Advanced Design and Construction of Marine Cut & Cover ELS Tunnel Cofferdam

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ABSTRACT

The most challenging aspect of the CKR-KTW Contract is the construction of maximum 35m deep Underwater Tunnel (UWT) submerged in Kowloon Bay which is a typhoon shelter with marine constraints from several stakeholders such as Hong Kong China Gas requiring 60m wide navigation channel for refueling tankers, Kowloon City Ferry Pier (AMO Grade 2 Historic Structure) operations for public ferry service and the marine traffic impact to Kowloon Bay. To overcome the substantial adverse impact to the environment and marine traffic of Kowloon Bay area from the conforming scheme of full temporary reclamation, an optimized scheme was employed for the marine cut & cover ELS cofferdam using only partial temporary reclamation. The use of this advanced design and construction method not only provided robust structural design with water-tight cofferdam, it also resulted in substantially less cost, construction risks / time and reduced disturbance to marine environment and traffic at Kowloon Bay due to substantially less temporary reclamation required.

Keywords: Marine, ELS, Cofferdam

1 Introduction

The CKR-KTW Contract no. HY/2014/07 is located at Kai Tak West and comprised of 125m long depressed road, 200m long underpass, 160m long cut & cover tunnel and a 370m long submerged tunnel under KWB including a separate 360m long underground ventilation adit connecting to the CKR-BEM contract. The most challenging aspect of the CKR-KTW Contract is the construction of the 370m long Underwater Tunnel (UWT) submerged in Kowloon Bay which is a typhoon shelter with marine constraints from several stakeholders such as Hong Kong China Gas requiring 60m wide navigation channel for refueling tankers, Kowloon City Ferry Pier (AMO Grade 2 Historic Structure) operations for public ferry service and the marine traffic impact to KWB as shown in Plate 1 below.

Plate 1: Marine Cut & Cover ELS at KTW

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In the conforming scheme for construction of the UWT, substantial temporary reclamation is proposed over the entire 35,511 m^2 footprint of the UWT. This was completed in 2 stages named UWT1 and UWT2 in order to maintain the 60m marine navigation channel and function as a large marine working platform for installation of diaphragm wall cofferdam and subsequent staged Excavation and Lateral Support (ELS) and tunnel construction works. The two stages of cofferdam for 60m wide navigation channel shown in Figure 1 below:

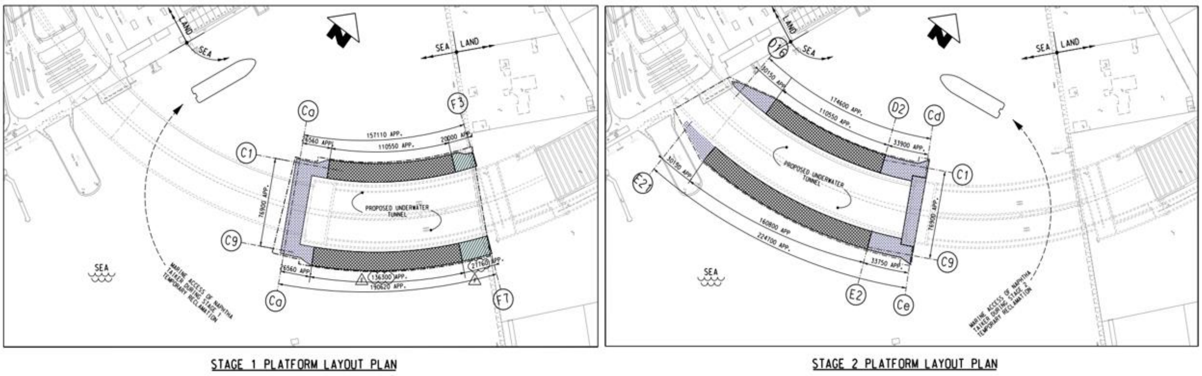

Figure 1: Provision of 60m wide Navigation Channel within KWB

Reclamation on marine deposit will result in on-going settlement and require to accelerate consolidation by surcharging to ensure a safe working platform. To overcome the expense and time-consuming resources required for the temporary reclamation works and the substantial adverse impact to the environment and marine traffic of KWB area from the conforming scheme, an advanced design and construction method was proposed for the marine cut & cover ELS cofferdam with by using a reduced temporary reclamation method. A reduced temporary reclamation scheme was proposed for the tunnel construction works comprised of a double wall tied system of 16m width reclamation area built up by FSPVL sheet pile on the seawall side and interlocking 813 Dia. Clutch Pipe Pile (CPP) wall on the tunnel excavation side. The design of the FSPVL outer wall functioned as the seawall while the CPP inner wall served as the ELS cofferdam wall. The double wall system was tied together at the top by waler / wall tie system at 6m c/c spacing prior to backfilling of the temporary reclamation works. The typical cross section of UWT is shown in Figure 2 below.

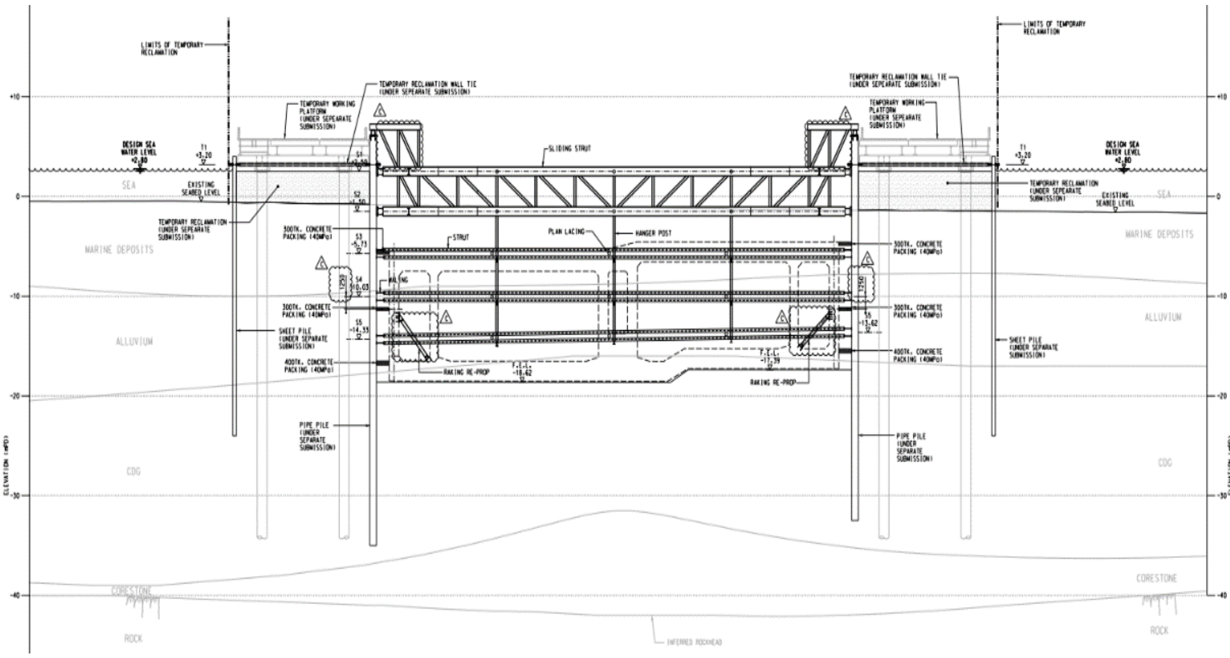

Figure 2: Typical Cross Section of UWT Stage 1 ELS Arrangement

This overall arrangement reduced the temporary reclamation impact by 62.9% in UWT1 and 52% in UWT2 compared to the conforming scheme. In order to carry out the piling works before the temporary reclamation is completed, a marine working platform all around each UWT1 / UWT2 cofferdam was constructed. These platforms were supported by 2 rows of 1.2m diameter staging piles that are vibrated by crane barges until the pile toe is founded firmly on hard Completely Decomposed Granite (CDG). The marine platform allowed for several work fronts of CPP piling rigs for inner cofferdam wall, installation of the innovative skidding system for S1 / S2 mega trusses with hanging king posts, telescopic excavators and crawler cranes for the installation of the modular ELS system and tunnel construction works. The temporary reclamation between the CPP and Sheet Pile walls were set close to high tide for two purposes. First was to provide a soil medium that could allow remedial grouting outside the CPP wall in the event of localized leaking. The second was to provide significant mass to mitigate berthing marine barges or accidental impact. The tie between outer and inner walls was envisaged as a fuse, acting only in tension but not transferring direct compression loads from berthing vessels to the ELS struts. Another benefit of the steel working platform was founded on piles was that the reclamation backfill would not be subjected to heavy construction surcharge loading which helped reduced lateral loading to the ELS cofferdam walls and shoring system. The use of this advanced design and construction method resulted in substantially less cost, construction risks / time and reduced disturbance to marine environment and traffic at KWB.

2 Advanced Design and Construction of Marine Cut & Cover ELS Tunnel Cofferdam

2.1 Key Constraint

The reduced temporary reclamation scheme along with the temporary steel working platform above allowed the CPP cofferdam wall to be installed along the platform deck and eliminated the need to form full temporary reclamation from the conforming scheme where it was used as a temporary earth working platform. This greatly reduced the material required to complete excavation of the cut and cover tunnel meaning reduced transporting and disposal of fill material. By removing the temporary reclamation within the excavation area of the two inner CPP walls, a reduction in the temporary reclamation backfilling volume of 62.9% in UWT Stage 1 and 52% in UWT Stage 2 could be achieved. The construction sequence employed the use of skidding mega trusses for installation of strutting layers S1 and S2 with hanging king post which eliminates the necessity of piling works of lateral shoring vertical mid span supports. The skidding mega truss struts also allowed installation without dewatering within the cofferdam. Once the skidding mega trusses are installed, the dewatering works commence and the remaining modular struts are installed by traditional staged excavation, mucking out and bolt and nut fixing of modular struts to the final excavation level. The reinforced concrete tunnel box is cast from the bottom up within the CPP walls with staged backfilling and strut removal up to the existing seabed level. The Contract requirement for removal of minimum 2m of the temporary cofferdam wall below seabed level is another benefit of the CPP wall compared to the diaphragm wall of the conforming scheme. A combination of proprietary Water Cutting Jet (WCJ) machine and traditional Divers was employed, the WCJ is installed inside each CPP and remotely rotates and cuts the CPP walls while divers with plasma torches along excavated side of CPP wall cut the clutches and remaining CPP not cut by WCJ. The use of the above design and construction method allowed significant mitigation of the key constraints and benefited by reducing the working time and impact to the live marine traffic at existing Kowloon Bay area, the marine traffic includes Ferry operations in Kowloon City Ferry Pier, vessel traffic in To Kwa Wan Typhoon Shelter. The mitigation measures to key constraint is outline in Table 1.

Table 1: Key Constraint and Mitigation Measures for Marine Cofferdam

Key Constraint	Proposed Mitigation Measures
Working in live marine traffic conditions of busy Kowloon Bay	• Reduce marine construction traffic by reducing extent of temporary reclamation. • Use crawler crane on temporary steel deck for excavation and tunnel construction; reduces requirement for derrick barges and improves access. • Implement Marine Traffic Management Plan and coordinate through the Marine Traffic Working Group. • Maintain 60m-wide navigation channel for each ferry service. • Dedicated staff for coordination of marine craft movements and coordination with Marine Department (MD) and Vessel Traffic Centre (VTC).
Impact on marine traffic	• A dedicated team will be responsible for coordination with Kowloon City Ferry, Hong Kong China Gas and the MD. • Light buoys to clearly identify works area. • Maintain a minimum 60m-wide navigation channel during construction as per "Final Updated Marine Traffic Impact Assessment Report" • Marine traffic deck to assist transportation of materials to ELS by land.
Vessel damage temporary reclamation	• Install outer piles wall with reclamation soil fill to re-distribute ship impact load. • Install light buoys to clearly identify works area.
Ferry operations and mooring	• Recommend, provide a pontoon system for the ferry operation and mooring of standby vessels. • Closely liaise with marine ferry operator, obtain ferry timetable, and plan our movements to maintain normal ferry services.
Maintain access to Hong Kong China Gas pier for Naphtha delivery	• Maintain marine access by using guard boats and light buoys to demarcate the navigation channel. • Liaise with HKCG on their requirements and obtain naphtha delivery schedule. Plan our marine movements to maintain smooth tanker route.

2.2 Site Set up

The general design of the UWT ELS cofferdam comprise of an inner and outer retaining wall backfilled with temporary reclamation all around the tunnel excavation area. A temporary steel working platform founded on steel tubular vibrated piles is installed within the temporary reclamation area. The double retaining walls are tied back at the top of the 16m width reclamation area with outer wall of interlocking FSPVL sheet pile retaining wall as the seawall side and inner interlocking 813mm Dia. Clutch Pipe Pile (CPP) retaining wall at the tunnel excavation side. The FSPVL outer wall is designed to function as a seawall while the CPP inner wall served as the ELS cofferdam wall, providing a watertight seal against water ingress and prevent any loss of reclamation material into surrounding waters. The overall view of the double wall cofferdam ELS of UWT Stage 1 and installation of marine working platforms and CPP piling works for UWT Stage 2 are shown in Plate 2 below.

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UWT Stage 1 UWT Stage 2

Plate 2: General View of Marine Cut & Cover ELS UWT Stage 1 and UWT Stage 2 installing CPP wall

The temporary reclamation for both stages 1 and 2 was reduced by eliminating the temporary reclamation within the area of tunnel excavation footprint as shown in Figure 3 below.

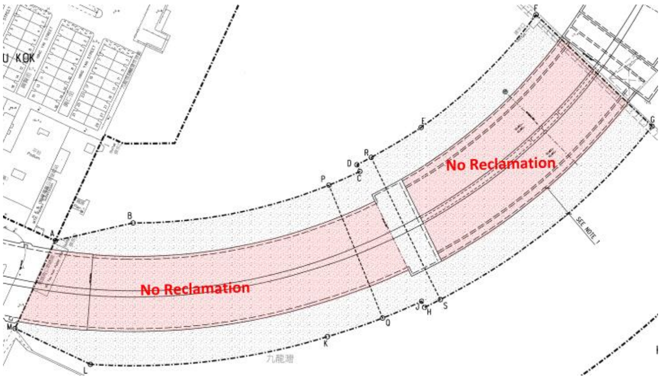

Figure 3: Reduced temporary reclamation area

The reduced volume and percentage of reclamation works compared to the Conforming scheme is shown in Table 2 below:

Table 2: Temporary Reclamation for under water tunnel.

	Conforming Scheme	Gammon's Scheme	Reduction in Temporary Reclamation
Stage 1	16,832m^2	6,244m^2	62.9%
Stage 2	18,679m^2	8,973m^2	52.0%

An added advantage of this reduction of the total area of temporary reclamation is that the environmental carbon footprint is also substantially reduced for noise impact, air impact, visual impact, land and marine traffic impact to the residents of Ma Tau Kok as well as the massive soil stockpile management and disposal impacts. The proposed use of CPP cofferdam wall is able to be installed directly from the marine working platforms as compared to earth work platform required for the conventional diaphragm wall method of conforming scheme. The ability to quickly install CPP by erecting a marine working platform saves considerable time compared to backfilling the central portion of the cofferdam with temporary reclamation just to install the ELS vertical members and reduces the total reclamation fill requirement of the project by some 69%. If the need for additional fill material is required due to consolidation effect of the marine mud layer, the total reclamation fill project reduction may well be in excess of 75%. Reduced fill quantities translate into direct programme benefits to the project and eliminates over 300 barge journeys for material delivery (124 journeys for stage 1 and 190 journeys for stage 2). Reducing the number of barge journeys means less disruption to public marine traffic, less congestion in Kowloon Harbour, improved carbon footprint through reduced emissions (1,269 tonnes embodied carbon saving). The reduction of temporary reclamation fill greatly benefits the environment and reduces the overall volume of backfill material to be imported and later disposal.

2.3 Robustness of the Cofferdam against Marine Impact

The continuous CPP wall is known for its inherent water tightness due to the clutched system, as illustrated in Figure 4 below.

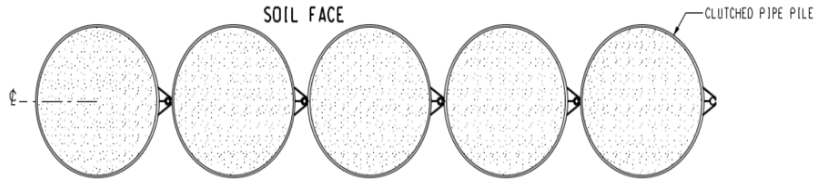

Figure 4: Clutch Pipe Pile Wall

- The ELS is designed as top-down staged excavation and lateral shoring method with bottom up for tunnel construction and backfilling / strut removal works with consideration for constraints of marine environment.
- Internal loads from accidental plant or impact loading on the ELS is considered at any point and in any direction. This is intended to cover situations such as accidental contact by excavation machinery and crane lifts where objects and equipment have routine movements within the excavation and in close proximity to ELS structural members.
- External dynamic loads due to berthing, mooring and accidental impact are included in the ELS wall and strut design. 3D finite element analysis has been used to quantify magnitude and distribution of accidental impact forces through the reclamation fill mass and residual loading passing through to the ELS wall and struts.
- Dynamic environmental loads from the marine environment in accordance with the Port Works Design Manual.
- The top two layers of struts in the marine section are of a robust modular mega truss design which are skidded into position. They are connected together to form a rectangular mega truss of 4m depth by 2.5m width with free span of 57.7m for UWT Stage 1 and 48.1m of UWT Stage 2. The depth to span ratio means these mega trusses can support 3 nos. of hanging king post running longitudinally across the cofferdam to provide vertical support and restraints for all the strut layers below.

The skidding mega trusses combine the top two strut layers S1 and S2 and simply supported at each end on skidding rails installed at top of CPP cofferdam wall. The mega truss depth and width were designed with beam deflection 75% less than the deflection limit of L/200 required by local code requirement. For the strut layers below S3 level, the compression loads induced during excavation required the use of lateral restraints provided by the 3 rows of hanging kingposts and longitudinal runner beams with plan bracing to control strut buckling and sway. The strut spacing was determined based on the clear width required for mucking out operations of the telescopic excavators and crawler crane grabs as well as provide windows for material delivery to construct the permanent works. The mega trusses hanging king post avoid requiring driven piles as king posts and thus provides for a wide clear working area for the reinforced concrete tunnel construction works and travelling formwork system. The UWT cofferdams are located in marine area and material delivery or excavated material disposal will require the use of barges or marine vessels which will subject the double cofferdam wall system to berthing and mooring loads or accidental impact collision loads from other marine vessels. The marine impact traffic assessment report outlines the existing vessel fleet that typically operates in this area of the harbour.

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Together with the construction barges to be used as part of Kai Tak West Contract PS requirements, a deterministic 2000T vessel was selected to carry out analysis. These berthing and collision loadings and the impact to the ELS system were considered in the ELS cofferdam wall design. The mass of the temporary reclamation fill and plasticity of the soil provide robust mass to absorb the impacts due to berthing loads and accidental ship impact. Since the deformation is largely absorbed by the soil mass of the temporary reclamation area, the CPP wall and its water tightness of its clutched system is not compromised from the event as shown in Figure 5 below.

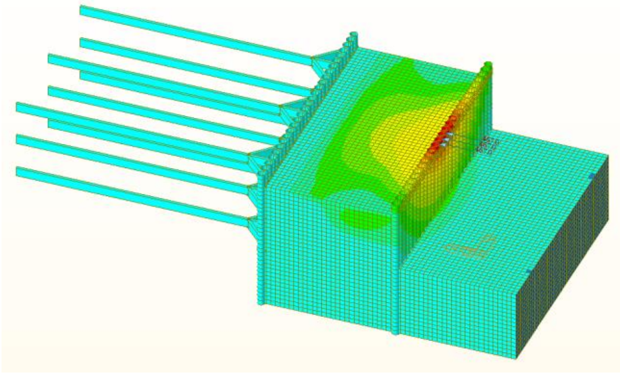

Figure 5: Peak displacement analysis for accidental ship impact

The method of deriving impact loading follows the Port Works Design Manual to evaluate the impact energy. A 3D soil structure interaction analysis is carried out to assess the displacements of the reclamation and derive the distribution and magnitude of loads that develop through the fill and transferred onto the ELS struts. Despite plasticity in the soil mass and load spread from the patch of impact, the analysis concludes that 30% of the load may be passed into each of the top three layers of ELS struts of the excavation and that this is an important provision to include in their design for overall robustness. In addition, The ELS ties within the reclamation is designed as one way ties and only work for tension loads avoiding direct compression loads transferring through the steel ties to the CPP wall in the event of accidental ship impact. The steel working platform deck and CPP cofferdam wall was designed with free tolerance (no-touch) for vessel berthing and typical environmental background movements. The ship impact collision load as maximum displacement or deformation were modelled in computer programme OASYS GSA and the induced force was checked against the moment bending and buckling capacity of the CPP wall as shown in Figure 6 below:

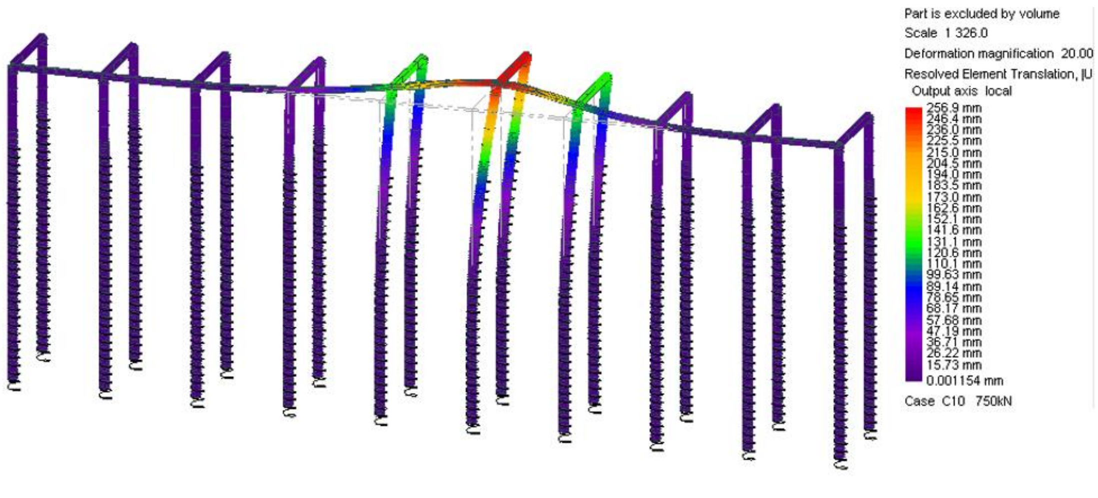

Figure 6: OASYS GSA computer modelling of accidental collision to temporary marine working platform

Together, both the ELS cofferdam wall and steel marine working platform provides significant robustness in the design to safely allow berthing and mitigate catastrophic events such as ship collision into the design.

2.4 Temporary Steel Working Platform

In order to construct ELS walls in the reclamation and provide working space for the subsequent earthworks and tunnel construction, temporary steel working platform deck built up from 3 nos. of modular decks with widths of 4m, 6m, 6m by 11.5m lengths to form 1 bay were constructed around the outer edge of the tunnel box. The assembled marine platform will have an overall deck width of 15.4m, and is designed to carry all plant, materials and equipment needed for our operations as shown in Plate 3 below.

Plate 3: General View of UWT Stage 1 Temporary Marine Working Platform

The temporary working platform is wide enough to accommodate plant movements and maneuvering with 1 clear lane of 3m width for simultaneous access of delivery trucks. The crawler crane boom turning also remains clear of the designated barriers and separated personnel walkways as shown in Figure 7 below.

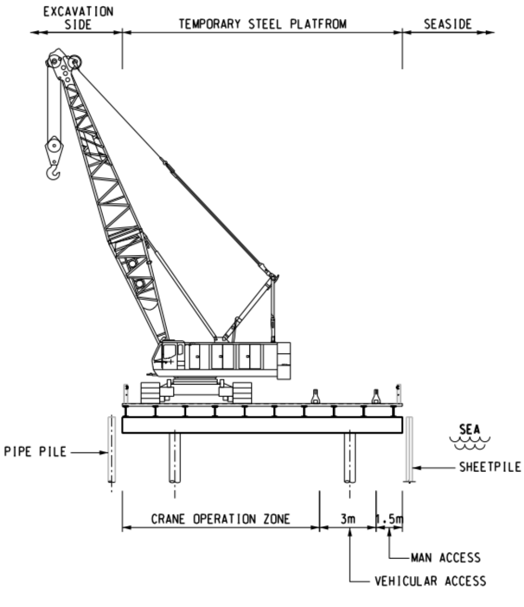

Figure 7: Modular marine platform arrangement

Construction of the temporary steel working platform will involve installation of the prefabricated standard size modules of 4m, 6m and 6m by 11.5m as mentioned above. Primary beams for the temporary steel working platform will be installed and span across the completed 1200 dia. pipe piles installed by vibro hammer. The pre-fabricated platform modules lifted on top will comprise of secondary beams and sections of sheet pile and pre-fixed edge protection, similar to what Gammon has

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done at Tuen Mun Chek Lap Kok Link. All of pre-fabricated platform modules have a standard size which are fabricated in Gammon wholly owned steel fabrication yard in the PRC. This engineering solution simplify onsite fixing and save more than 3,886 man-hours of labour. The platform geometry was set to maximize deck panel sizes to suit the backfilling and removal of reclamation fill while allowing the crawler crane to pass over the temporary reclamation works on the platform. The handling logistics and our selected crane sizes drove the geometric designand also reduce total marine traffic for delivery of materials and shorten the mooring durations in Kowloon Bay, minimizing the potential for impacting marine traffic and providing an overall safer working environment. Gammon have extensive experience working with the construction of temporary marine platforms and using them for successful delivery of major civil works projects. They include Shenzhen Western Corridor, Central Wanchai Bypass and Tuen Mun Chek Lap Kok Link projects, altogether totaling more than 30,000m2 of temporary working platforms installed in the last 15 years.

2.5 Clutched Pipe Pile (CPP) Wall

All piles for construction of temporary reclamation on this project will be made fully continuous using CPPs. CPP will be installed from the steel working platform. We will commence installation of the CPP after we have completed 40m of the temporary steel deck. The inner layer of CPP will be installed using Gammon's modified down-the-hole drilling equipment, enabling pre-boring of the CPP into rock with a minimum of ground disturbance during installation. Gammon was the pioneer Contractor in Hong Kong and continues to develop this technology for the excellent water-tightness the system provides. The CPP wall is able to provide a relatively stiff retaining wall for the compact diameter of 813mm due to the inherent geometric strength of circular sections along with the selected CPP wall thickness with thickness varies with depth and design requirement. Where additional rigidity is required for areas of large bending moments, the thickness of the CPP wall and bending capacity is locally increased. Together with water tightness of the fully clutched system, the CPP wall allows for a very cost effective, programme beneficial and constructible cofferdam wall at marine area of KWB. Another advantage of the CPP system is that during installation it can drill through hard obstructions compared to an older method where clutched pipes were vibrated in. At the outer wall, sheet piles were proposed and if any hard obstruction were encountered, they can be overcome locally by changing to pipe piles or pre-bored sheet piles. However, if the drilling encountered a steel anchor, a sunken ship or even dumped vehicles in the sea such as by historic British Army, the CPP drill bit would be unlikely to overcome such obstruction and design review would need to be carried out for the as-built CPP's with short toe levels in the ELS Cofferdam wall design. The CPP clutch system and splicing is shown in Plate 4 below.

Plate 4: Clutch Pipe Pile Wall

As the CPP wall is proposed on the tunnel excavation side and design of the FSPVL outer wall functioned as the seawall. The double wall system was tied together at the top by waler / wall tie system at 6m c/c spacing prior to backfilling will provide the dual purpose of acting as an impact protection fender and as a working surface for TAM grouting for additional sealing should it be required.

2.6 Modular Strut for ELS

The design of the lateral shoring system for the UWT Stage 1 and 2 cofferdams considered all the loadings mentioned above inputted PLAXIS computer model to determine the strut forces at each design section. The layout of the lateral strut shoring arrangement for UWT Stage 2 and UWT Stage 2 are shown in Figure 8 below.

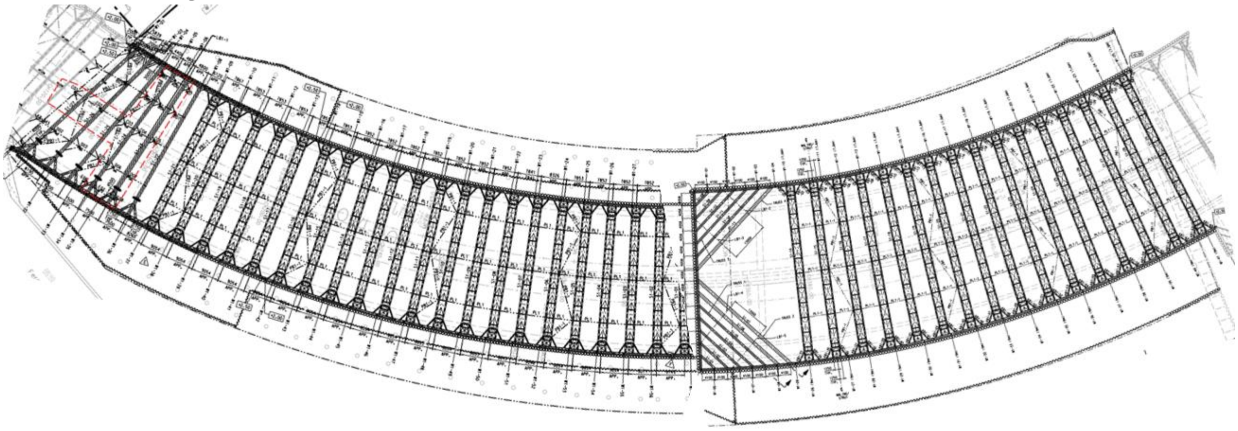

Figure 8: UWT Stage 1 and 2 ELS Layout Plan

This was modelled along with the double tie back wall and marine working platforms directly in the PLAXIS computer simulation. Several design cross sectional slices were analyzed by the PLAXIS model and the strut forces were assessed to determine the range of standard sizes to be used for the modular strut fabrication. The typical PLAXIS model geometry of one section is shown in Figure 9 below.

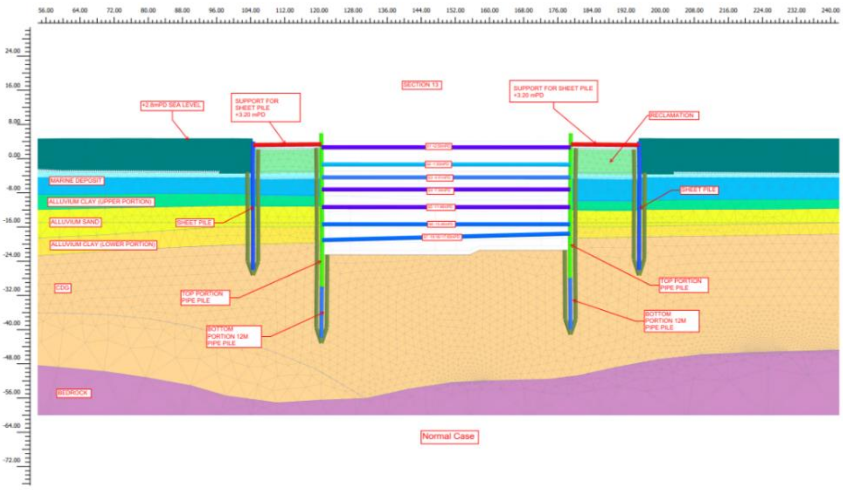

Figure 9: PLAXIS modelling of ELS and Mega Truss Strut

Since the CPP wall effectively functions as both a retaining wall and vertical support for the mega trusses above, the CPP wall was modelled as a retaining wall. The vertical load applied at the top was checked against the structural and geotechnical capacity of the CPP. Additionally, the predicted maximum wall deflection at the top after would need to be known to allow suitable tolerance for the skidding system upon the time for the removal of struts. The actual performance of the ELS UWT

Stage 1 was in fact better than the design prediction with actual maximum deflection of the CPP cofferdam wall at 40% less than that predicted by the computer model which indicates that the ELS cofferdam is indeed very robust. The reason of better performance is due to the conservative estimation of stiffness contribute from both the mega trusses system and the adoption of double wall tie back scheme. The aerial view of UWT Stage 1 ELS works is shown in Plate 5 below.

Plate 5: Ariel view of UWT Stage 1 ELS works

Construction of the temporary steel struts and wailing will involve installation of standard size, pre-fabricated modular struts and traditional non-modular struts. The main struts are installed directly underneath each of the mega trusses spanning across the CPP cofferdam wall. Over 90% of all pre-fabricated steel strut and wailing modules will have a standard size of 914 series Twin UB and length of 12m, which are fabricated in Gammon's factory in the PRC. The modular standard size of strut and wailing in UWT Stage 1 have been design for re-used in UWT Stage 2. A typical span of each main strut is comprised of several straight main beams with preload module located slightly mid span and forks on each end connected to modular walers as shown in Figure 10 below.

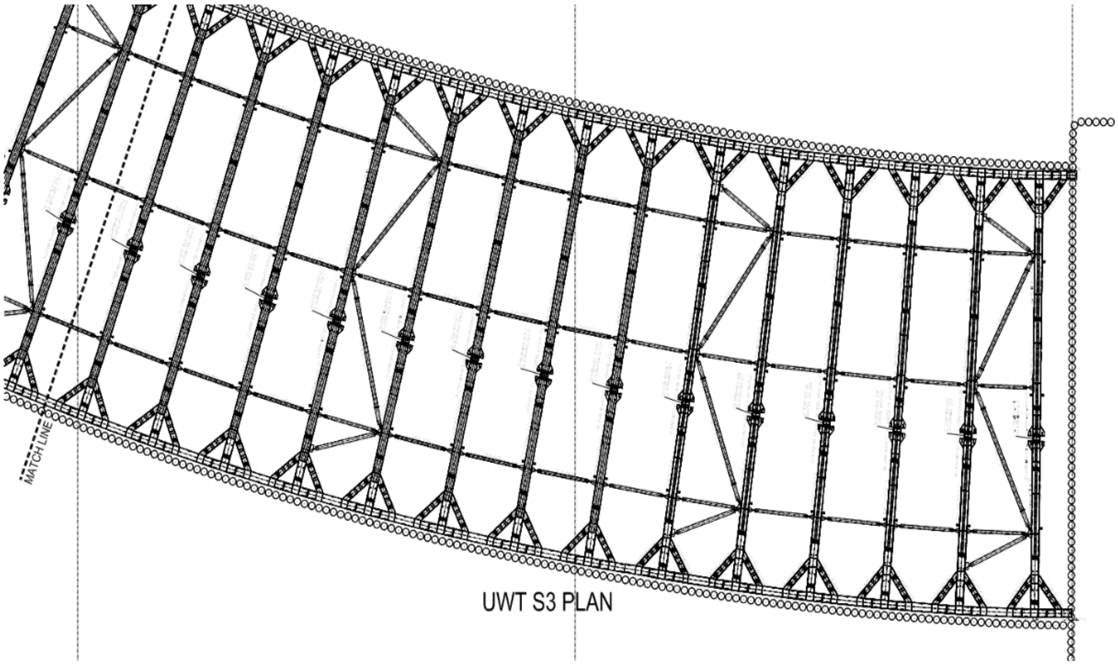

Figure 10: UWT Stage 2 Modular Strut Layout Plan

The modules are fixed by bolt and nut which saves substantial time if welding were used and reduces the safety risk of these hot works at height. The modular struts reduce the installation time and provide an overall safer working environment. The modular strut layouts were inputted into the 3D BIM model to ensure optimum fit of the fabricated modules and the reused strut shown in grey color in Figure 11 below.

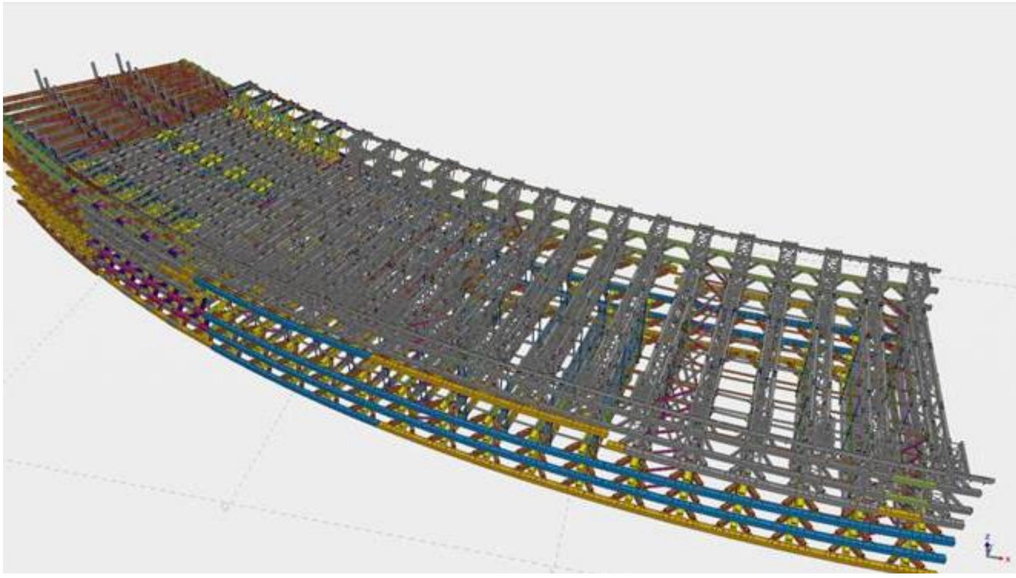

Figure 11: 3D BIM model of UWT Stage 2 Reusable Modular Strut arrangement

As the modular struts were to be used in a marine environment and designed to be reusable, corrosion due to the marine environment was a real concern. All reusable modular struts were painted with corrosion protection paint and prior to reuse of modular struts, they were inspected to ensure the sacrificial corrosion thickness did not exceed the designed capacity. Any struts with excess corrosion were checked, repaired, modified and repainted before reuse.

Figure 12: Modular Strut with corrosion check and awaiting for re-paint. (Clark et al. 2011)

3 Conclusions

The reduced reclamation scheme between the CPP and sheet pile double tied back wall system, the modular temporary steel working platform deck, the skidding modular mega truss strut system with

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hanging king posts and the ELS design comprised of reusable modular struts provides benefits to the Contractor, environment and project. The advanced design and construction of the ELS Cut and Cover cofferdam for the UWT submerged tunnel greatly reduces the material and time required to complete construction of the 370m length tunnel despite the constraints such as stakeholders, provision of navigation channel requiring works carried out in two stages and substantially less cost, construction risks / time and reduced disturbance to marine environment and traffic at Kowloon Bay from the substantially reduced temporary reclamation design.

4 Declarations

4.1 Acknowledgements

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