RE-ENGINEERING OLD FOUNDATIONS FOR A NEW STRUCTURE – GREENLAND CENTRE

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ABSTRACT

The concept of reusing existing building elements during site redevelopment within urban environments is gaining momentum. With ever-increasing pressure from modern society for engineers to focus on sustainable solutions, the industry is also beginning to recognise other benefits from maintaining, improving or re-engineering existing structures. These include fast tracking decommissioning and construction programs while at the same time saving on demolition and waste disposal costs. Along with the various challenges, such as testing, confirming the integrity of older structures and understanding foundation conditions, one of the major obstacles to effectively reusing existing building elements is the often complex re-engineering required to design and prove a solution is viable. In urban areas where space is at a premium, usually the 'bigger is better' approach prevails, and existing columns and footings will be required to support higher applied loads than they were originally designed to carry.

The Greenland Centre in Sydney's CBD is an example where the re-use of existing structural elements has been successfully adopted, by re-engineering of footing arrangements. The steel portal frame and piled footings of an old 27 storey building were retained, with the piles augmented with new pad footings to increase the footing bearing capacity to support a significantly higher 67 storey building. Finite element analysis was conducted to assess various footing arrangements to optimise the final design so that serviceability limits for the new structure could be achieved. Settlement monitoring and stress, strain measurements have been conducted through construction, with results so far shown to be within the limits predicted in the initial modelling process.

The paper discusses the general issues involved in the reuse of foundations and present results from the Greenland Centre to illustrate the advantages and challenges of reusing existing foundation elements.

1 INTRODUCTION

Many buildings around the world erected during the construction boom of the mid-1900s are nearing the end of their design life. When old buildings require demolition to make way for new, developers and engineers are required to make the decision to either demolish and rebuild an entirely new structure or to explore the opportunity to integrate the old structure or part thereof into the new design. Foundations are often considered the most feasible structural elements to reuse due to their functional value, the challenges associated with removing them (they are usually left in place) and the lack of available space in the ground below existing buildings for new footings, particularly in urban environments (Agrawal, *et.al.* 2018).

The decision to re-use foundations and develop a viable approach to achieve this requires consideration of many different factors such as existing foundation conditions, geological setting, spatial constraints and the design and loading distribution of the new structure. The first step in this process is to understand the arrangement and condition of existing footings, as this will inform whether foundation reuse is feasible. Once the condition and as-built information of the existing footings are understood, the load distribution from the design of the new building requires interrogation to explore the most efficient option for the given footing arrangement. For footing reuse scenarios, this typically consists of either supplementing existing footings with new footings, implementing ground improvement techniques to increase subgrade strength or altering the existing footings or foundation material to achieve the required support for the new structure.

2 WHY CONSIDER REUSING EXISTING FOOTINGS

In urban environments, there are several factors that can lead to advantages or requirements for footings to be reused. Inevitably, foremost in the mind of developers is money - if there is potential for cost savings by reducing material and demolition costs this can often be the biggest driver to pursuing the reuse of foundations (Valenta, *et.al.* 2007). In some cases, particularly in urban environments, the complexity around removal of old or installing new footings can be time consuming and a time saving can be made implementing reuse strategies which can ultimately also save the bottom line.

In the past few decades a key driver for reuse has been to enhance sustainability and reduce the environmental impacts associated with development. With a carefully developed foundation reuse plan, a substantial reduction in impact to the environment can be achieved through both reduction in waste and construction materials, as well as avoiding significant CO_2 emissions and the increased congestion that result from transportation of old and new materials in and out of urban spaces.

Developers, architects, engineers, consultants and construction firms have a moral imperative to design and construct environmentally and socially responsible developments, including incentives such as enhanced reputations and commercial rewards that may come with implementing this strategy.

Another important factor that can often apply when reusing or repurposing existing structures is the requirement to maintain and protect historical significance. Urban areas often contain a higher density of items of historical value, many of which are protected by State or Federal Law. As a result, removal of old building elements can be prohibited and developers are required to design and construct new structures either avoiding any protected items or integrating them into their future proposed design.

3 FOOTING REUSE METHODOLOGY

The concept of foundation reuse is not new, with numerous examples evident around the world dating back as far as 2000 years ago (Muench, 2015). Advancements in investigation and construction techniques have changed some of the methods in which foundations are tested and re-purposed, however the methodology largely remains the same. There are a number of different approaches available for design and construction of footings in previously developed urban environments. Chapman, *et.al.* (2007) suggested that footing options can be generalised into four categories listed below and illustrated in Figure 1:

- Option 1: Avoid old footings (leave in place) and build new footings
- Option 2: Remove old footings and replace with new footings
- Option 3: Direct re-use of old footings; and
- Option 4: Reuse old footings and supplement with additional footings

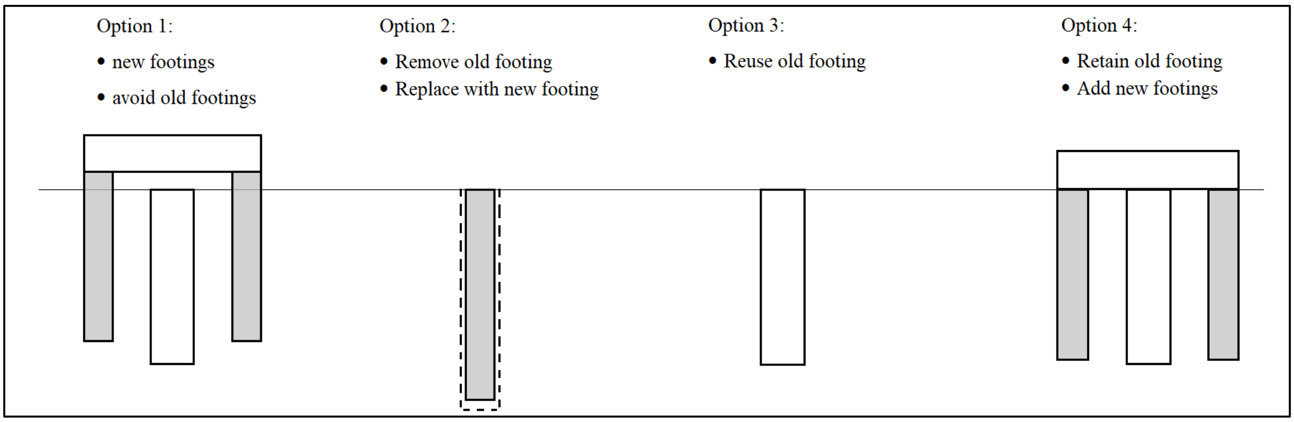


Figure 1: Foundation options for new structures in urban environments (Chapman, et. al. 2007)

Options 1 and 2 are not considered a form of footing re-use as the pre-existing footings are essentially made redundant due to avoidance or removal. Nowadays, due to urban areas being prime real-estate and developers typically opting for bigger and often taller structures, Option 3 is not considered a viable stand-alone option as pre-existing footings will rarely be fit for purpose for the new structure due to different loading distributions and typically higher loads.

A review of foundation reuse examples across the globe shows that Option 4 is the most common form of foundation re-use, particularly within urban settings, because of the flexibility it allows in integrating the old footings into the new load carrying arrangement. Other recent examples of foundation reuse suggest that there are two additional categories:

- Option 5: Direct re-use of old footings in conjunction with ground improvement; and
- Option 6: Direct re-use of old footings with structural alterations or augmentation

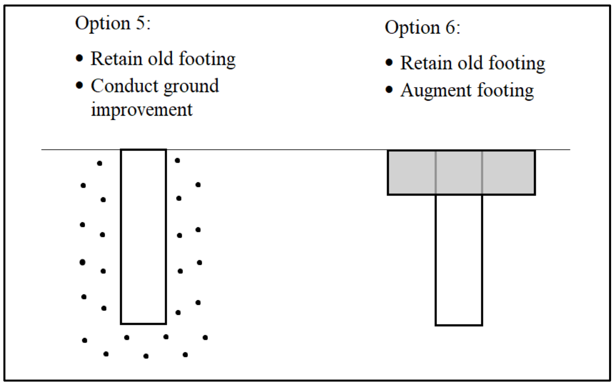


Figure 2: Alternate foundation options for new structures in urban environments

Option 5 can often be an economical approach in cases where existing footing arrangements can be effectively integrated into the new structure, however higher bearing capacity is required due to higher loads imposed by the proposed structure. Option 6 involves the altering or augmenting of existing footings to allow for either higher loads or alternate load distributions between the old and new structures.

3.1 ADDING NEW FOOTINGS TO EXISTING (OPTION 4)

Adding new footings to structures in conjunction with using existing footings is the most commonplace form of foundation reuse due to the flexibility it permits in design. It can be implemented through a variety of footing arrangements, which can be adjusted to suit the specific construction and installation limitations of developments in urban areas, namely spatial constraints associated with congestion of building elements and utilities (buried cables, pipes, sewers, stormwater drains).

Watanabe, *et.al.* (2015) provides an excellent example of where the developers successfully implemented a sophisticated design and construction integrating new bored piles between old, within one of the most congested metropolises in the world, Tokyo, Japan.

While additional new footings can be constructed in a similar manner to that of the old structure, with recent advances in footing design and construction practices there are often alternate ways to satisfy the bearing capacity of the new structure that are more optimal from both commercial and practicality of installation points of view. Often an inhibiting factor to the use of conventional footing installation or piling methods in footing reuse scenarios is the lack of available space for installation equipment, particularly low headroom restraints when structures or basements are retained. The Condor Tower redevelopment, summarised by Stewart (2012), provides a typical example of this, where although the original building was founded on a raft slab, the alternative method of micro-piling was adopted to enable installation within the restricted spatial constraints available.

3.2 REUSE OLD FOOTINGS WITH GROUND IMPROVEMENT (OPTION 5)

Ground improvement methods come in various shapes and forms, and under the right circumstances can provide a very economical solution to meet additional loading requirements for foundation reuse scenarios, particularly in the urban environment. The spatial constraints on developments in built-up areas often do not allow for mobilisation of large piling rigs, but may be suited to some ground improvement equipment that can have a smaller working footprint. Depending on the presence, arrangement and condition of existing footings and surrounding infrastructure, this can be the preferred option to enable protection and maintenance of historic or sensitive structures in close proximity to existing footings (Chepurnova, 2014).

Typically ground improvement is conducted to improve the strength and stiffness of poor soil subgrades, but it can also have some application in improvement of rock. The efficiency of improvement techniques is dependent on ground conditions, with methods such as vibro-compaction and dynamic compaction being better suited to granular soils and methods like soil stabilisation and column/displacement methods more applicable for cohesive soils. Ground improvement in rock conditions typically consists of either reinforcement methods (bolts/anchors/tendons), consolidation grouting for fractured rock or underpinning.

Many standard ground improvement methods are impractical in foundation re-use applications, due to old foundations and associated structures impeding installation. Jet grouting is the most common form of ground improvement in foundation re-use applications, where a chemical compound is injected into subgrade material to increase its strength, stiffness and bearing capacity. Historically cementitious material was used, however due to recent advances in chemical engineering other compounds such as resins and polymers are being more utilised (Sabri, *et al.* 2018).

The Kentucky International Convention Centre redevelopment is an example showing the success of ground improvement techniques in enabling footing re-use (Post, 2019). The foundation solution adopted was the injection of polyurethane grout to reinforce and strengthen sand subgrade beneath existing footings. This method was proven to provide the additional bearing capacity required for the additional loads, and enabled the existing structure to remain in place while foundation treatment was underway which would not have been possible with conventional piling rigs due to limited head-room.

Depending on subgrade conditions, ground improvement can effectively be undertaken in conjunction with installation of additional footings to enable footings re-use. This is illustrated in the example of the Condor Tower (Stewart, 2012).

3.3 AUMENTATION OF OLD FOOTINGS (OPTION 6)

Footing augmentation, although a similar concept to Option 4, is unique as the aim is to modify or enhance the existing footings, without adding any new footings, to meet the requirements of the new structure. Depending on the existing footing arrangements and the ground conditions, this would typically involve the widening of existing footings (to create a pad footing) and increase the surface area in contact with the subgrade. The outcome is to spread the load over a larger area and hence decrease the applied pressure on the subgrade.

The advantage to this solution is that there is limited additional footing construction required, generally negating the requirement for large piling equipment that is not suited to difficult access urban environments. A limitation of this option is that footing augmentation is only considered to be suited for footings founded in rock due to its higher stiffness and bearing properties, particularly for high-rise buildings or settlement sensitive structures (pad footings in sand or clay may need to be unpractically large to meet serviceability requirements of any new larger structure).

4 EXISTING FOOTING CONDITION ASSESSMENT

Prior to progressing with any option feasibility study or design for structures that involve footing reuse, a detailed assessment of the existing footings is essential. This typically involves understanding the as-built details, foundation material properties and the condition of the structural elements. It is critical to assess the reliability and capacity of existing footings in order to determine whether foundation reuse is even feasible (Laefer and Farrell, 2014), and if so what level of additional foundation support the new structure will require.

Gathering this information and interpreting it can be challenging due to foundations often being difficult to access (below utility rooms or basements, etc.) and that they are typically buried and embedded into the subgrade. Due to relatively recent advances in geotechnical investigation methods and footing inspection and testing techniques, successful collection of information and data from existing footings can be achieved in many cases, but this can require significant planning and careful execution (Colls, 2019).

4.1 AS-BUILT INFORMATION

Many buildings where developers are considering foundation re-use are likely ageing and nearing the end of their design life. In urban areas this often means they were constructed several decades ago and are likely to have gaps or inaccuracies in the as-built information due to less accurate measurement techniques and often inadequate record keeping (prior to cameras and computers being available). For these ageing structures it is generally the case that accurate records of the as-built construction are not available, possibly because the likelihood of re-use of foundation elements was not ever considered. Nowadays, there is greater emphasis on full life cycle considerations and for foundation construction a need for better record keeping which should facilitate reuse in the future. (Berglund, *et al.* 2006)

It is necessary to determine and prove the footing dimensions and embedment depths to understand the existing bearing capacity of the footings before progressing to choosing foundation reuse options. There are a variety of different ways to assess as-built footing information, and these can include:

- Borehole Drilling: Core through middle of footing to determine toe level (see Figure 3). Holes can also be drilled adjacent to footings to assess the width and extent of concrete (see Figure 4).
- PIT (Pile Integrity Testing): footing toe level can be calculated using wave technology.
- Geophysical methods: Can include downhole hydrophone testing as well as magnetometer testing (only for steel reinforced piles - to locate where steel reinforcement extends to and hence infer pile toe).

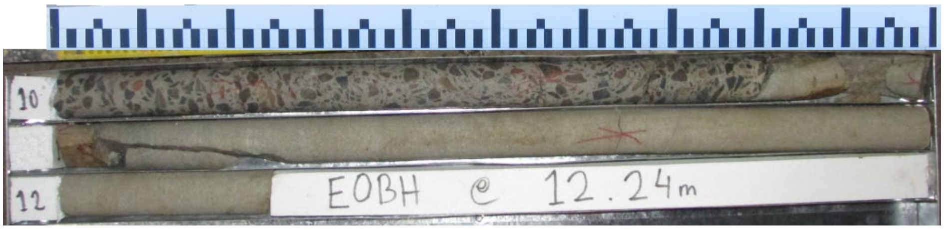


Figure 3: Borehole drilled through centre of pile – pile toe ~10.8m depth

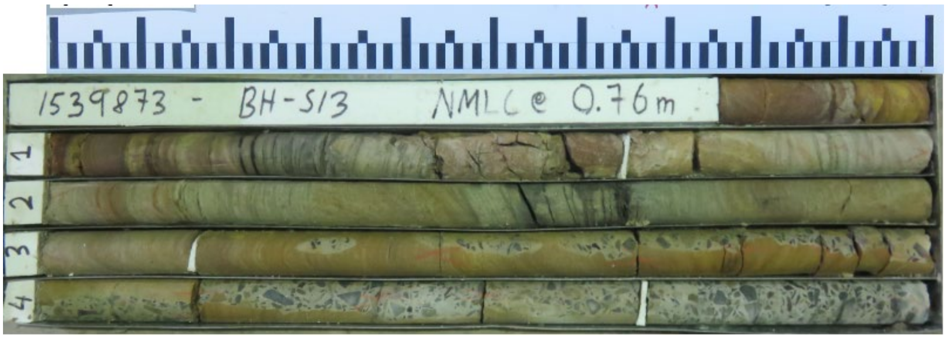


Figure 4: Borehole drilled through edge of pile/footing – evident between ~3.5m and ~4.5m depth

Although borehole drilling is typically the preferred method, often multiple methods are conducted to provide confidence in results.

4.2 CONDITION OF FOUNDATION MATERIAL

Foundation material is typically assessed using borehole information, often attained in conjunction with as-built investigations. This typically includes production of geotechnical logs to map the strata adjacent to and below existing footings. This enables formulation of site geological model, which can be utilised for footing capacity assessment and performance modelling.

Boreholes testing is one of the most common methods used to assess subgrade conditions, by assessing and collecting samples at various depths. Samples collected from investigations can be tested in the laboratory, with a wide range of testing possible, including consolidation and shear strength testing for soils and strength tests on rock such as Point Load Index and Unconfined Compressive Strength (UCS). In-situ tests can also be conducted, such as Cone Penetrometer Testing in soils to better understand the in-situ parameters of different soil strata, and pressuremeter testing in rock to enable assessment of rock mass modulus and estimate the expected settlement.

4.3 CONDITION OF STRUCTURAL ELEMENTS

The condition of the structural elements of footings such as concrete and steel is a critical step in deciding on whether the foundation is likely to perform as desired for the design life of the new structure. As the existing building being partially demolished or re-purposed is likely to be ageing, it is not reasonable to assume that the foundations are in the same condition as when they were first installed. Tsubakihara and Yamashita (2005) suggest that the three important factors requiring evaluation for existing footings are integrity, durability and bearing capacity.

Foundation integrity is a function of how structurally sound the footing element is, and whether there are any defects, cracks or deformities that are likely to impede on footing performance. A standard test to assess integrity is the Pile Integrity Test (PIT), which is a non-intrusive low strain test that utilises wave theory to determine the homogeneity of the footing material. There are other methods such as thermal and cross hole integrity testing which can supplement the standard PIT method.

There are a variety of different methods to assess footing durability. These can include carbonation testing techniques, tests to determine if concrete has been subject to chloride or sulphate attack, permeability testing, petrographic evaluation of aggregates and X-ray diffraction to assess mineralogy.

Concrete strength testing is also recommended to check against as-built information. In a similar manner to testing foundation material, UCS testing can be conducted on the concrete core samples attained from boreholes. This enables confirmation of strength for footing design purposes and performance analysis.

4.4 BEARING CAPACITY AND SERVICABILITY OF EXISTING FOOTINGS

Structure designers rely on sound foundations to ensure that the new structure will not degrade over time. Therefore checking the existing foundations will stand up to the new loads as well as assessing how much movement they may incur is critical for design.

Assessment of bearing capacity for foundations in soil is critical, to ensure amended and often increased load distributions will not lead to failure of the subgrade. In rock conditions, bearing capacity can be less important due to higher strengths and confinement. For assessment of bearing capacity, first principle footing capacity formulae are often used, in conjunction with footing design software using the information attained from the investigation of foundation and structural elements. Assessing footing serviceability and expected ground settlement beneath footings is also critical, so that structural designers can include provision within the structural elements to withstand the expected movement.

The capacity and serviceability of footings can be assessed using in-situ testing to provide information on real time footing performance. This can include high strain dynamic load testing using the Pile Driver Analyser (PDA) or undertaking a static load test to simulate expected loads for the new structure while monitoring pile head movements. Depending on the magnitude of the proposed loads, these in-situ testing techniques can be challenging to undertake in difficult access urban environments - dynamic load testing can require a high force to mobilise the pile (large hammer dropped from a height) and static load test can require a very high reaction force.

5 SUMMARY OF FOUNDATION REUSE LITERATURE

Foundation reuse has been successfully implemented in many scenarios and offers advantages in urban environments where space and access constraints apply, However, engineering innovation is required as it will generally require bespoke solutions. Modern societal expectations to reduce waste and reutilise scarce resources has compelled the industry to pursue reuse opportunities, with technological advances in testing and construction making this process more achievable. The key to determining the feasibility of adopting such methods, is to understand the existing condition of the foundation and subgrade, while interrogating the various footing integration and supplementation options available given the spatial and design constraints of integrating old with new. To illustrate some of the issues discussed above, the example of the Greenland Centre is presented where the original foundations have been reused in a development which is more than twicethe height of the building it replaced.

6 GREENLAND CENTRE – FOUNDATION REUSE PHILOSOHY

The Greenland Centre, located at the centre of Sydney's CBD, is a noteworthy example of where footings and additional structural elements were successfully reused as part of a new structure within a challenging urban environment. The reuse strategy was centred around retaining the steel skeletal frame and associated pier footings, while implementing an augmented footing approach to enable a significantly higher building to be constructed.

6.1 PROPOSED DEVELOPMENT

The project was conceived as part of the redevelopment of the former Sydney Water office tower into the proposed Greenland Centre Sydney, with the structure completed in August 2020 and the building currently undergoing fit-out and commissioning. The Greenland Centre Sydney is one of Australia's highest residential buildings. The project consisted of the partial demolition of the original 27 storey building, including the removal of the building interior, façade and above ground concrete elements. The steel frame and concrete pier footings have been retained from the old structure, and integrated into the new 66 storey, 235 m high super structure. The existing 3 basement levels were retained as part of the redevelopment, which involved the removal of all slab and column concrete material to the top of the existing basement excavation.

The main driver for the push to reuse the footing and steel structure was to maximise proposed floor space due to heritage site boundary restrictions. Other incentives included the obvious sustainability benefits attained from reusing materials, and that the developer had commercial incentive to conduct Research and Development as part of the unique reuse opportunity.

Figure 5: Pre-existing structure

Figure 6: Old steel frame retained

Figure 7: New building (at ~80%)

6.2 EXISTING FOOTING INVESTIGATIONS AND GEOLOGICAL SETTING

Prior to any significant advancement in feasibility or design of the proposed structure, a detailed understanding of the existing footings and geological conditions was required to assess subgrade and likely performance of the footings retained. Several stages of geotechnical investigations were conducted, which typically involved intrusive borehole drilling to enable core recovery for inspection and laboratory testing as well as some in-situ testing. Boreholes and core samples were used to both confirm the as-built information and condition of the existing footings, and to assess foundation conditions.

Strength testing was conducted on the collected core samples, with Point Load Strength Index (Is50) and Unconfined Compressive Strength (UCS) testing on the rock to determine rock classification and UCS testing on concrete samples to assess footing material strength. In-situ pressuremeter testing was also conducted to assess rock mass modulus and rock stiffness to inform design.

The original building as-built documentation (hand-drafted and dated early 1960s) indicates the retained steel frame is founded on an arrangement of concrete piers, embedding approximately 8m depth into the subgrade with a belled base designed to provide additional bearing capacity of the footings (see Figure 8). Boreholes were drilled through the concrete piers, targeting both the edge of the piers and the edge of the belled pile base to confirm as-built details such as pier toe levels, pier shaft width and belled toe dimensions. Generally the original as-built information was identified as slightly conservative with investigation results indicating pile toe levels were up to 2m lower and the belled section of piles extending up to 1m further from pier centre than documented.

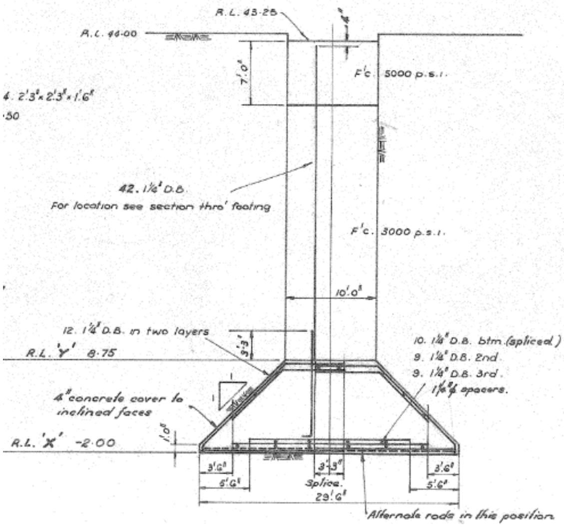
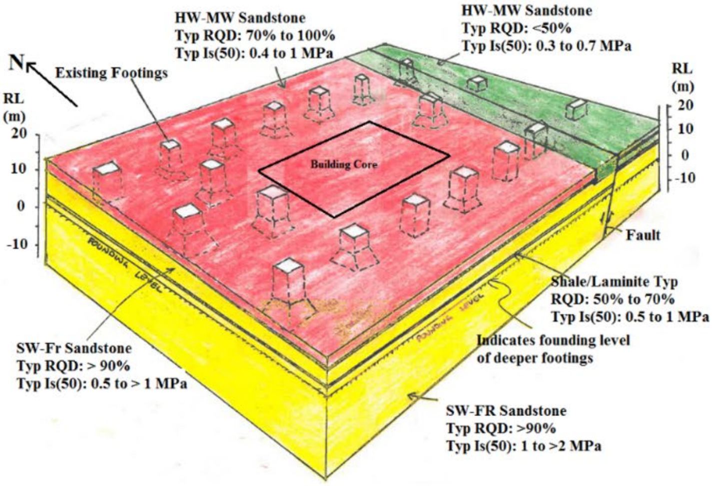


Figure 8: Typical belled pier arrangement (extracted from as-built drawings)

From information attained from the geotechnical investigations, a geological model was developed to inform footing design and aid footing performance modelling. Due to Sydney's CBD being found on relatively shallow sandstone and 3 levels of existing basements, the thin soil and weaker weathered rock profiles had been removed as part of the original building developments for the old structure. The geological model is illustrated in Figure 9 below, with adopted model parameters. The lower basement floor is predominantly found on medium to high strength sandstone (Upper Zone) and the piers are found in high to very high strength sandstone (Mid to Lower Zones). Assessment of investigation data inferred a lower strength 'Upper Zone' on the eastern edge of the site due to an inferred fault structure.



Zone	Upper	Mid	Lower
RL (m AHD)	15-10	5-10	<5
Weathering	HW-MW	MW	SW-FR
Strength (Is_{50}) MPa	0.4to1.0	0.5to>1.0	1.0to>2.0
Modulus (MPa)	1400	2400	5500
Typical RQD (%)	70-100	>90	>90

Figure 9: Geological Model and adopted model parameters

6.3 ADOPTED AUGMENTED FOOTING DESIGN

The significant increase in building height between the old and new structures resulted in an approximately 2-fold increase in applied force through the columns. With the requirement to retain footings and the steel structure, several foundation re-use options were originally considered. Installation of new footings to supplement the old was a problematic concept as spatial constraints due to existing basements and the steel structure would not allow for large piling equipment that would be required to penetrate the high strength rock. Ground improvement was not considered feasible due to the already high bearing capacity of the subgrade, limited footprint of existing footings and the high forces imposed by the new super structure.

The decision to adopt an augmented footing approach was largely influenced by two aspects. The first was spatial constraints dictating that only small to medium plant equipment with relatively low head-room had access to the lower basement. This resulted in rejection of a deep foundation solution (piles) and with shallow footings being considered the most practical approach for footing construction. The second factor that supported this approach was the relatively high subgrade strength at basement level and the efficiency at which shallow footings could transfer load to meet load bearing and serviceability requirements for the new structure.

As the developers opted for a reuse design strategy using the same column arrangement as the old, augmenting the existing pier footings with pad footings was a rational method so as to avoid any excessive load transfer systems which would ordinarily be required to integrate independent footings into the structure. The methodology was simple; encase the existing pier into a steel reinforced concrete pad footing, and integrate the steel reinforcement and concrete from the pad footing into the new structure. This included encasing the steel columns in steel reinforced concrete to help the structure support the higher loads from the additional building height and eccentricity (refer to Figure 10). Therefore, the bearing capacity borne by the original piers would be supplemented with additional capacity of the pad footings to meet the new applied loads.

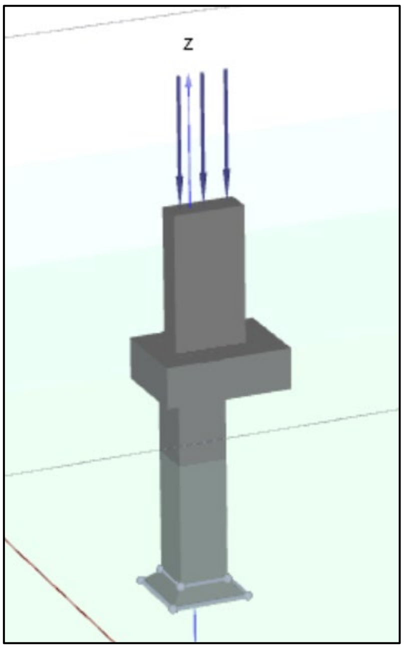


Figure 10: Example of existing belled pier augmented with pad footings

7 GREENLAND CENTRE – FOUNDATION REUSE DESIGN RATIONAL

With an understanding of the existing footing and subgrade conditions and a feasible footing reuse methodology selected in principle, the next step was to validate design. To accommodate the new loading arrangement of the proposed structure, many of the proposed columns were required to be slightly eccentric to the centre of the existing piers. Therefore consideration of the orientation, dimensions and position of augmented pad footing was necessary to withstand the variation in load distribution.

Three-dimensional finite element analysis was conducted on selected footings using the geotechnical software package PLAXIS3D. The purpose of the modelling was to:

- Assess the performance of selected existing belled piers without footing augmentation under the higher and eccentric loading from the proposed new structure
- Explore various pad footing augmentation geometry to assess performance and optimise pad constructability
- Confirm a pad foot design to augment existing belled piers that meets the settlement and serviceability requirements of the structure

7.1 MODELLING RESULTS

Two of the highest loaded columns were selected for analysis, with the maximum serviceability loads provided by the structural designer.

Parameters from the geological model developed and outlined in Section 6.2 were used as input for the model, including some assumptions of the new and old concrete using Young's Modulus values of 20 GPa and 30 GPa respectively (from as-built documentation). The new pad footing is assumed to have no structural connection to existing belled pier. The analyses were conducted considering isolated footings, as group settlement effects were considered to be minor due to the high strength and stiffness of the subgrade.

Settlement results modelled using the Ultimate Limit State (ULS) loads for the new building on the original footings without pad augmentation indicated expected settlements as high as 20 mm, which was typically more than 2 times higher than the serviceability limits stipulated by the structural designers. This confirmed that footing augmentation was required, with the next stage of the assessment involving modelling of various pad footing sizes and dimensions to optimise design.

With challenges associated with excavating high strength rock in low headroom basements, the objective was to adopt pad footings that required minimum excavation. Thin pads with a large surface area typically showed inefficiencies in limiting settlement due to large bending moments and stiffness limitations in the pad structure. Thicker pads with smaller footprints were also unsatisfactory as they only provided minor improvement to footing performance, although generally speaking the ground conditions improve with depth. The modelling indicated the optimal pad footing dimensions had a similar width/length ratio to that of the new column, with the pad depth approximately half the length of the shorter side of the pad. Figure 11 indicates an example of the reduced settlements resulting from footing augmentation with the pad footing that meets the serviceability limits of the new structure.

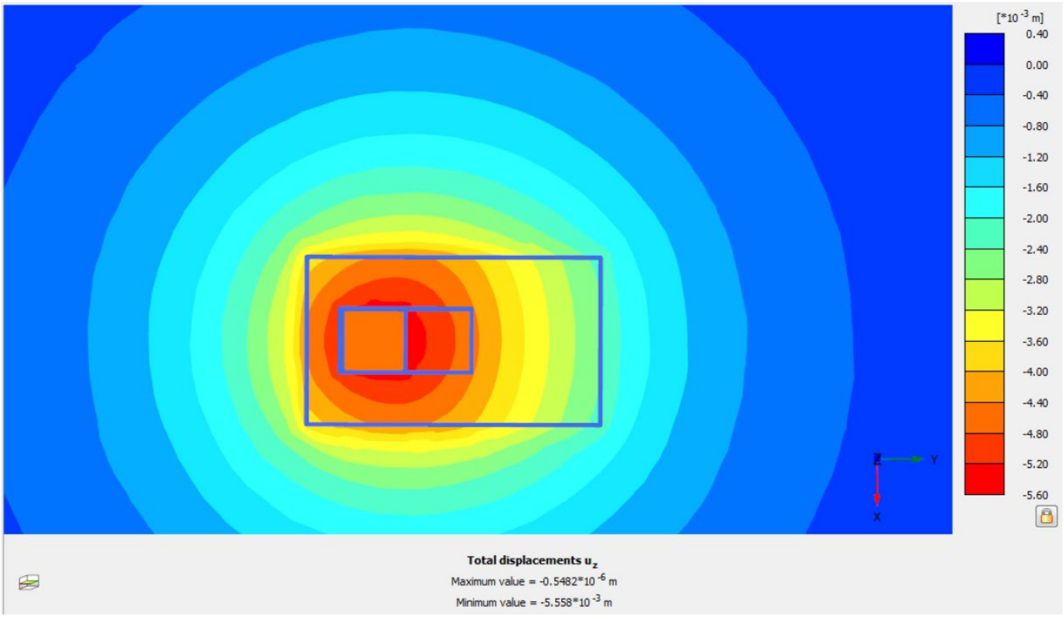


Figure 11: Example of new augmented footing under ULS loading

7.2 MONITORING DURING CONSTRUCTION AND OBSERVED PERFORMANCE

Survey targets were installed on several columns near the footing/column interface. A monthly level survey was commenced approximately halfway through the demolition phase of the project (removal of concrete elements from the structural frame). Survey results indicated that during the second half of the unloading phase footing levels 'rebounded' approximately 1 mm (extrapolated to a total of 2 mm rebound over full unloading phase) and that settlements measured during construction increased by between 5mm and 7 mm at the heavily loaded piers.

To enable comparisons between predicted settlement with observed settlement, two columns were modelled in Plaxis at 25%, 50%, 75% and 100% ULS, with maximum predicted settlement estimated. Figure 12 plots these predicted settlements for dates where completion milestones of 25%, 50%, 75% and 100% were observed, alongside actual settlement measured through level survey. Results indicate that the model over predicted settlement by about 25 percent. Further work to understand the cause of the discrepancy between prediction and reality is ongoing.

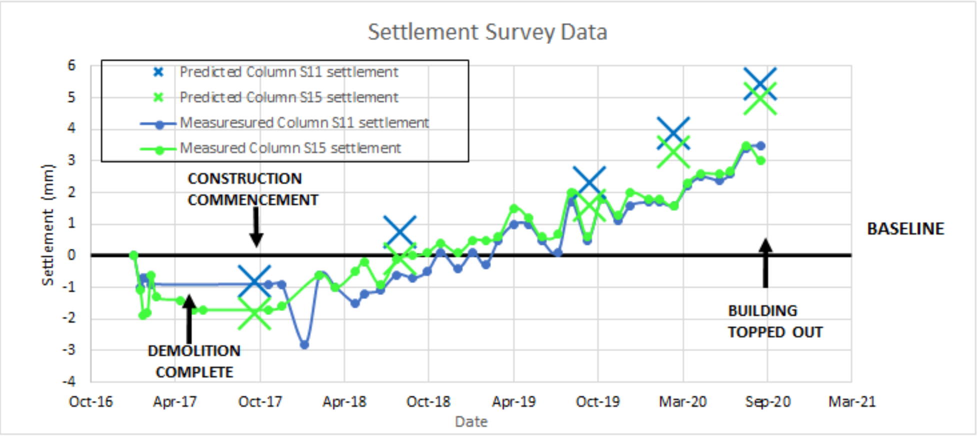


Figure 12: Predicted settlement from modelling compared with observed settlement during construction

8 CONCLUSIONS

Foundation reuse is becoming more commonplace, due to its potential for cost savings, ethical obligations on developers to design and construct sustainable solutions as well as other factors such as heritage constraints. Examples from around the world show that the philosophy and application of foundation reuse is not new, however, relatively recent technological improvements have helped implement this process. Advancement in investigation and testing techniques as well as numerical modelling can help significantly decrease the risks associated with reusing old foundations and constructing new in spatially challenging urban environments.

The Greenland Centre Sydney provides a benchmark example where the foundations and steel frame from an existing building were successfully reused and integrated into a significantly larger structure, within an urban environment. Spatial and heritage constraints were managed by implementation of an augmented footings methodology, supplementing existing pier footings with pad footings. Numerical modelling was utilised to optimise and validate the footing augmentation design process. Survey monitoring of footings through the construction process showed settlement during construction was slightly less than that predicted during modelling, indicating serviceability limits were within those stipulated by the building designers.

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