CONSIDERING GROUP BEHAVIOR OF FRICTION PILES FOR SETTLEMENT ANALYSIS

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It is quite common to utilize friction piles in foundations supporting low to medium-rise buildings in Japan. The choice of friction piles is mostly dictated by ground conditions where such buildings are located. One of the important design considerations of friction pile foundations is to ensure adequate settlement performance. However, rational approach for determination of settlement distribution in the building and foundation system, considering the friction piles and the ground condition of the site, is quite complex in nature. One of the authors (Matsuo) has proposed a practical method of analyzing the settlement behavior of buildings considering a foundation system of single piles for each column. In this paper, the authors have proposed a method of modeling the friction pile groups to replace the single piles per column. The method is simple and involves representing the friction pile groups by an equivalent large diameter pile, referred to as the 'virtual single piles'. The applicability of the proposed method is investigated by comparing the results of analysis with data from field monitoring of a building at a clayey ground condition. It is found that the analytical results based on the proposed model compare satisfactorily with the measurements from field monitoring of the building supported on friction piles.

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CONSIDERING GROUP BEHAVIOR OF FRICTION PILES FOR SETTLEMENT ANALYSIS OF BUILDINGS

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ABSTRACT:

Owing to the prevalence of deep soft soil deposits in most urban areas in Japan, the use of friction piles in foundations supporting low to medium-rise buildings is quite common. Proper design of such foundations hinges on ensuring adequate settlement performance. For this, refinement and development of methods for rational evaluation of the spatial distribution of settlement, considering realistic representation of the building-foundation system, becomes necessary. With the advent of performance based approach to design, evaluation of settlement performance is of particular significance. In this context, the paper introduces a method of representing groups of friction piles in a building by 'virtual single piles' for the purpose of settlement analysis considering the overall building-foundation system. It is found that the analytical results based on the proposed model are similar to those of a detailed model where piles are considered to interact individually, and also compare well with the measurements obtained from field monitoring of a warehouse building supported on friction piles.

1 Introduction

The choice of friction piles in foundations supporting low to medium-rise buildings in Japan is mostly dictated by ground conditions where such buildings are located. One of the important considerations in the design of foundations adopting friction piles is the need to ensure adequate settlement performance. However, rational approach for determination of settlement distribution in the building-foundation system, considering the behavior of friction piles and the ground condition of the site, is quite complex in nature. Matsuo and Yamagata [1] have proposed a practical method of accounting for the rigidity of building structure in the analysis of settlement behavior of buildings assuming a foundation system of single piles for each column. In practice, however, it is common to have a group of friction piles supporting the columns of a building. In this paper, the possibility of replacing a group of friction piles under a column by a single pile for settlement analysis is evaluated. The method is simple and involves representing the friction pile groups by an equivalent large diameter pile, referred to as the 'virtual single piles'. The applicability of the proposed method is investigated by comparing with a detailed model and verified by conformity of the analytical results with data from field monitoring for settlement of a warehouse buildings.

1 Analytical Framework to Account for Superstructure Stiffness

It is evident that mutual interaction exists between stresses developed in the superstructure under vertical loads and the extent and nature of foundation settlement inherent in building structures. In essence, the nature and amount of settlement for a given type of foundation at a certain ground condition depends to a large extent on the distribution of loads and stiffness in the building superstructure. As a result, it becomes essential to ensure conformity between superstructure movements and the ground movements for a rational evaluation of foundation settlement. The analytical framework [1] satisfying this requirement is illustrated by the flow chart in *Fig. 1*. The method basically consists of making the evaluation of the foundation settlement an integral part of the method of three-dimensional frame analysis utilized widely in Japan. Basic assumptions inherent in the method are:

1) Total ground settlement is limited to immediate settlement and the end of consolidation settlement.

1) Immediate settlement is given by the Mindlin's solution, with the strain dependence of elastic modulus of soil taken into account.

1) End of the consolidation settlement in clayey layers is based on the modulus of volume compressibility m_v obtained from the field consolidation curve constructed from one-dimensional consolidation tests.

1) The superstructure is represented by a space frame, in which the stiffness degradation due to plasticity and creep in material behavior taken into consideration.

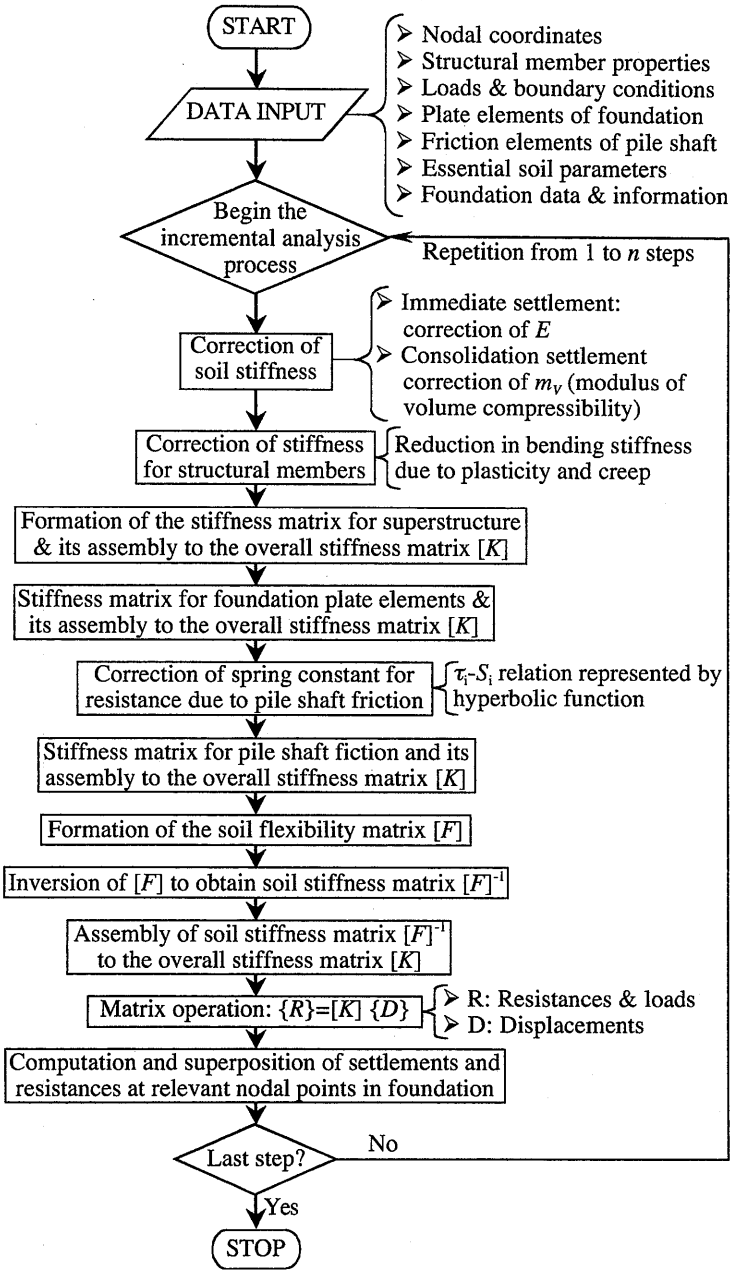


Fig. 1 The schematic flow of the method of analysis

1) The virtual single piles replacing the pile groups in various column footings are assumed to be extensions of the respective ground floor columns that are imbedded into the layered ground. The virtual single piles are divided into nodes at suitable intervals such that shear springs representing load transfer by shaft friction connect the respective pile nodes to the adjacent soil nodes.

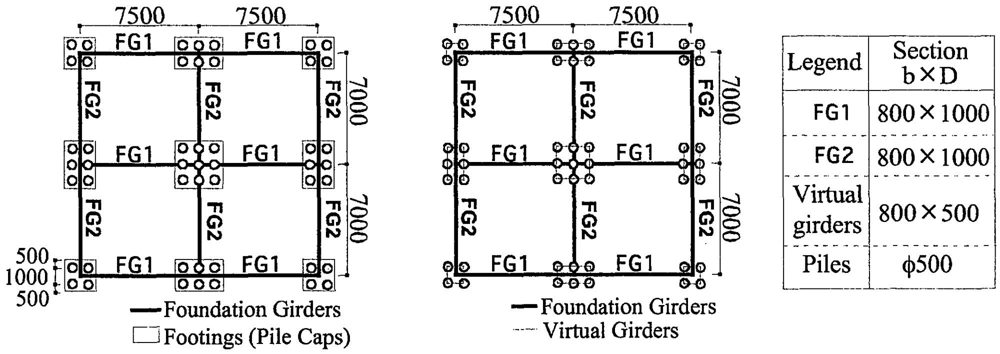
1) The shear springs representing the load transfer by shaft friction to the adjacent soil is given by Equation (1) relating the shaft friction τ_i (kN/cm^2) with relative movement S_i (mm) between adjacent pile and soil nodes, a and b being constants of hyperbolic function.

$$\tau_i = \frac{S_i}{a + b \cdot S_i} \tag{1}$$

1) The nature of load transfer by direct bearing at pile toe is represented directly by Young's modulus in case of sandy soil layers and by the field consolidation curve ($e - \log\sigma'$ relation) in case of clayey soil. Soil layers to an adequate depth, below which the influence of load transferred by pile toe becomes negligible, is considered in the analysis.

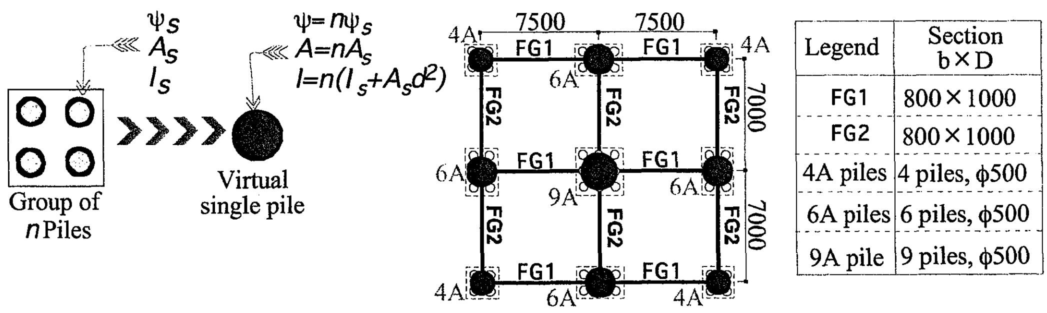
1 Applicability of Virtual Single Pile Method

Randolph [2] has given various approaches available for the analysis of pile groups. One of such methods commonly utilized in practice is the equivalent pier consisting of the piles in the group together with the soil enclosed. This means the need to account for the enclosed soil in evaluating the axial stiffness of the equivalent pier. To assess the possibility of further simplification, the concept of 'virtual single pile' representation is proposed and investigated



Legend	Section b×D
FG1	800×1000
FG2	800×1000
Virtual girders	800×500
Piles	ϕ500

(a) Tentative foundation plan (b) Detailed model of pile groups (virtual girders)



Legend	Section b×D
FG1	800×1000
FG2	800×1000
4A piles	4 piles, ϕ500
6A piles	6 piles, ϕ500
9A pile	9 piles, ϕ500

(c) Concept of virtual single pile & representation of foundation based on this model

Fig. 2 Simple foundation plan investigated and the representation of pile groups by virtual girder (detailed) method and virtual single pile method.

for its applicability. *Fig. 2* (a) shows a simplified foundation plan of an existing 11 story building in Japan, where the distance between piles in all the footings is 1000mm. The sectional dimensions of the foundation girders are also given in *Fig. 2.* All the piles in a footing may be accounted for separately in a 'detailed model' shown in *Fig. 2* (b), where the footings are replaced by 'virtual foundation girders' and letting all the piles in the group to interact individually in transferring the column load to the ground. The proposed method of replacing the pile group with a 'virtual single pile' is illustrated in Fig. 2 (c). In this method, n piles of cross-sectional area A_S, perimeter ψ_s and area moment of inertia I_S in group are replaced by a single pile of sectional area nA_S, perimeter $n\psi_s$ and area moment of inertia $n(I_S + A_S \cdot d^2)$, where d is the distance a pile center from the neutral axis of pile group.

3.1 Ground Conditions and Soil Parameters

Three different soil conditions shown in *Fig. 3* were considered for the building site, such that the friction piles (bored PHC nodular piles [3]) for the respective sites are designed based on the Japanese practice by keeping the layout unchanged from the plan in *Fig. 2* (a). The weight of the building was about *24MN* such that the vertical load bearing capacity of each pile was about *490kN*. Accordingly, different pile lengths and diameters may be noted in *Fig. 3* depending on the soil condition (soils A, B and C) [4]. Soil-A consists of sandy soil within the pile length, where N-value varies from 10 to 15. In soils B and C the pile toe is located in over-consolidated clay with N-value in the range of 1-2, for which the field consolidation curve ($e - \log\sigma'$ relation) is shown in *Fig. 3.* The parameters of the field consolidation curve were obtained from the results of laboratory tests for one-dimensional consolidation.

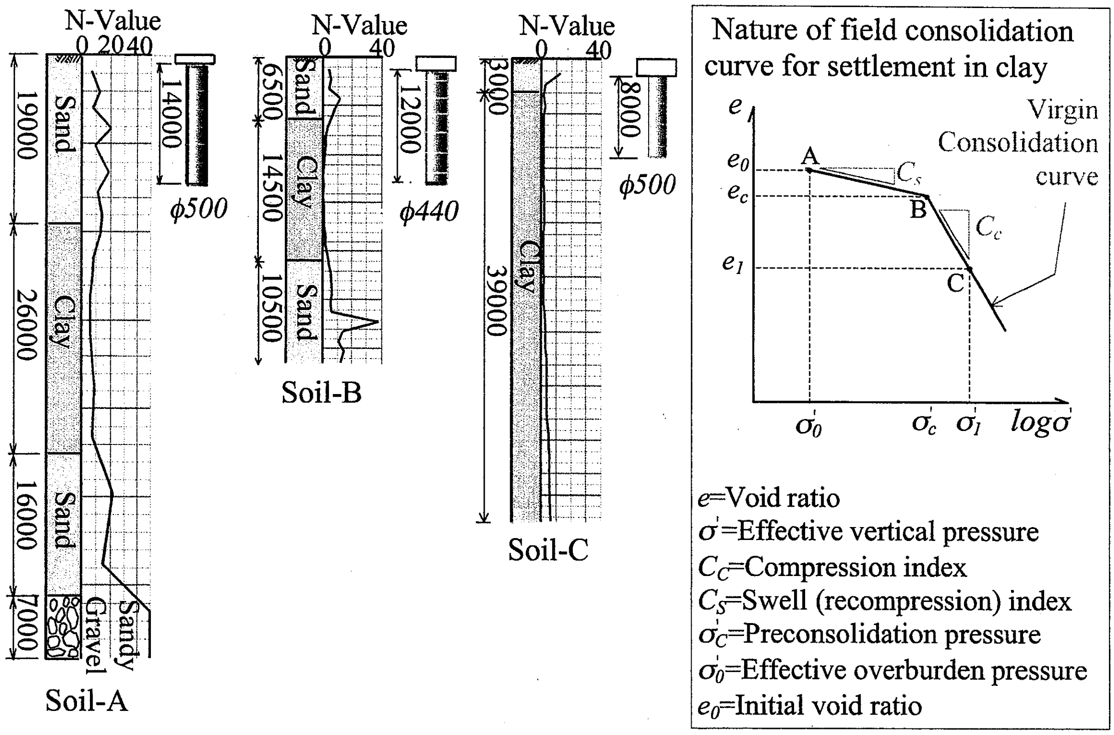


Fig. 3 Three cases of friction piles together with the respective soil conditions, and the field consolidation curve (parameter values from laboratory tests) for clayey soil layers.

As noted above, load transfer from piles to soil by shaft friction is represented by hyperbolic curve of Equation (1). For this, values of the parameters a and b were obtained from correlation with N-values [5] developed based on the database system of static loading test on fully instrumented piles of the type under consideration (bored PHC nodular piles [3]). Considering that measurement in the database utilized in the correlation with N-value of the parameters a and b involves total settlement of piles, the initial slope of the τ_i–S_i curve applicable for the relative movement between soil and pile can be expected to be larger than $1/a$. In fact, it is reported that the τ_i–S_i relation considering relative movement alone is close to rigid-plastic [6]. Accordingly, the initial slope of the τ_i–S_i curve (*i.e.*, $1/a$) obtained from correlation with N-values was multiplied by 100 to approximate a rigid-plastic behavior. The Young's modulus E of the soil was estimate from shear wave velocity V_S, which in turn was obtained from correlation with N-values [7]. Load transfer at pile toe was assumed to include 500mm pile length at the toe, which was directly based on E of sandy soils and $e-\log\sigma'$ relation of clayey soils.

Table 1 Comparison of Settlements (mm) at Footings

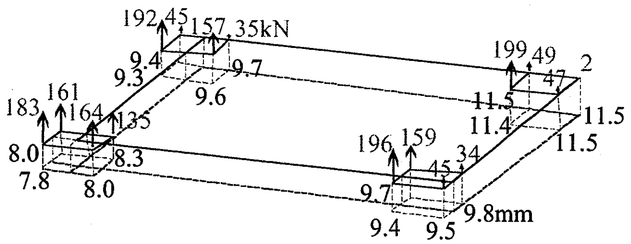
Footing position (*Fig. 2*)	Sandy (Soil-A)		Clayey (Soil-B)		Clayey (Soil-C)	
	Detailed method	Virtual pile	Detailed method	Virtual pile	Detailed method	Virtual pile
Corner	20.1	20.0	8.0	9.3	6.5	7.2
Front	23.9	23.7	9.6	10.7	7.5	8.3
Left	23.6	23.4	9.5	10.6	7.4	8.2
Center	28.4	28.0	11.5	12.4	8.7	9.5
Average ratio	1.00	0.99	1.00	1.13	1.00	1.11

Table 2 Comparison of Reactions (kN) at Footings

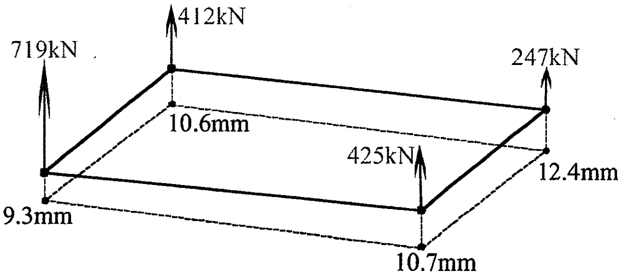
Footing position (*Fig. 2*)	Sandy (Soil-A)		Clayey (Soil-B)		Clayey (Soil-C)	
	Detailed method	Virtual pile	Detailed method	Virtual pile	Detailed method	Virtual pile
Corner	2173	2218	643	719	449	494
Front	2886	2943	868	850	574	561
Left	2844	2881	858	824	564	544
Center	3885	3517	1188	988	738	623
Average ratio	1.00	1.01	1.00	1.02	1.00	1.01

3.1 Comparison of Results

Two sets of analysis, including the detailed model and the virtual single pile model, were undertaken for each of the three types of soil shown in *Fig. 3*, keeping the building structure unchanged. In view of the square plan of the building, symmetry was utilized by considering only 1/4 portion, shown by sky-blue shading in *Fig. 2* (b) & (c), in the analysis. *Tables 1* and *2* compare the settlements and reactions respectively at the four corner columns of the shaded quadrant of the building



(a) Settlements and reactions from the detailed model (soil B)



(b) Results of virtual single pile representation (soil B)

Fig. 4 Distribution of Settlements & Reactions plan. *Fig. 4* shows an example of the results of analysis in case of Soil-B. The average values for all the piles in a footing, such as shown in *Fig. 4*(a), are given in *Tables 1* and *2* for the detailed model. Since only a quadrant is analyzed utilizing the symmetry in the building plan, tabulated reactions are 2 times those shown in *Fig. 4* and for the front & left footings. Similarly, tabulated reactions for central footing are 4 times of those shown in *Fig. 4*.

Settlements as well as the reactions obtained from the virtual single pile method compare well with those from the detailed method. The average ratio is the mean of the respective values divided by the corresponding values from detailed method. Overall, it is noted from comparisons in *Tables 1 & 2* and also from *Fig. 4* that the reactions obtained from both the methods compare very well. While the settlements obtained from virtual single pile method are of the order of 10% higher compared to the detailed method in case of piles in clayey soil (Soil B & C), settlements as well as reactions compare closely in case of sandy soil (Soil-A).

1 Observation of Settlement and Comparison with Computations

4.1 Settlement Monitoring System

A 2-storied warehouse building of steel structure with a fairly large ground floor area of about 1020m^2 and total building weight of about 18MN was supported on friction piles at a soft ground site [4] shown in *Fig. 5*. It may be noted that the sandy layer of about 5m at the surface is underlain by alluvial clay, with N-value less than 2, all the way to a depth of about 25m. As shown in *Fig. 5*, 10m long friction piles supporting the building have substantial lower portion imbedded in the alluvial clay. Foundation plan of the building is shown in Fig. 6 (a) where the settlement monitoring locations (footings) are numbered from 1 to 33. Monitoring of the building settlement was initiated from the time the foundation girders were placed and the monitoring has been continuing for about 12 years to date. The longitudinal settlement profiles along north and south gridlines of the building, shown in *Fig. 6* (b) and (c) respectively by red dots, are based on the measurements taken in May 2001. Actually, the total settlement measured includes the general ground settlement that occurs without the building being constructed. Ground settlement in the vicinity was also monitored and was found to be about 73mm during the period since construction. The ground settlement of 73mm was subtracted from measured foundation settlement values in arriving at the longitudinal settlement profiles in *Fig. 6*(b) & (c). Similarly, transverse settlement profiles along west and east gridlines are shown in *Fig. 7*. It may be noted from *Figs. 6* and *7* that the settlement attributable to the building weight is of the order of 40 to 50mm and there is differential settlement of about 30mm between west and east gridlines. However, over 10 years since its construction, the warehouse building has not suffered any problem concerning structural integrity. Since the settlement has been continuing for as long as over 10 years, it may be expected that consolidation settlements are practically complete. Other details of the settlement measurement are discussed in Bando *et al.* [8]. As the method of analysis illustrated in *Fig. 1* involves the end of consolidation settlements, the observed data can be logically compared with computational results.

4.2 Computed Settlements and Comparison with Measurements

Each of the pile groups of 40 column footings in the foundation plan of warehouse building shown in Fig. 6 (a) were modeled as virtual single piles as described above. The foundation settlement was computed by assuming the building weight to be acting simply as concentrated loads at column locations. Values of computed settlement are also plotted in the

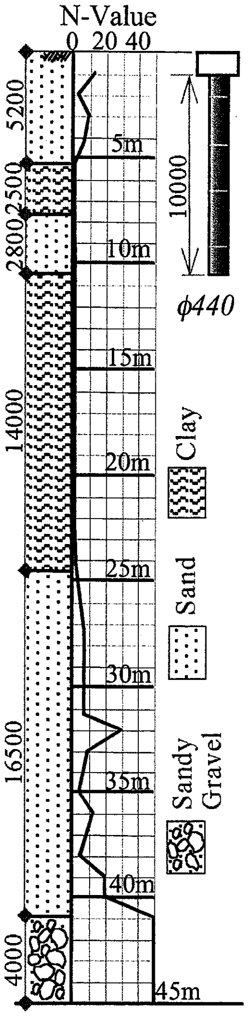


Fig. 5 Soil Condition & Piles in the Warehouse Building

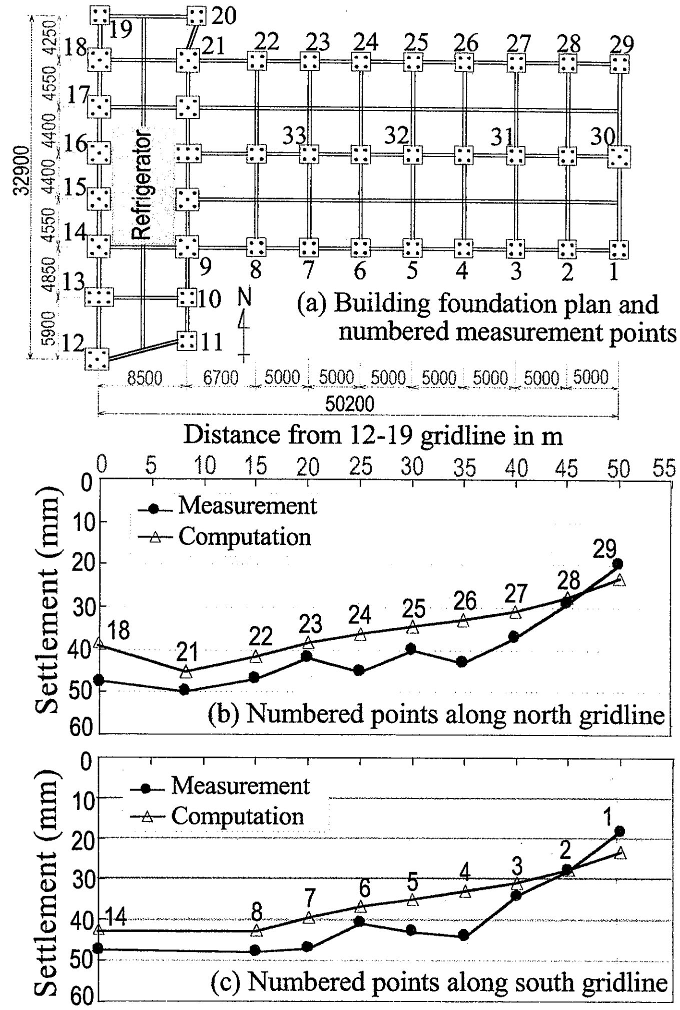


Fig. 6 Foundation Plan Showing Settlement Monitored Locations and Longitudinal Settlement Profiles

profiles of *Figs. 6* and *7* for direct comparison with measured values, and are denoted by blue triangles connected by blue lines.

Although the computed settlements in *Figs. 6* and *7* are somewhat smaller than measured values, general trend of settlement behavior is realistically displayed by results of the numerical analysis. Larger settlement on the east side of the building, where the heavy equipment of the refrigeration unit can be noted in *Fig. 6* (a), is clearly seen in both the computed and observed results shown by settlement profiles in *Fig. 6.* The effect of

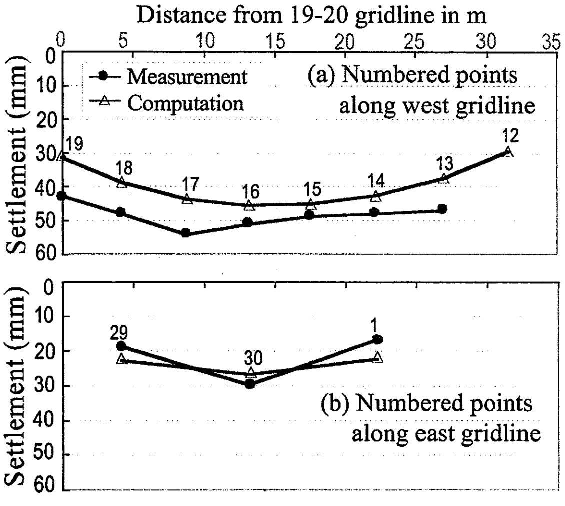


Fig. 7 Transverse Settlement Profiles

the heavy equipment is also well represented by the saddle in transverse profiles of measured and computed settlements in *Fig. 7* (a). Overall, computed settlements provide realistic representation of measurements from monitoring system in the warehouse building.

2 Conclusions

The 'virtual single pile' method of modeling friction pile groups, for the purpose of settlement analysis considering the building-foundation system, is found to provide results very close to the somewhat detailed model where individual piles in various footings are considered to interact separately. In addition, use of this method of modeling pile groups in the analytical framework developed by one of the coauthors [1] provides results comparable to settlements observed in a warehouse building over 10 years after its construction.

The agreement of the building foundation settlements computed based on the virtual single pile model with those computed based on the detailed model, as well as with the observed settlements from direct monitoring of the building after construction, shown that the proposed model for friction pile groups is effective for settlement analysis.

In view of the increasing acceptance of performance based design of building foundation, the results of this investigation demonstrate the viability of considering the building-foundation system for realistic evaluation of the settlement performance of building foundations adopting friction piles.

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