Geotechnical Challenge for Total Cost Reduction related to Construction of Connecting Bridge with Pile Foundations

Défi géotechnique pour la réduction totale des coûts liés à la construction du pont de liaison avec les fondations sur pieux

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ABSTRACT: Changes of geotecnical engineering profile are briefly mentioned based on the density of in-situ investigations and laboratory tests. Then, the method used for evaluating the vertical bearing capacity of driven piles in the actual design is presented.. The applicability is also verified by comparing the predicted results with the results from the full-scale pile load tests, whose results were linked with the reduction of the safety factor for design. Finally, the significance of geotechnical investigations including in-situ and laboratory tests and full scale pile load tests are discussed in terms of the cost performance of the construction of pile foundations for supporting the connecting bridge. It is concluded that in-situ and laboratory investigation with reasonable geotechnical considerations can reduce the total cost of the construction of the bridge with pile foundations for New-Kitakyushu airport.

RÉSUMÉ : Dans ce papier, la politique de base et des concepts pour des études géotechniques et de conception fondation sur pieux du pont qui relie pour la Nouvelle-Kitakyūshū sont introduits. Les changements de profil géotechnique sont brièvement mentionnés basés d'après la densité du terrain (in-situ) et des essais au laboratoire. Ainsi, la méthode utilisée pour l'évaluation de la capacité portante des pieux battus conçu selon la méthodologie actuelle est présentée sur la base des considérations géotechniques. L'applicabilité est également vérifiée en comparant les résultats prédits avec les résultats des essais en vraie grandeur de chargement de pieux. Les résultats ont été comparés en termes de réduction du facteur de sécurité utilisé au dimensionnement. . Enfin, l'importance des études géotechniques y compris les essais in situ et en laboratoire et les essais en vrai grandeur de chargement de pieux sont discutés en termes de performance des coûts de la construction des fondations sur pieux pour soutenir le pont de liaison.

KEYWORDS: cost reduction, field investigations, pile foundations design, bearing capacity

1 INTRODUCTION

A connecting bridge has been constructed on the sea as an access road for New Kitakyushu airport, which will be opened in 2005. The length of the bridge is about 2km and 24 piers are mounted for supporting the bridge. An overview of the connecting bridge under construction is shown in Figure 1. In order to clarify the geological and mechanical characteristics of the ground for supporting the bridge and the manmade airport island, a large number of in-situ and laboratory tests had been performed for five years from 1991 to 1995.

In this paper, the basic policy and concepts for geotechnical investigations and design of this project are introduced. The changes of geotecnical engineering profile are briefly mentioned based on the density of in-situ investigations and laboratory tests. The process of producing a model ground for design is also made clear, which is used for estimating the bearing capacity of driven piles. Further the method used for predicting the vertical bearing capacity of driven piles is presented based on the geotechnical considerations. The applicability is also verified by comparing the predicted results with the results from the full-scale pile load tests, whose results are linked with the reduction of the safety factor for design. Finally, the significance of in-situ investigations and full scale pile load tests are discussed in terms of the cost performance of the construction of pile foundations for supporting the connecting bridge.

2 GEOTECHNICAL INVESTIGATIONS AND DESIGN

Figure 2 shows the policy and concept of geotechnical investigation and design for constructing the connecting bridge

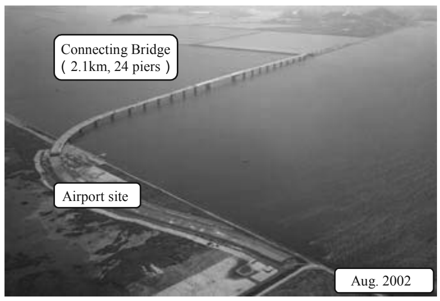

Figure 1. Overview of connecting bridge under construction

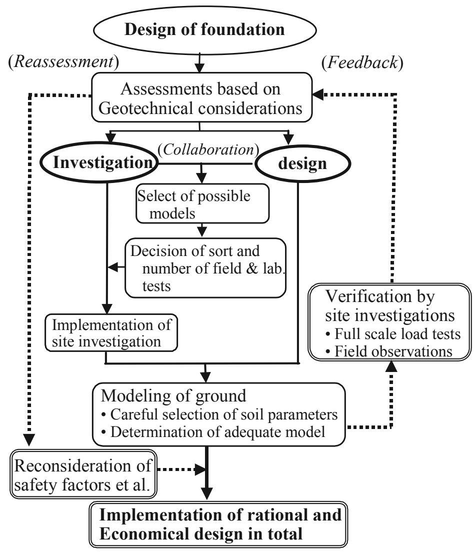

Figure 2. Collaboration of geotechnical investigations with design

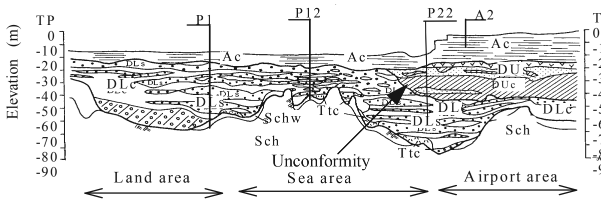

Figure 3. Final geotechnical engineering profile obtained

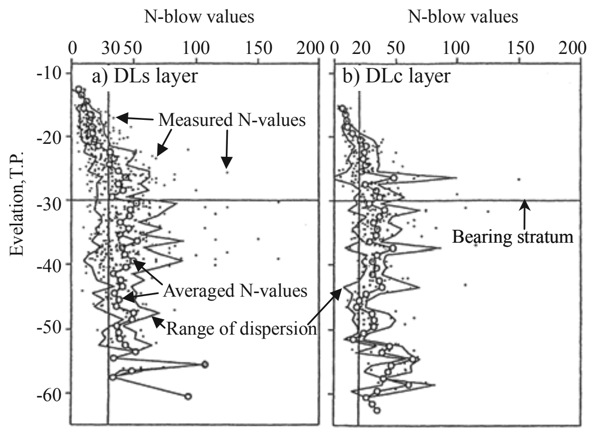

Figure 4. Distribution of N-values in DL layer against depth

for New-Kitakyushu airport. As shown in this figure, the field and laboratory investigations and the engineering design are conducted based on the clear policy, which includes that:

1) The strong collaboration between geotechnical investigators and designers should be made for a rational design and construction in pile foundations.

2) The design parameters should be determined based on the geotechnical considerations, which reflect the results obtained from the geotechnical investigations and laboratory soil tests. The model for estimating the bearing capacity of piles in design should be based on the geotechnical considerations.

3) A rational bearing stratum should be carefully selected based on the geological and geotechnical investigations.

4) The predicted performance in design should be checked by a full-scale model tests as much as possible. The results are reflected to the reduction of factor of safety for design.

Such policy seems to be strongly linked with the performance based design, which may become the mainstream in foundation design near future.

3 GEOTECHNICAL ENGINEERING MAP FOR DESIGN REFLECTED THE SOIL PROPERTY

3.1 *Geological profile with increases of site investigation*

Figure 3 shows the final geotechnical engineering profile mainly by the field investigations from 1992 to 1995, which covers the land, sea and airport areas. Figure 3 was drawn by adding the boring data in each pier of the access road, where the total number of borings became more than 65 with 3500m in total length, and the geological investigations on the diatom earth and also volcanic ash deposit with the results of the seismic exploration. The boring densities of each area in 1992, 1993 and 1995 are roughly 350m, 180m and 70m respectively.

It is judged that the geotechnical engineering profile becomes more precise with the increasing boring density and quality of in-situ investigations. The accuracy of geotechnical investigations is believed to lead to the economical and rational design and construction, even if the percentage of investigation cost to the total one might be somewhat increased (see Table 2).

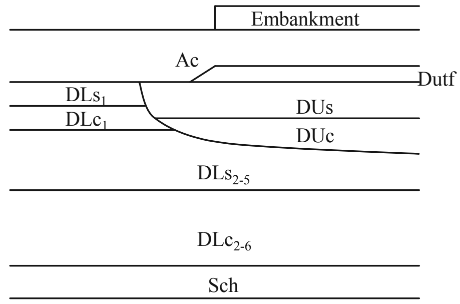

Figure 5. Model geotechnical engineering map for design

Figure 3 clarified that 1) the investigated ground consists of alluvial clayey layers with 7-9m thickness and Pleistocene layers laminated by sandy and clayey soils with 20-60m thickness below the alluvial layers and also weathered crystalline schist as the base layer. The corresponding ground is therefore roughly divided into 3 layers. 2) The undulation of base layer is extremely high in which the difference becomes more than 45m. 3) The structure of Pleistocene layers is complicated and the continuities in horizontal direction are not so clear, and so the lens shape layers are found here and there. 4) The surface of unconformity in Pleistocene layers is clearly found from sea area to airport area of which inclination is about 15 degrees in the longitudinal direction.

3.2 *Model geotechnical engineering map for design*

When determining a good bearing stratum for pile foundation, Japanese design code by Japan Road Association recommends that the N-values of sandy or sand-gravel layers are grater than 30 blow counts, and also N-values of clayey layers are more than 20. Figure 4 shows the characteristics of N-values in Pleistocene sandy and clayey layers obtained from the SPT. The N-values of both layers tend to become more than 30 in average when the depth is roughly deeper than 30m T.P. level. Based on the results, the following guideline for pile foundation design was determined such that: 1) The layer at 30m T.P level was judged as an effective bearing stratum for driving the pile foundation. A steel pipe sheet-pile foundation was selected as a type of pile foundation in this project, where, all of pile tips are set up in Pleistocene laminated ground at around 30m T.P. levels. 2) As shown in Figures 3 and 4, the scatters of N-values seems not to be small and also it is not easier to distinguish from the sandy and clayey layers from N-values obtained because the site consists of the complicated laminated sandy and clayey layers. In this circumstances, the uniform and empirical method based on the N-values is not rational and precise to evaluate the pile bearing capacity. Thus, a method for evaluating the pile vertical bearing capacity should be introduced together with a proper geotechnical engineering map for foundation design, which is derived by geotechnical

Table 1. Soil constants of each layer

			N-value	γ'	Strength parameters c'	ϕ'	ϕ'_{cv}	OCR*
				(tf/cm^3)	(tf/m^2)	(degs.)	(degs.)	
Alluvial clay		Ac	0.0	0.53	0.292	0.0	33.0	1
Pleistocene (Upper)	Volucanic	Dutf	11.0	0.66	0.6	30.0	33.7	1-6
	Sandy	DUs	30.4	0.90	0.0	37.0	34.6	1-2
	Clayey	DUc	0.0	0.53	8.1	24.0	36.9	1-6
Pleistocene (Lower)	Sandy	DLs_1	17.0	0.90	2.6	35.4	35.7	1-2
		DLs_{2-5}	40.0	0.53	5.5	32.6	35.7	1-2
	Clayey	DLc_1	27.0	0.94	2.6	34.8	35.5	2-8
		DLc_{2-6}	32.4	0.97	4.4	29.6	36.4	2-8
	Gravel	DLg	47.5	0.99	0.0	36.0	36.0	1
Metamorphic rocks		Sch-w	29.7	0.90	5.7	22.7	-	1
		Sch	98.3	0.90	5.7	22.7	-	1

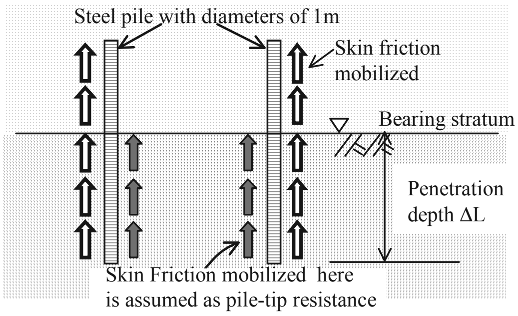

Figure 6. Basic idea of pile bearing capacity

considerations based on the results of the large numbers of in-situ and laboratory tests. The resultant geotechnical engineering map and the soil constants of each layers as characteristic values are summarized in Figure 5 and Table 1, in which the soil constants are mainly obtained by the standard consolidation and triaxial undrained and drained compression tests. 3) Full-scale pile load tests are conducted to confirm the validity of the predicting method used for foundation design. The possibility of reducing the safety factor for design to 2.5 from 3.0 is considered through the geotechnical point of view based on the field investigations, laboratory test results and the accuracy of the predicting method with full scale pile load tests.

4 EVALUATION OF VERTICAL BEARING CAPACITY OF DRIVEN PILES

4.1 *Basic idea*

Specification for Highway Bridge gives a following equation as an estimating method of the ultimate pile bearing capacity based on the results of the field and laboratory investigations (JRA, 1996):

$$R_u = U \sum L_i f_i + q_d A \tag{1}$$

Where R_u: ultimate bearing capacity of pile, A: pile tip area, q_d: pile end bearing capacity, U: pile circumference, L_i: thickness in each layer, f_i: maximum skin friction of pile. The first and second terms are related to the skin friction of pile and pile-tip bearing capacity, respectively. However, the main part of the vertical bearing capacity of a pile is often mobilized from the

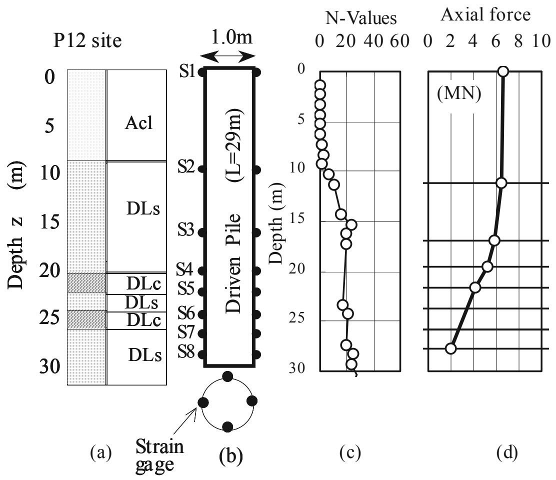

Figure 7. Soil profile, N-values and measured axial force in pile load test at P12 site

skin friction in practical designs within the limits of allowable displacement, because relatively large displacements are needed to mobilize the end bearing capacity. In addition, as a normal open-end pile is used as a type of pile foundation, the end bearing capacity strongly depends on the degree of the blockade effect and thus the precise prediction of the end bearing capacity was considered to be quite difficult. Then, as shown in Figure 6, the skin friction mobilized through the internal face of the pile under the bearing stratum was assumed as the equivalent end bearing capacity in the design. Therefore, the second term q_dA is expressed as $U\Delta Lf_i$.

4.2 *Evaluation of skin friction*

4.2.1 *Basic equation*

The following basic equation is therefore used for calculating the skin friction of piles which is determined as the sum of pile to soil adhesion and friction components:

$$f = c'_\delta + \sigma'_h \tan \phi'_\delta \tag{2}$$

c'_δ and ϕ'_δ are the adhesion and friction parameters between pile and soil, and σ'_h is the effective lateral stress acting on the pile.

4.2.2 *Soil constants as characteristic values*

An idea that the adhesion between pile and soils is roughly equal to the apparent cohesion of soils c' is widely used for a practical design. It is mentioned that the applicability of this idea is effective, irrespective of type of soils such as clay and sand (e.g. Tomlinson 1980). Therefore, c'_δ in eq. (4) was assumed to be equal to the apparent cohesion c' of soils. In practical design, the axial pile capacity is estimated for the settlements of approximately 10% of the pile diameter. The 10% settlements usually exceed those for mobilizing the maximum skin friction of pile. Further, when considering that the mobilized mechanism of skin friction between pile and soils surrounding the pile, it is reasonable to use the friction angles at the critical state corresponding to sufficiently large displacement ϕ'_{cv} as ϕ'_δ (Yasufuku et al. 1997). Here ϕ'_δ is assumed to be conservatively two-third of ϕ'. ϕ'_δ is thus given by

$$\phi'_\delta = \frac{2}{3}\phi' \tag{3}$$

where, ϕ': effective friction angle at peak strength state.

4.2.3 *Coefficient of lateral effective stress K*

The mobilization of the skin friction is dependent on the lateral effective stress σ'_h and thus in turn is dependent on the overburden pressure σ'_v. When considering σ'_h is given by $K\sigma'_v$, Eq.(2) is rewritten by

$$f = c'_\delta + K\sigma'_v \tan \phi'_\delta \tag{4}$$

K is a coefficient of lateral effective stress and σ'_v is vertical effective stress. The coefficient of lateral effective stress K was estimated from the previous research findings related to the K_0-value. K-values in Pleistocene clayey layers were determined by the following equation (Mayne and Kulhawy, 1982).

$$K = (1 - \sin\phi')OCR^{\sin\phi'} \tag{5}$$

where, OCR is over-consolidation ratio defined as the ratio of the consolidation yield stress p_c to the overburden pressure σ'_v. Values of OCR, ϕ' in average and the calculated K-values in Eq.(5) are measured against elevation. We can say that applying this equation into the Pleistocene clayey layers, most of K-values became more than 1.0. Based on the experimental evidence, K-value for design was decided as 1.0, irrespective of type of Pleistocene layers. Thus, the presented model for evaluating the vertical bearing capacity is expressed as

$$R_u = U \sum L_i f_i + U\Delta L f_i \tag{6}$$

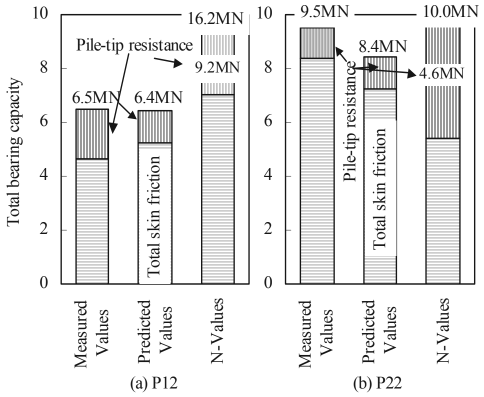

Figure 8. Comparison of predicted total bearing capacities with those of pile load tests

$$f_i = c' + 1.0\gamma' z \tan\left(\frac{2}{3}\phi'\right) \tag{7}$$

where, z is an arbitrary depth from the surface and ΔL is a penetration depth from the bearing stratum (see Figure 6).

5 FULL-SCALE PILE LOAD TESTS AND THE REDUCTION OF FACTOR OF SAFETY

In order to verify the applicability of the presented model and to confirm the characteristics of the pile bearing capacity of each layer, full scale pile load tests were conducted at two representative sites, which locate at 12P and 22P sites shown in Figure 3. As an important engineering judgment in this project, the reduction of the factor of safety from 3.0 to 2.5 for pile foundation design was discussed through comparing the predicted results with the results of full scale pile load tests.

Figure 7 shows the soil profiles and N values with depth for 12P site. N-values can be seen to widely change with depth from nearly zero to more than 20 and also N-values at pile tips are roughly 30. The steel piles with a diameter of 1.0m were carefully driven using vibration and hydraulic hummers. The effective length of each pile was about 30m. Tests were conducted based on the multi-cycles method, which is recommended by the JGS (1993). Four strain gauges were located at each of the cross sections as shown by the dots in Figure 7.

Figure 8 shows the comparison of the estimating total vertical bearing capacities with those of full-scale pile load tests at 12P and 22P sites, in which Eqs. (6) and (7) was used to calculate the predicted values. The bearing capacity calculated by the empirical model based on the measured N-values recommended by JRA is also depicted in this figure. The model used here can reasonably estimate both total skin friction and pile tip resistance at both sites, comparing with those from JRA recommendation. As shown in Table 1 and Figure 3, we have a clear grasp of the soil characteristics values for each layer and a practically efficient geotecnical profile. Therefore, the model can apply very well to evaluate the pile bearing capacity according to the ground profile at each site, with the consequence that the accuracy of the prediction clearly increased and these facts became an important evidence to reduce the factor of safety for pile foundation design from 3.0 to 2.5.

6 EFFECT OF A REDUCTION IN TOTAL COSTS

The comparison of the cost performance in terms of the construction of pile foundations driven in P1 to P24 sites is summarized in Table 2, which is a result of trial calculation. Note that the cost is normalized by the cost obtained by the standard manner for evaluating the pile bearing capacity using N-values (JRA, 1993) without any full scale pile load tests. For comparison, the layer of the bearing stratum for each case was assumed to be same, however, the penetration depth ΔL was considered to depend on the calculation manner. Total cost are divided by 2 parts, in which one is the part for the cost related to the geotechnical investigations which include in-situ and laboratory soil tests, and full scale pile load tests, and the other is related to the normalized total pile construction cost in terms of P1 to P24 piers. The presented manner used here is expected to cut the cost more than 15% comparing with the total cost by the standard approach using N-values. Thus even if the cost of the geotechnical investigations became roughly two times higher comparing with the general manner, the appropriate in-situ and laboratory investigation with a reasonable considerations can reduce the total cost in the project. This is due to the highly accurate ground profile and the proper evaluation method of pile bearing capacity with the results of the full scale pile load tests which reflected the decrease of safety factor from 3.0 to 2.5. It is believed that the geotechnical considerations and manner treated here can give an important information for the geotechnical investigators, structural designers and construction engineers.

Table 2. Total cost benefit

	Method by N-values	Method proposed here
Cost for geotechnical investigations*	1	2.11
Construction cost for piles	1	0.82
Total cost	1	0.84
* the cost includes full scale load tests		

7 CONCLUSIONS

An importance of integrating the geotechnical investigations with pile foundation design was clarified through a case study in terms of connecting bridge for New-Kitakyushu airport. The following major conclusions were drawn:

1) A rational method for evaluating the pile bearing capacity was presented which reflected the soil characteristic values and geological environmental history. In addition, the applicability of the presented method was confirmed through full-scale pile load tests, with the consequence that the safety factors for pile foundation design were reduced from 3.0 to 2.5.

2) In-situ and laboratory investigation with reasonable geotechnical considerations can reduce the total cost of the construction of the bridge for New-Kitakyushu airport.

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