Soil-structure interaction of piled buildings on ground subject to liquefaction and lateral displacements

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ABSTRACT

The lateral design of piled foundations for buildings in liquefiable ground is challenging because of potential reduced lateral support and possible lateral ground displacements. Soil-structure interaction (SSI) analysis is an iterative process and requires effective communication between structural and geotechnical engineers. This paper presents the details of how this process was implemented for a building located on Wellington's reclaimed waterfront. Understanding the potential for lateral spread and assessing how lateral spread could vary across the building footprint is important as lateral stretch of a building is very damaging. Different design scenarios representing the ground and structure behaviour at different stages of earthquake shaking need to be considered. The process generally comprises the geotechnical engineer providing geotechnical information required for the structural analyses such as soil springs range and any soil loadings on the structure (e.g. passive pressure pushing on the sub-structure). The structural engineer, after performing their analyses, provide information (e.g. base shear loads, pile stiffnesses, fixity, moment capacities etc.) to the geotechnical engineer to carry out an independent analysis. Discrepancies in the analyses must be discussed and investigated. The process is then iterated such that similar pile actions are obtained from both the geotechnical and structural engineer.

1 INTRODUCTION

The paper presents Site 9 on Wellington's CBD waterfront as a case study for soil-structure interaction (SSI) in pile lateral design. Site 9 is the location proposed for the construction of a five-storey development (see Fig. 1). The structure is approximately 60m by 12m in plan, base isolated, and founded on 1.5m diameter bored piles. It is approximately 10m west from the current shoreline of Wellington Harbour at its closest point.

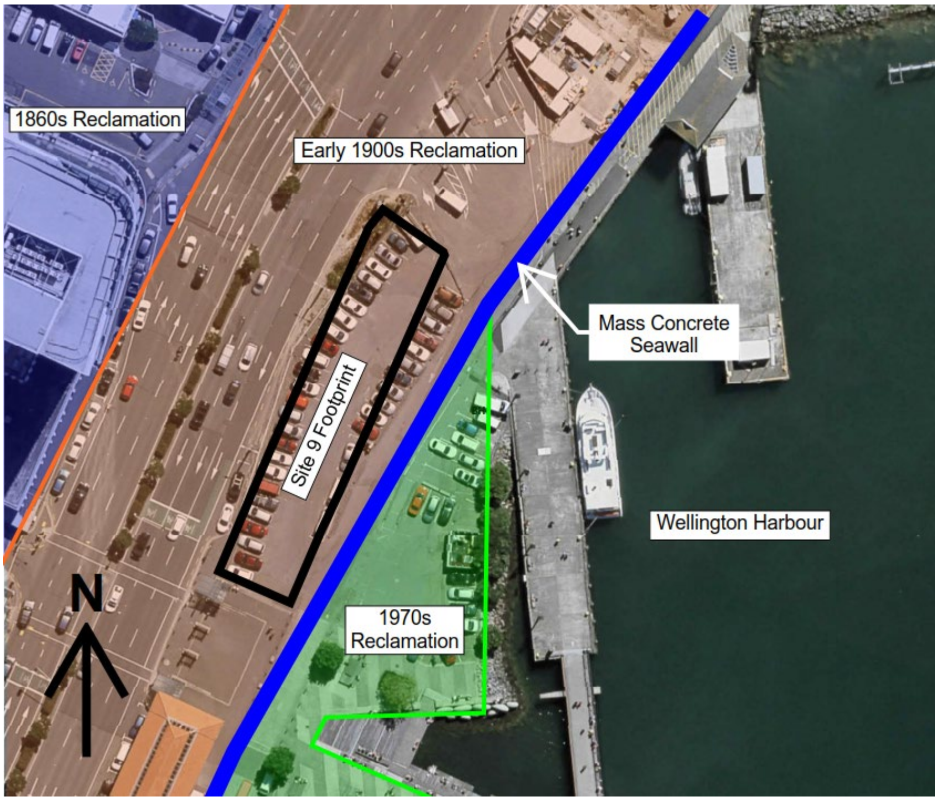

Figure 1: Location Plan

Reclamation beneath and adjacent to Site 9 was undertaken in three distinct stages during the 1860s, early 1900s, and 1970s. A mass concrete seawall runs parallel longitudinally to the building. To the south, this seawall is buttressed by the 1970s fill on the seaward side, and to the north the seawall is the free face to the harbour. The seismically active Wellington Fault lies approximately 1km north-west from the site.

The geometry and geological setting of Site 9 described above presents unique challenges to the lateral design of the foundations. While we cannot accurately predict how lateral spread will occur, we can present different possible scenarios to inform the design. SSI assessment between the geotechnical and structural engineer is an important process in all stages of design. This paper presents how the SSI assessment was undertaken throughout concept and preliminary design, developing scenarios of ground actions on the foundation system, and through to developed design. It also provides guidance on how this approach can be adopted in lateral design of other structures and demonstrates the importance of the geotechnical and structural engineer communicating effectively throughout the design process.

2 CONCEPT AND PRELIMINARY DESIGN

2.1 Ground model

The general soil profiles at Site 9 is summarised in Table 1. Design groundwater level coincides with the bottom of the ground beams/top of piles.

Table 1: General soil profile at Site 9

Layer	Geological Unit	Soil Description	Layer Thickness (m)	SPT N (blows/300mm)
1	Reclamation Fill (1902)	Very loose to loose well graded sandy GRAVEL With lenses of: • very loose SAND • soft to firm SILT	3.5 to 6.5	1 to 11
2a	Beach deposits – Silt	Soft SILT	0 to 0.5	1 to 3
2b	Beach deposits – Sand	Loose silty SAND with some gravel, trace shells	0 to 1.0	1 to 8
3a	Upper Alluvium	Interbedded: • Stiff SILT/CLAY. • Dense to very dense silty SAND and GRAVEL.	4 to 7	10-25 25-50+
3b	Lower Alluvium	Very dense slightly silty SAND and GRAVEL and hard SILT, with possible occasional weaker silt beds.	35	50+
4	Basement Rock	Greywacke	N/A	N/A

2.2 Liquefaction effects

Investigation and assessment of the site indicated that as a consequence of strong earthquake shaking, widespread liquefaction of the reclamation fill, beach deposits and upper 1.5m of the Upper Alluvium could occur. Cyclic displacement, lateral spread, sand boils and settlement were identified as possible consequences of liquefaction.

2.3 Lateral spread scenarios

While the pattern and magnitude of lateral spread displacements cannot be predicted a series of possible scenarios can be developed against which the building foundation design can be tested.

A possible lateral spread scenario to consider is one where the seawall displaces along its full length, represented in Figure 2. Lateral spread would occur transversely across the building footprint towards the reclamation edge and kinematic loading would only be considered in this direction.

Another possible scenario is shown in Figure 3. In this scenario, the northern section of seawall fails, while the section of seawall at the southern extent of the site is less likely to fail due to the presence of buttressing by the 1970s reclamation fill. This creates lateral spread in the longitudinal direction to the building towards the north, possibly over part of the building.

The above illustrates that lateral spread could be in any direction towards the free edge, with respect to the building. It is important to communicate to the structural engineer so that all possibilities are considered to assess the performance of potential foundation systems.

During cyclic displacement, lateral movement of liquefied soils may be in any direction across the entire building footprint.

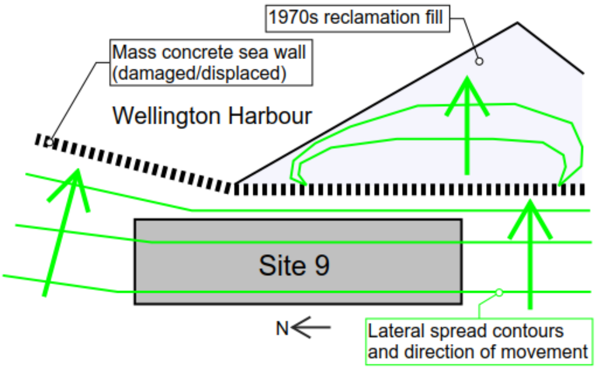

Figure 2: A possible lateral spread scenario with movement transversely across the building.

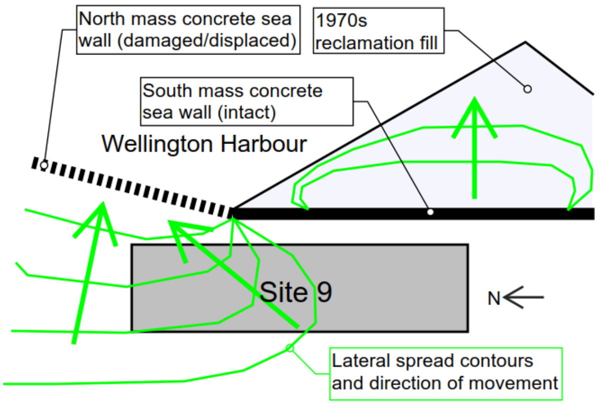

Figure 3: A possible lateral spread scenario with movement longitudinally and transversely across the building.

2.4 Lateral loading on foundations

With possible lateral spread scenarios for the site identified, building foundations were assessed against four possible kinematic (soil) loading stages of earthquake shaking. Pseudo-static analyses were applied. The loading stages consider different ground behaviour and displacements combined with different building inertia loadings (base shear) in an earthquake.

For further information refer to a companion paper presented at this conference; Rolfe, Chin, and Palmer (2019) “Design scenarios for piles in ground subject to liquefaction”.

2.5 Foundation options

Table 2 summarises the foundation options considered. These foundation options were critically evaluated in conjunction with the structural engineer. Their merits and disadvantages were weighted against performance, costs, reliability and constructability. The assessment by the design team concluded that the bored pile option was preferred.

Table 2: Foundation options considered for Site 9.

Foundation Option	Advantages	Disadvantages
Transverse CFA walls	• Lower cost than bored piles. • Minimal excavation required.	• Poor performance for lateral spread in the longitudinal direction (see Fig. 3). • An innovative design (not done before locally) requiring assumptions of ground behaviour which is difficult to predict reliably.
Cellular CFA wall structure	• Lateral performance not dependent on the direction of lateral spread.	• Higher cost.
Bored piles	• A more common construction technique in Wellington. • High compression resistance. • Lateral performance not dependent on the direction of lateral spread.	• Pile excavation stability. • Higher cost.
Bored piles with gravel column ground improvement	• Lateral performance not dependent on the direction of lateral spread. • Smaller bored pile diameter possible.	• Higher cost. • Ground improvement required outside of building footprint.

3 DEVELOPED AND DETAILED DESIGN

3.1 Ground actions on foundation system

The soil (kinematic) loading on the building substructure and the bored piles was assessed for the three scenarios presented in Section 2.3 above. The following kinematic loads were considered:

- Passive force behind ground beams and slab;
- Sliding force on the trapped soil between ground beams;
- Side shear along substructure;
- Passive force on the bored piles due to laterally moving liquefied soils.

Figures 4 to 6 show how the above loading was presented to the structural engineer in a simple and concise manner. The loadings were discussed with the structural engineer to ensure they understood them. In particular, the lateral spread over a partial building footprint can be very damaging as the differential ground movement can cause 'lateral stretch' and potentially 'rip' the building apart. Lateral spread, stretching and damaging buildings was observed as a consequence of the Christchurch and other historic earthquakes.

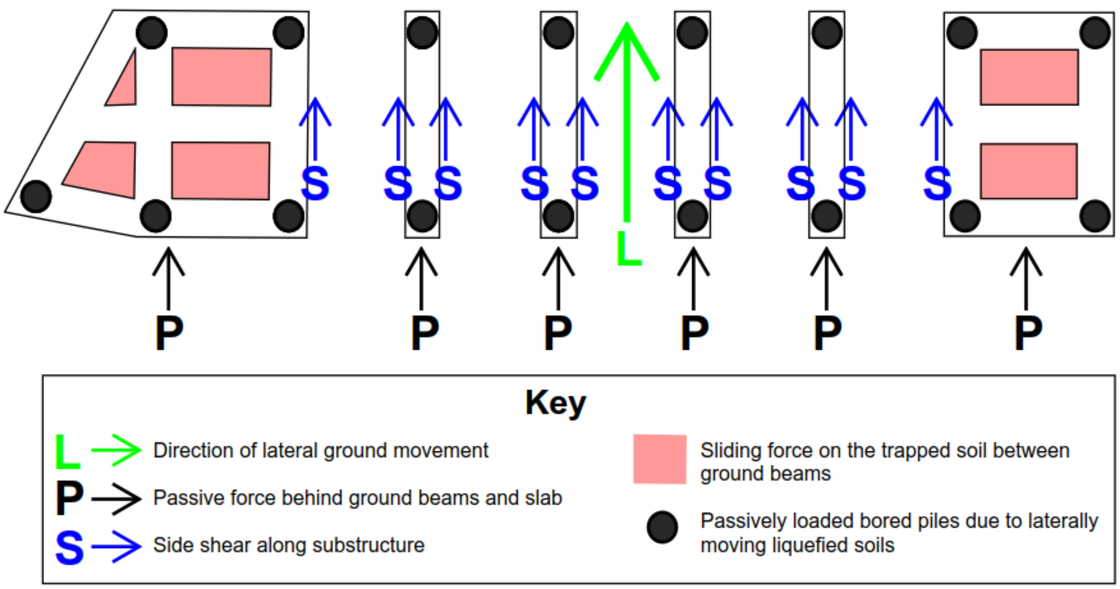

Figure 4: Foundation loading for cyclic displacement and lateral spread in the transverse direction over the entire building footprint (see Fig. 2)

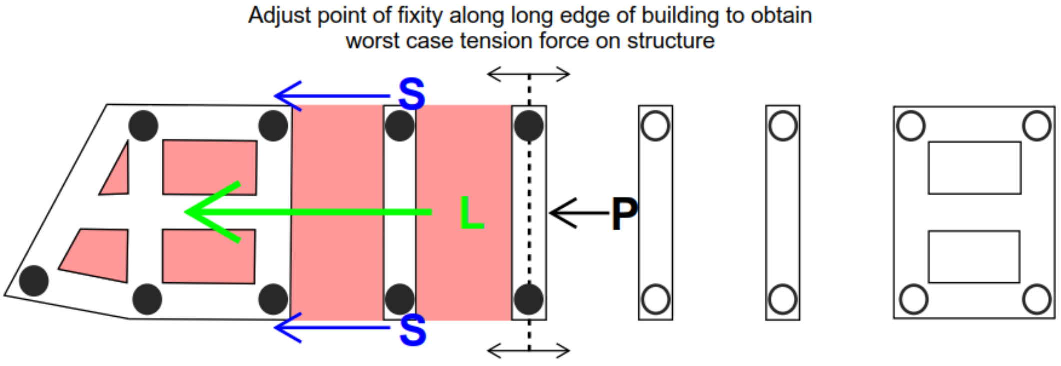

Figure 5: Foundation loading for lateral spread in the longitudinal direction over part of the building footprint (see Fig. 3)

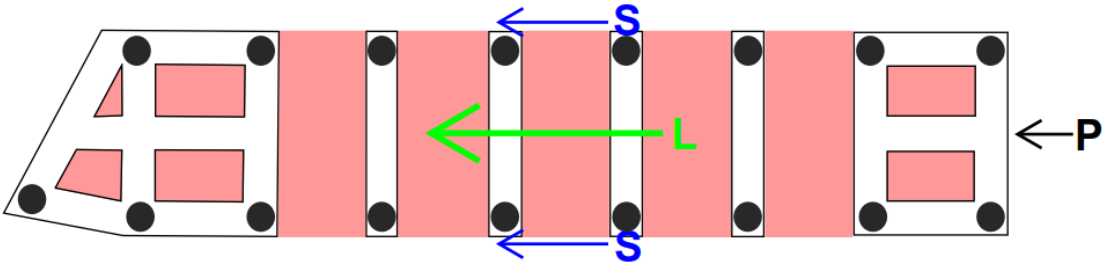

Figure 6: Foundation loading for cyclic displacement in the longitudinal direction over the entire building footprint.

3.2 Soil Structures Interaction (SSI)

3.2.1 Geotechnical parameters for structural analyses

In addition to the kinematic loading described in Section 3.1 above, the following geotechnical parameters were also provided and discussed with the structural engineer to enable them to perform the structural analyses.

- Non-linear lateral soil springs with depth. There are inherent uncertainties in obtaining these soil springs. Accordingly, an appropriate range should be provided to obtain the worst-case building displacements and loadings (e.g. the impact of one or a few soft piles at critical locations).
- Recommended load combination of soil kinematics and building inertia.

3.2.2 Structural parameters for geotechnical analyses

To enable a geotechnical pile lateral analysis the following information is required from the structural engineer:

- Pile head fixity and rotational stiffness;
- Pile flexural and axial stiffness;
- Pile moment capacity;
- Building base shear loads at pile head level;
- Axial loads;
- Moment capacity.
- Loads on the pile shaft from soil kinematics.

3.2.3 SSI analysis process

The SSI analysis process can be summarised in three simple steps:

1. Structural engineer performs their analyses based on the geotechnical information provided including a sensitivity study. This usually comprised a 3-D model with simplified ground properties.
2. Geotechnical engineer performs their analyses based on the structural information provided as listed above in Section 3.2.2. This models the soil properties more accurately (compared to the structural analysis). The analyses typically comprise a laterally loaded single pile modelled in LPile software. The soil kinematics was modelled as a load in this case study.
3. Deflections and pile actions from the two independent analyses are compared. Discrepancies in the analyses must be discussed and investigated. The process is then iterated such that similar pile actions are obtained from both the geotechnical and structural engineer.

4 CONCLUSIONS

Site 9's ground conditions and location presented challenges in the lateral design of the foundations. Such challenges are unique and are not common in a typical building development. Absolute cooperation, understanding, technical knowledge, collaboration and communication is required. The foundation design at Site 9 was successfully completed because the structural and geotechnical engineers demonstrated such attributes throughout all design stages.

ACKNOWLEDGEMENTS

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