Use of Slurry and CSM Wall for Excavation and Lateral Support Works

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doi: https://doi.org/10.21467/proceedings.126.10

Abstract

Steel beams embedded in soil cement columns or soil cement panels can be used for construction of embedded walls for excavation and lateral support works. The soil cement columns can be formed using the secant pile method or deep cement mixing while soil cement panels can be constructed using cutter soil mixing (CSM). Steel beam walls formed by CSM are called the CSM wall. Another method for forming a soil cement panel is by using the method for construction of diaphragm wall and such walls are known as slurry wall. In this paper, the design concepts and construction procedures of steel beam walls are discussed. Case histories of slurry walls and CSM walls are also presented to illustrate the use of steel beam walls in supporting deep excavations in Hong Kong.

Keywords: Cement soil mixing, Deep excavation, Hong Kong

1 Introduction

The scheme of using steel sections embedded in cement stabilized soils or hardened cement slurry as embedded walls for excavation and lateral works (ELS) is commonly used outside Hong Kong. There are many different names for such types of embedded walls in the literature. In this paper, this type of embedded walls will be referred to steel beam walls. If there is no space restriction, I-beams are usually preferred to other steel sections (e.g. universal column) for construction of steel beam walls as I-beams are usually more effective in resisting bending moment per unit weight of steel.

There are different methods for forming a steel beam wall. If the steel sections are inserted in cement stabilized soils mechanically mixed insi tu, the steel beam walls so constructed are sometimes called the *soil-mix walls* (e.g. Denies & Huybrechts, 2017). If a steel beam wall is formed by placing steel sections inside excavated panels or trenches filled up with cement slurry, it is often called a *slurry wall* in Hong Kong.

The materials encasing the steel beams are collectively called the soil cement, although the cement slurry for constructing a slurry wall will normally contain only a small proportion of bentonite. The term 'cement slurry' will mean fluidic cement slurry when discussing an excavated panel and hardened cement slurry when discussing a completed steel beam wall.

Soil-mix walls are formed by inserting steel sections into soil cement columns constructed using the secant pile method or deep cement mixing method (DCM). Steel sections can also be inserted into soil cement panels constructed using the technique of cutter soil mixing (CSM) to form a CSM wall. Slurry walls are generally formed using similar construction techniques for diaphragm wall (D-wall).

Proceedings DOI: 10.21467/proceedings.126; Series: AIJR Proceedings; ISSN: 2582-3922; ISBN: 978-81-954993-7-3

This paper aims to discuss the design concepts of steel beam walls and present some case studies of CSM wall and slurry wall in Hong Kong.

2 Steel Beam Walls

A steel beam wall is a composite wall with steel sections encased by cement stabilized soils or cement slurry. This is similar in concept to the soldier pile wall or pipe pile wall system for ELS works. The steel sections provide the structural strength to resist the bending moment and shear force induced by soil and water pressure behind the steel beam wall during bulk excavation while the soil cement between steel sections act as the lagging wall.

In Hong Kong, tube-a-manchette (TAM) grouting is commonly provided behind a soldier pile wall or pipe pile wall to serve two functions. First, it enhances stability of the soils to prevent soil collapse before installation of the lagging wall across adjacent soldier piles. Second, it provides an impermeable barrier below the excavation level to prevent excessive seepage flow into the cofferdam and hydraulic failure of the soils. These two functions are often not fulfilled because it is difficult to produce uniform grouted soils using TAM grouting.

It is not uncommon to see collapse of soils before the lagging wall is installed in time to seal the exposed face of excavation even when the exposed vertical cut face of soils is often limited to a small area. Also, the grouted soils formed by TAM grouting may not be sufficiently uniform to provide a water-tight barrier below the excavation level for limiting the drawdown of water level outside the cofferdam during excavation.

Steel beam walls offer a much more robust system of embedded walls than soldier pile walls or pipe pile walls in reducing the risk of soil collapse during excavation and providing a reliable water-tight barrier for the cofferdam. Soil cement is a much more uniform material than soils treated by TAM grouting. The strength of soil cement can be suitably adjusted such that it is strong enough to resist the soil and water pressure without the use of lagging walls. Being a more uniform material, the soil cement in a steel beam wall is a much more reliable impermeable barrier than soils treated by TAM grouting in providing a water-tight cofferdam.

The choice of a suitable embedded wall for ELS works depends on many factors. For deep excavations with adequate space for storage and maneuvering of construction plants, the option of steel beam walls offers distinct advantages in terms of overall costs and construction programme than soldier pile walls or pipe pile walls when one takes account of the cost and time needed for installation of the lagging wall.

3 Construction of Steel Beam Walls

Steel beam walls can be constructed using different construction techniques as discussed below.

3.1 Secant Pile Construction Technique

Contiguous soil cement columns can be formed using the same techniques for construction of secant piles as shown in Figure 1. The soil cement columns are first formed by mixing the soil and cement insitu using augers. If there are underground obstructions, bored piling equipment can be used for forming the soil cement columns. The steel sections are inserted into the secondary columns before the soil cement has hardened. This method of construction is generally less efficient than other techniques described below and hence less common.

Proceedings DOI: 10.21467/proceedings.126
ISBN: 978-81-954993-7-3

Series: AIJR Proceedings
ISSN: 2582-3922

3.2 Deep cement mixing

Different techniques of DCM involving multiple auger-based or blade-based tools as described in Bruce et al (2013) can be used as an alternative means for forming contiguous soil cement columns. The method is generally more efficient than the secant pile method as two or more soil cement columns can be constructed by DCM at the same time. The technique of DCM is not suitable for soil profiles with obstructions. After the soil cement columns have been formed, the steel sections are exerted into the soil cement to form a steel beam wall. Figure 2 shows the procedures for constructing a steel beam wall using DCM. This technique is commonly used in many parts of the world including the Mainland China for constructing steel beam walls.

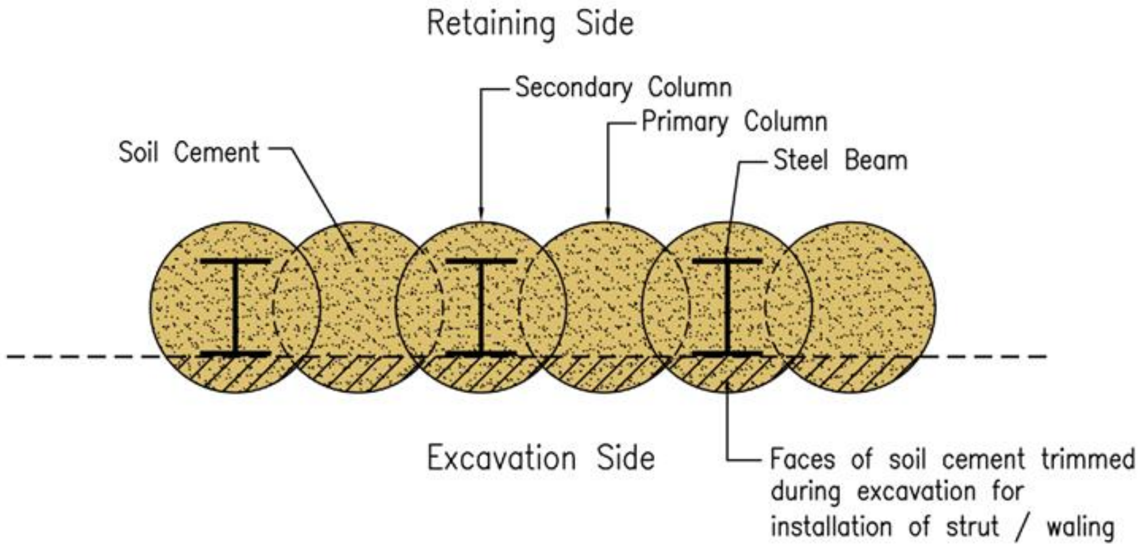

Figure 1: Steel beam columns constructed using secant pile technique

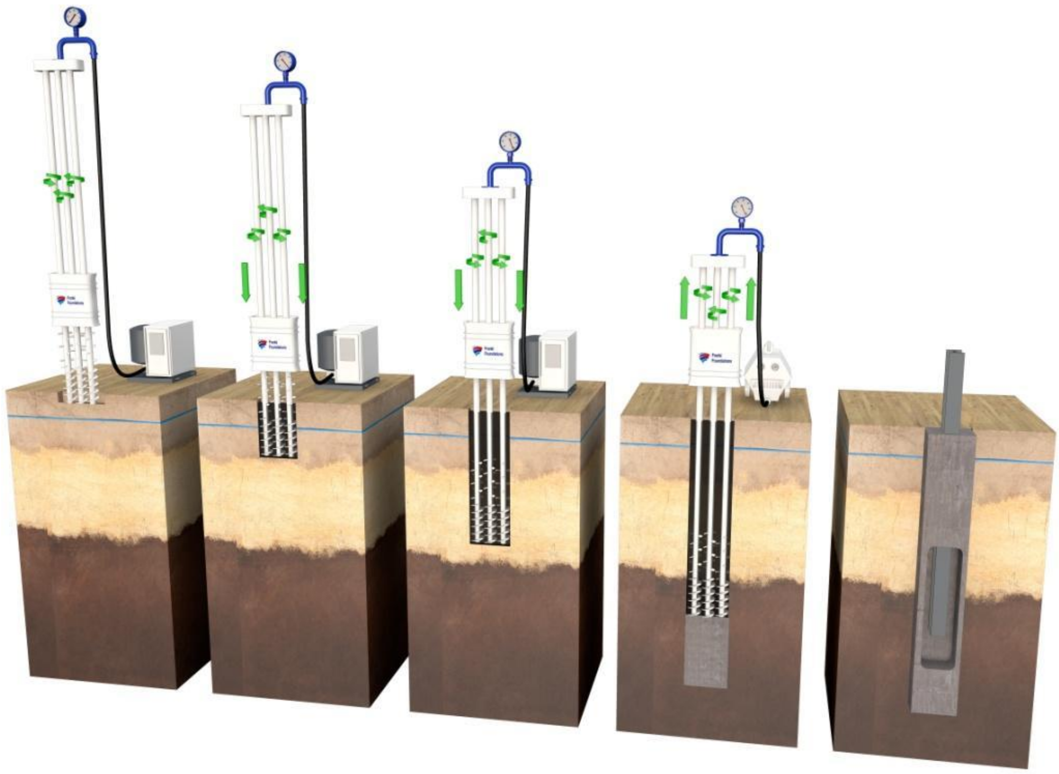

Figure 2: Steel beam wall constructed using DCM technique (Franki Foundations, 2021)

3.3 Diaphragm walling technique

A steel beam wall can also be formed using a similar technique for construction of D-wall. A panel is to be excavated using a grab or cutters to form a trench for placement of steel sections. The trench will be supported initially by bentonite slurry. When the excavated panel has reached the required depth, a cement slurry is then pumped into the trench to displace and completely replace the lighter bentonite slurry. This is called the substitution method of placement. The cement slurry will fully encase the steel section. With time, the cement slurry will harden to form a composite embedded wall.

The cement slurry can be placed into the excavated trench before or after insertion of the steel sections depending on the contractor’s preference and the design mix of cement slurry. If the design strength is high, the cement slurry will be thicker and may harden more quickly. Under this situation, it may be preferable to place the steel section before placing the cement slurry into the excavated panel.

If the steel beam wall is purely designed as an embedded wall for ELS works and not a load bearing wall, it may not be necessary to spend too much efforts to reduce the sand content of bentonite slurry in the excavated panel as long as the contractor is confident that the bentonite slurry can be displaced by the cement slurry. If the steel beam wall is designed to also perform as a load bearing wall, it is preferable to de-sand the bentonite slurry and to clear the soil debris accumulated at the base of the excavated panel before placement of cement slurry to avoid reduction in load bearing capacity due to the presence of loose soil debris at the bottom of the wall.

3.4 Cutter Soil Mixing

CSM can be used as an alternative to the D-wall method for forming the steel beam wall. Figure 3 shows the procedures for constructing a CSM wall. The rotating soil cutters are sunk progressively to slurrify the soils. Depending on the soil conditions, bentonite slurry may need to be fed into panel through the feeder pipe connected to the cutters to help maintain stability of the panel when cutting in sand. When the soil cutters reach the required depth, cement slurry will be fed to the rising cutters. The rotating cutters will mix the cement slurry with the slurrified soils to form a soil cement mixture. Unlike the D-wall technique, the steel section can only be inserted into the soil cement panel after it is completed. The strength of soil cement can be adjusted by varying the design mix of cement slurry and more importantly by controlling the rate of upward movement of the cutter during soil mixing.

CSM is usually more efficient and less costly than the D-wall technique because CSM is faster and consumes less cement. In addition, CSM tends to induce less settlement of adjacent ground than the D-wall method as the soil cement panel is at all time supported by disturbed soil mixture or soil cement during construction. CSM has difficulties in overcoming large stones or boulders and is hence not suitable for ground profile with large obstruction materials. Perhaps, the D-wall remains the only choice for constructing a steel beam wall when there are underground obstructions.

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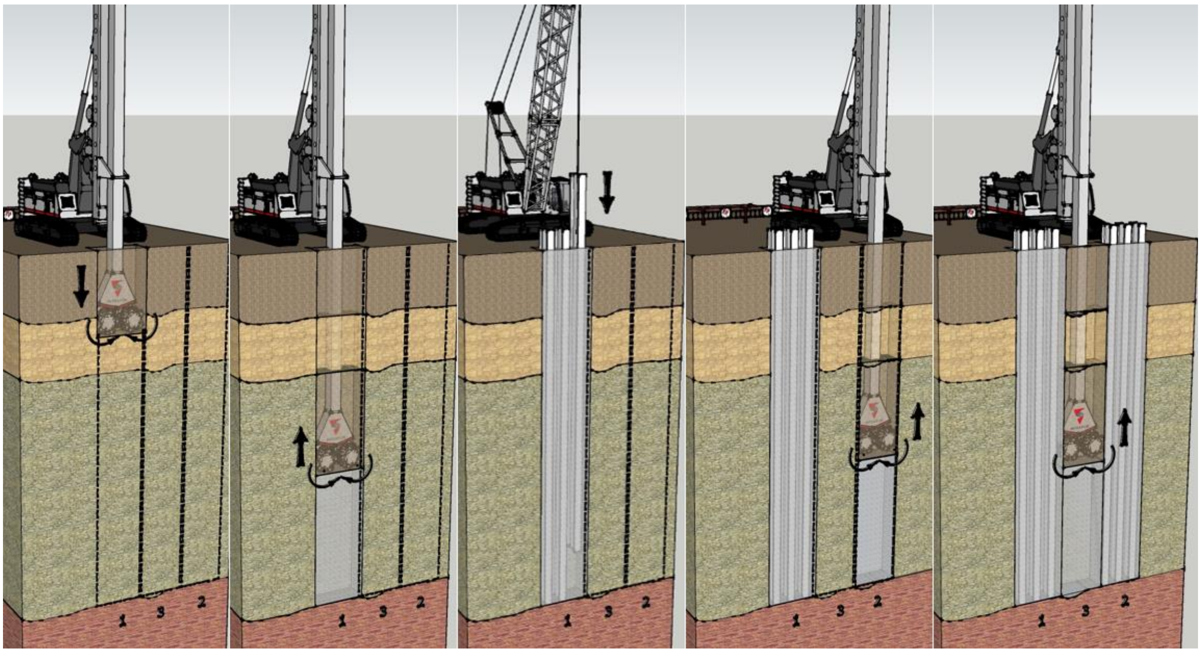
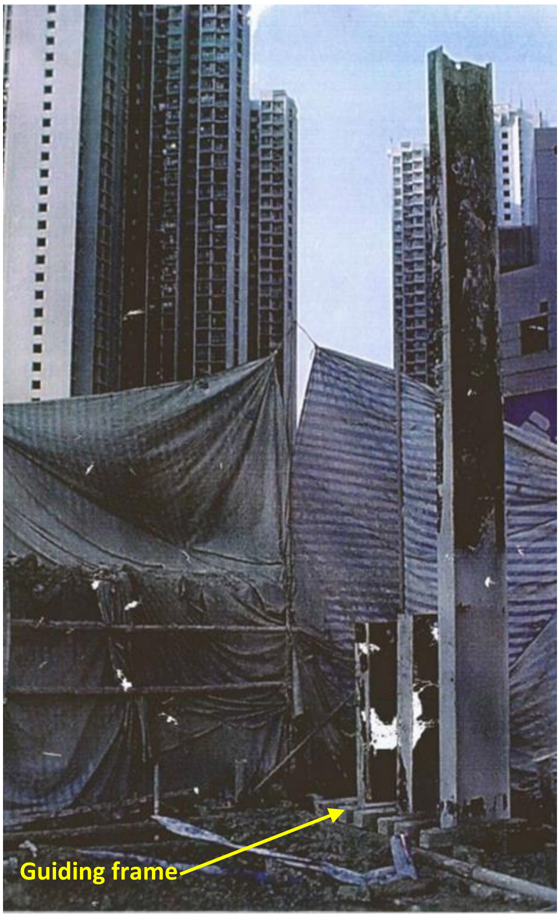


Figure 3: Steel beam wall constructed using CSM

3.5 Other details of Construction

When constructing a steel beam wall using the D-wall method, a steel guiding frame is often provided to facilitate accurate placement of the steel sections at their designated positions. The guiding frame restrains and supports the steel beams before the cement slurry has hardened. Plate 1 shows an example of a guiding frame used for the project of Site A to be described later.

In the Mainland China, bituminous paint is often applied onto the surface of steel sections to reduce the interface friction to allow the steel sections to be extracted by jacking upon completion of ELS works and re-used for other purposes. If the steel beams are to be extracted later, they should be spliced by butt welding without the provision of splicing plates.



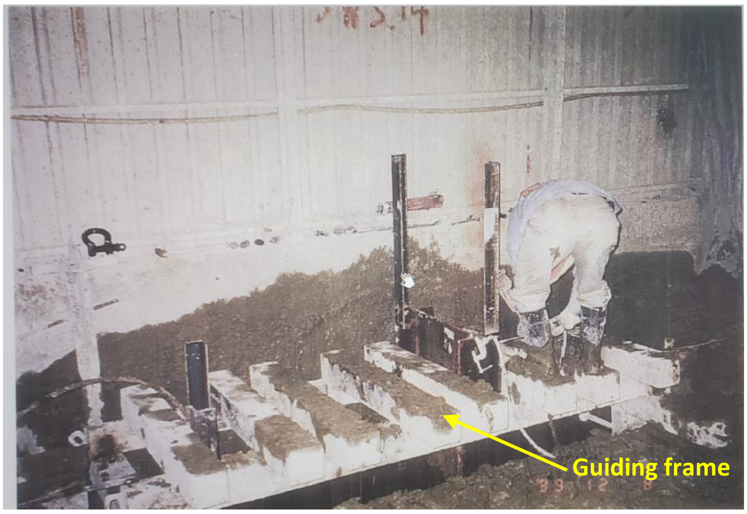


Plate 1: An example of guiding system for placement of steel section

4 Design Aspects of Steel Beam Walls

The design principles for a steel beam wall are well established in the literature. Figure 4 taken from Denies & Huybrechts (2017) depicts the load transfer mechanism of a steel beam wall. Arching effects will develop in the soil cement to withstand the soil and water pressure behind the steel beam wall. The stress arch transfers the load to the flanges of the steel section near the excavation side, and in turn to the walings/struts supporting the steel beam wall. The arching effect can also develop to a lesser extent in the soils behind the wall in helping to transfer part of the earth and water pressure directly onto the steel sections. This will reduce the soil and water loads transferred to the soil cement sandwiched between adjacent steel sections. As long as the soil cement has adequate compressive and shear strength to resist the induced stress, failure of the material will not occur and it will not be necessary to provide steel lagging walls between adjacent steel sections.

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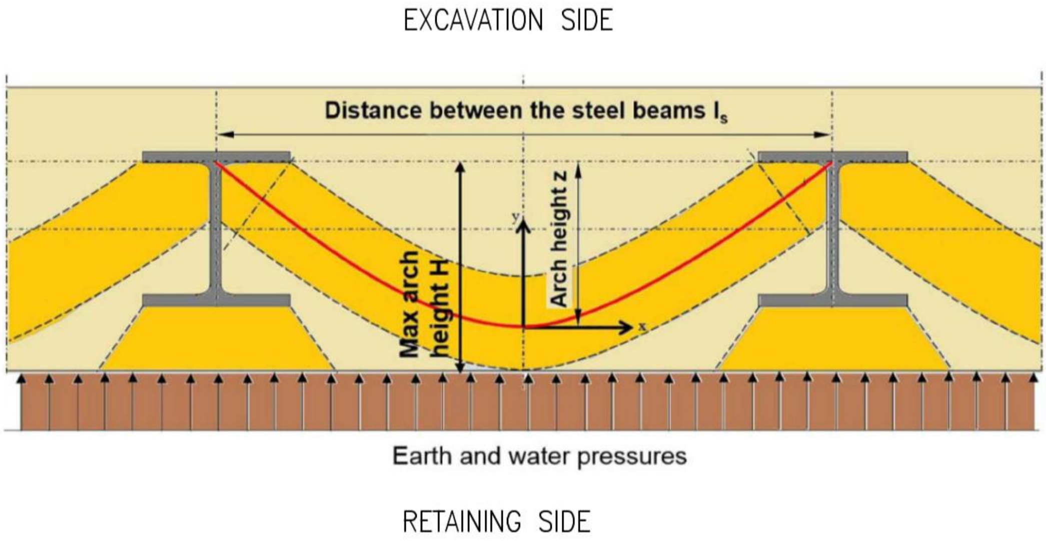


Figure 4: Load transfer mechanism of a soil cement wall (after Denies & Huybrechts, 2017)

The stability of soil cement can be easily analyzed using a geotechnical software such as Plaxis, FLAC or SIGMA/W in which the material is modelled as a geo-material with shear strength *c*. For a material with design unconfined compressive strength *U*, the design shear strength can be taken as $c = U/2$. If the calculated compressive and shear stress within the soil cement do not exceed their design strength, stability of the soil cement in the steel beam wall will be assured.

Structural engineers familiar with reinforced concrete design may find it uncomfortable to accept the idea that soil cement can be stable without reinforcement or lagging wall and may require a designer to justify that bending failure of the material will not occur. This may be a reasonable concern because the arching effect can only develop effectively when the spacing of steel sections is small relative to the thickness of the soil cement. As the spacing increases, a higher tensile stress will develop in the soil cement to cause failure of the material similar to bending failure. Based on a series of finite element analyses, Taki & Yang (1991) have developed a design rule as presented in Figure 5 for checking the likelihood of bending failure. If *D* is taken to be depth of the steel section *h* (i.e. $D = h$) and the steel sections are assumed to be placed centrally in the steel beam wall (i.e. $e = 0$), the criterion in Figure 5 will reduce to a simple rule that bending failure will not be a problem if the clear spacing between steel beams is less than twice the beam depth (i.e. $L_2 / h < 2$).

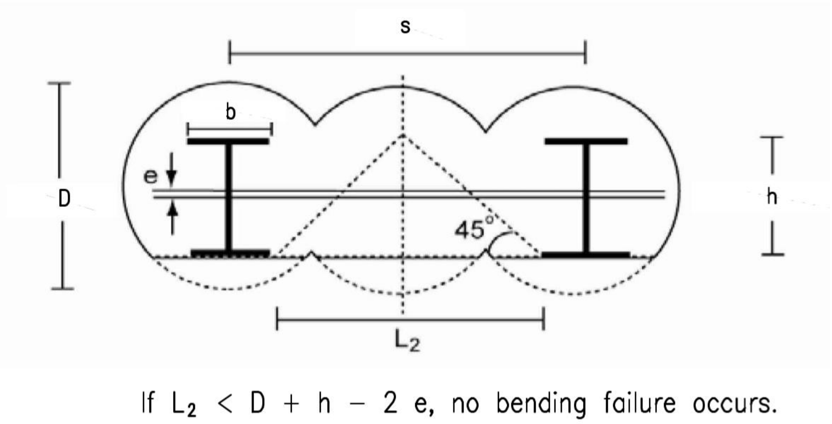


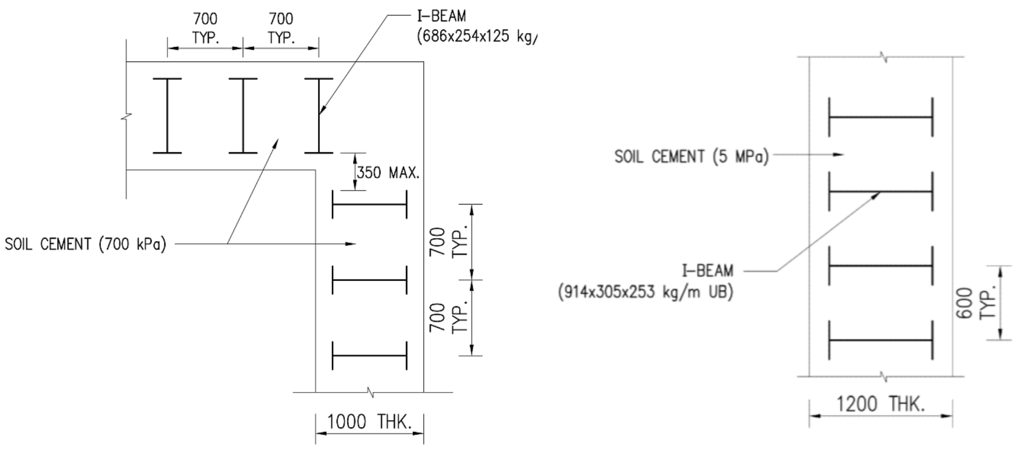
Figure 5: Structural checking of soil cement wall against bending failure (after Taki & Yang, 1991)

5 Case Histories

Three case histories are described for Site A, B and C in this section. Table 1 shows information of the clear spacing and beam depth of the steel sections for these sites. In all cases, I-beams were used with the L_2/h ratio less than 2. The criterion shown in Figure 5 was met and bending failure of the sol cement was therefore not a concern for the steel beam walls, rendering steel lagging walls unnecessary for all these projects. Figure 6 shows the layout of steel beam walls for Site A and Site B.

Table 1. Details of steel beam walls

Site	Clear spacing between steel beams, L_2 (mm)	Beam depth, h (mm)	L_2/h ratio
A	446	686	0.65
B	295	914	0.32
C	970	914	1.06



(a) (b)

Figure 6: Layout of steel beam walls for (a) Site A and (b) Site B

5.1 Site A

The design of ELS works for Site A required formal approval by the Buildings Department as the ELS works formed part of the substructure works for a private project development in Tseung Kwan O, New Territories. The soil profile comprised a stratigraphy of fill, marine deposit, alluvial deposit and decomposed tuff with increasing depth. The fill comprised some rockfill which made the driving of sheetpiles difficult. The ELS works involved an excavation with a general excavation depth of about 14m. The original design scheme developed by the Engineer involved forming an excavated trench using the D-wall method and filling it up with weak plastic concrete. Lassen 6 sheetpiles were then installed by driving through the plastic concrete to form the embedded wall. The sheetpile walls were to be supported by up to 7 layers of steel struts.

The contractor considered the Engineer's design scheme difficult to implement as driving of sheetpiles through plastic concrete would be impractical if not infeasible. The contractor then proposed an alternative scheme of using a steel beam wall for the ELS works. As the fill layer comprised rockfill which might be difficult to overcome using other construction methods, it was decided to use slurry walls to replace the sheetpile walls.

The I-beams for the steel beam walls were of 686×254×125 kg/m UB placed at 0.7m spacings inside 1.0m wide panels. The guide frame used for facilitating the placement of I-beams is shown in Plate 1. The I-beams were hung onto the guide frame after placement. The hung I-beams would maintain a vertical alignment due to their own weight. After the cement slurry had hardened, a composite soil-cement wall would be formed.

The design 28-day unconfined compressive cube strength of the cement bentonite was 700 kPa, giving a design shear strength of 350 kPa. The design mix proportion for the soil cement was:

Cement	450 kg
Bentonite	20 kg
Water	878 litre
Additive (retarder)	1.5 litre

The design mix was based on results of trial mixes collected from past job references. It was predominantly a cement slurry, but with some bentonite and retarder added to improve the performance and setting time of the material. As the design strength of the soil cement for this project was not high, the cement slurry was not thick. This allowed the contractor to make the decision of using cement slurry directly for supporting the trench excavation. Once trench excavation had been completed, I-beams could be immediately placed into the cement slurry to complete the construction of steel beam walls without the need of using the substitution method to replace the bentonite slurry. For this project, trench excavation and placement of I-beams for each panel could all be completed within the same day resulting in a very efficient operation for construction of the slurry walls.

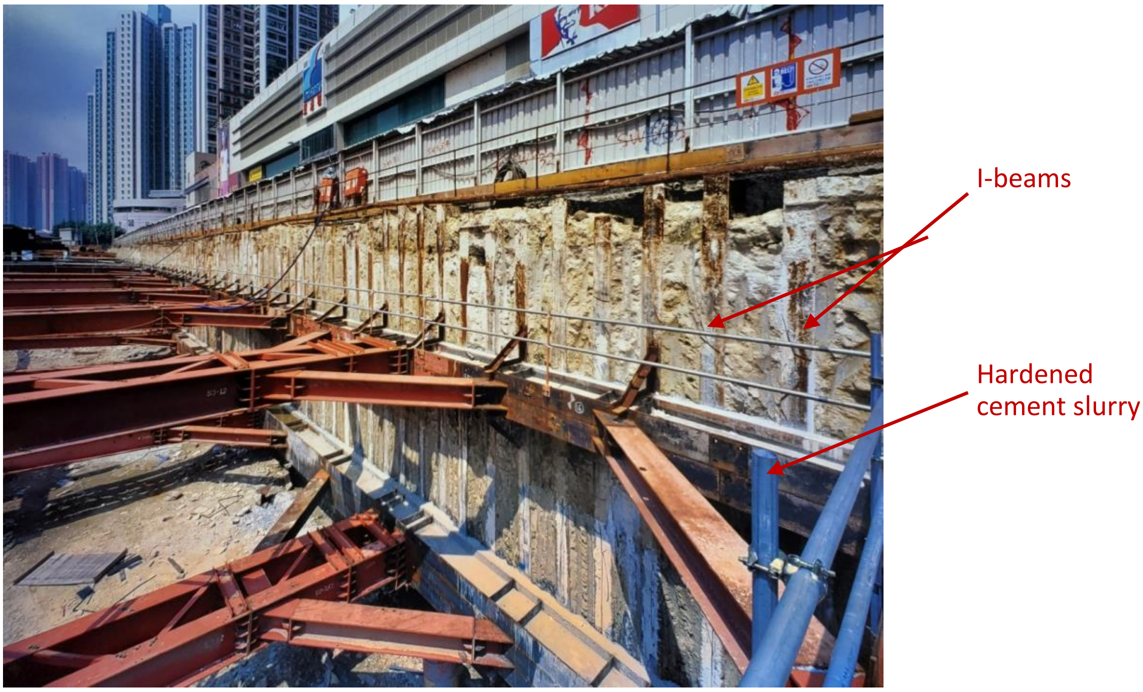


Plate 2: Photograph of soil cement wall during excavation

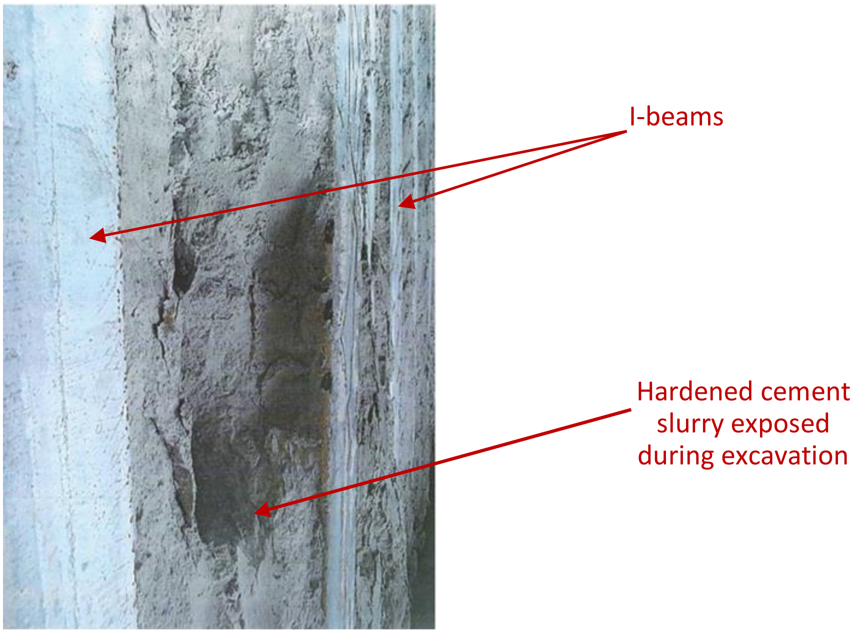


Plate 3: Exposed face of soil cement

Plate 2 shows a photograph of the soil cement wall during excavation and Plate 3 a close-up view of the excavated face of soil cement. The soil cement was soft enough to be excavated easily by a backhoe but strong enough to resist the soil and water pressure behind the wall without the need of steel lagging wall.

Quality control of the soil cement was implemented by testing of cube samples prepared in a similar manner for quality control of concrete for private development projects. In addition, core samples were taken in top 3m of specified panels for compression test for further verification of strength

Proceedings DOI: 10.21467/proceedings.126
ISBN: 978-81-954993-7-3

Series: AIJR Proceedings
ISSN: 2582-3922

parameters. Due to self-compaction under its own weight, the density of soil cement is expected to increase with depth. Therefore, taking the core samples within the top 3m of soil cement should give a conservative indication of the in-situ strength of soil cement in the panel.

Adequacy of the soil cement was confirmed by performing analysis of a typical unit of the steel beam wall using the program SIGMA/W under the anticipated maximum applied water and earth pressure acting behind the embedded wall. The calculated maximum principal stress and shear stress were both within the design compressive and shear strength of the soil cement with a factor of safety exceeding 2.0.

The ELS works for this project were carried out over 20 years ago. Although the scheme of soil cement wall was not even something new in other parts of the world at that time, it was one of early projects if not the first project involving the use of steel beam walls in Hong Kong. It is also the first such design approved by the Buildings Department. The steel beam wall scheme had proven to be a big success for this project. With the higher stiffness and structural capacity of the I-beams than sheet piles, it was able to reduce the struts from 7 to 3 layers. As steel lagging wall was not necessary for the ELS works, the progress of ELS works could be greatly enhanced. The soil cement had proven to be a uniform material and impermeable during bulk excavation, providing an extremely good water-tight barrier against seepage flow across the soil cement wall throughout the entire excavation.

5.2 Site B

In Site B, a temporary slurry wall was used for construction of a cut-and-cover tunnel. The slurry wall was designed to support an excavation of over 50m deep. Figure 6(b) shows the layout of the slurry wall for this project. The wall was formed using I-beams of 914×305×253 kg/m UB placed at 0.6m spacings inside 1.2m wide excavated panels. The design compressive strength of the soil cement was 5 MPa necessary for resisting the relatively high water and soil pressure behind the slurry wall. A lower water/cement ratio as compared with Site A was required to achieve this higher design strength. The rockhead profile for Site B was not deep below the final excavation level. Shear pins were used to enhance the stability of the slurry wall against kickout failure. The installation of shear pins was carried out by welding reservation pipes to the full length of selected I-beams during construction of the steel beam walls. When the slurry wall had been completed, drilling would be carried inside the reservation pipes to required depths in rock for installation of the shear pins. The drillholes would then be filled up by cement grout.

5.3 Site C

The third case history involved using CSM walls as temporary embedded walls for supporting a 20m deep excavation. The site was located in a reclamation formed by hydraulic sand fill which made the CSM technique most suitable for constructing the steel beam wall. The I-beams were of similar size as that of Site B. As the excavation depth is shallower for Site C, a larger spacing of the I-beams and a lower design strength of 3 MPa for the soil cement were found to be sufficient. The cement slurry used for constructing the CSM wall had a water/cement ratio of about 1.5. Again, no lagging wall was needed for Site C.

6 Conclusions

The design principles of steel beam walls are discussed. Although steel beam walls are commonly used in other parts of the world for ELS works, it is still not common in Hong Kong. It may be due to engineers in Hong Kong not familiar with this scheme of embedded wall and perhaps due to the engineers not being comfortable in accepting the fact that unreinforced soil cement can be strong enough to resist the soil and water pressure even without steel lagging walls. The main purpose of this paper is to encourage wider use of steel beam walls, particularly slurry walls and CSM walls, for ELS works by sharing the successful experiences gained from some case histories in Hong Kong.

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ISBN: 978-81-954993-7-3

Series: AIJR Proceedings
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