Issues for the Reduction of the Embedded Length of Cantilevered Steel Tubular Retaining Wall Pressed into Stiff Ground

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ABSTRACT

Due to the performance improvement of construction machines and the increase in case studies in mountainous areas, cases have increased where the pile foundation is supported by a bedrock as a bearing layer. In a rock layer that is thought suitable as a load bearing foundation because of its high strength and high deformation modulus compared with those in general ground, it is considered that the embedded length into rock could be shortened if a rational design method were established. Consequently, the existing knowledge and guidelines are sorted out in this paper, focusing on the characteristics of rock mass, modelling of horizontal bearing capacity characteristics of foundations, and the behavior of short piles subjected to lateral loading, for extracting issues arising when proposing cantilevered steel tubular pile retaining walls with shortened embedded length in a relatively stiff rock layer. At the end, issues arising at a time of making the embedded length shorter in a rock layer will be described.

Key words: *horizontal bearing capacity, stiff ground, steel tubular pile, embedded length, cantilevered retaining wall*

1. INTRODUCTION

In the pile foundation structure with the expected vertical and horizontal bearing capacities, a rock layer by which the bearing capacity can be stably obtained tends to be selected as a load bearing layer. Due to the performance improvement of construction machines and increase in case studies in mountainous areas, cases have increased where the tubular pile installation is supported by a rock foundation (**Fig. 1**).

Generally, rock is thought to be a good load bearing layer. However, if the embedded length is determined by the semi-infinite length obtained from Chang’s equation, there are some existing issues: the construction methods are limited since the embedded length becomes large as the pile stiffness increases; and the design is economically irrational., To solve these issues, the authors have been studying rationalization of the design method by making the embedded length shorter for cantilevered steel tubular pile retaining walls installed in stiff ground. For example, the Socket Pile has been widely used as a load bearing pile method especially overseas (Rowe, 1984; Williams, 1981; Pells, 1999). It is a construction method developed mainly in North America, UK and Australia in the 1960’s, and it effectively secures vertical and horizontal bearing capacities, ensuring a certain embedment into a rock layer. However, no cases have been reported in Japan.

On the other hand, especially when aseismic

Fig. 1 A case study of the installation (Seki et al., 2016)

performance is required recently, high horizontal stability has been required in the rock layer. However, there are many researches into vertical bearing capacity (*e.g.*, Okahara *et al*. (1989); Nanazawa *et al*. (2015); JGCA 2016) and horizontal resistance for deep foundations (*e.g.*, Yoshii *et al*. (1982); Matsuo *et al*. (2000); Takahashi *et al*., 2000), but few researches into horizontal resistance for piles have been reported except for Akazawa *et al*. (2016).

From the background described above, the objective of this paper is to extract and sort out the issues in proposing structures with short embedded lengths in relatively stiff ground including soft and hard rocks. In this paper, existing researches and guidelines are sorted out, by focusing especially on the characteristics of rock layers, modelling of horizontal bearing capacity characteristics of pile and wall foundations, and the behavior of short piles subjected to horizontal loading.

2. CHARACTERISTICS OF ROCK

2.1. Overview

Compared with general ground, rock has high strength and high deformation modulus, which is suitable for a load bearing layer. However, investigation methods and design parameters of rock are different from those for general ground, and various methods have been proposed (Rock Net Japan, 1985). In addition, their characteristics are very different, depending on the type of rock. Furthermore, few design methods have been clearly prescribed in design guidelines.

Consequently, the characteristics in consideration of horizontal stability and the points of attention in each standard are sorted out here.

2.2. Discontinuity

In the design of discontinuous rock mass, technical evaluation of discontinuous surfaces such as joints, bedding planes and faults becomes issues. Since the vertical bearing capacity of the rock also depends on crack, many uncertain factors are involved in the evaluation of the ground parameters, and it is difficult to estimate the supporting force calculation formula. For example, in the design of vertical bearing capacity in JRA (2017), upper limits of bearing capacities are set for soft and hard rock with uniaxial compressive strength as a guide. On the other hand, the horizontal bearing capacity is designed to limit the displacement as with general ground. However, in the case where only the pile toe is embedded into rock in a multi-layer including a hard rock layer at deep depth, it is possible that an unexpected failure mode may take place on the basis of the discontinuous plane as a failure surface, when the pile is subjected to horizontal resistance.

On the other hand, the International Society of Rock Mechanics (ISRM) recommends the following 10 parameters as indices to describe the existing form of discontinuous planes quantitatively: direction, separation distance, continuity, roughness, wall strength, pore width, filling material, seepage water, number of sets, and block size (Rock Net Japan, 1985).

In addition, Takahashi *et al*. (2014) reported for a sloped ground, "*The destruction of the slope ground was thought to be influenced by the discontinuities, but it was thought that as a whole, almost horizontal slip line was formed and destroyed, gradually progressing in the depth direction from the top*." Regarding the problems on discontinuities like this, it is difficult to verify them by numerical analysis. Collection and sharing of the results are therefore hoped, including those for other structures than pile foundations.

2.3. Failure Criteria

In the tunnel excavation analyses by finite element method (FEM) or finite difference method (FDM), the models based on the Mohr-Coulomb and Drucker-Prager failure criteria are commonly used. In these models, rupture envelope lines are often described by linear relationship, and the shear strength increases linearly with confining pressure. These are developed mainly to evaluate soil materials. On the other hand, it has been shown by experiments that the slope of the failure envelope of rocks becomes small with the increase in confining pressure. For this reason, especially in the case of a large overburden, these models mentioned above cannot describe the rock strengths at low confining pressures by the same strength parameters as those at high confining pressures (Nakaoka and Hata, 2017).

Hoek-and Brown (1980) had proposed a practical failure criterion that has a parabolic rupture envelope line, in which necessary strength parameters can be defined from the rock observation and uniaxial compression strength of rock cores.

Furthermore, in the case where the ground around the foundation plane consists of intact rock, the residual strength after the peak strength tends to become smaller. When the ground around the foundation surface is in such a condition like this, JRA (2017) is suggesting the use of lower values of cohesion and the angle of internal friction after/before the material shows plastic behavior.

2.4. Construction Methods

Due to the performance improvement of construction machines and the increase in case studies in mountainous areas, cases have increased where the pile foundation is supported by a bedrock layer. However, it is possible that fractures may develop in the rock, or rock strength will become smaller due to stress relief by the construction, which needs to be carefully watched. In addition, especially in Japan, rock formations are widely distributed in mountainous areas. Stratification is however often very complex, and it is required to improve accuracy of, and to establish a verification method on the penetration into load bearing foundation.

For example, it is often the case that borehole exploration is carried out about every 30 m in architectural construction sites in Japan. As described previously, since it is thought that there may be unevenness in the rock layers in mountains, considerations should be given to safety against it, and to disturbance on the ground surface due to construction. Mori *et al*. (2016) have sorted out points to look at for each construction method on support piles. It is also known that axial force occurs due to a rotation at the pile toe when the embedded length is short. Especially for open-ended steel tubular piles, the pile edge is susceptible to local failure.

Table 1. Reference to Rock in Japanese Design codes

	Design codes
Japan Road Association (JRA), 2017	Rock has a large strength as a material, and a large bearing capacity can be expected, when a uniform rock is used as a load bearing layer. However, in case there are discontinuities, or rock is susceptible to effects such as slaking, there are cases where sufficient bearing capacity cannot be expected, compared with uniform rock. It is therefore necessary to investigate these effects in advance, when rock is used as a load bearing layer
	When considering skin friction of pile in the design, it is required to obtain necessary design information by conducting individual loading tests. Also, for the construction method, in which rock is pre-drilled, and piles and sheet piles are buried after filling the hole with sand, it is necessary to carry out individual loading tests and to evaluate and verify horizontal and vertical bearing capacity characteristics used in the design.
Railway Technical Research Institute (RTRI), 2008	The behavior, especially short pile foundation, is close to that of spread foundation or caisson foundation, and it is important to properly set the design limit. However, in this standard, design limit values of lateral displacement and rotational angle are set, considering the continuity with direct foundation and caisson foundation. Therefore, the same design values to those for the pile foundation in general design can be applied to horizontal displacement and rotational angle, even for especially short pile foundation.
Port and Harbour Association of Japan (PHAJ), 2007	It is known that the property of ground around a pile may be different from that obtained soil investigation, depending on the type of pile installation. This may affect the bearing capacity in the direction perpendicular to the pile axis. Careful consideration should be given since there are cases where the ground resistance became smaller due to a poor construction that might have loosened the surrounding ground.

2.5. Points Considered in Japanese Criteria

Here, the points to consider on this theme in each guideline is quoted in **Table 1**. As seen in the table, rock is considered different from usual geotechnical materials, but there are no generalized concepts in any guideline for a variety of rock types, and effects caused by the adopted construction method. It seems the final judgement is currently up to the designer.

3. DEVELOPMENT OF FOUNDATION ANALYSIS

Design methods at each research organization are sorted out here. Broadly speaking, the design methods for the horizontal bearing capacity performance of pile foundation or wall foundation are divided into limit equilibrium analysis, elastic subgrade reaction, combined subgrade reaction method and others. Each method has its merits and demerits, such as complicated calculation scheme and evaluation of ground resistance force. The most appropriate method is currently selected, depending on their applicability (**Table 2**).

3.1. Limit Equilibrium Analysis

The limit equilibrium analysis evaluates horizontal resistance of piles from the balance of the subgrade reaction at the 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 relationship, and one that assumes the subgrade reaction by linear relationship or by arbitrary curves (Engel, Broms).

This method has a merit that the calculation can be easily carried out with several parameters, but it has a drawback that displacement cannot be directly calculated due to the assumed ultimate situation. Note that from the model experiment to simulate soft rock, Akazawa *et al*. (2016) pointed out that the safety factor of moment for rotation can be used to understand the behavior of short piles. If combined with another method described later, there may be possibility to use this method to evaluate horizontal resistance of piles.

3.2. Elastic Subgrade Reaction Method

Assuming the soil is elastic, horizontal resistance of piles is calculated as a beam on an elastic floor. The pile behavior is calculated from the following differential equation that is satisfied by the deflection curve of the beam:

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

$$p = kx^m y^n \tag{2}$$

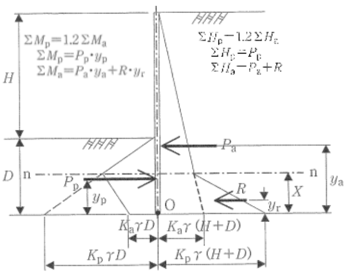
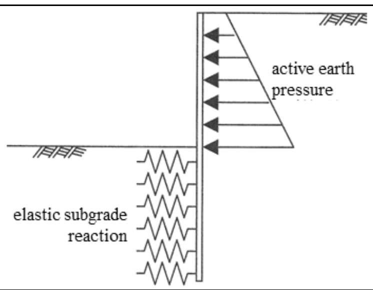
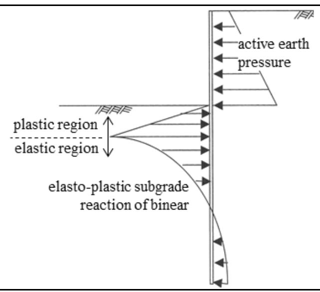
where,

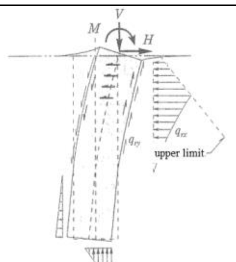
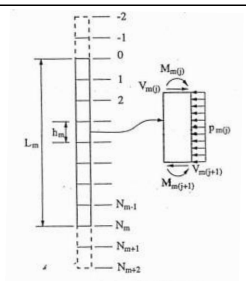
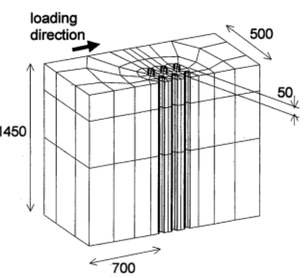
x: depth from the ground surface, and

y: deflection at a depth of x.

This may include a widely used Chang's method where n =1 and m = 0 are assumed in **Eq. (2)** above (JRA 1999). In this method, it is assumed that the horizontal subgrade reaction has a linear relationship with displacement. Okahara *et al*. (1989) collected data from the horizontal loading tests on actual piles and clarified

Table 2. Overview of analysis methods

Method	Limit Equilibrium Analysis	Elastic Subgrade Reaction Method	Combined Subgrade Reaction Method
Section	3.1	3.2	3.3
image			
subgrade reaction	$p_u=\alpha K_p \sigma_{v'}$ $(\Sigma M_a=\Sigma M_p)$	$p=kx^m y^n$ $p=Ap_u \tanh(kxy/Ap_u)$ $(k=k_0(y/y_0)^n)$	$p=kx^m y^n$, $p_u=\alpha K_p \sigma_{v'}$
e.g. reference / design code	RTRI (2004)	Kubo (1966), PHAJ (2007), API (2002), ACTEC (2007)	JRA (1999), ACTEC (2007)
e.g. Embedded Length	$L \geqq 1.2L_0$	$L \geqq 2.25/\beta$-$3.0/\beta$, $L \geqq 1.5l_{m1}$	-

Method	Other		
	Rotational Displacement Method	Shear Deformation Method	FEM
Section	3.4.1	3.4.2	3.4.3
image			
e.g. reference / design code	JRA (2017)	Lianyang *et al*.(2000)	Wakai (1999)

that the elastic range was more than 1 % of the pile diameter, regarding the characteristic point on the Weibull distribution curve as the elastic limit.

In addition, PHAJ (2007) sets n = 0.5, and it is said to be in good consistency with the experimental results. On the other hand, American Petroleum Institute (API, 2002) expresses horizontal subgrade reaction by hyperbolic function of displacement and depth in a similar logic as PHAJ (2007).

3.3. Combined Subgrade Reaction Method

In this method, the limit equilibrium analysis method is used near the ground surface, where deformation is large and in a plastic region, while the elastic subgrade reaction method is used in the elastic region below. This elasto-plastic analysis gives an easy theoretical explanation, and is often used, since theoretical values are highly consistent with the experimental data in a practical range (JRA, 1999; ACTEC, 2007).

3.4. Others

Other methods may include FEM and FDM. Unlike the ones described above, the continuity of ground can be considered in these methods. As will be described later, especially when the shear modulus of rock becomes large compared with elastic modulus, it is pointed out that the elastic subgrade reaction method gives large displacement (Lianyang *et al*., 2000).

3.4.1. Rotational Displacement Method

In the case of foundations with short piles for the pile stiffness, it is pointed out that horizontal resistance is difficult to evaluate by the spring on an elastic floor (*e.g.* Aoki *et al*., 1983; Iwakami *et al*., 2001). For short foundations such as caisson foundations and caisson type pile foundations, it is generally common to consider rotational displacement and floating, and to evaluate the ground reaction at the foundation bottom (JRA, 2017).

3.4.2. Shear Deformation Method

In FDM, considering the effects of ground and rock that affect the pile behavior and yielding, it is proposed to use an existing method to calculate ultimate resistance of ground, and to calculate rock resistance (Keming Sun, 1994). Lianyang *et al*. (2000) suggests that if this logic is followed, especially in stiff ground where pile stiffness is large compared with shear stiffness of the ground, smaller displacement is estimated than the elastic subgrade reaction method above, and the estimated displacement is closer to the experimental value.

Analysis methods to take shear deformation into consideration include Sato *et al*. (1996). In this method, the behavior of piles is obtained from the assumptions that a linear slip surface is created in front of a rigid body foundation, and that shear force acting on the slip surface is proportional to the rotational angle.

3.4.3. FE Method

With the development of computers, 3-dimensional FEM analyses have often been used (*e.g.* Wakai, 1999; Agui *et al*., 2014). In this method, multi-layered ground to which the application would be difficult in other methods can be easily dealt with, and calculation parameters can be considered for each individual layer.

Other than the FE method, those for discontinuous rock mass with fractures as described previously may include rigid body spring model (RBSM), discrete element method (DEM) and discontinuous deformation analysis (DDA). In each case, fractures are quantitatively evaluated and used in the analysis (Kuraoka, 1998). In dealing with rock mass as discontinuous body in the FEM, joint elements are used. This method is effective to describe the behavior of pile foundation, since it can be thought that the accuracy in calculated stress and displacement is high, and that it is suitable for limit equilibrium analysis of slip and infinitesimal deformation problems, though it is difficult to analyze large deformation behavior such as toppling. In the real design, however, drawbacks may be that it is difficult to obtain parameters required, and that it takes time to carry out the calculation.

4. EMBEDDED LENGTH

4.1. Determination of Embedded Length

Determination of pile embedded length for cantilevered steel tubular piles can be divided into the following three. a) The limit equilibrium analysis, b) Elastic subgrade reaction method and c) others.

a) The limit equilibrium analysis described before is a method to consider the factor of safety at a depth where subgrade reactions and rotational moments due to the subgrade reaction are balanced.

b) A product of a characteristic value β, which is the stiffness ratio of pile to ground and the embedded length L is also often used for evaluating whether the embedded length is sufficient. In this evaluation, it is known that there is little difference in behavior when $\beta L = \pi$ or more. In Japan, often-used βL values are 3.14 for rivers (Bureau of Construction, Tokyo Metropolitan Government, 2008), 3.0 for roads (ACTEC, 2007), 2.5 for temporary structures (JRA, 1999), and 2.25 for architectural structures (AIJ, 2001). In addition, in the ground where the stiffness linearly increases in the depth direction, using a stiffness factor T ($=\sqrt[5]{EI/n_h}$) (where n_h is values of the coefficient of modulus variation) the embedded length is expressed by a short pile (rigid) if it is shorter than $2T$, and by a long pile (elastic) if it is longer than $4T$ (Michael and John 2007).

c) On the other hand, assuming that, in the case where horizontal load works, the embedded length is given by the depth l_{ml} where the bending moment becomes 0 (primary bending moment = 0) for a pile of which the length is long enough, the PHAJ method described earlier defines the factor of safety for that depth. In addition, especially for piles that are thought to be used in multi-layered ground, it may be difficult to evenly use the estimation from stiffness of both ground and steel tubular piles as mentioned above. For these problems with multi parameters, investigation has been carried out to study the effect given to the behavior of the embedded length by numerical calculation methods such as FEM analysis, including the pile top fixture conditions (*e.g.* Kanaizuka 2002).

4.2. Cyclic Load/ Aseismic Stability

It is known that in a typical ground, deformation increases when subjected to cyclic loading (San-Shyan Lin and Jen-Cheng, 1999; Kubo, 1966). Under cyclic loading in an ordinary ground, it is pointed out that residual deformation converges in the case of long piles, whereas in the case of short piles, deformation tends to become large as cyclic loading progresses. It is necessary to investigate the effect of cyclic loading for rock although rock mass tend to be stable and not likely to become plastic even on the ground surface.

In addition, it is expected that a phenomenon similar to cyclic loading takes place at the time of earthquake. Nagao and Fujimori (2007) investigated the seismic performance of the self-sustaining retaining wall. ACTEC (2007) has carried out dynamic loading test, varying the embedded length from 1.9 / β to 3.0 / β, and has reported that the shorter the embedment depth is, the closer the behavior where the pile rotates from the pile toe becomes.

5. SUMMARY

In evaluating horizontal stability of steel tubular pile foundation embedded into rock mass, existing knowledge that is considered important has been compiled, focusing on a) the characteristics of rock mass, b) modelling of horizontal bearing capacity characteristic and c) determination method of pile foundation embedded length. As a result, the following points are thought to become issues in shortening the embedded length:

1. Rock mass has discontinuities such as fractures. Its layer also exhibits non-linear behavior. To assume the pile behavior in rock in plastic state, attention has to be paid to that discontinuities. Rock mass may be loosened during construction. Since embrittlement due to stress relief is apprehended in rock mass, it is necessary to select a proper construction method.
2. The horizontal stability of the foundation may be underestimated when assuming a beam on an elastic floor in a rock mass with high stiffness compared with that of the pile. In addition, in a multi-layered ground, behavior on the rock surface is unclear.
3. In the case where the embedded length is short, the behavior of pile under horizontal resistance is different from that for piles in semi-infinite length and is in a failure mode of rotation from the pile toe. It is pointed out that residual displacement in an ordinary ground becomes large, especially when subjected to cyclic loading. The effects on rock should be clarified.

From now when high aseismic performance is required, in order to make a more rational design, it will become an important issue to clarify the way the rock surface should be treated after plasticity occurs, and the effect of construction on rock foundation.

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