Mitigation of liquefaction-induced lateral spread ground displacements using an in-ground pile wall

A.R. Rolfe and S.J. Palmer
Tonkin & Taylor Ltd, Wellington, New Zealand

ABSTRACT

Liquefaction-induced lateral ground displacements (lateral spread) can be damaging to buildings and their foundations. Buildings can either be designed/strengthened to tolerate such displacements, or ground improvement (e.g. compaction, grouting etc.) may be implemented to mitigate these displacements to a tolerable magnitude. For existing buildings that cannot tolerate such displacements, foundation strengthening is not always a feasible option and site constraints limit ground improvement options. Therefore non-routine engineering solutions will be required. This paper presents the development of such a solution (an in-ground pile wall to mitigate lateral spread) for a site occupied by existing buildings located on a reclaimed waterfront in Wellington. Lateral spread ground displacements cannot be reliably predicted and there is uncertainty in prediction of the loads imposed on the in-ground pile wall by lateral spreading ground. Appreciating these uncertainties, the design included both displacement-based and force-based approaches along with sensitivity analyses. The sensitivity analyses considered the uncertainty in the input parameters and in the analysis methods. Resilience in the event of earthquake shaking or ground displacements beyond the design allowances was provided.

1 INTRODUCTION

The paper presents St. Patrick’s College, Wellington (the Site) as a case study for using an in-ground pile wall solution to mitigate liquefaction-induced lateral spread displacements. The Site (see Figure 1) is located near the Evans Bay waterfront in Kilbirnie, Wellington. The pile wall is an important part of the wider project. It enables cost-effective strengthening solutions for the existing buildings at the Site. Individual buildings are not discussed in this paper.

The Site’s seaward-end is located approximately 40m to 80m southwest of the current shoreline. The seaward buildings are located approximately 50m to 150m from the current shoreline. The Site gently slopes seaward. Reclamation beneath and adjacent to the Site was undertaken in two stages. During the 1920’s, reclamation was undertaken up to just west (landward) of the Site and Evans Bay Parade roadway. During the 1950’s, a larger area was reclaimed further seaward of Evans Bay Parade, extending beneath the Site up to the current shoreline, i.e. the reclamation edge.

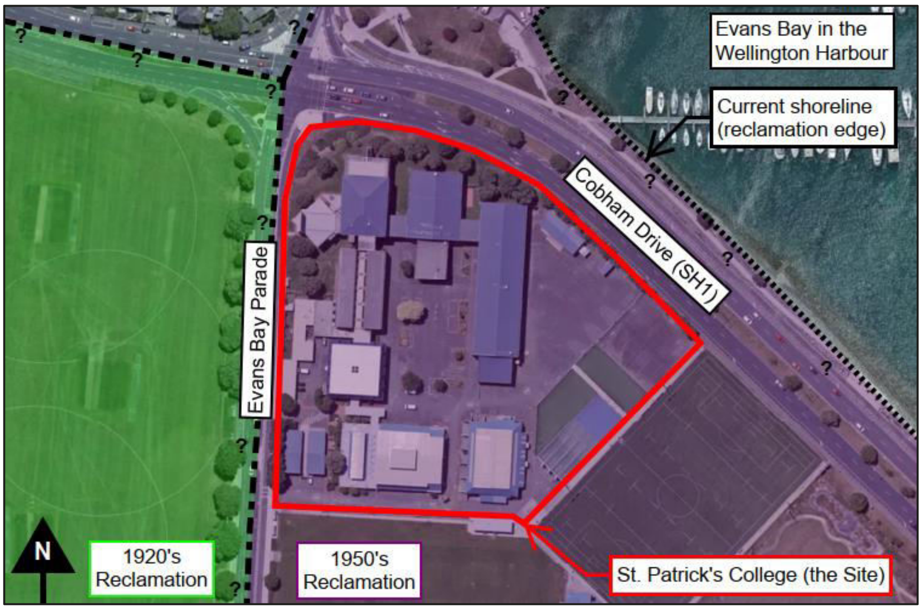

Figure 1: Location Plan

2 BACKGROUND INFORMATION

2.1 Soil profile and groundwater

The general soil profile at the Site is summarised in Table 1. Across the Site, depth to groundwater below the current ground surface is between 2m and 3m, and is influenced by tidal effects. The higher groundwater level is noted in standpipes closer to the sea due the ground surface sloping seaward. Sea level rise was also considered for this project.

Table 1: General soil profile at the Site

Layer	Geological Unit	Soil Description	Layer Thickness (m)	SPT N (blows/300mm)
1a	Reclamation Fill (above groundwater table)	Medium dense, SAND and GRAVEL, with some cobbles	2 to 3	15 to 30
1b	Reclamation Fill (below groundwater table)	Very loose to loose, SAND and GRAVEL, with some silt	1 to 3	< 10
2	Beach Deposits	Very loose to loose, silty SAND, with some shells	0 to 1	< 10
3a	Upper Alluvium	• Loose to medium dense, SAND and SILT; interbedded with • Firm, clayey silt.	1 to 5	5 to 25 < 10
3b	Lower Alluvium	Medium dense to very dense, silty SAND, with localised lenses stiff, clayey silt.	0 to 10	25+
4	Basement Rock	Greywacke, highly weathered, very weak or better	Proven 5m	50+

2.2 Consequences of earthquake-induced liquefaction

Soil Layer 1b, 2 and 3 are assessed as susceptible to liquefaction. Associated consequences are assessed as:

1. Lateral spread within Layer 1b and 2 towards the sea.
2. Cyclic displacement.
3. Liquefaction within localised pockets/lenses of weaker sand and silt in Layer 3a leading to reduction in soil strength and stiffness.
4. Sand boils.
5. Differential settlement.
6. Loss of support to foundations.
7. Negative skin friction on piles (post-earthquake).

Item 1. above is the issue dealt with in this paper.

2.3 Lateral spread and existing buildings

Different methods for estimating lateral spread of the unimproved site were used and compared. The calculations included sensitivity analyses for soil parameters, groundwater level, geometry of the reclamation edge, earthquake shaking etc.

The existing buildings are founded on Franki piles driven into the upper alluvium. As a result of lateral spread, lateral forces (kinematic loads) will be imposed onto the piles. In conjunction with the structural engineer, it was concluded that piles at the most seaward buildings are not expected to tolerate estimated lateral ground displacements without presenting a life safety hazard. Accordingly, seismic strengthening was proposed.

It is important to note that there is extreme difficulty in predicting the magnitude of lateral spread given the inherent uncertainties within available methods, soil parameters etc. Actual displacements could be several times larger or smaller than calculated. Rather than focussing on the significant unknowns i.e. estimating lateral spread, a more pragmatic approach was taken to focus on the resilience i.e. things that we can more reliably predict and control in design. This is discussed more in subsequent sections.

2.4 Possible foundation options to improve building seismic performance

Working collaboratively with the structural engineer, a series of possible foundation options were assessed to improve the seismic performance of the buildings. The options fall into two main groups (note that superstructure improvements are also required but not covered here):

1. Foundations that can tolerate lateral ground displacements (e.g. raft foundations, large piles).
2. Mitigating liquefaction and/or lateral spread (e.g. ground improvement).

Feasible foundation options were limited due to several site constraints (limited space and access for plant, active school operations) and costs. Considering the constraints, a less conventional solution of an "in-ground pile wall" (referred to as Pile Wall – see Figure. 2) was selected. The objective of this option is to laterally restrain the Site along its seaward side to control potential lateral spread to a level which can be tolerated by the existing buildings. This option has benefits compared to foundation or ground improvement options of substantially lower, cost and disruption to the buildings and school operations. The Pile Wall being located beyond the buildings substantially reduces disruption compared to other options.

The final Pile Wall solution comprises 1050mm diameter reinforced concrete bored piles spaced at 2m centres. Piles are founded a specified embedment into the lower alluvium (Layer 3b) and/or rock (Layer 4).

Pile lengths are typically 15m. All pile heads are connected by a buried reinforced concrete capping beam to ensure the Pile Wall acts as a single structure.

The development of the Pile Wall solution is presented in the subsequent sections.

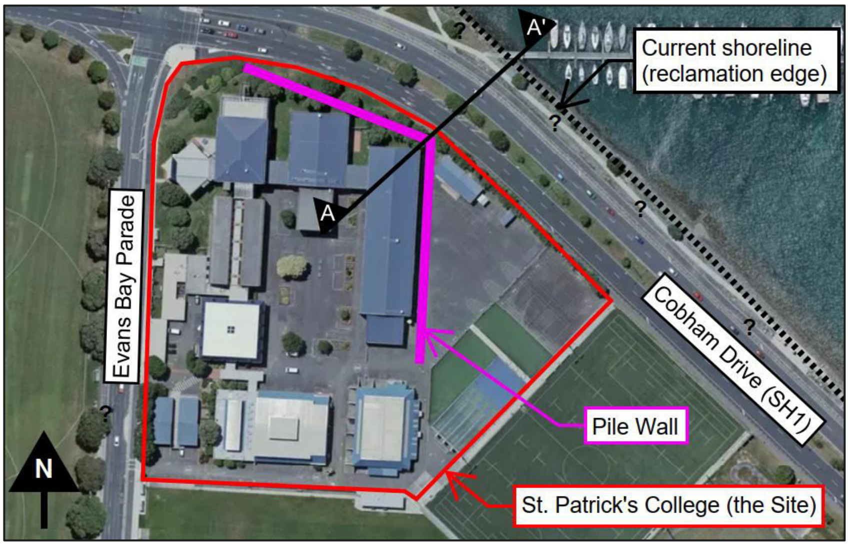

Figure 2: Pile Wall alignment

3 DEVELOPMENT OF THE PILE WALL SOLUTION

The objectives of the Pile Wall is to:

1. Mitigate (reduce) estimated lateral spread at the seaward buildings to 100mm, and
2. Maintain structural integrity of the Pile Wall during an extreme lateral spread (and earthquake shaking) event, i.e. resilience.

3.1 High-level overview of the Pile Wall concept

The presence of the Pile Wall is expected to add substantial lateral restraint at a specific location. During lateral spreading, tension cracks can be expected at the seaward side of the Pile Wall as the liquefied ground moves towards the harbour. Landward of the Pile Wall, it is expected that the lateral restraint will significantly reduce lateral spreading.

The reduction of ground displacements landward of the Pile Wall is due to the lateral restraint applied by the Pile Wall to the laterally spreading ground.

The close spacing (2 times the pile diameter) of the piles and the linking ground beam creates a virtual continuous wall. There will still be some lateral displacement of the ground due to rotation and bending of the pile wall as it takes up load and passive deformation between ground and piles/ground beam.

3.2 Design approaches

The development of the Pile Wall solution was undertaken using two approaches:

1. Displacement-based approach to assess if the Pile Wall can provide sufficient lateral restraint to achieve 100mm (mitigated) lateral spread (refer Objective 1 of the Pile Wall), and
2. Force-based approach to assess the resilience of the Pile Wall for an extreme case of lateral spread, i.e. very large ground displacements (refer Objective 2 of the Pile Wall).

These approaches are discussed in the subsequent sections.

3.3 Displacement-based approach

This approach assesses the lateral restraint which the Pile Wall must provide to the ground to reduce estimated lateral ground displacement to 100mm in the design seismic event.

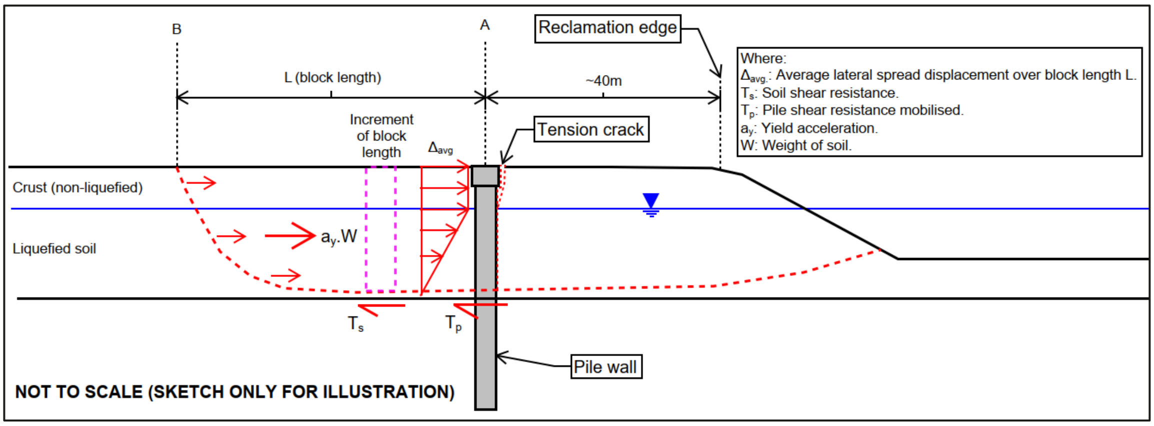

Figure 3: Sketch of problem assessment model (based on cross-section AA' indicated in Fig. 2).

The step-by-step approach undertaken is outlined below (refer Figure. 3):

- **Forward analysis without the pile wall.** Empirical and numerical methods, Youd et al. (2002), Zhang et al. (2004) and Bray and Macedo (2019), were applied to assess the potential average lateral spread ($\Delta_{avg.}$) of the ground surface between locations A and B (Refer Figure 2) for the design seismic event (M7.1, 0.59g). The analysis and engineering judgement concluded an "expected" displacement of 200mm. There is considerable uncertainty in these predictions and actual displacement could be 1/3 to 3 times this "expected" value. Predicting an "expected" value is consistent with the philosophy of assessment of existing buildings (NZSEE, 2017).

- **Back analysis without the pile wall**. Consider the block of displacing soil between locations A and B. This block's expected average displacement under the design shaking has been estimated to be $\Delta_{avg.}$= 200mm. This displacement and Newmark Sliding Block (NSB) assumptions were applied to an increment of the block length in a back analysis to evaluate the soil shear resistance T_s, as indicated on Figure 3. The soil shear strength determined by this back analysis was compared to that of residual shear strength of liquefied soil and found to be consistent.

- **Forward analysis with the pile wall**. Consider the block of displacing soil between locations A and B (block length L). It is assumed that the soil block seaward of the Pile Wall moves away, i.e. a tension crack forms seaward of the Pile Wall. The lateral restraint provided by the Pile Wall (T_p) and the soil shear strength (Ts) were applied in a NSB analysis of block L to estimate the mitigated lateral spread. The NSB analysis indicated that the Pile Wall would need to provide 150kN/m additional lateral resistance (T_p = 150kN/m) to block L to limit the "expected" displacement of the block to the design objective of 100mm at the design level shaking (M7.1, 0.59g).

- **Selection of pile diameter and spacing**. The lateral load displacement behaviour of the Pile Wall was estimated for different pile sizes and spacing using the geotechnical computer software "Wallap". "LPile" software was also applied to challenge the "WALLAP" results. The load displacement behaviour varied depending on the assumed pile embedment conditions, which varied along the Pile Wall. Figure 4 indicates the calculated load displacement behaviours for the selected pile arrangement of 1050mm diameter piles at 2m centres. This selected pile arrangement provides the required 150kN/m lateral resistance at less than 100mm displacement (see Figure 4).

- **Sensitivity analyses**. Sensitivity analyses were undertaken for critical parameters at each step of the analysis. A moderately conservative approach was applied in selecting the design base case. The sensitivity analyses included:
  - Varying assumed displacement (Δ_{avg}) for back analysis
  - Varying block length L in the back and forward analyses
  - Applying different NSB references; Jibson (2007) and an in-house method of double integration of selected time histories. Because the same reference was used in the back analysis as the forward analysis this was not sensitive.
  - Pile embedment conditions.

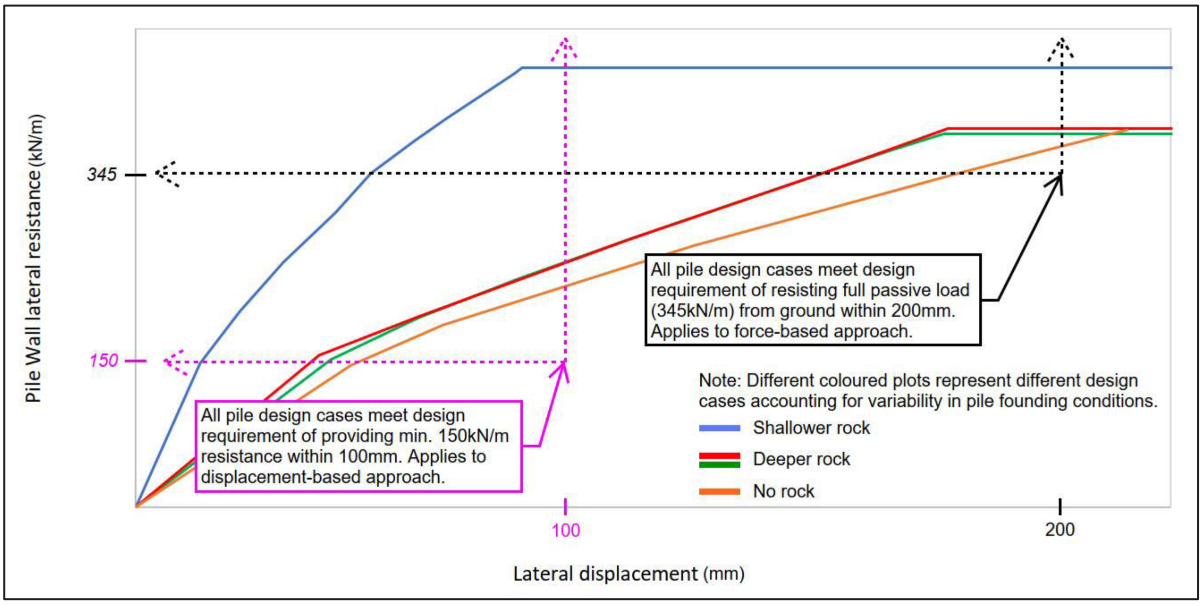

Figure 4: Load-displacement behaviour of selected Pile Wall arrangement, and design requirements.

The displacement-based approach provided a prediction of mitigated lateral displacement, but with considerable uncertainty. The NSB assumptions are a poor representation of the mechanism of lateral spread leading to uncertainties in the predictions with the wall in place. This was compensated for to some extent by applying the NSB in a back and forward analysis, i.e. the NSB was calibrated to the prediction of lateral spread without the Pile Wall. But there are uncertainties in those predictions and uncertainties in ground conditions. Because of these displacement uncertainties further analysis was undertaken using a force-based approach.

A structural analysis was undertaken, which produced the design actions for which the piles were then designed to resist elastically.

3.4 Force-based approach

The philosophy of the force-based approach was, if the Pile Wall provided lateral resistance equal to the full passive pressure of the liquefied ground and overlying non-liquefied crust, then resistance to movement in the seaward direction would be equal to that in the landward direction. With no imbalance of resistance (seaward-landward) permanent lateral spread beyond that necessary to develop the wall resistance would not occur. Cyclic displacement could still occur. It is noted that the base of the reclamation fill and the old seabed have virtually no slope seaward, they are almost level.

The passive load is independent of the assumed earthquake shaking and lateral spread predictions, thus providing resilience to the design. More intense earthquake shaking would not be expected to impose additional load on the wall.

The analysis steps for this approach were:

- **Calculate passive load** which could be imposed on the Pile Wall. A continuous virtual wall was assumed and a passive load of 345kN/m was calculated.
- **Design the piles to resist this passive load.** The 1050mm diameter piles at 2m centres were found to be adequate with special reinforcing details.
- **Calculate wall displacement** for this passive load. The results of this calculation was 50mm to 175mm depending on the pile embedment conditions, as indicated on Figure 4.

A structural analysis was undertaken, which produced the design actions for which the piles were then designed to resist elastically.

4 DISCUSSION

The overall conclusion of the displacement-based and force-based design was that; with the ultimate limit state design earthquake shaking (M7.1, 0.59g), lateral displacement of the ground behind the Pile Wall is expected to be less than 100mm and is unlikely to be greater than 200mm. This compares to the expected displacement without the wall of 200mm. Because of uncertainties the actual displacement without the wall could be 3 times this 200mm. Further in the event of more intense earthquake shaking or larger than predicted lateral spread the wall has been designed to maintain its structural integrity. The wall is designed to resist passive loads, giving it resilience.

This assessed wall performance aligns well with the objectives for future use of the Site. The existing buildings have limited remaining life. The combination of mitigated lateral spread and structural strengthening of the buildings has allowed mitigation of assessed life safety hazard to a level considered acceptable by the school's board. The school can continue to operate while these works are being undertaken. The wall has a life beyond that of the existing buildings. New buildings can be built behind the wall. Foundations for these buildings can be designed to tolerate 200mm of ground movement. Without the wall the possibility of 3 times this displacement would have to be considered. It is noted that with the wall in place the existing buildings are assessed relative to the "expected" displacement of 100mm while new buildings are designed to be "dependable" and thus allow for the possible displacement of 200mm. This is consistent with the philosophy for assessment and new design respectively.

5 CONCLUSIONS

The identified potential for lateral spread at the Site was assessed to be damaging to existing building foundations, presenting a life safety hazard. Options of re-founding the buildings on rafts and/or ground improvement beneath the buildings were discounted because of cost and disruption to the buildings. Mitigating the lateral spread by providing the lateral restraint of a Pile Wall seaward of the buildings was identified as a cost-effective solution with limited disruption to the buildings. The Pile Wall solution was adopted.

The Pile Wall was designed by applying both displacement-based and force-based approaches. The displacement-based approach indicated expected ground displacements within the assessed tolerance of the existing buildings; 100mm at ultimate limit state earthquake shaking. The force-based approach indicated resilience of the design. The force-based design was independent of the uncertainties associated with lateral spread displacement predictions and the selected intensity of design earthquake shaking.

6 ACKNOWLEDGEMENTS

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