Fabric Formwork Systems Used In Marine Construction

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Fabric formwork systems are regularly used underwater to achieve controlled and reliable concrete and grout construction. Marine construction is much more onerous than construction on land and fabric formwork systems have developed to provide effective construction solutions. Principally, fabric formwork prevents concrete and grout washout and allows pre-made engineered forms to be placed and filled by diver or automation. The paper will describe the various aspects of fabric formwork technology and concrete construction systems generally developed to date with reference to case studies. It will also discuss the current and future prospects for both marine and land applications.

1 Fabric Formwork Technology

Significant use of fabric formwork for marine construction commenced in the 1960's after the development of synthetic yarns and fabrics. Systems were initially developed in North America and Europe using these higher strength fabrics.

Fabric formwork systems allow controlled and reliable concrete and grout construction underwater. The systems overcome marine conditions and are usually individually designed and purpose made. Fabric formwork systems are generally considered as lost shuttering and are usually of little interest after the concrete has set (other than the filter points of filterpoint mattress).

1.1 Benefits:

- Prevents mix washout
- System avoids segregation
- Controlled compartment size
- Engineered, premade, reliable
- Avoids trapped water voids
- Lightweight, easy to fix or lay
- Adaptable to bed profiles and joint widths
- Produces good quality grout and concrete construction
- Cost effective

Figure 1: Concrete Mattress Installation

Figure 2: Grout Bag Trial

1.2 Concrete Strength Improvement

Forms are made from a porous yet grout tight woven fabric which causes free water in the mix to bleed out through the fabric during filling and before initial set (Price 2000).This produces a lowering of the water : cement ratio in the surface zone until the mix ceases to be a fluid and reaches what is termed a mechanical set. This results in a significant rise in strength and abrasion resistance for sand : cement micro concrete mixes typically as shown in (Fig 3) (Cannon, 1987).

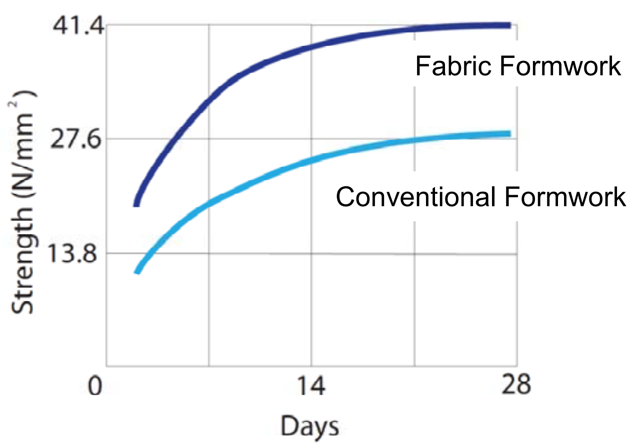


Figure 3: Free Water Bleed and Strength

For neat cement grouts the bleed depth is typically 50-100mm with greater bleed depth to sand : cement micro concrete mixes of typically 100-200mm. Traditional concrete mixes with larger aggregate have a lower bleed depth than micro concretes. Further research & measurement of bleed depths is needed.

2 Design Process

The forms are engineer designed to cater for the filling pressures, and to provide the required concrete section. Forms can be prefixed for automated filling to precast caissons and elements (Fig. 2, 4, 23 & 35) or laid and fixed by divers (Fig. 1).

Once the performance parameters are established for the concrete works and the form system, the design process for fabric formwork systems is typically shown below:-

Typical Design Process:

- General Arrangement Drawings
- Risk Analysis
- Installation Guide
- Fabrication Drawings
- Size and Shape
- Filler and Vent Position
- Joint Design
- Fabric Selection
- Form Strength
- Fixings
- Mix Design Development and Testing
- Mix Supply and Pumping Plant
- Filling Plan

Sewn seams are naturally the weakest part of forms and twin stitched seams are usually used for robustness and back up. Seams are designed and tested for reliability.

Segregation of the mix is avoided as filler sleeve discharge points are provided to the bottom of forms which ensures the mix is reliably placed in tremi fashion. Tremi placement of concrete or grout is where the bottom of the gravity tremi tube or pump hose is placed or controlled to be below the concrete or grout surface. Vents are located to the top of form compartments to control filling pressure (Fig 6).

General arrangement drawings are developed for the concrete work allowing fabrication drawings then to be produced for approval, manufacture and form check before delivery.

Project specific installation guides are developed in consultation with site staff and divers to typically cover mix design and development, mixing/pumping plant, fabric formwork installation and filling. Where required these systems can be tested (Figs 2, 4, 16) which is beneficial for site training, etc.

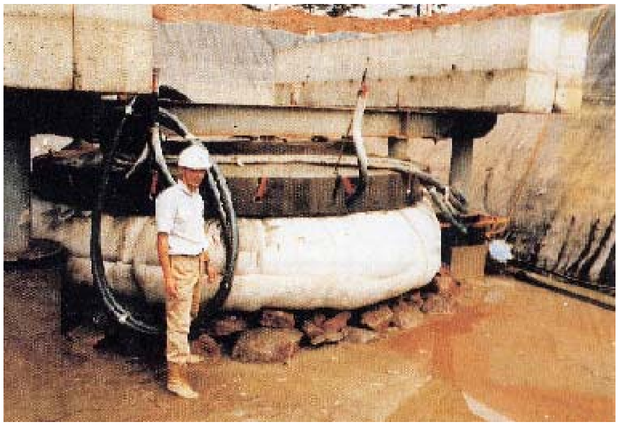


Figure 4: Grout Bag Trial Filling

Supervision and support on site by experienced Engineers is important. This often involves initial preparation works and initial concrete or grout construction works.

3 Fabric Formwork Material

The form material is usually a porous polyester / polypropelene woven fabric (Fig 7) which avoids trapped water voids and gives a high quality dense concrete finish due to free water bleed. The forms are engineer designed to provide the required concrete section and to cater for filling pressures. The unsupported side radii have a fabric tension (T) equivalent to the fabric radius (R) multiplied by the relative filling pressure, refer to (Fig 5 & 6).

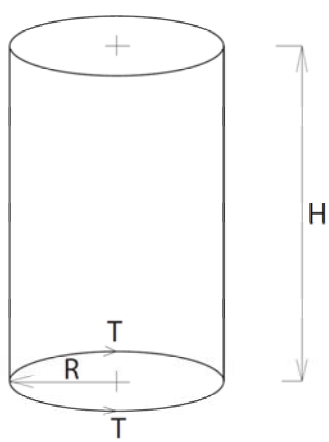


Figure 5: Column Form

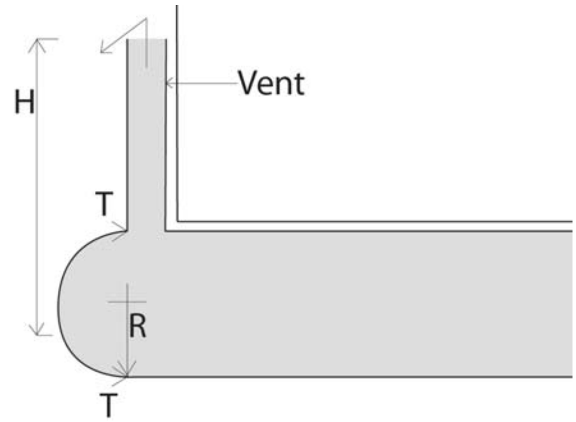


Figure 6: Foundation Grout Bag

Form Tension T (kN/m) = R x (ρ_C-ρ_w) H

Where ρ_c is the density of concrete and ρ_w is the density of water in kN/m^3.

Design safety factors are usually 3 to 4 due to maritime risks, local stress and importance of the work. There are no specific design standards or manuals to fabric formwork, requiring engineering based upon fundamental principles and experience.

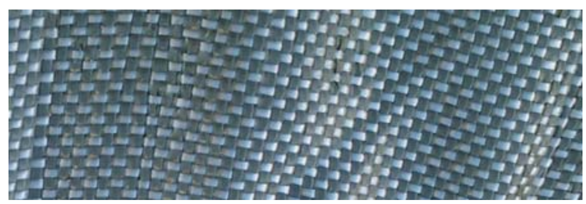


Figure 7: 1100 Desitex Fabric

For micro concrete (sand and cement) the fabric opening size O_{90} is usually controlled relative to the size of sand in the mix to ensure micro concrete tightness. In common with geotextile filter use, the 90% largest opening size of the fabric O_{90}, is usually less than the average sand size D_{50}. For neat cement grouts, it is common to use 2 layers of fabric for robustness or a much tighter fabric weave.

4 Marine Concretes and Grouts

Concretes and grouts need to be designed and developed for their particular application and to overcome marine conditions.

Mix Parameters	***Typical Mix Design & Control***
Strength & Durability	Mix design & testing
Mix Separation	Pumping/placement in tremi fashion
Avoid Mix Washout	Provide protective compartments where needed
Fluidity	Flow cone control (Fig 9), pumping/ filling trials where required
Fluid Period	Retard mix beyond filling period, control compartment size, site testing.
Top Laitance Layer (light grout layer)	Avoid horizontal joints between pours (back up systems)
Shrinkage	Shrinkage is reduced under water, only use additives where required
Thermal Cracking	Mix engineered where required
Environmental	Check pH rise and any local issues

Table 1: Mix Parameters

Mix design, development and testing is more complex and important for successful maritime work than on land, as it has to meet a wider range of parameters in more onerous conditions as outlined in (Table 1). The setting behavior of grouts and concretes is similar to on land. Underwater curing is beneficial with shrinkage behavior much reduced due to the near elimination of drying shrinkage.

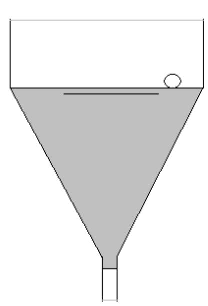


Figure 9: Flow cone

4.1 Traditional Concrete

Traditional concretes of stone aggregate: sand : ordinary Portland cement mixes can be used with fabric formwork for simple mass pours. Fluidity is limited for horizontal travel, and larger pumping hoses have to be handled underwater.

4.2 Micro Concrete

Micro concrete is a sand : cement mix with an aggregate size usually below 5 mm. This mix type has traditionally been used for concrete mattress scour protection work and other uses of fabric formwork where it protects from wash out. Historically, a 2:1 sand: cement mix has typically been used which has good fluidity for filling and good strength and durability. The free water bleed from the mix increases strength and durability (Fig.3) and along with curing underwater causes shrinkage to be minimalised. The selection of good local sands is important to achieve a reliably pumpable mix with good fluidity and self compaction properties.

4.3 Neat Cement Grouts

These mixes are often used with grout bag systems for the grouting of wide foundations or joints to precast elements or similar.

These grouts are highly prone to wash out, and in other than still protected conditions, are often used with grout bag protection. Mixes are highly fluid with compartment lengths up to 24 m achieved. Neat cement grouts are relatively easy and reliable to pump and are often chosen for important or irreversible construction. Typical strengths are 50 to 70 N/ mm².

5 Concrete Mattress

A two layer mattress form is pre laid and then pump filled with a sand: cement micro concrete. The permeability of the fabric allows excess mixing water to pass out through the shutter fabric resulting in a concrete which has a high strength, density and resistance to abrasion whether constructed above or below the water.

Concrete mattress can be fabricated to any shape or size. There are two main types of mattress ***Constant Thickness Mattress*** and ***Filter Point Mattress.***

5.1 Constant Thickness Mattress

Figure 10: Filled Constant Thickness Mattress

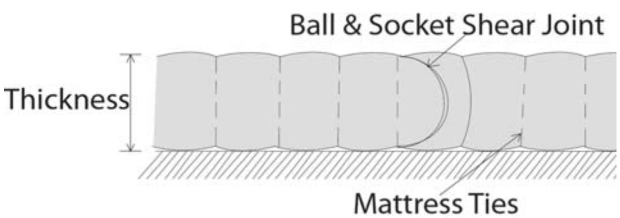


Figure 11: Section - Constant Thickness Mattress

Constant Thickness Mattress is formed from two layers of woven fabric, connected with ties of various lengths connecting the layers in order to control the thickness as the mattress is filled.

Mattress panel joints are made by stitching or zipping both top and bottom layers of fabric together. When filled, mattress joints take the form of a 'ball and socket' shear joint which allows some articulation of the concrete mattress slabs whilst providing important shear interlock.

5.2 Filter Point Mattress

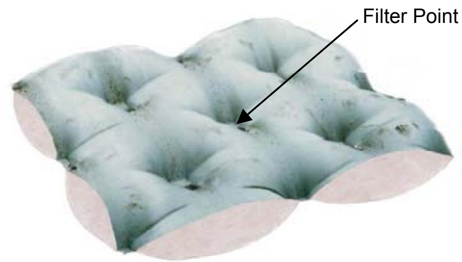


Figure 12: Filled Filterpoint Mattress

Filter Point mattress type has been used for some 50 years mostly to revetment slopes subject to tidal or wave action (Loewy et al. 1984, Pilarczyk 2000). The two layer fabric is woven together at regular intervals to join the fabric layers and also to form porous filter points. The filter points allow ground water pressures under the mattress to dissipate. For efficient use in wave action the mattress porosity should be greater than the revetment soil porosity (McConnel 1998). Mattress is often supplied in a green colour with mattress panel widths of 3m – 4.4m.

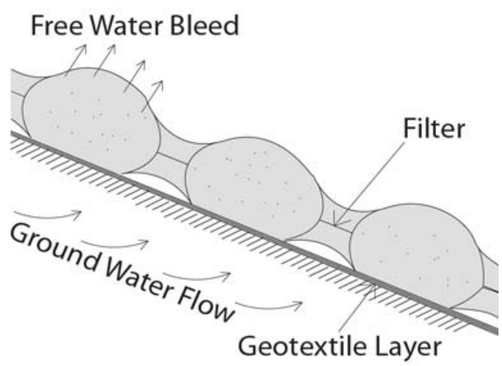


Figure 13: Section – Filter Point Mattress

This mattress is laid over a geotextile filter material to protect against filter point material loss due to UV light degradation or any other cause.

5.3 Concrete Mattress Design

Concrete Mattress in principally used for scour protection against the following actions.

- Current Flow
- Propeller or Jet Thrusters
- Waves

Unlike rock armour, concrete mattress does not fail in rolling or sliding, but generally in panel failure due to uplifting (Fig 14). Thickness wise it is much more effective and can readily cope with higher flows, propeller and jet action.

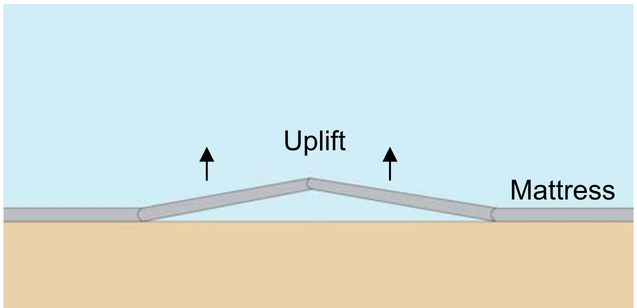


Figure 14: Mattress Failure Mode

Mattress thickness deadweight is designed to overcome the computed uplift/suction forces or by reference to proven performance.

5.4 Mattress Fabrication and Installation

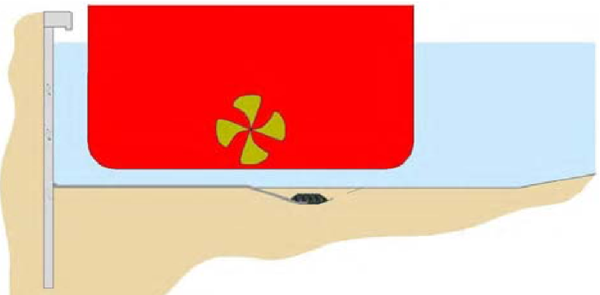
Mattresses are fabricated in workshops by cutting and sewing to form a mattress of a convenient size for handling, commonly 70 – 140m^2 (50 - 100kg in air). Each mattress is normally rolled out into position on a prepared stable slope or bed, zipped to its neighbour and any perimeter fixed as may be required. The mattress is then filled by pumping micro-concrete through the filler sleeves from the lowest end upwards.

Matts are normally pumped filled underwater by divers, typically a 2:1 sand : cement micro concrete mix of typical strength 35-40 N/mm².

5.5 Example: Port of Cotonou, Benin, Africa 2011

Constant Thickness Mattress was used to provide propeller scour protection to two new container berths at the port of Cotonou with a depth of 15m to accommodate larger container vessels. The scour apron was designed to resist the suction forces due to container vessel propeller action 240mm and 150mm thick constant thickness mattresses were used.

Figure 15: Section Through Quay Wall Showing



Mattress Bed Protection

Figure 16: Mattress Trial Filling on Site

A local micro concrete mix was developed and trialled with pumping and mattress filling trials (fig 16/17) initially. The mattress system was diver installed using the roll out technique and then pump filled automatically via pre installed lay flat hoses. 15,000m2 was installed in some 6 weeks using 2 large dive teams. A rip rap stone falling apron edge detail was provided to overcome edge scour in the sand and clay bed.

Figure 17: Lowering Mattress to be Rolled Out by Divers

5.6 Example: River Arun, U.K, 1968

Flood defenses were required on the tidal reaches of the River Arun. This was achieved by the addition of chalk rubble embankments, which were then protected from both tidal and river flow erosion using Filter Point mattress of 150mm overall thickness.

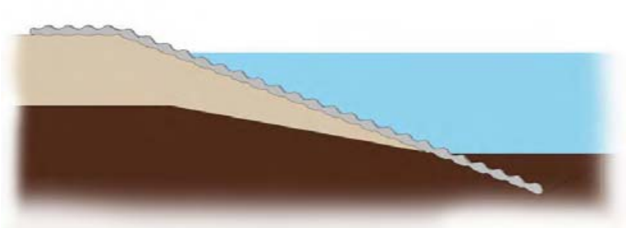


Figure 18: Typical Section

The mattress was designed to protect against erosion caused by currents up to 3.5 m/s and was installed in 1966 to 1968 giving 45 years of good performance to date.

Figure 19: Mattress Revetment Currently

Vegetation, in time, overgrows the top edge of the matt, and establishes itself in the filter points outside the tidal range of the river. This can be seen to improve the aesthetic qualities of the mattress.

6 Foundations to Precast Structures

Grout bag systems reliably provide infill foundations to precast elements in the marine environment (Hawkswood & Allsop, 2009). The forms are normally prefixed to the precast foundation element before immersion (Fig 23). When the element is held in its final position, the grout bag system can be pump filled (Fig 20 & 24). Figure 20 shows a typical section of a grout bag foundation showing the grouting method. The system can be engineered to offer the following:-

- Reliable grouting compartments
- Protection against washout
- Control of compartment size
- Control of filling and uplift forces
- Overcome undulating beds
- Risk management via multiple compartments

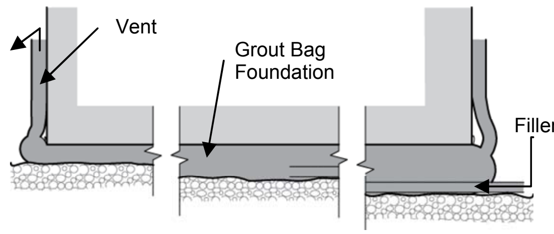


Figure 20: Grout Bag Foundations

Grout Bags are made from porous fabric which is grout tight yet water permeable and therefore avoids trapped water voids. They are often condensed with side break ties or diver release ties. Form compartments are zipped to one another whilst fixing for large bases. Once the element is lowered and positioned on jacks and/or temporary foundations, the compartments can be pump filled. Compartments are normally filled with neat cement grout or with sand cement grout/micro concrete. Filler sleeves sewn into the bottom enable filling in tremi fashion with grout travelling to the side vents. The side vents control and limit the compartment pressure which protects against failure of the grout bag and controls uplift pressures.

Figure 21: Grout Bag Trial

The system has been used for foundations on major marine projects for some 20 years. It can typically cope with bed tolerances of ± 150 mm to ± 450 mm. The system can be diver worked or completely automated with prefixed hoses, and grout monitors to the vents. The system can also be used to form seals and bearings to precast elements.

Grout bag foundation systems are normally developed using a risk management process where the mix, pumping and form systems are developed and where necessary tested (Fig 21). These systems usually require a high level of engineering and experience.

6.1 Example: Second Severn Crossing, UK, 1994

The Second Severn Crossing comprises a 5.2 km crossing of the Severn Estuary.

The foundations of the bridge were made of 37, 35m long precast concrete caissons, each weighing up to 2,000 tonnes each. Before these caissons were moved into their final position, fabric formwork units were positioned onto the underside of the caissons using high strength webbing, and held tight and condensed with stretch webbing so that they would be less likely to be damaged during positioning. This webbing was designed to break during the filling procedure.

Figure 22: Second Severn Crossing

Figure 23: Seals Positioned with Break Ties

Figure 24: Filled Seals at Base of Caisson

Each Unit was filled automatically from prefixed hoses and internal pressures were monitored and controlled by the vent tubes to confirm the complete filling of each unit. The system was used to found the caissons onto dredged rock head, and was designed to be part of the bearing area of the foundation. Once the units had been filled the caisson cells were then tremi filled with concrete to complete the base.

6.2 Example: ITT Central Artery, Boston, USA, 2001

The Fort point channel crossing to the 'Big Dig' project in Boston used a concrete immersed tube tunnel system. The grout bag system was used to form strip foundations to remote areas of the immersed tube.

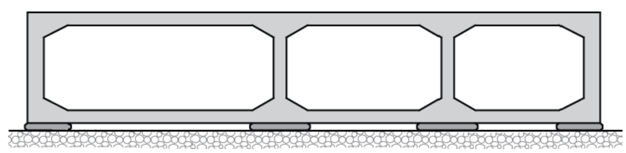


Figure 25: Strip Foundations

6.3 Example: Confederation Bridge, PEI, Canada, 1996

Figure 26: Bridge and Automated Installation Fram

The 13km sea crossing to Prince Edward Island used a precast bridge construction system. The pier foundations were formed by an automated installation frame for initial grout bag foundations, in water depths to 30m.

7 Marine Pile Repairs

The pile jacket system is used to protect, repair or strengthen steel and RC piles by encasement in high quality concrete (Hawkswood, 2011). The repairs can be designed for medium to long-term protection to prolong the lifespan of jetties and marine structures.

7.1 Typical Repair Engineering Process

- Condition surveys
- Structural appraisal of piles/ jetties
- Design of repairs
- Micro concrete mix development
- Supervise repairs

Steel Pile Repair Concrete Pile Repair

Figure 27: Section Through Repairs

7.2 Pile Jacket System

- Piles cleaned and repaired
- Fix spacers and any reinforcement
- Fix and zip up pile jacket (lost shutter)
- Fix re-usable Tensar 'corset'
- Pump fill in tremie fashion

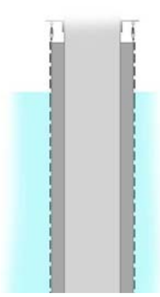


Figure 28: Completed Pile Repair Section

Importantly, as the porous fabric jacket causes the sand & cement micro concrete mix to bleed down to a water : cement ratio approaching 0.4, as outlined before this gives a significant improvement in durability against carbonation and chloride ion penetration (Price, 2000). It enables the design of efficient encasement protection using modern codes & standards.

As the fabric pile jacket remains in place, it provides protection for concrete curing above water. Pile jackets are relatively easy for divers to fix and can be adapted to a variety of pile shapes & lengths. Steel reinforcement can be included for pile strengthening where required. The bottom of the jacket can incorporate a self-sealing turn up and also self-sealing fillers that readily allow observation of pump filling in submerged tremie fashion which is very important.

These features and engineering enable a high durability concrete encasement to be formed that is robust and should require little or no maintenance for its design life.

7.3 Example: Bulk Jetty, Dublin Port, Ireland - 2006

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. The pile jacket system enabled strengthening and protection by concrete encasement and allowed the jetties use to continue.

Figure 29: Holed Pile Due To ALWC

The jetty piles had suffered from Accelerated Low Water Corrosion (ALWC) (Fig 29). Following a steel thickness survey and structural appraisal, the Consultant Engineers selected a 100mm thick concrete encasement with weakened lengths to be reinforced with steel sprit rings.

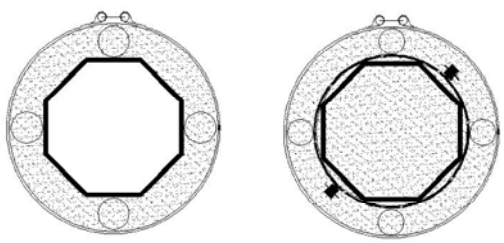


Figure 30: Section Through Pile With and Without Strengthening

A traditional 2: 1 sand: cement micro concrete mix was developed to achieve C35 /45 strength. Polypropylene fibres were included to aid shrinkage control. A site test was conducted on the strengthening arrangement to demonstrate the systems use.

Figure 31: Dublin Pile Repairs

The rendex steel section piles were 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.

8 Wall Construction

Walls are constructed and repaired underwater using fabric formwork facings attached to mesh covered frameworks formed in steel or aluminium. The fabric is usually removed after frame removal.

8.1 Example: Grand Canal, Dublin, Ireland 2007.

The stonework gravity walls to the historic dock basin were suffering from face failure underwater due to loss of its original weak lime mortar. An underwater concrete face repair was selected as the repair method, nominally 100 mm thick.

A 10 m long mesh control frame system was adopted which carried a fabric formwork face shutter connected to base and leading side grout bag seals.

Figure 32: Fabric Formwork Facing Attached to Framework

The frame was temporally supported by driven piles with rams to the bottom and drilled anchor ties to the top. The shutter system was filled with a sand: cement micro concrete. The bleed combination of the micro concrete mix and fabric face formwork quickly reduces concrete filling pressures and allows a lower weight frame system to be used.

Figure 33: Top of Concrete Wall Repair

It also produced a good quality concrete face repair which also in-filled failed stonework areas due to the high fluidity of the mix.

9 Other Marine Fabric Formwork Systems

Apart from the principal applications previously described, systems are often used to the following:-

- Foundation underscour repairs
- Pipe support and protection
- Seals to pipes and cofferdams

10 Risk Management

Marine construction has much greater risks than construction on land and a risk management approach is often adopted. The use of reliable factory made fabric formwork units can aid risk management. Also, the use of automated or near diverless systems also generally aids reliability.

11 Land Based Use

To date, land based use is relatively modest and apart from concrete bagwork, applications are mainly limited to providing solutions for confined space usage:

11.1 Concrete Bagwork

Used to waterways and for minor embankments support, often as temporary repairs.

Figure 34: Concrete Bagwork

11.2 Tunnel Seals

Fabric ring seals are grouted to aid the launch or recovery of tunnel boring machines TBM's. Condensed ring seals (Fig 35) are prefixed and held in place by a break cover which breaks upon grouting to allow the grout seal to develop.

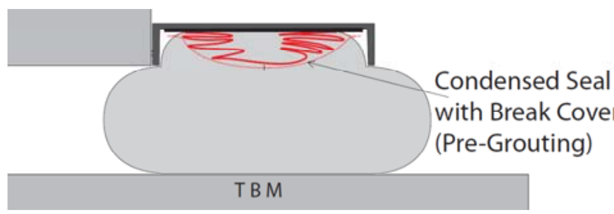


Figure 35: Grouted Ring Seal Section

11.3 Bearings

To bridges, slabs and propping etc.

Figure 36: Grout Bag Bearing

11.4 Mine- working Support

Grouted forms can be used to support old mine working without human access using drilled shaft installation. A condensed fabric form can be lowered into place on a tubular grouting shaft before grouting to form a concrete column.

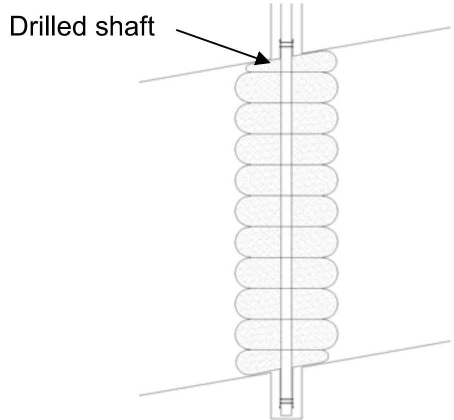


Figure 37: Fabric Formwork Support

11.5 Pile Liner

Specially woven fabric tubes are now being used to control pile concreting in soft grout. Fabric tubes can also be used to overcome negative skin friction caused by ground settlement.

Figure 38: Pile Liner (Courtesy of Huesker)

12 Future Use

12.1 Marine Fabric Formwork

The following areas need to be addressed in order to promote the continuing development of fabric formwork systems for marine concrete construction:-

- Increasing engineer awareness
- Concrete mattress efficiency for high flows
- Standards, manuals and papers developed for design
- Increasing trends towards precast construction (needing foundations/ joints)

An example of this is the MOSE, Venice Barrage project where a largely automated grouted fabric formwork system is being applied for the foundations to the barrage caissons in water depths up to 27m. The system overcomes tidal flows and allows controlled and accurate caisson founding, which is important for the flap gate barrage operation.

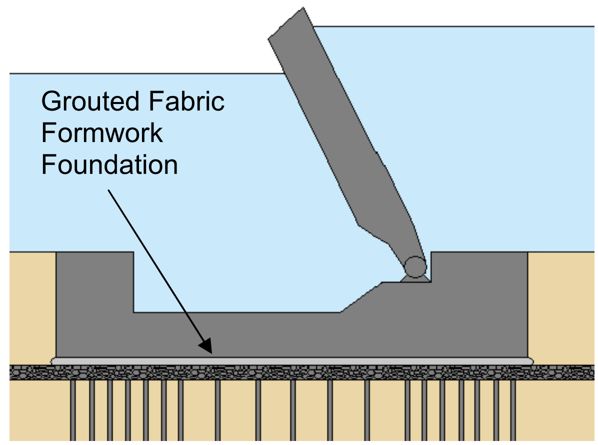


Figure 39: Venice Barrage

Although marine fabric formwork systems are becoming more common with more manufacturers worldwide, the marine sector is relatively small.

12.2 Land Based Fabric Formwork

Fabric formwork use on land has a much greater market, but to date there is relatively little usage developed. Simple forms can typically be provided for £8-11-/m² for larger projects in Europe.

12.2.1 Advantages

- Porous, bleed, greater durability
- Lightweight
- Reduced surface blemishes
- Fabric pattern
- Lighter support frames

12.2.2 Disadvantages

- Member junctions difficult
- Needs filling control
- Vulnerable to hot metal works
- Material elastic stretch
- Fabric pattern repair problem
- Fabric/ reinforcement snagging, wind action

Elastic Stretch is a constant problem to overcome with commercial polyester and polypropylene having an elongation at break of the order of 25%. For marine pile jackets, this is overcome with a stronger reusable corset or alternatively a more expensive fabric. On land the appearance is much more important than underwater.

The use of fabric formwork to provide an aesthetic pattern and also to form architectural shapes is known and research is pushing this area forward. Work is advancing on the use of minimised sections for material efficiency (*Orr et al. 2010).*

Fabric formwork may well be suited to precast construction in a controlled environment with trained teams. It is also very beneficial in areas of high R.C. exposure, marine structures and other structures subject to road salts etc. In these cases the improved surface strength and durability can be utilised. Alternatively, Engineers can of course specify increased concrete cover to reinforcement as Eurocode EC2. Fabric formwork has proven useful in confined spaces as It can be readily be condensed and this could be further developed.

Knowledge and experience from the marine sector can readily be applied to land based applications.

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