WELLINGTON RAILWAY STATION REFURBISHMENT

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SUMMARY

The Wellington Railway Station was sold to the Crown who in turn secured a lease with Victoria University to create a central city education campus, whilst maintaining the existing services of Tranz Metro, Tranz Scenic and Tranz Rail. This change of use required an extensive building upgrade coupled with a building-wide earthquake strengthening to modern seismic standards. Structural modifications included the construction of new shear walls and installation of uplift anchors. During the conceptual stages of the project, the anchors were recognised as being an important part of the seismic upgrade and this paper provides an overview of the design and construction processes used to ensure the successful performance of the uplift anchors.

INTRODUCTION

The Wellington Railway Station has dominated New Zealand's northern gateway since 1937 and was also the first major New Zealand structure to incorporate a significant measure of earthquake resistance.

Designed by local architectural firm Gray Young, Morton and Young and built by Fletcher Construction, it was the largest building in New Zealand.

It was built on reclaimed land and was designed in accordance with studies of seismic effects on contemporary buildings in Japan. The steel frame is encased in reinforced concrete and supported on groups of reinforced concrete piles.

The building is a dignified and largely undated structure with impressive architecture as illustrated in Figure 1. It is listed by the NZ Historic Places Trust.

The Wellington Railway Station has worn well and the solidly built structure was a bonus for the seismic-strengthening design team. However, the challenge lay in having to deal with the reclaimed earth and underlying marine sediments.

Holmes Consulting Group was responsible for the structural engineering design and carried out a seismic analysis of the entire structure to determine the optimum upgrade solution.

Structural modifications to the building include the construction of new shear walls and installation of uplift anchors which would provide the crucial connection between the massive railway station structure and the sensitive ground beneath it.

Figure 1: Wellington Railway Station

Fletcher Construction was appointed the main contractor and project management was undertaken by Victoria University's Facility Management section.

The ground anchoring subcontract was awarded to Construction Techniques with a scope of work which included the drilling, supply, installation and testing of 11 Williams bar anchors and 13 BBR strand anchors. Drilling for the anchors was in turn subcontracted to Webster Drilling & Exploration.

PRELIMINARY INVESTIGATIONS AND DESIGN

Geotechnical Investigations

The performance of the ground anchors was recognised as being critical to the overall resistance to an earthquake of the railway station structure and Holmes Consulting Group

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commissioned Connell Wagner to investigate the ground conditions.

Bore log information indicated the Railway Station area was underlain with 3m to 4.5m of loose silty gravel derived from old reclamation fill overlying marginal marine sediments. These sediments included interbedded silts, sands and gravels.

Proving Trials

To enable an early evaluation to be made on the likely performance of the uplift anchors in the underlying marine sediments, proving trials were carried out as a separable contract prior to final design.

Two trial anchors were fabricated from 45mm diameter high grade stress bar with UTS 1780kN. The anchors were installed in 125mm diameter holes that included a series of bells or under-reams in the bond length as the anchorage mechanism. Figure 2 provides a schematic representation of the under-ream anchorage.

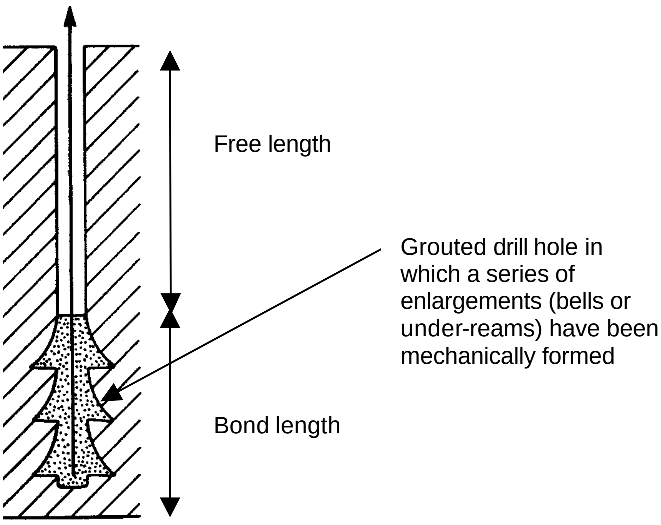

Figure 2: Under-reams or bells in bond length

The holes were drilled by Webster Exploration and Drilling using the rotary mud method and SPT values were recorded over the proposed bond zone of each anchor. The anchors were supplied, installed and grouted by Pendleton Corporation. The first trial anchor was installed to a depth of 15m and only the lower 4m was grouted. The second trial anchor was installed to a depth of 12m and the lower 6m was grouted.

Both anchors were bonded into the underlying marine sediments and allowed to cure for 10 days before testing.

A steel frame mounted on timber bearers was used to provide a reaction mechanism for the stressing operation.

The first trial anchor failed at 1025kN and it showed significant residual deflections at the end of each loading stage. This deflection was attributed primarily to the movement of the soil around the lower two or three under-reams and some of the deflection was probably caused by the stretching of the bars and slight movement or loosening of the couplers.

The second trial anchor was successfully loaded to 1500kN with a residual displacement of 50mm. The test results indicate that up to about 1300kN there was very little residual movement at the end of each load cycle (less than 5mm) and it was concluded that this movement was probably a mixture of movement within the couplings and settling down of the anchor in the ground.

At 1300kN there were small movements, possibly as the heavily loaded soils around the under-reams started to deform, with up to 85mm of movement measured at peak load during the second 1500kN load cycle. The residual anchor movement at the end of testing was 50mm (i.e. the anchor apparently pulled 50mm out of the ground) but the anchor still held the load for 15 minutes at the final two 1500kN load cycles.

It was noted by Connell Wagner that the anchors will deflect elastically under loads and this deflection could be in the order of 20mm at 1000kN depending on the exact anchor length and bar diameter. It was also noted that if a more rigid anchor was required, high pressure post-grouted anchors could be used for the production anchors.

DESIGN AND CONSTRUCTION OF PRODUCTION ANCHORS

Design

Holmes Consulting Group evaluated the results of the proving trials and the production anchors were designed using a mixture of under-reaming and post-grouting. A combination of bar and strand anchor types was selected to provide the range of uplift forces required.

The specified working load for each anchor type was 200kN and anchor geometry requirements dictated a minimum free length of 9m, a minimum bond length of 6m and drill hole diameters between 125mm and 200mm. All anchors were vertical.

16 number bar anchors were specified as 45mm diameter (UTS 1780kN) located in a 125mm diameter drill hole with six 200mm diameter under-reams evenly spaced in the bottom 6m of the drill hole (bond length). The anchorage mechanism (tremied grout in the drill hole coupled with under-reams) in this application is mobilised primarily by end bearing.

17 number strand anchors were specified as comprising nine 12.7mm diameter superstrand (UTS 1674kN) located in a 200m diameter drill hole and post-grouted. No under-reams were required over the 6m bond length and the anchorage mechanism relies on enhancement of the installation grout using the technique of pos-grouting which relies on the enlargement of the bond zone of the anchor by hydro fracturing the ground mass to provide a bulging effect beyond the core diameter of the drill hole. Post-grouting takes place as a secondary injection after the initial stiffening of the primary or installation grout with pressure ranging from 500 to 1000psi.

The anchors were to be permanent and constructed in accordance with FIP 1996 and comprise double corrosion protection in accordance with BS8081:1989.

This required full encapsulation of the strand and bar with cement grout inside a single corrugated plastic duct.

The main performance requirements of the ducting are two fold. Firstly, the duct must allow transfer of the capacity of the anchor tendon from the inner grout to the outer grout without cracking, and secondly, the duct must provide a continuous impermeable barrier to moisture which will not degrade during the lifetime of the anchor. The outer grout does not provide any corrosion protection; it simply provides the bond mechanism for the anchor.

Anchor lengths were expected to be in the order of 15m from existing floor level and the final depth was to be confirmed during drilling.

The anchors were designed to be incorporated into the new concrete foundation beams that formed the base for the new shear walls. The foundation beams required either 2 or 3 anchors grouped at each end to deal with the uplift forces.

The strengthening concept for the building consisted of 12 concrete shear walls distributed around the ‘U’-shaped plan of the building, extending to varying heights. Each wall was founded on a concrete beam, supported by the existing piles and held down using the new ground anchors. The anchors are grouped at either end of the foundation beam, and the effects of the close spacing was reviewed in the design, but found not to reduce the anchor capacity.

Pre-award Meeting and Risk Profile

The initial tendered price of the ground anchors exceeded the project budget. A pre-award meeting was held with all relevant parties to identify any potential cost savings, and, clarify the risks attached to the ground anchoring component of the project to minimise the potential for cost over-runs.

The main cost savings identified related to reducing the number of anchors required, although this meant that a proportional increase in the capacity of some of the anchors would be required.

From a value engineering perspective, it was relatively simple to reduce the number of anchors. The foundation beams that required 3 anchors at each end could be reconfigured to include only 2 anchors at each end and this would effectively delete 9 anchors from the scope of work providing an overall cost saving in the order of 20%. However, the capacity of the anchors would have to increase from 1674kN to 2232kN which contained an additional risk profile.

It was acknowledged that the proving trials effectively verified the under-reaming anchorage system in the marine sediments. However, the specified post-grouted anchors had not been tested. The main risk therefore related to the performance of the yet un-tested post-grouted strand anchors and, any variability in the ground conditions found to be present. It was decided that the first production anchor should be proof tested to verify the performance of the strand anchors.

As a result of the proposed value engineering, 11 bar and 13 strand anchors would be required.

The programme identified that the ground anchors and shear wall construction were on the critical path and three weeks after the pre-award meeting, work on the production anchors had commenced.

Proof Anchor

The 33% increase in capacity of the strand anchors from 1674kN to 2232kN dictated that the bond length also be increased. The first production anchor was configured with 12-strands, a bond length of 7.5m, and a free length of 12.5m and installed inside the 200mm drill hole to a depth of 18m below existing slab level. Post-grouting was carried out 24-hours after the introduction of the primary grout.

Following a 7 day curing period, the anchor was successfully proof load tested off a steel beam supported on the existing railway station foundations (Figure 3) to 1700kN (76% UTS) which verified the post-grouted anchorage system.

It was agreed to make use of the increased capacity to reduce anchor numbers and realise the cost savings.

Figure 3: Reaction frame for 1700kN proof test

Construction Constraints

As the hub for New Zealand's entire railway network, the station operates 24 hours a day and uses sophisticated technology to ensure the stringent timetables and performance standards are met. The entire project had to take place within a business-as-usual environment and this meant enabling trains to arrive and depart without delay, providing easy thoroughfare for the 20,000 daily commuters, and ensuring people working in the building could do so with minimal interruption and noise.

To minimise the effects of noise, work areas were cordoned off with sound-proof barriers and noisy equipment was located as far as possible away from the public and fed to the job site by umbilical lines.

Drilling

The restricted access and extremely confined working space dictated specialist drilling expertise which was provided by Webster Drilling and Exploration Ltd.

In selecting the drilling equipment to be used for this project, special considerations had to be given to the fact that the work was to be carried out in a fully operational facility with a high public pedestrian factor, in conjunction with the requirement to drill through a variety of substrates that included reclamation fill material, running marine sands, hard and "soft" gravel layers, buried concrete slabs and old timber wharf piles. In addition, containment and removal of waste was a large component of the work.

Consistent with the proving trials, the holes were to be drilled using the rotary mud method. To ensure that the drilling fluid would have no detrimental effect on the grout, Construction Techniques conducted an experiment to verify that the installation grout adequately displaced the mud, and, did not affect the bond of the grout to the corrugated duct.

The experiment involved installing a mock anchor complete with corrugated duct inside a 200mm PVC pipe (Figure 4) to simulate the drill hole and filling the annulus with mud.

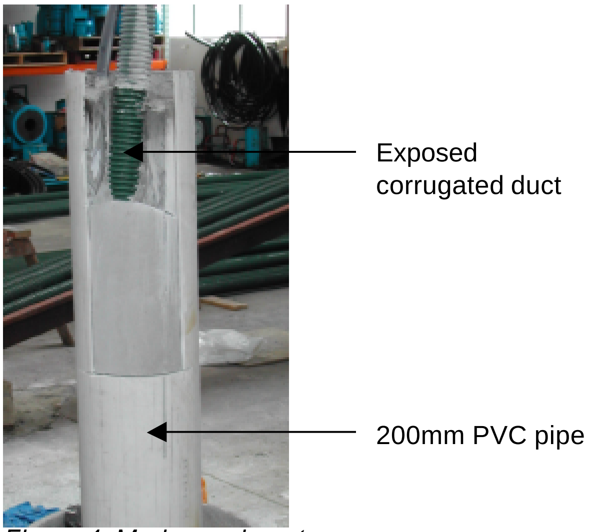

Figure 4: Mud experiment

Grout was then pumped into the corrugated duct and PVC annulus until the mud was fully displaced from the PVC pipe. At 24-hours, a section of the duct was exposed and no mud residue was found either at the corrugated duct-grout interface or at the PVC pipe-grout interface.

It was considered that the hydration of the cement generated enough heat to ensure that the drilling fluid was completely broken down and was therefore unlikely to compromise the bond capacity of the anchor.

The drilling rig selected for this project was an Atlas THR 48, hydraulic top drive rig (Figures 5 and 6). A special stub mast was fabricated to deal with local height restrictions and the rig was mounted on wheels for ease of movement around the site.

With limited access at each shear wall location, coupled with the requirement to minimise noise, the hydraulic power pack and compressor were located outside the railway station building and connected to the rig via umbilical hydraulic power lines up to 45 metres long.

Figure 5: Drilling rig

For the strand anchors, the drilling operations involved cutting a 250mm hole though the existing concrete foundations and auger drilling a 230mm hole into sound material and securing an 8" casing into the top of the hole. The remainder of the hole was then drilled at 200mm using rotary mud in readiness for the anchor installation and grouting, during which time the casing was progressively extracted from the drill hole.

For the bar anchors, a 165mm hole was cut through the existing concrete foundation followed by auger drilling a 160mm hole into sound material and securing a 5" casing into the top of the hole. The remainder of the hole was then drilled at 125mm using rotary mud complete with under-reams at 1m centres over the 6m bond length.

Figure 6: Drilling rig

A Gardner Denver "five by six" double acting duplex pump was used to circulate the drilling mud. The drilling mud has a number purposes, including cooling the bit, flushing cuttings from the hole, and assisting in hole stabilisation by controlling the density of the mud.

The under-reams were constructed using the under-ream assembly shown in Figure 7 and as outlined in the following the procedure.

The under-ream assembly is run in to the required reaming point with the reaming arms in the retracted position. Drilling fluid is then pumped down the drill string and on passing through the under-reamer, the fluid acts on a piston, driving it down. The piston is connected to the reaming arms, forcing the reaming arms outwards.

The lateral force of the reamer arms is dependent on the formation type and varied by altering the pump flow rate / pressure.

The drill string is rotated, and the wall of the hole reamed accordingly. The drill fluid exits the assembly both around the reaming arms and through the drilling bit at the bottom. This fluid returns to the surface, flushing out the drill cuttings in the normal manner.

The rotary torque of the drilling rig is monitored to determine when the reamers have deployed to the set hole diameter.

After extraction of the under-ream assembly, the drill hole was then ready for anchor installation and grouting, during which time the casing was progressively extracted from the drill hole.

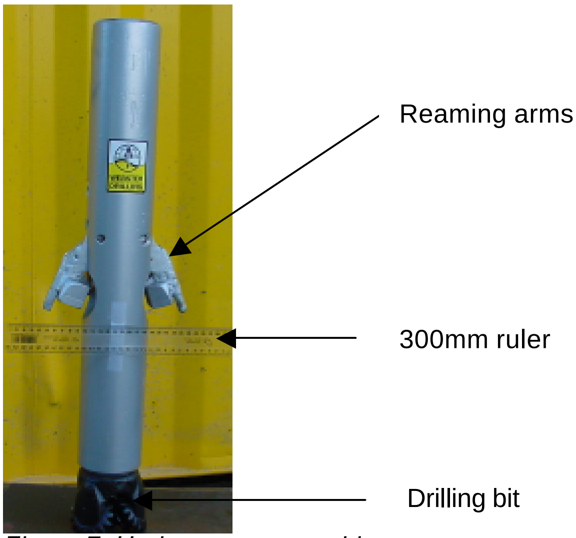

Figure 7: Under-ream assembly

The holes were drilled once the excavations had been made for the new concrete foundation beams and termination drill hole depths were confirmed by Holmes Consulting. In some cases, anchor lengths were increased due to the presence of particularly soft material encountered in the bond zone.

<u>Anchor Manufacture</u>

The anchors were specified as double corrosion protection and the tendon fabrication was mostly conducted off site in a controlled environment to minimise the risk of damage to the tendon and or corrosion protection system.

For the strand tendons, each individual strand was run through a greasing and sheathing machine to provide protection of the strands over the free length, and allow the strands to elongate during tensioning. The individual greased and sheathed strands were then configured into the 12 strand arrangement by installing plastic spacers over the bare bond length to create a basket weave (Figure 8) and fitting the internal grout tube and steel nose guide (Figure 9). The end of the corrugated duct was sealed and water tested to verify its intactness prior to inserting the tendon.

Figure 8: Strand anchor arrangement

Plastic centralisers were then fitted to the corrugated duct over the bond length and a compressible foam packer fitted to the corrugated duct at the top of the bond length to enable the anchor to be grouted full length in one operation. The packer isolates the bond from the free length, thus ensuring the anchor load is only transferred into the bond length. Two primary injection grout tubes were then fitted to the completed anchor, one terminating at the bottom of the anchor and one terminating below the top of the bond length. The post-grout tube was also fitted with flapper valves at regular intervals over the bond length.

Figure 9: Internal nose guide

The bar anchors were pre-grouted in 6m lengths on a purpose built inclined pre-grouting bed. Prior to grouting, the assembly was water tested to confirm integrity of the corrugated duct.

Following hardening of the grout, the pre-grouted bar assemblies were transported to site for fabrication into the final anchor length using couplings and smooth HDPE tube over the free length.

As with the strand anchors, two primary injection grout tubes were fitted to the anchor, and, as a precautionary measure, post-grout tubes were also fitted so that in the event an anchor did not meet the specified proof loads, post-grouting could be carried out to enhance the bond capacity.

Anchor Installation and Grouting

The flexible nature of the strand anchors meant that they were able to be man-handled into the drill hole with relative ease. However, due to the weight, rigid nature and coupling requirements of the pre-grouted bar assemblies, a winch was used to lift the pre-grouted bar anchors and hold the assembly in place during the installation and grouting process.

Once the anchors had been installed, they were secured in place and held off the bottom of the drill hole. Grouting was carried out using a high speed, high shear mixer (Figure 10) with grout delivered to the bottom of the drill hole / anchor via the primary grout lines.

Figure 10: Grouting equipment

For the strand anchors, the grouting took place simultaneously on the inside and outside of the corrugated duct to maintain an equal pressure and minimise the risk of damage / collapse to the corrugated duct. As the bar anchors were pre-grouted, grouting was only required to fill the drill hole.

Within 24-hours of the primary grouting operation, the post-grouting process commenced. The high pressure pump (Figure 11) is capable of pumping at a pressure of 4000psi. Neat cement grout was injected until either a constant target pump pressure was maintained, or a target volume had been injected. If the target volume was reached prior to attaining the target pump pressure, another stage of post-grouting was scheduled for the next day and the process repeated. The target pump pressure was adopted from the results gathered during grouting of the proof anchor.

Figure 11: High pressure grout pump

Once all anchors had been installed at a particular shear wall location, the anchorage (bearing plate, trumpet and spiral) was fitted to the anchor, taking particular attention to seal the trumpet to the corrugated duct or HDPE pipe for the strand / bar anchors respectively to complete this component of the corrosion protection system.

The concrete foundation was then constructed up to within 300mm of the finished floor level, incorporating the anchorage and allowed to cure for 14 days prior to any stressing of the anchors could take place.

Stressing and Anchor Head Protection

The stressing operations included proof testing and subsequent locking off to the specified working load.

Prior to stressing taking place, grout strengths were verified by cube testing.

Stressing was carried out against the newly constructed anchor foundation beams using a 200 tonne centre hole jack and trestle as shown in Figure 12. The strand anchors were proof tested to 1700kN and the bar anchors were proof tested to

1379kN in a single load cycle in increments of 20% UTS. Creep tests were not required.

A levelling device located remote from the anchor was used to record extensions off a graduated scale rule attached to the end of the bar or strand tendon. Displacements of the new concrete foundation beams were also recorded but were negligible.

Figure 12: Centre hole jack and trestle

The documents required that the anchors were able to load tested in the future. For the strand anchors, excess strand was cropped to within 150mm above the anchor head and the head protected with denso tape prior to fitting a grease filled PVC cap (Figure 13). The bar anchors were cut to leave sufficient bar protruding above the anchor nut to allow future coupling for testing and protected as per the strand anchors.

Figure 13: Strand anchor head prepared for protection

All anchors where then incorporated into the final section of the new concrete foundation pour.

<u>Underperforming Anchors – Remedial Work</u>

The ground anchor work was a critical programme activity and the concept of partnering was promoted by Fletcher Construction at an early stage to ensure any problems encountered were promptly and effectively dealt with. This required open channels of communication between Construction Techniques and Holmes Consulting, and in effect, provided the perfect link between consultant and contractor.

The underlying marine sediments were variable in nature and as a result, $^{1}/_{3}$ of the bar anchors and $^{1}/_{4}$ of the strand anchors did not achieve the specified proof load. This could not have been foreseen by the designer or contractor and remedial options were openly discussed to determine how the required uplift loads could be provided.

In most cases, this was able to be achieved by a combination of down-rating the load factors of the anchor in conjunction with additional post-grouting operations using the spare post-grout tube installed with the anchor. However, one bar anchor only achieved a maximum load of 1200kN with a residual load of only 1100kN.

A minimum load hold of 1200kN was required and Construction Techniques proposed a remedial option that involved the concept of enhancing the ground in the vicinity of the bond zone of the anchor to improve its performance. This was achieved by installing a pair of steel tube-a-manchettes (TAMs) approximately 500mm from the centre of the underperforming anchor complete with a series of valves adjacent to the bond length.

The new concrete foundation had already been constructed and to facilitate installation of the TAMs, a 150mm ID hole was cored through the existing slab and concrete backfill to a depth of 500mm. A 130mm down-the-hole-hammer was then used to drill through the balance of the concrete (approx. 0.6m) and a 115mm OD / 100mm ID HW casing advancer used to advance each hole through the ground to a depth of 13m below slab level.

The TAMs were installed cement grout was used to seal each TAM into the ground to restrict the grout flow up the outside of the TAMs during the post-grouting operation. The HW casing was extracted from the hole and the grout left to harden overnight.

After 24-hours, the initial cement grout used to seal the TAMs in place was broken by injecting water using the high-pressure pump to each of the TAM valves in turn. Cement grout was then introduced into each of the TAM valves using an inflatable straddle packer. This was connected to a ½ steel pipe and progressively lowered inside the TAM to the deepest valve and inflated.

Cement grout was slowly injected, all the while monitoring pressure and grout take. The straddle packer was progressively relocated to each of the remaining valves and the process repeated until the top valve was reached.

The TAMs were flushed with water after each post-grout operation to leave them clean for subsequent post-grouting operations.

After the final post-grout cement had been allowed to cure for 7 days, the anchor was re-tested and after reaching and maintaining a load of 129T (which represents a 17% improvement in load carrying capacity from the residual load of 110T), the Engineer instructed the testing could be terminated as he was satisfied with the load achieved and did not want to risk failing the anchor again by attempting to apply higher loads.

Conclusions

The reclaimed land and underlying marine sediments that formed the foundation block for the Wellington Railway Station when originally constructed presented a real engineering challenge to both the designer and contractor. However, a proactive approach by all parties involved at both the design, and, during the construction phase ensured that the best possible solutions were provided.

The combination of ground anchoring techniques including under-reaming, post-grouting and ground enhancement is quite unique and enabled the seismic upgrade to proceed relatively unhindered. The Railway Station remained operational throughout the upgrade and isolated work areas were progressively handed over to Fletchers to enable the conversion work to proceed with as little disruption as possible.

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