Engineers Australia Queensland Division -
2009 Engineering Excellence Awards

soul™ inTension

High strength concrete for tension piles

Category 2: Research, Development and Innovation
Also submitted for the Innovation Award

Submission by
Piling Contractors Pty Ltd & Grocon Constructors (QLD) Pty Ltd

ABSTRACT

Soul is a 77 storey apartment tower currently being constructed in Surfers Paradise that, when completed, will be Australia's third highest residential building. 44 large diameter bored piles, installed using bentonite drilling fluid and constructed using high strength concrete, were required to transfer the structural loads safely into the ground. Piles were founded up to 45m below working platform and pile diameters of 1500mm, 1800mm and 2200mm were utilized.

Soul will be exposed to extremely high winds which will cause very high tension and compression loads to be transferred into the piles beneath the building. All piles are designed with sufficient rock socket into high strength Argillite to achieve the required geotechnical capacity.

The structural design model of a building relies heavily on stiffness to estimate the deflections which will occur under load. To achieve the necessary foundation stiffness 65MPa concrete was specified for the construction of all pile shafts. However, should cracking occur in the pile shaft, as a result of high tension loads, the pile stiffness would reduce dramatically. Load would then be diverted to adjacent piles that could become overloaded causing pile after pile to crack. The building would then experience unacceptable deformations. In an innovative approach, the required pile concrete tensile capacities for this project have been assessed according to clause 6.1.1.3 (b) of AS3600.

The original design proposed 3000mm piles, but the large cross-sectional area has major implications for spoil volume to be disposed of, concrete to be delivered and required machine torque and hence drilling time. A proposal by Piling Contractors to reduce pile diameters to 2200mm offered some very beneficial outcomes for the project. Smaller diameters reduced the time requirements for hard rock drilling significantly, which had a positive effect on the overall construction program and the budget. Furthermore 170 concrete truck and 200 spoil truck movements were eliminated due to the reduction of piling volume. As a result the noise, traffic and other environmental impacts on neighbours, the community and holiday makers could be reduced dramatically. However, a challenge arising from the proposal to use smaller pile diameters with unchanged tension loads was the requirement for increased tension shaft capacity. 7 of the 44 piles required additional measures to increase their tensile capacity above that of the proposed 65MPa concrete mix.

Piling Contractors and Grocon mutually agreed to seek to use very high strength concrete for the seven critical piles. Research indicated that an 85MPa concrete mix could achieve the tensile strength requirements, while maintaining the excellent workability necessary for self compacting concrete placed under bentonite. Indirect tensile strength tests were proposed to determine tensile capacity of the concrete rather than use the more conservative formula usually adopted. As AS3600 does not detail suitable methods to adequately define the very important flow criterion of the proposed mix, the slump-flow test method detailed by VicRoads was successfully adopted.

Three different concrete mixes were designed and an innovative detailed test program, including a series of laboratory and site trials, was designed and carried out. The required workability could be maintained over a period of about 10 hours, and indirect tensile strength tests carried out during the project proved that the strength requirements had been met.

When members of the public stroll past the magnificent slender Soul tower in years to come, or when residents of the building admire the views from their balconies, they are unlikely to appreciate the innovation in foundation design and construction, hidden below ground, that was necessary to enable the building they so admire to be constructed.

TABLE OF CONTENTS

INTENTIONALLY LEFT BLANK

Introduction

The 77 stories of the Soul apartment tower will rise to 277m above the beaches of Surfers Paradise. Its slender aspect perpendicular to the seafront, and the potential for high wind speeds and pressures, means that exceptionally large tension forces are required in the foundations to prevent it from blowing over. These foundation tension forces posed unique problems to the design and construction teams.

Figure 1

When completed the apartment tower will be the third highest residential building in Australia and one of the highest residential buildings in the Southern hemisphere. Soul is positioned in a prime location at the corner of Cavill Avenue and The Esplanade right on the beachfront and in the heart of Surfers Paradise (see Figure 1 and Contents Page Picture). The apartment tower will be surrounded by a four storey retail area.

The project developer, Juniper, awarded a design and construct contract to Grocon Constructors (QLD) Pty Ltd. Works on site started in November 2007, with the demolition of the existing buildings. The proposed completion date of the high rise project is August 2010.

Piling works started in January 2008 with the installation of Continuous Flight Auger (CFA) piles for the retail area, which was carried out in 3 stages. Large diameter bored piles for the apartment tower were installed from March to August 2008.

Figure 2

High profile projects like Soul demand very thorough design and management skills and standards, particularly for the design and construction of the foundation piles. Extremely high load capacity piles, such as those for the main tower of the building, require exceptionally accurate project and design preparation.

The tower piles have been designed for ultimate loads of up to 90MN (compression) and up to 19MN (tension). Grocon Constructors (QLD) Pty Ltd and Piling Contractors Pty Ltd believe that these loads are probably the highest pile loads that have ever been designed for single piles in Australia.

Design Approach

Structural Design

The overall structural design model of the apartment tower consists of flat floor slabs supported on columns, around a central core section to give the building a stiff centre. Underneath the core the foundation is a 1.8m thick concrete slab supported on 16 large diameter piles. Around this another 28 piles between 1500mm and 2200mm in diameter were designed as foundations for the columns.

The spectacular location of Soul, right on the ocean front, will offer outstanding views, but this means that the building will be exposed to high wind loads which will create very large horizontal forces and overturning moments, causing high tension and compression loads. These compression and tension loads will be transferred into the piles and the load case 'wind loads' is the most critical structural load case for the building and the piles.

The ratio of building height to foundation depth for Soul is about 10:1. Other high rise buildings on the Gold Coast typically are much more "squat", with a ratio of 4:1 or 6:1. Soul is a very slim building and this exacerbates the compression and tension forces in the foundation piles (see Figure 3).

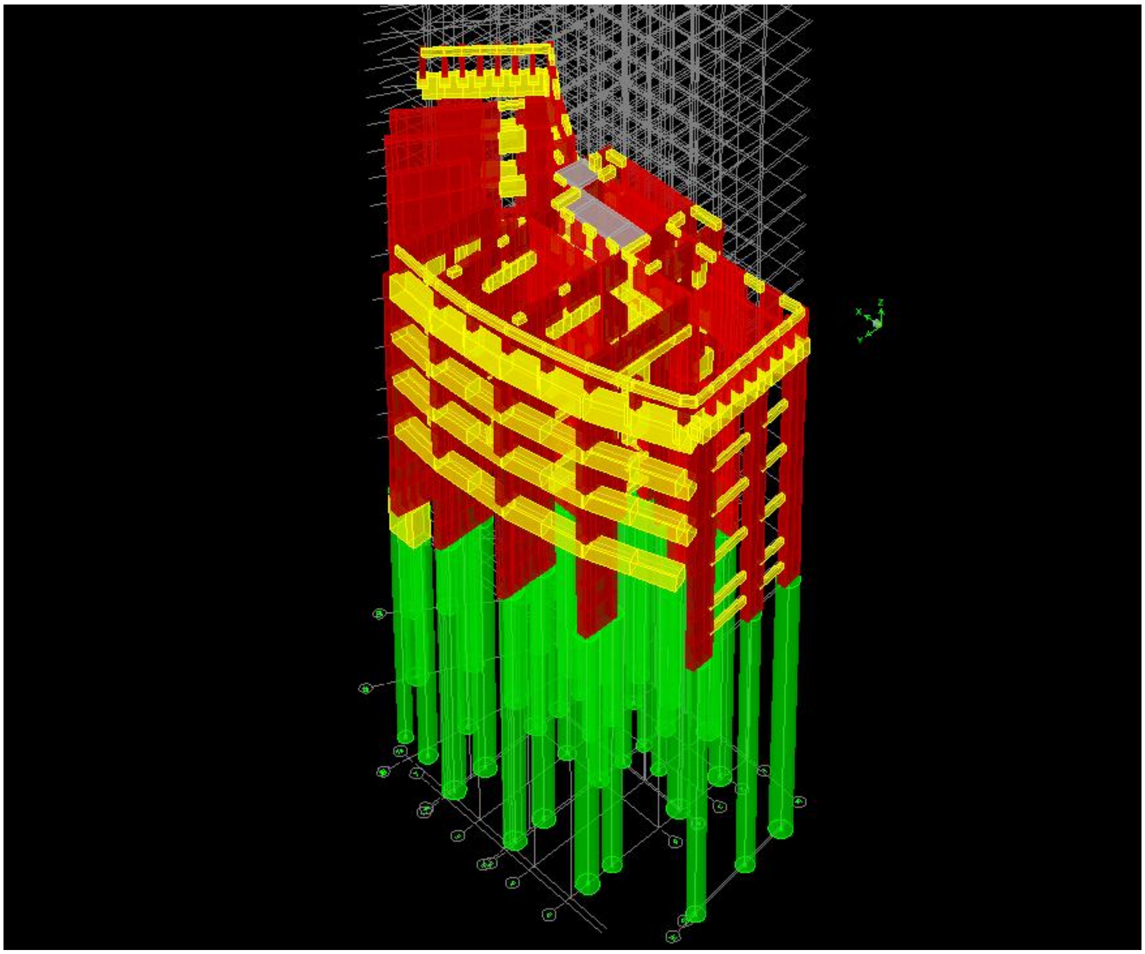

Figure 3

Pile lengths on the Gold Coast are generally limited to about 40-45m due to prevailing geotechnical conditions. Like many similar buildings the tower piles for the Soul project are founded into high strength rock. As the strength of the foundation rock increases drilling becomes more and more difficult and often, after several meters drilling, refusal will occur. Excessive rock socket drilling has significant impacts on the construction program and budget.

Compression loads are transferred into the ground through shaft friction and through end bearing at the pile toe. For extremely high compression loads, the rock quality underneath the pile toe is a very important geotechnical design criterion, as most of the loads are transferred through the pile base.

Tension loads can only be transferred through shaft friction, so piles with higher tension loads require longer pile shafts to transfer loads into the ground safely.

For a very high tower like Soul, where the wind loads combined with large lever arms (due to the height of the building) create very high pile tension loads, and where pile lengths are limited due to geological conditions, tension piles must be designed and constructed very carefully in order to achieve the required capacities.

Soul and its foundation elements require a high stiffness in order to limit deflections when the loads are applied. If a pile loses its stiffness due to a horizontal tension crack, the pile group will not work as designed, and adjacent stiffer piles have to carry additional loads. These additional loads might then cause further cracking and hence a further loss of stiffness in a domino effect.

When the concrete section of a pile is fully cracked (maybe multiple cracks in different layers) the stiffness of the pile is solely based on the quantity of steel reinforcement, and the area of this is usually less than 2.5% of the concrete area. The stiffness of the steel is about 6 times higher than the stiffness of concrete and therefore the resulting loss of overall pile stiffness for a fully cracked shaft can be around 60-85%.

Even when all piles are cracked the superstructure is unlikely to collapse, but deformations may well be above the serviceability limit and the building might be unusable.

The maintenance of pile stiffness is an important criterion for the structural pile design. Usually reinforced concrete sections will crack when the tensile strength of the concrete is reached and the steel then carries the tensile stresses. For Soul, cracks in the piles have to be avoided under all circumstances, not only to limit deflections but also to minimise the risk of corrosion of the reinforcement. Because of this, the concrete pile shafts had to react in a similar way to un-reinforced concrete columns for the ultimate load case ‘wind loads’. The pile shaft needed to have the tensile capacity to transfer tension loads in the ground safely without cracking.

65MPa concrete was specified for the construction of the pile shafts and the characteristic principal tensile strength for this concrete mix, calculated in accordance with AS3600 6.1.1.3 (a), is:

$$(f'_{ct}) \geq 0.4\surd f_c' \quad = 0.4\surd 65\text{MPa}$$
$$= 0.4*8.06\text{MPa}$$
$$= 3.2\text{MPa}$$

In the original design, pile diameters were determined to suit this maximum tension capacity. Pile diameters of 1500mm, 1800mm, 2200mm and 3000mm were specified, for all of which the tension capacity of 3.2MPa was sufficient.

Piling Contractors carried out a review of the pile diameters and Figure 4 indicates that drilling rock sockets for 3000mm piles takes significantly longer than for 2200mm piles. Furthermore the concrete volume for the 3000mm piles is 86% higher than for the 2200mm option. As a result it was decided to investigate if all 3000mm piles could be replaced by 2200mm piles. The reduced pile diameter offered a positive impact on the construction program as drilling rates and construction time could be reduced.

In addition indirect benefits, such as the reduction of concrete trucks per pour and reduced spoil load out volumes, would have an important impact on the project and the community. More than 170 additional concrete trucks and 200 spoil trucks would have been required for the piling works of the tower if the seven 3000mm piles had not been replaced by 2200mm diameter piles. Less trucks not only means reduced costs, but also less impact on the community (air pollution, traffic, noise emissions). Late night pours could be avoided and both neighbours and tourists staying near the site could enjoy a quiet environment after working hours and a reduced impact as the construction time for the piles could be reduced.

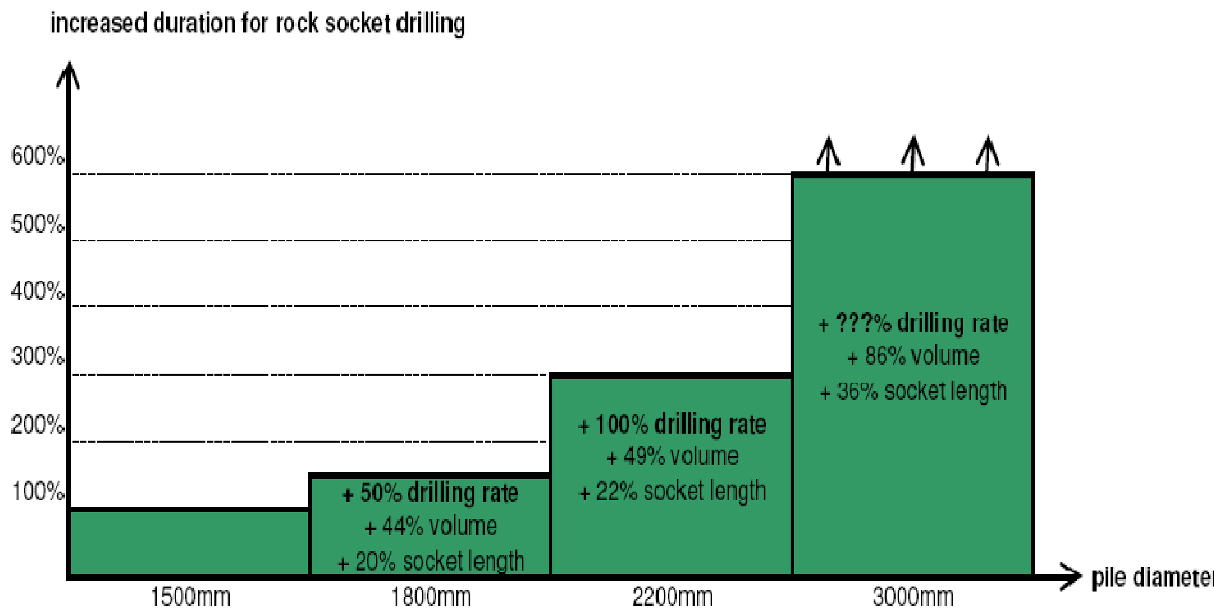

Figure 4

However, a significant challenge resulting from the desire to reduce the pile diameters and hence the concrete shaft area is an increase in the applied stresses, as the loads remained the same per pile. A reduction of the concrete cross section while maintaining a constant load will increase stresses in the pile shaft ($\sigma = F/A$). As noted above, for the 65MPa concrete mix proposed, the tensile strength was already on the limit for 3000mm diameter piles. In order to reduce the diameter to 2200mm, a concrete mix capable of providing a higher tensile strength needed to be developed. The process to achieve this will be described later, in the section on Research & Development.

Geotechnical design

The geotechnical conditions adopted for pile design for the Soul project are shown below in Figure 5. These were derived from a geotechnical investigation undertaken prior to the works.

ELEVATION	BRIEF DESCRIPTION
+5m to -1.5m	Fill (loose silty sand and clayey sand)
-1.5m to -21m	Sand (dense to very dense with some sandy clay lenses)
-21m to -33m	Sandy clay and clayey sand (ranging from stiff to medium dense)
-33m to -36m	Greenstone / Argillite (very weak)
-36m to -48m	Argillite (Neranleigh - Fernvale Group)
-48m to -60m	Argillite (Neranleigh - Fernvale Group) but RQD > 70%
below -60m	Massive Argillite

Figure 5

The natural groundwater level was found between RL+0.2m and RL+1.0m. Due to tidal influences on the groundwater level, Grocon elected to install a dewatering system to maintain ground water level constant at RL+0.2m. This was beneficial as the working platform for piling activities had to be installed at least 2m above ground water level to ensure a minimum head pressure for the bentonite drilling fluid.

A working platform designed for 300kPa bearing pressure was provided by Grocon to accommodate the proposed heavy piling equipment. Pile cut off levels were designed to be 9m and 14m below the working platform at the third basement level and the core section of the tower respectively.

Construction works were supervised by an independent geotechnical consultancy. For every pile a bore log sheet was produced recording rock levels, layers, rock strength and rock socket details (see Figure 6).

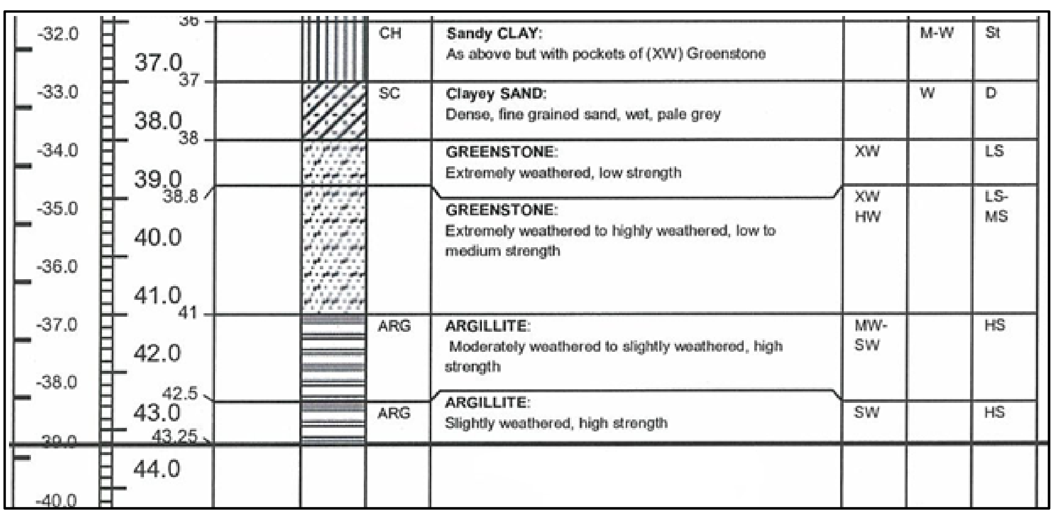

Figure 6

All piles for the tower were designed with rock sockets of at least one pile diameter into high strength Argillite below -36m. Figure 7 shows a picture of rock core samples from -32.5m to -42.0m taken during the geotechnical investigation prior commencement of piling works.

The over-riding constraint on the geotechnical design was maximum settlement for the serviceability load case in order to limit the maximum deflections and deformations of the building. It allowed skin friction for compression and tension only in the rock sockets, and ignored any shaft friction in layers above the rock.

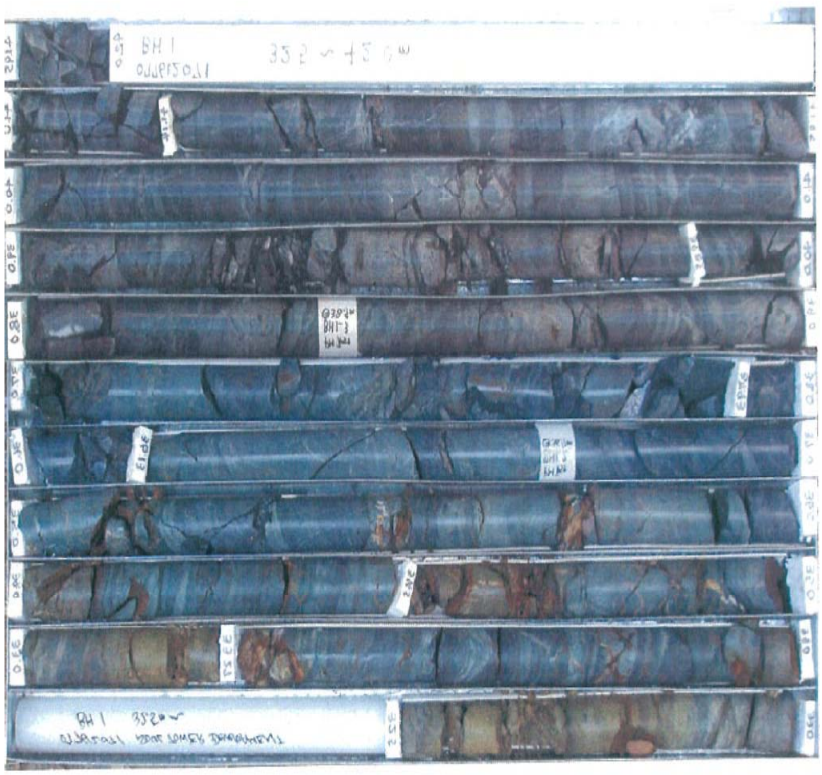

Figure 7

Technical requirements for the tension piles

In all tower piles with tension loads, plunged steel columns were required to be installed in order to transfer tension loads from the building into the piles. They act as dowel bars or tension reinforcement, and were fitted with many shear studs as shown in Figure 8.

Figure 8

All columns were extended to higher levels of the superstructure, some to the 77th floor, as indicated in Figure 9.

Figure 9

The plunged steel columns required were 200UC, 250UC, 310WC and 400WC. In order to ensure effective load transfer, the columns had to be plunged into the fresh pile concrete by between 6 and 8m (see Figure 10). Because pile cut off levels were already between 9m and 14m below the working platform, the columns had to be plunged up to 22m into the pile excavation with a high degree of precision.

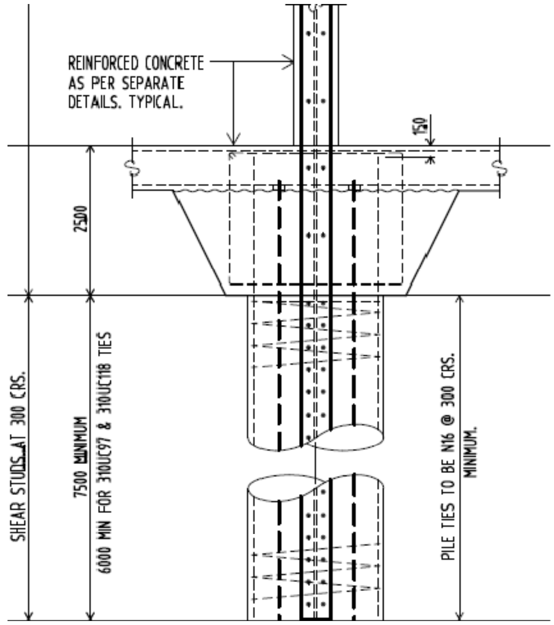

Figure 10

Research & Development

Once the decision had been made to reduce pile diameters, the seven 2200mm diameter piles needed higher tension capacities. As stated above, tensile strength for a 65MPa concrete can be determined according to AS3600 6.1.1.3 (a) as:

$$(f'_{ct}) \geq 0.4\sqrt{f_c'} = 3.2\text{MPa}$$

Ultimate tension loads between 12.5MN and 19MN result in tensile stresses between 3.3MPa and 5MPa. A typical calculation for the estimation of the maximum tensile capacity is carried out below:

σ = tensile capacity (stress) = F/A
F = tensile load = 19MN (ULS tension load)
A = concrete cross section of pile = $3.86m^2$ for 2200mm piles
$\sigma = 19MN / 3.86m^2 = \underline{5MPa}$

The maximum tension load of 19MN was selected by the design team as the governing criterion for the seven tension piles and therefore the tension capacity for these piles was specified to be 5MPa.
Following the recommendations of AS3600 6.1.1.3, there are two options to determine the characteristic principal tensile strength of concrete (see Figure 11):

6.1.1.3 *Characteristic principal tensile strength*

The characteristic principal tensile strength of concrete (f'_{ct}) may be either —

(a) taken as equal to $0.4\sqrt{f'_c}$ at 28 days and standard curing; or

(b) determined statistically from indirect tensile strength tests carried out in accordance with AS 1012.10.

Figure 11

If method (a) is adopted the characteristic concrete compressive strength required to achieve 5MPa characteristic tensile strength would be:

$$(f'_{ct}) \geq 0.4\sqrt{f_c'} \quad \rightarrow \quad f_c' = (f'_{ct})^2 / (0.4)^2 = (5*5) / (0.16) = 25/0.16 = 156.25\text{MPa}$$

A mix containing the extremely high cement content required to achieve 160MPa was considered to be unlikely to have acceptable workability. It was considered impractical to achieve a slump of 260mm maintained for 8-10 hours, and suitable characteristics to ensure adequate flow around reinforcement bars, with this proposed 160MPa mix. In addition the cost of such a mix would be significantly greater than conventional concrete mixes. The project risks associated with the use of a 160MPa mix for the piles for Soul were considered to be too high.

If method (b) were adopted, the characteristic principal tensile strength of concrete could be determined from indirect tensile strength test results in accordance with AS1012.10

Grocon's and Piling Contractors' engineering teams decided together to investigate this option further and to carry out tests and trials in order to find a suitable concrete mix design (see Figure 12). Previous experience suggested that the tensile strength of concrete would be approximately 5 to 8% of the maximum compressive strength. A high strength concrete with a target maximum compressive strength of f_c`≥ 85MPa could therefore be expected to provide at least the target tensile strength of 5MPa.

Concrete supplier CEMEX provided information from two indirect tensile strength laboratory tests they had previously carried out, for a different project, using a 70MPa concrete mix. The indirect tensile strength results for both specimens showed a characteristic principal tensile strength of 5.5MPa after 28 days. It was decided to carry out laboratory tests to determine the real tensile capacity of an 85MPa mix.

Figure 12

The project team therefore aimed at a target compressive concrete strength of f_c`≥ 85MPa as the minimum requirement in order to achieve indirect tensile strength of 6 to 7MPa. For six of the seven critical piles, tensile capacities below 4MPa were actually required. However if a 50-70% higher capacity could be achieved, the pile foundation of the slim Soul tower would be able to be constructed with an additional factor of safety.

Three different design mixes were developed by CEMEX based on the proposed 85MPa requirements for the piles (see Figure 13).

- The first mix **S851FLL** was based on the same workability characteristics as the 65MPa mix that had been used successfully on site for the compression piles.

- The second design mix **S851FLL Fib** was broadly similar to the first mix, but with added synthetic fibres. The purpose of the fibres was to further increase the tension capacity of the concrete.

- The third design mix **S851FLL mod** had reduced hydration stabilizing admixture, to investigate possible improvements with respect to addition of admixtures.

Trial mix	maximum Aggregate [mm]	Cementitious Material [kg/m3]	w/c Ratio	Intention	Remarks
S851FLL	10	670.0	0.29	to transfer workability and flow criteria of successful 65MPa mix	target flow criteria of 600mm (slump flow test as per Vic.Road RC 252.01)
S851FLLFib	10	670.0	0.29	to improve tensile strength adding synthetic fibers	similar to S851FLL but with added synthetic fibers - 5kg per m3 test effect of fibers on workability
S851FLL mod	10	670.0	0.29	investigate effects of reduced hydration stabilizingadmixure on workability and flow characteristics	similar to S851FLL but with reduced hydration stabilizing admixture

Figure 13

Innovation

The flow characteristics of the concrete to be used were identified as being very important, as the concrete must flow around the reinforcement bars displacing bentonite and achieving a good bond between concrete and steel. Furthermore, segregation or uneven distribution of aggregates must be avoided. A concrete slump of 260mm was targeted, as the mix must be self compacting, and this workability must be maintained for at least 8-10 hours.

With such a high target slump, another measure of concrete workability was required. The slump gives only an indication about the consistency of the mix, not about flow characteristics. Neither Australian Standards nor Queensland DMR Standards give any guidance on other measures of concrete workability of a self compacting concrete. However the Victorian Government VicRoads Manual of Testing RC 252.01 specifies a procedure for determining the “slump-flow” of super workable self-compacting concrete. The team therefore adopted the slump-flow test in order to measure the flowing capabilities of each of the proposed mixes, and this is considered to be an innovation in Queensland.

For the slump-flow test, a cone placed on a levelled graduated base plate (see Figure 14) is filled with concrete as per AS1012.1. This cone is then lifted vertically in one movement without interfering with the flow of concrete. The slump-flow is the average of the largest diameter and that at 90° to it, expressed to the nearest 10mm.

For the 65 MPA mix used in compression piles at Soul a slump-flow of 600mm had been established, and it was decided that this would be adopted as the target for the new 85MPa mix.

Each of the three trial mixes had excellent workability criteria up to two hours after mixing. The base mix **S851FLL** could maintain a slump-flow of 600mm for more than eight hours. Even after 12 hours the slump-flow was still 500mm. The initial set of this mix occurred at 28 hours after mixing.

Figure 14

Figure 15

The synthetic fibres in mix **SF851FLL Fib** reduced the flow criteria of the concrete. The mix appeared dryer than the original (see Figures 14 & 15) and the target slump-flow of 600mm could only be maintained for less than two hours. A spread of 500mm and reduced flow criteria were achieved for another 5 hours until the initial set was achieved after 25 hours. The **SF851FLL mod** mix had a measured slump-flow of 600mm for two hours before hydration occurred quickly with a decreasing workability. The initial set was achieved after only 12 hours. The workability of this mix was therefore considered to be insufficient and it was decided to focus further mix testing on the first two mixes. The workability results are summarized in Figure 16.

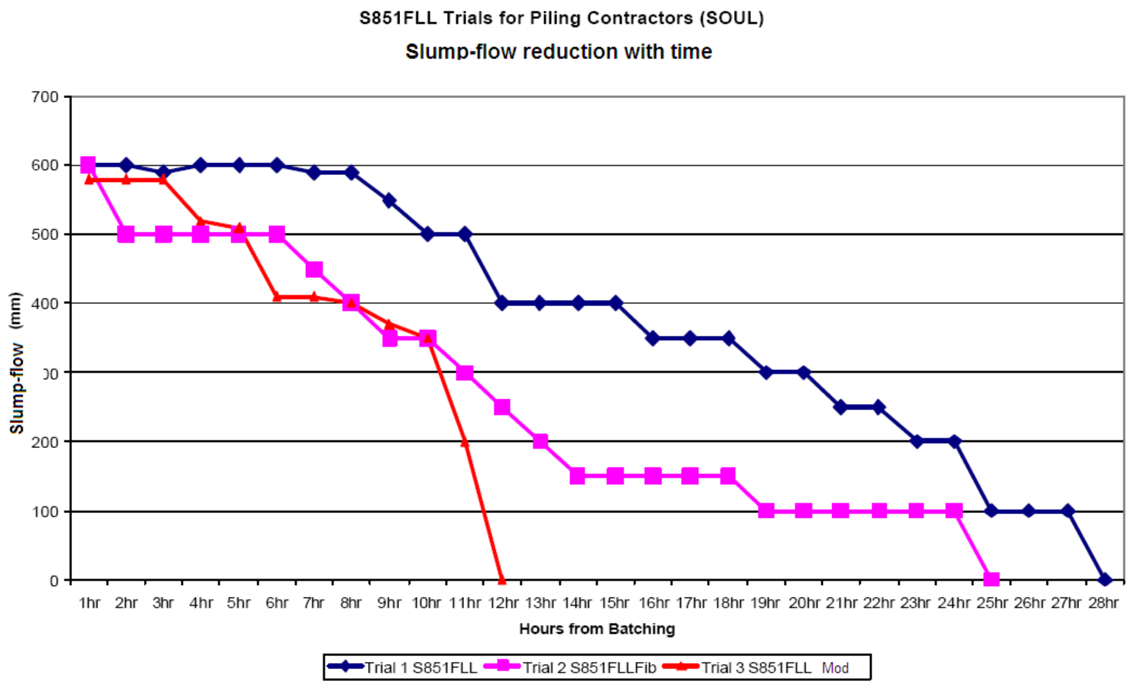

Figure 16

Workability and flow criteria for **SF851FLL** and **SF851FLL Fib** were satisfactory, with much better results for the first mix design. Tensile strength tests were then carried out on samples of both mixes in order to confirm which mix was the most suitable for the challenging tension pile construction. To determine the indirect tensile strength of a concrete sample, a Tensile Strength Test as per AS1012.10-2000 (Splitting Test) was carried out.

Figure 17

Figure 18

Concrete samples were taken in a standard test cylinder (see Figure 15). The samples were placed into a jig inside a hydraulic test frame (see Figures 17 & 18). A compressive load was applied to the samples perpendicular to the longitudinal sample axis. Inside the concrete sample tensile stresses are created (see Figure 19). Cracks will therefore occur in the upper and lower part of the sample (see Figure 20).

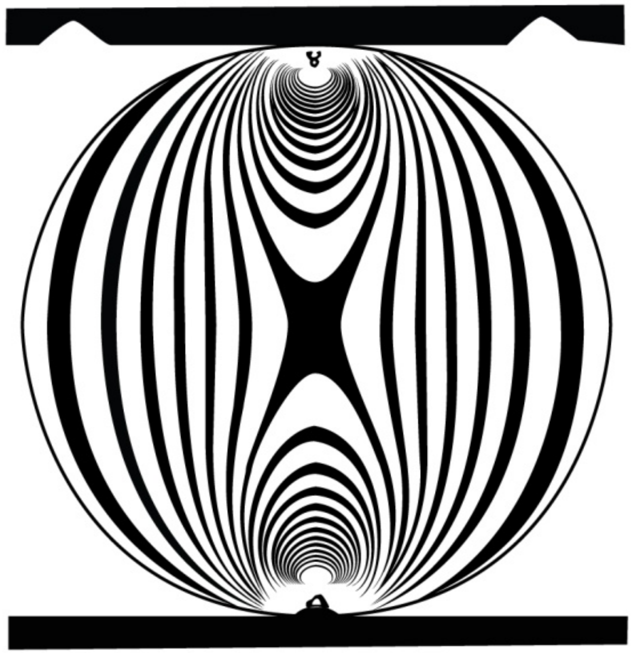

Figure 19

Figure 20

Two tests for each laboratory trial mix were carried after five days and seven days. In addition, the third mix **SF851FLL mod** was tested after seven days to demonstrate whether the reduced hydration admixture had an influence on the tensile strength development. All samples had already achieved the target tensile strength of 5MPa after seven days. Considering that the concrete developed only 70% of its final compressive strength after this period of time, all tensile test results were considered satisfactory. Final tensile strengths between 6-7MPa were expected.

It can be seen from Figure 21 that the fibres increased the tensile capacity by 12-28%. However the fibres also reduced the compressive strength of that mix by 10-11%. The final strength results of the early tests are shown in Figure 22.

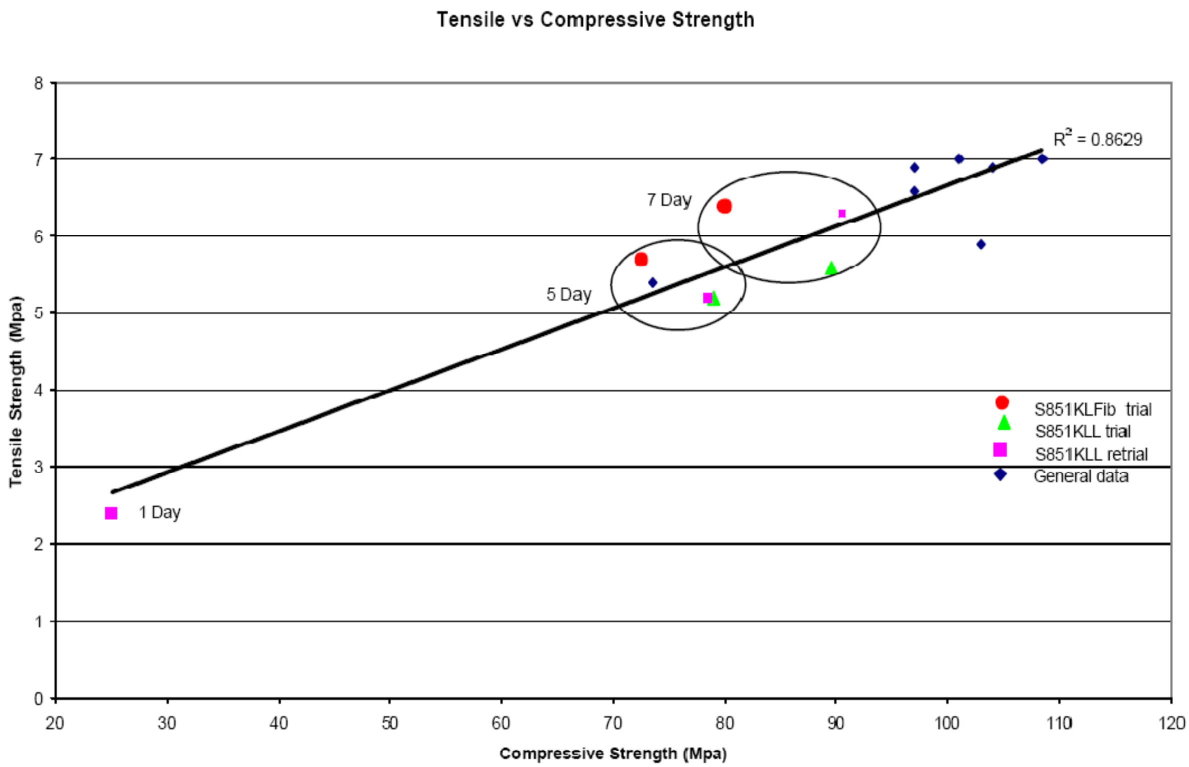

Figure 21

Trial	Age [days]	Compressive Strength fc` [MPa]	Tensile Strength f`ct [MPa]	Ratio [%] f`ct to fc`	Ratio Improvement with fibers
S851FLL	5	79.0	5.2	6.6%	
S851FLL	7	89.5	5.6	6.3%	
S851FLLFib	5	73.5	5.4	7.3%	12%
S851FLLFib	7	80.0	6.4	8.0%	11 to 28%
S851FLL mod	7	90.5	6.3	7.0%	

Figure 22

Site Implementation

Figure 23

After the successful laboratory trials, a field trial was arranged to verify the laboratory test results under site conditions. This was done by using the 85MPa mix in a pour for a compression pile. Knowing that the strength criteria could be achieved by both mixes, the field trial was intended to clarify the concrete workability. If the mix is too stiff the concrete at the pile centre rises faster than the concrete at the edge and the flow around reinforcement bars is reduced. As a result there might not be sufficient bond between steel and concrete and the risk of bentonite inclusions between concrete and reinforcement is increased.

Furthermore the concrete mix to be used needed the consistency to allow plunged steel columns (350WC) to penetrate about 8m into the fresh concrete six or seven hours after the concrete pour started on site. The influence of groundwater flow on the wet concrete also has to be considered. The mix should not absorb water from the environment, and neither should it release water to the environment.

Workability on site was found to be very good for the 85MPa basic mix (Figure 23) although there were some limitations after the synthetic fibres were added.

The team were concerned that the fibres in mix **SF85LL Fib** would get caught on the reinforcement cage (see Figures 24 & 25) and as a result the fibres would not be uniformly distributed throughout the concrete shaft of the pile. This could increase the risk of having bentonite inclusions between reinforcement cage and surrounding soil.

Figure 24

The possibility of having almost no fibres in the concrete cover between soil and reinforcement was also considered not to be acceptable. During the site trial of the fibre reinforced mix, the fibres caught up in the mesh used to simulate pile reinforcement as shown in Figure 25.

Figure 25

As the tensile and compressive test results for the 85MPa basic mix **SF851FLL** were above the required range, and the site confirmation tests of its workability were excellent, there was no benefit seen in using the fibres to further increase the tensile strength (which also decreased the concrete workability). It was therefore decided by the team to proceed to construct the seven critical piles with the basic concrete mix **SF851FLL** (without fibres).

A field trial was also carried out to verify that the steel columns could be plunged into the fresh concrete as it would be at the end of pouring. If the required workability of the concrete was not provided and the mix started to set too early, the installation into the stiff concrete would be difficult. Due to the high tension loads, the minimum embedment and sufficient bond between concrete and steel were absolutely crucial. The influence of the shear studs was also considered an unknown.

One option considered was to hang the columns into the excavation and pour the concrete later. This alternative carried the risk that concrete might push the column to one side and then the location of the column would be out of tolerance. A site trial confirmed that the steel columns could be plunged very comfortably into the fresh concrete.

All concrete was placed under water / drilling fluid using the tremie technique. For under water applications special concrete properties are required as described earlier. During a tremie pour the first batch of concrete placed must remain workable until the end of the pour, as it is the one that rises to the surface as the pile is filled. Maintenance of the workability is imperative as the tremie pipe has to be removed and plunged columns installed after concreting the pile.

For the 2200mm piles, up to 30 concrete trucks were required each carrying 5m^3 of concrete. If trucks arrive and discharge their loads at 10 minute intervals, the time to pour the pile is 5 hours. Another hour is then required to set up the plunged column frame. The remaining 2-4 hours were allowed for contingency considering breakdowns, traffic or technical problems.

The pile layout for the core is shown in Figure 26.

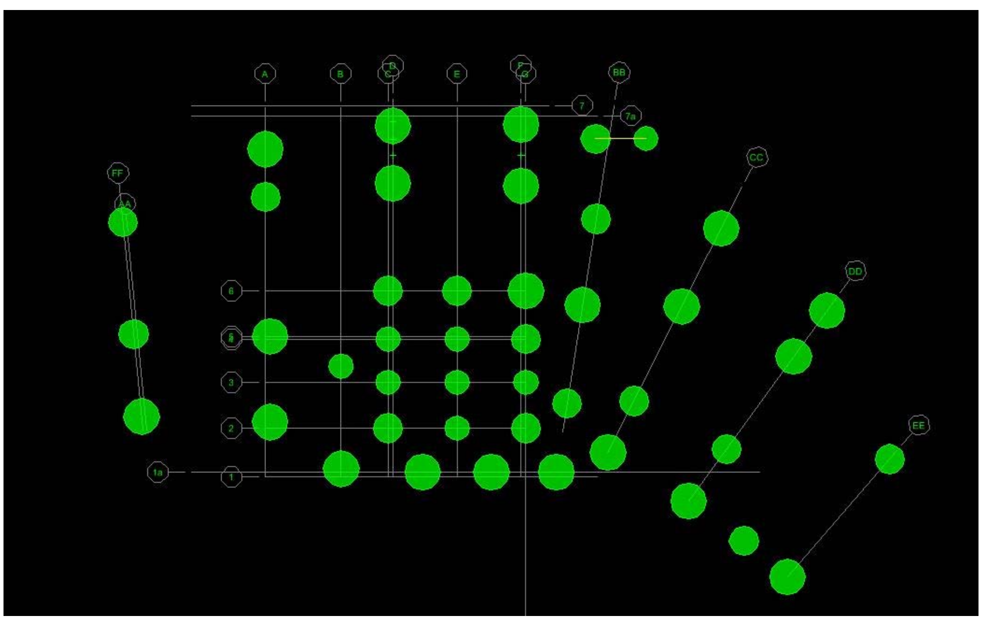

Figure 26

The site was located in the heart of Surfers Paradise yet the concrete supply provided was excellent, even during a Surfing Competition right opposite the Soul project site! The concrete setting contingency time allowed did not need to be used, as the selected mix design performed very well.

Concrete Test Results and Pile Verification

The results of indirect tensile concrete tests on all 74 samples taken from the concrete used for the seven critical piles were above the requirement for 5MPa after 28 days. The selected mix achieved about 120MPa compressive strength and 6.5-8.5MPa tensile strength. These results, shown in Figure 27, confirmed the assumption that the tensile strength of concrete is about 5-8% of the compressive strength.

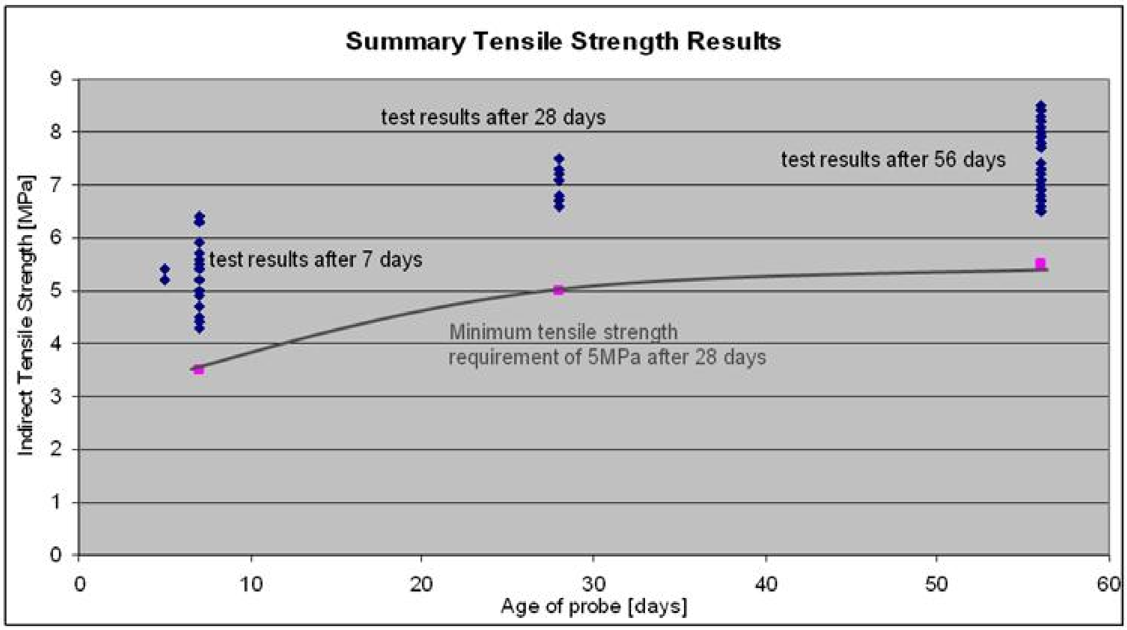

Figure 27

In order to verify the pile integrity, cross-hole sonic logging tests were carried out on five piles.

This is a non-destructive test method where a transmitter probe and a receiver probe are lowered down to the pile toe inside two steel tubes, attached to the reinforcement cage of the pile and installed prior to concreting. Both probes are raised from the base of the pile simultaneously. The arrival time of the wave through the concrete is measured. If there are changes in concrete density (inhomogeneous areas or bentonite / sand inclusions) there will be change in velocity and hence arrival time.

Constant arrival times indicate homogeneous pile shafts without failures or inclusions. Figure 28 shows the result of a cross-hole sonic logging test carried out on a pile for Soul. All piles tested showed good results.

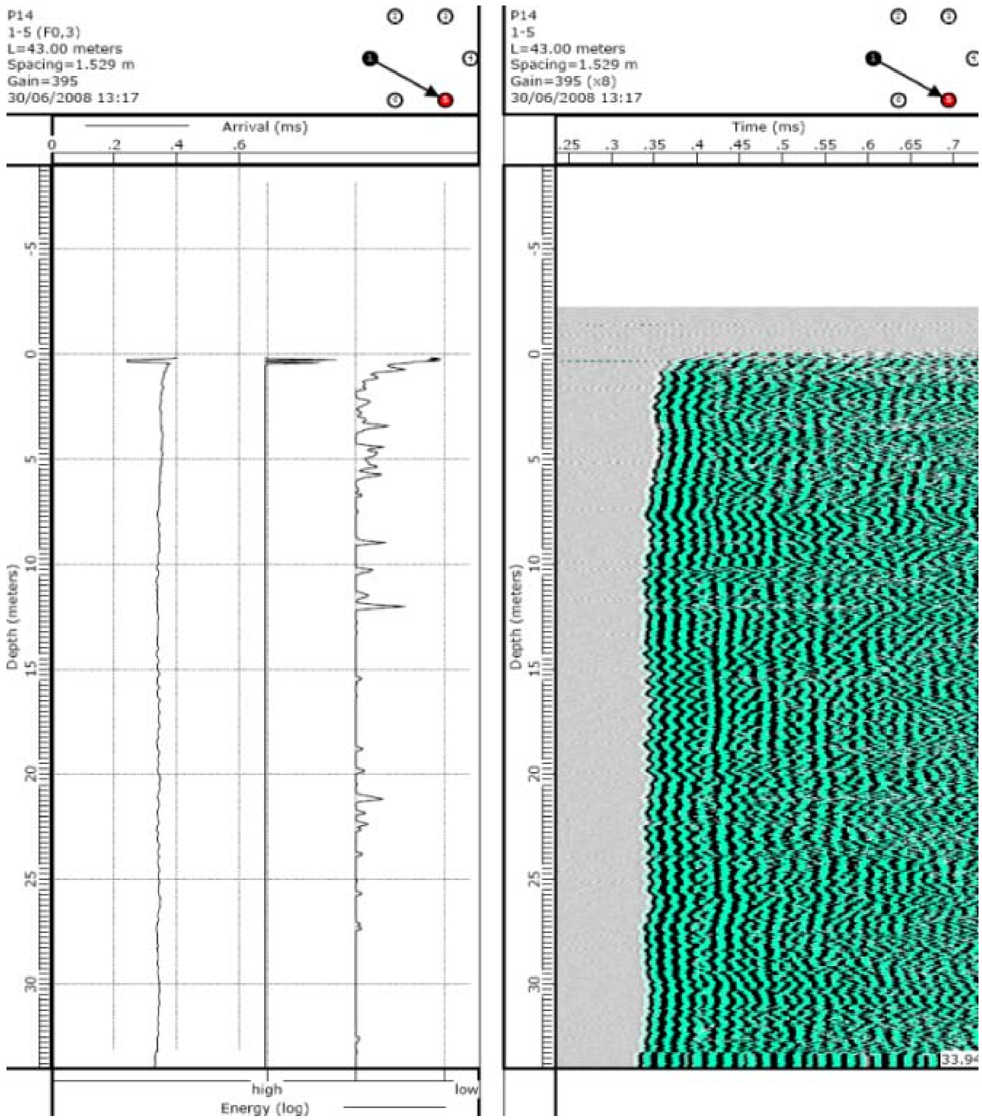

Figure 28

World's Best Practice

The use of high strength concrete for the tower piles of Soul has demonstrated world's best practice. Concrete strengths for piles for high rise buildings typically range up to 65MPa. The concrete used for the Soul piles is well beyond this range. For this particular project the tensile strength of the concrete was a very important criterion and maintenance of pile stiffness was a crucial element for the design of the slim Soul tower. A world class approach for the design and construction of the foundations of the landmark project was provided.

The engineering teams of Grocon and Piling Contractors chose to use concrete beyond the normally used criteria of Australian Standard AS3600.

In so doing, it was found that flow characteristics for super workable concrete are not specified in Australian Standards, and an approach reaching beyond AS3600 was required in order to provide for this very important, project specific, element. Test criteria from VicRoads were used for Soul.

Rigorous testing, both prior to and during construction, has been undertaken to select and then prove the very best mix for the seven critical piles. The execution of workability, flow and strengths tests in the laboratory, field and on site demonstrates the high quality approach of the engineering team to achieve world class standards for the project.

Safety, Program and Budget

Piling works for the tension piles were carried out from March to August 2008. During this six month period there was a piling crew of 15 workers full time on site. During the bored pile installation there were many other activities on site, e.g. earth works, deep soil mixing, installation of CFA piles, pile trimming, erecting of tower cranes, ground water monitoring, anchoring works, steel fixing, form work erection and concreting.

Figure 29 illustrates that the site was extremely busy and congested, and there was a lot of traffic and movement throughout the day. During a concrete pour there were up to 30 concrete trucks on site in a 4 to 5 hour period, yet the activities of the other trades were not adversely influenced by the pour.

Figure 29

In spite of this operational challenge there were no incidents and the target of zero Lost Time Injuries (LTI) was achieved during piling works. This was a credit to Grocon’s outstanding attention to safety management on site.

The reduction of the seven 3000mm diameter piles to 2200mm diameter piles had an important impact on the program and the budget. Drilling time was reduced significantly and a reduction in concrete volume by more than 40% per pile was beneficial for the overall construction time and the budget. In addition, the environmental impact of this part of the project construction, both in terms of materials used and vehicle movements generated to deliver concrete and remove spoil, was reduced. The tower piles were installed within the programme and to budget.

Lessons Learnt

The team did not unnecessarily reinvent the wheel (see Figure 30) to overcome the issues raised during these works. Instead they researched previous practice and combined elements of these practices to provide a comprehensive solution for this project.

Excellent communication between all parties, teamwork, a cooperative approach to R&D and innovation, as well as the determination to find the best solution for the project, not for the individual, were the key drivers for this project.

Only a team can achieve outstanding results and only cooperation between main contractor and the piling subcontractor will deliver outstanding piling solutions. Constant communication and free flowing exchange of ideas leads to innovation and world class results.

Figure 30

The team's research indicated that use of synthetic fibres for the piles was not beneficial for this project; however the engineering team obtained valuable insights into how fibres might be used in other piling applications. There will be applications in the future where fibres can be beneficial and Grocon as well as Piling Contractors have successfully demonstrated that they have in place strategies to develop outstanding results using research, development and innovation.

When members of the public stroll past the magnificent slender Soul tower in years to come, or when residents of the building admire the views from their balconies, they are unlikely to appreciate the innovation in foundation design and construction, hidden below ground, that was necessary to enable the building they so admire to be constructed.

INTENTIONALLY LEFT BLANK

soul™

PILING CONTRACTORS

Grocon