessment will be necessary to check that sufficient displacement occurs to develop the assumed point load resistance.

Soil parameters should be lower estimate values because they are being relied on for resistance.

<u>Base shear (BS)</u>

The foundation system is to be designed to resist the full design inertia load from the building (100% BS).

4.2 Design Scenario 2: Liquefaction without lateral ground displacement

In this scenario the earthquake shaking has reached an intensity and duration which triggers soil liquefaction, but not sufficient to develop widespread liquefaction and cyclic displacement. The consequence is reduced lateral resistance to the piles but no kinematic loading as indicated by Figure 2. The designer should consider modelling a portion of the piles in Scenario 2 conditions and the remainder in Scenario 1 to represent a portion of the site in liquefied condition. This could represent variable conditions across the site. Assuming pile heads are tied together (displace equally) the consequence of this analysis would be for piles in non-liquefied soil (Scenario 1) attracting high shear loads which may be critical to the design. The designer needs to assess what portion of the piles are to be modelled in liquefied soils (Scenario 2) and what portion in non-liquefied (Scenario 1). In assessing this consider the variability of site ground conditions and the % ULS shaking triggering liquefaction. If the % ULS shaking triggering liquefaction is relatively low, a greater proportion of the site being liquefied should be allowed for. In a recent project the authors nominated 70% of the piles to be in liquefied ground and 30% in non-liquefied ground.

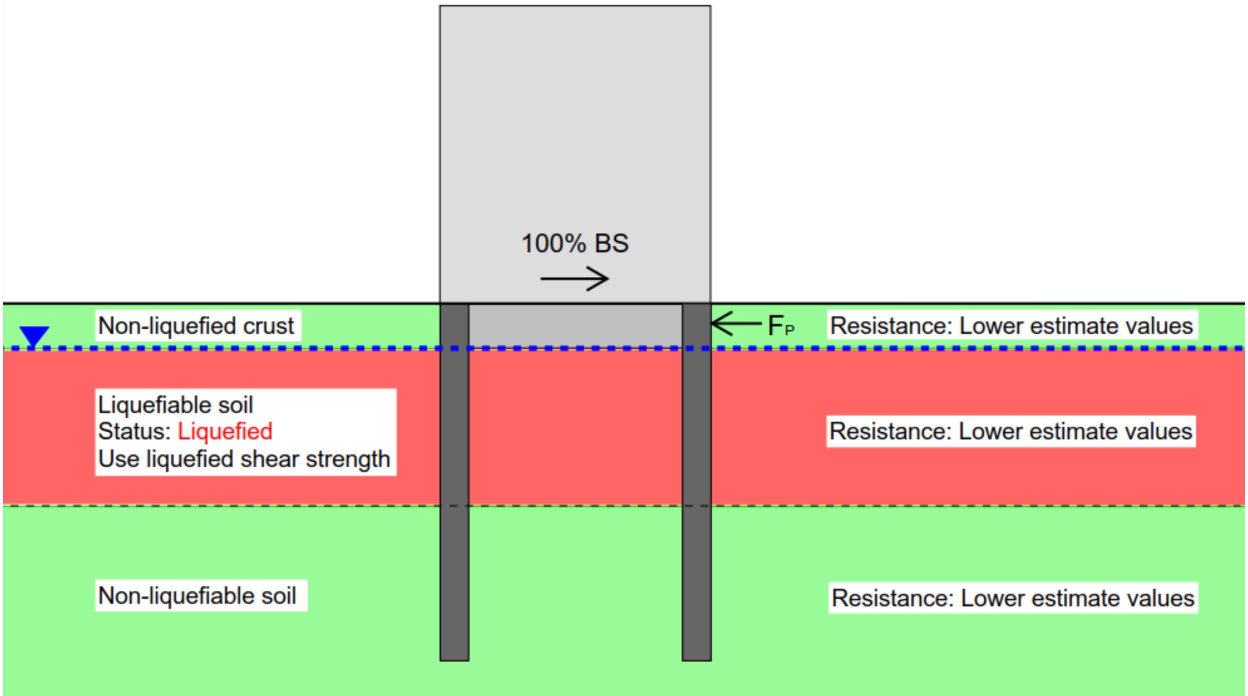

Figure 2: Liquefaction & 100% BS.

BS: Base shear from building inertia.
F_P: Passive soil resistance against buried elements including substructure and basement.

Analysis model

As for Scenario 1

Soil strength/stiffness parameters

The passive resistance of the soil against the buried substructure or basement (F_p) can be modelled as a non-linear spring or as a point load. If a point load is assumed an assessment will be necessary to check that sufficient displacement occurs to develop the assumed point load resistance.

An additional consideration is that the amount of passive pressure transferred from the crust to the sub-structure could be influenced by the presence of the liquefied 'weaker' layer underneath. (Ashford et al. 2011) provides further discussion and guidance on this aspect.

Soil parameters should be lower estimate values because they are being relied on for resistance. In instances where ground displacements are imposing kinematic loads on the piles and substructure upper estimate values should be used.

Module 3 (MBIE/NZGS 2016) provides several references for the estimation of liquefied soil strength. For guidance on the reduction of soil stiffness due to liquefaction and other associated factors, refer to (Cubrinovski et al. 2006), (Tokimatsu and Asaka 1998), (Yasuda and Berrill 2000), and (O'Rourke et al. 1994). There is typically great uncertainty in predicting these parameters, and the designer should therefore perform appropriate sensitivity analysis. The sensitivity of the pile response to soil strength/stiffness parameters is influenced by the soil-structure interaction, this is investigated by (Cubrinovski et al. 2012).

Base shear (BS)

If the % ULS shaking triggering liquefaction is low (say 50%) liquefaction could be expected to develop relatively early in the earthquake shaking making it more likely that design base shear loading could be felt in conjunction with liquefaction; i.e. it may be appropriate to consider 100% BS in conjunction with this scenario. If the trigger for liquefaction is approaching 100% ULS shaking a lower % BS could be considered; i.e. it is less likely that 100% BS would be felt in conjunction with liquefaction.

4.3 Design Scenario 3: Liquefaction-induced Cyclic Displacement

With widespread liquefaction, cyclic displacement could be expected to develop as indicated by Figure 3. As a result, the piles are subject to passive pile loading from the displacing crust and liquefied layer. The non-liquefiable base layer provides passive resistance to the piles.

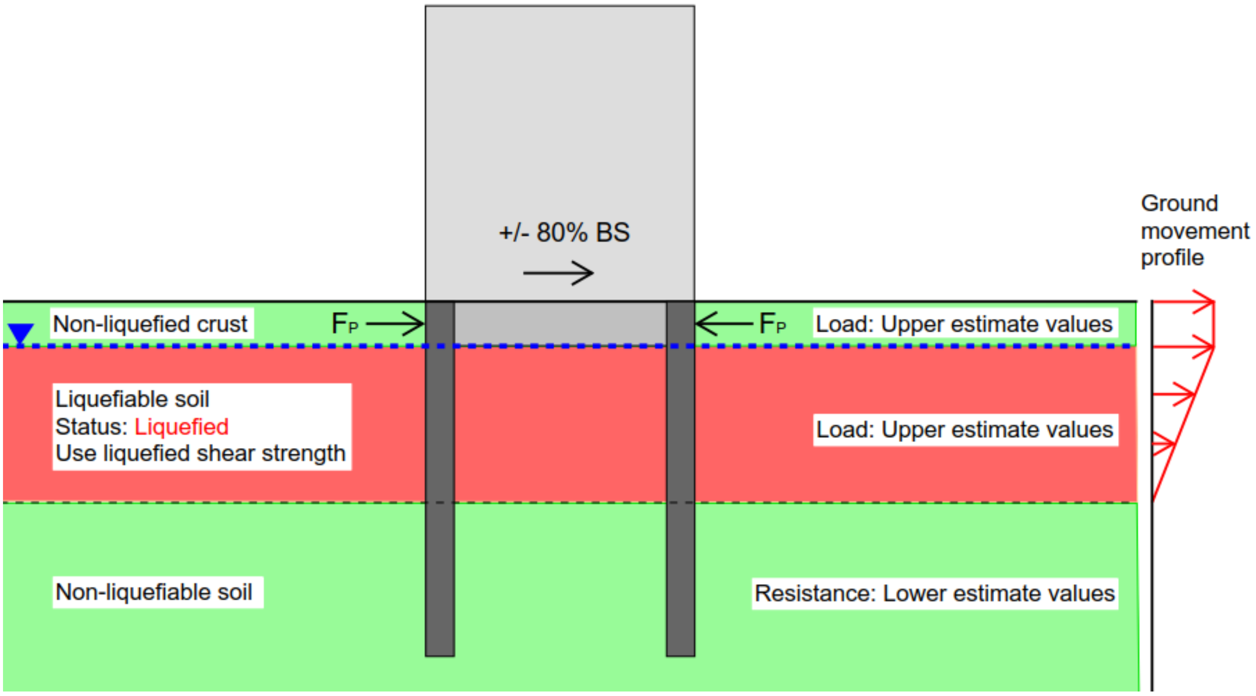

Figure 3: Liquefaction & +/- 80% BS & Cyclic Displacement & +/- F_P.

BS: Base shear from building inertia.
F_P: Passive soil resistance against buried elements including substructure and basement.

Analysis model

As for Scenario 1

Soil strength/stiffness parameters

F_p, the passive force on the substructure/basement, could be a load if the piles are relatively stiff and the sub-structure displaces less than the ground, or it could be a resistance if the piles are relatively flexible and the sub-structure displaces more than the ground. The designer needs to assess this and model as a load or resistance as appropriate.

The magnitude of the passive resistance or load (F_P) will differ depending on whether it is resisting (the structure pushing into the ground) or if it is loading (the ground pushing into the structure), (Cubrinovski et al. 2006) and (Ashford et al. 2011) provide further information on this.

Refer Scenario 2 for further comments on liquefied soil strength and stiffness.

Base shear (BS)

The designer needs to consider what portion of the design base shear is reasonable to assume to occur cumulatively with kinematic loading from cyclic displacement. It is reasonable to assume less than 100% because kinematic and base shear loading are not likely to be 100% in phase, and because cyclic displacement could be expected to develop later in the shaking and thus full design base shear loading is less likely to occur concurrently. 80% base shear is commonly assumed but may not apply in all instances.

Further discussion and guidance on the % of base shear to be allowed for in combination with kinematic loading is provided by the Bridge Manual (NZTA 2018), (Cubrinovski et al. 2012), (Tokimatsu et al. 2005), (Ashford et al. 2011), (Tamura and Tokimatsu 2005), (Liyanapathirana and Poulos 2005) and (Haskell 2009).

4.4 Design Scenario 4: Liquefaction-induced Lateral Spreading

The fourth scenario represents lateral spread (cumulative permanent displacement in one direction) as indicated by Figure 4. This is likely to develop toward the end of an earthquake or post-earthquake. In this Scenario the piles are subject to passive lateral loading within the crust and liquefied layer, and resisting passive pressures within the non-liquefiable base layer.

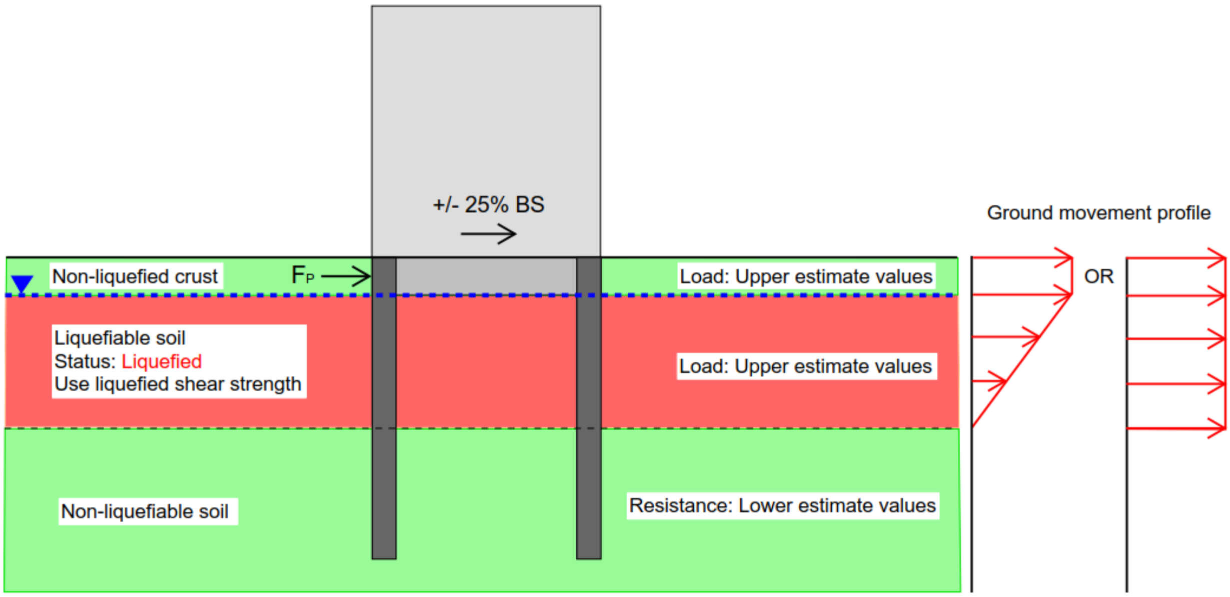

Figure 4: Liquefaction & +/- 25% BS & Lateral Spread & F_P.

BS: Base shear from building inertia.
F_P: Passive soil resistance against buried elements including substructure and basement.

Analysis model

As for Scenario 1

Soil strength/stiffness parameters

With lateral spread, ground could be pushing against the structure developing full passive pressure against the buried substructure as a load. The designer needs to assess if this is a reasonable assumption for the particular site conditions.

Refer Scenario 2 for further comments on liquefied soil strength and stiffness.

Base Shear (BS)

Because lateral spread is likely to develop late in the earthquake shaking, or possibly post the shaking, it is less likely that a high proportion of the design base shear loading will be felt in conjunction with lateral spread. As discussed under Scenario 2 if the % ULS shaking triggering liquefaction and lateral spread is relatively low, a higher % of the design base shear load could be expected to be felt in conjunction with lateral spread, compared to the case of % ULS shaking liquefaction trigger approaching 100%. Furthermore, the intensity of shaking of possible aftershocks is also a consideration. The designer should consider these and other factors in selecting the % BS to be allowed for in conjunction with Scenario 4. 25% Base shear is commonly assumed (Bridge Manual, NZTA 2018) but may not apply in all instances, refer to Scenario 3 for further comments.

5 CONCLUSIONS

We cannot reliably predict the behaviour of ground during strong earthquake shaking and liquefaction. This behaviour can be damaging to a building and its foundation. We can approach this uncertainty by; developing an understanding of the site conditions, and undertaking analysis to provide an indication of liquefaction, cyclic displacement and lateral spread potential. We can then apply this information and engineering judgement to identify scenarios of possible ground behaviour for which the building design is to be tested.

A companion paper by (Smith et al. 2020) presented at this conference reports a case study in which the procedures proposed in this paper were applied.

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