Overview of the Self-standing and High Stiffness Tubular Pile Walls in Japan

Tomoko MIYANOHARA
Construction Solutions Department, GIKEN LTD., Tokyo, Japan
Email: miyanohara@giken.com
Tatsuaki KUROSAWA
Senior Manager, Construction Products Development Div., Nippon Steel & Sumitomo Metal Corporation, Tokyo, Japan
Noriyoshi HARATA
Senior Manager, Construction Products Development Div., Nippon Steel & Sumitomo Metal Corporation, Tokyo, Japan
Kazuhiro KITAMURA
Assistant Manager, Construction Headquarter, GIKEN SEKO CO., LTD., Tokyo, Japan
Naoki SUZUKI
Construction Solutions Department, GIKEN LTD., Tokyo, Japan
Koji KAJINO
Department Leader, Press-in Technologies Support Department, GIKEN LTD., Tokyo, Japan

ABSTRACT

The equi-distantly pressed-in self-standing steel tubular pile retaining walls (hereinafter referred to as steel tubular wall(s)) are column row structures. They are often adopted where the construction yard is limited and when the construction schedule is tight, since they can be installed in smaller construction yards, compared with other structures such as gravity type walls and those with inverted T-type footings. The Press-in Method is suitable for space-saving constructions, and the applications of self-standing steel tubular walls with high stiffness are increasing, since a rotary cutting press-in machine that can press-in large diameter steel tubular piles has recently been developed, enabling its application of the method to taller walls.

This paper presents an overview of the design methods of the self-standing steel tubular walls, along with the site conditions, surrounding environments and the details and reasons for their adoptions in the 3 projects where self-standing steel tubular walls with high stiffness were used. The walls are generally designed using a beam expressed by a linear spring element on a floor that can be regarded elastic in semi-infinite domain, following the guidelines and manuals for other structure types (*e.g.*, Advanced Construction Technology Center, 2006; IPA, 2017). With the increase in diameter, secondary moment of inertia and stiffness of steel tubular piles tend to become larger, consequently to make the embedded length longer. Three case studies presented here are all for road retaining walls, and they clarified the construction constraints such as limited construction yard, construction in stiff ground and limited construction time. The features of the wall structures and advantages in the press-in operation together with the points of attention are addressed through these case studies, sorting out the future issues thereby.

Key words: *retaining wall, self-standing wall, steel tubular pile, high stiffness, narrow space*

1. Introduction

Many kinds of infrastructures such as roads, bridges and river embankments were constructed after the period of high economic growth. In the future, it is expected that the number of structures over 50 years will increase therefore renewal construction will further increase throughout Japan.

Nowadays constructions of the equi-distantly pressed-in self-standing steel tubular walls are increasing for urban river renovation works and road widening works. The self-standing steel tubular walls are different from usual inverted-T shaped or gravity walls, since there needs to be no footing, and required site areas can be smaller. In addition, unlike cast-in-place piles, prefabricated steel tubular piles can be used. Advantageous points may be that construction can be carried out with high quality in a short period of time. In particular, self-standing steel tubular walls are highly evaluated in the works such as disaster restoration works and those with limited construction time, since it is possible to construct the walls with fewer construction types/stages. In the past, steel tubular piles with a diameter of 1,000 mm or so were mainly used for the construction of road retaining walls. However, use of steel tubular piles with larger diameters of, *e.g.*, 1,500 mm or 2,000 mm is increasing in these days with the increase in the types of construction machines available.

As a construction method used for the installation of self-standing steel tubular walls in narrow urban areas, the Press-in Method, especially the Gyro Press (Rotary cutting) Method, is often used. It is a suitable method for construction sites under strict constraints in urban areas. Installing cutting bits at the pile toe, the steel tubular pile can penetrate not only stiff ground but also boulders and existing concrete structures. For this reason, it is applicable even without removing the existing structure(s).

This paper presents an overview of currently used self-standing steel tubular walls, together with the site conditions, surrounding environments and the process and reasons for the adoption of the method in the cases of the 3 construction projects where the large-diameter steel tubular walls were used. The features of the wall structures and advantages in the press-in operation together with the points of attention are addressed through these case studies, sorting out the future issues thereby.

2. Existing design method

2.1. Design method of self-standing steel sheet pile road retaining walls in Japan

Similar to steel tubular walls, self-standing wall structures made of steel may include steel tubular sheet pile walls and steel sheet pile walls. They are both often used for quay walls, temporary earth retaining walls, as well as river levees. The constructions of steel tubular sheet pile or steel sheet pile earth retaining walls follow existing standards (e.g. Japan Road Association (JRA), 2012; The Ports and Harbours Association of Japan, 2007; Public Interest Incorporated Association of Nationwide Disaster Prevention, 2017).

Recently applications of steel sheet pile walls to road works have increased. In the above JRA guideline of the retaining walls for road works, steel sheet pile walls are categorized in “other earth retaining walls”, and there are no descriptions of design and construction. The guideline describes the earth retaining wall as one selected in a site with strict construction conditions from the effects on the adjacent construction or those on current traffic and surrounding environments, when there is no extra space in the construction site, and/or ground excavation is difficult. The height of the wall is generally lower than approximately 4 m, and the walls are often applied in relatively firm sandy soil or hard clayey soil. On the other hand, the design method of steel sheet pile walls for road work is suggested in the “Design manual of self-standing steel sheet pile walls” (Advanced Construction Technology Center (ACTC), 2006), and the required performance is prescribed, as shown in **Table 1**. Note that the standard is applicable only for walls lower than approximately 4 m.

Table 1. List of detailed investigation items for the required performance of steel sheet pile walls

<table>
<tr><td rowspan="2">Necessary performance</td><td colspan="2">Stability of steel tubular sheet piles/piles retaining wall</td><td rowspan="2">Usability of surrounding facilities</td></tr>
<tr><td>Stability of steel tubular sheet piles/piles retaining wall itself</td><td>Stability of ground on the passive side in front of the retaining wall</td></tr>
<tr><td>Performance 1</td><td>Stress ≤ Normal allowable stress or allowable stress at the time of earthquake</td><td>Horizontal displacement of steel tubular sheet piles/piles retaining wall on the design ground surface ≤ displacement at which the horizontal resistance of ground at the embedded portion of steel tubular sheet piles/piles retaining wall can be considered elastic geotechnically</td><td>Horizontal displacement at top ≤ allowable displacement</td></tr>
<tr><td>Performance 2</td><td rowspan="2">Stress ≤ yield stress</td><td rowspan="2">There is an elastic area in the ground at the tip of embedded portion of the wall</td><td>Horizontal displacement at top ≤ allowable displacement</td></tr>
<tr><td>Performance 3</td><td></td></tr>
</table>

2.2. Current design method of self-standing steel tubular retaining walls

In the case where land acquisition is difficult for river levee restoration works and existing road widening works in urban areas, or in the case where there is an existing structure adjacent to a construction site and it is necessary to remove existing concrete structures, steel tubular walls with high stiffness constructed by means of the Gyro Press Method may be used as an applicable construction method. Application of the Gyro Press Method is increasing in actual projects, since it has a function of excavating ground, and facilitates installation of column row steel tubular walls in stiff ground. Both in river levee and road retaining wall works, the design is carried out mainly with a simplified ground reaction model and the calculation of embedded length, in which the deformation and stress are examined in detail and the necessary length of the steel tubular piles are determined. In the calculation model where a beam is simulated by a linear spring model on an elastic floor, assuming that the pile is semi-infinitely long, the embedded length is determined from the correlation of the ground stiffness with the pile stiffness. As can be inferred from **Eqs. (1)** and **(2)**, the necessary embedded length of l_0 tends to become larger, since the larger the diameter of steel tubular pile is, the larger the moment of inertia as well as the stiffness becomes. Note that it is necessary to ensure the embedded length of l_0 to be 2.5/β for temporary structures, and 3/β for actual structures.

$$l_0 = \frac{3}{\beta} \tag{1}$$

$$\beta = \sqrt[4]{\frac{k_H B}{4EI}} \tag{2}$$

β: characteristic value of pile
k_H: coefficient of subgrade reaction (kN/m^3)
B: unit width of steel tubular earth retaining wall (=1m)
l_0: effective embedment depth of pile (m)
E: Young's modulus of steel tubular earth retaining wall (kN/m^2)
I: secondary moment of area per unit width of steel tubular earth retaining wall (m^4)

The design method of self-standing steel tubular walls constructed by means of the Gyro Press Method is suggested by IPA (IPA, 2017), and, as shown in **Table 2**, it is in compliance with the "Manual of self-standing steel sheet pile walls" (ACTC, 2006). In the IPA's suggestion, the allowable deformation in performance 1 is given by reference to the ACTC's value, while it suggests to determine the allowable deformation separately in reference to the conformity standard mentioned in section 2.1, in the case where the wall is higher than 4 m.

Table 2. Outline of conformity standard of self-standing steel tubular walls

<table>
<tr><td colspan="3"></td><td>Design Manual of self-standing steel sheet pile</td><td>Press in retaining structures: a handbook</td></tr>
<tr><td colspan="3">Applied wall height</td><td>Height of steel sheet pile wall less than about 4 m (road works)</td><td></td></tr>
<tr><td colspan="3">Structure calculation method</td><td colspan="2">(Performance 1) Simplified method: beam-spring (ground) model
(Performances 2&3) Elasto-plastic method or dynamic analysis</td></tr>
<tr><td rowspan="5">Design for performance 1</td><td colspan="2">Selection of coefficient of ground reaction</td><td colspan="2">$k_H = k_{H0}\left(\frac{B_H}{0.3}\right)^{-3/4}$</td></tr>
<tr><td colspan="2">Selection of design ground surface</td><td colspan="2">Design ground surface = front ground surface</td></tr>
<tr><td colspan="2">Calculation of embedment length</td><td colspan="2">3/ β</td></tr>
<tr><td rowspan="2">Allowable displacement</td><td>Normal condition</td><td colspan="2">Lateral displacement at the top of steel sheet pile: less than 1 % of wall height, and lateral displacement on the design ground surface: less than 15 mm.</td></tr>
<tr><td>Under seismic condition</td><td colspan="2">Lateral displacement at the top of steel sheet pile: less th.5an 1 % of wall height, and lateral displacement on the design ground surface: less than 15 mm.</td></tr>
</table>

3. Case studies

In this section three construction cases with large diameter self-standing steel tubular walls are introduced.

3.1. Case study 1

This project is a road-widening work in order to secure sidewalks on a two-lane major road which connects major cities, in which the outline of the construction of a 13 m-high road retaining wall on a slope is summarized in **Table 3**.

Table 3. Overview of project

Purpose of Project	Road retaining wall
Pile Section & Length	dia. =2,000mm, t=20mm, L=20 to 24m, n=12
Duration	February 1, 2018 to April 30, 2018

3.1.1. Site and ground conditions

The site was on a slope close to the boundary between a terrace and a river (Figs. 1 and 2). The slope was between a major road and a residential area with the largest elevation difference of 13 m. In the case of the construction of the road wall, it was necessary to pay attention to the effect on the major road and the surrounding crowded houses.

The site ground was consisted of a sand and gravel layer with clay. The converted Standard Penetration Test (SPT) *N*-value was calculated using **Eq. (3)** shown below (Japanese Geotechnical Society Standards, 2013). The maximum *N*-value was 500.

$$N = 50 \times \frac{0.3}{\delta z_{SPT,50}} \tag{3}$$

N: SPT *N*-value

$\delta z_{SPT,50}$: the penetration depth of the SPT sampler in meter at the blow count of 50 (m)

3.1.2. Reason for selection of self-standing steel tubular walls

In the original design, the ground-anchor type walls were selected equivalent to the existing road retaining walls. However, since the use of the residential area was limited, the structure type of the walls had to be reviewed. For comparison with the self-standing walls, the caisson pile walls, the cast-in-place pile walls and the steel tubular pile walls were considered. Making a comparative review of the aforementioned methods, it was found that, in terms of the construction cost, the ratio of the steel tubular walls to the caisson pile walls was 1:0.6, and that of the cast-in-place pile walls was 1:0.6. On the other hand, in terms of the construction period, the comparison was 1:6 for the caisson pile walls, and 1: 8 for the cast-in place concrete pile walls. After consideration of these studies, the steel tubular pile walls, which would facilitate the construction in a shorter period, were highly evaluated and adopted.

3.1.3. Structural type and piling method

A cross section of a self-standing steel tubular wall is shown in **Fig. 1**, and the material used is summarized in **Table 3**. The steel tubular piles were connected by welding plates between each two adjacent piles. This way the soil movement behind the wall was restricted. In addition, drain pipes were installed between steel tubular piles. The types of construction work were minimized by using cladding panels on the front side of the steel tubular pile walls. The construction work of the piles for an extension of approximately 30 m was thus completed in a period of 89 days. (**Figs. 3** and **4**).

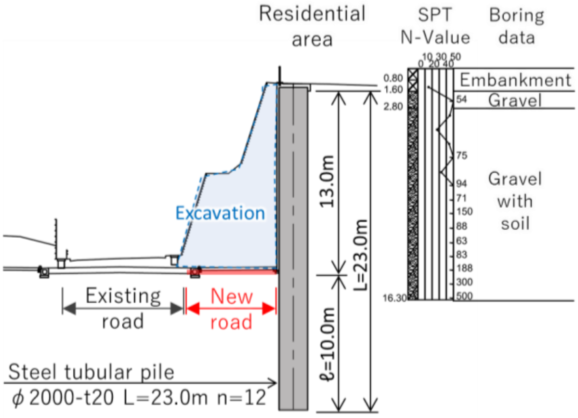

Fig. 1 Cross section of retaining wall

Fig. 2 Photo taken prior to construction

Fig. 3 Photo taken during pressing-in steel tubular pile

Fig. 4 Photo taken during construction of cladding panels

3.2. Case study 2

This is a road widening project from 2 to 4 lanes on a major road with heavy traffic to reduce traffic jams and traffic accidents. A sloped ground adjacent to the road was to be excavated and a road retaining wall with a height of 11.5 m was to be constructed, while allowing the traffic on the road. An overview of the project is summarized in **Table 4**.

Table 4. Overview of the project

Purpose of Project	Road retaining wall
Pile Section & Length	dia. = 2,000mm, t=20mm, L=24.5 to 27.5m, n=44
Duration	July 26, 2016 to October 22, 2016

3.2.1. Site and ground conditions

The construction site was located on a slope between a major road in a dense residential area and a cemetery (**Figs. 5** and **6**). The cemetery was at the top of the slope and the construction yard was surrounded by residential houses. For this reason, the effect on surrounding areas from the construction method required should be minimized. The first 8 m from the ground surface in the site consists of a loam layer, underlain by clayey fine sand layer. The converted *N*-value of the lower clayey fine sand layer was approximately 125.

3.2.2. Reason to select self-standing steel tubular walls

It was necessary to excavate the slope adjacent to the construction site and construct an 11.5-meter-high road retaining wall, while allowing the traffic on the road. The self-standing steel tubular walls and the caisson pile walls were compared and examined as to which was a suitable structural type for a limited space construction site. As a result, the steel tubular walls were applied from the points of both construction period and cost. In addition, although the pile installation by either a vibration hammer or inner excavation were also considered for installing steel tubular piles, judging from the narrow space on stiff ground, the only possible method that could be applied to the site was the Gyro Press Method.

3.2.3. Structural type and piling method

The cross section of the self-standing steel tubular wall is shown in **Fig. 5**, while the pile material used is outlined in **Table 4**. The construction was carried out, creating a construction yard of a maximum width of 15 m on the primarily excavated ground (**Fig. 5**). After pressing-in the steel tubular piles, the secondary excavation was made so that the ground in front of the steel tubular walls was excavated down to the designed elevation of the widened road, and then the road surface was paved. The front side of the steel tubular walls was covered with cladding panels. The construction of the piles was completed in a period of 89 days for an extension of 100 m (**Figs. 7** and **8**).

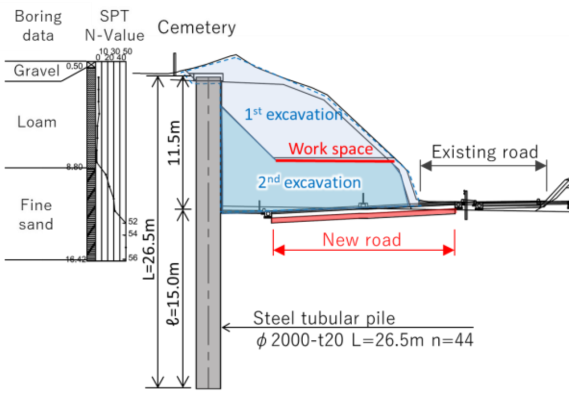

Fig. 5 Cross section of retaining wall

Fig. 6 Photo taken prior to construction

Fig. 7 Photo taken during construction

Fig. 8 Photo taken after construction

3.3. Case study 3

The project was a reinforcement work of a slope surface along an express way in a mountainous area. It was required to construct a 10.5 m high earth retaining wall. An outline of the project is summarized in **Table 5**.

Table 5. Overview of the project

Purpose of Project	Road retaining wall
Pile Section & Length	dia. = 1,500mm, t=25mm, L=24.0 to 26.0m, n=54
Duration	December 9, 2011 to April 11, 2012

3.3.1. Site and ground conditions

The site was located along the side road of an express way. Since box culvert structure was buried underneath the side road, the weight of the machine that could be used was limited to 20 to 30 tons (**Fig. 9**). In addition, the construction had to be completed by the time the express way was put into use.

The site ground consists of sand and gravel layer with occasional boulders, underlain by stiff ground with a converted *N*-value of approximately 300.

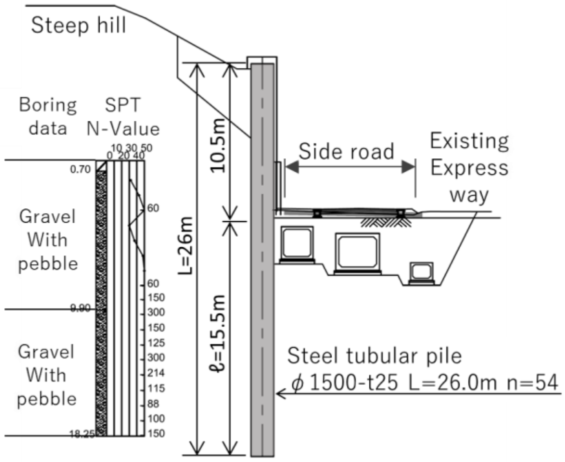

Fig. 9 Cross section of the wall

3.3.2. Reason to select self-standing steel tubular walls

As a construction type that could be applied to a narrow construction space adjacent to a road, a self-standing steel tubular walls by the Gyro Press Method was adopted. As other construction types, also considered were the steel tubular wall by the inner excavation method by means of a combination of a temporary platform and a crane type, and the PC wall structures by means of a combination of a temporary platform and inner excavation. The construction cost of the steel tubular walls was similar to that of the PC wall structures. As a result of considerations, it was found that if the Gyro Press Method with the GRB system were used, in which all the piling works could be completed on the previously pressed-in pile tops, use of a temporary platform would become unnecessary, and that the machine weight could be relatively small, and use of heavy cranes could be avoided. Because of these advantages, the Gyro Press Method with the GRB system was selected as the construction method suitable for the project.

3.3.3. Structural type and piling method

A cross section of a self-standing steel tubular wall is shown in **Fig. 9**, while the piles used are outlined in **Table 5**. It was possible to carry out the construction by the GRB system in a situation where heavy cranes could not be used, without hindering the upper structure work of the express way. The construction of the piles was completed in a period of 125 days for the extension of 100 m (**Figs. 10** and **11**).

Fig. 10 Photo taken during construction

Fig. 11 Photo taken after construction

3.4. Analysis of adoption factors

The above-mentioned 3 case studies may suggest the following common features in the reasons of adoption of the self-standing steel tubular walls:

- Road retaining walls of high height in a narrow space
- Construction adjacent to existing structures
- Along beside a road where stopping the traffic was difficult
- Construction in a relatively short period of time required, and
- Use of the construction yard of adjacent road was impossible or limited

With the development of construction methods and construction machines represented typically by the Gyro Press Method, it has become possible to press-in piles even in such difficult site conditions as described in this paper. Similar construction cases seem to be increasing in number. It is expected that the same construction type will likely be adopted in future in sites with narrow space and under limited construction time.

4. Conclusions

Through the construction cases described in this paper, the following merits can be pointed out for the structures of self-standing steel tubular walls with high stiffness:

1) It is a structure type suitable for the application to narrow space with strict construction limit, since it is a direct wall structure and requires only small construction yards; and
2) Since prefabricated piles are used for the construction, types of works as well as construction stages can be fewer and the construction time can be shorter.

In addition, the following advantages and points of attention during press-in operation may be listed:

1) The Gyro Press (Rotary cutting) Method can cope with stiff ground; and
2) The press-in operation is possible in a narrow space, since the press-in machine can be operated on the top of the piles already pressed-in, and a temporary platform is not required.

One of the future challenges may be to establish a more rational design method. Currently there are no existing design standards that systematically prescribe the design method for self-standing steel tubular walls with high stiffness. The walls are currently designed following the design guidelines for other structural types. With the existing design method, the embedded length of piles is determined from the correlation between the ground and the piles. Therefore, the larger the diameter is and the higher the wall is, the longer the piles become. In addition, it is often the case that the pile diameter is determined by detailed displacement investigation rather than by detailed stress investigation. This may lead to the fact that the pile members tend to possess enough stress allowance, and the design tends to become too conservative.

Currently researches into steel tubular retaining walls with high stiffness in the stiff ground have been conducted at a technical committee TC1 of IPA (Committee on Application of Self-Retaining Tubular Pile Wall to Stiff Ground). Following this, it is thought to be necessary to carry out researches on application of the structure in the general ground as well. It will also have to be clarified how rational the current design method could be, how big the diameter and how high the wall should be.

5. Acknowledgements

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6. References

Advanced Construction Technology Center. 2006. Design manual of self-standing steel sheet pile walls, 2p, pp. 28~38.

International Press-in Association. 2017. Press in retaining structures: a handbook, pp. AD II-17~AD II-26.

Japanese Geotechnical Society Standards. 2013. Geotechnical and Geoenvironmental Investigation Methods, pp. 310~311. (in Japanese)

Japan Road Association. 2012. Guideline of road works and retaining walls.

Japan Road Association. 2017. Specifications for Highway bridges, Parts II: Steel Design, and V: Seismic Design.

The Ports and Harbours Association of Japan. 2007. Technical standards and commentaries for port and harbour facilities in japan.

Public Interest Incorporated Association of Nationwide Disaster Prevention. 2017. Design outline of disaster restoration works.