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TTMJ – THE NEW SYSTEM FOR SLURRY (DIAPHRAGM) WALL JOINTS

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ABSTRACT
TTMJ is the acronym for the Slurry (Diaphragm) Wall Tension Track Milled Joint currently in development as part of the European Union's innovative and far-reaching Horizon 2020 initiative (FTI Pilot-2015-1 720579). The TTMJ Project has been specifically set up to deliver this versatile new step-forward in Slurry Wall technology. The TTMJ System is protected by patent in Europe and the USA, and is currently under development by a consortium comprising Trevi SpA (Italy), Arup (Netherlands) and CCMJ Systems (UK). The principles of the TTMJ System together with the installation process are herein described in general terms. The system is still under development with field trials scheduled for early 2018, so some of the detail will not be disclosed at this stage. It is the intention of the Authors that the results of these field trials and a more complete description of the System will be presented in a paper we intend to submit for the DFI/EFFC International Conference on Deep Foundations and Ground Improvement to be held in Rome, Italy in June 2018. The final section of this paper explains how the TTMJ system can be applied to a common application of slurry wall construction; deep circular or multi-cell shafts. The system can be used to construct shafts more easily and at less cost than current methods. It also allows shafts with smaller internal dimensions to be constructed than is currently practical.

Keywords: slurry walls, diaphragm walls, milled joints, trimmer, guide track

INTRODUCTION
CCMJ Systems (UK) realised that an innovative new approach to forming joints in both Slurry (Diaphragm) Walls and Secant Pile Walls would provide greatly improved joint integrity to greater depths, to the overall benefit of retaining wall quality, across the world-wide foundations industry.

In particular this new system is designed to:

- Increase the effective depth range of Slurry Walls (especially walls excavated by grab) and Secant Walls
- Remove the requirement for Stop-ends or Joint Formers
- Allow for a Shear Key at the joint
- Allow for a Water Stop to be installed at the joint
- Permit Continuous Reinforcement across the joint
- Optimise Reinforcement Density and hence Concrete Flow
- Facilitate joints in corner panels eliminating the need for “L” shaped cages and reducing large single-pour concrete volumes and slurry storage capacity requirements.
- Enable the construction of smaller-dimensioned square and circular deep shafts (especially useful for city-centre sites) than is possible with current methods.

CCMJ Systems approached other industry specialists with a view to forming a development team to explore the possibilities for this new technique.

TTMJ is the acronym for the Diaphragm Wall Tension Trimmed Milled Joint, currently in development as part of the European Union's innovative and far-reaching Horizon 2020 initiative. The TTMJ Project has been specifically set up to deliver this versatile new step-forward in Slurry Wall technology. The TTMJ

Joint is protected by patent in Europe and the USA, and is currently under development by a consortium comprising Trevi SpA (Italy), Arup (Netherlands) and CCMJ Systems (UK).

BACKGROUND

The average depth of Slurry or Diaphragm Walls has increased steadily over the last 50 or so years. When the technique was first developed in the 1950s, the grabs had rounded clam shells and the joints were formed by installing steel tubes at the end of the panel and extracting them immediately after the concrete had achieved an initial set. When square ended clamshell grabs came into use, the steel stop-end / joint-former became rectangular with a protrusion to form a shear key or a row of smaller diameter pipes welded together (organ pipes). These joint formers still needed to be extracted at the right time. In the United States the preferred method was to use cast-in steel wide flange beams (W beams). The soil side of the beam was filled with a void forming material which could be removed during excavation of the adjacent panel.

In the 1990s the "peel off" continuous water stop (CWS) Steel Joint Former (*Fig.1*) came into use, particularly in Europe. This became a highly successful and efficient method for forming the joint between adjacent Slurry Wall panels. The joint could incorporate a water bar and it was no longer necessary to pull out steel joint-formers in the middle of the night!

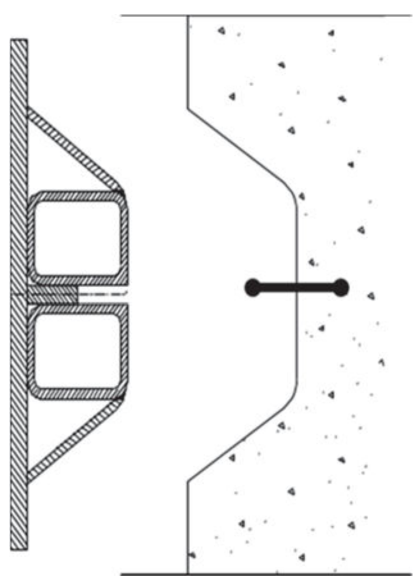

Fig.1 CWS Stop-end

As slurry wall depths have increased, problems have arisen with the removal of the CWS joint formers. It was found that beyond 30m (100ft) it was sometimes difficult and time consuming to install, and peel them away from the concrete of the previously constructed panel. The trend to change from rope operated grabs to the more cumbersome but more efficient hydraulic grabs seemed to exacerbate the problem. As the depths increased, contractors began fixing plywood and other materials to the steel surface, to try and reduce the bond between the CWS former and the concrete (*Fig.2).* Using such methods, the CWS system has been used to depths in excess of 50m (165ft) but only by the most experienced specialist foundation companies and even then the risk of problems with removal is high.

Fig. 2 Wood and plastic covered CWS Stop-end

The other option, particularly used for the construction of circular shafts and dam cut off walls is to employ reverse-circulation ‘hydro-mills’ to form joints by cutting into the concrete of the adjacent panels. Hydro-mills are now routinely being used to install slurry walls to depths of over 50m, and 100m deep is not uncommon. In 2012, Trevi installed a test panel to a depth of 250m (820ft) (Pagliacci, 2013). However, a joint formed by over-cutting the concrete with the “hydro-mill” cannot accommodate a water stop and shear connection between the panels is likely to be limited. When used in the construction of circular shafts the joints are all in compression - wall movement tends to be inwards due to the external radial pressures. Water leakage through the wall is often minimal (although seepage may still result from the presence of joint defects or voids in the wall) but this may not be the case if the structure is a propped or cantilever linear wall, where there is a greater potential for differential movement between panels.

To summarize; the existing joint forming methods have 'lagged behind' to the extent that they no longer adequately fulfil the role for which they were originally designed. The result is that the integrity of the completed joint may be compromised as a result of unrealistic expectations for verticality and other tolerances.

THE BASIC PROCESS / OBJECTIVES

The reader is invited to imagine a road planer removing the surface of a road. The TTMJ Trimmer works in a similar manner, but on the vertical concrete end surface of the slurry wall panel, to form a profiled (vertical) joint. Guides attached to the body of the trimmer run in Guide Tracks fitted to and installed with the reinforcement cage in the previous panel. These Guide Tracks maintain the vertical alignment and plan position of the trimmer cutting wheel relative to the guide track, and ensure that the trimmer cannot move away from the concrete (joint) surface.

The fundamental basis for the TTMJ process is to allow Slurry Wall excavation to increased depths, without compromising the quality of the joint between adjacent Slurry Wall panels. Crucially, the trimming of the secondary panel is controlled by the profile of the primary panel. With suitable care and attention (standard procedure for the competent Slurry Wall specialist contractor!) the joint can be formed to considerable (ie. increased) depth without risk to vertical or plan tolerances. This process automatically compensates for all reasonable verticality tolerance issues to any depth that can be (sensibly) excavated by hydraulic grab. If the TTMJ system is used with a hydro-mill there is theoretically no limit to the depth that can be achieved.

If we consider a Slurry Wall of alternating primary and secondary panels:

- The circular guide tracks (2 per joint) are attached to the primary panel reinforcement cages.
- The guide tracks are allowed to fill with bentonite (or polymer) fluid as the reinforcement cage is placed in the excavated trench, but 'closed' sufficiently to ensure that high-slump concrete is unable to penetrate into the tracks during concreting of the primary panel.
- Secondary panels can be excavated when the concrete in the adjacent primary panels has attained sufficient strength.
- When excavation of the secondary panel has been completed, the Trimmer is used to prepare the TTMJ Joint. The guides are introduced into the guide tracks and the Trimmer is run down the joint to the required depth, removing concrete cover and the sacrificial wall of the guide tracks
- When the concrete and track debris has been removed and other Slurry Wall cleaning processes completed, the water-bar positioned (if specified) and any other operations completed, the secondary panel can be concreted.

TTMJ TRIMMER & GUIDE TRACK

TTMJ Trimmer

The Trimmer *(Fig.3)*, which is being designed and built by Trevi with the assistance of sister company Soilmec, is required to work under considerable hydrostatic pressure, resulting from the trench support fluid (bentonite or polymer), constraints that mirror Slurry Wall operating conditions. For most applications, the Guide Track will have a typical concrete cover of ±50mm (2ins) so the anticipated output of the Trimmer is expected to be similar to the road planer ie. ~ 50 to 60m (165 to 200ft) of joint per hour.

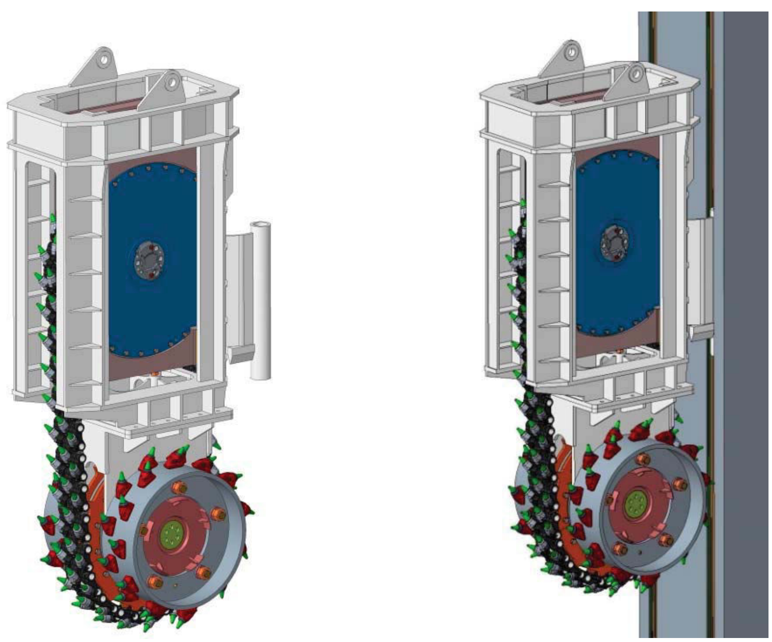

Fig.3 The TTMJ Trimmer

The trimmer design is based on a combination of Slurry Wall mill and road planer technology. (One of the key considerations is the ability to work under a considerable head of bentonite or polymer). The trimmer is being designed to remove a variable thickness of concrete as well as the sacrificial portion of the Guide Track. It incorporates an hydraulic motor powering a cutter drum via a chain drive. The chain drive can be used to form a profiled joint ie. to deliver a shear key between adjacent Slurry Wall panels.

At this stage there is no plan to incorporate a pump or other system to remove the cuttings. They will fall to the bottom of the trench and will need to be removed periodically by a grab or possibly by a separate air lift or pump.

TTMJ Guide Track

The TTMJ Guide Track is being developed by CCMJ Systems. A simplified illustration of how it might look is shown below (*Figs 4 & 5).* The track will be installed with the reinforcement cage in the adjacent completed panel. The trimmer removes a sacrificial portion of the track as it passes to allow the guides to descend.

Fig. 4 Guide Tracks fixed in the primary panel

Fig.5 End of Primary Panel showing trimmed face of concrete & shear key

TTMJ SYSTEM – ADDITIONAL BENEFITS

The Trimmer has to follow the Guide Track set in the concrete of the adjacent constructed panel; consequently concrete-to-concrete contact is assured. It should be noted that the prototype machine is intended to form joints in 1.2m (4ft) thick slurry walls. It will have a 1m (3.3ft) wide cutter wheel so that soil from the side walls will only be removed if the excavation of the second panel has deviated vertically relative to the adjacent concreted panel by more than 100mm (4ins).

The Trimmer cutter wheel can have a raised centre section to form a shear key, as required.

When the design demands, the TTMJ System will allow the installation of an effective water stop in the panel joints. Details are currently confidential.

The Guide Tracks used for the TTMJ System can also be used to provide a tension connection across the panel joint. A simplified illustration is shown below. (*Fig.6)*

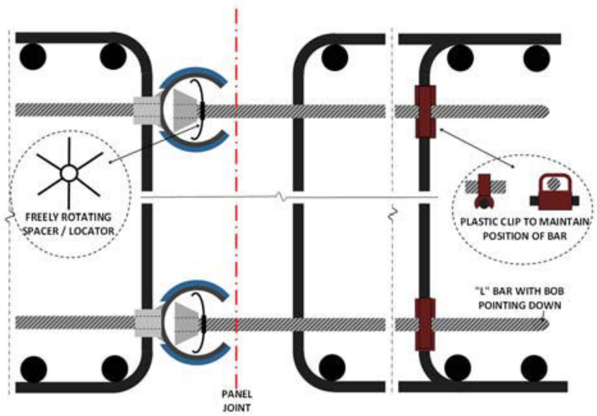

Fig.6 Simplified sketch of the tension joint arrangement

In early 2015, ARUP carried out research into the TTMJ tension joint based on Finite Element modelling. Their preliminary study focused on the capacity of a diaphragm wall panel joint to carry shear and tension across the interface of adjacent panels, important as it allows diaphragm walls to spread concentrated loads from the building structure over a wide area of the foundation. On the completion of their desk study ARUP concluded that the TTMJ system *"promises to offer designers an opportunity to deliver foundation solutions that are more efficient, effective, robust and buildable….".* (Internal Arup Report).

The TTMJ Development Project will bring innovation to the market for the benefit of the foundations industry worldwide, and at the same time will bring substantial added value at different levels:

- Construction Sector: the achievements of the action will improve the technical procedures for constructing slurry walls. TTMJ is a better way to construct slurry wall joints; the benefits for companies using the system will include the ability to generate cost savings whilst delivering a superior quality product. This represents a clear commercial advantage and an equally clear improved risk profile.

- Clients: for Clients and Owners, the commercial advantage can be translated into project-cost savings, a higher-quality product and a better profile in terms of risk reduction, quality and durability of walls. The risk of conflict with residents in the area will be diminished, due to the reduced impact of construction.

- Economy and Society: the improvement in slurry wall technique will be sustainable and have a lesser impact on the environment, by reducing the effect on the integrity of surrounding buildings in highly urbanized areas. This innovation has global appeal and potential to achieve a substantial market share. Alongside the commercial advantages, it delivers a step□change improvement in Health and Safety, and Environmental and Quality considerations.

The TTMJ system fills a current void in the market and provides a fundamental step forward in slurry walling, leading to technical, environmental and economic advantages:

- An effective jointing system for deeper hydraulic grab excavation.
- An improved jointing system for slurry wall excavation.
- Shear/tension capacity across slurry wall joints.
- Ability to construct 'tighter' slurry wall shafts (reduced land-take)

TTMJ DEVELOPMENT

The TTMJ System development, funded by the EU, started from the work already completed by CCMJ Systems (which confirmed the viability of the system) and will finish with its commercial use on an actual project. Development proceeds through the following stages:

- Develop, design and construct a full scale Joint Trimmer.
- Develop and test the guide track system, the tension joint and water stop.
- Laboratory trials of the guide track and tension joint,
- Full scale field trials of the Joint Trimmer and guide track.
- Specify, validate and issue industry accreditation for the TTMJ System.
- Enter the final stage of the project, by creating the right conditions to introduce the new product into the worldwide market place.

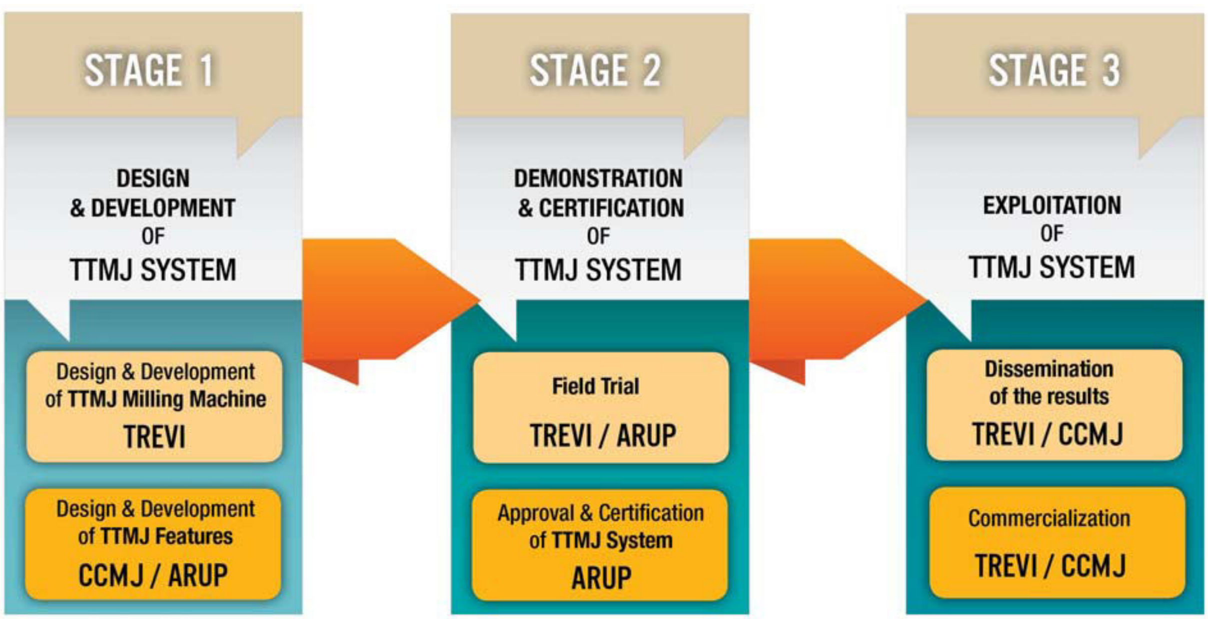

Fig.7 Principal Roles of Consortium Members

VALIDATION

Arup is responsible for formal validation of the system. The first consideration is that the TTMJ System must work within current Slurry Wall specifications – the second that is provides the next step forward in Slurry Wall technology. The Project will clearly benefit from the scrutiny of the world's leading geotechnical consultancy!

Materials Testing

Testing of the guide track components and the way they will interact with the Slurry Wall reinforcement cage / concrete will be carried out by CCMJ. Testing falls into two basic areas:

- Fundamental definition of system strengths and the efficiency of introducing new materials.
- Optimisation of design parameters, including developing the most cost-efficient product.

FIELD TRIAL

Full scale field trials are typically extremely difficult to specify, organise, deliver and analyse. The TTMJ Project has the all-important advantage of access to the 20m (65ft) deep test facility in the Trevi / Soilmec works at Cesena, Northern Italy. This will allow the team to build a mock-up of the panel joint for test trimming – with detailed observation - and recourse to a repeat trial if deemed necessary. In terms of industry confidence, this will provide clear confirmation of the effectiveness of the complete system *in situ*.

There will undoubtedly be some modifications and improvements carried out during the trials to optimise performance. Concurrent with the manufacturing stage, laboratory testing on guide and tracks will be undertaken. Throughout the process, the work will be monitored to ensure compliance with recognised standards and allow a specification to be compiled such that at the end of the Field Trials a fully accredited system will be ready to enter the market. The TTMJ Project Management Team will ensure the results of all the tests and trials are recorded and disseminated.

TTMJ SYSTEM – SHAFT CONSTRUCTION

During the development process to date it has become apparent that where slurry walls are used for shaft construction there could be considerable benefits from the introduction of the TTMJ System. In 2014 Trevi tendered for five deep slurry wall shafts in London. For one of these shafts, the slurry wall had an internal diameter of 28m (90ft), and the panels were more than 70m (230ft) deep. Due to the close proximity of apartment blocks, houses and a school, there were noise limits and restricted hours of working. In order to meet these constraints, the work was tendered on the basis of single 'bite' panels (essentially one grab in plan-length) because longer multiple-bite panels (typically 6-7m (20-23ft) in plan length) could not have been concreted within the available working hours. The panel arrangement consisted of 17 x 2.8m (9ft) long primary panels and 17 x 2.8m (9ft) long secondary panels which overcut the primary panels. Excavation of the primary panels was to be carried out by both hydraulic grab and hydro-mill working concurrently. As it was necessary to overcut the concrete of the primary panels, the secondary panels could only be excavated with the hydro-mill.

If the TTMJ System had been available, the panel arrangement would have been 14 x 2.8m (9ft) long primary panels and 14 x 3.2m (10.5ft) long secondary panels. Both primary and secondary panels would have been excavated by both the grab and the hydro-mill - with the grab crane also used with the TTMJ trimmer to form the joints.

Using exactly the same excavation rates for the grab and the hydro-mill, the revised scheduled construction duration was reduced by 40%, and the cost reduced by 20%.

Possible shaft panel layouts using the TTMJ System are shown below:

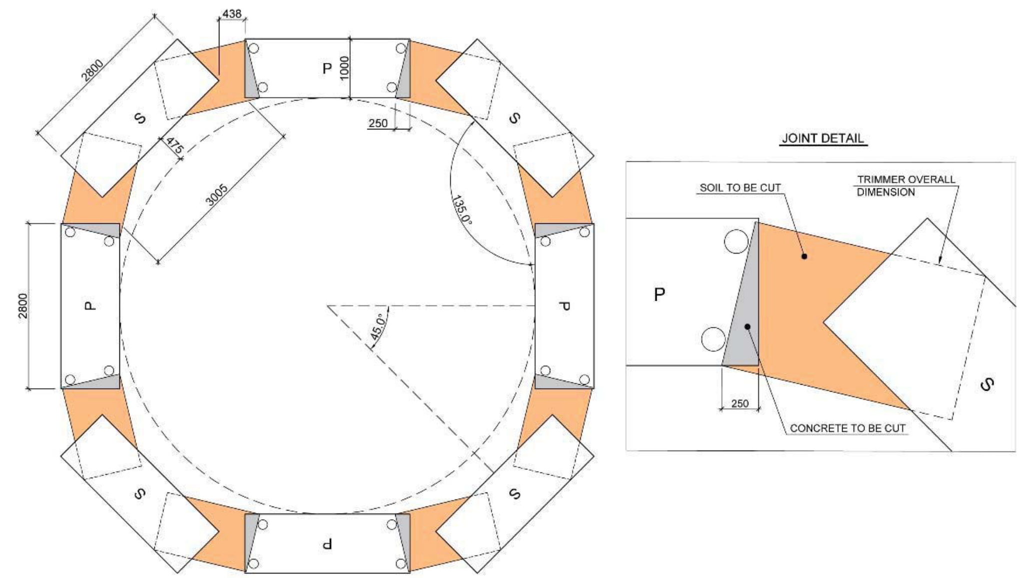

Fig. 8 7m (23ft) Internal Diameter Shaft using 8 panels

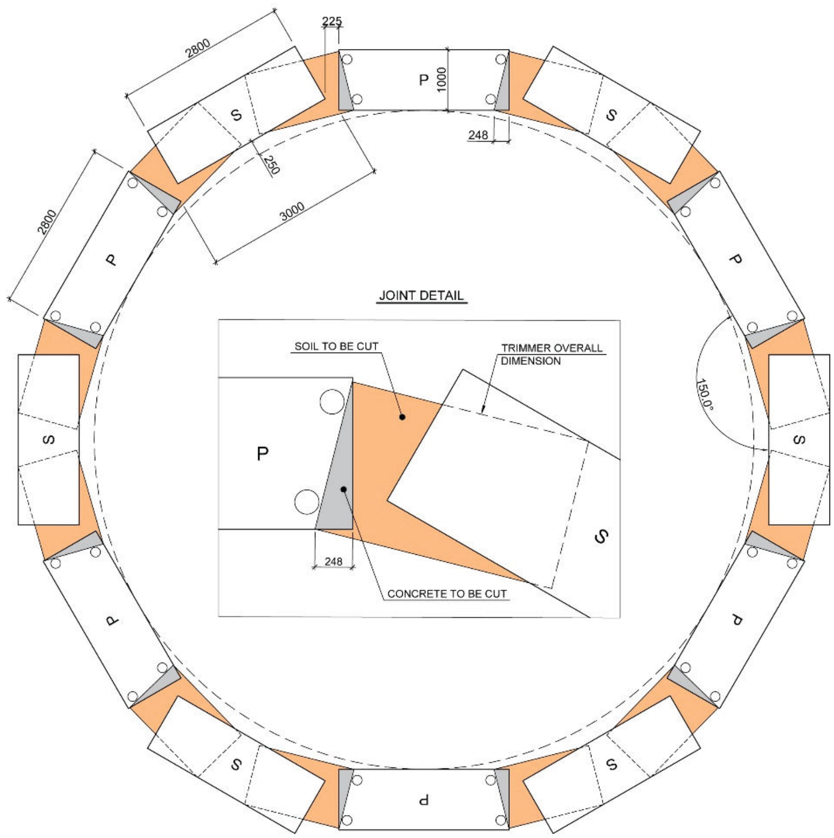

Fig. 9 11m (36ft) Internal Diameter Shaft using 12 panels

Small diameter shafts such as those shown above are not easy to construct solely using just grab excavation - unless either very large panels are used, or joints are formed with either steel or precast concrete elements cast permanently into the wall. Hydro-mills can be used to construct such shafts but we believe the TTMJ System will provide a better technical solution at lower cost.

CONCLUSION

Since the development of the hydro-mill, improvements in slurry wall technology have only been incremental advances. In particular, real-time verticality monitoring during excavation and steerable excavation equipment are two important developments. Hydraulic grabs have improved excavation rates. Depths have increased. Polymer use, instead of bentonite, has become more common. Filter presses and centrifuges for treating waste slurry are now more and more popular on sites.

The one thing that has not really moved forward in the last 25 years is the method of forming panel joints. We believe that the TTMJ System will be the catalyst and step change needed to push the Foundation Industry to the next level in constructing better Slurry (Diaphragm) and Secant (Pile) Walls.

REFERENCES

2013, Pagliacci, F. – Paper on 250m (800ft) deep Gualdo Test Diaphragm Wall.