Proceedings of the Second International Conference on Press-in Engineering 2021, Kochi, Japan – Matsumoto et al (eds)
 ISBN 978-1-032-10414-0

Discussion about design method for embedded length of self-standing steel tubular pile walls pressed into stiff ground

T. Sanagawa
Railway Technical Research Institute, Tokyo, Japan

ABSTRACT: Application of the steel tubular piles as the retaining walls are increasing. Especially, Gyropress method are often used because this method can install the piles penetrating stiff ground and underground obstacles. Design methods of the self-standing retaining walls in Japan vary depending on the objects of structures and assumed actions, and there are mainly three analysis methods. The self-standing retaining walls using steel tubular piles pressed into stiff ground are also designed conformed to each design method, and it is known that the calculated embedded lengths differ depending on the analysis methods. However, there is few case studies about the evaluation results depending on the design method and the ground condition. In this paper, the overview of each analysis method is introduced, and the optimum method is discussed by the comparing the calculated embedded length depending on different analysis methods and the design condition.

1 INTRODUCTION

The press-in method is a piling method which accurately installs pre-formed piles using static loading without noise and vibration. There are several penetration modes available by using driving assistance, therefore the Press-in Method is universally applicable and can be used in soft to extremely hard ground conditions due to these wide varieties of penetration modes.

Gyropress method, one of the press-in method, is a reaction based rotary press-in method to install tubular piles with cutting bits (shown in Figure 1) with self-walking functions. It can penetrate the gravels, hard rocks, and existing reinforced concrete structures (Figure 2, 3) and expand the scope of the application of press-in method. In addition, amount of soil displacement is controlled by rotary cutting mechanism which excises just the obstacle part.

Recently, piles with a large diameter are widely used for road and port structures against the large earthquake motions. Considering design methods, a simple method based on the beam on elastic subgrade and the Winkler's hypothesis is widely used. According to this method, embedded lengths of the piles is determined only by the stiffness of the piles and ground. This method may make the designed embedded length long and lead increment of the cost and construction period depending on ground and structure conditions.

Considering this background, rationalization of the design calculation method is required. This paper describes the outline of the design method and discuss about the effect on the design for the cantilever pile wall embedded into stiff ground by trial calculation.

2 DESIGN METHOD

2.1 *Outline of design calculation method of embedded length of self-standing walls*

There are three major design calculation methods for embedded length. (a) Limit Equilibrium Analysis Method, (b) prerequisite of Elastic Subgrade Reaction Method, (c) Combined Subgrade Reaction Method. The outline about these design methods are described below.

2.2 *Limit equilibrium analysis method*

The limit equilibrium analysis can evaluate the member stress and required embedded length of the cantilever wall from passive and active soil pressure at the ultimate condition. Figure 4 shows the outline of this method. The earth pressure from background is usually calculated at the range from top to toe of wall by the Coulomb and Rankine-Resal equation.

Horizontal resistance of piles is calculated from the balance of the subgrade rection at ultimate condition of soil and the external forces. This is to assume empirically the distribution of subgrade reaction, and may include one that assumes quadratic parabolic

DOI: 10.1201/9781003215226-32

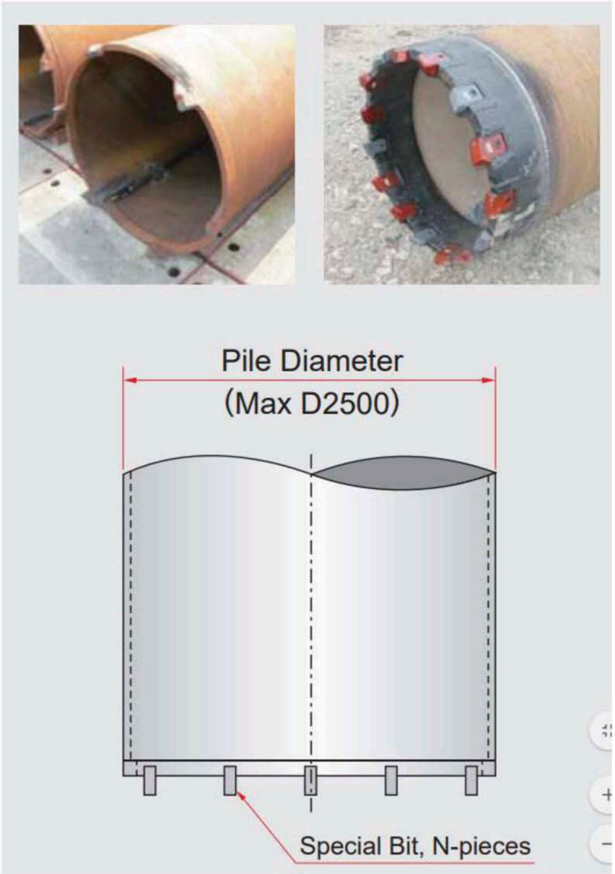


Figure 1. Cutting bits (Giken, 1999).

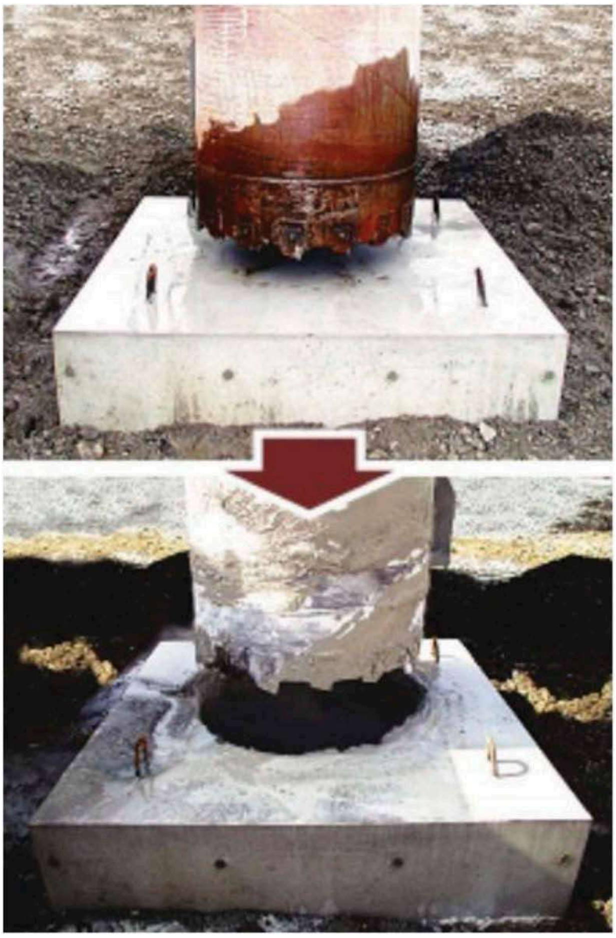


Figure 2. Coring reinforced concrete (Giken, 1999).

relationship, and one that assumes the subgrade reaction by linear relationship or by arbitrary curves.

2.3 *Elastic subgrade reaction method*

Figure 5 Shows the outline of the elastic subgrade reaction method. Assuming that the soil and the pile are elastic, the behavior of the pile can be calculated as a beam on an elastic floor, as the following equation.

$$\frac{EI}{D}\frac{d^4y}{dx^4} + p = 0 \tag{1}$$

Where,
E: Young's modulus of pile (kN/m^2)
I: secondary moment of pile (m^4)
D: pile diameter (m)
p:subgrade reaction (kN/m^2)
x: depth from the ground surface (m)
y: deflection at a depth of x (m)

Elastic subgrade reaction method uses Winkler spring model (Winkler, 1867), and p is shown as

$$p = P(x, y) \tag{2}$$

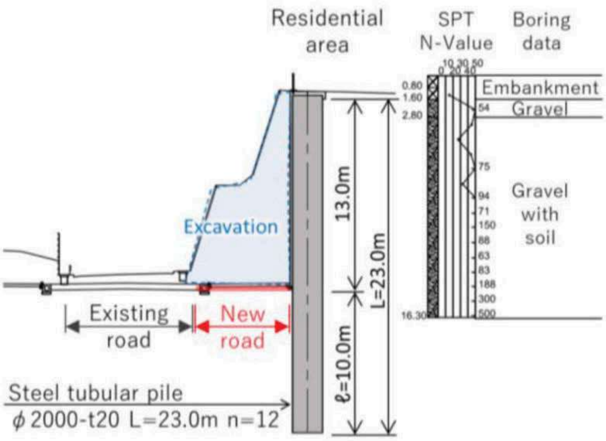
The elastic subgrade reaction method is divided into three methods by modeling of $P(x,y)$. The linear elastic subgrade reaction method includes Chang's equation, where $p=k_h y$, (k_h: coefficient of subgrade reaction). In this equation, it is assumed that the horizontal subgrade reaction has a linear relationship with displacement. Under this condition, the pile behavior is shown as a simple equation, then widely used.

Generally, it is considered that piles have semi-infinite length when embedded length is more than π/β (usually $3/\beta$ are used in some design standards). β is called as characteristic value of pile and described as:

$$\beta = \sqrt[4]{\frac{k_h D}{4EI}} \tag{3}$$

Under this condition, the behavior of the piles like displacement and stress, and design embedded length can be easily calculated.

Some design standards describe that the required embedded length is $3/\beta$ because it ensures that sufficient stability, and can simplify pile behavior, such as



(a) Cross section and ground information

(b) Pressing-in steel tubular pile

Figure 3. Example of construction (Suzuki, 2018).

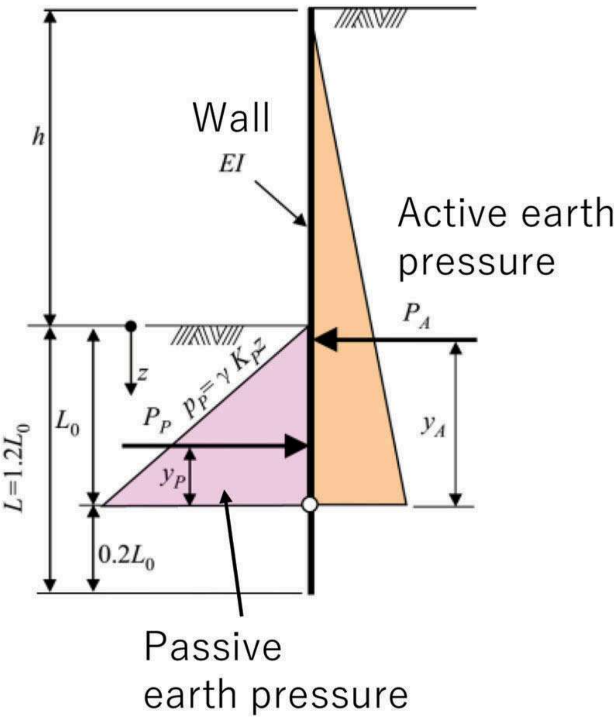


Figure 4. Outline of limit equilibrium analysis method.

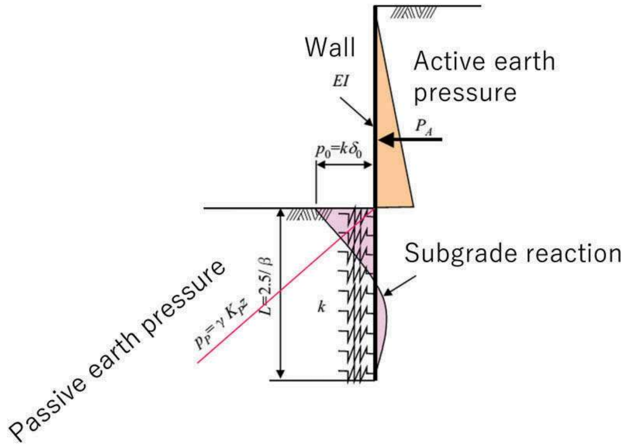


Figure 5. Outline of elastic subgrade reaction method.

deflection and member stress can be simple. However, displacement of wall a should be restricted at small value (e.g. 15mm or 1% of pile diameter) because non-linear behavior of k_h become large and to check that the coefficient of subgrade reaction k_h is within the elastic range.

2.4 *Combined subgrade reaction method*

In this method, it is assumed that the soil around the surface of the excavation subgrade is perfectly plasticized because the pile displacement is large, and lower subgrade is elastic. The former is called as the plastic region, the latter is the elastic region, and the limit equilibrium analysis method is adopted to the plastic region, and the elastic subgrade reaction method is adopted to the elastic region. The sample of the distribution of the subgrade reaction is shown in Figure 6.

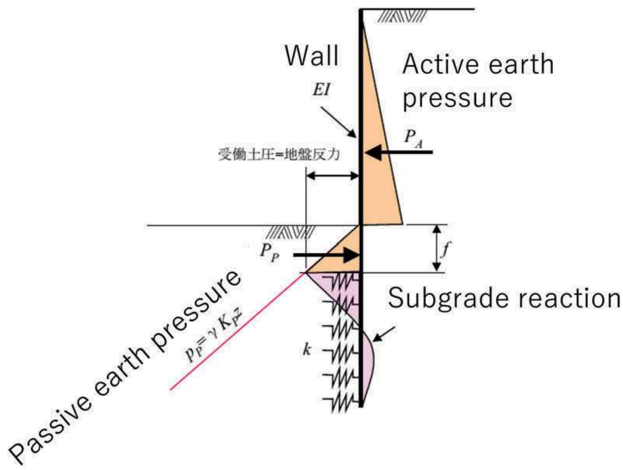


Figure 6. Outline of combined subgrade reaction method.

2.5 *Issue of design method of self-standing steel tubular pile walls pressed into stiff ground*

Issues of the design method for cantilever steel tubular pile walls embedded into stiff ground is described below.

(1) Selection of a design calculation method

Design methods of embedded length of a self-standing retaining wall used in design standards are shown in Table 1. Many design standards use the elastic subgrade reaction method, but not unified.

(2) Evaluation of characteristic values of stiff ground

Most standard ground investigation methods for determining the characteristic of soil is SPT in Japan. However, SPT cannot evaluate the stiff ground like sandstone, then the engineers must select the other investigation method. However, it is not ruled.

(3) evaluation of design value of k_h

All standards use the elastic subgrade reaction method or the combined subgrade reaction method, and they set the estimation equations of the design value of horizontal subgrade reaction coefficient k_h. However, evaluation of design value of k_h is difficult for several reasons. One of the reasons is the displacement dependency and load width dependency of k_h. This As a result, estimation equations of k_h are all different in Japanese standards (shown in Table 1). Another is the modelling of the distribution of k_h in the depth direction. When the elastic subgrade reaction method is used, it is assumed that the distribution of k_h is constant. Therefore, the design value of k_h is usually evaluated as the average value around the surface region of excavation subgrade. However, when the self-standing steel tubular pile walls is designed by the elastic subgrade reaction method, the tubular piles have high stiffness because of allowable displacement in seismic, therefore, β becomes smaller, and required embedded length (e.g. π/β *or* $3/\beta$) become longer.

Table 1. Design calculation method of Japanese standards.

(a) Permanent structures

	Road	River	Port and Harbour
Standard	ACTEC, JASPP, 2007	PIIANDP, 2018	PHJA 2007
Scope	Sheet pile wall whose height is less than about 4.0m	–	–
Design embedded length	$3/\beta$ from excavated ground surface	$3/\beta$ from virtual ground surface	1.5 l_{m1} from virtual ground surface l_{m1}: depth of first point where bending moment is zero
Estimation formula of k_h	$k_h = k_{h0}\left(\frac{B_H}{0.3}\right)^{-3/4} k_{h0} = \frac{1}{0.3}\alpha E_0$	$k_h = 6910N^{0.406}$	
Calculation method of k_h	Average in range $1/\beta$ from ground surface	No mention	–
Allowable displacement	Wall top: 1% of wall height (non-seismic) 1.5%of wall height (seismic) Excavated ground level: 15mm	Wall top: 50mm (non-seismic) 75mm (seismic)	Wall top: 100mm (non-seismic) 75mm (seismic)

(b) Temporary structures

	Road	Architecture	Railway
Standard	JRA, 1999	AIJ, 2001	RTRI 2008
Scope	Wall height is less than about 3m	Wall height is less than about 5m	–
Designembedded length	$2.5/\beta$ from excavated ground surface	At least $2/\beta$ from excavated ground surface	Limit equilibrium analysis method or combined subgrade reaction method
Estimation formula of k_h	$k_h = k_{h0}\left(\frac{B_H}{0.3}\right)^{-3/4} k_{h0} = \frac{1}{0.3}\alpha E_0$	$k_h = 1000N$	$k_h = 600N$
Calculation method of k_h	Average in range $1/\beta$ from ground surface	Calculated from average characteristic of soil in range $1/\beta$ from ground surface	–
Allowable displacement	Wall top: 3% of wall height	Depending on the situation	Depending on the situation

3 TRIAL CALCULATION RESULT OF SELF-STANDING STEEL TUBULAR PILE WALLS PRESSED INTO STIFF GROUND

3.1 *Overview*

In the design of a self-standing wall, the embedded length is usually determined by stability and displacement of the wall. However, the effect of embedded length to the behavior on the wall is not clearified.

In this chapter, this effect is studied by trial calculations using the three methods described in Chapter 2. Specifically, the required embedded length was calculated by the Equilibrium Analysis method and the elastic subgrade reaction method at first. Next, the displacement of the wall is calculated by the combined subgrade reaction method, and the effect of embedded length was explored from the relationship between the embedded length and the wall displacement.

3.2 *Calculation conditions*

This section describes the calculation condition. Figure 7 shows the outline drawing of the calculation condition. The wall height is 5.0m, background is sand (*N*-value is 10), and bearing stratum is sand (*N*-value is 15) or rock. The diameter of the tubular pile has 1.0m and the thickness is 25mm. Table 2 shows the specification of piles, and Table 3 shows the specification of soil. Variation parameters are the kind of bearing stratum and the thickness of soft

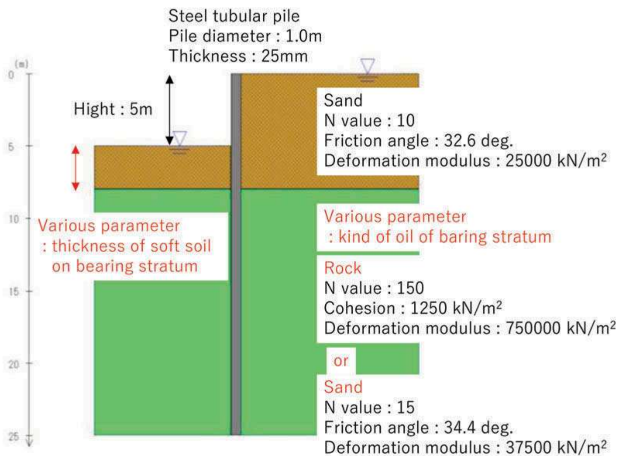


Figure 7. Outline drawing of calculation condition.

Table 2. Condition of piles.

Diameter	1.0 m
Thickness	25 mm
Young modulus	200 GPa
Area of cross section	649 cm^2
Secondary moment	772000 cm^4

Table 3. Characteristic value of soil.

	Soil	Rock
N value	10	150
Friction angle (deg.)	32.6	0
Cohesion (kN/m^2)	0	1250
Deformation modulus (kN/m^2)	25000	750000
Unit weight (kN/m^3)	18	20

ground layer (sand with *N*-value 10) on the bearing stratum.

The earth pressure and the soil springs (e.g. the coefficient of horizontal subgrade reaction k_h and the limit value of k_h as the passive earth pressure) are modelled from soil characteristic values based on Japanese Railway structure standard (RTRI, 2008).

The active earth pressure is calculated by equation (4), (5).

$$p_a = K_a\left(\sum \gamma_t \cdot z - p_w\right) + p_w + p_s \tag{4}$$

Where
p_a: active earth pressure (kN/m^2)
K_a: coefficient of active earth pressure
γ_t: unit weight (kN/m^3)
z: depth (m)
p_w: pore water pressure (kN/m^2)
p_s: earth pressure from overload (kN/m^2)

$$K_a = tan^2(45^\circ - \varphi/2) \tag{5}$$

Where φ: friction angle of soil (deg.)

The passive earth pressure (used as the limit value of the reaction force of the soil spring) is calculated by equation (6), (7).

$$p_p = K_p\left(\sum \gamma_t \cdot z - p_w\right) + p_w \tag{6}$$

Where
p_p: passive earth pressure (kN/m^2)
K_p: coefficient of active earth pressure

$$K_p = \frac{cos^2\varphi}{\left\{1 - \sqrt{\frac{\sin(\varphi+\delta)sin\varphi}{cos\delta}}\right\}^2} \tag{7}$$

δ: friction angle between pile and soil (deg.)

In addition, the characteristic value of pile β is calculated as average value of k_h in $1/\beta$ surface region. k_h is estimated from the deformation modulus of soil by following equation (RTRI, 2008).

$$k_h = 0.24E_d \tag{8}$$

Where, E_d: deformation modulus of soil (kN/m^2)

3.3 *Calculation results of required embedded length*

The required embedded length calculated by the Equilibrium Analysis method and the elastic subgrade reaction method are compared. The results of 4 cases are shown in Table 4.

In all cases, the required embedded lengths of limit equilibrium analysis method are smaller than that of the elastic subgrade reaction method. And especially the gap is larger when the embedded length into rock is large.

This result shows that the embedded length of self-standing steel tubular pile walls pressed into stiff ground can be economically designed by using other method like the limit equilibrium analysis method or the combined subgrade reaction method, not only the elastic subgrade reaction method.

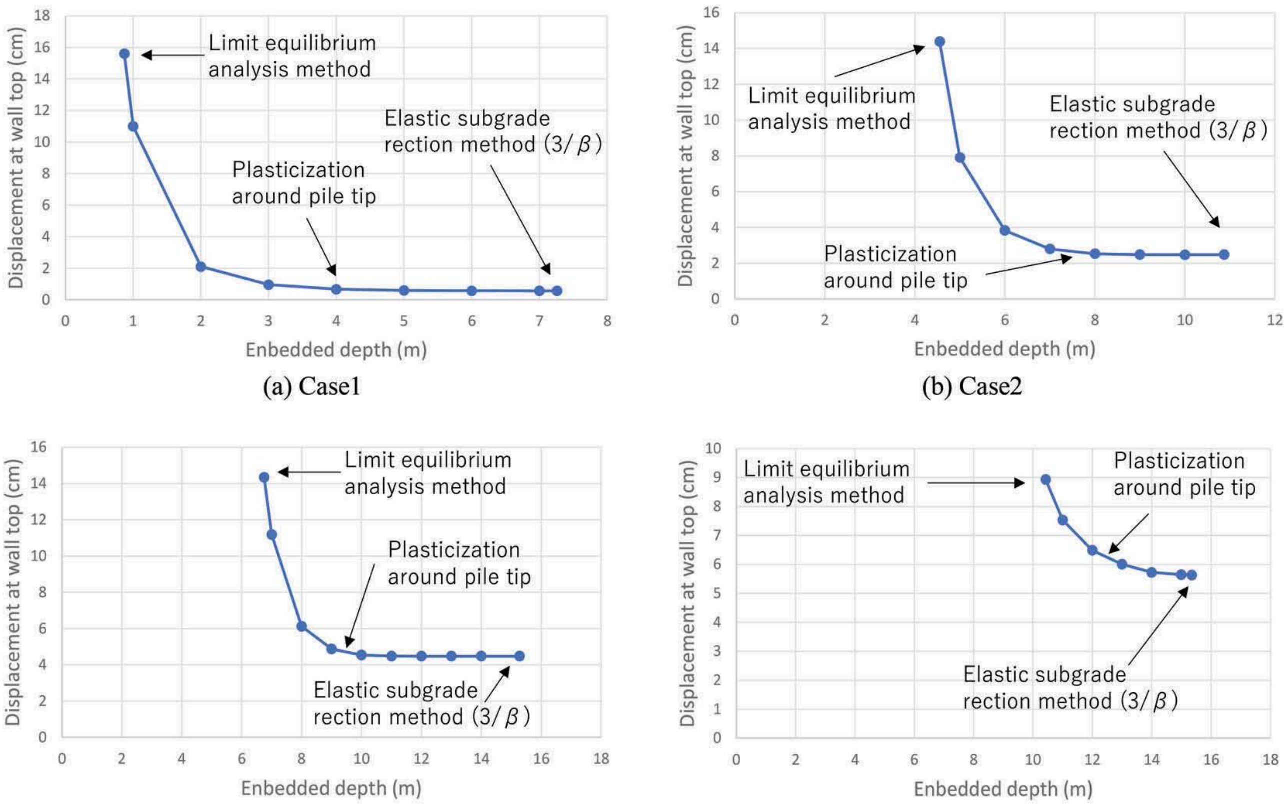
Table 4. Required embedded length of pile.

			Required embedded length (m)	
	Bearing stratum	Thickness of soft ground	Limit Equilibrium Analysis method	Elastic Subgrade reaction method (3/β)
Case1	Rock	0m	0.87	7.26
Case2		3m	4.55	10.87
Case3		5m	6.75	15.28
Case4	Sand	0m	10.43	15.35

3.4 *Calculation results of relationship between embedded length and wall displacement*

In usual, the limit value of displacement at the wall top is set as required performance considering the surrounding environment, and the specifications are mainly determined by this factor. Then the displacement at the wall top are calculated at each embedded length by the combined subgrade reaction method.

Figure 8 shows the relationship between displacement at the wall top and embedded for each case.



(a) Case1 (b) Case2 (c) Case3 (d) Case4

Figure 8. Relationship between embedded length and wall displacement.

The relationship is not linear, and the displacement is rapidly increase after plasticization around pile tip regardless of the thickness of the soft soil when the bearing stratum is rock.

On the other hand, displacement is gradually increasing before the plasticization. This behavior is different from soil type of baring stratum, Especially, the gap between the embedded length with rapid increase of displacement and required embedded length by limit equilibrium analysis method is not large, so it is especially important to check the embedded length in design and construction when the pile is installed into stiff ground like hard rock.

4 CONCLUSION

In this paper, the overview of each analysis method is introduced, and the optimum method for the self-standing retaining walls using the steel tubular piles pressed into the stiff ground is discussed by the comparison with the calculated embedded length depending on the analysis method and the design condition.

Use of the limit equilibrium analysis method or the combined subgrade reaction method may lead the economical results of design when the piles are pressed into stiff ground.

On the other hand, the embedded length influence on the stability of a self-standing wall pressed into the stiff ground, therefore a ground investigation and a check at construction become very important.

REFERENCES

Advanced Construction Technology Center (ACTEC), Japanese Association of for Steel Pipe Piles (JASPP). 2007. Design manual of self-standing steel pipe walls.

Architectural Institute of Japan (AIJ). 2001. Design Recommendations for Architectural Foundation.

Giken Ltd. 1999. Rotary Press-in. https://www.giken.com/en/press-in_method/penetration_tech/rotary_cutting/ (accessed 2020.11.15).

Japan Road Association (JRA). 1999. Guideline of road works and temporary structures.

Port and Harbour Association of Japan (PHJA). 2007. Technical Standards of port and harbour facilities and explanations.

Public Interest Incorporated Association of Nationwide Disaster Prevention (PIIANDP). 2018. Design Guideline for Disaster Recover work.

Railway Technical Research Institute 2008. Design Standards for Railway Structures ana Commentary (Cut and Covered Tunnel).

Suzuki, N. and Kajino, K. 2018. Issues for the Reduction of the Embedded Length of Cantilevered Steel Tubular Retaining Wall Pressed into Stiff Ground, Proceedings of the First International Conference on Press-in Engineering 2018, pp.159–166.

Winkler, E. 1867. Die Lehre Von Elasticitaet Und Festigkeit, 1st Edn.