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 environment.

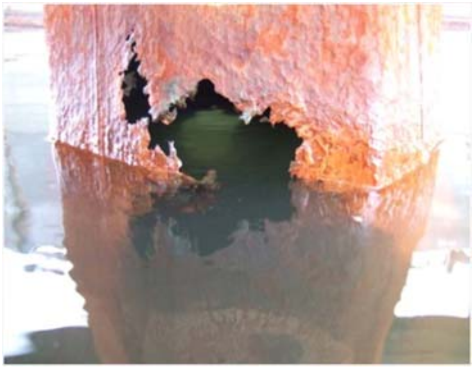

Fig. 1 – ALWC Damage.
Dublin Jetty

Many steel piles suffer from Accelerated Low Water Corrosion (ALWC) or Anaerobic Corrosion 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.

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 reinforced concrete (R.C.) piles.

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 Systems

Fig. 2 – Pile Protection
Mombasa

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 through porous jacket · Strength · Durability · Abrasion resistance	Higher water: cement ratio produced, lower quality concrete Honeycombing risk at joints, more joints to seal
Segregation Risk	Avoided by tremi fill 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. Limpit dam systems used to sheet pile walls are difficult to handle, seal and operate safely to piles under jetties and are understood to have a poor safety record from operation in Eastern Europe. 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 in a method that is suitable underwater.

More short term repair options exist for steel piles with cathodic protection, wrap or paint systems becoming more common. The benefits and limitations of cathodic protection are summarised in the "Port Designers Handbook" by Carl. A. Thoresen[1] although it may not be effective against anaerobic corrosion. Concrete encasement can achieve medium to long term repair life spans 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

Concrete encasement protection or repair can be readily designed by engineers to appropriate codes and guidance. Piled jetty and pier design is currently covered by the British Standard for Maritime Structures BS6349[2]. 'Rigid' jetties are tied or braced horizontally, whilst 'flexible' jetties 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[3].

Eurocode 2[4] and BS EN 206[6] now offer a more rational approach to reinforced concrete durability than BS8110[5] taking into account a wider range of influences for the design of concrete and its durability. Eurocode 2[4] also appropriately calls for increased durability specification for marine concrete in tidal, splash and spray zones. For concrete encasement to provide a 50 year design life, a 20 mm surface tolerance is recommended for a pile jacket system with good spacer control in conjunction with a further 10 mm allowance for marine durability robustness. For increased durability, cement replacement with GGBS (CEM III cement[18]) has been used in conjunction with the low water cement ratio achieved using fabric formwork.

Steel Piles

Corrosion Risk


Fig. 3 – Anaerobic Corrosion

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 anaerobic corrosion (Fig 3) and ALWC (Fig. 1) are described in the I.C.E Maritime Board Briefings on ALWC[7] and on Concentrated Corrosion[8]. As the understanding of ALWC increases, the Briefing Sheet[7] states:-

> *"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"[2] classifies 0.08 mm average and 0.17 mm 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.

The 'Briefing Sheets'[7,8] and the 'Port Designers Handbook'[1] outline the expected causes of Anaerobic Corrosion and ALWC. Anaerobic corrosion is caused by microbic action and typically displays a bright orange corrosion product with general section loss throughout the water depth (Lerwick), although occasionally it is found in isolated patches. ALWC occurs at just above the low water zone (LAT) due to oxidisation corrosion forming layers of rust laminates. Fig 1 demonstrates ALWC after pile cleaning.

Corrosion rates are increased in high temperature regions, or with low pH levels, pollution, wave and current action, salinity, as well as other effects[1] or where poor quality steel has been used. Many jetties with steel piles are not monitored until holing visibly 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

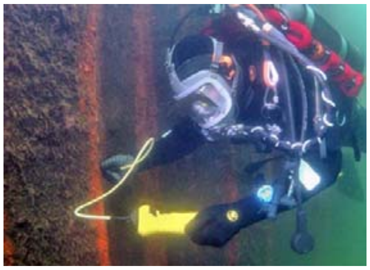
Fig. 4 – Thickness Monitoring

Historically, many steel pile structures have been designed with a corrosion allowance, typically in the order of around 5 mm[1,2]. Accelerated and concentrated corrosion rates from ALWC clearly threaten these structures in the short term. This threat can usually be managed by visually checking for the development anaerobic corrosion and steel thickness monitoring for ALWC using suitable measuring instruments. Initially this can be conducted quite simply and cost effectively from a boat at low water. 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 and weld elements due to differing corrosion performance. Extruded steel circular piles are typically 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 using safe diving procedures[10]. Where anaerobic or 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 case histories.

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'[2] 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[2,3]. Encased steel sections can be designed as composite construction to Eurocode 4[9].

Cover and Durability

The concrete cover to steel piles (Fig. 13), or any strengthening reinforcement (Fig.16), can be guided by modern reinforced concrete codes[4] and appropriate guidance[10,11,12,13,18]. 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 significant anaerobic 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 below an appropriate height at risk. The protection is usually taken up to the deck soffit with a concrete infill joint. Where an extended dry zone is present, a suitable paint treatment, overlapped into the encasement can be adopted, similar to Lerwick.

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


Fig. 5 – Reinforcement Cage

section basis[9]. 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. 5).

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. Above the splash zone, magnetite corrosion of hard rust laminates is often difficult to remove and often requires shot blasting or similar. Engineer inspection of the cleaning is important.

Cast Iron Piles

Corrosion rates for cast iron are much less than for mild steel and they are not known to suffer from anerobic or ALWC. Cast iron is mainly found in Victorian pier structures (Fig. 6). 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.

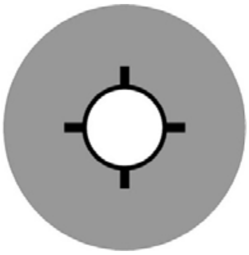

Fig. 6 – Encased C.I. Pile, Cromer

Reinforced Concrete Piles

Fig. 7 - Damaged R.C. Pile, Hunterston

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 (Fig. 7). Reinforcement corrosion is not generally found in the continuous immersion zone.

Condition and Corrosion Monitoring

The corrosion loss of reinforcement is usually determined by suitable trial breaking out and cleaning reinforcement to allow direct bar thickness measurement.

Protection

Where the structural loss of reinforcement is within acceptable limits, the section can be prepared, cleaned and encased in high quality concrete, with appropriate cover as previously described. A thickness of 75 mm is often adopted to the corners of small square pile sections with corner thickness increased to larger piles for robustness, See Odessa (Fig.19). Polypropylene fibres generally used in concrete encasement also aid the durability of concrete encasement to corners.

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 5 & 20).

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[13]. All rusted bars should be cleaned back to bare metal. Concrete cutting, removal and reinforcement cleaning is best undertaken underwater by appropriate hand held high pressure water jetting equipment. 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.

Timber Piles

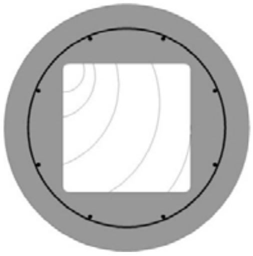

Fig. 8 – Timber Pile

Repair of timber piles by concrete encasement is not very common in the U.K. It is more widely used in North America[14] where timber piles are more common. Concrete encasement repair (Fig.8) 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

Fig. 9 – Concrete Encasement

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 construction,[15,16] within which, a C 20 mix can develop surface properties equivalent to that of a C50 mix.[17]

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 cement ratios are typically some 0.55 to 0.7 at the mixer.

Pre dried and blended micro concrete mixes are now often available with silo storage and mixing on site. This aids quality control and concrete availability during the works.

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[15]. This causes a significant increase in strength[15] (Fig. 10), chemical resilience, durability[17], and abrasion resistance. To replicate this process in mix development and quality control tests, the mix is usually placed

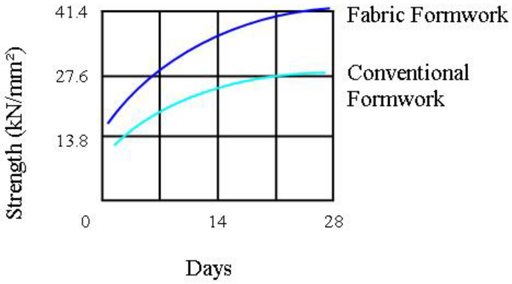

Fig. 10 – Bleed Strengthening

into 100 mm diameter fabric test socks to allow matching concrete 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, to aid durability.

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 a controlled 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. Dive teams should have continuous communication and video monitoring for effective quality control.

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
- Pump fill in tremie fashion
- Next day, remove ‘corset’

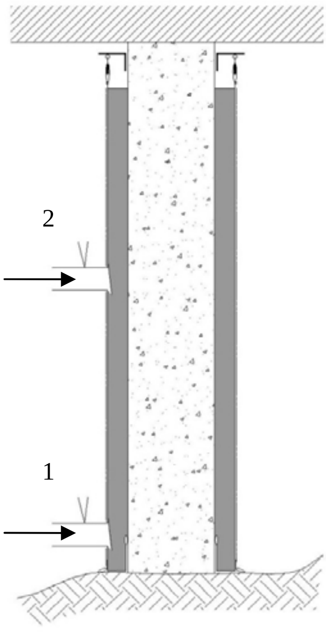

Fig. 11 – Vertical Section

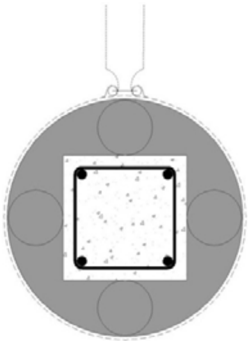

Fig. 12 – R.C. Pile

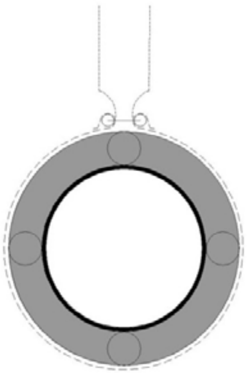

Fig. 13 – Steel Pile

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 prefixed. The jackets incorporate self-closing fillers, that importantly allow easy pump filling in submerged tremie fashion, and have a self-sealing turn ups at the bottom, to tubular piles. 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 recorded by diver camera. Mix segregation occurs at very low mix drop heights in water, and this risk must be managed.

The corset system was first used in Mombasa in 1988 and provides better surface and cover control. 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. The system is suitable for working on jetties in sheltered ports and harbours with wave heights during working periods to approx 0.5 m.

Pile jacket systems usually require a method statement, dive plan, 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

A new jetty was constructed in 1988 by Mowlem International for the Kenyan Navy (Fig. 2). It was immediately protected by concrete encasement using the pile jacket system (Fig.14) to cope with the mild pollution in the harbour. 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.

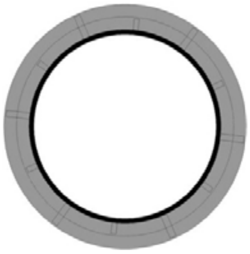

Fig. 14

Lerwick, Scotland

Consultant: Arch Henderson

In 1997/98, 186 piles to the Holmgarth (Fig. 15) and Gremista piers were protected full height with a 75 mm nominal thickness of sand: cement micro concrete encasement with polypropylene fibres. Anaerobic corrosion was evident to the piers and other harbour structures generally.

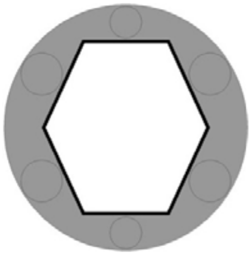

Fig. 15

Anaerobic corrosion was found to be significant through the immersion zone and particularly just above bed level possibly due to local pollution, so the protection was cast 0.6 m into the sea bed to protect against this.

Cork, Ireland

Consultant: Malachy, Walsh & Partners

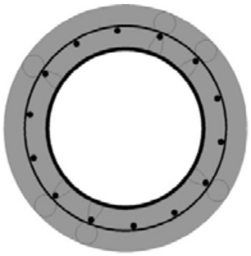

Fig. 16

By 2007, ALWC had holed many of the steel piles around low water level. From thickness surveys, the worst piles were prioritised and repaired in 2007, with strengthening by reinforced concrete encasement. A concrete thickness of 160 mm was used with a nominal 75 mm cover to reinforcement (Fig. 16). 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), to aid durability.

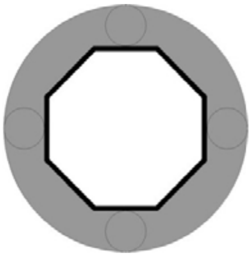

Fig. 17

Dublin, Ireland

Consultant: Jacobs, Babtie

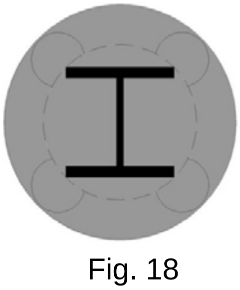

Fig. 18

The Bulk Jetty was built in 1950. The steel piles had suffered from ALWC with so many of the 13 mm thick coated Rendex piles holed by 2006 that the jetty was considered for demolition. 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 traditional 2:1 sand: cement micro concrete mix was developed to achieve 45 N/ mm² strength (C35/45) with polypropylene fibres.

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 from ALWC. 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.

Concrete Pile Case Histories

Odessa, Ukraine

Consultant: Proserve

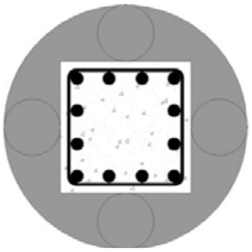
Fig. 19

Reinforced concrete piles, some 40 years old, and 400 mm sq. had suffered from the onset of reinforcement corrosion causing concrete splitting and spalling to 1.5 m above low water. Reinforcement loss was not significant, allowing it 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. 19). The micro concrete mix is a sand: cement mix, of 40 N/ mm² strength (C32/40) with polypropylene fibres.

Hunterston, Scotland

Consultant: Jacobs

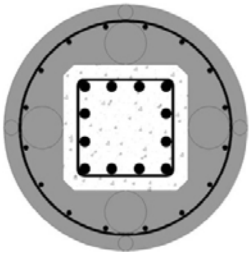
Fig. 20

The jetty piles had been suffering from reinforcement corrosion within the tidal range.(Fig. 7) Repairs currently underway are using a reinforced concrete encasement (Fig. 20). 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

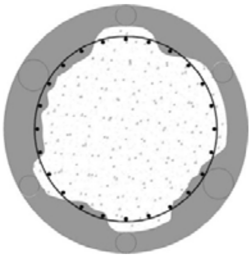
Fig. 21

The 1 m diameter R.C. jetty piles were formed using a colloidal concrete technique, leading to weak grout areas having been eroded away. The exposed reinforcement had only slight section loss. The piles were simply cleaned and encased with a 100 mm nominal thickness of plain micro concrete (Fig. 21) using a 1.2 m diameter pile jacket system. 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.

Acknowledgements

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