

# A REINFORCED SOIL MIX WALL COFFERDAM SUPPORTED BY HIGH CAPACITY REMOVABLE SOIL ANCHORS

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## SYNOPSIS

The temporary works construction of a deep walled cofferdam unhindered by the presence of internal struts provides a distinct benefit for the bottom-up construction of an underground structure. Extensive planning and trial work were required prior to the installation of deep soil mix walls and support by several rows of high capacity soil anchors. Total removal of the steel anchor tendons from adjacent areas was carried out as backfilling proceeded upwards around the completed structure.

## 1.0 Introduction

One of the Hong Kong Airport Core Projects is the Mass Transit Railway Hong Kong Station, which is the island's terminus for the 34 km airport railway link to Check Lap Kok airport.

This paper describes the design, construction and usage of two innovative systems. **Soil Mix Wall** cofferdam combined with **High Capacity Removable Soil Anchors**, which provided a temporary works scheme for the construction of one element of this project, the Cut and Cover tunnel section.

Due to its innovative nature, the proposed schemes went through a detailed period of preliminary design verification and development. This consisted of additional site investigations and trial anchor tests to confirm that the proposed anchors would perform in the newly placed and compacted sand fill, and the completely decomposed granite (CDG). In order to demonstrate the viability of the proposed scheme, a number of meetings and presentations were held with the client, in addition to the technical research.

Following the success of the initial trial anchors, the design of the retaining system commenced in earnest to ensure that the Client was provided with a safe, economic geotechnical solution which would not jeopardise the stability of an adjacent multi-storey building, nor detract from the viability of foundation works associated with future adjacent developments.

## 2.0 Cut and Cover Tunnel Particulars and Construction Constraints

The cut and cover tunnels comprise four tunnels, namely two Airport Express Line Tunnels (AEL) and two Tung Chung Line Tunnels (TCL). These diverge in elevation as the tunnels approach the station from a grade level at the junction with the submerged section of tunnels under Victoria Harbour. They are designed to be constructed bottom up within cofferdams.

The tunnels were constructed within two distinct temporary work schemes:

- i) The Engineer's temporary works scheme, which consisted of 1.5m diaphragm walls and barrettes, together with five levels of cylindrical props for a distance of 40m from the station and end of the tunnels.
- ii) The Contractor's temporary works scheme, which is the subject of this paper, extends from the Engineer's temporary works diaphragm wall to the ventilation building. (See Figure 1).

The construction sequence incorporating the constraints imposed by the Engineer is summarised as follows:-

- a) Install cut-off cofferdam wall.
- b) Dewater within the cofferdam to  $-18\text{mPD}$  in the West area and  $-15\text{mPD}$  in the East area to allow preloading of the soil prior to excavation, for a period of 120 and 60 days respectively.
- c) Through piezometer and extensometer measurements to the Engineer to confirm the time when the substrate had been preloaded to his design criteria.

(Actual consolidation periods were:	East Area	47 days
	West Area	37 days)

- d) Progressive excavation and installation of soil anchors down to the formation level.
- e) Construction of AEL tunnels units.
- f) As backfill progressed soil anchors to be destressed and removed.
- g) Backfill to PD level allowing groundwater to rise to  $-5\text{ PD}$ .
- h) Backfill to continue progressively whilst destressing and removing anchors up ground level ( $+4\text{m PD}$ ) to allow water to rise to ambient level.
- i) Finally stitching strips to be cast at the ventilation building and station ends of tunnels.

### 3.0 Cofferdam Wall and Support Options

The following four options were considered:-

- i) The use of Larssen (6) sheet piles, together with six layers of circular struts ranging in diameter from 750 upto 1220mm diameter
- ii) The use of 1.2m thick diaphragm walls with five levels of struts.
- iii) The use of diaphragm wall and soil anchors
- iv) Soil mix wall with soil anchors.

The sheet pile option was discarded due to the uncertainty and high risk of not being able to drive the sheet piles to the required cut-off levels, particularly on the south side of the site where old jetty piers and sea walls had been.

Reasons for not adopting options (i) and (ii) included to the restricted access created by the multiple levels of struts and complication of having to cast additional concrete props as the structures are constructed.

The final objection was due to costs, particularly with the diaphragm wall options.

#### Adopted Option

The decision to use soil mix wall instead of sheet pile or diaphragm wall was also influenced by the contractor's experience in Japan where this system is used quite extensively, as well as being a more economical option.

The decision to use soil anchors instead of props was primarily to provide unrestricted access for the construction of the tunnels, resulting in an overall, more efficient solution both from a buildability and economic point of view.

### 4.0 Cofferdam Design

The soil mix wall cofferdam was required to perform two functions:

- a) to create a cut-off wall to allow dewatering of the future tunnel areas.
- b) to retain a 20m deep excavation to allow the tunnels to be constructed.

## 4.1 Design Data

Component	Specification and Sizes	Reasons for Specification and Sizes	Comments
Soil Mix Wall (smw)	850mm diameter overlapping sections in plan Effectively at 600mm c/c	The size and centres dictated by the SMW drilling machine	Provides the water cut off barrier of the system
Steel Section in Soil Mix Wall	594 x 302 I beam section embedded to a max depth of 30m and min depth of 27m	Suitable size for embedment within the wall and readily available	Provides the structural strength of the retaining wall
SM Wall Depth	From ground level 38m deep (+3.0mPD GL to -35mPD toe of wall)	Engineer's prescribed cut off level	
Soil Anchors	Two types of anchors: 1) With working load of 1400kN 2) With working load of 2000kN	Based on trial anchor results	Provides the support to the retaining wall system
Water Levels	Within cofferdam dewatered to 1m below formation level-18mPD External of cofferdam level at +2.0mPD (ambient level)		
Excavation	Inside cofferdam each excavation proceeds to 0.5m below the soil anchor levels	To facilitate waling construction and soil anchor installation	
Soil Composition	Natural Sandfill above -7.5mPD Marine Sandfill above -16.0mPD Aluvium to -19.0mPD Completely decomposed granite (CDG) below	Soil Properties  N > 15  N > 30	Ground level at 3mPD

## 4.2 Design Analysis of Cofferdam

The cofferdam consisted of two halves, the south wall and the north wall which was further subdivided into sections depending on physical restrictions (See Figures 1 and 2).

- Excavation depth which varied from -15m PD to -13m PD required a maximum of 6 levels of anchors down to a minimum of 4 levels.
- Dewatering levels being - 18m PD – 15m PD in the West and East areas respectively
- Anchor inclinations, which are affected by adjacent structure foundations, dredge levels and access restrictions.

The analysis of the anchored soil mix wall was undertaken using the programme "WALLAP".

The initial design was based on proposed anchor lengths and inclinations from the anchor designer. These were fine-tuned to account for access restrictions and adjacent foundations. Through analysis, it was determined that conservatively a maximum anchor inclination of

40° would be safe against the wall reinforcement members failing vertically. It was therefore decided that the angles of inclination of the anchor would range from 10° to 40°.

The spacing of the anchor was optimised to a maximum of 3m c/c in the upper most rows down to 1.2m c/c in the lowest rows.

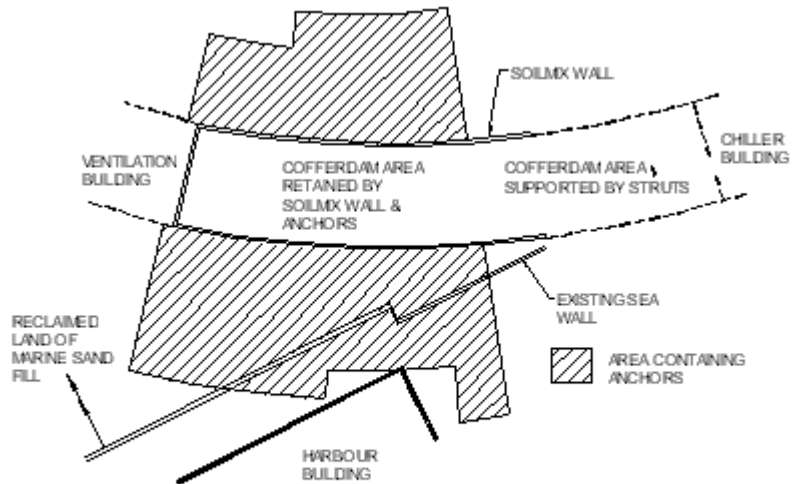


FIGURE 1  
 PLAN VIEW OF CENTRAL STATION AREA, HONG KONG ILLUSTRATING  
 AREA OF SOILMIX WALL & HIGH CAPACITY ANCHORS

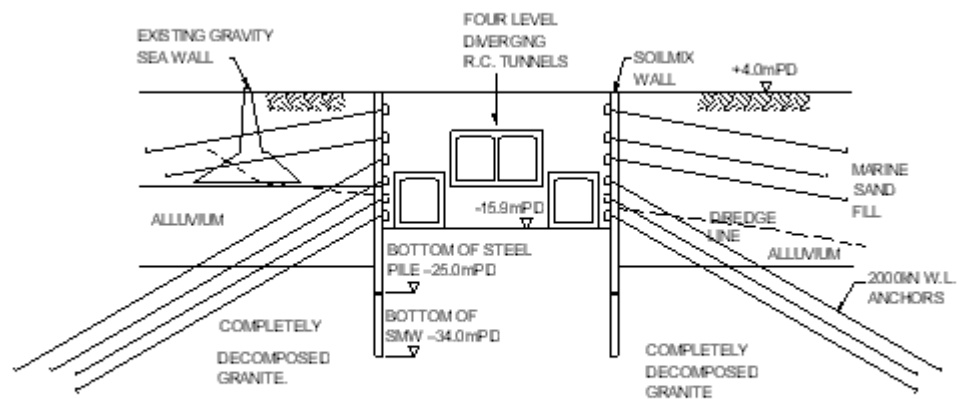


FIGURE 2  
 SECTION THROUGH THE ANCHORED SOILMIX WALL  
 COFFERDAM

The walings were designed as reinforced concrete units to spread and distribute the anchor loads, to accommodate the punching loads stressing, and also to resist vertical shear at the connection to the wall steel members.

In the initial design analysis, it was considered necessary to apply 50% of the total anchor prestress in two stages. However, for programme advantages the final solutions accommodated 80% of the load being applied in a single operation.

## 5.0 Soil Mix Wall

### 5.1 Introduction

In the early 1970's, the SMP (Soil Mix Pile) method as "cut-off walls and excavation retaining" system was developed in Japan. Based on the experience gained with this system, a multi-shaft auger machine was in use in 1976. With this machine it was possible to construct a soil-cement continuous wall which is now known as the Soil Mixing Wall method.

The specially developed three-shaft auger equipment is used to drill three holes simultaneously in the ground and to mix the soil insitu, with cement grout, bentonite liquid or other additives. These fluids are pumped from the tips of the augers into the drilled holes and the three circular elements are overlapped to form a single wall.

### 5.2 SMW Design

As the SMW diaphragm wall is constructed with the insitu soil as part of its main components, its structural strength can vary considerably as it is dependent on the soil conditions. Its strength can also vary from top to toe of wall as soil condition changes from layer to layer. The specialist contractor of this system could only offer a range of 0.005 to 0.030N/mm<sup>2</sup> for cohesive, sandy and gravel soils based on project data. For this reason the SMW strength included in the design calculations. Notwithstanding the fact that structurally the wall strength is not dependant on the soil mix strength, it is essential that it is homogenous and impermeable. To achieve this, trials were carried out with the insitu material to establish a design mix for this SMW and ensure a minimum strength of 0.005N/mm<sup>2</sup> (5kg/cm<sup>2</sup>). The determined mixing ratios for every 1m<sup>3</sup> of soil, were 280kg cement, 15kg bentonite, 150 litres of water, w/c ratio 200%.

Cube test data exhibited higher strength values:

7 Day	=	0.7 N/mm <sup>2</sup> - 3.8 N/mm <sup>2</sup>
28 Day	=	0.4 N/mm <sup>2</sup> to 6.4N/mm <sup>2</sup>

However, the major structural design components of the SMW wall were the vertical reinforcing member and soil anchor ability to resist the applied forces and soil reactive loads.

Consistent with normal practice for temporary works anchors, design policy ensured that design had an inherent factor of safety in excess of the 1.6 was used in the anchor design. The vertical "I" beam design was based on:

- a) Maximum moment in wall stage, and coincident axial loads in the wall.
- b) Maximum axial load in the wall stage and coincident moments in the wall

The axial load in the wall is taken to be a summation of all the vertical components of the anchors installed at any stage. This is conservative, as it does not consider the friction between the soil mix wall and the soil around it, through which a proportion of the vertical load will be transferred out of the steel section.

### 5.3 Construction Equipment

The base machine for the SMW system is a large modified crawler drilling machine, (Figure 3). An electric powered auger with a special reduction gearbox for multi-shafts turns the auger shaft. This equipment is unique in the alternation of auger flight and mixing paddles on the three shafts, each rotating out of phase, thereby homogeneously mixing in situ the soils with bentonite and cement. The drilling machine is serviced by a mixing plant and attached cement silo which measures, mixes and pumps the grout through the auger shaft and into the excavation through the auger tips.

Additional equipment for the wall installation includes cranes and hydraulic shovel, a spoil pit holding area is also required.

### 5.4 Installation of Reinforcing Members

Once the drilling and mixing is complete, a guide template is placed over the trenches.

The reinforcing member is then lowered into place by the slave crane, the member is then fixed at the correct level by a hanger held by angle sections spanning the SMW wall width and supported by the template supports.

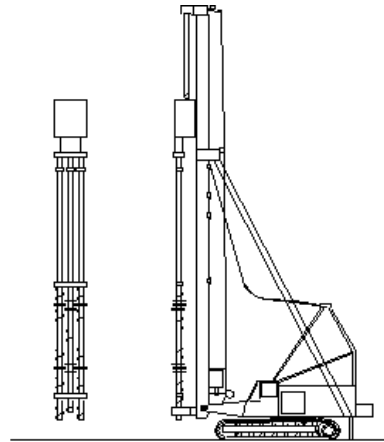


FIGURE 3  
EQUIPMENT AND AUGERS FOR THE SMW METHOD

## 6.0 The Ground Anchor System

### 6.1 Introduction

The very high load requirement at up to 6 waling levels in the cofferdam demanded the utilisation of the highest anchor loads attainable in soils, if an anchor solution was to be economically attractive. Furthermore, the tight time-constraints demanded the completion of the entire anchor works, the waling systems and the excavation within a 33 week period. The overriding factor, however, was the Works Specification: In the event of the use of temporary anchors for the wall support, then the entire steel tendons installed in each anchor must be fully *removed* from the grouted anchor bore after use. This removal of steel “contamination” from ground after use would then allow the safe unobstructed installation of piles and services into the ground outwith the cofferdam walls after the contract completion. The further development and utilisation of “air space” around and above the station area could then proceed without foundation problems.



### 6.2. Proposals

The development of the Keller Single Bore Multiple Anchor System (SBMA) (Ref 1 and 2) over a seven year period in the UK, prior to these works allowed the design proposals for the use of over 500 high capacity soil anchors to be evolved. On the north side, the middle and upper rows of anchors were founded in the compacted marine sandfill, whilst lower rows of anchors passed through the softer underlying alluviums and penetrated into the dense to very dense silt of the completely decomposed granites (“CDG”) (Fig. 2). On the east side only the two upper rows could utilise the marine sandfill in the fixed length. The middle and lower level anchors penetrated through the existing granite sea walls, through soft alluvium and into the CDG.

The Single Bore Multiple Anchor System consists of a multiple of unit anchors, each unit containing its own tendon and stressed with its own jack and bonded to the ground over its own fixed length in the anchor bore. This system allows each unit to utilise the grout to ground bond strength efficiency over a multiple of unit fixed lengths which may total over 20 metres in one anchor borehole. Each unit anchor fixed length design is based on the in-situ ground strength or ultimate bond strength available at that particular depth. This allows some units in a bore to be founded in sand in the upper part of the bore and some in CDG in the lower bore. Furthermore, the bond lengths of unit anchor founded deep in the CDG will be shorter than those founded at a shallower depth in a weaker material. In addition, this anchor system can fully accommodate the encounter of weak zones, which may lead to failure of one or two unit anchors. The remaining unit anchors are designed to safely accept an overload, if so required.

The initial design selected an anchor working load of 1400kN utilising 6 unit anchors in each anchor bore and providing a factor of safety of 2.0 against failure at the grout/ground interface. However, owing to the novelty of founding anchors in both marine sand fill and CDG and the proposal to utilise such very high loads in soil anchors, a complete trial anchor programme involving four trial SBM anchors was required, prior to commencement of production works.

In conjunction with the development of the SBM anchor system in the late 1980’s and early 1990’s, the use of a special looped sheath strand system had been researched and advanced for use as multiple units within a single bore (Ref 3). This allowed the “loop” of strand complete with load bearing saddle and other refinements, to transfer load in shear and compression into each designed unit length of grouted bore but then on completion of the usage to be destressed, then fully withdrawn from the grouted bore, along with all other looped strands. The trial anchor programme was also carried out to demonstrate that the steel tendons could be entirely removed from the bore.

### **6.3 Trial Anchors**

Trial anchors were installed in two stages; the initial stage demonstrated that working loads of 1400kN or more could be safely utilised in both founding materials and that the steel strands could be fully withdrawn from the bores. Loads between 2000 and 2800kN were obtained but in the majority of instances the unit anchors could not be failed (Ref 4). As installation of the two upper rows of 1400kN working load anchors progressed, a further 7 trial production anchors were installed and their performance substantiated the safe use of 2000kN working load anchors below row 2. These anchors achieved between 2500 and 3300kN without many units failing and all demonstrate extremely satisfactory load hold behaviour (extremely low creep characteristics).

### **6.4. Production Anchors Installation**

Production anchors were installed using 6 Casagrande, C6, drilling rigs each advancing 152mm casing and 101mm rods up to anchor depths of 60m using controlled water flush drilling techniques. Special precautionary measures and safeguards were evolved to reduce and control ingress of water into the cofferdam as a consequence of the external groundwater head present. This head equated to 18m when drilling the wall for the bottom row anchors. Furthermore, the presence of the 25 storey Harbour Building just 2m beyond the extremity of the anchor works demanded further measures of extreme control in order to prevent heave or settlement. After tendon installation, end of casing grouting methods required application of pressures ranging from 5 to 15 bar during casing withdrawal over the fixed length. On

completion of casing extraction from the bore, a special extended anchor cap was temporarily fitted to allow controlled application of grout pressure through the waling to the back of the wall in order to counter any nominal soil loss and subsequently restrict or eliminate water inflow whilst the anchors were in use. These were particularly sensitive balanced operations such that they did not jeopardize the stability of the wall.

### **6.5 Production Anchor Testing**

Each anchor containing six or seven unit anchors was loaded simultaneously with six or seven 600kN capacity, hydraulically synchronised hollow ram jacks to a test load of either 1750 or 2500kN. After a satisfactory load cycle and load hold monitoring period, each anchor was locked off at 80% of the designated working load. Each seven unit anchor was required to satisfy 21 basic test requirements prior to its acceptance into the works. Out of 3010 unit anchors installed, only 23 units failed and in only two instances did this necessitate the re-drilling of an anchor. In all other cases the designed "fall-back" system accommodated the unit failures encountered in occasional zones of weak ground.

### **6.6 Wall Movement and Monitored Anchor Loads**

Despite the severity of testing of individual anchors, a monitoring system were in place to assess both the wall movement and the load change in three vertical panels of anchors (Ref. 5). No data produced any reason for concern;

- i. none of the monitored anchors were subjected to significant load change (more than 5%)
- ii. generally, where outward or inward movement of the wall was recorded, the direction of the small change in anchor load (gain or loss) was as expected.
- ii. the inward wall movement did not exceed 50% of the pre-calculated wall movement of 70mm.

### **6.7 Tendon Withdrawal**

After excavation was completed and whilst the four reinforced concrete rail tunnel structures were built upwards, backfilling was carried out gradually, making the anchors obsolete. Each unit anchor was unloaded in turn using a monojack and after removal of all barrels and wedges, one end of the looped strand was jacked out for approximately a metre. The strand end was then connected to a crane or winched and the full strand loop length, up to 120m, was withdrawn from the bore. The removed strands were cut and removed from the site. General backfilling, anchor destressing and tendon removal progressed until finally surface level was attained.

## **7.0 Summary**

The 38m deep soil mix wall surrounding the 240m x 75m x 20m deep cofferdam, fulfilled its intended purpose in providing both an efficient cut off trench and a 27m deep structural retaining wall. The wall support system which required up to six rows of soil anchors, was extremely demanding in load requirements and in overcoming physical difficulties in construction; penetration of the existing granite sea walls was achieved where required; head of groundwater, 18m above the level where the lower row anchors penetrated the wall, was satisfactorily controlled throughout drilling and grouting and during the anchor working life.

The Single Bore Multiple anchors allowed utilisation of working loads of 1400 and 2000kN in unusual soils, namely marine sand fill and completely decomposed granite. Furthermore, the system allowed on completion of the temporary works the full extraction of the strand tendons from both the fixed and free length of the grouted bore.

These temporary works, on a fast track programme, effectively utilised two relatively novel systems. Their successful use adjacent to an existing 25 storey building and in a critical environmental area demonstrate an excellent example of Engineering Innovation.

## 7.1 Acknowledgements

Client:	Mass Transit Railway Company, Hong Kong
Main Contractor:	Aoki Corporation
Soil Mix Wall Sub-Contractor:	Seiko Kogyo & Co. Ltd.
Anchor Specialist:	Keller Ground Engineering
Anchor systems Sub-Contractor:	Freyssinet Hong Kong, and Austress Freyssinet (Sydney)
Temporary Works Designer:	Robert Benaim & Assoc. (Asia) Ltd.

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