

PILING IN SYDNEY HARBOUR

Jim Millar

Waterway Constructions Pty Limited

1 INTRODUCTION

The City of Sydney surrounds Sydney Harbour and much of the focus of life in the city has always been around the harbour. Initially, the use of Sydney Harbour focused on commerce and transport. It also became the home base of the Australian Navy. In more recent times, the harbour has become more gentrified with increased housing around the shores and a greater emphasis on tourist activity. The wharves and other structures built around the shores of the harbour have reflected these uses and changes in use.

2 DEVELOPMENT OF SYDNEY HARBOUR

Prior to 1901, practically all the wharves in Sydney Harbour were in private hands and most were apparently in poor condition. A bubonic plague outbreak in 1900 caused the government to resume all of the wharves and adjacent lands. The Sydney Harbour Trust, which was formed to administer the port, spent more than 5 million pounds over the next 25 years rebuilding most of the wharves in Sydney. 200 new berths were built in port areas adjacent to Sydney City, approximately 50 additional berths were built for the defence forces. Ship building and ship repair facilities were built at Cockatoo Island, Balmain, Woolwich, Garden Island and Goat Island with smaller facilities at Ryde and other locations. There were also more than 100 other wharves constructed around the harbour for the ferry services, fishing fleet and other smaller vessels.

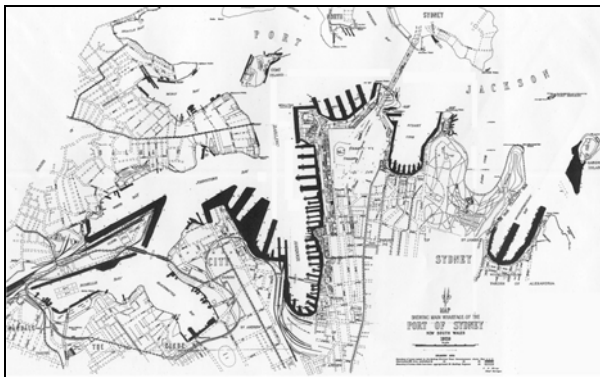


Figure 2.1 Wharves in Sydney Harbour in 1929

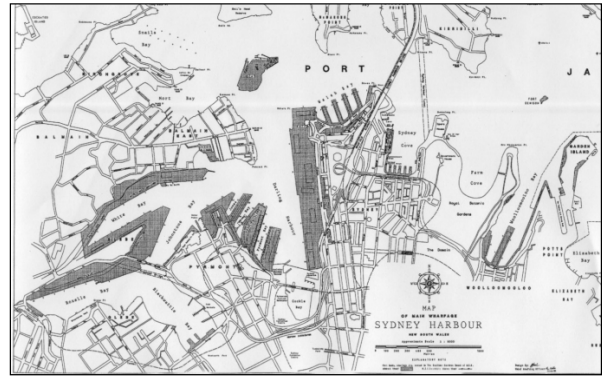


Figure 2.2 Wharves in Sydney Harbour in 1991

The Maritime Services Board replaced the Sydney Harbour Trust as the government administrator for the port in 1936. From 1910 to 1960 and beyond, between 120 and 200 vessels visited the port each week. The MSB continued to upgrade the ports spending more than 1.5 million pounds per year on wharf construction.

The engineers and artisans of the time became very skilled at constructing these wharves. Standard designs were developed by engineers such as Walsh using hardwood timber piles, headstocks, girders and decks. Many of the commercial wharves were constructed for storing wool with a design uniformly distributed load of 26 kPa (25 cwt/sq ft).

In no other port in the world was timber used more extensively for wharf building than in Sydney. Up until the 1950's, most of the wharf structures were built from timber. The wharf builders had abundant areas of forest for the supply of timber just to the north of Sydney. Only the royal species of hardwood Iron bark, Tallowwood, Grey Box, Grey Gum and White Mahogany were used. These are high-grade hardwoods with compressive and bending strengths exceeding 50MPa. We estimate that more than 100,000 of these trees were used for the construction of wharves in Sydney. A large grove of fully-grown trees had to be cut down for each wharf. However, demands for timber for wharf construction were minor compared with other kinds of construction such as telegraph poles, railway sleepers, bridges, fence posts, house construction and papermaking.

There was some construction in concrete and steel (for example Jones Bay Wharf at Pyrmont). Also, the timber decks on many of the earlier wharves were replaced by concrete in following decades.

The basic design of commercial wharf construction did not change until the late 1950's. At this time, many of the wharves were rebuilt using steel piles and concrete decks or with concrete caisson construction. However, in Sydney, the change away from timber construction was slower than elsewhere because the timber structures had been so successful. For example, the Finger Wharves at Walsh Bay had been expected to last for about 25 years when constructed. In fact, 80 years later, they are still in generally sound condition with little deterioration of the substructure timbers except in locations such as the aprons where fresh water could rot the timber and in the piles which are attacked by various marine organisms. The timber in these structures will last for hundreds of years more if they are protected from fresh water and termites.

3 HISTORY OF PILING IN SYDNEY HARBOUR

There has been 3 phases of piling techniques used in Sydney Harbour for wharf construction.

- a) Timber piles driven or socketed into rock generally installed for a working load of 300kN. Timber piles have been used from the earliest times up to the present day. Timber piles have long effective lives in Sydney Harbour and design loads can be safely carried even after significant deterioration of the pile shaft. All marine structures require regular maintenance. Timber piles in timber structures have the added advantage that they can easily be replaced during the life of the structure. Because of its strength and elastic properties, hardwood timber is particularly suitable for use as fender piles as well as for vertical load capacity. However, we anticipate that timber piles will become more difficult to obtain in the coming years because of government forestry policy. Consequently, we expect that their use will more and more be limited to the replacement of old timber piles, for fender piles and for architectural reasons.
- b) Steel tube piles and H piles driven or socketed into rock. These have been used since the 1960's and most of the early piles are still in excellent condition. The coal tar epoxies used up until the 1980's provided excellent corrosion protection. Where the coatings were damaged, steel corrosion rates in Sydney Harbour appear to be low. We have tested pile thickness on fender piles which have been left unpainted for 10 to 20 years and exhibit a corrosion loss of only approximately 1 mm.
- c) Steel tube piles installed using low noise installation techniques. Such methods have been used spasmodically since 1995.

Very few concrete piles have been used for fixed structures in Sydney Harbour, however they have been commonly used in floating marinas.

4 GEOTECHNICAL CONDITIONS

Sydney Harbour is a sunken river valley with steep sides. Water depths are up to 30m in some parts and often 10m to 12m near the shore. In many areas, rock is close to the surface. However, in bays especially on the south side there can be up to 40 metres of soil deposited on top of the rock. This silt varies from very weak marine deposits near the surface through to stiff clays and loose sands above the rock. The rock is generally sandstone ranging from extremely weathered to fresh.

Weathered zones of class 4 and 5 rock overlying stronger class 2 or 3 rock typically range in thickness from 0.5m up to 6m thickness. On some sites, this weathered rock is quite variable in thickness whereas on other sites, it is quite consistent. As a result, piles are founded in a range of materials from the stiff overburden to a number of metres into rock.

5 PILE INSTALLATION

5.1 Driven Piles

Pile installation by hammering has been used by harbour constructors for centuries. The method is simple and effective. It is a far more efficient installation system than any other invented to date, hence, its continued dominance as an installation method.

For wharf construction, one of the advantages of driving steel and concrete piles is the balance between geotechnical capacity and structural capacity. Driven piles can be installed in hard clays, sands, weak or strong rock to a geotechnical capacity that approaches the structural capacity of the shaft. Consequently, the minimum quantity of pile material can support the maximum load.

This is a little more complicated for timber piles. Because of likely deterioration with time, their structural capacity at the time of installation is generally far greater than the geotechnical capacity. Traditionally, for marine works, the

working load on timber piles has been limited to 300kN compared with in excess of 1000kN for land works where the pile is fully protected from deterioration by the soil.

Large steam and air piling hammers have been available for decades but were generally used for driving piles with modest applied loads. For large loads, excavated caissons with rock sockets were constructed.

Large hydraulic hammers were developed for offshore work in the oil industry driving massive piles for very high loads. The cost of purchase and more particularly handling large hammers for onshore works was prohibitive until the 1990's. John Holland purchased the first large hydraulic hammer in Australia from Finnish manufacturer Junttan for a wharf contract at Karratha in WA in 1996. This was a free fall hammer with a ram weight of 14 tonnes. Baulderstone Hornibrook purchased a similar hammer, this time with a 16 tonne accelerated ram for the Western Link Bridge across the Yarra River in Melbourne in 1996. This hammer was used to drive 45m long steel tube piles to ultimate capacities in excess of 21,000kN per pile. The same hammer is currently being used to drive piles of a similar capacity for the M5 motorway construction in Sydney.

Waterway Constructions are currently driving steel tube piles at the Walsh Bay Wharf 6/7 redevelopment to 13,000kN capacity per pile using a Junttan hammer with a 9 tonne accelerated ram.

Larger section steel piles can be driven significant distances into rock using these large hammers. The 800 mm and 1000 mm diameter piles at Walsh Bay Wharf 6/7 are driven more than 3 metres into rock having an unconfirmed compressive strength of 20MPa. As a result large amounts of shaft adhesion are available to provide reliable load capacity at low deflections. Driving piles to carry these high loads on a single unit is very economical but the large capacities can only be relied on if you have a good understanding of the mechanics of driving load transfer and the limitations of the founding material.

5.2 Noise and Vibration

In Cities where there has been a history of driven piles for founding buildings, there is a reasonable level of tolerance for the noise and vibration caused by pile driving. Cities where pile driving has been common including Melbourne, Brisbane, Adelaide and many European and Asian Cities generally have large areas of the City founded on soft often clayey deposits.

Sydney is generally founded on rock or sandy soils. There has been relatively little pile driving over the years. In many cases, the driven pile projects have been in areas of dense sand where transmission of vibrations can be a real problem. Perth and the Gold Coast have similar problems.

The human body is very sensitive to levels of vibration and is able to detect vibration particle velocities of less than 0.1 mm per second. It generally takes velocities of more than 50 mm per second to damage most buildings and more than 10 mm per second for very sensitive structures. Consequently, people think that vibration is more significant than it really is, and more importantly, there has been a tradition here of associating the noise from piling with vibration.

Vibration is not generally a problem with marine piling in Sydney because piles are driven through relatively soft and often clayey marine deposits and until recent years noise was not considered a significant problem.

Sensitivity to noise has risen dramatically to the point that significant restrictions are being place on major piling projects. These restrictions relate to both the level of noise permitted and the timing and duration of piling activity. Extensive community consultation has become a feature of major marine piling projects taking place in proximity to residences. It is of concern that increasing community intolerance is based on a lack of understanding or permissible noise dosage rates and the relative intrusiveness of pile driving compared to other construction activities and existing background noise levels.

Background noise levels in many parts of the city have been rising and it is appropriate that construction noise levels be addressed in an attempt to counteract this trend. However, the noise from driving piles should not be singled out when it does not contribute significantly to overall noise levels and when other much more noisy activities such as hydraulic rock breaking are accepted and allowed to continue.

Pile driving is an intermittent noise source and the actual time of impact is a very low proportion of the total time. At the Walsh Bay Redevelopment for example, actual driving time represents less than 1% of the total construction time. The cost of alternative pile installation procedures is very high. The cost per unit load is often double. As a result, the construction industry has an interest in keeping the noise levels as low as possible.

The Northside Storage Tunnel Project, a \$400 million tunnelling project in suburban Sydney, was a recent example where noise levels had to be minimised. For the marine construction components pile installation methods other than

driving were investigated but proved not to be technically viable. Consequently, the construction plant had to be made as quiet as possible. Pile hammers were noise insulated together with cranes and all other machinery. Also, piles were wrapped with noise insulating material.

As a result, noise levels were reduced by 20db. These measures were put in place for a single job however, more sophisticated arrangements would be needed to give the durability required for permanent attachments to the hammer. In the Netherlands where almost all structures over 1 storey are piled using mainly driven piles, there is a plan to reduce the noise output from pile hammers by 10db by the end of this decade.

5.3 Screwed In Steel Caisson Piles

The traditional alternative to driven piles was the installation of rock socketted caissons. Because the cost of these is so high, Waterway Constructions have been developing the use of an alternative process since 1994 using screwed in steel caisson piles (SIC).

Structurally, SIC piles use the same steel tubes as driven piles. Typically, they are steel tubes ranging in diameter from 300 mm to 800 mm with wall thickness from 9.5 mm to 25 mm. These piles have rock teeth fixed to the bottom and are drilled into the rock in a manner similar to a core barrel. They should not be confused with the screw piles which are now popular for land works and installed in soil for low loads using a flight on a smaller tube.

The installation of SIC piles is very quiet and they are well suited to applications such as fender piles which are subjected to predominantly lateral loads. However, for compression loads the performance of screwed piles is much more dependant on rock quality than for driven piles.

During the installation of a driven pile, the ground is compressed around the pile shaft and toe. As a result, when the pile is loaded, the ground resists the load at a relatively small deflection. Installation of each pile is monitored by recording the final “set” which gives a very good indication of the capacity of each driven pile.

On the other hand, when a drilled pile is installed, soil is flushed from the pile shaft and toe, so that the soil around the pile is decompressed. On loading, much more deflection is required to mobilise the capacity of the soil. The effect of this is that drilled piles have effectively only 50 to 60 percent of the compression capacity of a driven pile. The other problem with bored piles is proving the capacity of each pile. The capacity of traditional bored piles is gauged by an often subjective inspection of the excavated rock or the rock socket.

For screwed in caisson piles the resistance to penetration of the steel tube is a guide but the speed of installation is affected as much by the cohesion of the soil around the pile shaft as resistance at the toe. Weak weathered sandstones and shales act like cohesive soils so penetration through these weak rocks can be slower and more difficult than penetration through stronger rock. Because only a thin annulus of rock is removed, penetration through strong fresh sandstone is not generally a problem.

At present, where compression load capacity is required, piles have been driven after screwing to improve their load deflection performance. Only a modest number of blows is required to gauge the capacity and to effectively change the performance to act similarly to a displacement pile. Whilst the noise produced by this small amount of driving is low, it does tend to spoil the objective of a silent installation method and adds an expensive additional activity to the installation method.

The effect of driving after screwing can be seen in the following summary from a number of projects:

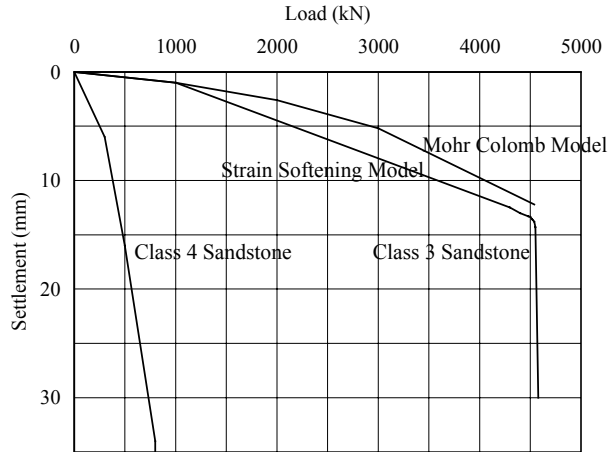
Project	Distance drilled	Mobilised Capacity after Drilling	Distance driven	Mobilised Capacity after Driving
Sydney Casino				
worst case	1.8 m	2300kN	23 mm	3000 kN
best case	1.0 m	3200kN	10 mm	3200 kN
Abbotsford Wharf (medium strength rock after 1.5m)				
worst case	4.0 m	700kN	31 mm	1300 kN
best case	2.7 m	1300kN	9 mm	1600 kN
Woolloomooloo Marina (very low to medium strong rock)				
general case	2.6 m	1200kN	47 mm	1500 kN
worst case (2 piles)	5.1 m	400kN	192 mm	2000 kN

Note: (i) Pile sizes vary from site to site.

(ii) The above are mobilised capacities only, not necessarily ultimate capacities.

Table 6.1 Effect of driving screwed in caisson piles

From Table 6.1, it can be concluded that the increase in capacity at serviceability loads due to driving is more pronounced for weak rock than for strong rock. Also, driving a short distance can counteract the variation in capacity from pile to pile due to variation in rock strengths. This observation was verified by a finite element analysis performed by Dr. Terry Wiesner of Douglas Partners for 600 mm diameter 16 mm wall SIC piles penetrating 320 mm



into rock of varying strengths for the Northside Tunnel Project.

Figure 6.1 Load Deflection Curves from Numerical Analysis

We are continuing research into methods of installing screwed in caissons in certain conditions without driving. Current investigations include the use of instrumented drilling to gauge the strength of the rock at the toe of the pile. This would work well in consistently strong rocks. However, on sites with variable rock strengths where high compression loads are required, there is little prospect at present of eliminating the driving activity.

6 MONITORING AND TESTING

Reliably achieving the required pile capacity is inherently one of the most risky construction activities.

- Piles are installed into soil whose properties are much more viable than other construction materials
- Much of the work associated with piling cannot be seen and therefore can only be checked indirectly
- Many design methods lack reliability
- Piles directly carry the loads from the structure and the consequences of pile failure can often be catastrophic.

As a consequence, monitoring and testing of pile installation is very important. Current construction practices have made pile testing even more important than in the past. In traditional marine structures, conservative design and structural redundancy has been of great assistance in ensuring that structures remain stable.

Take for example, the redevelopment of the historic wharves at Woolloomooloo and Walsh Bay in Sydney Harbour. These wharves were typically designed for the dead load plus 27kPa live load. Timber piles were installed on a 3 metre pile grid with multiple piles at load points. Even though up to one third of the piles have deteriorated over the years, the decks can still support significant loads. We have recently tested extensive areas of one of these so called “deteriorated” wharf decks with a superimposed load of 50kPa without any sign of distress. If there was no redundancy in the deck and pile structure, this would not be possible. In the redevelopment process, there are far fewer piles with much higher loads per pile (see Table 7.1).

Location	Original Arrangement		New Arrangement		New / Old Numbers
	Number of Piles	Working Load per Pile	Number of Piles	Working Load per Pile	
Woolloomooloo Wharf	3,900	300kN	430	1500kN	23%
			460	270kN	
Walsh Bay Pier 8/9	1,100	300kN	100	1400kN	24%
			170	270kN	

Walsh Bay Pier 6/7	1,400	300kN	174 80	6000kN 100kN	18%
--------------------	-------	-------	-----------	-----------------	-----

Table 7.1 Comparison of pile numbers before and after redevelopment

In traditionally constructed wharf structures, if some piles performed better than others, it was not noticeable. Now, with a small number of structural piles, each pile must be installed to reliably carry its design load. The level of proving and testing of piles therefore must be more rigorous.

Although we understand more about pile performance than in the past, we also have pushed pile working loads to their limits. Pile loads in Australia are currently higher than in general international practice.

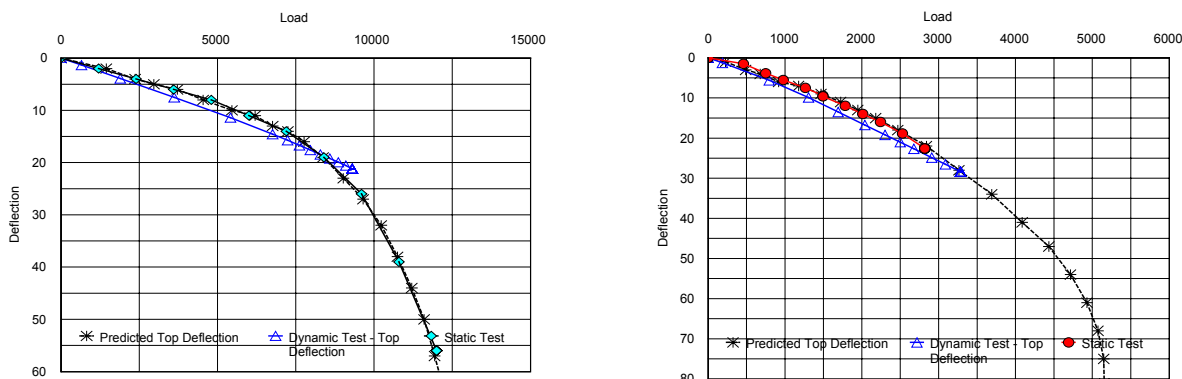
To date this has been more of a problem in land based piling than in marine works but it is now becoming an issue for marine works. Some of the members of the Standards Australia Piling Code Committee are concerned about these trends and are currently trying to improve the requirements for strength reduction factors in the Australian Piling Code.

When the current code was introduced in 1995, getting acceptance for the concept of limit state design and specifying strength reduction factors in pile design was a significant hurdle. It might be noted that the previous code only gave guidelines for factors of safety and did not mandate them at all. Now that the concepts of specifying factors have been accepted, more sophisticated consideration can be given to issues such as varying the strength reduction factors applicable to pile testing according to the percentage of piles tested and other factors.

6.1 Analysis of Tests

Because of limitations of testing equipment and often specifications, most static and dynamic load testing of piles is to proof loads only, often far below ultimate capacities. The results of such proof load capacities give only a limited understanding of the mode of operation of piles.

Further analysis of the performance of load tests can increase our understanding of the performance of piles considerably. I have written a program based on load transfer functions to predict the load deflection performance of piles and to back analyse test piles. I have been using and refining this program for the past 9 years. As a result, most load tests results can be closely matched to give ultimate shaft adhesion and end bearing capacities.



Figures 7.1 and 7.2 Comparisons of static test results, dynamic test results and predicted load deflection curves.

Figures 7.1 and 7.2 give two examples of comparisons between static test results, dynamic test results and predicted load deflection curves for steel tube piles driven at two Walsh Bay Wharves. Note that the dynamic and static test results agree very well. We find there is generally good agreement between these two types of tests for steel tube piles driven onto rock. This is because the modulus of steel is accurately known. This compares with highly variable module values for concrete or timber piles which result in less accurate results for the dynamic tests.

The predictions of the load deflection performance using our computer program also generally agree well. For the test pile in Figure 7.1, we predicted the load deflection curve prior to testing. Predicted deflections up to 9000kN load were within 1mm of the actual static test results. Between 9000kN and 12000kN there was some deviation because of unexpected relaxation of the end bearing. However, results were still reasonably accurate. When the reduced end bearing was taken into account, the curves virtually coincided as shown above.

These predictions also calculate the shaft adhesion, end bearing capacity and load distribution down the pile shaft. Also, the load deflection performance of the pile toe can be calculated as shown in figure 7.3. For the Walsh Bay tests tension and lateral load tests on the piles confirmed the calculated values.

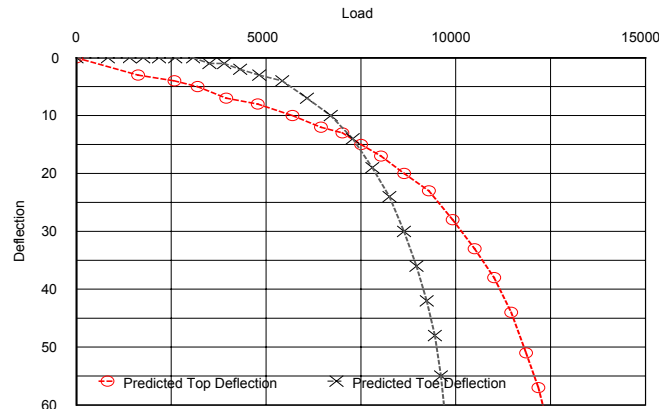


Figure 7.3 Load test Walsh Bay Wharf 6/7 showing head and toe load deflection curves.

Whilst the sandstone underlying Sydney Harbour is of relatively consistent strength at some locations, it is more commonly quite variable in strength. This variability is often only detected where high pile capacities are required. For example, at Walsh Bay Wharf 6/7, the penetration required into rock to achieve the design capacity varies in the most extreme cases from 600 mm to 6 metres over a distance of 8m. This is because in some cases there is strong class 2 rock at the top of the rock layer, whereas in adjacent areas there may be many metres of highly weathered class 4 or class 5 rock. In contrast, at the adjacent Wharf 8/9 site only 100m away, this variability was much less pronounced.

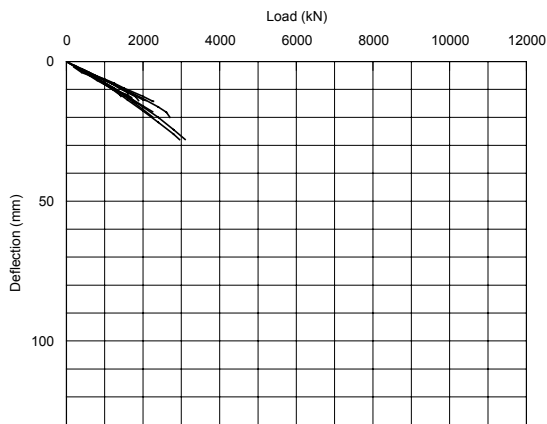


Figure 7.4 Load deflection curves from Dynamic tests at Rozelle Bay.

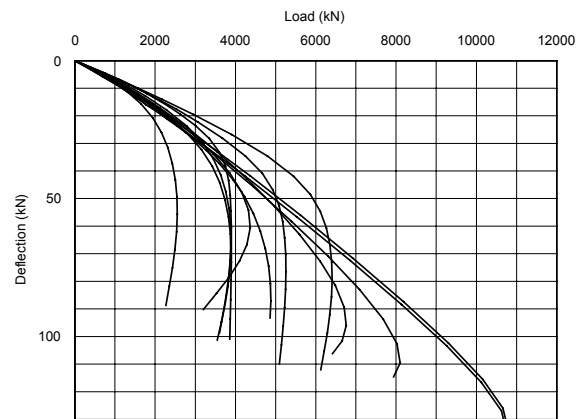


Figure 7.5 Load deflection results at Rozelle Bay after further analysis.

Proof testing often does not clearly detect the rock strength variations and the resulting scatter in ultimate capacities. Figure 7.4 shows the results of 11 dynamic tests taken on steel tube piles at Rozelle Bay Wharves 5 to 10. These tests to approximately 3000kN were sufficient to confirm that the piles are satisfactory for the design working loads of 700kN to 900kN. Figure 7.5 shows these results after further analysis. This further analysis showed that the ultimate end bearing stresses on the rock varied from 9MPa to 60MPa with a resulting wide scatter in ultimate pile capacities.

Additional information can similarly be obtained from static test results. Figures 7.5 and 7.6 show the results of nine static pile tests on 80 year old timber piles at Woolloomooloo Finger Wharves before and after additional analysis.

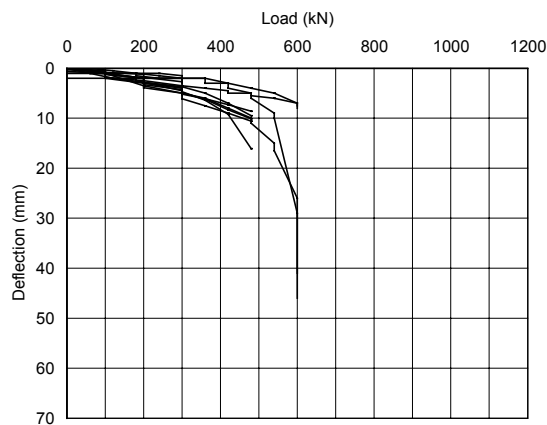


Figure 7.6 Load deflection curves from static tests on timber piles at Woolloomooloo.

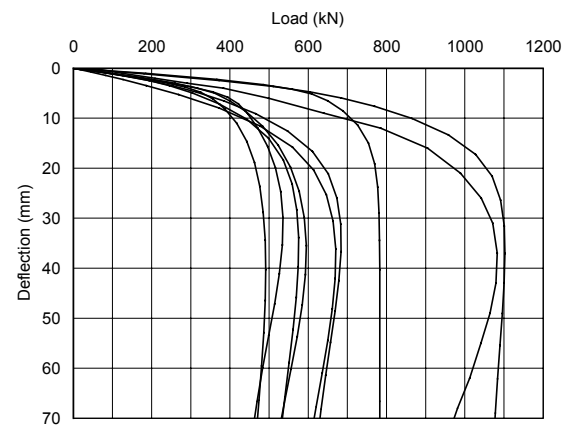


Figure 7.7 Load deflection curves from further analysis on timber piles at Woolloomooloo.

Once again, the proof test results are sufficient to prove that all the piles are satisfactory for a working load. With additional analysis, we can predict the failure load end bearing and shaft adhesion at various depths. In this case, piles were extracted and sonic tests were used to confirm the predicted pile lengths and adhesion values. This analysis gave average adhesion values between 40kPa and 72kPa with ultimate end bearing stresses ranging from 800kPa to 4000kPa. In this case, the additional analysis was used to establish the maximum design load on the piles. A working load of 270kN was selected.

These results indicate that these old timber wharf piles were generally driven with low energies and, in most cases, the pile toes do not reach rock. A number of tests at Circular Quay Jetties and Walsh Bay Wharves similarly indicate that most of the old timber piles do not penetrate into rock.

6.2 Lateral Load Capacity

Many marine structural and fender piles are subjected to lateral loads so their capacity to carry these loads at acceptable deflections is important. Where there is a significant depth of weak soil, laterally loaded piles act as “long” piles. That is, there is a point of effective fixity of the pile at which rotations and bending moments become negligible. The depth of fixity is known as the “critical” depth. Tests on piles in this category at various locations around the harbour indicate that soils in the upper layers are generally very soft. These soft silts can be modified for lateral load analysis using a lateral modulus of zero at the surface increase at the rate of 0.5MPa per metre with increased depth. For “long” piles in soft marine soils, the critical depth to fixity ranges from about 4m for a typical timber pile to between 6m and 10m for steel tube piles of varying diameters.

Where piles are socketed into rock or driven into hard material, they act as a “short” pile. That is, the toe rotates at failure with no point of fixity. In this case, a different type of analysis is required and penetration depths can be considerably reduced.

7 TRENDS

In summary, the trends in marine piling in Sydney Harbour are:

- A transition in pile types used from predominantly timber piles to predominantly steel tube piles.
- An increase in the specified design life for piles up to 100 years for major projects.
- An increase in the design load of piles with resulting increases in the size of installation equipment required.
- A reduction in structural redundancy resulting from finer designs. This, combined with higher pile loads increases the importance of each pile so that increased testing and analysis is required.
- Increased attention to noise containment during piling operations including the noise insulation of hammers and piles and alternative installation techniques such as screwed in caissons.