Proceedings of the Second International Conference on Press-in Engineering 2021, Kochi, Japan – Matsumoto et al (eds)

Proposal of vertical design bearing capacity estimation formula of Gyropress method based on Japanese railway standard

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ABSTRACT: In recent years, Gyropress method (Self-Walking Rotary Press-in Method for Tubular Piles with Tip Bit) has become popular as one of the methods for installation of piles. In the previous Japanese railway design standard, the limit state design method have been used. However, in 2012, it was revised to adopt the concept of the performance-based design method. In this paper, the authors propose a design vertical bearing capacity estimation formula and a partial resistance factor for Gyropress method based on the concept of the performance-based design method.

1 INTRODUCTION

1.1 *Gyropress method*

Damage to social infrastructure has occurred in various parts of Japan due to the torrential rains caused by the recent abnormal weather. In addition, an occurance of large-scale earthquake is also predicted in the near future. Therefore, it is also necessary to implement countermeasures against large-scale earthquakes and torrential rains.

In recent years, Gyropress method (Self-Walking Rotary Press-in Method for Tubular Piles with Tip Bit) has become widespread as one of the construction methods for steel pipe piles. Gyropress method is one of pile installation methods, a steel pipe pile with a ring bit consisting of a steel ring and a bit for cutting hard ground is pressed-in by rotary cutting at the tip (Figure 1). Gyropress method is expected to be applied, especially in places where it is difficult to construct structures, such as hard grounds and restrictions on the use of upper space. Moreover, it has been used for seismic reinforcement and scours measures for existing railway bridge piers (Figures 2-3).

1.2 *Current design vertical bearing capacity of usual construction method and Gyropress method*

In the Japanese design standard of railway foundation structures, the design bearing capacity of piles R_{vd} is expressed as follows Eqs.(1)-(3).

$$R_{vd}=f_{rf}R_f^k+f_{rt}R_t^k \tag{1}$$

$$R_f^k = U\sum r_{fi}{}^k l_i \tag{2}$$

$$R_t^k= q_t^k\ A_t \tag{3}$$

where R_{vd} = total design vertical bearing capacity; R_f^k = characteristic value of the ultimate bearing capacity of shaft friction; R_t^k = characteristic value of the ultimate bearing capacity of the tip resistance; f_{rf} = partial resistance factor of the shaft friction; f_{rt} = partial resistance factor of the tip resistance; U = circumferential length of the pile; $r_{fi}{}^k$ = characteristic value of the intensity of the ultimate shaft friction at i th layer; l_i = thickness of i th layer; q_t^k = characteristic value of the intensity of the ultimate bearing capacity of the tip resistance; and A_t = the area of the pile tip.

In this paper, the value with the superscript notation k denotes the characteristic values, the subscript f denotes shaft friction resistance, and the subscript t means tip resistance.

The partial resistance factor of the shaft friction f_{rf} and that of the tip resistance f_{rt} are distinct, as shown in Eq. (1). Hence the design vertical bearing capacity can be takes into consideration the effects of the ratio of the tip resistance to the shaft friction. The characteristic values $r_{fi}{}^k$ and q_t^k shown in Eqs. (2)-(3) are defined as the unit ultimate resistance when the settlement of the focused part of the pile (pile at i th layer for r_f^k, pile tip for q_t^k) reaches 10% of the

DOI: 10.1201/9781003215226-11

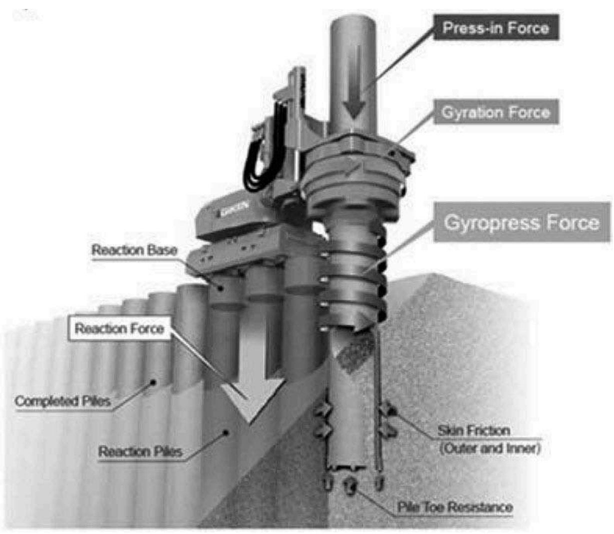


Figure 1. Mechanism of Gyropress method (GIKEN LTD. 2015).

Figure 2. Overview state of Gyropress method (Kimura et al. 2019).

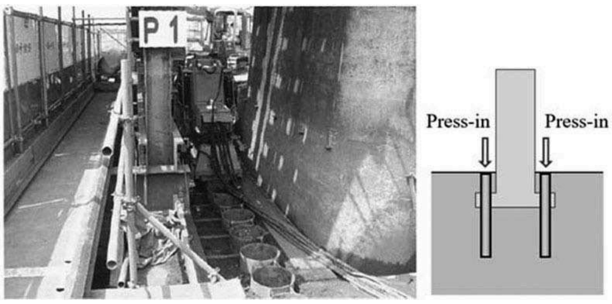


Figure 3. Detail state of Gyropress method (Kimura et al. 2019).

pile diameter. This definition follows the standard for the pile loading tests of Japanese Geotechnical Society (JGS 2007).

The characteristic values r_{fi}^{k}, q_t^{k}, and the partial resistance factors f_{rf}, f_{rt} of the bearing capacity of the pile should be determined based on the results of the loading tests with a full-scale pile at a specific construction site for each project. However, in terms of cost, it is not ractial to conduct the pile loading tests for design calculation at all construction sites. For this reason, the Japanese railway design standard presents the estimation formulas of the characteristic values r_f^{k}, q_t^{k}, and the partial resistance factors f_{rf}, f_{rt} derived on the basis of the soil investigation results. In fact, almost all the structures have been designed using only the soil investigation results (N-value measured by standard penetration test is most prevalent in Japan).

On the other hand, in Gyropress method, with the estimation formulas of the characteristic value r_f^{k}, q_t^{k}, and partial resistance factors f_{rf}, f_{rt} are not presented in the Japanese railway design standard. This is because the track record of vertical loading test results by Gyropress method is insufficient. Therefore, the design vertical bearing capacity has been currently designed with a safety margin that is more sufficient.

On the basis of the above, in this paper, we propose the estimation formulas of the characteristic values r_f^{k}, q_t^{k} of Gyropress method in Chapter 3, and the partial resistance factors of that f_{rf}, f_{rt} in Chapter 4 with the derivation method.

2 OUTLINE OF VERTICAL STATIC LOADING TEST OF PILE INSTALLED BY GYROPRESS METHOD

First, the authors collect the data of the vertical loading test by Gyropress method.

We evaluate 5 cases shown in Table 1, which are a multi-stage static loading test results following the standard of JGS. The converted rooting depth in the support layer is longer than the outer diameter of steel pipe D, which is 800 to 1000 mm.

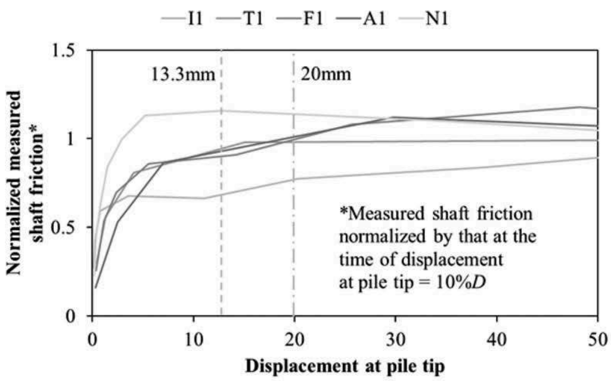
Figure 4 shows the relationship between the pile tip displacement and the load. The y-axis load is the value when the pile tip displacement reaches 10% of the pile diameter, and the displacement in Figure 4 (b) is normalized by the pile diameter. For reference, the reference displacement in the Japanese railway design standard is shown in Figure 4.

The resistance of the shaft friction reaches the limit with a displacement of about 5 to 20 mm. Since the resistance of the shaft friction in case of general method reaches the limit when the pile head displacement is about 10 to 20 mm, we find the tendency of Gyropress method is the same as genral construction methods. Besides, regarding the pile head bearing capacity, a route exerts a large bearing capacity from the initial stage of displacement is drawn. The variation of between in each case is small.

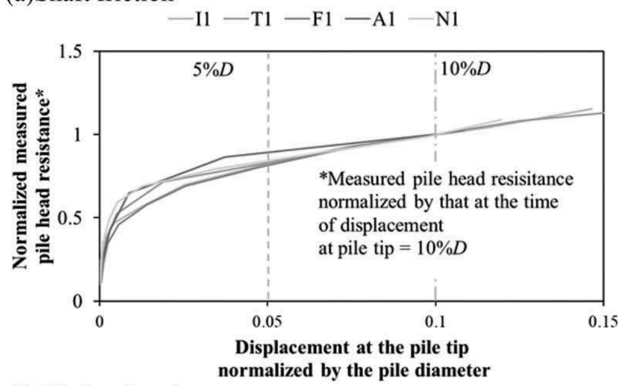
Table 1. Outline of loading test data of Gyropress method.

Test name	Diameter	Thickness of steel pipe pile	Length of pile	Normalized depth into support layer	Support layer: Soil clasiffication	Support layer: N value	Medium layer: Soil clasiffication	Medium layer: N value	Medium layer: Soil clasiffication	Medium layer: N value
I1	800mm	16mm	19.65m	2.5m	G	86	G	43~66	-	-
T1	800mm	16mm	17.5m	2.0m	G	36	S	3	S	9
F1	1000mm	16mm	15.0m	3.1m	S	58	S	7	S	58
A1	800mm	12mm	4.7m	0.8m	S	15	C	3	-	-
N1	1000mm	12mm	25.0m	2.4m	G	60	S	6	C	4

Soil classification G:gravel S:sand C:clay (Suzuki et al.2019)



(a)Shaft friction



(b)Pile head resistance

Figure 4. Relationship between pile tip displacement and normarized bearing capacity (Suzuki et al. 2019).

3 ESTIMATION FORMULAS FOR VERTICAL SUBGRADE REACTION OF PILE INSTALLED BY GYROPRESS METHOD

3.1 *Proposed formulas for coefficient of vertical subgrade reaction*

3.1.1 *Coefficient of vertical subgrade reaction at pile tip*

The estimation formula of the coefficient of vertical subgrade reaction at the tip of the pile k_{tv} is established as follows. The closed area is used as the pile tip area when adpoting Eqs. (4)-(5) for calculating the vertical ground spring constant K_{tv} at the pile tip.

$$k_{tv} = 1.4\rho_{gk}E_dD^{-3/4} \quad (4)$$

$$K_{tv} = k_{tv}A_t \quad (5)$$

where k_{tv} = coefficient of the vertical subgrade reaction at the pile tip, ρ_{gk} = geotechnical modification factor, E_d = deformation modulus of the ground, and K_{tv} = vertical ground spring constant.

Figure 5 shows the relationship between the coefficient of the vertical subgrade reaction force and the deformation modulus of the ground estimated from the N value at the pile tip in each loading test case. The measured coefficient of the vertical subgrade reaction is obtained by dividing the ground spring constant at the tip of the pile by the tip area A_t and the effect of the load duration time is corrected to ρ_{gk} = 1.0.

The dotted line in Figure5 shows the result by the proposed estimation formula. From Figure 5, it is seen that the proposed estimation formula can evaluate the loading test results roughly equivalent to the average value.

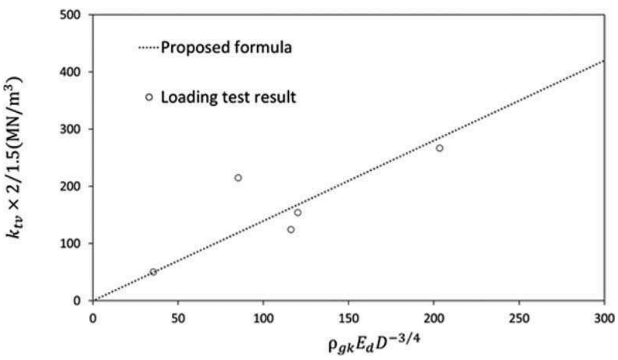


Figure 5. Relationship between coefficient of vertical subgrade reaction force at pile tip and deformation modulus of ground (Kimura et al. 2019).

3.1.2 *Coefficient of vertical subgrade reaction on pile shaft*

The estimation formula of the coefficient of vertical subgrade reaction of shaft friction k_{fv} is established as following Eq. (6).

$$k_{fv} = \min(0.3\rho_{gk}E_d, 6000) \tag{6}$$

Although the upper limit of the coefficient of the vertical subgrade reaction force is not set, the upper limit is set in consideration of the loading test results in Gyropress method. It is presumed that this is because Gyropress method often targets the hard support ground and the dependence on the original strength of the ground becomes smaller due to the effect of rotary cutting during press-fitting into the hard support ground.

Figure 6 shows the relationship between the coefficient of the vertical subgrade reaction and the deformation modulus of the ground on the shaft of the pile. In Figure6, the measured coefficient of the vertical subgrade reaction force is calculated back from the loading test result, and the effect of the load duration time is increased by 1.33 times so that it is equivalent to ρ_{gk} = 1.0, the same as one of the tip resistance.

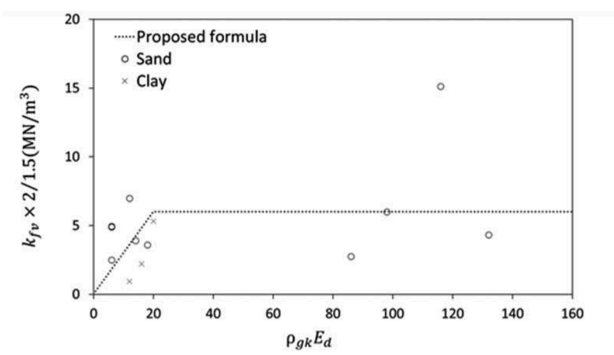


Figure 6. Relationship between coefficient of vertical subgrade reaction force on pile shaft and deformation modulus of ground (Kimura et al. 2019).

3.2 *Proposed estimation formula for reference bearing capacity*

3.2.1 *Reference bearing capacity at pile tip*

Figure 7 shows the relationship between the reference bearing capacity at pile tip and the *N* value. The reference bearing capacity at pile tip is obtained by dividing the measured value of the reference tip bearing capacity R_t of the loading test by the tip area of the closed steel pipe. The Japanese railway design standard indicates to use "the minimum *N* value in 1*D* above and 3*D* from the pile tip in the depth direction" as the tip *N* value. However, if the minimum *N* value is used in this study, the coefficient of variation during statistical processing (described later) is large. Therefore, "average *N* value in 1*D* above and 3*D* from the pile tip in the depth direction "is used. However, it should be notedit is better to design on the safe side in actual operation by using the minimum *N* value as in other pile construction.

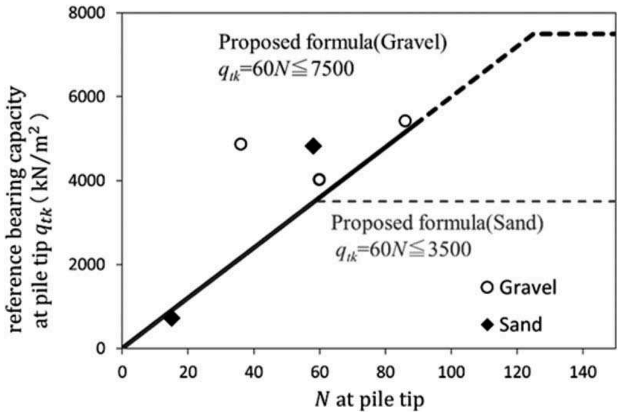


Figure 7. Relationship between reference bearing capacity at tip and *N* value (Kimura et al. 2019).

As for the estimation formula of the reference bearing capacity at pile tip of the pile installed by Gyropress method, we propose the following Eq. (7). The proposed formula, which is shown by a solid line, is derived from Figure 7 as a model equivalent to the lower limit value as in other pile construction methods. Since the loading test range is limited, the range confirmed by the loading test is shown by the solid line, and the dotted line shows the outside of the range.

$$q_{tk} = \begin{cases} \min(60\text{N}, 3500): \text{sand} \\ \min(60\text{N}, 7500): \text{gravel} \end{cases} \tag{7}$$

The proposed estimation formula is equivalent to the cast-in-place pile formula presented in the Japanese railway design standard. On the other hand, in the driven pile method with a pile diameter of 800 mm or less, which is the same open-ended steel pipe pile method, q_{tk} = 35 (*L/D*) *N* is presented. In the case where the embedding ratio *L/D* in the support layer is 1 to 2, q_{tk} = 35 to 70 *N*, which is almost the same as the proposed estimation formula. The mechanism of the Gyropress method is considered to be closer to one of the driven pile rather than the cast-in-place pile in the process of constructing piles near the support layer.

However, for the upper limit, we apply mutatis mutandis the value of cast-in-place pile, which has the smallest estimated value of bearing capacity at the tip in the pile construction method. This value is likely to be changed by increasing the number of loading tests in the future.

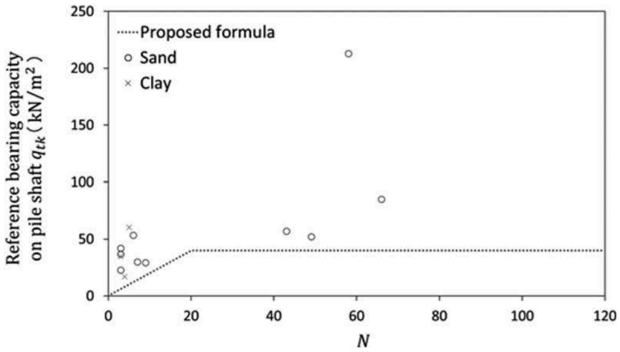


Figure 8. Relationship between reference bearing capacity on pile shaft and N value (Kimura et al. 2019).

3.2.2 *Reference bearing capacity on pile shaft*

Figure 8 shows the relationship between the reference bearing capacity on pile shaft obtained from the loading test and the N value. Here, since there are few data on clay, we propose the following Eq. (8) which is the same reference bearing capacity of pile shaft estimation formula for sand and clay. The proposed formula is shown by dotted lines in Figure 8.

$$r_{fk}= \min(2N, 40) \quad (8)$$

From Figure 8, it is confirmed that the proposed estimation formula evaluates the loading test results at the lower limit, as with other pile construction methods.

Moreover, estimated reference bearing capacity including both tip resistance and shaft friction is calculated by Eqs. (1)-(3), (7)-(8) . The relationship between estimation value and measured value is shown in Figure 9. The characteristic values estimated from Figure 9 are generally smaller than the measured values, indicating that the estimation formula exists in the safe side.

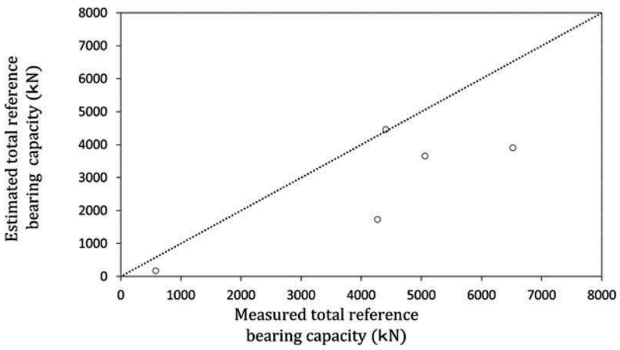


Figure 9. Relationship between measured value and estimated value of total reference bearing capacity (Kimura et al.2019).

4 CALCULATION OF PARTIAL RESISTANT FACTOR BY RELIABILITY ANALYSIS

4.1 *Calculation method of partial resistance factors*

4.1.1 *Definition of partial resistance factor*

In this section, we dfine the partial resistance factors f_{rf} and f_{rt} using the method in the Japanese railway design standard.

First, we calculate the normalized resistance force of pile (NRF), which is the measured shaft friction and the tip resistance of each limit state divided by the characteristic value of total resistance R_k ($=R_{fk}+R_{tk}$). Moreover, the database of NRF for Gyropress method for each limit state is created. In this procedure, singular values are excluded by Grubbs' test (Grubbs 1950).

The partial resistance factors f_{rt} and f_{rf} are calculated using FORM as follows on the assumption that the NRF database follows the normal distribution:

$$f_{rt}=\mu_{Xt}-\beta_a\alpha_t\sigma_{Xt} \quad (9)$$

$$f_{rf}=\mu_{Xf}-\beta_a\alpha_f\sigma_{Xf} \quad (10)$$

$$\alpha_t= R_t^k\ \sigma_{Xt}\ /\sqrt{\left(R_t^k\ \sigma_{Xt}\right)^2+\left(R_f^k\ \sigma_{Xf}\right)^2} \quad (11)$$

$$\alpha_f= R_f^k\ \sigma_{Xf}\ /\sqrt{\left(R_t^k\ \sigma_{Xt}\right)^2+\left(R_f^k\ \sigma_{Xf}\right)^2} \quad (12)$$

where β_a = target reliability index; α_t, α_f = sensitivity coefficients; μ_{Xt}, μ_{Xf} = mean values; σ_{Xt}, σ_{Xf} = standard deviations of NRF database.

However, the calculated mean values μ_{Xt} and μ_{Xf} are low with a confidence level of 0.75 because the number of data is small. The partial resistance factor of the shaft friction f_{rf} and that of the tip resistance f_{rt} can be calculated by Eqs. (9)-(12).

Moreover, the partial resistance factor of the total resistance f_r is defined as the function of the ratio of pile tip bearing capacity p_t ($=R_{tk}/(R_{tk}+R_{fk})$) as following Eqs. (13)-(14) from a practical perspective.

$$R_{vd}=f_r\left(R_t^k+R_f^k\right) \quad (13)$$

$$f_r = \left(f_{rt}R_t^k + f_{rf}R_f^k\right)/\left(R_t^k + R_f^k\right) = p_tf_{rt} + (1 - p_t)f_{rf} \quad (14)$$

However, in the case where μ_X is small and σ_X is large, some of the calculated results become very small (or sometimes become negative). In the case, the actual phenomena and the calculation result are incompatible.

Therefore, we adopt the calculation method by Sanagawa et al. in order to approximate NRF distribution more highly in the next section. In the method, NRF database follows the lognormal distribution.

4.1.2 *Approximation by lognormal distribution*

1) Evaluation by lognormal distribution

It is assumed that the NRF database follows the lognormal distribution as shown in Figure 10 (a). After the x-axis, which denotes the probability density function of NRF, is logarithmically transformed as shown in Figure 10 (b), the mean $\mu_{\ln X}$ and the standard deviation $\sigma_{\ln X}$ are calculated. The statistic parameters $\mu_{\ln X}$ and $\sigma_{\ln X}$ can also be calculated from the mean μ_X and the standard deviation σ_X of NRF as following Eqs. (15)-(16) (μ_X and σ_X are the statistic parameter, without logarithmic transformation).

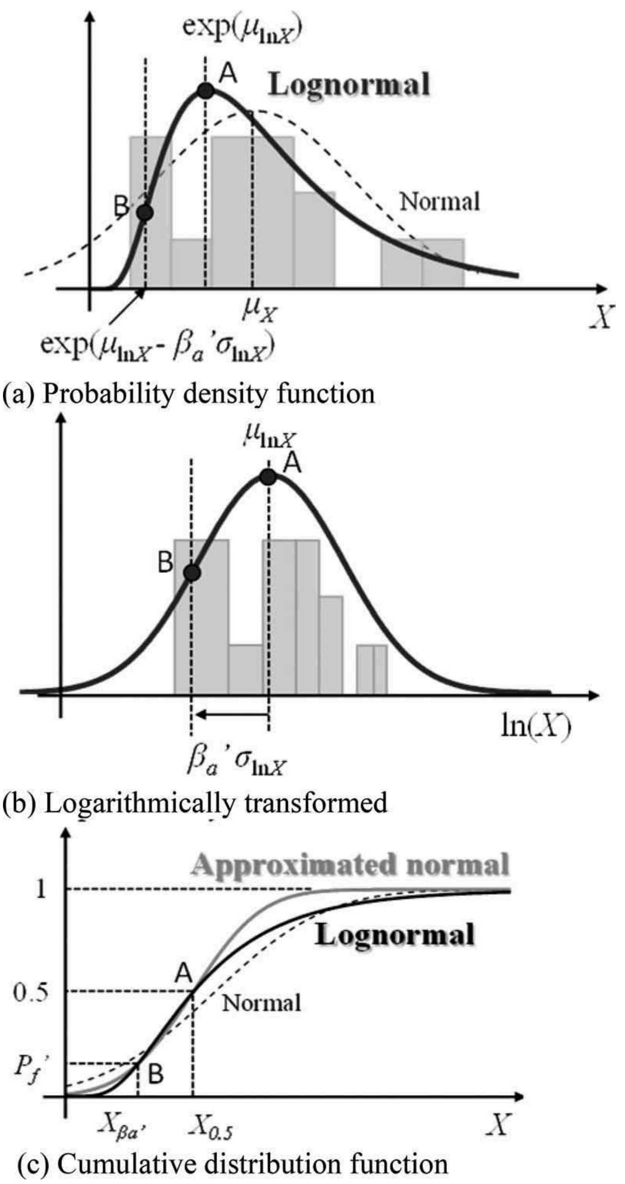


Figure 10. Outline of approximation of distribution (Sanagawa et al. 2019).

$$\mu_{\ln X} = \ln(\mu_X) - 1/2\sigma_{\ln X}{}^2 \tag{15}$$

$$\begin{aligned}\sigma_{\ln X} &= \sqrt{\ln\left(1+(\sigma_X/\mu_X)^2\right)} \\ &= \sqrt{\ln\left(1+V^2\right)}\end{aligned} \tag{16}$$

where V = design coefficient of variation.

2) Set the part for normal distribution approximation

The part of the lognormal distribution, which considerably influences on the partial resistance factors f_r is approximated by the normal distribution. The approximated part is set as the part whose cumulative probabilities is between P_f and 0.5 shown in Figure 10 (c). The random variable of NRF (X), whose cumulative probability are from 0.5 ($X_{0.5}$) to P_f' ($X_{\beta a'}$) can be calculated by $\mu_{\ln X}$ and $\sigma_{\ln X}$ as following Eqs. (17)-(18).

$$X_{0.5} = \exp(\mu_{\ln X}) \tag{17}$$

: Cumulative probability of failure is 0.5

$$X_{\beta_a'} = \exp(\mu_{\ln X} - \beta_a'\sigma_{\ln X}) \tag{18}$$

: Cumulative probability of failure is Pf'

3) Approximation by normal distribution

The cumulative distribution function of the lognormal distribution is approximated by that of the normal distribution which passes through two points, A ($X_{0.5}$, 0.5) and B ($X_{\beta a'}$, P_f') as shown in Figure 10 (c).

The mean value μ_X' and the standard deviation σ_X' of the approximated normal distribution are given as following Eqs. (19)-(20).

$$\mu_X = X_{0.5} = \exp(\mu_{lnX}) \tag{19}$$

$$\begin{aligned}\beta_a'\sigma_X' &= X_{0.5} - X_{\beta a'} \\ &= \exp(\mu_{lnX}) - \exp(\mu_{lnX} - \beta_a'\sigma_{lnX})\end{aligned} \tag{20}$$

4.1.3 *Definition of reference settlement for each limit state*

In order to calculate the statistic parameter of NRF for each limit state from the loading test database, it is necessary to define the reference settlement for each limit state. We determine the reference settlement so as to correspond to the limit state in the Japanese railway design standard.

Table 2 shows an example. These reference settlements are empirically determined considering the

Table 2. Example of limit state and reference settlement for each limit state for railway structures (Sanagawa et al. 2019).

Limit state	Reference settlement for each limit state s	Assumed damage condition	Action
Serviceability	20mm	Cracks on superstructure by differential settlement	Variable (Train load)
Restorability	Min. (50mm, 0.05D)	Need to restore track because of residual settlement	Accidental (Level 1 earthquake)
Ultimate	0.1D	Need to restore structure because of large settlement	Accidental (Level 2 earthquake)

limit states for maintenance (serviceability), restorability, and safety for the structures (restorability and iltimate).

4.1.4 *Subdividing of design coefficient of variation*

In in Eq. (18), the design coefficient of variation V ieffects of variations are considered as differences in the quality of the pile construction, variations when calculating the coefficients of the ground and variation due to diversion of soil investigation results. In this section, the design coefficient of variation V is divided into three factors as following Eq. (21).

$$V = \sqrt{V_1^2/n + V_2^2 + V_3^2} \tag{21}$$

where V_1 = coefficient of variation depending on the pile construction method, V_2 = coefficient of variation of estimation ground strength from N value, V_3 = coefficient of spatial variation of stiffness and strength of soil, and n = number of piles integrated as a group pile.

Although V_2 is originally considered to be variable, we assume V_2 as a constant value of V_2 = 10% (conversion error from N value to internal friction angle φ) with reference to (Nishioka et al. 2017) V_3 is estimated by linearly interpolating the minimum value V_{3min} = 18% to the maximum value V_{3min} = 45% according to the distance ΔL from the ground survey position with reference to the research by (Otake et al. 2014) Here, the minimum value V_{3min}, the value where $\Delta L \leq 5$ m, corresponds to the design by the boring nearby the pile construction spot. On the other hand, the maximum value V_{3max}, the value where $\Delta L \geq 50$ m, corresponds to the design by boring diversion.

We assume that V when n = 1, V_2 = 10%, and $V_3 = V_{3min}$ are assigned to Eq. (21) is the same as the coefficient of variation V_{test}. Then, V_{test} is obtained by convering into consideration of the lognormal distribution after statistically processing the loading test database. Here, n = 1 because the loading test is conducted with a single pile; $V_3 = V_{3min}$ because the loading test is conducted by the test pile. Moreover, V_1 is considered to be a unique value for each pile construction method corresponding to the construction quality and is calculated by the following Eq. (22).

The result of each design coefficient of variation is shown in Table 3.

$$V_1 = \sqrt{V_{test}^2/n - V_2^2 - V_{3min}^2} \tag{22}$$

4.1.5 *Target reliability index*

The target reliability index β_a' indicates the probability of the failure that the pile settlement exceeds the reference settlement. There are

Table 3. Each coefficient of variation about Gyropress method loading test with normal distribution.

Limit state		Serviceability		Restorability		Ultimate	
Reference settlement for each limit state s		20mm		Min. (50mm, 0.05D)		10%D	
Resistant part		Tip resistance	Shaft friction	Tip resistance	Shaft friction	Tip resistance	Shaft friction
Subdivision of coefficient of variation	Actual coefficient of variation V_{test}	0.54	0.53	0.48	0.55	0.49	0.49
	variation depending on construction method $V_1=\sqrt{(V_{test}^2-V_2^2-V_3^2)}$	0.50	0.49	0.43	0.51	0.44	0.44
	Coefficient of variation using in design: V	0.68	0.67	0.69	0.64	0.64	0.69

Table 4. Example of target reliability index β_a' and probability of failure P_f'.

Approximated normal distribution	Limit state		
	Serviceability	Restorability	Ultimate
Target reliabilit index β_a'	0.85	0.4	0.1
Probability of failure P_f'	20%	34%	46%

various methods to determine the values of β_a'. The Japanese railway design standard determine β_a' by code calibration. The code calibration is conducted based on the reliability of the design bearing capacity of driven pile in the current standard, so that it becomes equal to that of the previous one about driven pile (Railway Technical Research Institute 1997). And all the construction methods adopt the same target reliability indexes. Target reliability index β_a' and the corresponding probability of failure P_f' for each limit state are shown in Table 4 (Sanagawa et al. 2020).

4.2 *Calculation of partial resistance factor of Gyropress method*

Table 5 shows the statistic parameter of NRF for each limit state calculated from the NRF database for Gyropress method.

The partial resistance factor was calculated using the formulas in section 4.1 and values in Table 4 and Table 5. Figure 11 shows the relationship between the partial resistance factor of the total resistance f_r and the pile tip bearing capacity ratio p_t.

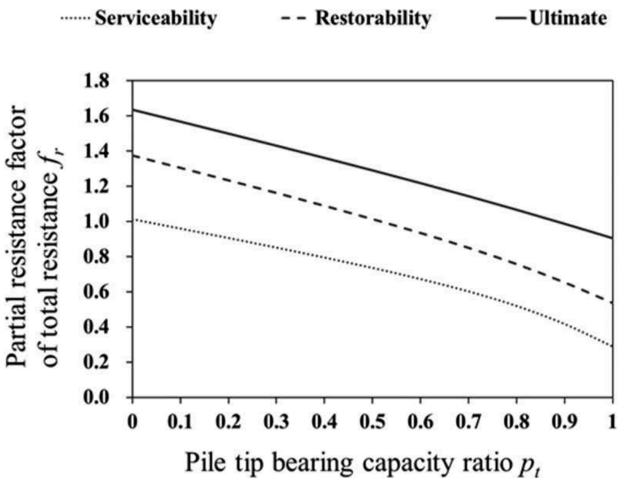


Figure 11. Partial resistance factor f_r for each limit state.

5 CONCLUSION

In this paper, on the basis of the collected loading test results of piles constructed by Gyropress method,the authors proposed the design method for Gyropress method on the concept of reliability design of the Japanese railway design standard. In addition, the authors proposed the partial resistance factor. As described above, the number of loading tests is not large enough. Therefore, the proposal is made with enough safety margin. In other words, it is highly possible that it is improved by increasing the number of loading test databases in the future.

The Gyropress method was initially used for the revetment repair of urban rivers. After that, it has been also used for installing steel pipe piles into hard rock and rubble mounds, and as of the end of August 2018, there are more than 400 construction records (of which 25 are expected to have bearing capacity).

Construction machines for Gyropress method applying for large diameter tubular piles up to φ2500 mm have been used. Various

Table 5. Statical parameter of Gyropress method for each limit state.

Limit state		Serviceability		Restorability		Ultimate	
Reference settlement for each limit state s		20 mm		50 mm or 5%D		10%D	
Resistant part		Tip resistance	Shaft friction	Tip resistance	Shaft friction	Tip resistance	Shaft friction
Static parameter (Approximated normal distribution)	Valid data number n	5	5	5	5	5	5
	Mean value μ	0.49	1.70	0.68	1.76	0.96	1.73
	Coefficient of variation using in design: V	0.48	0.48	0.52	0.55	0.57	0.57

considerations will be conducted so that the standard design method can be introduced to such large diameter tubular piles.

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