THE DESIGN AND CONSTRUCTION OF VERY DEEP EXCAVATIONS – RECENT DEVELOPMENTS

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ABSTRACT

Technical advancements in construction plant, materials and numerical analysis tools have made possible a step change in the achievable depth of excavations required for infrastructure, building and mining projects. This has been in response to an increased complexity in such projects particularly in connection with rail, water and power infrastructure sectors around the globe. Such advances do not come without some risks and a clear understanding of the limitations of the techniques, capabilities of construction monitoring and the benefits of practical design details are key to successful execution. In addition, a sound knowledge of the behaviour and testing of materials particularly fresh concrete and support fluids is essential in the minimisation of defects in deep earth retaining structures, which can be extremely costly to remediate.

This paper considers the state of the art in the construction of very deep and complicated excavations by making reference to a number of recent case histories, where records have been broken and new technologies have been deployed. The construction of diaphragm walls to depths well in excess of 100 m and with wall thickness of 1800 mm and using concrete with a 28-day cube strength in excess of 60 MPa are now possible, provided great care is taken. Improved verticality tolerances of better than 1 in 400, coupled with precise monitoring and advanced design techniques, means that the structural capacity of earth retaining walls in shaft construction have increased significantly which has led to the realisation of deeper excavations, together with deep openings which may be necessary for associated tunnels.

The author will also include the presentation of recent improvements in safety both in cage lifting, handling and splicing as well as around open diaphragm wall excavations. A better understanding of the causation of defects in concrete which has been placed under support fluid via a tremie, has been gained through painful experience and has greatly benefitted from the recent publication of useful guidance in Australia, UK and by the EFFC (European Federation of Foundation Contractors). This has led to a number of new site tests on fresh concrete for mix stability and bleed potential which are gaining increasing traction in the industry. In addition, the introduction of more stringent testing on support fluid such as bentonite during excavation means that instances of defects including leaks, inclusions and areas of poor concrete cover can be reduced. However, despite the availability of extensive guidance on good reinforcement cage detailing for diaphragm cages, examples of poor practice still remain, with great potential to lead to extensive defects such as mattressing which may compromise the durability of permanent works. The author will highlight examples of good and bad practice.

1 INTRODUCTION

The requirements of new transportation infrastructure in road and rail to be threaded beneath existing assets has led to the development of deeper excavations in increasingly challenging ground conditions for cut and cover approaches and shafts for ventilation as well as TBM launch and reception. For example, on the Tuen Mun – Chek Lap Kok Link Project in Hong, a 500 m long section of highway tunnel was constructed within a 43 m deep excavation within a cellular diaphragm wall also known as the "Caterpillar" comprising 15 interlocking cells (Schwob, 2019). Other new infrastructure projects for stormwater storage have also required exceptionally large shafts for pumping stations, for example the Lee Tunnel Project in the UK (Stanley, 2014) which included the construction of five very deep diaphragm wall shafts up to 98 m deep with the deepest for a pumping station 38 m in diameter and an excavation depth of 86.5 m. Meanwhile in countries such as Mexico twelve level basements have been constructed for car parking for commercial buildings. Finally, in a somewhat unusual application a diaphragm wall shaft of 120 m depth was fully excavated as part of a mining project in the UK.

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2 CONSTRUCTION PROCESSES ASSOCIATED WITH VERY DEEP EXCAVATIONS

Earth and groundwater retention to facilitate such deep excavations is generally beyond the range of application of sheet and bored piling techniques and necessitates the installation of diaphragm walling. A key driver in the achievement of very deep diaphragm walls is due to the advancements made in the development of excavation plant by equipment manufacturers such as Bauer and Soletanche Bachy (see **Figure *1***). The Trench Cutters or Hydrofraises produced by both companies are able to excavate panels to well in excess of 100 m and equipped as they are with the latest on-board monitoring equipment which enables real time correction of the vertical alignment during excavation by the operator such that tolerances better than 1 in 400 are achievable.

Figure 1: Bauer Trench Cutter (left) and Soletanche Bachy Hydrofraise (right)

For the purpose of this paper, the author would like to focus on the design and construction of deep diaphragm wall shafts. A structural slurry wall or diaphragm wall consists of a series of reinforced concrete panels which are usually structurally discontinuous and abut each other at panel joints which are commonly defined by temporary steel or occasionally permanent precast concrete stopends. However, in the case of diaphragm walls greater than ca. 75m in depth the use of such stopends is impractical and the excavation usually necessitates the use of a trench cutter or hydrofraise with joints created by overcutting concrete previously formed in primary panels with secondary panels (see **Figure *2***).

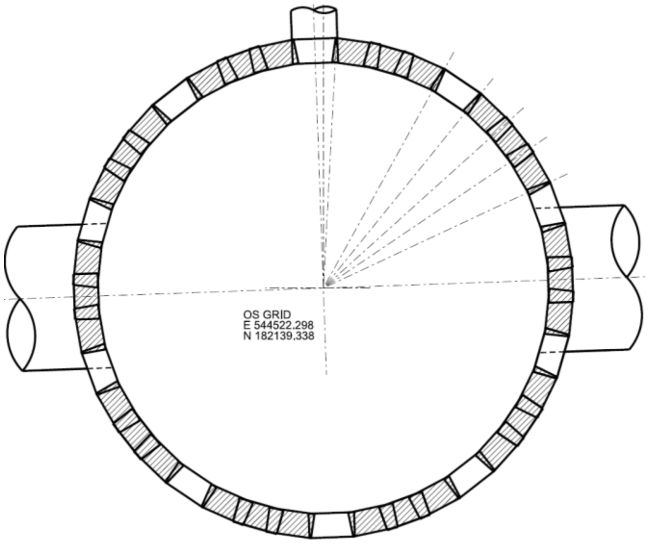

Figure 2: Example of shaft panel layout incorporating overcut panel joints (Lee Tunnel Project)

This form of panel joint is generally considered to be less watertight than in the case of a joint formed using a stopend system. However, in the case of a circular shaft where the nature of structural forces is in most cases overwhelmingly hoop compressive across panel joints it is generally found that groundwater leakage across overcut joints formed in this way is acceptably low.

Effective centralisation of primary panel cages to minimise the risk entanglement with reinforcement during overcutting secondary panels with potentially disastrous consequences for plant is essential. Two different temporary works solutions are shown in **Figure *3*** below. On the left at Lee Tunnel, corrugated plastic pipes were used as spacers together with triangular polystyrene wedges to minimise the volume of concrete in the panel overcut. At the Woodsmith Mine (on the right) sacrificial glass fibre reinforcement was used to centralise primary cages.

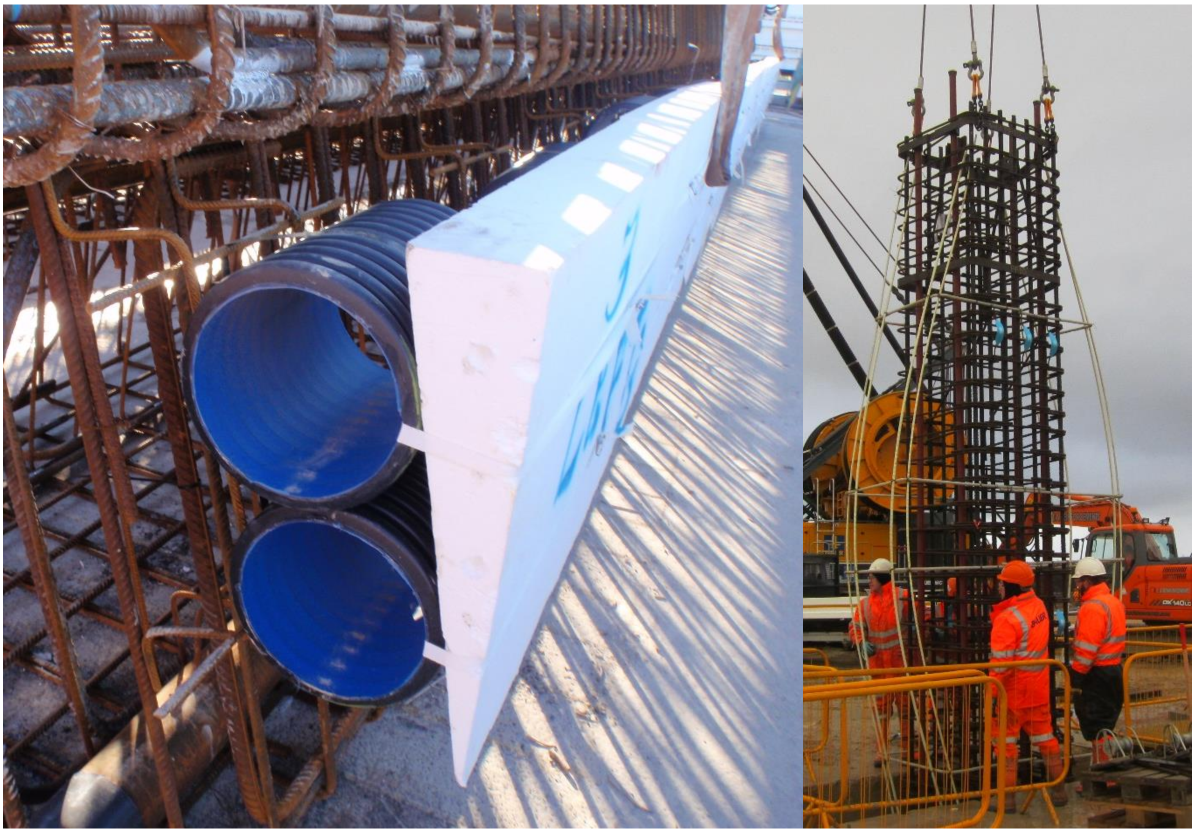

Figure 3: Measures taken to minimise risk of overcutting primary panel reinforcement

The design of diaphragm wall shafts is frequently governed by the magnitude of hoop stresses which are generated by earth and groundwater pressures and which can be concentrated locally around opening for tunnels. Since hoop stresses must be resisted across the net contact area between panel joints allowing for construction tolerances, advances in both wall thickness with 1800 mm now in use and improved accuracy during excavation, has permitted bigger and deeper shafts. Verticality monitoring using a combination of on-board real time systems together with confirmatory checks after excavation using Koden (Ultrasonic Drilling Monitor) provides reliability that tolerances specified in the design have been achieved.

Acknowledging the fact that the excavation tool whether hydrofraise or trench cutter can be effectively steered by the operator adjusting hydraulic pads as excavation proceeds, means that a simple verticality tolerance of 1 in xxx is not strictly appropriate for very deep diaphragm walls and in fact an absolute deviation of xx cm is more relevant. For example at the Woodsmith Mine, 120 m deep shaft panels were constructed to within a 20 cm absolute deviation which would correspond to a verticality of 1 in 600. This was achieved by Bauer using a combination of Cutter Inclination Survey (CIS) together with a Koden check on every panel (see **Figure *4***). The shaft design required only a 1200 mm thick wall with a concrete strength of a C45/55 for an 8 m diameter shaft which was excavated over its full depth to 120 m.

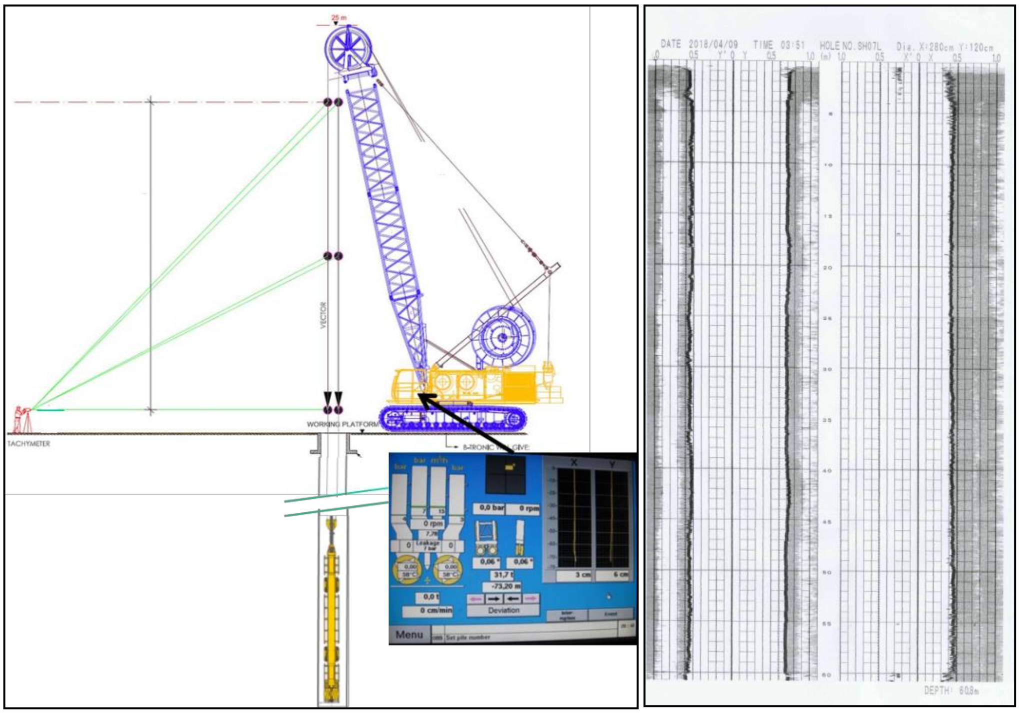

Figure 4: Verticality monitoring during excavation by CIS (left) and afterwards by Koden (right)

3 IMPROVED UNDERSTANDING OF THE BEHAVIOUR OF CONSTRUCTION MATERIALS

3.1 TREMIE CONCRETE

The construction of very deep diaphragm walls places additional requirements on the performance of concrete which must be placed via a tremie through a support fluid. Large pour volumes in excess of 1,000 m3 require high workability over an extended duration and with panel depths reaching 100 m this means that mix stability and the control of bleed under high pressures is particularly important. It is often the case that structures for infrastructure projects are designed for an intended life of greater than 100 years and this together with potential exposure to de-icing salts and/or marine conditions places high requirements on durability.

The combination of these requirements in the fresh and hardened state has led to increasingly complex concrete mix designs with various admixtures and cement combinations. As a consequence, a deeper understanding of the behaviour of tremie concrete has become essential and accompanying new methods of specifying and testing have become accepted practice.

The Concrete Institute of Australia Guide first published in 2012 showed much foresight paving the way for new forms of concrete testing to be introduced (Concrete Institute of Australia, 2012). Later on, The European Federation of Foundation Contractors (EFFC) Guide to Tremie Concrete for Deep Foundations (EFFC-DFI, 2018) and Institution of Civil Engineers Specification for Piling and Embedded Retaining Walls (ICE, 2017) were published with more developed requirements and guidance on concrete mix design, control and testing as well as tremie practice. The key driver in developing these new guidelines was the avoidance of defects primarily in the cover zone of completed panels. For example, excessive bleed rate can cause channelling or outwash of fines from the concrete in the cover zone and along reinforcement bars. Premature loss of workability coupled with poor reinforcement detailing can cause mattressing features whereby concrete is unable to flow around and coalesce fully around reinforcement bars leaving a patterning visible on the surface of panels on exposure.

As a result, gone are the days when simply testing workability by slump or flow table together with strength testing of cube or cylinder is sufficient. In order to minimise the risk of defects associated with excessive bleed, mix instability of loss of workability it is essential that any concrete mix design which has not been previously used successfully in comparable works is validated in pre-start trials and is subject to the following tests.

a) Visual Stability Index (VSI)

Visual Stability Index is a qualitive measure of segregation resistance and water retention. Unstable concrete with a VSI of 2 or 3 will exhibit a halo of water around concrete placed on a flow table and may indicate clear segregation of coarse aggregate. Only concrete with a VSI of 0 or 1 should be considered acceptable (see **Figure 5**).

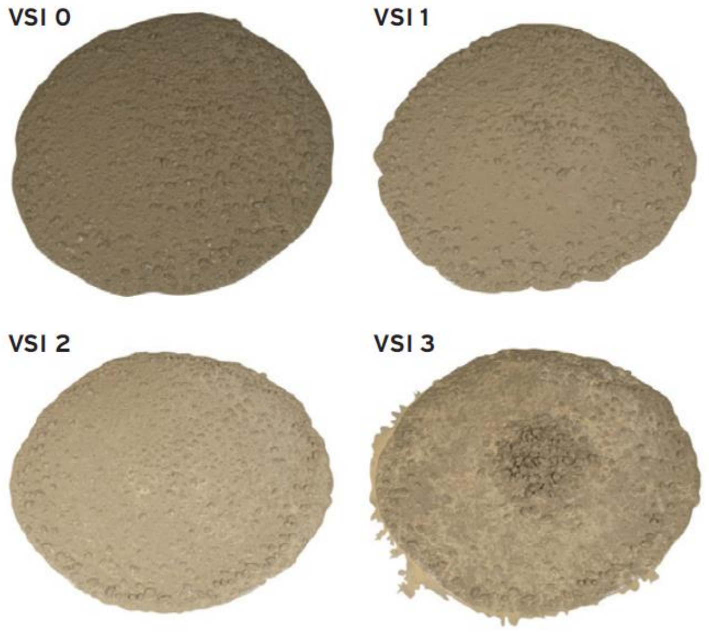

Figure 5: Assessment of visible stability index according to EFFC Guide

b) Bleeding and Bleeding Rate

Bleed rate can be assessed at atmospheric pressures in a steel vessel according to ASTM C1610. If the rate at which bleed water is expelled over the first two hours of bleeding exceeds 0.1 ml/min then there is an increased risk of channelling. Bleed rates below 0.1 ml/min are considered acceptable.

c) Bauer Filtration

The Bauer Filtration test is a rapid test lasting only 5 minutes where a cylinder of 1.5 litres of concrete is subjected to a pressure of 5 bars and the filtrate volume displaced is measured. Values greater than 22 ml are considered to be indicative of a risk of segregation and excessive bleed.

d) Consistence (Workability) Retention

Workability retention involves repeating flow or slump testing at intervals (usually 30 minutes) to assess whether there is a risk of sudden loss in workability which may lead to problems of adequate flow of concrete during tremie placement, taking into account the size of the panel and the likely duration of the pour.

3.2 SUPPORT FLUID

Support fluid, usually in the form of bentonite slurry is maintained in the trench to maintain stability from excavation through to completion of concreting. However, in the case of deep diaphragm walls excavated by trench cutter or hydrofraise the support fluid also provides the transport medium for the spoil during excavation and this means that in certain soils the support fluid can load up with fine material very rapidly. This can contribute to excessively thick bentonite cake which can be difficult to remove effectively. This can in turn adversely affect the end bearing and shaft friction resistance of walls subject to vertical loading. Also fragments of thick filter cake can break off and become included in the concrete or within the reinforcement cage particularly at box outs and reservations. In order to reduce the risk of excessive cake build up, the ICE Specification indicates a recommended maximum density of 1.35 g/cm^3 for bentonite support fluid during excavation. The EFFC/DFI Guide to Support Fluids published in 2019 provides an excellent reference dealing with bentonite and polymer support fluids.

The author would like to make one further point with respect to best practice using support fluids in deep diaphragm walling and that is it is highly recommended to keep separate storage of excavation and concreting muds and to carry out a full exchange prior to concreting in order to afford the concrete, placed by tremie, the best opportunity to fully displace the slurry with minimum risk of entrapment within the body of the panel.

4 IMPROVEMENTS IN DESIGN AND MONITORING

Deep excavation design is routinely undertaken using three dimensional numerical models. Whereas once circular shaft analysis would be carried out assuming axisymmetric conditions, nowadays the ability to consider for example the effects of surface surcharges, openings in the wall for tunnels or multiple cellular shafts lends itself to three-dimensional modelling. In the case of the Woodsmith Mine the analysis required consideration of the main 120 m deep service shaft located within a 55 m deep headgear chamber (see *Figure 6*). Such deep and complex excavations should always be accompanied by an effective geotechnical monitoring scheme in order to compare actual performance with design predictions.

In designing geotechnical monitoring for diaphragm wall shafts it should be borne in mind that the structure will have high stiffness and that wall deformations are likely to very small and less than can be accurately monitored by inclinometers (Schwamb, 2016). Alternatives using strain gauges and/or fibre optics should be considered in order to obtain useful data.

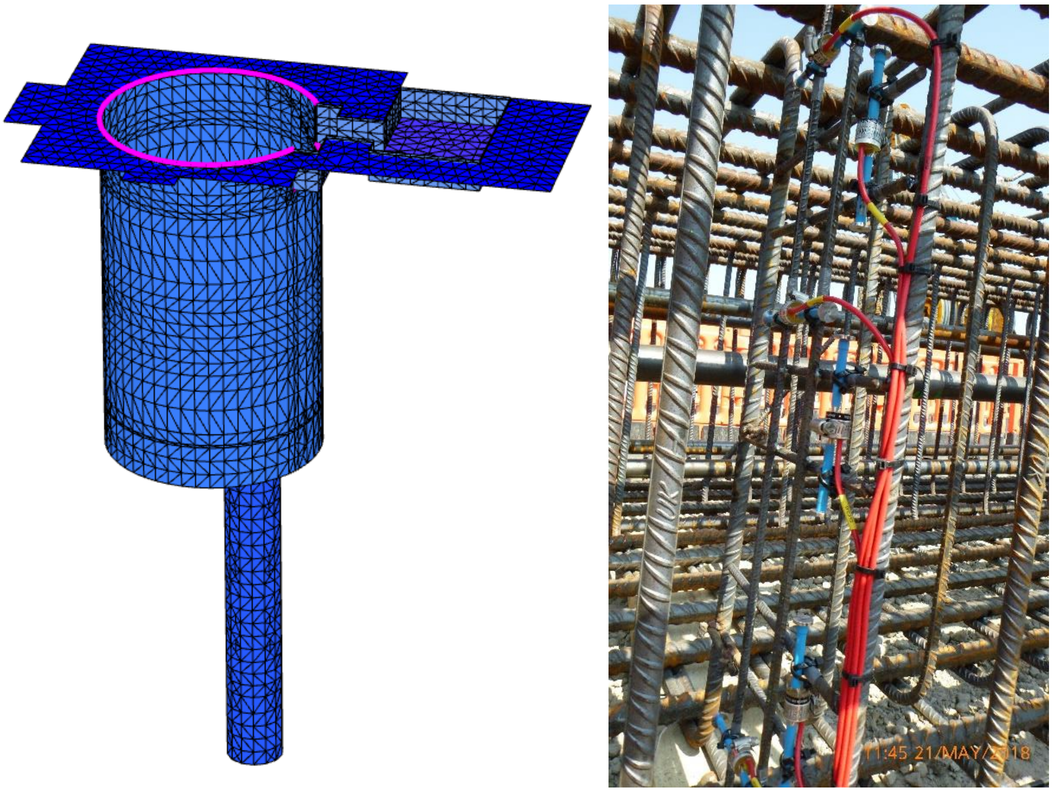

Figure 6: Sophisticated numerical modelling complemented by effective geotechnical monitoring

5 IMPROVEMENTS IN CONSTRUCTION SAFTY IN DIAPHRAGM WALLING

As constructors continue to strive to reduce the potential to cause harm to operatives during construction, processes evolve and practices considered unavoidable in the past can be replaced by improvements which lead to a step change in health safety risks. The author would like to highlight three areas of development in diaphragm wall construction.

5.1 EDGE PROTECTION AND PANEL COVERS

Previously, diaphragm wall excavations were carried out without edge protection leading to potentially hazardous conditions especially on poorly lit sites during night shift working. Recently though, simple systems have been developed employing railings which are temporarily fixed to guide walls to act as barriers to keep operatives out of harms way. Concreting covers are also placed on guide walls to provide a safe working platform for operatives involved in handling tremies during concreting (see Figure 7).

Figure 7: Edge protection barriers fixed to guide walls (left) and panel covers during concreting (right)

5.2 CAGE DESIGN

In the past, the incorporation of temporary works steel in reinforcement cages to facilitate fabrication, handling, transportation, loading and unloading, storage and then lifting to the vertical prior to lowering into the panel was based on previous experience, usually without any specific design. However, this has changed during the last few years in the UK supported by the Federation of Piling Specialists (FPS) and cage design is now required to be carried out by a competent designer (FPS, 2016). For example, taking into account cage weight and centre of gravity suitable lifting points must be established for safe lifting and the cage must be designed to be suitably rigid taking into account all bending moments and shear forces induced in the cage during lifting.

5.3 CAGE SPLICING

Hand injuries remain amongst the commonest form of injury in construction and yet operatives are still required to place their hands in harms way when splicing together reinforcement cages during lowering into the open trench. This unsafe practice is unavoidable if cages are spliced by welding or bull dogs but there are now a number of faster and safer cage splicing systems available which do not require fingers to be placed in dangerous locations. For example, the Superlatch system employs a spring-loaded latch which rides over and then engages with a lifting band at the splice location (see Figure 8). However, challenges still remain as reservation tubes installed in cages for grouting, sonic testing or inclinometers require pushing together at cage splices which still represents a risk to operatives.

Figure 8: Superlatch cage splicing system

6 RECOMMENDATIONS FOR SUCCESSFUL OUTCOMES

The significant advances in diaphragm wall equipment, concrete materials and numerical analysis means that diaphragm wall shafts in excess of 100 m depth are readily achievable. However, with these advances there are accompanying risks which need to be mitigated and the following recommendations are made by the author.

a) Employ at least two independent methods of monitoring actual deviation of excavation (on board real time and post-excavation using Koden).
b) Utilise effective measures to ensure that primary panel reinforcement cages remain in their intended plan position to minimise risk of overcutting reinforcement.
c) Carry out rigorous testing on full scale concrete batching trials unless the same concrete mix design has been used successfully on a comparable application. Tests to include Visual Stability Index, workability retention, bleed to ASTM and Bauer Filtration as a minimum.
d) Consider checks of support fluid density during excavation in order to minimise risk of excessive filter cake build up.
e) Ensure effective geotechnical monitoring is implemented using strain gauges and/or fibre optics to ensure reliable measurements.
f) And most importantly, deploy the latest in best safety practice by providing edge protection around open trenches and panel covers as safe working platforms during concreting. Ensure reinforcement cages are designed by a competent person to be handled and lifted safely. Utilise safe systems for splicing cages together during installation in the panel.

Figure 9: Diaphragm wall shaft

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