

MODERN CONCRETE TECHNOLOGY AND PLACEMENT METHODS AND THEIR INFLUENCE ON WATERPROOFING PERFORMANCE OF DIAPHRAGM WALLS

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SUMMARY

Embedded retaining walls are a well-established method to construct retention systems for deep excavations and to create a barrier against the inflow of groundwater. Several factors need to be considered when selecting the most suitable wall type to achieve compliance with the project requirements and specifications. The selection of the retaining wall type provides a direct link to the expected grade of water proofing performance which is the focus of this paper.

It should be noted that embedded retaining walls in general should not be assumed to be absolutely water tight as complete water tightness is neither practical nor economical. Even cast in-place concrete diaphragm walls with very low permeability can't be considered completely water tight despite having the least number of vertical construction joints of all embedded retaining wall systems. British Standard BS 8102:1990 clearly highlights the requirement of additional water proofing elements and methods to meet the relevant water proofing levels for such walls and basements in general. However, unless the diaphragm wall (or other wall type) itself provides adequate and realistic water retention performance, the performance of the additional tanking can be put at risk, too.

The required performance criteria for fresh tremie concrete to be used for the construction of diaphragm walls, must be selected to achieve optimal concrete density to fully comply with the expected structural, durability and water proofing performance criteria of the entire basement.

INTRODUCTION

Expectation and perception on water proofing performance and 'water tightness' of basement structures can differ significantly amongst stakeholders. Therefore the requirements and construction limits of different retaining wall systems must be clearly understood and defined during the planning and construction stages of a basement. Designers, builders, concrete suppliers and piling constructors have to work together and select carefully between various stiff and more rigid embedded retaining wall options to achieve the desired outcomes and to satisfy structural and waterproofing performance criteria of the entire basement structure.

There has been little clarity and guidance on definitions concerning the levels of water and vapour migration through the joints and surface of embedded retaining walls. This has led to wide spread misperceptions and misunderstandings about the achievable, realistic and economically feasible degree of 'water tightness' of embedded retaining wall structures. The construction method to be applied and the appropriate water proofing performance in comparable environmental conditions (especially with respect to ground water levels, tidal influences, soil conditions, underground obstructions, etc.) have to be considered for a realistic assessment of the expected water proofing performance of the planned basement structure.

As briefly summarized in in Table 1, different embedded retaining wall types provide different levels of structural, water proofing and durability performance.

Table 1. Types of embedded retaining walls and their corresponding performance criteria

| Aspect | Wall type | | |
|----------------|---|---|--|
| |  Sheet Pile Wall |  Secant Pile Wall |  Diaphragm Wall |
| Water proofing | Good with joint treatment | Satisfactory with some seepage and wet patches | Excellent with water bars across panel joints |
| Durability | Coating and sacrificial steel thickness | Tremie concrete and internal lining for long-term seepage | Tremie concrete and internal lining for long-term seepage |
| Wall movement | Flexible | Stiff | Very Stiff |

The number of vertical joints per m² of wall surface area is an important indicator to assess the extent of seepage through the wall and joints. Diaphragm walls have only two vertical joints per panel length (usually 6m long). Secant pile walls on the other hand, with comparable stiffness and equivalent wall thickness have usually one vertical joint every 0.6m to 1.0m, depending on pile diameters and spacing, increasing the extent of seepage and risk of leaks significantly. Figure 1 shows the typical water proofing performance which can be expected from a diaphragm wall and a secant pile wall, constructed next to each other in similar soil conditions with high ground water tables. Seepage and wet patches along the vertical joints are clearly visible, especially at the joints between the individual secant piles and the construction joint which separates the two wall types.



Figure 1. The diaphragm wall section (left) has fewer vertical joints per m² of wall surface, which provides superior water proofing performance than the secant pile wall section (right)

It is important to understand the required concrete technology and appropriate placement methods for the accurate construction of diaphragm or secant pile walls. The application of both, state of the art material technology and best practice workmanship, is critical to achieve optimal water proofing and structural performance of embedded retaining walls and basements.

Specification of Embedded Retaining Walls (SPERW) 2007

The Institution of Civil Engineer's (ICE) *Specification of Embedded Retaining Walls 2007* (SPERW 2007) was developed to provide guidance with respect to the expected water proofing performance of embedded retaining walls. The specification considers an embedded retaining wall element to be 'watertight' even though some seepage is allowed to occur as described below. The document also highlights that any joint or wall element of an embedded retaining wall should not be considered 'watertight' if the following criteria are not met:

- (a) No weeping water or greater rates of water ingress between the top of the wall and Water Tightness Assessment Level (WAL). Beading and damp patches are permitted.
- (b) Damp patches that do not exceed 10% of the visible area of the front of the wall and no individual patch should exceed 4m²

SPERW (2007) also provides the following important definitions and clarifications:

- *'Water Tightness Assessment Level' (WAL) is the lowest level visible on the front face of the wall at the time of the water tightness assessment.'*
- *'Damp patches leave behind a slight film of water on the hand rather than droplets of water.'*
- *'Beading of water leads to individual droplets of water that form on the surfaces; they do not coalesce and hence water does not flow.'*
- *'Weeping of water comprises a state whereby droplets of water coalesce and thus they develop water flows down the wall.'*

SPERW (2007) also provides a useful direction to achievable water retention capabilities of embedded retaining walls and their direct correlation with the overarching system of BS8102:1990. With respect to additional components of waterproofing, usually outside the scope and capabilities of embedded retaining walls constructed in accordance with best practice and standard industry standards (examples are shown in Table 1), SPERW (2007) provides guidance in terms of water proofing performance of basements and corresponding criteria for the relevant retaining wall components as stated in Table 2.

Table 2. SPERW definitions of water proofing requirements in accordance with BS 8102:1990

| BS 8102 requirements for the whole system | | Corresponding criteria for retaining wall component |
|--|--|--|
| Grade of basement | Performance level | |
| 1 (basic utility) | Some seepage and damp patches tolerable | Beading and limited damp patches tolerable. No weeping. |
| 2 (better utility) | No water penetration but moisture vapour tolerable | Beading and limited patches tolerable. No weeping. Other components will be needed in addition to the wall component to achieve the required water tightness of the whole system. |
| 3 (habitable) | Dry environment | |
| 4 (special) | Totally dry environment | |

It is important to note that except for the basic utility grade of basements, the design and planning process must be extended to include additional waterproofing elements and components in order to achieve the desired 'grade of basement' as outlined in BS 8102:1990. Consequently, basements with requirements higher than the basic utility grade need additional, external water proofing components beyond the diaphragm wall panels themselves, individual secant piles, sheet piles and subsequent joints. The additional components can include but are not limited to, tanking, drains, epoxy coating, drained cavity walls and/or floors.

Diaphragm walls

Diaphragm walls are cast in place embedded retaining walls consisting of individual panels excavated from existing ground levels. These panels are typically between 6m long and vary in thickness from 0.6m to 1.5m, depending on structural and water proofing requirements. Diaphragm wall panels can be constructed up to 100m depth if used for shafts or dam remediation works. For basement structures this wall type is usually built up to 25m depth, depending on ground conditions, wall deflection limits and the required lateral support system.

Diaphragm walls are very attractive for deep excavation support systems in excess of two basement levels. They can be installed within tight construction tolerances and, as shown in Table 1, they offer high structural stiffness and excellent water retention performance. The typical construction sequence of an individual diaphragm wall panel is shown in Figure 2.

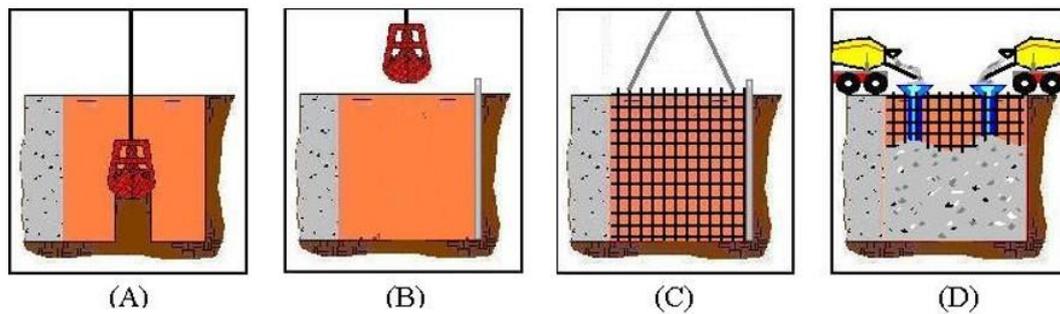


Figure 2. Typical construction sequence of a diaphragm wall panel – (A) panel excavation, (B) recycling / replacement of drilling fluid and placement of stop-end with water-bar, (C) reinforcement cage installation and (D) concrete placement using the tremie method

Waterproofing performance

In general, similar properties which make concrete less permeable also make it more watertight. Therefore, the reduction of the permeability of the hardened concrete will reduce chloride ingress and improve the overall durability of the hardened concrete. Fine particles like silica fume have the ability to fill micro voids inside the concrete matrix and to increase the concrete density. However, the subsequent side effects of such additives need to be considered carefully, especially with respect to concrete placement requirements (e.g. reduction of viscosity).

Diaphragm walls are considered the ‘most watertight’ embedded retaining wall system available to be built using cast in-situ concrete, primarily due to the low number of construction joints and the option to seal the joints with ‘water-bars’ (Figure 3). Such additional barriers (or ‘water stops’) are installed in-between the individual panels to provide enriched water tightness.



Figure 3. Different ‘stop-end’ profiles showing varying profiles with the purpose to extend the potential flow path of water along the joint (left). Water-‘stops’ are installed inside the joints.

The finished surface of a diaphragm wall panel is obviously not an architectural feature. The concrete is placed inside a deep and narrow trench filled with bentonite or another drilling fluid. The concrete is placed using the wet tremie method and cast against the walls of the trench which consist of soil and rock, acting as 'formwork' of the wall. Figure 4 provides typical finished surfaces of various diaphragm wall constructed in ground conditions with high ground water tables, soft soil conditions and narrow walls with only 0.6m wall thickness.



Figure 4. Selected narrow diaphragm walls constructed in soil conditions with high ground water tables showing minor damp patches, thus providing adequate 'water tightness'

There are visible leaks and wet patches along the vertical panel joints, albeit the addition of water bars inside the vertical joints. According to SPERW (2007), these walls are being considered to be 'watertight', even though some of them needed additional drains and tanking in front of the walls to comply with BS8102:1990 water proofing requirements. Wet patches and moisture can be observed some distance apart from the vertical panel joints. These patches can be related to restricted concrete flow as a result of congested areas of reinforcement, unsuitable drilling fluid performance, insufficient concrete technology or a lack of best practice during placement.

The installation of ground anchors can damage the integrity of the diaphragm wall as shown in Figure 4 (far right) and thus directly influence the water tightness of the basement. It is important to consider appropriate measures as part of the construction methodology for the ground anchors to be installed in soil conditions with high groundwater levels.

Concrete placement using the tremie technique

The construction of diaphragm walls is virtually a blind operation where a deep and narrow trench which is excavated under bentonite or polymer slurry. Heavy reinforcement cages (up to 30 ton weight) are lowered into the trenches and concrete is placed afterwards. All processes require in-depth knowledge of the soil conditions on site, drilling fluid and concrete technology and relevant placement techniques. Advanced quality assurance is critically important.

Casting of each panel is carried out using the wet tremie technique (Figure 5). A steel pipe with a hopper or chute on top and consisting of several jointed lengths and watertight joints is assembled, lowered down into the open trench and is then placed at the bottom of the excavation. Vermiculite or another suitable separator is placed inside the tremie pipe, floating on top of the drilling fluid, before the concrete is discharged into the hopper. The fluid level inside the trench must be close to ground level to avoid free falling concrete between hopper and separator. The tremie pipe is not sealed at the bottom (and consequently filled with drilling fluid) and the outlet is suspended about 200-300mm above the bottom of the excavation. When concrete is discharged into the pipe, the separator divides the concrete from the drilling fluid to avoid mixing or inclusions of fluid into the concrete. Concrete is discharged in the hopper continuously and the tremie pipe has to be filled with concrete throughout the entire pour.

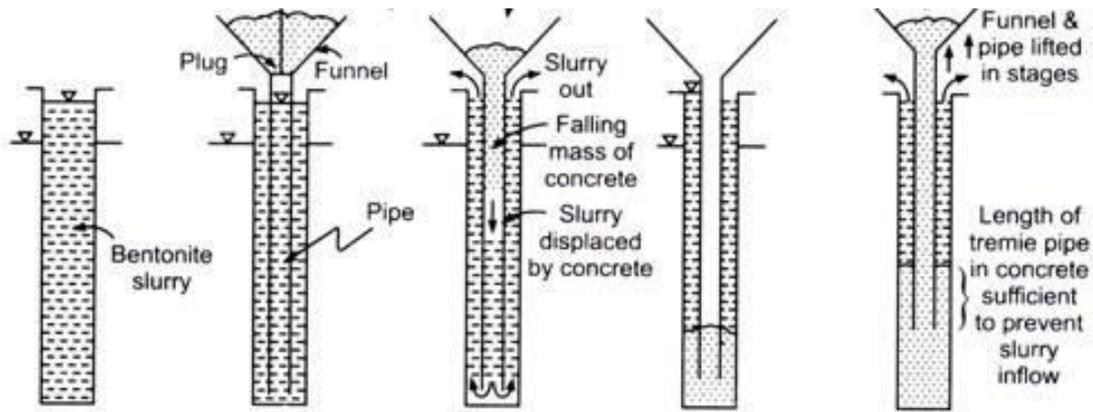


Figure 5. Typical tremie pour for a diaphragm wall panel installed under bentonite fluid

Concrete should flow through the tremie pipe only by gravity, never be placed under pressure. The level of the leading front of the concrete, raising inside the panel, is monitored at appropriate intervals. As the concrete rises, the tremie pipe should be withdrawn in sections to improve flow, ensuring that a minimum immersion of 2 m of the tremie pipe into the concrete is maintained at all times. If the tremie pipes is withdrawn during the pour, placement must be stopped and the pipe shall not re-immersed into the fresh concrete to avoid fluid inclusions into the already placed concrete. Embedment should not increase 5m as concrete flow might stop due to a possible lack of hydraulic head inside the tremie pipe. Concrete placement shall continue in an uninterrupted manner until the panel is completed and sound concrete is at the required top level of the element, which is usually well above the design concrete cut-off level, over-pouring height of at least 1m is recommended to trim back the contaminated concrete.

Concrete flow inside the panel (from bottom to top)

During the placement process using the tremie method, concrete displaces the drilling fluid and rises inside the diaphragm wall panel as shown in Figure 6. Flow resistance is built up between the concrete flowing upwards, the reinforcement and the surface of the excavation.

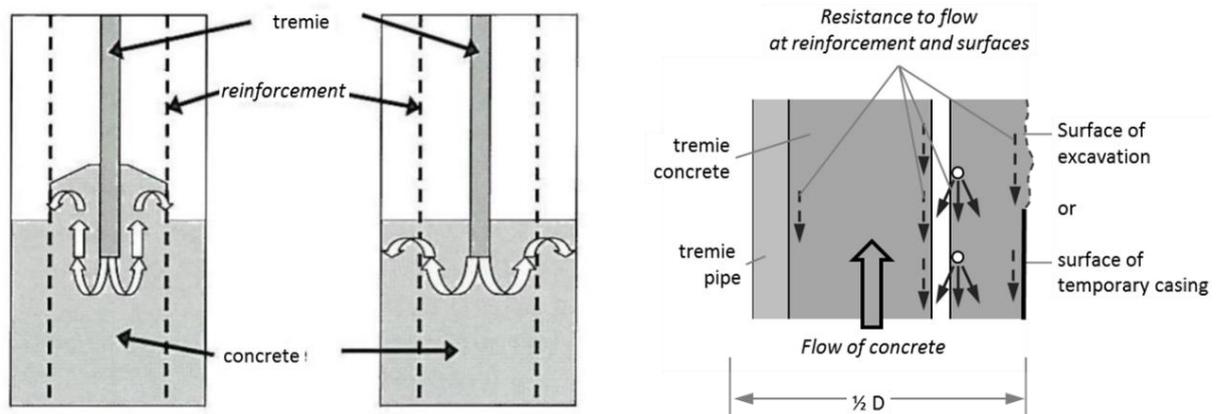


Figure 6. Risk of concrete rising faster inside the reinforcement causing fluid inclusions in the cover area (left) and schematics of 'resistance of concrete flow' during a tremie pour

Due to the shape of the panel and the friction between the rising concrete front, the reinforcement bars and the surface of the excavation, the velocity profile of the concrete is unbalanced. There is a significant risk of concrete rising too fast inside the reinforcement cage and then 'falling' through the openings of the cage into the concrete cover section, instead of filling up the entire cross section of the panel horizontally by flowing around 'obstacles' easily.

Current research at University of Queensland has revealed that the general flow behaviour of concrete under fluids is reduced. Trials have shown that slump and spread test results carried out in dry conditions were about 20% higher than those carried out in submerged conditions.

Concrete technology

In order to achieve dense concrete with low permeability, excellent durability and optimal water proofing characteristics, concrete flow in diaphragm wall panels (and in bored piles placed under fluid) has to meet specific performance criteria. Such concrete shows distinct rheological behaviour with respect to yielding, viscosity and slump retention times. During the tremie placement process the fresh concrete must displace the drilling fluid inside the panel, 'squeeze' itself through tight openings (reinforcement cage) and needs to fill voids to ensure bonding and sufficient concrete cover. Furthermore it must be self-levelling to avoid inclusions (Figure 6) and self-compacting to ensure optimal density and permeability. With the development of advanced concrete admixtures and additives in the past decade, modern concrete technology offers new opportunities to achieve performance criteria which seemed impossible in the past. Compressive strength results of 85MPa (Larisch 2009) with low water binder ratios have been successfully used for deep foundation applications. High binder contents and the replacement of Portland Cement with supplementary cementitious materials like flyash, slag or silica fume were utilized to improve the durability performance of such concrete mixes.

It is important to note that after the placement of the concrete inside the excavated diaphragm wall trench, the concrete quality (density) can't be further improved. External vibration of tremie concrete is not permitted and would cause undesired effects like drilling fluid inclusions as well as segregation, where larger sized aggregates travel to the bottom of the trench. Modern tremie concrete mixes for diaphragm walls (and bored piles) need to display the following fresh concrete workability attributes to achieve the required characteristics for optimal density:

- (a) Flow-ability: The ease of flow of fresh concrete when unconfined by formwork or any other obstacles such as reinforcement.
- (b) Passing-ability (blocking resistance): The ability of fresh tremie concrete to flow through tight openings such as spaces between reinforcing bars without segregation and blocking.
- (c) Filling-ability: Concrete flows into the excavation and completely fills all its spaces.
- (d) Self-compacting behaviour: The process during which the concrete de-aerates and compacts as a result of concrete head pressure and without any external vibration.
- (e) Self-levelling: The concrete flows to a virtually uniform horizontal level under gravity.

These important fresh concrete attributes need to be measured and quantified, so that suitable mixes can be reliably replicated with different aggregates and admixtures in different places. The current approach to quantify workability for tremie mixes for diaphragm walls relies mainly on the slump test alone, which is insufficient to reflect the complex behaviour of modern tremie concrete as described above. The slump test measures the horizontal collapse of the fresh concrete after lifting the cone. Therefore, only limited conclusions about the overall workability performance for concrete placed under fluid can be drawn by using this test method alone.

Figure 7 shows the rheological behaviour of tremie concrete in comparison with 'normal class' and 'self-compacting' concrete (SCC). As a Bingham material, fresh concrete requires a certain amount of energy (yield stress) to start moving before it resists this movement by viscosity. These two key rheological parameters vary for different concrete types and applications. 'Normal class' concrete needs to be compacted by external vibrators and has both, a high yield stress and high viscosity. SCC requires very low yield stress for self-levelling and compaction by self-weight alone. Tremie concrete requires a low viscosity for a good filling-ability at a relatively high cohesion, which is represented by the higher yield stress value, for the unhindered displacement of drilling fluid and for controlling segregation under pressure.

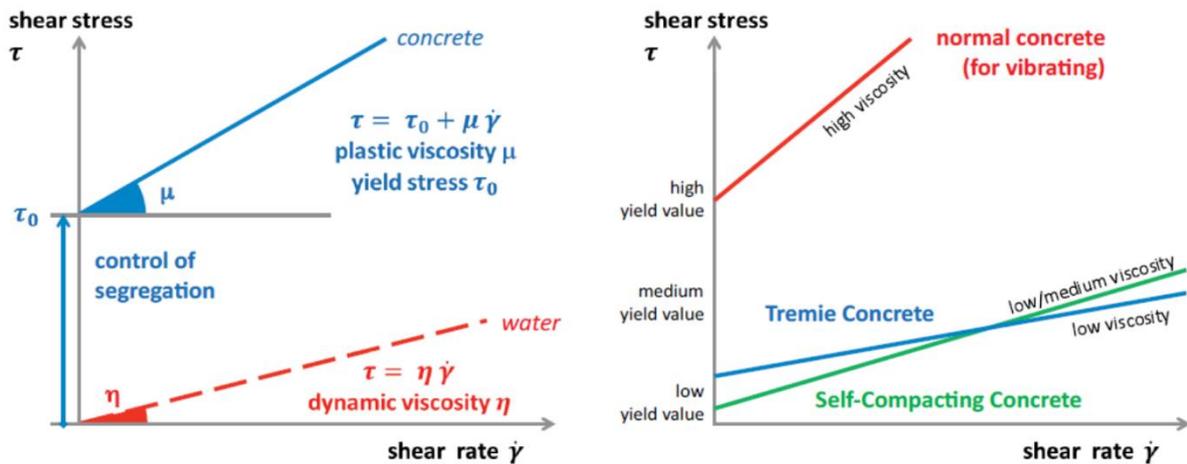


Figure 7. Rheological behaviour of concrete in general (left) and for different concrete types (right), after *EFFC / DFI Best Practice Guide to Tremie Concrete for Deep Foundations*, 2016

It is obvious that the rheology of fresh tremie concrete for diaphragm walls (and bored piles) can't be adequately measured using 'normal class' concrete performance and testing criteria. It is closer related to SCC and therefore relevant fresh concrete performance tests like L-box, spread, T_{500} and VSI should be utilized to measure performance criteria of tremie concrete more reliable than the slump test alone (Larisch et al. 2013). The general workability performance of a tremie mix can be measured with the L-box test, which also gives a good indication about the expected 'filling-ability' and 'passing-ability'. After passing the bars which obstruct the undisturbed concrete flow after opening the gate, the matrix of the fresh concrete has to 're-bond' and keep flowing until the end of the L-box is reached (Figure 8).

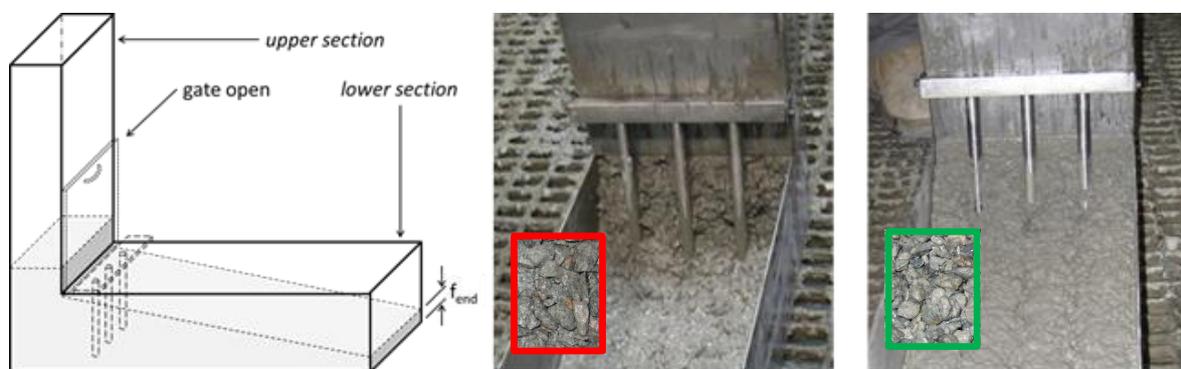


Figure 8. Schematics of the L-box test (left), effects of the aggregate shape on the passing-ability of a highly flow-able tremie mix (centre, right)

It should be noted that the aggregate grading and shape has a great influence on the behaviour of tremie concrete workability in general and passing-ability in particular, as shown in Figure 8. As displayed, the rounded aggregate was able to pass the L-box obstructions with ease and reached the end of the horizontal L-box section. The same concrete mix design using 'sharp and flat' aggregates, 'bridged' between the bars of the L-box and concrete flow was obstructed, not reaching the end of the L-box and showing signs of segregation. Both concrete mixes had similar w/c ratios, binder, aggregate and admixture contents as well as very similarly T_{500} times (about 4 seconds) and almost identical spread values of around 550mm.

In addition to excellent workability, outstanding concrete stability is required for a suitable diaphragm wall mix. Stability refers to the ability of a fresh concrete to maintain the required workability under the specific conditions, such as under a certain hydraulic head pressure (like

inside a diaphragm wall panel). The fresh concrete stability controls the concrete's segregation, bleeding, filtration and thixotropic behaviour, all of which are required to be restricted.

Fresh concrete placed inside a diaphragm wall panel (or bored pile) is subject to significant hydraulic pressure, exerted by the self-weight of the fresh concrete and providing compaction to the fresh concrete inside the panel. This pressure is about 0.25 bar per meter depth and it will 'squeeze' water out of the fresh concrete matrix. The amount of 'bleed' water under pressure needs to be limited to avoid the formation of 'bleeding' channels inside the panel or along the reinforcement bars, jeopardizing structural, durability and water tightness of the structure. In addition, the concrete matrix will change its rheological performance after the loss of water and concrete workability will be reduced respectively, moving towards a 'normal class' concrete behaviour. Figure 9 shows the fresh concrete pressure inside a diaphragm wall panel and the filtration test apparatus to measure the expected water retention ability of the concrete. The test measures the amount of filtrate water loss over a pre-defined time period. It also produces the 'filtration cake', which is the concrete placed at the bottom of the test cylinder which experienced water loss in its matrix (as a result of the pressure applied) resulting in changed rheological behaviour (Figure 9). It should be noted that bleeding under pressure can't be avoided completely, the volume of filtrate should be limited to about 10 litres per m³ of concrete and the size of the 'filter cake' to about 100mm length.

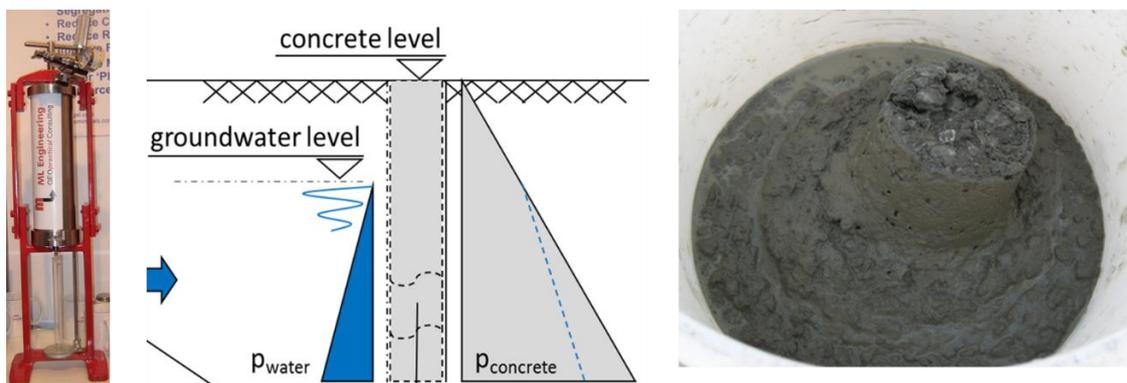


Figure 9. The filtration test apparatus (left) helps to detect tendencies of concrete bleeding under pressure in fresh concrete (centre) which results in changes in rheology, effecting flow

Summary

Embedded cast in-situ concrete retaining walls like diaphragm walls or secant pile walls are not completely 'watertight' structures, even though they usually show good water proofing performance. According to SPERW 2007 they can be defined as 'watertight' despite some leaks and wet patches are permitted. Depending on the required water proofing performance for the entire basement, additional measures like tanking, drainage channels, surface coating or others might be required to achieve the project specific criteria as defined in BS8102:1990.

Diaphragm walls can exhibit excellent water proofing characteristics if best practice construction methods are followed and appropriate concrete technology is utilized. Highly workable concrete mixes with specific rheological characteristics like optimum yield points, low viscosity, excellent stability and extended slump retention periods are required for the construction of dense, low permeable concrete to meet structural standards. Aggregate shape and grading are as important as the right admixture strategy to achieve these objectives.

It is recommended to review the required thickness of diaphragm walls and to consider thicker walls for improved water proofing and structural performance. Despite the application of best practice construction methods and sufficient fresh concrete rheology, thin wall panels very

often impose high risks of reduced concrete flow due to very dense and ‘congested’ reinforcement cages and anchor ducts. This has resulted in severe integrity issues effecting water proofing, durability and structural performance criteria (author’s personal experience). Costly remediation works were often required to repair unforeseen leaks and water ingress.

In 2012 the Concrete Institute of Australia has published a guideline for ‘*Tremie Concrete for Deep Foundations*’. The documents provides advice and guidance on performance criteria for tremie concrete in general and for special applications in diaphragm walls and bored piles installed under drilling fluids in particular. Recommendations derived from this guideline, combined with the author’s personal experience are shown in Table 3. The suggested values should be used for a first assessment only and project specific requirements must be established to govern and control the final concrete performance criteria for each individual project and application.

Table 3. Recommended performance criteria for tremie concrete for diaphragm walls

| Test Method | Recommended Value |
|---------------------------------|--|
| Slump, spread, VSI Tests | |
| Slump test (actual) | H > 220mm |
| Spread test (actual) | D = 500 – 600mm |
| T500 time | T ₅₀₀ = 3.0 to 5.0 seconds |
| Visual Stability Index (VSI) | 0 |
| L-box Test | |
| L-box test | Reach the end of the L-box |
| L-box time | Reach the end of the L-box within 12 seconds |
| Filtration Test | |
| Filtration loss | V _{loss} < 15ml (equivalent to 10l/m ³) |
| Filtration cake length | V _{cake} < 100mm |

Further research and strong collaborations between industry and academia are necessary to further improve concrete technology for tremie concrete with the aim to improve water proofing performance of diaphragm walls and basement structures.

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