ENGINEERING GEOLOGY OF FREMANTLE HARBOUR

(AN HISTORICAL PERSPECTIVE)

Matthew Tutton
Golder Associates, Perth

ABSTRACT

Prior to the construction of the Inner Harbour in Fremantle in the closing years of the nineteenth century, the body of water that is now the Inner Harbour comprised a broad estuary, and the Swan River flowed in to the sea across a shallow rock bar between two rocky headlands.

The history of construction of the Inner Harbour is described to illustrate the complexity of the geology in this part of Fremantle. The geology includes a deep sediment filled palaeochannel associated with a former course of the Swan River during the Quaternary when the sea level was considerably lower than its current level. The construction of the harbour involved blasting of the rock bar, major dredging and land reclamation and extensive piling. The distribution and impact of the various geological units on the harbour and a number of the geotechnical issues that have lead to construction difficulties in the past are detailed.

1 INTRODUCTION

The Port of Fremantle comprises two harbours; the Outer Harbour which includes the approaches to the Port and anchorages and jetties in Cockburn Sound, and the Inner Harbour (Fremantle Harbour). The Inner Harbour (Figure 1) and the immediate surroundings are the subject of this paper.

Fremantle Harbour is a particularly interesting part of the Perth area. A number of interesting features can be seen either as outcrop or in the records of the very large number of boreholes and Electric Friction-Cone Penetrometer probe holes associated with over one hundred years of Port development. In addition, this part of Fremantle is an historical centre and the engineering of the Port is well documented and can be directly related to the geology. This paper presents the geology and engineering issues in an historical context in order to illustrate how geological conditions have both assisted and hindered the construction and development of the Port.

2 GEOTECHNICAL INFORMATION

Given the history and the past construction and development at Fremantle Harbour a very large number of geotechnical studies have been carried out, dating back to the mid-19th century. Geotechnical studies have been performed for various developments with the Port, including, but not limited to, capital dredging, berth construction, breakwater construction and general port developments. Records are available in Fremantle Port's archives and have been summarised in a desk study undertaken as part of a study associated with the Deepening of the Inner Harbour (Golder Associates, 1999).

3 HISTORY OF THE INNER HARBOUR

Although many designs were considered for shipping in Fremantle from 1830 onwards, it was not until the1890's that construction of any harbour structures were undertaken. Up until this time the hub of Port activities was on a short peninsula known as Anglesea Point (refer Figure 1) from which two ocean jetties were built.

The early harbour engineers assumed that the vast sand banks in Cockburn Sound (refer Locality Map, Key Figure 1, at beginning of this volume) were the result of a significant north to south movement of sand, so that removal of the rock bar would be quickly followed by the formation of a sand bar across the harbour mouth (Le Page, 1986). However the arrival in 1891 of C.Y.O'Connor as Engineer-in-Chief to the colony resulted in further studies. O'Connor was of the opinion that the drift of sand across the harbour mouth was minimal (Evans, 2001). He decided a harbour in the river mouth was the most feasible scheme for creating a port. In 1892 construction of the north and south moles began in order to provide protection against the sea at the mouth of the river (Le Page, 1986). Tamala Limestone, predominantly a calcarentite, was won from the outcrop at Arthur Head (refer Figure 1) to form the South Mole. Similar material was quarried from Rocky Bay a few kilometres upstream on the north side of the river to win rocks for the North Mole (Le Page, 1986). This was the start of major works to develop ship berthing and loading facilities in the mouth of the Swan

River. These facilities were to form the Inner Harbour, and the present day configuration is very similar to that created at the turn of the century by C. Y. O'Connor.

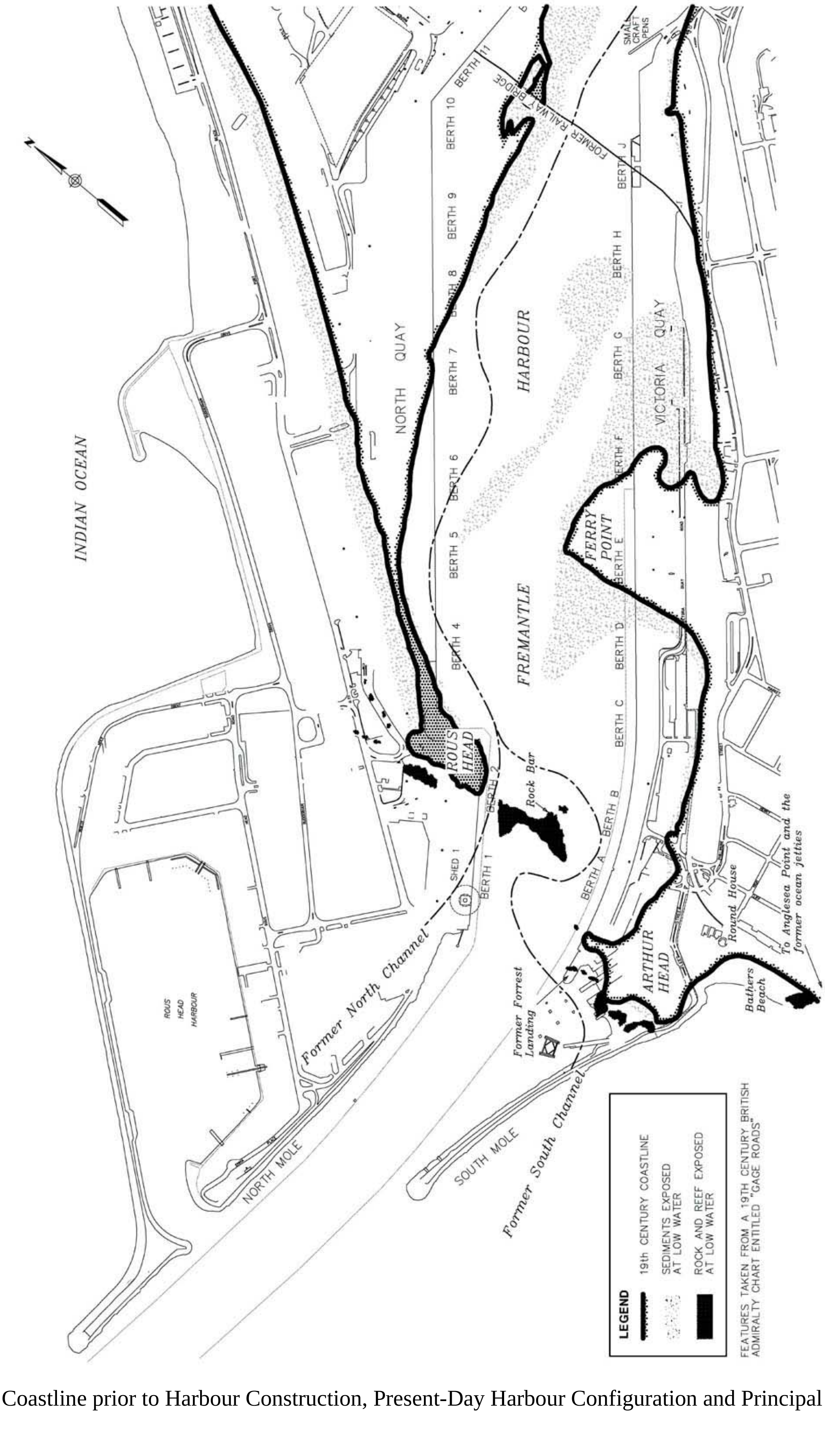

Figure 1: The Coastline prior to Harbour Construction, Present-Day Harbour Configuration and Principal Features.

One of the major obstacles in developing and constructing an Inner Harbour port in Fremantle was the presence of a limestone rock bar across the mouth of the Swan River between Rous and Arthur Heads, low rocky outcrops of Tamala Limestone. The location of this rock bar relative to the present development is shown on Figure 1. Today Rous Head has been either removed or buried beneath the Port structures. Part of the original Rous Head was exposed and removed by blasting as recently as 1996 when Berth 3 was removed and Berth 4 extended westward (refer Figure 1). Arthur Head (refer Figure 1) has been much reduced by quarrying, in part for the South Mole and development activities. The large outcrop that the Roundhouse (Figure 1) stands upon is part of the original Arthur Head and outcrops of limestone can still be seen beneath the suspended decking of Berth A, close to the new maritime museum.

In 1894 a blast and dredge operation was undertaken to remove the bar and allow the dredging of a channel in the Swan River to take place to a final depth of 30 feet (9.14 m) below Fremantle Low Water Mark (LWM). Material dredged from the channel was used to reclaim land on the southern shore (Le Page, 1986). The former shoreline is shown on Figure 1.

A summarised history of construction within the Inner Harbour is given below (Golder, 1999):

1892
Construction of North and South moles begins.

1895
Blasting of rock bar, dredging and reclamation of Inner Harbour begins. Blasted rock was removed by bucket dredger. Bucket and Suction dredgers were used to dredge harbour. New railway bridge constructed over river.

1897
Wharf construction on south side of harbour (Victoria Quay) began using a jarrah pile foundation system. Projecting jetty (finger pier) constructed on the northern side of the harbour. Wharves also constructed along the north and south moles. The jarrah piles were driven through the limestone rip-rap and core materials forming the moles.

1902
Major construction works completed. Depth of harbour 30 feet below LWM. Victoria Quay 5,000 feet long, North Quay 2,000 feet long. A 650 tonne slipping capacity temporary slipway was also constructed at Rous Head.

1908
Construction began for dry dock on North Quay near Rous Head.

1912
Construction of Dry Dock abandoned due to unsuitable subsurface conditions and the presence of sulphuretted hydrogen gas.

1911 - 1913
Extensions and strengthening work on North and Victoria quays were undertaken. All piles driven were encased for their underwater length in concrete to protect against the *teredo* borer. Victoria Quay extended 200 feet in east direction; North Quay extended 1000 feet east and 137 feet west.

1913 – 1921
Dredging to 36 feet completed. Finger pier removed, North Quay extended, Inner Harbour extended up river as far as possible (limited by railway bridge).

1923
Reconstruction of Victoria Quay began using reinforced concrete piles for the first time in a marine environment in Western Australia. Owing to very soft ground (palaeochannel deposits) at Berths C to E, two additional piles were added to each bay at 8-9 feet and 23 feet from wharf face.

1929
Dredging to 36 feet finally completed. Reconstruction of wharves switches from Victoria Quay to North Quay due to increased deterioration at North Quay.

1937
Reconstruction works at Victoria Quay completed.

1940 – 1942
Construction of new slipway (2000 tonne capacity). Associated with World War 2 a boom defence system was installed at the entrance to the harbour.

1946
Extension in east and west directions along North Quay completed.

1951
Reconstruction of Berths 1, 2 and 3 completed.

1952
Construction of No. 10 Berth commenced. This berth was designed differently to the other wharves, consisting of reinforced flat concrete slab supported by tapered pileheads. Problem with sand escaping through sheet piles at the rear of the berth. A second row of sheet piles (steel) was later installed behind concrete sheet piles as a form of remediation.

1957
Berth 10 construction completed.

1958
Berths F and G on Victoria Quay reconstructed.

1959
Slipway improved to increase maximum slipping capacity to 2,750 tonnes. A second slipway, at Arthur Head also constructed.

1966
Berth H constructed.

1968
Berth 12 on North Quay constructed comprising reinforced concrete decking supported by driven reinforced piles.

4 GEOLOGY

4.1 STRATIGRAPHY

4.1.1 Summary

The following units are present in and around the harbour or encountered beneath engineering structures:

Geological Unit	Principal Materials	Geological Age
Reclaimed materials	sands, silts, dredged materials	Recent (<200 years)
Alluvial Sediments	sands, silts	Holocene
Tamala Limestone	calcarenite, calcirudite, beachrocks	Pleistocene
Osborne Formation	glauconitic sandstone, shale	Cretaceous

4.1.2 Osborne Formation

The Osborne Formation is the oldest unit in contact with engineering structures in Fremantle Harbour. It does not outcrop and is generally present at depths of between 20 m and 45 m. The Osborne Formation is of Cretaceous age and typically is a Glauconitic Sandstone (Playford et al., 1976)). Borehole records for Berth E held by Fremantle Ports record the Osborne Formation as sandy clay (CH), hard, grey/green, high plasticity, moist, fine-grained sand fraction. The only place where this material is encountered in the harbour is as a founding material for some of the piles in the Inner Harbour supporting quays and other structures and only in areas where Tamala Limestone is not present as a founding material for piles (Golder, 1999).

4.1.3 Tamala Limestone

Although not entirely obvious from a walk around the harbour today, Tamala Limestone and its uncemented sand derivatives and associations are the principal surficial lithologies in the area. The Arthur Head outcrop is a good example of the Tamala Limestone that dominates the Swan Coastal Plain and is present for about 5 kilometres inland from the coast.

The Tamala Limestone consists of aeolianites, beachrocks, fossil soils (palaeosols) and shallow marine beds. The aeolianites, principally calcarenites, dominate the Arthur Head outcrop. Calcisiltite and calcirudites containing a shell fraction and clay palaeosols have been recorded from core recovered from boreholes drilled into the harbour floor (Golder Associates, 1999).

The Tamala Limestone is of late Pleistocene age in Perth (Playford et al., 1976) and has a maximum thickness in the Perth area of about 110 m (Davidson, 1995). The Tamala Limestone extends to a depth of about 30 m below sea level in Fremantle (Golder Associates, 1999). The actual thickness of limestone present beneath Fremantle is in many cases only about 20 m, due to erosion by the Swan River. Indeed, there is a buried channel beneath Fremantle where the river has in the past completely eroded through the entire limestone sequence cutting into the underlying glauconitic sandstone of the Osborne Formation (Golder Associates, 1999; Gordon, 1999).

4.1.4 Alluvial Sediments

A variety of marine and alluvial sediments are present near the Inner Harbour.

Within the Inner Harbour, the impact of dredging, to first construct, subsequently deepen and maintain the Inner Harbour, has resulted in removal of much alluvial material. Both silts and sands however continue to enter the Inner Harbour from upstream and are deposited in a large shallow bank just downstream of the railway bridge.

At the outer end of the Inner Harbour, there is little introduction of marine material into the Inner Harbour or Bellmouth (the area between the moles).

The greatest concentration of alluvial material is found in a sediment-filled trough, infilled after the Swan River abandoned a former channel. The palaeochannel is described later in this paper. The infill sediments are Holocene in age and are indicated by probe holes and boreholes to be typically loose and very loose sands and soft silts.

4.1.5 Reclaimed Materials

The construction of Fremantle Harbour has involved the reclamation of several hectares of land. Initially the land was reclaimed on the southern side to form Victoria Quay, later on the northern side to form the North Quay, later still to form Berths 10, 11 and 12 and followed more recently with the construction of the Rous Head Small Boat Harbour (Golder, 1999). An impression of the extent of land reclamation can be gained by comparing the pre-construction coastline with the present day harbour layout shown on Figure 1.

Much of the materials used for reclamation were derived from dredging and as such are highly variable in nature, comprising predominantly sands, both siliceous and calcareous, but also silty material and Tamala Limestone dredged freely as a gravely detritus or removed as coarser fragmented material following the use of cutter-suction dredgers. Much of the backfill encountered behind the sheet piles forming the Berths is a fine to medium-grained sand. The relative density of reclaimed materials is highly variable depending on the age and nature of the backfill, whether the backfill material was hydraulically placed or placed using conventional earthmoving machinery above water level, the degree of compaction and, in some instances, the nature of the Port operation at individual berths.

4.2 ARTHUR HEAD OUTCROP

Different depositional environments contribute to the variation in the Tamala Limestone that is seen around Perth. The aeolianite seen at Arthur Head (refer Figure 1) however is one of the major units and it is the processes of weathering, leaching (solution) and re-precipitation of calcium carbonate that is principally responsible for the significant variations that are to be seen. The Round House, the first public building in Western Australia surmounts the Arthur Head outcrop.

The aeolianite that makes up the visible part of Arthur Head is calcium carbonate cemented lime sand with about a 15% siliceous fraction (Gordon, 1999). Cross-bedding is a feature, reflecting the dune bedding, sometimes modified by water with the presence or absence of calcite cementation depicting the bedding planes. Sometimes the bedding is depicted by slight variations in grain size, e.g. laminae of fine-grained weakly cemented sand interbedded with slightly coarser grained cemented sand.

Within the aeolianites of the Tamala Limestone, a top downward lithification process may be observed. This is particularly apparent in the Arthur Head outcrop. Rainfall or sea spray containing CO_2 forms carbonic acid that percolates into the upper surface of the dunes, calcium carbonate is dissolved from the dune sands and is drawn to the surface by the heat of the sun where it is deposited as a strong fine grained caprock (Gordon, 1999). Typically, the caprock is about 1.5 m thick. The upper surface of the caprock can be seen exposed as a pavement immediately in front of the Round House and indeed forms the foundations of the building itself.

This process is effective in depleting the aeolianite below the caprock of its cementation agent, calcium carbonate. Depending on how much depletion takes place not only is the sand left in an uncemented or weakly cemented state but also some of the sand grains themselves can be lost in solution and the sand can be left in a very loose, even vuggy, condition.

Tamala Limestone is often observed to contain structure, usually associated with either former vegetation or cross-bedding. In former times, plants (particularly eucalyptus trees) were present and have had a significant contribution towards the structures seen within, and geotechnical behaviour of, the aeolianite. At Arthur Head a zone can be seen, characterised by ‘Rhizocretions’ or deposits resulting from roots. Rhizocretions can be in the form of significant tubes often some 0.5 m wide and up to six metres deep. The tubes represent the line of the taproot, which has since rotted away and often becomes lined with layers of calcrete, the centre remaining as a void or becoming infilled with sand or *terra rossa* soil washed down from above. Some of the smaller tubes become completely infilled with concentric calcrete bands and calcified finer roots. (Gordon, 1999).

4.3 GEOLOGY OF THE SEAFLOOR - BELLMOUTH THROUGH TO BERTH 2

A number of boreholes have been drilled in the past in the vicinity of Arthur Head, in the South Mole area, and in the vicinity of Forrest landing and in the rock bar between the Berths 1 and A, i.e. the general Bellmouth area (Golder, 1999). A number of these boreholes are dated pre-1892 and present only very basic information, e.g. rock, sand, mud etc. It is apparent however that the pre-dredging depth to rock-head (presumed limestone) varied from ground level (surface rock) to about 6 metres below LWM (beneath parts of the former Forrest Landing) and about 11.5 m below LWM (beneath the end of the South Mole). Figure 1 shows those areas where rock was exposed above the LWM. Boreholes drilled for the construction and re-construction of Victoria Quay indicate rock was present at a depth of between 10 m and 12 m below LWM for Berths A and B. A very simplified stratigraphy for the Tamala limestone Formation in the Bellmouth area is given below (Golder, 1999):

Approx. level	Lithological unit
Above AHD	Calcareous caprock (medium to high strength calcrete), and aeolianite (weakly cemented sands)
0 to 10 m below AHD	Coral reef (medium to high strength)
10 to 30 m below AHD	Calcirudite, calcarenite and calcsiltites (calcareous cemented gravel, sand and silts) interbedded with uncemented clays and sand horizons
> 30 m below AHD	Glauconitic sandstone (Osborne Formation)

With successive deepening of the harbour much of the harder coral reef units have been removed from dredged areas of the harbour.

4.4 PALAEOCHANNEL

During the last glaciations the sea level was lowered by over 150 m giving rise to the potential for the Swan River to cut down to greater depths than the present day. 120,000 years ago the coastline was also several kilometres west of Rottnest Island. As a result the Swan River cut an incised channel into the coastal sediments from where it left the Darling Range to where it entered the sea. This channel cut down through the Tamala Limestone into the underlying Osborne Formation by up to 45 m beneath Fremantle (Golder, 1999). As the sea level rose the channel infilled with soft and loose sediments (silts, sands, clays and some organic material). About 7000 years BP (before present) the sea level was in fact slightly higher than the current level and Arthur Head would have been an island (Gordon, 2001). Indeed much of present day Fremantle would have been underwater. In the last 5000 years the sea level has fallen to its present level and the Swan River abandoned completely its former course and entered the sea over a shallow bar of coral reef that lay between the outcrops at Arthur and Rous Heads (Gordon, 2001).

The Victoria Quay boreholes for Berths A and B consistently show the depth to rock (presumed limestone) to be between 10 m and 12 m below LWM until the western end of Berth C (refer Figure 1 for locations). At the western end of Berth C the depth to rock-head falls rapidly and for the majority of Berth C and for all of Berths D and E rock is not encountered until below 30 m. Instead thick deposits of soft or loose silts and sands are present underlain by the sandstones of the Osborne Formation (Golder, 2001). The Osborne Formation is normally encountered beneath the Tamala Limestone in this part of Fremantle at a depth of about 30 m. However at Berths D, E a broad ancient river channel approximately 200 m wide has cut completely through the limestone down into the Osborne Formation The channel has cut down to a depth of 45 m below LWM beneath the western edge of Berth E.

Boreholes and probeholes carried out for building works on the corner of High Street and Cliff Street close to the Round House also identified part of the palaeochannel. The results of a geophysical survey within the Inner Harbour (Golder, 1999) clearly depict the margins of the palaeochannel beneath the water of the harbour. Figure 2 presents the margins of the palaeochannel and is based on a number of sources, including hydrography, borehole records and the geophysical survey. There is reasonable correlation between the various data sources. The available information indicates that the western margin of the palaeochannel also passes beneath part of the North Quay. From the information summarised on Figure 2, the Tamala Limestone sequence is absent beneath Berths C, D E and Part of Berth F and also absent beneath Berth 8 and 9, part of Berth 7 and possibly part of Berth 10. The approximate depths of the palaeochannel based on borehole records are shown on Figure 2.

The palaeochannel is generally backfilled with uncemented sediments, typically loose and very loose sands, soft to firm sandy silts, overlying firm to stiff sandy clays, with a variable organic component.

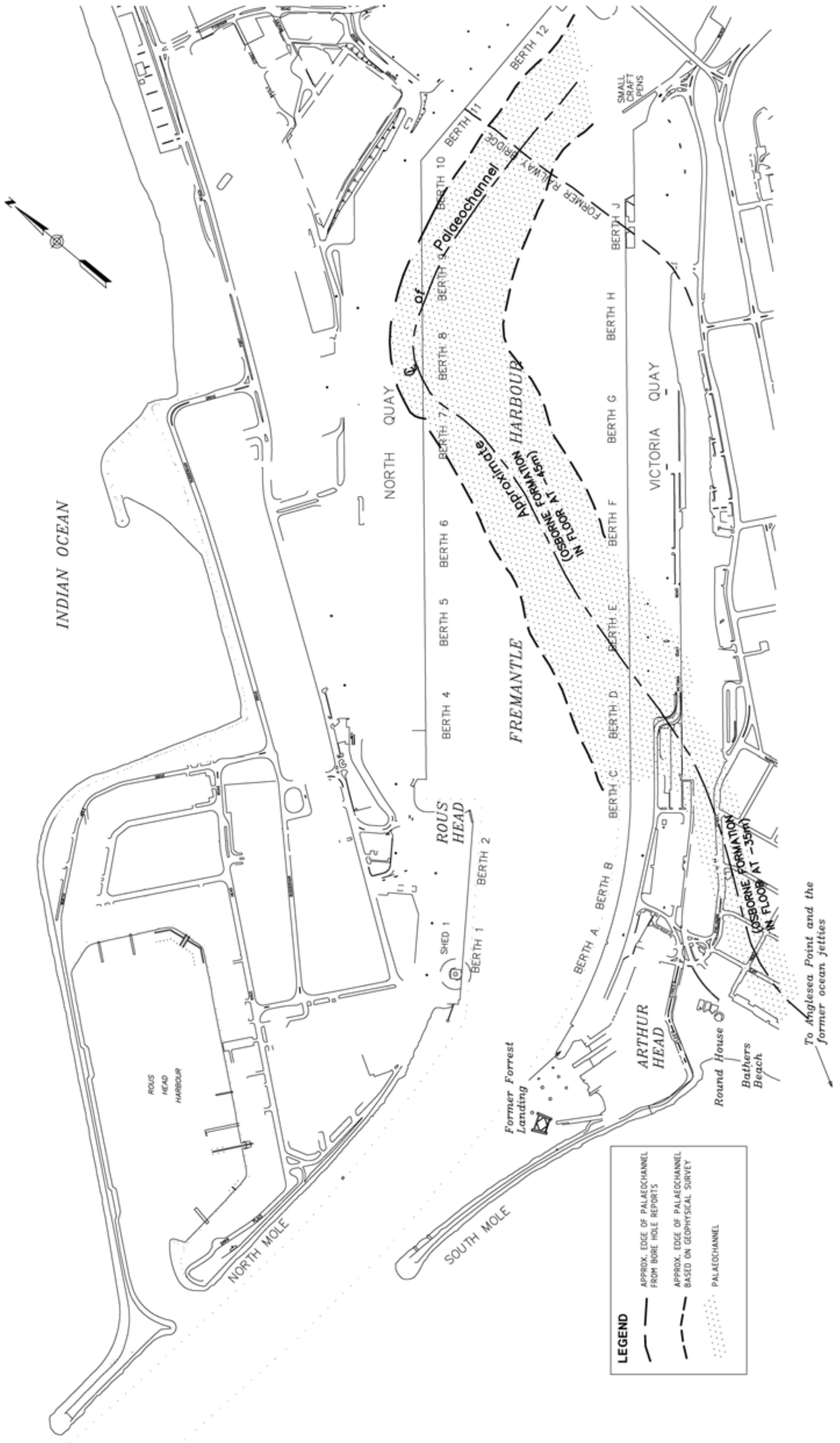

Figure 2: Approximate location of Palaeochannel passing beneath Inner Harbour and Town Centre.

Seabed conditions within the extent of the palaeochannel are likely to be sands and silty sands. In this respect, it is interesting to note the erosion that has occurred within that part of the Inner Harbour underlain by the palaeochannel (Golder, 1999).

There is also evidence from the 1999 hydrographic survey to indicate that the main area defined by the -13.5 m LWM contour roughly corresponds with the outline of the palaeochannel (Golder, 1999). The harbour is dredged to -13 m thus the seabed at -13.5 m is below the dredged depth. Much of the harbour floor is limestone and as such, the hard conditions would mean that overdredging or subsequent scour is unlikely. However, within the margins of the palaeochannel, the soft and loose silts and sands that form the harbour floor would mean that overdredging or scour is more likely and may be the reason for this relationship being observed.

4.5 PALAEOCOASTLINE

There have been some significant changes to the coastline around the Fremantle area. The formation of the harbour itself involved the removal of a large bank of low lying sand known as Ferry Point and the reclamation of the land behind both North and Victoria Quays (refer Figure 1). Even the coastline of Bathers Beach (west of the Round House) has been pushed westward by about 50 m and the reserve known as The Pines, located south of the Round House, is entirely on reclaimed land. This reserve was formerly South Bay and the Esplanade was the former coastline at the time of the first settlers arriving in 1829 (Le Page, 1986). A line in the pavement can be seen between the Round House and the Small Boat Harbour to the south and marks the former shoreline.

5 ENGINEERING ISSUES

5.1 CONSTRUCTION OF THE INNER HARBOUR

Sir John Coode, an eminent British Harbour engineer at the time, was asked in 1876 to design a harbour at Fremantle. Coode concluded that a north to south littoral drift would block the harbour entrance and the river and tidal flows through the entrance would not be sufficient to sluice away the accumulation of sand (Le Page, 1986).

C Y O'Connor, who arrived in 1891 as Engineer in Chief for the colony, had different ideas to Coode and concluded that the littoral drift system was of a minor nature and removal of the rock bar would enable a safe inner harbour to be constructed. The following is part of the transcript of a parliamentary committee meeting in which O'Connor is answering questions. The Minister for Lands, Marmion, had asked a question (Le Page, 1986). O'Connor's answer given below indicates the pressure he was put under as Chief Engineer. The pressure was sustained throughout his 11-year career as Engineer in Chief and lead to his suicide in 1902 (Evans, 2001).

"If you ask me my opinion I will give it to you; but why endeavour to drive me continually into controversy with Sir John Coode? You may come to the conclusion yourself, if you like, that we are at variance, but why ask me to come into conflict with him? You may draw your own inferences…I am Engineer-in–Chief of the colony, as you say, and as such I am prepared to express my own opinion, though I feel the responsibility of the position as much as anyone can do…. and for a layman to form an opinion as to whether one engineer's views are in conflict with another engineer's views, upon purely technical points…is difficult…if you had more experience in marine engineering you would probably come to the conclusion that we are not at issue at all…"

O'Connor's harbour finally got approval partly through the support of the Premier of the time, John Forrest, and construction of the North and South Moles began in 1892 and blasting of the Rock Bar commenced in 1895. The harbour was first built with a depth of 30 feet (9.14 m). The harbour was subsequently deepened to 36 feet (11m) and later to the current depth of 13 m. Hard dredging conditions requiring the use of cutter-suction dredgers were encountered over about 60% of the harbour floor. The possibility of deepening the inner harbour to accommodate the latest generation of container ships has been considered (Golder, 1999; D. Vallini, Pers. Comm., 2003).

O'Connor was right in his conclusion regarding littoral drift. The harbour entrance has no sand bar, and very little maintenance dredging is required to maintain the declared depths in either the approaches within the harbour (D. Vallini, Pers. Comm., 2003).

5.2 FORREST LANDING

Forrest Landing was removed during the construction of the Maritime Museum and is the site of the original Arthur Head. Behind the former landing are two slipways.

This part of the harbour first became associated with submarines during World War 2. At the outbreak of the war a slipway was under construction. Following America joining the war, US submarines used Fremantle and the US forces completed and extended the first slipway. A smaller slipway had been in operation since 1900 on the west side of Rous Head. The Arthur Head slipway was to be used by US submarines until 1945, British submarines until the 1950s (when the British Navy no longer had a presence in Fremantle) and by Australian submarines for several more years. The area is characterised by shallow limestone, much of which has had to be removed to facilitate both the construction of the South Mole and the slipways themselves. Whilst limestone in principle should form a sound founding material for the large loads imposed from a ship on the slipway carriages, as a result of the variable nature of the Tamala Limestone, foundation problems were experienced. A sheet piled cofferdam was used to allow the dry excavation of the lower parts of the slipway. The hydraulic head created by the cofferdam resulted in the heaving of a thin sheet of rock in the floor of the excavation and the washing out of uncemented sand layers sandwiched beneath the limestone reef. Fortunately these problems occurred on the part of the slipway carrying the least loads as the ships would still be partially buoyant at this position on the slip.

5.3 GRAVING DOCK

Fremantle's unique position as a first port of call for ships arriving from Europe has meant that there has been a need for a graving (dry) dock since the day the port opened for essential ship repairs.

O'Connor had envisaged, no doubt for sound technical reasons, a graving dock to be located on the north side of the harbour close to the old railway bridge (in fact around the location of the present day Berth 10). After O'Connor's death in 1902 his successors had other ideas and Royal Assent was given on 20 December 1907 for a graving dock to be constructed on Rous Head. Work commenced on the dock in 1908 (Le Page, 1986).

It was envisaged the construction could be carried out initially entirely in the wet without the need for a cofferdam. It was considered that a cofferdam was unlikely to work due to the porous nature of the limestone. The plan was to first blast to fragment and loosen the limestone, then to dredge the barrel of the graving dock. Following this, it was planned that a concrete invert would be placed over the floor of the dock by means of men operating within a diving bell. A cofferdam was then to be constructed sealed against the concrete floor of the dock to enable the walls of the graving dock to be constructed (Le Page, 1986). Unfortunately, a combination of geotechnical problems and political pressure lead to the abandoning of the scheme in 1912. The geotechnical problems included the presence of a cave beneath the floor of the dock, water bursting into the excavation under pressure from the cavernous limestone and the presence of sulphuretted hydrogen gas. The gas was reported to have caused great discomfort to the workers, some of whom went temporarily blind, others contracted eczema, and apparently everyone went a bad colour of yellow and became very lean. A silver coin placed in the water in the floor of the excavation was reported to have turned to a bronze colour within a few seconds (Le Page, 1986).

The sulphuretted hydrogen gas presumably emanated from strandline deposits of seaweed that subsequently got buried beneath drifting dune sand, that was in turn later cemented into the limestone forming Rous Head. The presence of cavernous limestone and caves is something to be expected given current knowledge of Tamala Limestone. Loose sand is typically encountered beneath the caprock, and this loose material could easily have been eroded away, particularly when consideration is given to the marine exposure of Rous Head.

Fremantle was not to have its graving dock. A floating drydock was however introduced during the war years by the US navy and was moored on the North Quay.

5.4 BERTH CONSTRUCTION AND BERTH SUBSIDENCE

The construction of the wharves involved the construction of timber over-water structures. During construction a small ship could berth either side of the structure. However once the structure was completed the land behind the wharf structures was reclaimed and an underwater batter formed beneath the structure itself. Large boulders of limestone and later granite where placed to form a rock armour and some form of short retaining wall was constructed at the top of the slope to retain the uppermost 1 m to 4 m of backfill.

In the early years of the port, ship born vermin came ashore and found a home amongst the waste and flotsam that accumulated amongst the interstices of the rock armour beneath the wharf structures. Mainly through fear of bubonic plague the boulders were 'napped' with concrete as far as the low water mark in an attempt to remove the rats habitat. This napping however exposed a weakness in the construction of the wharves. Wave energy from the wash of vessels was confined beneath the napping and at several locations has removed sufficient material to undercut some of the shallow retaining structures around the harbour (Tutton, 2000). In late 1998 a hole opened up in the carpark between Sheds B and C immediately behind the wharf-line. Inspection revealed an extensive void measuring about 8 m by 3 m and 300 mm to 500 mm deep. The bitumen pavement and limestone sub-base materials were largely successful in spanning this void. Upon excavation it was found that the retaining wall was constructed of straight-web sheet piles. This is a type of pile normally only used for circular caisson or cofferdams as the piles are designed to carry hoop stress and virtually no bending moment. Interestingly the piles were only 6 feet in length and the wash from passing vessels could be seen to filter under the sheet piling with virtually no loss in energy (Tutton, 2000). A temporary repair was carried out but this is an illustration of a problem encountered elsewhere in the port.

Many of the berths have been reconstructed in the 1940s and 1950s and concrete sheet piles have been driven to a depth of about 6 m. The toe level is generally sufficient to prevent flow beneath the pile but loss of sand sized material has occurred through the clutches of the piles. The clutch system is a simple tongue and groove and particularly if the piles have not been driven straight a gap of 10 mm or 15 mm occurs. The sand backfill may be capable of bridging such a gap but only until a change in water pressure across each side of the gap occurs during the passage of a wave and sand is lost to the harbour. This problem is occurring behind many of the berths. Plate 1 illustrates a void approximately 100 mm thick beneath a pile cap that has resulted from the upward migration of the void that developed through sand being washed out through gaps in the clutches.

Plate 1: Void (approx. 100 mm thick) behind sheet piles on Berth 1 and beneath the pile cap.

At Berth 10 the problem is even more noticeable. In the 1950s a second row of sheet piles were driven some 1.2 m behind the row of concrete piles that formed the wharf-line. These piles were driven presumably due to the recognition of a backfill washout problem. The clutches of the concrete piles were mortared down to the low water mark and the ground reinstated with a concrete slab cast on the ground. A void of a volume of about 500 m^3 was subsequently discovered during works to lay some new services behind the wharf-line. A considerable volume of sand was being lost to the harbour, leaving a floor of coarse sediment devoid of fines and with the sheet pile tie-bars and services left hanging. Plate 2 illustrates the size of the Berth 10 void.

Plate 2: Void beneath Berth 10. To the left are concrete sheet piles and beyond the harbour. To the right of the void are more recent steel sheet piles. Since the time of driving the steel sheet piles the large void has developed.

5.5 HARBOUR DEEPENING

Fremantle Ports has considered deepening the Inner Harbour to accommodate shipping trends towards larger and deeper draught vessels (Golder, 1999)

Should harbour deepening take place there are a number of important geotechnical considerations.

Successive harbour deepening has already created under-berth batter slopes that are steeper than the angle of repose of some of the materials forming the batter slopes. It appears that the piles supporting the decking of each berth are also having a significant effect on improving berth stability (Golder Associates, 1999).

Potential instability associated with berth deepening is most significant for those berths located over the palaeochannel.

Dredging to deepen the Inner Harbour may:

- steepen under berth batters creating possibly instability problems,
- could potentially reduce passive restraint in front of sheet and laterally loaded tubular and fender piles,
- could reduce the load capacity of the axially loaded piles supporting the berth structures,
- break-through stronger horizons of well cemented limestone exposing weaker materials to scour and erosion and
- overstress piles because they will tend to restrain under-berth slope movement.

The Berths of the Inner Harbour fall into two categories:

- Those berths where limestone is to be found at and below dredged level (Berths 1 to 6, 10 to 12, A to C and F to J) (refer Figure 2).
- Those berths where soft sediments (the backfill to an ancient river channel or palaeochannel) are to be found at and below dredged level (Berths D and E, part of 7 and Berths 8 and 9) (refer Figure 2).

Further harbour deepening is likely to encounter mixed conditions possibly requiring different types of dredgers. Soft and loose deposits will characterise the palaeochannel and except for a thin covering of contemporary surficial seabed sediments, Tamala Limestone and its various associations is generally found elsewhere.

6 CONCLUSIONS

The Inner Harbour at Fremantle is a fine example of simple and cost effective 19th century engineering that created a harbour that has barely changed in one hundred years and yet continues to be a busy and important commercial port.

The geotechnical problems experienced in the past are as relevant today as at the time of construction. An understanding of the geology is clearly a prerequisite to economic and successful construction. The graving dock is a clear example of this. With this in mind, there are two questions to ask.

1) Did C.Y. O'Connor know of the existence of the palaeochannel when he made his plans for the Inner Harbour?

2) Had he been aware of its existence, would he have chosen to dredge out its soft contents opening a deep 200 metres wide approach channel from the south through what is now Fremantle Town centre thus leaving the rock bar intact?

The questions are hypothetical, the decision to remove the coral limestone forming the rock bar was taken and with successful results.

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