Reclamation resilience improvement at CentrePort, Wellington, New Zealand

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ABSTRACT

CentrePort operations were significantly disrupted following damage to strategic assets sustained in the 2016 Kaikōura Earthquake, demonstrating the port's seismic vulnerability. Improved resilience is a necessity to long-term business sustainability and a core objective of the port's regeneration.

Much of the earthquake damage was attributable to liquefaction of the gravel reclamations. This paper describes the strategy being implemented to improve ground resilience at the port and how a systematic, resilience based approach was adopted to quantify risks and improvements.

Based on extensive data gathered following the earthquakes, port systems and operations have been evaluated to identify and prioritise soft and hard measures to improve resilience, enhance safety, reduce operational costs and environmental impacts. Resilience based performance requirements for strengthening have improved value compared to traditional performance metrics that solely consider life safety and limiting damage but not business disruption.

In the medium and long term, the port layout is being adjusted to reduce exposure of critical assets to hazard effects and improve operational redundancy. Asset strengthening is focused on perimeter ground treatment to constrain areas of reclamation that are most prone to lateral spreading and securing key berths and buildings. Stone column ground improvement has proven to be an effective technique in the gravel fills and provides the robustness required to meet resilience objectives.

1 2016 KAIKŌURA EARTHQUAKE – LIQUEFACTION AND DAMAGE

The November 2016 M_w 7.8 Kaikōura earthquake was responsible for widespread triggering of liquefaction and subsequent damage and disruption at CentrePort in Wellington/Te Whanganui-a-Tara. The subsequent reclamation resilience improvements as part of the port's regeneration programme of works is presented and discussed in this paper.

The liquefaction and damage at CentrePort due to Kaikōura earthquake shaking has been well documented (Cubrinovski, 2018) and is summarised for context and background for the reclamation resilience works in the below sections.

1.1 Reclamation characteristics

The reclamation has been built in stages with the earliest stages dating back to the late 1800s. The gravelly fill reclamation south of the mass concrete seawall was constructed in the 1960s and 1970s by end tipping of gravelly fill sourced predominantly from local quarries (Figure 2). Historic records suggest that efforts were made to dredge soft marine seabed sediments prior to placement of fill and that filter rock was placed at the seaward faces. (Tonkin & Taylor, 2012). A non liquefiable crust of fill was created by compaction above the high water level. The reclamation edges adjacent the sea are revetment slopes with minor restraint on the east and west by pile pinning action at both Kings Wharf and Thorndon Container Wharf (TCW). (Refer Figure 1)

Figure 1: Plan of Thorndon Reclamation at CentrePort (prepared by author)

The fill increases in depth towards the southeast and is between approximately 10-20m deep. The slopes are generally at the angle of repose of the fill material ~1.75H:1V. However, the south coast seawall has undergone reprofiling during repairs following the 2013 Cook Strait and Seddon Earthquakes, and due to migration of material due to 2016 Kaikōura Earthquake shaking. These slopes are generally at 2.5-3.0H:1V.

The gravelly fill is a sand-silt-gravel mixture and varies in proportions across the port. However, generally these portions are dominated by gravel sized particles, with approximately 45-75% gravel, 15-40% sand and 10-15% fines (Cubrinovski, 2019). There are also large boulders present within the fill, with 0.5 m boulders excavated during 2017 TCW securing piling works.

The reclamation is underlain by marine deposits and alluvium. The marine deposits composition varies but generally consists of two layers:

1. Silty SAND with shells and organics. This layer is susceptible to liquefaction
2. Silty CLAY/Clayey SILT, firm to stiff with shells and organics and moderate to high plasticity. This layer is not susceptible to liquefaction but may lose some strength due to cyclic softening.

The marine deposits are highly variable in their deposition with thickness ranging from 1-5 m. Additionally, the marine deposits are no longer in a natural state of deposition due to pre-reclamation dredging and disturbance during reclamation. The alluvium consists of interbedded, non-liquefiable stiff silts and dense gravels. This unit is locally known as Wellington Alluvium and is the founding layer for piled structures at the port.

Reclamation has provided CentrePort (and Wellington/ Te Whanganui-a-Tara) with large areas of land with high value and utility within Wellington Harbour. These land areas, however, also have a high seismic risk due to their vulnerability to liquefaction and seismic amplification.

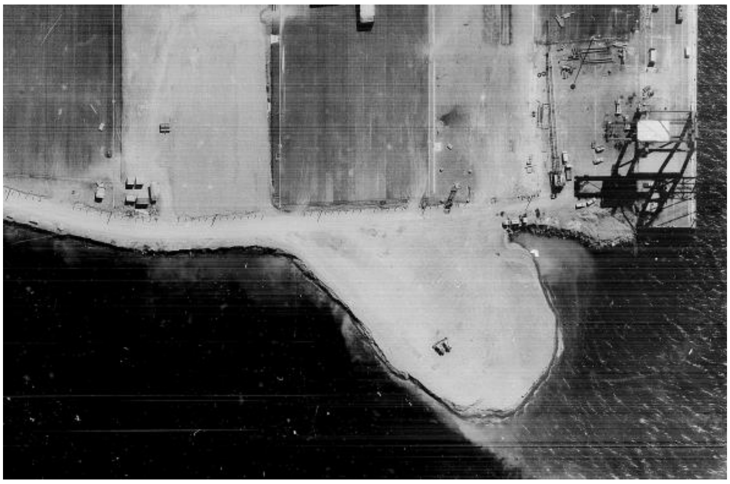

Figure 2: Historic aerial photograph of Thorndon Reclamation Construction, 1970s

1.2 Ground motion characteristics and liquefaction

Ground shaking during the Kaikōura earthquake at the port was measured as approximately 0.25g PGA at nearby strong motion stations. The ground shaking at CentrePort was amplified between periods of 0.6 and 2.5s due to both geometric (basin effects) and stratigraphic (deep soil profile) effects (Bradley et al. 2017).

Further research into liquefaction at the port is ongoing but the following has been concluded (Dhakal, 2020, Cubrinovski 2020, Cubrinovski et al., 2019) relevant to the reclamation resilience:

- The seismic behaviour of the gravelly fill was dominated by the finer soils in the matrix (sands and silts) even though their fraction is only ~10-40%
- The penetration resistance of the gravelly fill matrix will be increased by the gravel particles making a clean sand equivalent in-situ relative density difficult to correlate. Existing penetration resistance and relative density correlations do not consider the effect of particle size
- Simplified Cone Penetrometer Test (CPT) based methods for liquefaction triggering and volumetric strain predictions generally agreed with observations from the 2013 and 2016 Earthquakes, however were poor in differentiating performance
- The system response of the soil profile can influence (and even govern) the liquefaction severity and consequences

1.3 Liquefaction consequences and damage

These liquefaction consequences resulted in the following areas of damage:

- Damage to pavement surfaces and subgrade – cracks, voids and differential settlement (refer Figure 3). This damage was amplified adjacent to embedded elements (e.g. concrete slot drains). Cracking and stretch due to lateral spread increased in magnitude close to the seaward edge of the reclamation
- Wharf structures (Timber pile supported Kings Wharf, concrete pile supported TCW) pushed towards the sea due to lateral spread and kinematic soil loading with piles sheared and significantly damaged (refer Figure 4). Allowable wharf deck loading reduced
- Damage to underground services and overland flow paths
- Evacuation of the reclamation edge along parts of the southern seawall (refer Figure 3)
- Damage to structures on shallow foundations

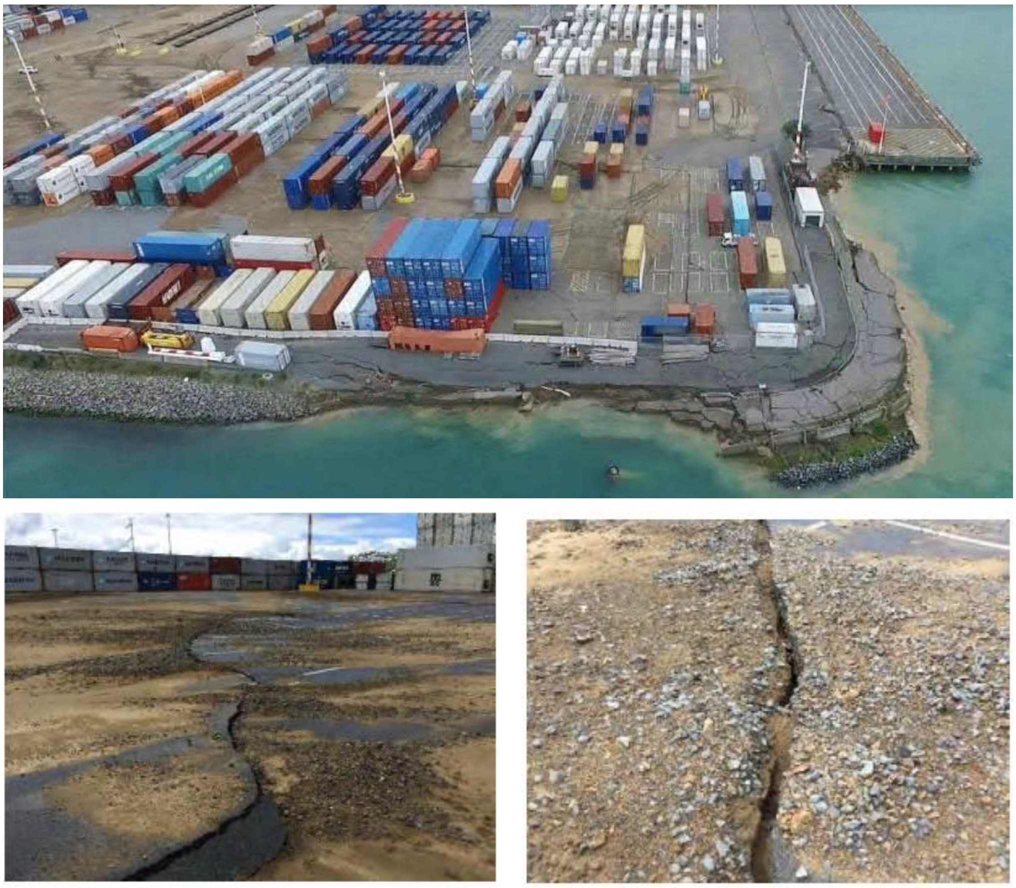

Figure 3: 2016 Kaikōura Earthquake damage, Top - Slope evacuation and lateral spreading at the southern end of the reclamation. Bottom - ground damage and ejecta as manifestation of liquefaction (reproduced from Cubrinovski et al. (2017).

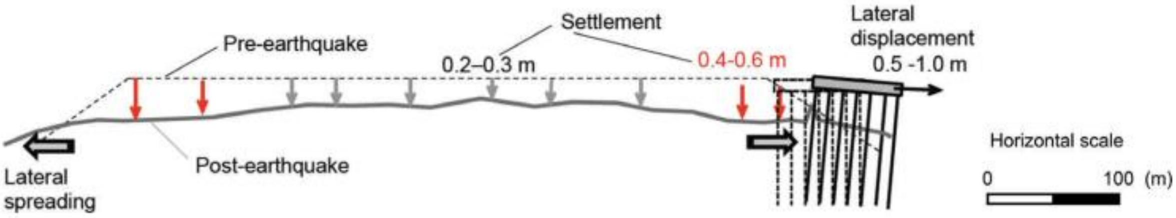

Figure 4 Ground displacement and damage patterns due to Kaikōura 2016 Earthquake shaking (reproduced from Cubrinovski et al., 2019)

1.4 Business disruption

This damage resulted in significant business disruption for the port including:

- Port operational vehicles (e.g. reach stackers and straddle carriers) unable to move containers across many operational areas efficiently
- Thorndon Container Wharf out of action until September 2017 when temporary berth securing works over a 125m length of wharf were completed
- Kings Wharf operational utility reduced
- Loss of operational land along south coast seawall road
- Loss of use of a large coldstore and other smaller operational structures around the port
- Significant pavement repairs for damaged pavement and subgrade layers
- Drainage issues following rainfall events

2 REGENERATION AND RESILIENCE

CentrePort Ltd have taken the opportunity following the Kaikōura earthquake to evaluate its future needs and have implemented a staged regeneration strategy (Terry et al. 2021) involving:

- Short and medium term stages focused on restoring key operations
- Long-term regeneration focused on optimising the port layout and reducing risk to business through improved resilience and other measures.

By reducing the length of business disruption CentrePort can improve the resilience of the port and allow continued service to its customers and the community. CentrePort aim to “build a long term sustainable and resilient business” (Centreport, 2020). The overall resilience objective is a return to near full service within a week of a moderate earthquake, similar to another Kaikōura Earthquake.

For continued operations following an earthquake, the primary infrastructure needs of the port in simple terms are:

- Operational berths to load and unload goods from ships,
- Pavements and civil services in working condition to enable unloading, loading and storage of goods and transfer between road and rail links to the port.

A range of hard and soft measures have been implemented in order to improve the resilience of port operations. The soft measures aim to improve responsiveness and redundancy in earthquakes and include:

- Reconfiguring the port layout considering the variation of seismic hazards across the port so that more vulnerable and critical infrastructure are located in areas of lower hazard.
- Improving the operational flexibility of the reclamation (by removing buildings for example) and berth infrastructure so that CentrePort can respond quickly to changing demands from different trades after an earthquake.
- Changes to operational procedures to reduce the criticality of vulnerable infrastructure. For example, use of the container crane back reach to eliminate the need for the container wharf to support heavy loads.
- Removal of redundant structures and buried elements that acted as discontinuities within the fill and concentrated ground damage (e.g. concrete slot drains) during earthquake shaking.
- Improving tolerance of operations to ground damage by introducing vehicles and systems that are more tolerant of uneven ground.
- Changes to drainage systems and pavements to make them more tolerant to ground movement.

Hard measures look to provide resilience through robustness and consist of:

- Securing and strengthening of key berths (TCW cranes, berthing and mooring structures and Kings Wharf).
- Ground improvement of the reclamation.

The stone column ground improvement to achieve resilience is discussed in detail in the following sections of this paper.

3 GROUND IMPROVEMENT DESIGN

3.1 Design objectives

There is a high level of seismic risk at the port due to the proximity of active faults, high seismicity and ground that has potential to liquefy in moderate earthquakes. Ground improvements have been implemented to mitigate damage and disruption from liquefaction and lateral spreading, although entirely eliminating the potential would be expensive and not commensurate with the reduction in risk to business. Therefore, the objectives of the ground improvement are:

- Minimising business disruption and repair costs following future moderate earthquakes.
- To be durable and adaptable to a changing port.
- Be safe to construct in a dynamic operational port environment.
- Minimise disruption to operations during construction.
- Minimise environmental impacts.

Use of resilience based performance criteria for the ground improvement, while more difficult to evaluate in design, focuses the design on outcomes of value to the business. This avoids potentially costly ground improvement solutions that can arise when the focus is on reducing damage (displacements) but without an understanding of how damage affects operability and how quickly damage and operations can be restored after an earthquake.

3.2 Design philosophy and features

The design philosophy has been to constrain the edges of the reclamation through the installation of ground improvement to mitigate liquefaction of the fill and consequent lateral spreading. This protects the seawalls, wharves and other critical infrastructure for berthing, mooring, loading and unloading operations. Damage to pavements and structures in the backlands is expected to be somewhat reduced as mitigating lateral spreading will decrease subsidence in the reclamation back lands.

Ground improvement is installed through the full depth of the liquefiable reclamation fill and the underlying marine deposits behind the crest of the revetment seawalls as shown in Figure 5. Ground improvement of the batter slope was not carried out because of the added construction complexity and considering that shallow slope movement and damage to the revetment rock armour can be repaired quickly and at relatively low cost in a post earthquake emergency response. The option remains for further treatment or confinement of the batter slope at a later date or if required for any new structures.

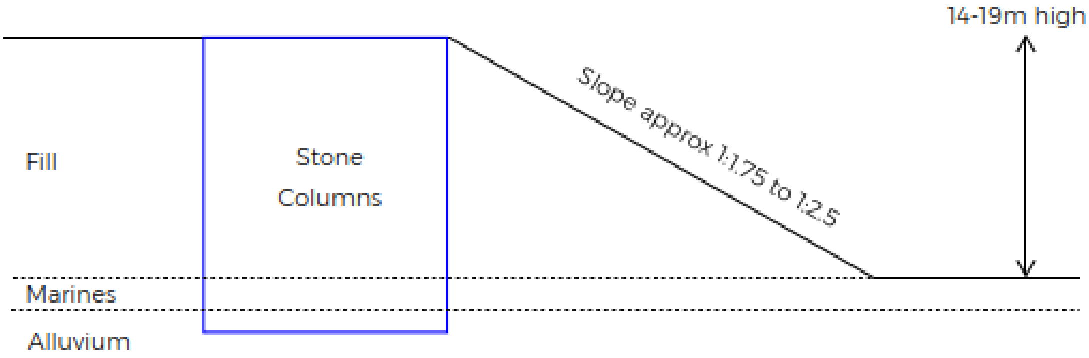

Figure 5: Sketch of general ground improvement layout with nominal width and typical soil profile

A transition pavement at the landward edge of ground improvement is included in order to smooth differential displacements between backlands and treated area. The transition pavement consists of a geogrid reinforced subgrade with imported and compacted AP65.

3.3 Selection of improvement method

A range of ground improvement methods are available. Wet top feed stone column ground improvement using vibroflots was selected for the works based on factors including:

- Seismic ductility – the stone column improved block can deform during an earthquake without losing substantial strength or its ability to mitigate liquefaction in future earthquakes. Alternative reinforcement or solidification methods have less seismic ductility.
- Densification of gravelly fill by stone column ground improvement had been proven at TCW and Kings Wharf for strengthening works. Additionally, stone columns have proven effectiveness in earthquakes.
- Availability of materials, rigs and ground improvement contractors with sufficient experience over a long construction programme (number of years).
- Depth of improvement required (up to 25m depth columns at the south eastern portion of the reclamation).
- Flexibility with depth of treatment achieved with additional follower lengths added to the vibroflot assembly in order to reach the desired depth - depending on the depth to alluvium in the ground improvement area.
- Ability to use demolition-won crushed concrete as a recycled aggregate material for the stone columns, providing a circular economy for materials and a positive outcome for environmental goals.
- Ability to verify improvement during construction with testing, unlike techniques that primarily rely on reducing soil shear strains to mitigate liquefaction.
- Relatively low noise impacts.
- Relatively low environmental and carbon impacts.
- Flexibility for future development and relative ease of integration into reinstatement work for other infrastructure (e.g., wharf tie-back system, increased treatment width or ability to pile through the improved block, install services).

Note that other stone column ground improvement methods were considered. A dry bottom feed vibroflot method was not successful due to the probe getting jammed with material falling behind shroud. Bottom feed casing installation was used in early stages of the project effectively but abandoned in later stages because of depth and equipment maintenance constraints, higher noise and vibration.

3.4 Design basis

The stone columns are designed to:

- Densify the reclamation fill and sandy layers within the marine sediments to increase resistance to liquefaction. The columns may also mitigate liquefaction through drainage, but this is considered a secondary benefit and has not been relied upon in design.
- Improve the shear stiffness and strength of marine silts.
- Found and key into the upper alluvium.

Trials and data from previous stone column ground improvement at the port have been used to confirm the area replacement ratio. An area replacement ratio of between 15 and 20 percent has been selected for consistent improvement with the wet top feed vibroflots.

Target Standard Penetration Testing(SPT) $N_{1,60}$ values for between column testing were calculated from simplified liquefaction triggering methodology (Boulanger & Idriss, 2014) to provide a margin of safety against liquefaction triggering in moderate earthquakes.

The width of treatment is dependent on the height of slope, depth to alluvium and batter slope profile. Dynamic finite element modelling has been carried out to assess performance including interaction with structures to design the extents of the ground improvement. The dynamic analysis allows for modelling of build-up in porewater pressure and greater insight into the mode of failure and displacements anticipated in earthquakes compared with simplified methods. Initial depths of stone columns were defined based on pre-improvement borehole and CPT investigations with additional boreholes drilled where required to better constrain the assumed depth to alluvium.

Where available, opportunities are taken to repair and replace services during ground improvement works to ensure consistent treatment and reduced operational disruption.

4 GROUND IMPROVEMENT CONSTRUCTION

Construction has proceeded with two crane suspended vibroflots working through ground improvement areas in tandem. Aspects of the construction contributing to the project's success include:

- Achieving a balance between productivity and how hard to work the equipment. Regular maintenance and spare parts/vibroflots can allow for productivity levels to be maintained and programme to stay on track. Global supply shortages and delays have created difficulty with parts, spares and maintenance. Forward planning and regular maintenance can reduce these impacts
- The client (CentrePort), contractor (HEB/March – VINCI Construction subsidiaries) and engineer (WSP) have worked together closely to manage project risks.
- Areas of ground improvement have been well defined by CentrePort and the contractor so that operational disruption can be minimised and operational teams are kept well informed regarding area handovers and interaction required.
- A significant volume of aggregate is required for the ground improvement works. Aggregate supply influences the cost, programme and environmental impacts of the works. Efforts have been made by port and contractor to secure long term supply contracts of quality aggregate from local quarries within the context of a constrained supply market.

5 GROUND IMPROVEMENT QUALITY ASSURANCE AND CONTROL

The primary quality control metrics for the stone columns have been column volumes, column depth and compactive effort. CPTs are generally preferred as a ground improvement verification test but are not practical as they cannot penetrate the improved gravelly fill reclamation. Crosshole shearwave velocity testing was also attempted as a verification test but time, cost and verification benefits were found to be limited.

For ground improvement verification within a construction context for these works, sonic core logging with SPT tests allowed for greater reliability and the ability to mobilise testing rigs at shorter notice as required. SPTs have been used as the primary tool to estimate in-situ relative density and therefore improvement. Due to the variable nature of the fill and coarseness of the SPT, some scatter in results is expected. SPTs have provided confidence that sufficient densification has occurred when comparisons are made against target and pre-improvement values.

SPTs due to the nature of the variable reclamation can encounter material such as boulders and cobbles which result in the test at some depths providing an overestimate of in-situ relative density. Larger particle sizes will increase penetration resistance compared with the clean sand equivalents utilised in simplified triggering procedures (Cubrinovski et al., 2019). These effects are unavoidable and therefore need to be considered when assessing verification SPT tests against the target values specified and the overall performance objectives. Verification testing is used generally to demonstrate that the target level of improvement has been achieved and correlate the column records (primarily volume and depth) with a level of improvement. However, it has also served a secondary purpose to inform areas of low volume/shallow refusal and explain variation in construction.

The gravelly fill reclamation was loosely deposited through sedimentation but is typically well graded and therefore generally responds well to the stone column vibro replacement, whereas the cohesive SILT layers in the marine deposits generally have not shown significant improvement. The shear strength of these layers is increased by reinforcement from the stone column at depth. Typical pre and post improvement SPT results are shown in Figure 6; the lower blow counts deeper in the profile are indicative of the marine deposit layers.

A level of non-conformance is usual for stone column construction but does not always greatly increase performance risk and can be costly to rectify. For example, one or two SPTs may not quite meet the target but overall the reduction in performance is not significant. A risk based approach to non-conformance against specification (i.e. areas of columns that have not achieved target depth or stone volume) has been undertaken so that informed decisions can be made, maximising value for CPL. For areas of non-compliance, the relative performance reduction compared with complying areas has been assessed. This information can then be used to consider whether there is any value in remediation or if a low additional performance risk can be accepted. Performance goals and cost of construction are balanced to arrive at a pragmatic position

Another issue is the time it can take for porewater pressures from installation to dissipate and the full degree of improvement to be realised. This creates a delay between installation and capability to adjust construction (either area replacement ratio or methodology).

Due to the volume of stone required for the works, different stone sources have had to be used. As such it has been important to ensure that aggregate specification requirements are being met throughout the works with quarry test results and visual site inspection.

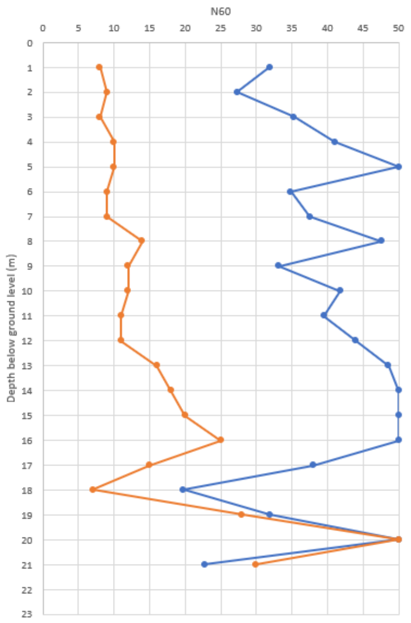

Figure 6: Typical unimproved (orange) and post improved SPT N60 values seen during verification testing

6 STONE COLUMN GROUND IMPROVEMENT LESSONS

The following lessons have been learned from the ground improvement resilience programme (so far):

- A pragmatic approach to non-conformance can assist in balancing productivity with target performance. If the relative performance reduction is low due to a non-conformance then there may not be value in remediation.
- The resilience and performance provided by the ground improvement must be communicated into meaningful terms for the client and align with their regeneration objectives in order for business decisions to be made.
- Understanding limitations of stone column data outputs and the uncertainties present in construction.
- More than one rig working at a time for improved productivity and flexibility. Maintenance and repair time should be included in any programming and spares available for contingency.
- With increased depth of stone column the risk of flots becoming stuck/jammed in the ground increases and this risk will need to be managed by the contractor during construction.
- Contractor and engineer should consider proposed sequencing of works. For example, issues can arise with achieving stone column depth if an area is ‘closed out’ by other columns such as when two rigs converge to a central row of columns.
- The marine deposit-alluvium unit contact can be difficult to define due to the depositional environment and dredging. Care needs to be taken in logging this contact and borehole logs interrogated against nearby CPT data when possible. Due to the alluvium depth uncertainty and variation, target stone column depths were defined to decrease the possibility of columns constructed shallow above the alluvium. Although some columns during construction may refuse before the target depth, verification testing boreholes provide further constraint of the alluvium surface model and allow for the depth criteria for the stone columns to be reassessed for QA checks.
- Transition pavements should be considered to smooth out surface response of pavements between improved and unimproved areas. Sharp discontinuities in the ground can amplify ground damage consequences due to earthquake shaking and should be avoided in design where possible.

7 CONCLUSIONS

Reclamation resilience improvements are underway at CentrePort as part of the port's regeneration. Responsiveness and redundancy have been provided with a number of soft measures. Stone column ground improvement has been selected and designed to meet CentrePort business objectives and primarily to reduce disruption following an earthquake. The ground improvement aims to achieve resilience through robustness.

The nature of the deep liquefiable gravelly fill presents challenges for ground improvement construction and verification A risk assessment approach has been taken to non-compliance during stone column construction in order to provide CentrePort with the best value from the works. Productivity and cost must be balanced against the overall resilience objectives to make pragmatic decisions for the ground improvement construction.

SPT tests have been used to verify improvement and ARR of 15-20% have proven to meet target levels of improvement for the gravel fill. SPT tests have been used diagnostically to constrain variations in construction compliance and provide confidence in performance. Ground improvement works continue around the reclamation edge at the port as a key part of the port's regeneration planning.

8 REFERENCES

Boulanger, R. W., & Idriss, I. M. (2014). CPT and SPT based liquefaction triggering procedures. *Report No. UCD/CGM.-14, 1*.

Bradley, B. A., Wotherspoon, L. M., & Kaiser, A. E. (2017). Ground motion and site effect observations in the Wellington Region from the 2016 Mw7. 8 Kaikōura, New Zealand earthquake. Bulletin of the New Zealand Society for Earthquake Engineering, 50(2), 94-105.

Centreport Regeneration Plan (2020) https://regeneration.centreport.co.nz/

Cubrinovski, M., Bray, J. D., Bastin, S., Bradley, B. A., Cappellaro, C., de la Torre, C., ... & Wotherspoon, L. (2017). Geotechnical Reconnaissance of the 2016 Mw7. 8 Kaikoura, New Zealand Earthquake. *A report of the NSF-Sponsored GEER Association Team, GEER-053, Ver, 1*.

Cubrinovski, M., Bray, J. D., de la Torre, C., Olsen, M., Bradley, B., Chiaro, G., ... & Krall, T. (2018). Liquefaction-induced damage and CPT characterization of the reclamations at CentrePort, Wellington. *Bulletin of the Seismological Society of America*, *108*(3B), 1695-1708.

Cubrinovski, M., Ntritsos, N., Dhakal, R., & Rhodes, A. (2019, October). Key aspects in the engineering assessment of soil liquefaction. In Proc., 7th Int. Conf. on Earthquake Geotechnical Engineering (pp. 189-208).

Cubrinovski, M., Bradley, B. A., Elwood, K. J., Johnston, D., Orchiston, C., Sullivan, T., & Wotherspoon, L. M. (2020). Wellington's earthquake resilience: Lessons from the 2016 Kaikōura earthquake. *Earthquake Spectra*, *36*(3), 1448-1484.

Dhakal, R., Cubrinovski, M., & Bray, J. D. (2020). Geotechnical characterization and liquefaction evaluation of gravelly reclamations and hydraulic fills (Port of Wellington, New Zealand). *Soils and Foundations*, *60*(6), 1507-1531.

Terry, P., Delaney, A., Juno, W., & Keepa, C. (2021). CentrePort Wellington: Resilient regeneration activity.

Tonkin & Taylor (2012). Thorndon Container Wharf – Geotechical Factual Report