Marine Pile Repairs by Concrete Encasement

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Introduction

Piled jetty and pier structures form a vital part of port infrastructure for worldwide trade and travel, yet their life span is often threatened by pile deterioration in the corrosive marine enviroment. Many steel piles suffer from Accelerated Low Water Corrosion (ALWC) with significant section loss well before the design life of the structure expires (Fig. 1). Port Owners and Engineers should respond by monitoring corrosion and steel thickness loss and provide appropriate protection or repair.

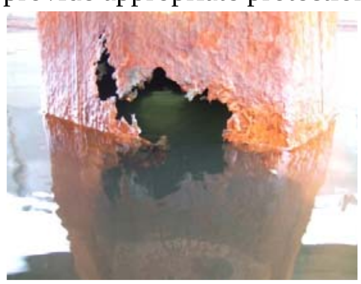

Fig. 1 – ALWC Damage

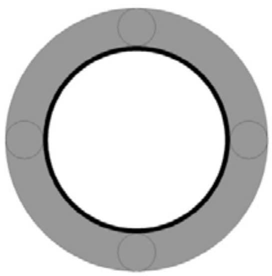

Fig. 2 – Steel Pile Protection

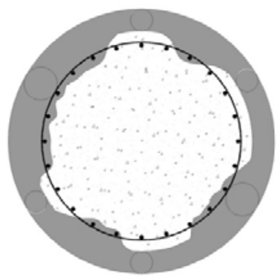

Fig. 3 – R.C Pile Repair

The protection and repair of marine piles is usually much more sustainable than jetty replacement, yet little published guidance is available.

The process of concrete encasement repair using a fabric pile jacket system will be described with reference to case histories of its application, to both steel and R.C. piles (Figs 2 and 3).

Case Histories:-

Ireland:	Dublin, Cork, Dun Laoghaire
Scotland:	Lerwick, Hunterston
Canada:	Lunenburg
Ukraine:	Odessa
Kenya:	Mombasa

Other concrete encasement repair methods are outlined along with their relative merits. The advantages of inspection monitoring and early protection are outlined and promoted.

Concrete Encasement Protection and Repair

Concrete is commonly used in conjunction with steel and has naturally been used to protect and repair steel or reinforced concrete marine piles. Concrete encasement repair or protection can be readily designed by engineers to appropriate codes and guideance.

Historically, concrete encasement using fabric pile jackets has been a common repair method for some 45 years, with more than 50,000 piles repaired worldwide. For underwater use the fabric pile jacket system has many practical and technical advantages over rigid shuttering systems such as steel, timber or fibreglass etc, as outlined in Table 1:-

Table 1. Relative Merits of Encasement Formwork

	Pile Jacket System	**Rigid Shutter System**
Concrete Quality	Enhanced quality by free water bleed[16] through porous jacket[7] · Strength · Durability · Abrasion resistance	Higher water: cement ratio needed, lower quality concrete Honeycombing risk at joints
Segregation Risk	Avoided by observation (fill level readily seen underwater)	More difficult to control
Diver Application	Lightweight system of fabric formwork regularly used for marine works, easy to seal	Heavy to handle under jetties and more difficult to seal
Health & Safety	Good record	Greater risk of injuries to divers and surface crew

The repair options for marine piles to jetties are quite distinct from sheet piles, as encasement options are readily available.

For damaged reinforced concrete piles, the pile jacket system of concrete encasement is a natural repair option. It replicates the repair process usually adopted to RC structures on land[5] in a method that is suitable underwater. Dewatering access to marine piles has been attempted using a pair of semi circular limpet dams in a similar fashion to adapted sheet piles. The system is difficult to handle and operate safely under jetties and is understood to have a poor safety record from operation in Eastern Europe.

More repair options exist for steel piles with cathodic protection and short term wrap systems becoming more common. The benefits and limitations of cathodic protection are well summarised in the “Port Designers Handbook” by Carl. A. Thoresen. However concrete encasement can achieve longer term repair lifespans with provision for repaired or strengthened pile sections.

Protection and Repair Engineering

Typical Process

- Condition and steel thickness surveys
- Structural appraisal of piles & jetties
- Design of repairs
- Micro concrete mix development
- Supervision of repairs

Piled jetty and pier design is currently covered by the British Standard for Maritime Structures BS6349 Part 2. ‘Rigid’ jetties are tied or braced horizontally, whilst ‘flexible’ ones support horizontal loads with piles acting in bending. Pile protection and repair should be designed for its range of load cases and environmental conditions for an appropriate future lifespan. The effect of additional encasement load on piles may need to be checked along with wave loading to increased pile sections to more exposed jetties[4, 13].

Eurocode 2 and BS EN 206 now offer a more rational approach to Reinforced Concrete durability then BS8110 taking into account a wider range of influences for the design of concrete and its durability. Eurocode 2 also appropriately calls for increased durability specification for marine concrete to tidal, splash and spray zones. For pile jacket encasement to a 50 year design life, a total surface tolerance of 20 mm is recommended in conjunction with a further 10 mm allowance for marine durability robustness. For increased durability, cement replacement with GGBS has been used.

Steel Piles

Corrosion Risk

Steel piles are now acknowledged to be prone to significantly advanced corrosion rates in contrast to previous understanding and design allowance. High corrosion rates due to ALWC (Fig. 4) are well described in the I.C.E Maritime Board Briefing on ‘Accelerated Low Water Corrosion’. As the understanding of ALWC increases, the Briefing Sheet states

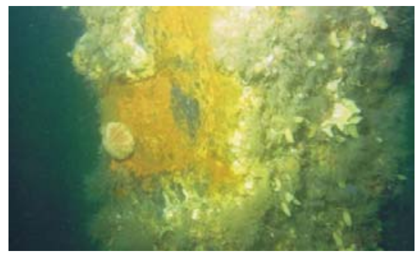

Fig. 4 - ALWC

> *“Although unclassified, varying rates of corrosion by ALWC up to 4 mm/ side/ year have been recently reported and cases in the order of around 1mm/ side/ year appear to be common.”*

Table 25 in BS6349-1:2000 “Code of Practice for Maritime Structures” classifies notional average and upper limit values of corrosion for exposed, unprotected structural steels in temperate climates in mm/ side/ year, given as a guide as to what could be expected. These are summarized in Table 2 below:-

Table 2. Marine Corrosion Rates for Steel

	Avg.	**U.L.**
Atmospheric zone (in the dry)	0.04	0.10
Splash zone (above MHWS)	0.08	0.17
Tidal zone (MLWS and MHWS)	0.04	0.10
Intertidal low water zone (0.5 m below LAT to MLWS)	0.08	0.17
Continuous immersion zone	0.04	0.13
Embedded zone (below seabed)		0.015 (max)

The concentrated corrosion risk from ALWC is acknowledged to be much higher although quite variable. The ‘Briefing Sheet’ and the ‘Port Designers Handbook’ outline the expected causes of ALWC. It typically displays a bright orange corrosion product and typically peak corrosion occurs at and just above the low water zone (LAT). Occasionally the section loss is significant throughout the water depth. The Lerwick case history demonstrated that ALWC was significant at bed level and in the immersion zone as well as at low water.

Corrosion rates are increased in high temperature regions, or with low pH levels, pollution, wave and current action, salinity as well as other effects[11] or where poor quality steel has been used. Many jetties with steel piles are not monitored until holing visably appears. At this stage the pile is probably structurally inadequate, plus the corrosion rate increases, due to the newly exposed internal faces.

Corrosion rates are extremely variable rendering monitoring highly important.

Condition and Corrosion Monitoring

Historically, many steel pile structures have been designed with a corrosion allowance, typically of the order of 5 mm[11]. Accelerated and concentrated corrosion rates from ALWC clearly threaten these structures in the short term.

Fig. 5 – Thickness Monitoring

This threat can be managed by visually checking for the development of ALWC and steel thickness monitoring using suitable measuring instruments. This can be conducted quite simply and cost effectively from a boat at low water and above. Reference should be made where possible to the original design and the corrosion thickness allowance, so that the section loss can be measured against this allowance.

When corrosion loss becomes significant relative to the design allowance, a full diver survey through the water column and up to the deck is advisable. Thickness readings should be at closer centres to areas of critical loss (usually to low water zone) and then adjusted to locate the areas of maximum section loss. H piles or Rendex piles (welded sheet pile sections, Lerwick & Dublin Port) should be checked on all flat elements due to differing corrosion performance. Extruded steel circular piles are normally checked on 4 sides to critical areas.

The management of sampling and testing should be overseen by a suitable engineer to pick up any local issues, other structural damage and determine the need for future monitoring or intervention repair[10]. Where ALWC is found to be occurring, more frequent monitoring is desirable or an immediate move to provide protection and preserve sections, see Lerwick and Dublin.

Design of Protection

For ‘rigid’ jetties where piles are purely compression members and no structural loss of sections has occurred beyond the corrosion allowance, the pile may be cleaned and encased in plain concrete. See Mombassa, Lerwick, Odessa and Dun Laoghaire case histories. Bracing and raker piles subject to significant direct tension loads should be reinforced.

For ‘flexible’ jetty structures, it is considered prudent to reinforce encasement protection to piles subject to bending action. This is to control durability cracking of concrete encasement in tension zones, particularly during extreme bending action such as seismic action, ship berthing impact or wave loading to exposed jetties[4,13]. Encased steel sections can be designed as composite construction to Eurocode 4.

Cover and Durability

The concrete cover to steel piles, or any strengthening reinforcement, can be guided by reinforced concrete codes. Concrete encasement protection principally protects against surface carbonation and chloride ion penetration causing the onset of further corrosion.

Typically, 75 mm encasement thickness has been adopted as a minimum locally with 40 – 50 N/mm² strength concrete (C32/40 to C40/50).

Protection Length

Where ALWC or significant corrosion is occurring at bed level it is common to extend the protection into the bed as Lerwick. Otherwise protection can be designed to commence at bed level or an appropriate height at risk. The protection is usually taken up to the deck soffit. Where an extended dry zone is present, a suitable paint treatment, overlapped into the encasement can be adopted as Lerwick or similar.

Repair and Strengthening Reinforcement

Where pile section loss is structural, the piles can be designed to be strengthened by reinforced concrete encasement. Where steel section loss is modest, it can simply be made up with reinforcement bars or similar. Where section loss is significant, it is more effective to design reinforcement using a composite steel and RC section basis. For ease of application, reinforcement is usually designed in 2 half cages which are accurately fabricated for relatively easy assembly round the pile with loose curved overlap links fixed by diver to link them together (Fig. 6).

Fig. 6 – Reinforcement Cage

Preparation

Steel piles need to be thoroughly cleaned of all marine growth and all corrosion deposits removed back to bare metal. This is usually done by hand held high pressure jetting equipment suitable for diver operation. Where sufficient repetition allows, automated jetting equipment can be adopted and Engineer inspection of the cleaning is important.

Cast Iron Piles

Corrosion rates for cast iron are much less for mild steel and they are not known to suffer from ALWC. Cast iron is mainly found in Victorian pier structures (Fig. 7). These columns are mostly prone to abrasion loss of thickness due to sand and shingle carried in wave action. A high quality abrasion resistant mix should be selected that can be produced in conjunction with the pile jacket bleed enhancement.

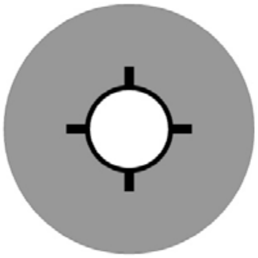

Fig. 7 – Encased C.I. Pile, Cromer

Reinforced Concrete Piles

Corrosion Risk

Damage to sections is normally caused by surface carbonation of the concrete with the penetration of chlorides (readily present in sea water) promoting rusting of the reinforcement and subsequent cracking and spalling of the concrete cover. Generally damage has occurred from just below low water (LAT) through the tidal zone and lessening into the splash zone. Reinforcement corrosion is not generally found in the continuous immersion zone.

Fig. 8 - Damaged R.C. Pile, Hunterston

Condition and Corrosion Monitoring

The corrosion loss of reinforcement and loss of spalled concrete area is usually determined by sampling suitable trial areas by breaking out spalled concrete and cleaning reinforcement to allow direct bar thickness measurement. Condition inspections should be managed by a suitable engineer as often unexpected conditions need to be interpreted, see Dun Laoghaire.

Protection

Where the structural loss of reinforcement is within acceptable limits, the section can be prepared, cleaned and encased in high quality concrete[6], with appropriate cover as previously described, or with a minimum thickness of 75 mm to the corners of square sections for robustness.

Repair and Strengthening

Strengthening reinforcement within the concrete encasement can be designed as required to cover the defective pile length. As previously described, reinforcement cages should be designed in two accurately made halves which can be readily linked together by divers using curved links (Fig 6).

Preparation

For long-term repairs, it is important to remove all marine growth, cracked and spalled concrete around all bars subject to any significant corrosion action. All rusted bars should be cleaned back to bare metal. Concrete cutting and removal and reinforcement cleaning is best undertaken underwater by appropriate hand held high pressure water equipment (Fig. 9) which is also suitable for diver use underwater. Engineer control and inspection of preparation works is important. Where piles are significantly weakened during repairs, suitable analysis, loading restrictions or temporary works arrangements should be made.

Fig. 9 – Jet Cleaning

Timber Piles

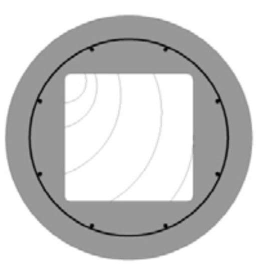

Fig. 10 – Timber Pile

Repair of timber piles by concrete encasement is not very common in the U.K. It is more widely used in North America[12] where timber piles are more common. Concrete encasement repair (Fig.10) should safely be considered as a short term repair as evidenced by current performance periods. No known evaluation or testing of the condition of encased timber piles is known and would be of benefit if undertaken. All decayed timber should be removed and encased sections reinforced with links and vertical bars to avoid timber movement and splitting action. Where timber section loss is high, preparation of load transfer ends should be engineer designed along with any temporary works requirements, which are common.

Encasement Concrete

A highly fluid, sand: cement micro concrete is usually used with the pile jacket system. This mix is typically pumped through 50 mm diameter hose, which can be readily handled by divers and surface crews. Historically a 2:1 sand: cement mix has been used with typical cube strengths at 28 days of 35 – 50 N/ mm². The strength is influenced by the sand selection. Higher strength mixes, in the usual design range of 40 – 50N/ mm², sometimes require increased cement content. Micro concrete is often used in conjunction with fabric formwork systems for marine constructions[7,8]

Fig. 11 – Concrete Encasement

A well rounded sand of river or sea origin is preferred with a good grading distribution, sand size is typically below 5 mm. The mix fluidity is controlled by a Marsh flow cone to aid pumpability and ensure the mix is readily self levelling within the pile jacket. Water content ratios are typically some 0.55 to 0.7 at the mixer. The highly fluid mix ensures complete encasement of the pile section (Fig. 11) and any reinforcement for increased durability.

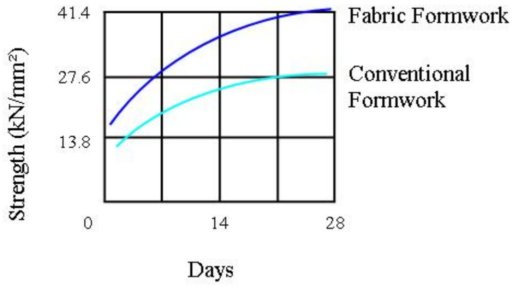

Fig. 12 – Bleed Strengthening

Once in place, free water bleed through the porous pile jacket, causes the water cement ratio in the mix to drop to a natural minimum of around 0.40. This causes a significant increase in strength, chemical resilience, durability and abrasion resistance (Fig. 12). To replicate this process in mix development and quality control tests, the mix is usually placed into a 100 mm diameter fabric test sock to allow matching material to be cut and tested in cylinders. The low water cement ratio minimises shrinkage in conjunction with submerged curing. Since 1998 at Lerwick, it has been common practice to include polypropylene fibres, in order to aid durability.

In hot tropical climates or similarly aggressive locations, a corrosion inhibitor additive can be used. Additives are generally kept to a minimum with plasticisers, retarders and anti-washout additives not usually required. A suitable mix design should be developed, tested and approved in advance of the works. The most important requirement is that the mix is reliably pump placed in tremie fashion to avoid segregation of the mix below water level.

Pile Jacket System

The system is applied by divers who should be suitably experienced or trained.

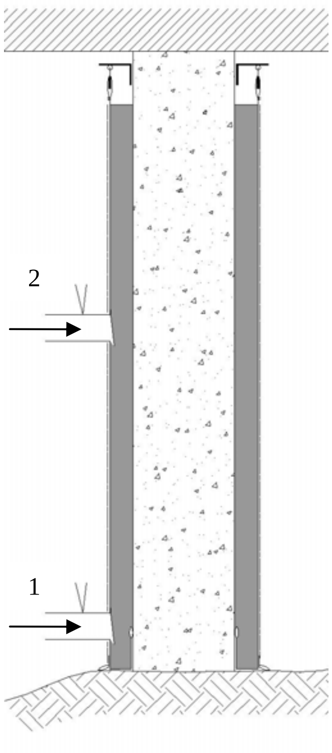

Fig. 13 – Vertical Section

Application Process

- Piles cleaned, repaired and inspected
- Spacers fixed and any reinforcement
- Pile jacket (lost shutter) is fixed & zipped up
- Re-usable PVC mesh 'corset' is fixed (Fig. 20)
- Pump fill in tremie fashion
- Next day, remove 'corset'

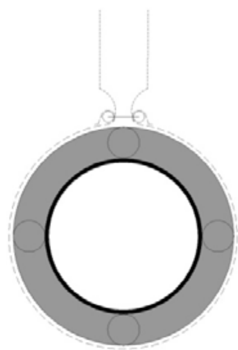

Fig. 14 – Steel Pile

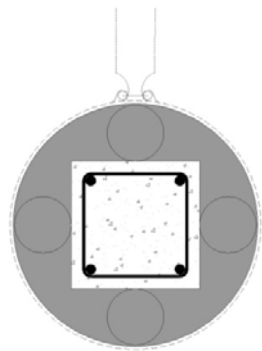

Fig. 15 – R.C. Pile

As the woven polypropylene pile jacket remains in place, it provides protection for concrete curing above water. Pile jackets are relatively easy for divers to fix plus they can be adapted to a variety of pile shapes and lengths. Steel reinforcement can be included for strengthening where required with PVC pipe spacers usually preferred (Fig. 15). The bottom of the jacket has a self-sealing turn up to tubular piles and jackets incorporate self-sealing fillers that importantly allow easy pump filling in submerged tremie fashion (Fig. 13).

For example, the pile jacket is pump filled from bottom sleeve 1, to above sleeve 2, before filling is transferred to sleeve 2. The micro concrete fill level can be seen in the fabric jacket and this important control process can be monitored or suitably recorded by diver camera. Mix segregation is found to occur at very low mix drop heights in water and this risk must be managed.

The system is suitable for working on jetties in sheltered ports and harbours with wave heights during working periods below 0.5 m.

The corset system was first used in Mombassa in 1998 and has been adopted ever since (Fig. 20, 24). Unsupported fabric jackets are prone to stretch during filling. This causes an increase in concrete thickness with the jacket becoming uncontrolled by its spacers, which can result in 'banana' shaped vertical repairs and an associated loss of cover.

Pile jacket systems should be obtained from experienced manufactures and suppliers who provide a temporary works design, an appropriate job specific installation guide and site support as may be required.

Steel Pile Case Histories

Mombasa, Kenya

Consultant: Bertlin and Partners

Fig. 16 – Encased Piles

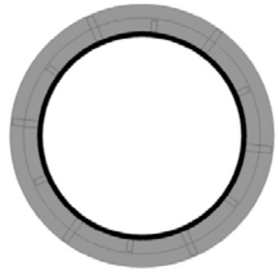

Fig. 16 – Encased Section

A new jetty was constructed in 1988 by Mowlem International for the Kenyan Navy (Fig. 16). It was immediately protected by concrete encasement using the pile jacket system (Fig.17). Concrete encasement was considered a cost effective solution to the harbour sea water environment with mild pollution. 450 tubular steel piles of 508 to 610 mm diameter were protected by an 85 mm thickness of micro concrete containing a polypropylene mesh. The protection length was some 10 m down to the bed. The corset system was first used on this project.

Lerwick, Scotland

Consultant: Arch Henderson

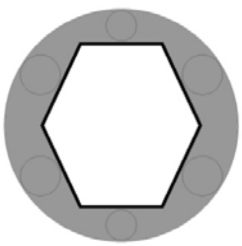

Fig. 18 – Holmsgarth Section

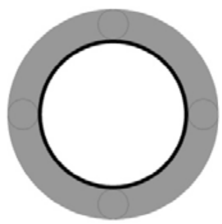

Fig. 19 – Gremista Section

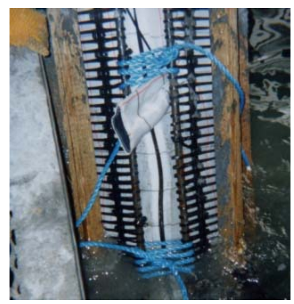

Fig. 20 - Corset

In 1997/98, 186 piles to the Holmgarth (Fig. 18) and Gremista (Fig. 19) piers were protected full height with a 75 mm nominal thickness of sand: cement micro concrete encasement. ALWC was evident to the piers and other harbour structures generally.
The consultant and Lerwick Harbour Board opted to protect the Holmsgarth piles just before they suffered structural section loss. Gremista Pier piles were also prudently protected before becoming structurally critical by ALWC. The upper pile height above the splash zone was protected by an appropriate paint treatment which overlapped into subsequent concrete encasement.

ALWC was also found to be significant through the immersion zone and particularly just above bed level and this is thought to be promoted by local pollution. The protection was cast 0.6 m below bed level to protect against this. Jetty stability was provided by bracing and raker piles. Both vertical and raker piles were protected by plain concrete encasement (Fig. 21).

This project was the first use of polypropylene fibres within the micro concrete mix to enhance durability. Pile lengths were up to 15 m long. The pile jacket system was adapted for bracing and raker piles with concrete spacers and stiffened corsets used to section topsides. Node joints were encased using tailored pile jackets and shaped steelwork node support.

The pile encasement is regularly monitored by the Consultant and is reported to be working well.

Cork, Ireland

Consultant: Malachy, Walsh & Partners

The jetty was built in XXX. By 2007 natural corrosion had caused significant corrosion with many piles holed around low water level. From thickness surveys, the worst piles were prioritised and 14 repaired with reinforced concrete encasement. The piles are 610 mm tubular sections, which were initially XXX mm thick giving a concentrated corrosion rate at holes of XXX mm/ year. A concrete thickness of 160 mm was used with a nominal 75 mm cover to reinforcement (Fig. 22, 24)

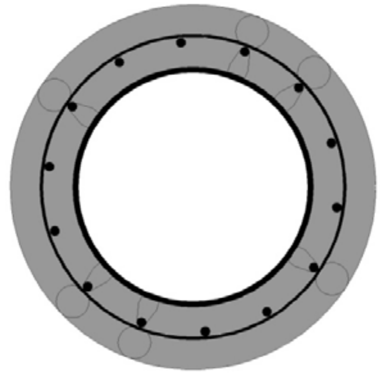

Fig. 22 – Reinforced Section

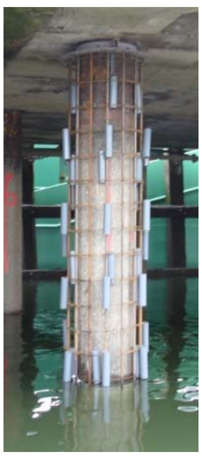

Fig. 23 – Cage & Spacers

Holed piles were locally sealed with fabric sleeves after high pressure jet cleaning. Reinforcement cages were accurately made by tack welding in a jig and pipe spacers pre attached to aid fixing round the pile (Fig. 23).

A 40 N/ mm² (C32/40) 1.4: 1 sand: cement micro concrete mix was used with polypropylene fibres and partial cement replacement by ground granular blast furnace slag (GGBS), all to aid durability. The mix was pre dried, blended and blown into mixer silos on site (Fig. 24) This gives improved mix proportion quality control. Fig. 24 also shows a micro concrete test sock being cured underwater for subsequent cylinder testing and quality control.

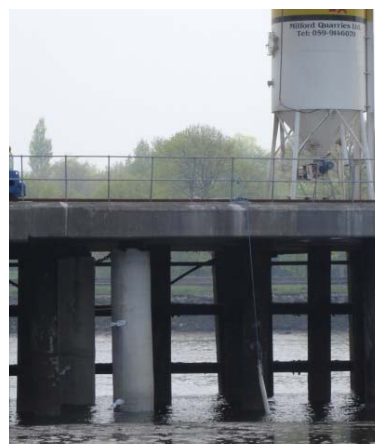

Fig. 24 – Pier & Silo

Dublin, Ireland

Consultant: Jacobs, Babtie

Fig. 25 – Bulk Jetty

The Bulk Jetty was built in 1950. The steel piles to the jetty where in such a poor condition with many piles holed through corrosion that the structure was considered for demolition (Fig 26).

The jetty piles had suffered from Accelerated Low Water Corrosion with many of the 13 mm thick coated Rendex piles holed by 2006.

Following a steel thickness survey and structural appraisal, the Consultant Engineers selected a 100mm thick concrete encasement with weakened pile lengths to be reinforced with bolted steel split rings. A site test was conducted to demonstrate the construction of this detail.

A traditional 2: 1 sand: cement micro concrete mix was developed to achieve 45 N/ mm² strength (C35/45). Polypropylene fibres were included to aid durability and shrinkage control.

Fig. 26 – Holed Pile

The steel piles where high pressure jet cleaned and inspected before the pile jacket system was applied. 138 piles were protected including raker piles. Pile encasement lengths were typically 9-11m long down to bed level. The top 0.3m of the pile was protected by sprayed concrete onto joint continuity mesh reinforcement. The work was completed in some 7 months, generally using 2 dive teams, putting the jetty back into working condition.

Holed pile sections were infilled with micro concrete in pumped tremie fashion along with the pile jacket.

Fig. 27 – Jetty Pile Repairs

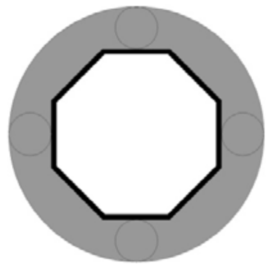

Fig. 28 – Encased Section

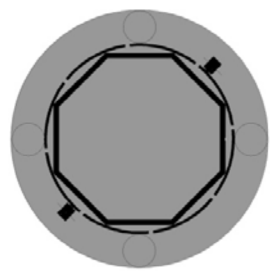

Fig. 29 – Reinforced Section

Lunenburg, Canada

Contractor: J. Mason

The steel H piles to the fishing jetty were severely corroded by 2001 with many pile sections completely rusted through and loose. Steel angle reinforcement was welded in where required and all sections wrapped in wrapping fabric steel mesh before encasing in sand: cement micro concrete with a 75 mm nominal cover. 84 piles were repaired.

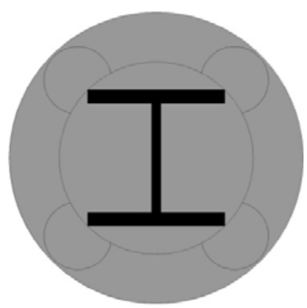

Fig. 30

Concrete Pile Case Histories

Odessa, Ukraine

Consultant: Proserve

Reinforced concrete piles some 40 years old supporting the passenger terminal had suffered from the onset of reinforcement corrosion and concrete splitting and spalling to the top 1.5 m pile length above low water. The piles are exposed to frozen ice and severe winter temperatures. Reinforcement inspection showed little loss of bar sections, allowing the reinforcement to be cleaned and the top 2.5 m of pile encased. A 90 mm thick encasement to pile corners has been used for robustness (Fig.31). The micro concrete mix is a sand: cement mix, of 40 N/ mm² strength (C32/40) with polypropylene fibres. 40 piles were completed in the 2010 season and repairs are ongoing.

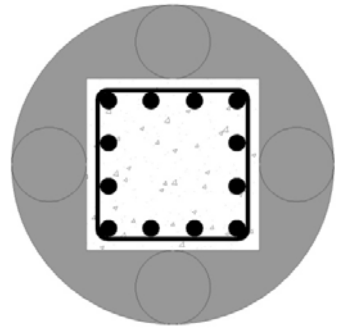

Fig. 31

Hunterston, Scotland

Consultant: Jacobs

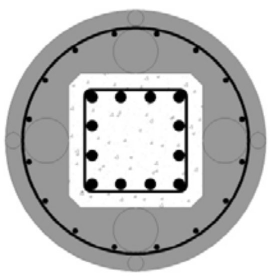

Fig. 32

The jetty piles had been suffering from reinforcement corrosion within the tidal range. Repairs currently underway are using a reinforced concrete encasement to 54 piles (Fig. 32). Preparation is by hydro demolition. The micro concrete mix is a 2: 1 sand: cement mix, 40 N/ mm² (C32/ 40) with polypropylene fibres with 50 mm cover provided to new reinforcement.

Dun Laoghaire, Ireland

Consultant: Moylan

The reinforced concrete jetty piles were formed using an old colloidal concrete technique of placing reinforcement, large aggregate and then after grouting in tremie fashion with a sand cement mix. Weak grout areas poorly formed by the technique have been eroded after the galvanised steel casing has corroded away (Fig 33). The reinforcement was found to have only slight section loss. This may have been due to the cathodic action of the corroding galvanised casing.

Fig. 33 – Damaged Piles

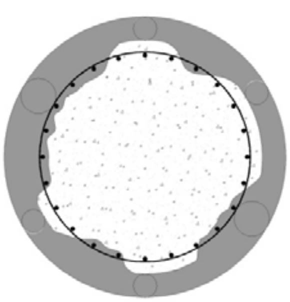

Fig. 34

The piles were simply cleaned, casing remains removed along with weak grout areas and encased with a 100 mm nominal thickness of plain micro concrete (Fig. 34). A 1.4: 1 sand: cement mix was used with a 50% cement replacement by GGBS and polypropylene fibres to achieve a 50 N/ mm² (C40/50) strength. 39 piles were repaired in 2006 (Fig 35) and a further 23 undertaken in 2011.

Fig. 35 – Repaired Pile

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