PROBABILITY STUDY FOR A HIGH-CAPACITY MICROPILE BEARING MECHANISM

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High-capacity micro-piles are cast in place and heavily depend on construction technique and soil properties. As such, uncertainties regarding the bearing capacity of the piles are involved. Therefore, utmost care must be taken in designing piles to ensure safety. This paper determines the performance function of a pile's push-in bearing capacity under three separate critical conditions: ground subsidence due to the insufficient bearing capacity of a pile, steel-pipe fractures due to compression, and fractures in non-steel-pipe areas due to compression. We examine these uncertainties in terms of probability and study how to use partial factor design in programming the push-in bearing capacity of high capacity micro piles.

Key words: High-capacity micro-pile, partial factor design, uncertainty, reliability theory

1. Introduction

Piles of 300mm or less that are used on construction sites are generally called 'micro piles' (abbreviated to MPs in this paper). The origin dates back to 1952 when F. Lizzi in Italy developed what was then called the 'root pile'.[1)] Lizzi invented MPs of 150mm or less which are composed of irregularly-shaped steel bars and grout, and are used mainly for adding strength to the supporting capacity of the ground and for underpinning the structures above.

Since then MPs have gained popularity all over the world, including the UK, Germany, France, the USA, and some Asian countries.[2), 3)] MPs were introduced into Japan in 1979, and in 1980 the first MP was placed in Asukayama Tenbodai [4)] in Tokyo. To date, 700 projects have been completed with the use of MPs. In 1971, 1989, and 1994, the State of California in the USA suffered widespread destruction of road bridges due to major earthquakes, and MPs were employed to support bridge foundations and to prevent bridges from collapsing.[5)]

Meanwhile, High-Capacity Micro-Piles (abbreviated to HMPs in this paper), which are the focus of the present paper, came into use particularly after the year

Table 1 Shape Standards [10)]

	Type	Standards	Dimensions	Strength/Quality
Supporting Steel Pipe	Oil-Well Pipe	API 5CT, N-80 fsy:80-110ksi (560-760 N/mm^2)	Outside diameter 178mm thickness 12.7mm	fc=703N/mm^2
Supporting Reinforcing Bar	twisted reinforcing bar irregularly-shaped steel	SD490 D51	Nominal Diameter 51mm Section Area 20.3 cm2	fb=490N/mm^2
Grout	Cement Paste	W/C=45% Fc =≧35N/mm^2		σ_{28} = 44-58 N/mm^2 (Average σ_{28}=53 N/mm^2)

1989, when the Loma Prieta earthquake occurred, to add strength to bridge foundations.[6)] In Japan too, HMPs were recognized as a new technology that can be used to improve the anti-earthquake performance of new and existing structures after the Nambu earthquake in Hyogo Prefecture in 1995.[7),8)] One typical project is the Sashiumi Bridge where HMPs were used to strengthen the anti-earthquake capacity of the footings of the bridge.

An HMP is shown in fig. 1; it combines irregularly-shaped reinforcing bars and steel pipes as shown in Tab.1, which makes it possible to have high durability and a high bearing capacity, even for this type of small-diameter pile. The HMP has outstanding advantages: the footing area can be minimized due to the small diameter of the pile when used as a technique to add strength to the anti-earthquake performance of bridge foundations, and the pile is suitable for reinforcing existing structures where construction space is limited. HMPs can be placed using small machines, even when there is a limited clearance of as little as 3.5 meters available above the pile top.[9)]

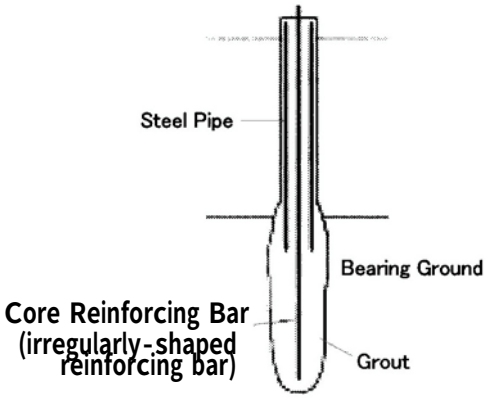

Figure 1 High-Capacity Micro Pile

On the other hand, the HMP is used on construction sites, and its bearing capacity depends greatly on the level of quality control at the construction site. The HMP is also influenced by various elements inherent in the individual ground conditions. As a result, uncertain factors are involved, and in order to ensure safety at the design stage, sufficient consideration must be given to examining the vertical and horizontal bearing capacity, the ground subsidence level etc. and to controlling these uncertain factors.

However, the current design guidelines (proposed) in the Design and Construction Manual (proposed) on HMPs [9)] employs an allowable-stress method, and safety of the allowable push-in bearing capacity, which is a typical

bearing capacity, is computed by using safety factors that are consolidated for the load/strength.

The bearing capacity of the HMP is determined by factors such as the strength of the pile body itself, and the frictional resistance between the surrounding surface of the pile and the ground.

Each of these factors is associated with corresponding uncertain elements. In order to evaluate these individual uncertain elements quantitatively, safety factors need to be varied depending on fluctuations in the component factors of the HMP bearing capacity.

This paper examines applications of the Partial Factor Design Method [10), 11), 12)] to the design and engineering of the push-in bearing capacity of the HMP based on probability theory.

Partial factor design is a method in

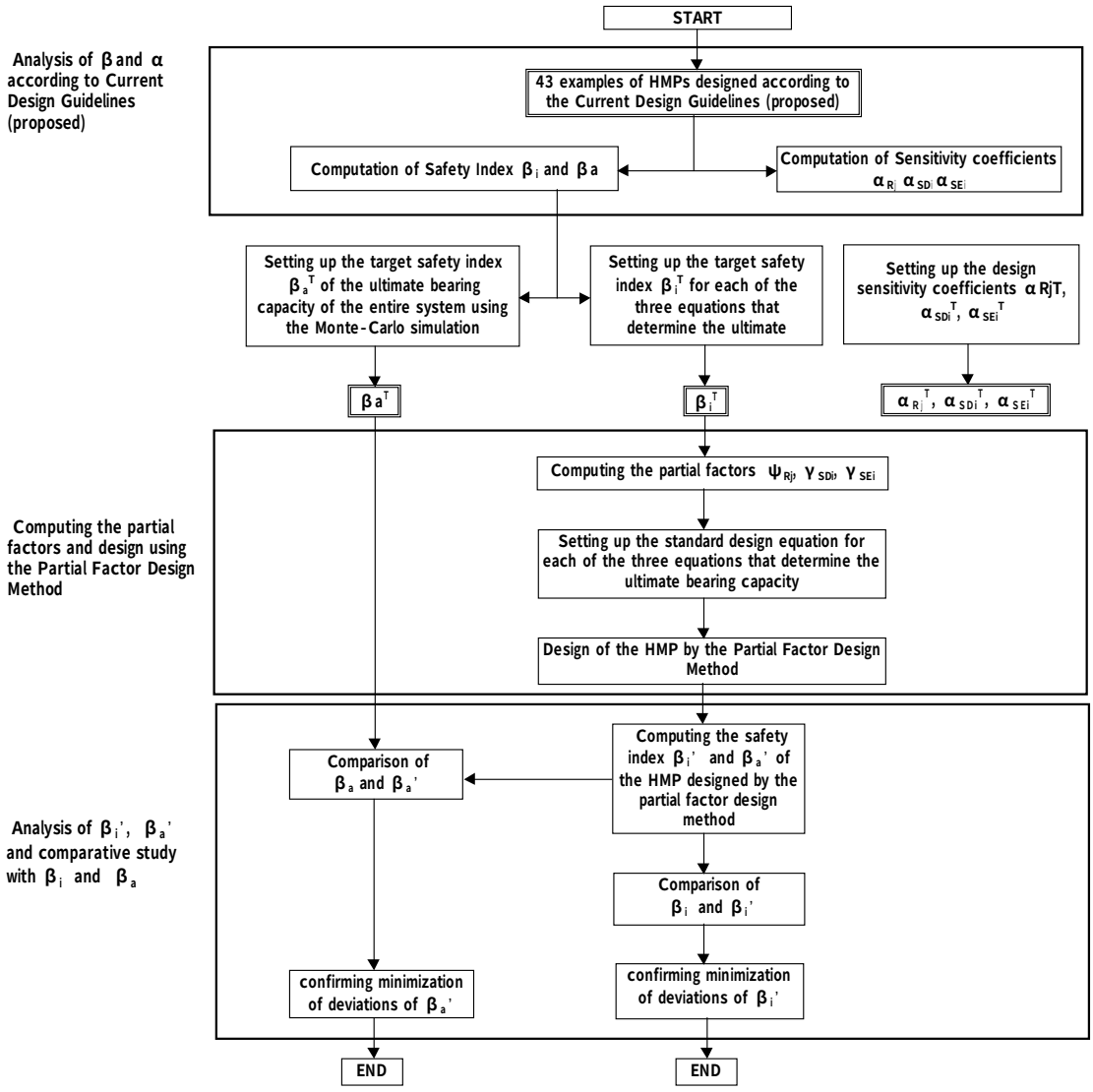

Figure-2 Reliability Analysis of the Push-in Bearing Capacity of the HMP

which different safety coefficients are given to multiple design loads and strengths, and it is employed in Europe and the USA, where globalization of the technology standards for performance/quality design has started. The aims of this paper are: (1) as shown in Figure 2, to carry out a reliability analysis on an actual HMP that was designed based on the Current Design Guidelines (proposed), and to examine the fluctuations in the reliability level of the HMP for this case; (2) to introduce design standards for Partial Factor Design and determine partial factors in compliance with the reliability levels shown in (1); and (3) to make a comparative study of the safety index between examples computed using the Current Design Guidelines, and examples computed using Partial Factor Design, and to demonstrate that Partial Factor Design can produce superior results.

2. Current Design Guidelines (proposed) and their problems

(1) Push-in bearing capacity in the Current Design Guidelines (proposed) and critical conditions

The allowable push-in bearing capacity of an HMP, R_{ca} is given by equation (1) below, according to the Current Design Guidelines (proposed) in the Design and Construction Manual on High-Capacity Micro Piles (proposed). The ultimate push-in bearing capacity, R_{cu} given in equation (2), is computed from the minimum values of the three bearing capacities for the corresponding critical conditions.

$$R_{ca} = \frac{rR_{cu}}{n} \quad (1)$$

r: correction coefficient for the safety factor due to the different assumptions in the method used for the ultimate bearing capacity

n: safety factor

$$R_{cu} = \min[R_{C1}, R_{C2}, R_{C3}] \quad (2)$$

R_{c1}: ultimate frictional bearing capacity

R_{c2}: compression strength of the steel pipe section of the pile

R_{c3}: sum of the ultimate compression strength of the non-steel section of the pile and the ultimate frictional resistance of the steel pipe section of the pile

The three critical conditions: condition 1 ($Z_1 \leq 0$); condition 2 ($Z_2 \leq 0$); and condition 3 ($Z_3 \leq 0$) corresponding to R_{c1}, R_{c2} and R_{c3} are described conceptually in Figure 3, Figure 4, and Figure 5. Z_i (i=1,2, and 3) is the performance function of equation (14), equation (15) and equation (16), and $Z \leq 0$ defines the occurrence of the critical condition i.

Figure 6 shows the resisting forces R_1 to R_7 of the HMP against the push-in bearing capacity.

Critical condition 1 is a state where

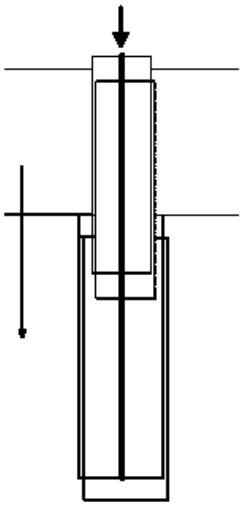

Figure 3
Conceptual Diagram of Limit State 1

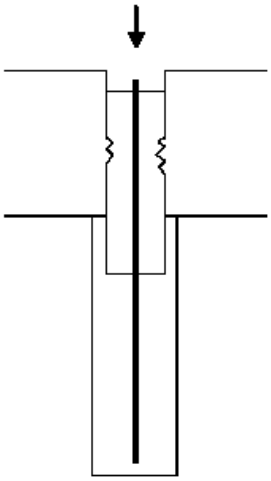

Figure 4
Conceptual Diagram of Limit State 2

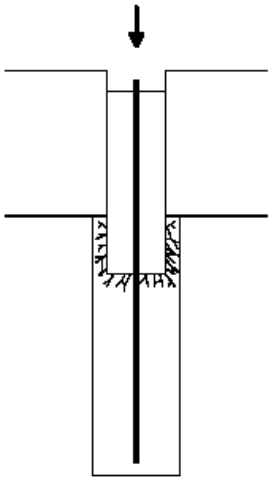

Figure 5
Conceptual Diagram of Limit State 3

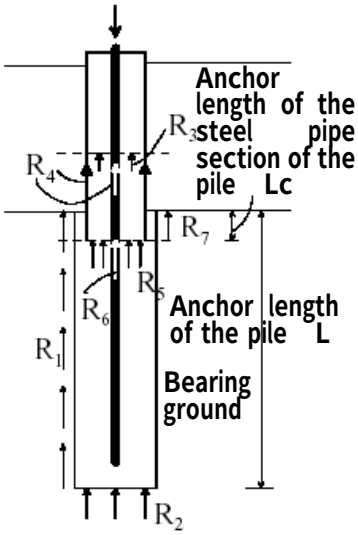

Figure 6
Outline Diagram of Each Resisting Force of the HMP

settlement is caused by insufficient bearing capacity of the ground. The force the HMP exerts in resisting this is a combination of the frictional force of the area surrounding the fixed pile, R_1 and the bearing capacity of the deepest bottom of the pile, R_2. Therefore, R_{c1} is expressed as the sum of R_1 and R_2, i.e., as the bearing capacity for critical condition 1, given in equation (5).

$$R_1 = \pi a D_0 \sum \tau_i L_i \quad (3)$$

$$R_2 = q\pi \frac{D_0^2}{4} \quad (4)$$

$$R_{C1} = R_1 + R_2 \quad (5)$$

a: correction coefficient for the pressurization effect of the grout

D_o: diameter of drill hole

τ_i: Frictional Strength of the perimeter surface of layer (i) of the anchor section that is affected by the frictional forces at the perimeter surface

L_i : Thickness of layer (i) that is affected by the frictional forces at the perimeter surface

q : Ultimate bearing stress per unit area determinable by the subject ground

According to the Current Design Guidelines (proposed) on HMPs, the ultimate frictional bearing capacity R_{c1} is computed using an equation similar to the one for the ultimate push-in bearing capacity of frictional piles shown in the Design and Construction Guidelines for Roads and Bridges.[13)]

According to the Current Design Guidelines (proposed) for HMPs, the bearing capacity of the bottom section of the small diameter type HMP can be discounted because it is considered that the frictional forces at the perimeter surface R_1 alone constitute a sufficient part of the ultimate strength of the bearing capacity for a more conservative

safety factor. However, this paper takes into account the bottom bearing capacity R_2 and adds it to the ultimate frictional bearing capacity R_{c1}, in order also to further examine the behavior of R_2.

Critical Condition 2 shows a compression failure in the steel pipe section of the pile, where the forces of resistance that the HMP generates against this failure consist of the ultimate compression strength of the grout in the steel pipe section of the pile, R_3 and the ultimate compression strength of the reinforcing bars and steel pipe, R_4. R_{c2} is expressed by equation (8).

$$R_3 = 0.85 f_G A_{G1} \quad (6)$$

$$R_4 = F_{BorC}(A_B + A_C) \quad (7)$$

$$R_{C2} = R_3 + R_4 \quad (8)$$

f_G: Compression strength of grout 28 days after placement

A_{G1}:Effective design sectional area of the grout for the steel pipe section of the pile

$F_{B\ or\ C}$: The lesser of either F/B or F/C

F/B is the yield strength of the core reinforcing bar

F/C is the yield strength of the steel pipe

A_B : Sectional area of the core reinforcing bar

A_C : Sectional area of the steel pipe

The constant value 0.85 in equations (6) and (9) is the maximum ratio of concrete stress to compression strength f_G for standard samples.

Critical Condition 3 shows a compression failure in the non-steel section of the pile. The HMP generates resisting forces R_5, R_6 and R_7. R_5 is the ultimate compression strength of the grout in the non-steel section of the pile. R_6 is the ultimate compression strength of the reinforcing bar, and R_7 is the frictional force at the perimeter surface of the anchor part of the steel section of the pipe. Thus R_{c3} is expressed by equation (12).

$$R_5 = 0.85 f_G A_{G2} \quad (9)$$

$$R_6 = f_B A_B \quad (10)$$

$$R_7 = \pi a D_0 \sum \tau_i L_{Ci} \quad (11)$$

$$R_{C3} = R_5 + R_6 + R_7 \quad (12)$$

A_{G2} : Effective design sectional area of the grout in the non-steel section of the pile

f_B : Yield strength of the core reinforcing bar

τ_i : Frictional strength at the perimeter surface of layer (i) that is considered to be affected by the frictional forces at the perimeter surface of the anchor part of the steel pipe section of the pile

L_{Ci} : Thickness of the layer that is affected by the frictional forces at the perimeter surface of the anchor part of the steel pipe section of the pile

In most cases, Critical Condition 1 will determine the ultimate push-in bearing capacity. However, according to equation (1), the allowable push-in bearing

capacity R_{ca} is computed with the single safety factor n, although the ultimate push-in bearing capacity R_{cu} changes with R_{c1}, R_{c2}, and R_{c3}.

In this way, the Current Design Guidelines (proposed) do not distinguish between the fluctuation levels of uncertain elements in the strength of the pile body itself, the frictional forces at the perimeter surface against the ground, and the operating load. The Guidelines simply use a single safety factor. We believe that by giving differentiated safety factors corresponding to each category of fluctuation level, significant improvements can be made to enhance safety levels.

In view of the above considerations, this paper attempts to apply the Partial Factor Design Method, which gives differentiated safety factors to each characteristic value of load and strength.

(2) Partial Factor Design Method

Performance functions Z and Z_i corresponding to the entire system and to

$$Z = \min[R_{C1}, R_{C2}, R_{C3}] - S_D - S_E \quad (13)$$

$$Z_1 = R_1 + R_2 - S_D - S_E \quad (14)$$

$$Z_2 = R_3 + R_4 - S_D - S_E \quad (15)$$

$$Z_3 = R_5 + R_6 + R_7 - S_D - S_E \quad (16)$$

each of the Critical Conditions are defined in the following equations (13), (14), (15), and (16):

$Z, Z_i > 0$ Safe

$Z, Z_i \leq 0$ Failure

S_D : Dead Load S_E : Earthquake Load

Equations (17), (18) and (19) can be used as the design standard equations by

$$\phi_{R1} R_1^* + \phi_{R2} R_2^* \geq \gamma_{SD1} S_D^* + \gamma_{SE1} S_E^* \quad (17)$$

$$\phi_{R3} R_3^* + \phi_{R4} R_4^* \geq \gamma_{SD2} S_D^* + \gamma_{SE2} S_E^* \quad (18)$$

$$\phi_{R5} R_5^* + \phi_{R6} R_6^* + \phi_{R7} R_7^* \geq \gamma_{SD3} S_D^* + \gamma_{SE3} S_E^* \quad (19)$$

using partial factors for the performance function Z_i.

R_j^* : Characteristic Value of each resisting force

(j=1,2,3,4,5,6, and 7)

S_D : Characteristic value of the dead load

S_E : Characteristic value of the earthquake load

In order to make equations (14), (15) and (16) and equations (17),(18), and (19) equivalent to each other, partial factors ϕ_{Rj}, γ_{SDi}, γ_{SEi} are derived with reference to Reliability Design Practice[10],

$$\phi_{Rj} = \frac{1 - \alpha_{Rj}^T \beta_i^T V_{Rj}}{1 - k_{Rj} V_{Rj}} \quad (20)$$

$$\gamma_{SDi} = \frac{1 + \alpha_{SDi}^T \beta_i^T V_{SD}}{1 + k_{SDi} V_{SD}} \quad (21)$$

$$\gamma_{SEi} = \frac{1 + \alpha_{SEi}^T \beta_i^T V_{SE}}{1 + k_{SEi} V_{SE}} \quad (22)$$

as shown below. Details of partial factor introduction are given in Appendix.

α_{Rj}^T : Design sensitivity coefficient for each resisting force

β_i^T : Target safety index for Z_i

K_{Rj} : Average coefficient for each resisting

force and characteristic values

V_{Rj} : Fluctuation coefficient for each resisting force

α_{SDi}^{T} : Design sensitivity coefficient for the dead load

V_{SD} : Fluctuation coefficient for the dead load

k_{SDi} : Average dead load coefficient and characteristic values

α_{SEi}^{T} : Design sensitivity coefficient for the earthquake load

V_{SE} : Fluctuation coefficient for the earthquake load

k_{SEi} : Average earthquake load coefficient and characteristic values

Design sensitivity coefficients α_{Rj}^{T}, α_{SDi}^{T}, α_{SEi}^{T} are determined in order to save computational time and costs, and the coefficients are derived from the distributions of α_{Rj}, α_{SDi}, and α_{SEi} [16]. α_{Rj}, α_{SDi}, and α_{SEi} are given by equations (23), (24), and (25). The coefficients show the ratio of the individual standard deviations of the probability variables that contribute to

$$\alpha_{Rj} = \frac{\sigma_{Rj}}{\sigma_{Zi}} \qquad (23)$$

the value of the standard deviation of the performance function Z_i.

Here, referring to equations (14), (15) and (16), when (i) = 1, j = 1, 2. Similarly, when (i) = 2, j = 3, 4; and when (i) = 3, j = 5, 6, 7.

$$\alpha_{SDi} = \frac{\sigma_{SDi}}{\sigma_{Zi}} \qquad (24)$$

The target safety index β_i^{T} is to ensure safety by specifying the target value of β_i and is given by the following formula.

$$\beta_i = \frac{\mu_{Zi}}{\sigma_{Zi}} \qquad (26)$$

Here, μ_{Zi} is the expected value of Z_i or the average of Z_i.

In Partial Factor Design, appropriate consideration must be given to determining the target safety index, the design sensitivity coefficient, and the fluctuation coefficient.

3. Characteristics of the Push-in Bearing Capacity

In order to clarify the probabilistic nature of the push-in bearing capacity, this section examines how the bearing capacity is influenced by changes in factors such as ground type and pile length.

The following variables are chosen as probability variables, with a large magnitude of uncertainty: τ_i, q, f_G, f_B, f_C, S_D, S_E. Table 2 shows the chosen probability variables. The fluctuation coefficient τ_i does not depend on the layer, and is given as 0.45 in reference to the relationships of the fluctuations in the N-value.[15] Therefore R_1 in equation

Table 2 Nature of Probability

Probability variable	Average / Characteristic values	Fluctuation coefficient V	Distribution shape	References
τ_i	1.0	0.45	normal distribution	17
q	1.0	0.45	normal distribution	
f_G	1.0	0.30	normal distribution	18, 19
f_B	1.0	0.03	normal distribution	20
f_C	1.0	0.03	normal distribution	
S_D	1.0	0.10	normal distribution	21
S_E	1.0	0.66	normal distribution	

(3) is a linear equation in τ_i. τ_i is normally determined based on data obtained through sounding experiments, and for this reason the fluctuation coefficient R_1 is set at 0.45 as in the case of the N-value.

R_2 is also a linear equation in q, and q is set at 0.45 for the same reason. Similarly, the fluctuation coefficients f_G, f_B, f_C, S_D, S_E are determined referring to documents[16),17)] and the fluctuation coefficients R_3～R_6 are derived. Based on the documents, all the probability variables are assumed to be normally distributed, although a rigorous analysis has not been carried out.

According to the Current Design Guidelines (proposed), the correction coefficient a is set at 1.00, 1.25, and 1.50, depending on the method used to pour the grout. Here, an average value of 1.25 is chosen. The dead load S_D and the earthquake load S/E operating on the pile are set at 400 (kN), the average value of each load, considering that the allowable bearing capacity in the event of an earthquake is some 1000 (kN), and that the average operating load should be significantly less than this.[9)]

First, Critical Condition 1 is examined based on the specific conditions assumed in actual cases. In Critical Condition 1, the anchor length L and the ground type are considered to be the most influential factors in determining the push-in bearing capacity. The three main types of material used for HMP; sand (τ_i= 3N/mm^2), gravel (τ_i= 5N/mm^2), and mudstone (τ_i= 7N/mm^2) are chosen and the changes in the sensitivity coefficients α_{R1}, and α_{R2} are studied with ground that has a uniform N-value of 50 for varied anchor lengths, L. Figure 7 shows the relationship between L on the

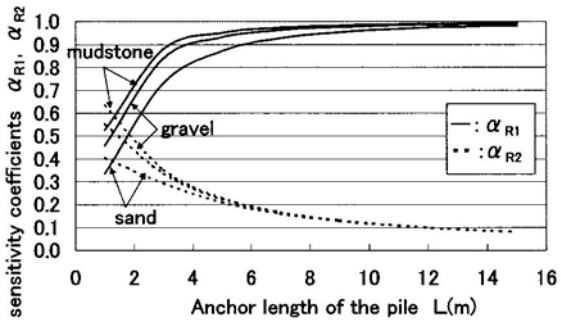

Figure 7
Effect of anchor length on sensitivity coefficients in different types of ground

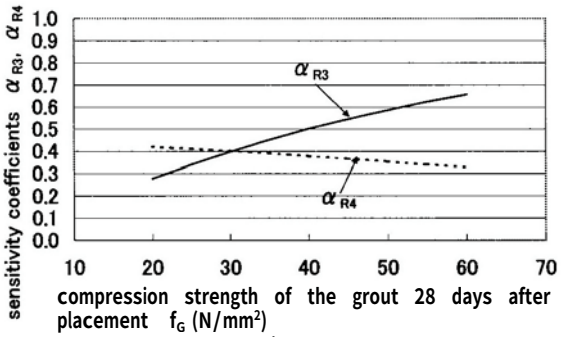

Figure 8
Effect of compression strength of the grout on sensitivity coefficients 28 days after placement

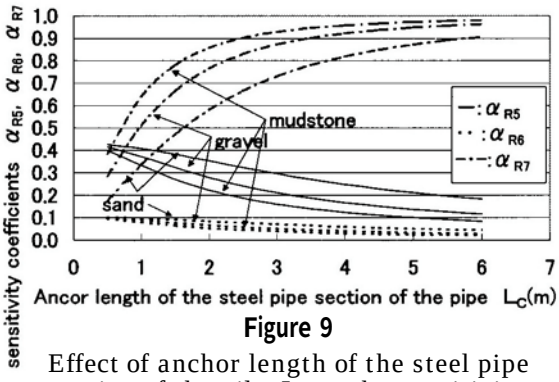

Figure 9
Effect of anchor length of the steel pipe section of the pile, L_c on the sensitivity coefficients for different types of ground

horizontal axis and α_{R1} and α_{R2} on the vertical axis.

Figure 7 shows that regardless of the ground type or anchor length, α_{R1} is always dominant. Namely in Critical Condition 1 , R_1 is considered to be an influential factor in determining the push-in bearing capacity.

Next, Critical Condition 2 is analyzed. The Current Design Guidelines (proposed) stipulate that steel pipes and irregularly-shaped reinforcing bars used for HMPs should meet the shape specifications shown in Table 1. Regarding the characteristics for Critical Condition 2, the compression strength of the grout 28 days after placement f_G is chosen as the major factor, and its relationship with the sensitivity coefficients α_{R3} and α_{R4} is studied. The results are shown in Figure 8.

According to the Current Design Guidelines (proposed), in order to fully utilize the performance of the core reinforcing bar, it is recommended that cement milk or mortar of 30 (N/mm^2) or more be used to obtain the required value for f_G.

In the domain where f_G reaches 30 (N/mm^2) or more, α_{R3} becomes dominant, and R_3 is considered to be an influential factor in the push-in bearing capacity under Critical Condition 2.

Our analysis of Critical Condition 3 was also carried out for three types of ground as for Critical Condition 1. Equation (12) shows that only R_7 is affected by the ground conditions. The relationships between the anchor length of the steel pipe L_C and the sensitivity coefficients α_{R5}, α_{R6}, α_{R7} are shown in Figure 9.

Figure 9 indicates that regardless of the ground type, α_{R7} increases with L_C. The Current Design Guidelines (proposed) stipulate that the minimum required length of L_C is 1 meter in order for the axial force of the pipe to be transmitted to the grout in a stable way.[9]. Where L_C is 1 meter or more, α_{R7} is always the largest sensitivity coefficient except for sandy ground. Even in sandy ground, from near the point 1.2 meters or more, α_{R7} becomes the largest sensitivity coefficient. Therefore under Critical Condition 3, α_{R7} is the most influential factor in determining the push-in bearing capacity.

4. Determining the Target Safety Index and Design Sensitivity Coefficients

The target safety index β_a^T, β_i^T and the design sensitivity coefficients α_{Rj}^T, α_{SDi}^T, and α_{SEi}^T are determined as follows: first the ground conditions are specified referring to the documents [12),17),18),19)] and 43 HMP samples are designed in Table 3 according to the Current Design Guidelines (proposed). The anchor ground is classified into the three categories: sand, gravel, and mudstone. A reliability analysis is carried out on these

Table 3 Pile lengths and ground conditions for the 43 HMP

sample NO.	Dimensions (m) of the pile		Thickness of the anchor ground Li (m)		Frictional strength (N/mm2)		Strength of material and correction coefficient		External force (kN)	
	L	Lc	L_1	L_2	τ_1	τ_2	a	f_G (N/mm^2)	S_D	S_E
1	9.0	1.2	4.9	4.1	3.5	4.4	1.50	32.0	343.6	351.3
2	8.0	1.3	4.4	3.6	3.9	5.1	1.50	35.5	310.7	430.4
3	10.0	1.1	8.0	—	5.9	-	1.50	32.1	411.9	361.6
4	9.0	1.2	7.5	1.5	3.9	4.9	1.50	36.0	468.8	382.0
5	7.4	1.0	7.4	—	4.4	-	1.00	38.1	483.7	415.9
6	7.7	1.5	7.7	—	5.5	-	1.25	40.0	331.2	397.9
7	7.5	1.7	3.5	4.0	4.4	5.4	1.25	32.0	394.9	422.3
8	7.1	1.1	4.0	3.1	3.9	6.4	1.00	31.4	372.0	393.1
9	7.0	1.4	4.0	3.0	4.4	6.9	1.25	38.1	345.5	440.5
10	7.1	1.2	5.0	2.1	4.4	6.4	1.00	31.8	439.7	437.7
11	7.6	2.0	7.6	—	4.4	-	1.00	37.1	311.6	384.8
12	7.6	1.9	3.6	4.0	3.9	5.9	1.00	32.4	403.8	407.0
13	7.1	1.7	5.9	1.2	3.7	5.9	1.00	31.2	408.1	437.2
14	9.0	1.6	6.2	2.8	3.5	4.9	1.50	31.5	452.7	427.1
15	8.5	1.3	4.5	4.0	4.4	5.6	1.25	41.4	410.0	371.8
16	9.0	1.6	6.4	2.6	3.9	4.4	1.25	36.6	394.3	383.6
17	7.9	1.3	5.6	2.3	4.4	4.9	1.25	35.6	465.8	393.5
18	8.0	1.3	5.0	3.0	3.7	4.9	1.00	32.5	489.0	420.4
19	7.1	1.1	7.1	—	3.9	-	1.25	37.3	436.3	396.3
20	6.9	1.6	1.4	5.5	4.2	5.8	1.00	32.9	483.5	352.2
21	7.6	1.2	4.0	3.6	4.0	5.9	1.00	32.1	352.2	385.4
22	7.0	1.9	4.7	3.2	4.9	5.7	1.00	34.7	377.5	425.8
23	8.1	1.0	8.1	—	4.1	-	1.25	39.0	470.3	418.7
24	7.6	1.7	4.6	3.0	4.7	5.3	1.50	39.9	422.0	361.8
25	7.0	1.5	3.4	3.6	4.9	5.9	1.00	31.8	470.7	419.5
26	7.4	1.2	2.7	4.7	3.9	4.9	1.00	41.4	482.5	360.8
27	8.6	1.6	8.6	—	3.9	-	1.25	39.5	326.3	399.8
28	7.1	1.6	1.2	5.9	4.0	4.4	1.25	31.8	462.2	373.8
29	7.4	1.7	7.4	—	5.5	-	1.25	33.5	471.7	383.4
30	7.3	1.7	2.8	4.5	4.4	5.3	1.25	40.2	351.6	440.2
31	7.3	1.5	7.3	—	2.9	-	1.50	40.2	365.3	401.6
32	10.6	3.7	7.7	2.9	1.3	3.4	1.50	30.0	310.7	411.9
33	11.1	3.9	10.0	1.1	1.4	6.8	1.50	38.9	483.7	331.2
34	12.9	3.1	5.0	7.9	2.5	2.5	1.50	35.1	372.0	345.5
35	9.9	1.5	6.0	3.9	1.8	2.6	1.50	37.4	311.6	403.8
36	10.2	1.9	1.9	8.3	3.1	3.1	1.50	35.8	452.7	410.0
37	11.6	3.3	6.0	5.6	2.0	2.6	1.50	37.3	483.5	352.2
38	11.1	4.7	15.0	—	2.6	-	1.50	34.3	470.3	422.0
39	18.0	5.0	5.0	13.0	2.1	2.1	1.50	39.0	482.5	326.3
40	7.5	1.2	2.0	5.5	2.2	3.4	1.50	39.4	375.3	354.5
41	6.9	1.6	4.0	2.9	1.2	6.7	1.50	35.1	371.5	448.8
42	9.1	2.8	7.5	1.6	2.1	6.1	1.50	36.9	400.7	410.1
43	4.8	1.5	1.1	3.7	6.5	6.5	1.50	30.9	413.5	378.7

43 samples and their distributions are studied.

In this section, the probability variables are τ_i, q, f_G, f_B, f_C, S_D, S_E and the same values are assumed for the fluctuation coefficients, the same as in the preceding section. With the above considerations, the distribution of the safety index is examined and valid target safety index values are determined.

(1) Determining the target safety index β_a^T, and β_i^T

In order to determine the target safety index β_a^T for the entire system, the distribution of the safety index β_a for the 43 HMP samples is examined. First, the failure probability P_f for the entire system is derived by the Monte Carlo simulation method[10] for the 43 HMP samples. The Monte Carlo simulation method is a numerical experiment that

repeats an experiment a number of times using random numbers to determine the probability of a failure. The Monte Carlo simulation method defines the failure probability P_f as the number of failures divided by the number of trials, providing that the number of trials is at least 300000.

The number of failures depends on the three Critical Conditions, 1, 2, and 3. β and β_a are derived from equation (27) showing the relation between P_f, and a histogram of β_a is drawn as shown in Figure 10.

$$P_f = 1 - \Phi(\beta) \qquad (27)$$

$\phi(\beta)$ is the probability function for a normal distribution with a mean of zero and a standard deviation of 1.0. In the histogram in Figure 10, the mean of β_a, i.e. $\mu_{\beta a}$, and the standard deviation $\sigma_{\beta a}$ are computed as 1.79 and 0.12 respectively. This paper sets up the target safety index in a more strict way and β_a^T is set to 1.85, the sum of $\mu_{\beta a}$ and $\sigma_\beta/2$ in order that the safety criteria in the Current Design Guidelines (proposed) are compatible with the present paper, although the number 1.85 may need further justification.

Next, the safety index β_i is computed from equation (26) for the 43 HMP

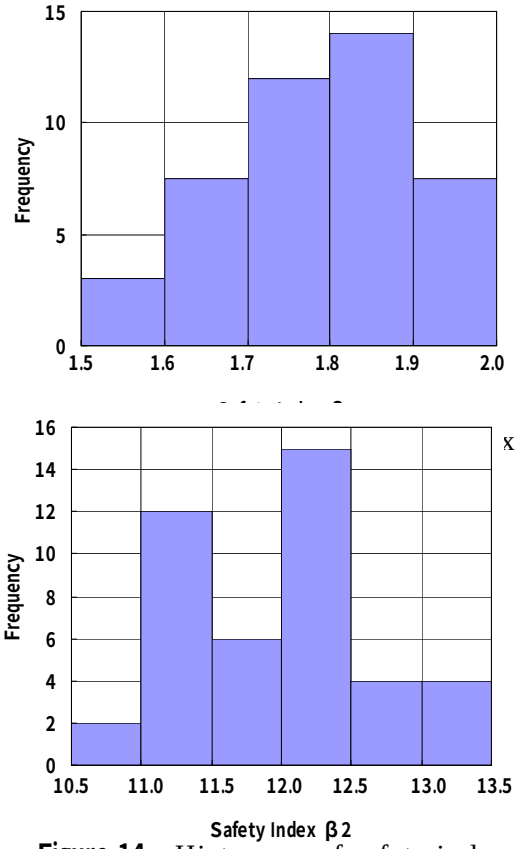

Figure 14 Histogram of safety index β_2 for Critical Condition 2

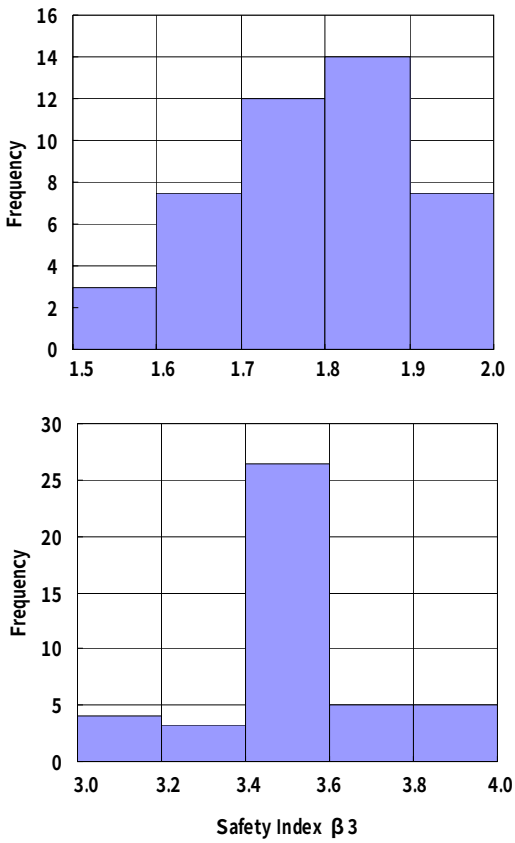

Figure 13 Histogram of safety index β_3 for Critical Condition 3

samples and the histograms in Figures 11, 12, and 13 show the distribution for each condition. Comparing Figure 11 to Figure 10, β_a for the entire system is determined by Critical Condition 1. However, there is a difference between β_a and β_1 due to the difference in the method used for the Monte Carlo simulation, to the theoretical equations used, and to the effects of Critical Condition 3 onto β_a.

A closer look at the distribution of β_2, show that it is extremely large compared to β_1 and β_3. Thus sufficient safety is ensured. Critical Condition 2 presents no dominant factors affecting the push-in bearing capacity, and a detailed examination was not made. From here on, the critical condition is neglected. Though β_3 is larger than β_1, this paper employs 5.0 as the safety index, in line with European standards for the allowable safety index. Our detailed examination is made up to this level. From here on, Critical Condition 3 is examined.

The target safety indexes β_1, β_3, β_1^T, β_3^T are determined in the same way as for β_a^T. Table 4 shows the target safety indexes β^T, β_1^T, and β_3^T thus determined.

Table 4 Target safety index

β_a^T	1.85
β_1^T	1.85
β_3^T	3.62

(2) Determining the design sensitivity coefficients α_j^T, α_{SD}^T, α_{SE}^T

The sensitivity coefficients α_{R1}, α_{R2}, α_{SD1}, α_{SE1} for Critical Condition 1 for the 43 HMP samples are computed using equations (23), (24), and (25). The ultimate bearing capacity R_{c1}* and its relationship to the sensitivity coefficients is examined, with the results shown in Figure 14. The figure shows the trend lines. Taking a closer look at the lines, the gradients of all the lines are moderate, and the sensitivity coefficients make small changes with changes in the magnitude of R_{c1}*. Therefore, this paper determines the design sensitivity coefficients α_{R1}^T, α_{R2}^T, α_{SD1}^T, α_{SE1}^T as the average of the values of α_{R1}, α_{R2}, α_{SD1}, α_{SE1}, which are computed from the

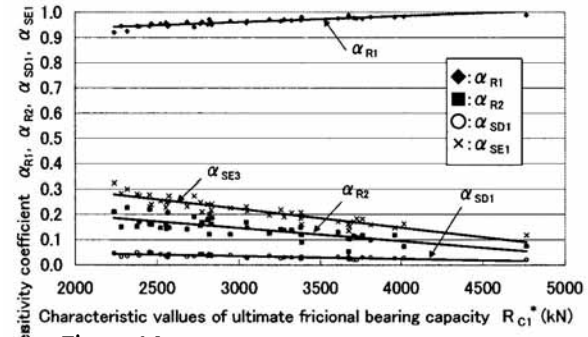

Figure 14 Relationship between sensitivity coefficient and R_{c1}*

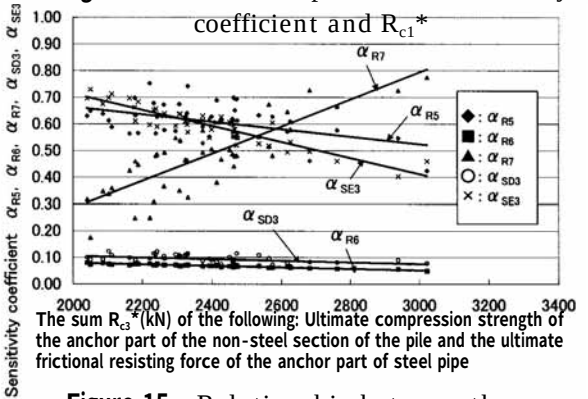

Figure 15 Relationship between the sensitivity coefficient and R_{c3}*

43 HMP samples. It is noted that the

value of $\alpha_{SE1}{}^{T}$ is arranged so that the total sum of the following should exceed 1.0 by some amount: ($\alpha_{R1}{}^{T}$) raised to the power of 2, ($\alpha_{R2}{}^{T}$) raised to the power of 2, ($\alpha_{SD1}{}^{T}$) raised to the power of 2, and ($\alpha_{SE1}{}^{T}$) raised to the power of 2.

This is because that the safety index is over-evaluated when the sum of the sensitivity coefficients, each raised to the power of 2, exceeds 1.0.

For Critical Condition 3, we examined the relationship between the sensitivity coefficients α_{R5}, α_{R6}, α_{R7}, α_{SD3}, α_{SE3} and the sum of the ultimate compression strength of the anchor part of the non-steel section of the pile and the ultimate frictional resisting forces of the anchor part of the steel pipe section of the pile. The results are shown in Figure 15. Looking at the trends for α_{R7} and α_{SE3}, the gradient is significantly steep. Namely, the sensitivity coefficients α_{R7} and α_{SE3} are influenced by the magnitude of R_{C3}*. Therefore the design sensitivity coefficients $\alpha_{R7}{}^{T}$ and $\alpha_{SE3}{}^{T}$ are fixed by classifying the magnitude of R_{C3}* into several categories because of this influence. It is noted that $\alpha_{R5}{}^{T}$, $\alpha_{R6}{}^{T}$, $\alpha_{SD3}{}^{T}$ are set as the average of the sensitivity coefficients computed from the 43 HMP samples, due to the small gradient of the sensitivity lines. $\alpha_{SD3}{}^{T}$ is determined as in the case of $\alpha_{SE1}{}^{T}$.

Table 5 shows the design sensitivity coefficients thus determined.

5 Designing an HMP by the Partial Factor Design Method

(1) Designing an HMP by the Partial Factor Design Method

In this section, partial factors ϕ_{Rj}, γ_{SDi}, γ_{SEi} are computed and the 43 HMP samples are designed using the Partial Factor Design Method. They are then compared with the results shown in the last section, where the same samples were designed using the Current Design Guidelines (proposed).

Table 6 shows the results for the partial factors, ϕ_{Rj}, γ_{SDi}, γ_{SEi} computed from equations (20), (21) and (22), using the values for the fluctuation coefficients V_{Rj}, V_{SD} and V_{SE} fixed in section 3, and values for the target safety index $\beta_i{}^{T}$ and design sensitivity coefficients $\alpha_j{}^{T}$, $\alpha_{SDi}{}^{T}$, $\alpha_{SEi}{}^{T}$ determined in the last section. It is noted

Table 5 Design sensitivity coefficient

$\Phi_{R1}{}^{T}$	$\Phi_{R2}{}^{T}$	$\gamma_{SD1}{}^{T}$	$\gamma_{SE1}{}^{T}$
0.963	0.142	0.034	0.24

R_{C3}*(kN)	$\Phi_{R5}{}^{T}$	$\Phi_{R6}{}^{T}$	$\Phi_{R7}{}^{T}$	$\gamma_{SD3}{}^{T}$	$\gamma_{SE3}{}^{T}$
～2600	0.610	0.069	0.267	0.094	0.74
2600～			0.567		0.545

Table 6 Partial Factors

Φ_{R1}	Φ_{R2}	γ_{SD1}	γ_{SE1}
0.198	0.882	1.006	1.293

R_{C3}*(kN)	Φ_{R5}	Φ_{R6}	Φ_{R7}	γ_{SE1}	γ_{SE1}
～2600	0.338	0.992	0.566	1.034	2.768
2600～			0.076		2.302

that an average is taken of the individual values.

Comparing the safety factor under the Current Design Guidelines with the partial factors here, the safety factor on the side of the bearing capacity is uniformly 0.5 in the Guidelines, imposing severe restrictions on design, while the partial factor ϕ_{R1} of the main bearing capacity R_1* in Critical Condition 1 is 0.198, giving much more freedom. Also in Critical Condition 3, a similar difference is found in the domain where R_{C3}* is 2600kN or more, although there is no difference between the safety factor and ϕ_{R7} when R_{C3}* is 2600kN or less.

Next the same 43 sample HMPs are designed using the partial factors ϕ_{Rj}, γ_{SDi}, γ_{SEi} and the design standard equations (17) and (19). In Critical Condition 1, the design variable is assumed to be the anchor length L, and in Critical Condition 3, the design variable is assumed to be the anchor length of the steel pipe.

In designing the anchor length L, an inequality is formed for L by substituting the characteristic values of each element, i.e. the average values, into the design standard equation (17). Then, giving an initial value of 0.1 meters to L and extending the length of the bearing ground in 0.1 meter increments, the minimum length of L that satisfies the inequality can be computed, and the minimum length thus obtained is fixed as the anchor length L' designed by the Partial Factor Design Method.

Similarly, L_c is designed by substituting the characteristic values of each element except L_c into the design standard equation (19) and by forming an inequality. The initial value of L_c is set as 0.1 meters and is incremented by 0.1 meters, and the minimum value of L_c that satisfies the inequality is computed and is taken as the anchor length of the steel pipe designed by the Partial Factor Design Method. However, note that in order to be compatible with the Current Design Guidelines (proposed), the minimum length L_c' is set at 1.0 meters to follow the requirement in the Guidelines that the axial force of the steel pipe must be transmitted to the grout in a reliable way.

The safety indexes β_i', β_a' are computed in order to examine the degree of safety of the HMP designed by the Partial Factor Design Method, as in section 4.

(2) Study on the safety of HMPs designed by the Partial Factor Design Method

A comparison is made with regard to the safety of the HMP between the Current Design Guidelines (proposed) and the Partial Factor Design Method. This is done by showing the distribution of β_i', and β_a' for each Critical Condition. Note, however that β has some deviations because β is varied with each individual HMP designed according

to the Current Design Guidelines (proposed). On the other hand β' has less deviation because β' is computed by applying partial factors to each element of load/intensity for β^T. Figure 16 compares β_1 and β_1' and Figure 17 compares β_3 and β_3'.

According to Figure 16, β_1' is more concentrated at the target safety index of Critical Condition 1, β_1^T than β_1 is.

Meanwhile, Figure 17 shows that no difference was found in the safety index between β_3 and β_3', although β_3' shows large deviations. The wide deviations are thought to be due to the fact that Critical Condition 3 does not impose a critical impact and the dimensions of the HMP cannot be determined.

For the HMP designed by the Partial Factor Design Method, Figure 18 shows a comparison between β_a', which is the safety index of the entire system derived in the same method as in section 4, and β_a. Figure 18 shows that β_a' has fewer deviations than β_a and β_a' is more concentrated at β_a^T. It follows that the HMP designed by the Partial Factor Design Method ensures sufficient safety for the push-in bearing capacity.

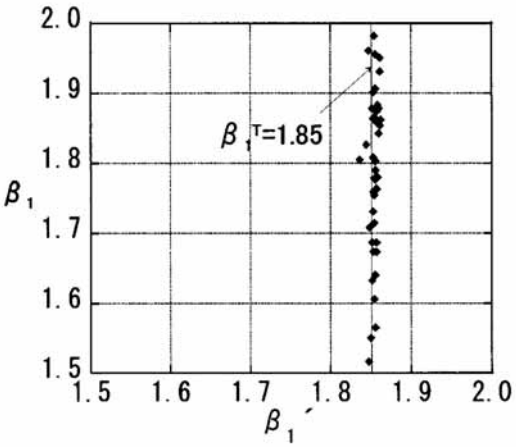

Figure 16 Comparison of β_1 and β

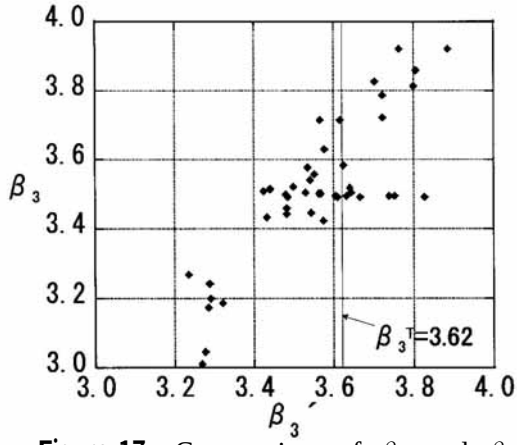

Figure 17 Comparison of β_3 and β_3'

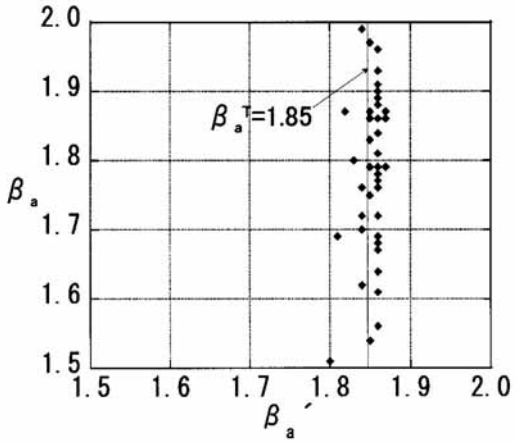

Figure 18 Comparison of β_a and β

6. Summary and Conclusions

Having studied the uncertainty in the component elements of the push-in bearing capacity for three critical conditions based on probability theory, and having also examined the use of the Partial Factor Design Method in HMP design, we have reached the following conclusions:

(1) The safety indexes β_a and β_i for the

push-in bearing capacity of an HMP designed by the Current Design Guidelines and the sensitivity coefficients α_{Rj}, α_{SDi}, α_{SEi} were computed and their distributions were clarified. It was established that a detailed examination is not required for critical condition 2, because the condition does not have a critical impact.

(2) The target safety indexes β^T and β_i^T and the design sensitivity coefficients α_{Rj}^T, α_{SDi}^T, α_{SEi}^T were determined using the results in (1) above. The HMP samples were designed by the Partial Factor Design Method. The safety indexes β_a', β_i' were computed and their distributions were compared. It was confirmed that except for β_3', β_a' and β_i' are concentrated at β_a^T and β_1^T respectively. It was also clarified from a comparison of the distributions of β_3 and β_3' that a detailed examination is not required for critical condition 3, because the condition does not have a critical impact.

(3) It was clarified that a detailed examination is not required for critical conditions 2 and 3 in determining the push-in bearing capacity of the HMP, and that a detailed examination for critical condition 1 alone is sufficient. Namely as shown in Figure 16, the distribution of β_1' is concentrated at β_1^T and a dependable level of safety can secured with due consideration to the uncertainty of each e

$$\beta_1 \geq \beta_1^T \qquad (A\cdot4)$$

Factor Design Method.

(4) For the c

$$\frac{1-\alpha_{R1}\beta_1^T V_{R1}}{1-k_{R1}V_{R1}}R_1^* + \frac{1-\alpha_{R2}\beta_1^T V_{R2}}{1-k_{R2}V_{R2}}R_2^* \geq \frac{1+\alpha_{SD1}\beta_1^T V_{SD}}{1+k_{SD1}V_{SD}}S_D^* + \frac{1+\alpha_{SE1}\beta_1^T V_{SE}}{1+k_{SE1}V_{SE}}S_E^* \qquad (A\cdot12)$$

the sections
Design is c
analysis flo
should be

application is chosen for the 43 HMP samples, their loads, and the characteristics of the ground. It follows that the application of the Partial Factor Design Method should be limited to within a certain framework. Therefore it is not recommended that the Partial Factor Design Method employed in this paper be applied to HMP design using data which is out of scope.

Appendix

Here we show how partial factors are derived for Critical Condition 1.

The partial factors ϕ_{R1}, ϕ_{R2}, γ_{S1}, γ_{S2} need to be determined so that design standard equation (17) for Critical Condition 1 is compatible with the performance function of Critical Condition 1; i.e., equation (14).

In the design,

The above equation needs to be satisfied

$$\mu_{Z1} = \mu_{R1} + \mu_{R2} - \mu_{SD} - \mu_{SE} \qquad (A\cdot1)$$

$$\sigma_{Z1}^2 = \sigma_{R1}^2 + \sigma_{R2}^2 + \sigma_{SE}^2 + \sigma_{SE}^2 \qquad (A\cdot2)$$

$$\beta_1 = \frac{\mu_{R1} + \mu_{R2} - \mu_{SD} - \mu_{SE}}{\sqrt{\sigma_{R1}^2 + \sigma_{R2}^2 + \sigma_{SD}^2 + \sigma_{SE}^2}} = \frac{\mu_{Z1}}{\sigma_{Z1}} \qquad (A\cdot3)$$

and equation (A-3) is substituted into equation (A-4) to give the following equation (A-5).

Here,

Equation (A-5) can be expressed in the form of equation (A-7) by using the above

$$\mu_{R1}+\mu_{R2}-\mu_{SD}-\mu_{SE} \geq \beta_1^T\sqrt{\sigma_{R1}^2+\sigma_{R2}^2+\sigma_{SD}^2+\sigma_{SE}^2} \quad (A\cdot5)$$

approximation for equation (A-6).

$$\sqrt{\sigma_{R1}^2+\sigma_{R2}^2+\sigma_{SD1}^2+\sigma_{SE1}^2} \cong \alpha_{R1}\sigma_{R1}+\alpha_{R2}\sigma_{R2}+\alpha_{SD1}\sigma_{SD}+\alpha_{SE1}\sigma_{SE} \quad (A\cdot6)$$

Substituting the fluctuation coefficients in equation (A-7) gives

Here the characteristic values are used as

$$\mu_{R1}+\mu_{R2}-\mu_{SD1}-\mu_{SE1} \geq \beta_1^T\left(\begin{matrix}\alpha_{R1}\sigma_{R1}+\alpha_{R2}\sigma_{R2}\\ +\alpha_{SD1}\sigma_{SD}+\alpha_{SE1}\sigma_{SE}\end{matrix}\right) \quad (A\cdot7)$$

the nominal values. For example, R_1* and S_{D1}* can be expressed as in equation (A-

$$\mu_{R1}+\mu_{R2}-\mu_{SD}-\mu_{SE} \geq \beta_1^T\left(\begin{matrix}\alpha_{R1}V_{R1}\mu_{R1}+\alpha_{R2}V_{R2}\mu_{R2}\\ +\alpha_{SD1}V_{SD}\mu_{SD}+\alpha_{SE1}V_{SE}\mu_{SE}\end{matrix}\right) \quad (A\cdot8)$$

$$\left(1-\alpha_{R1}\beta_1^TV_{R1}\right)\mu_{R1}+\left(1-\alpha_{R2}\beta_1^TV_{R2}\right)\mu_{R2} \geq\left(1+\alpha_{SD1}\beta_1^TV_{SD}\right)\mu_{SD}+\left(1+\alpha_{SE1}\beta_1^TV_{SE}\right)\mu_{SE} \quad (A\cdot9)$$

10) and equation (A-11) respectively.

Equation (A-9) can be reduced to (A-12) by using the characteristic values in (A-9).

$$R_1^*=(1-k_{R1}V_{R1})\mu_{R1} \quad (A\cdot10)$$

$$S_{SD}^*=(1+k_{SD1}V_{SD})\mu_{SD} \quad (A\cdot11)$$

The partial factors are expressed by equations (A-13), (A-14), (A-15), and (A-16) from equation (17) and equation (A-12).

If the HMP designer/user has to use the values each time from the above equations to compute the sensitivity coefficients, this can become a problem, particularly for users who have insufficient knowledge of the fundamentals of probability theory. Therefore, to simplify the process in this

$$\phi_{R1}=\frac{1-\alpha_{R1}\beta_1^TV_{R1}}{1-k_{R1}V_{R1}} \quad (A\cdot13)$$

$$\phi_{R2}=\frac{1-\alpha_{R2}\beta_1^TV_{R2}}{1-k_{R2}V_{R2}} \quad (A\cdot14)$$

$$\gamma_{SD1}=\frac{1+\alpha_{SD1}\beta_1^TV_{SD}}{1+k_{SD1}V_{SD}} \quad (A\cdot15)$$

$$\gamma_{SE1}=\frac{1+\alpha_{SE1}\beta_1^TV_{SE}}{1+k_{SE1}V_{SE}} \quad (A\cdot16)$$

paper, the sensitivity coefficients are unified in order to unify the partial factors into one, so that they can easily be computed. Thus, the partial factors are expressed by equations (A-17), (A-18), (A-19) and (A-20).

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$$\phi_{R1} = \frac{1-\alpha_{R1}^{T}\beta_{1}^{T}V_{R1}}{1-k_{R1}V_{R1}} \qquad (A\cdot17)$$

$$\phi_{R2} = \frac{1-\alpha_{R2}^{T}\beta_{1}^{T}V_{R2}}{1-k_{R2}V_{R2}} \qquad (A\cdot18)$$

$$\gamma_{SD1} = \frac{1+\alpha_{SD1}^{T}\beta_{1}^{T}V_{SD}}{1+k_{SD1}V_{SD}} \qquad (A\cdot19)$$

$$\gamma_{SE1} = \frac{1+\alpha_{SE1}^{T}\beta_{1}^{T}V_{SE}}{1+k_{SE1}V_{SE}} \qquad (A\cdot20)$$

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