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1 Introduction

A static loading test is widely used to evalute pile bearing capacity. However, since the static loading test is a time-consuming and costly procedure, it is impractical to control the bearing capacity of all piles by this method. On the contrary, the dynamic bearing capacity (penetration resistance) evaluation, which is based on pile behavior during driving, makes measuring much easier possibly even all the piles on a site; hence, even if these methods may be inferior to the static loading test in estimating the accuracy of individual pile bearing capacity, they are considered to lead to enhanced reliability of the entire pile foundation structure, because they can detect piles having possible problems in bearing capacity on a comparative basis.

Bearing capacity evaluation methods using dynamic penetration resistance can be broadly divided into so-called "dynamic bearing capacity formulae" such as the Hiley Formula and Construction Ministry Notification Formula, and methods based on stress wave theory represented by the CASE method and CAPWAPC method. The former, based on the kinetic energy equilibrium theory, obtains dynamic bearing capacity from the penetration and rebound during pile driving as a collision problem in the system of particles, but the variation is too wide in the loading test results,[1-3] leading to a rise of problems with application limits. The latter utilizes theories for estimating dynamic penetration resistance on the basis of the pile strain and acceleration during driving by applying the one-dimensional wave equation, and the practical use has rapidly progressed recently along with dynamic measuring techniques.[2,4-6]

Although the fact that one-dimensional equation well explains the dynamic behavior of a pile was long known,[7,8] its practical application is attributable to a pioneering role attained by a series of researches by

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Goble et al.[9-11] They showed the theory for the methods (CASE method, CAPWAPC anslysis method) of calculating dynamic bearing capacity by measuring the strain and acceleration of the pile head, and developed PDA (pile driving analyzer)[12] as measuring equipment. Since then, similar measuring methods such as TNO,[13] D-PAS,[14] and two-point strain measurement methods[15] have been sequentially developed. Particularly in foreign countries, these measuring systems are widely applied, and are used as a dynamic loading test in America as ASTM standardization[16] has progressed.[17-19] In Japan, methods based on the wave theory are incorporated into dynamic bearing capacity formulae in the Specification for Highway Bridges and Building Foundation Construction Design Guidelines. However, these systems have not yet been applied as prediction methods for pile capacity due to the following reasons:

(1) In Japan, pile capacity is generally evaluated by the static loading test, and the dynamic loading test based on stress wave theory has only just been introduced so that few records exist.

(2) The interrelation between the pile capacity obtained by the dynamic method (dynamic penetration resistance) and by the static loading test has not yet been clarified. While there are reports that the ultimate pile capacity estimated on the basis of the stress wave theory practically corresponds with the static loading test, there are some reports which question the accuracy of the bearing capacity obtained by the stress wave theory,[20] and therefore this method is not considered established for estimating pile capacity.

(3) At present, a number of analysis programs are available, but an engineering approach from the viewpoint of soil mechanics is lacking, and many problems such as analysis models and the method for determining constants still remain unsolved.

Such a dynamic loading method based on stress wave theory still has many unsolved problems. However, significant applications may be possible in piling construction, particularly with offshore and ocean projects, and future developments are expected. Since a steel pipe pile is made of uniform material through which a stress wave can propagate easily, measurements of stress waves can be made to higher accuracy than is possible with a concrete pile. The dynamic loading method is, therefore, more useful for steel piles than for concrete piles.

Against such a background, Kawasaki Steel Corp. introduced the above-mentioned PDA system in 1988, and has been experimentally examining its applicability. This report describes the applicability of the dynamic loading test based on stress wave theory by PDA measurements on a full-scale steel pipe, and also introduces applicable examples for pile-driving control in commercial construction work.

2 Evaluation of Pile Capacity Based on Stress Wave Theory

2.1 Outline of the PDA System

The PDA system is shown in **Fig. 1**. The strain and acceleration of the pile at each impact of the hammer are measured by a strain gage and accelerometer fixed at the pile head, converted into force and velocity, respectively, by an amplifier and integration circuit installed in the PDA, and displayed on an oscilloscope. Simultaneously, analog data for each driving are recorded on a tape recorder that is connected to the PDA. By using the measured data, the bearing capacity of a pile is calculated by the CASE method or the CAPWAPC method. The CASE method is a simplified one, the analysis being carried out for each driving, and the results output onto chart paper in real time. The CAPWAPC method is used for a more detailed analysis. This method applies a computerized analysis to the data, which are A/D converted by the PDA, using a program employing a characteristic curve model.

2.2 Comparison with Static Pile Capacity

Both dynamic and static tests were carried out at Chiba Works of Kawasaki Steel. Steel pipe piles were used with diameter $\phi = 609.6$ mm, plate thickness $t = 12$ mm and length $L = 39$ m. A diesel hammer (K-45; with a ram weight of 4.5 tf) was used for pile driving.

Ordinarily, the soil, which is disturbed during pile driving, recovers after a subsequent elapsed time, and accordingly, the bearing capacity increases after driving. Therefore, the ultimate pile capacity is promoted when a sufficient time has elapsed after driving. With the PDA and CAPWAPC methods, the soil reaction when a pile is driven is calculated as the dynamic penetration resistance before the full pile capacity has been obtained. In the present experiment, therefore, measurements were carried out at the end of driving and re-driving after a sufficient elapsed time. The dynamic penetration resistance was analysed by the CAPWAPC

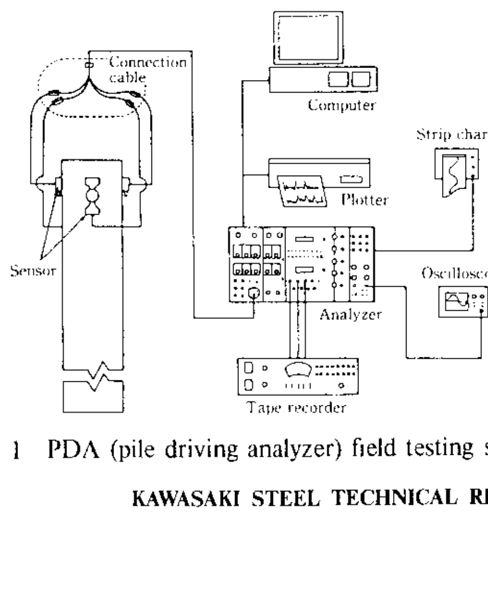

Fig. 1 PDA (pile driving analyzer) field testing system

Table 1 Results of dynamic and static tests (tf)

		Total resistance	Shaft resistance	Toe resistance	Pile driving formulae	
					Formula (1)[a]	Formula (2)[b]
Test A	End of driving	66.4	47.4	19.0		
	Redriving (elapsed 115 h)	502.3	375.4	126.9		
	Static loading test (elapsed 31 day)	475.0	414.2	60.8	346.6	193.7

[a] Formula (1) $R_d=\dfrac{AEK}{e_0 l}+\dfrac{\bar{N}Ul}{ef_0}$ [b] Formula (2) $R_d=\dfrac{F}{5S+0.1}$

method, and a static loading test was carried out, 31 day after the initial driving. The multi-cycle A loading method was used according to "Vertical Loading Test Standard for Piles and Related Comments" edited by JSSMFE, and the method of Davisson[21)] was used to obtain the ultimate bearing capacity from the results of the static loading test.

Table 1 summarizes the results. For reference's sake, values calculated by the pile driving formulae (1. Specification for Highway Bridges, and 2. Construction Ministry Notification Formula) are also shown in Table 1. When a comparison is made between the resistance at the end of driving and at re-driving, the increase is 7.56 times, indicating that the resistance has significantly increased after a suitable time interval. The ratio of the re-driving result to that from the static loading test was 106.7%, indicating that the estimated accuracy of ultimate resistance by the present method is sufficiently high for practical use.

Figure 2 shows the shaft resistance distribution with

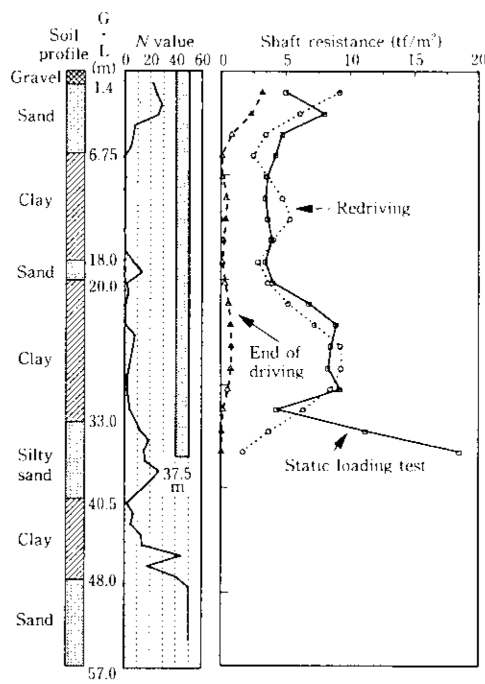

Fig. 2 Shaft resistances evaluated by CAPWAPC and static loading test (test A)

depth calculated by the CAPWAPC method, and the static loading test results of shaft resistance. When comparing the end of driving with the re-driving resistance, the re-driving results are considerably higher, indicating the effect of soil recovery. The results also indicate that the distribution of shaft resistance in the re-driving test is practically the same as that in the static test, except at the toe of the pile.

2.3 Examination of Applications

2.3.1. Increase in bearing capacity with elapsed time after pile driving

The application of PDA already mentioned makes clear that the dynamic penetration resistance, which changes with the time elapsing after initial driving, can be calculated. To further examine this method in more detail, measurements at the end of initial driving, and at the beginning of re-driving 20 days and 23 days later were taken. Piles were driven by a hydraulic hammer (IHC-500; ram weight 50 tf), and the CAPWAPC method was used for calculating the dynamic penetration resistance. **Table 2** summarizes the results. As time elapses from the end of driving, the dynamic penetration resistance increases, although the change in toe resistance is minimal, being about 10% up to re-driving 2 after 23 days. Thus, the increase in pile resistance can be mainly characterized by the increase in shaft resistance. In order to examine this increase in shaft resistance, its distribution with depth is shown in **Fig. 3**. At re-driving, the resistance has increased to about double that at the end of initial driving over the entire depth, the increase in the sand layer of $D3_{sm}$ being particularly significant.

Table 2 CAPWAPC results (tf)

	Total resistance	Shaft resistance	Toe resistance
End of driving	863.2	688.2	175.0
Redriving 1 (elapsed 10 day)	1 326.7	1 141.2	185.5
Redriving 2 (elapsed 23 day)	1 483.6	1 290.8	192.8

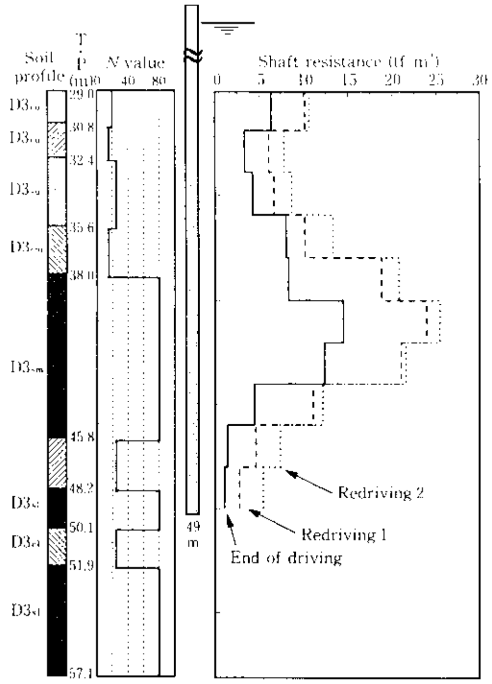

Fig. 3 Shaft resistance increase after pile installation

The rate of increase for re-driving 1 in the clay layer is about half that for re-driving 2, while in the sandy stratum, the increase in resistance has practically ended at the time of re-driving 1. This indicates that the calculated resistance significantly varies according to the timing of the driving test. Consequently, when the ultimate pile capacity is to be estimated by a driving test, it is important to allow sufficient time to elapse after the initial driving before carrying out the re-driving test. To define the optimum timing for re-driving, it will be necessary to carry out many re-driving tests in the future to accumulate data that can clarify the relationship between the time elapsing after initial driving and the increase in bearing capacity.

2.3.2 Effects of driving energy

In order to calculate the dynamic penetration resistance by driving tests, the driving energy used for the tests is important. Since the present method that employs the CAPWAPC analysis is aimed at calculating the reaction force of the soil to be achieved by pile driving in the form of the dynamic penetration resistance, it can be foreseen that if driving force differs, the reaction force generated by the soil will also differ. To examine how this resistance will change according to the change in driving energy, measurements were taken of five drivings each for re-driving 1 and re-driving 2. A hydraulic hammer with adjustable driving force was used, the driving energy ratio (ratio of the energy at re-driving to the energy at the end of initial driving) being varied from 0.5 to 2.0 as shown in **Table 3.**

The results are shown in **Fig.** 4. In both re-driving cases, the dynamic resistance increases as the driving energy increases until the driving energy ratio reaches 1.75–2.0, at which the pile begins to penetrate significantly, and the penetration resistance decreases. The calculated resistance produced differences of 15% in the case of re-driving test 1 and about 40% in re-driving test 2, depending upon the level of driving energy. In these tests, the total number of driving impacts increased as the driving energy increased; hence, the soil was disturbed gradually as the driving energy increased, and when the driving energy ratio rose above 1.75 to 2.0, the penetration suddenly increased. If ground properties were constant, however, the dynamic penetration resistance would approach a certain value as the driving energy increases, as shown by the dashed line. Consequently, in order to estimate the ultimate dynamic penetration resistance of a pile, measurements must be made while using sufficient driving energy.

Table 3 Energy ratio and driving energy used for redriving tests

Energy ratio*)		0.5	1.0	1.25	1.5	1.75	2.0
Driving energy (tf·m)	Redriving 1	5.7	11.0	15.9	18.2	20.9	
	Redriving 2	5.8	12.1	14.7	18.2	20.5	21.8

*) Energy ratio: $\dfrac{\text{Energy at redriving}}{\text{Energy at end of driving}}$

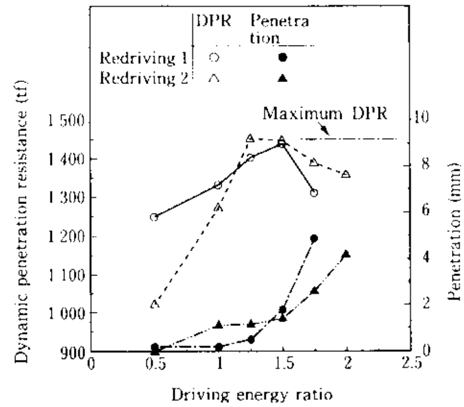

Fig. 4 Dynamic penetration resistance (DPR) and driving energy ratio (redriving/end of driving)

3 Application to the Bearing Capacity Control Method

3.1 Examination of the Pile Driving Control Method

In the past, the pile driving control method involved obtaining the targeted penetration and rebound quantities from pile driving fomulae such as the Hiley equation or Specification for Highway Bridges, and correctly interpreting these quantities. However, when the application limits for estimating ultimate pile capacity by the

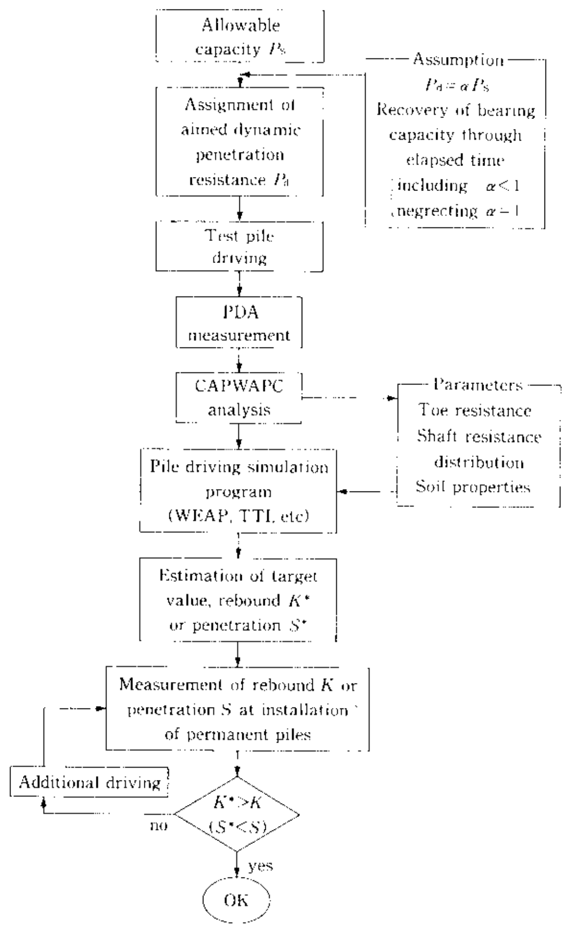

Fig. 5 Flow chart for driving control based on stress wave theory

pile driving formulae is taken into consideration, the establishment of a more rational control method becomes necessary. One such method that the authors have examined for pile driving control involves calculating the relationship between the dynamic bearing capacity based on stress wave theory and the penetration and rebound, using PDA data measured on site.

Figure 5 shows a flow chart for pile driving control based on this scheme. This method applies a piling simulation program based on the stress wave theory, and will feed back the PDA measurement and CAPWAPC analysis results from full-scale pile driving. The piling simulation program assumes the driving energy of the hammer, and estimates the dynamic behavior of the pile (penetration and rebound), using the same model as that for the CAPWAPC analysis. This program inputs values for the pile-toe and -shaft penetration resistance, the shaft resistance distribution and soil characteristic parameters being obtained from the CAPWAPC analysis, and claculates the penetration and rebound quantities corresponding to the dynamic penetration resistance, thereby permitting the effects of variation in the ground to be considered. The relationship between the static ultimate bearing capacity and dynamic penetration resistance is determined in relation to a pre-set ratio. As already mentioned, this method permits data measured during pile driving to be fed back into the calculation of penetration and allows for ground property at the site; hence, this method is considered reasonable.

3.2 Example of Sky Parking Area (South Building) at Tokyo International Airport

In connection with the offshore construction work at Tokyo International Airport, large-diameter, long-shaft steel pipe piles were driven as a foundation for the Sky Parking Area (South Building). Prior to this piling work, a comparison was made between the bearing capacity evaluated by the pile driving formulae, CAPWAPC method and vertical loading test. A piling control method based on the pile driving formulae and one based on stress wave theory were then compared with each other.

In the ground shown in **Fig. 6**, a test pile with diameter ϕ of 800 mm, wall thickness t of 22 mm and shaft length L of 73 m, and reaction piles (coated with a slip layer material down to the bottom of the consolidated stratum) with ϕ of 800 mm, t of 16 mm or 12 mm and L of 73 m were driven by a diesel hammer (KB80; 8 tf ram weight). Measurements taken during the driving test were the number of impacts for driving, rebounds and penetrations, ram falling distance and strains (at 8 cross-sections). For one pile each of the loading test and reaction piles, PDA measurements were taken.

Fifteen days after initial driving, a static loading test was conducted according to Vertical Loading Test

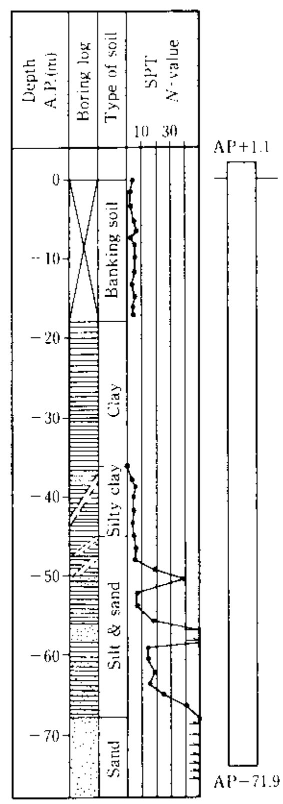

Fig. 6 Soil condition and test pile in final seating

Table 5 Results of dynamic test (tf)

		Total resistance	Shaft resistance	Toe resistance	Pile driving formulae		
					Formula (1)[a]	Formula (2)[b]	Formula (3)[c]
Testing pile	End of driving	323	278	45			
	Static loading test (elapsed 15 day)	1 400	890	510	1 473	1 059	1 650
Reaction pile	End of driving	317	278	36			
	Redriving (elapsed 47 h)	756	736	20	1 179	1 026	1 026

[a] Formula (1) $R_d=\frac{AEK}{e_0 l}+\frac{\bar{N}Ul}{ef_0}$ [b] Formula (2) $R_d=\frac{F}{5S+0.1}$ [c] Formula (3) $R_d=\frac{ef\cdot W_H\cdot H}{S+(K/2)}$

Table 4 Driving data at the end of installation

	Penetration (mm)	Rebound (mm)	Blow count	Ram height (m)	Max. stress at pile top (kg/cm²)
Test pile	3.6	18.0	3 938	2.6	1 446
Reaction pile	4.3	32.0	2 921	2.6	1 507

Standard for Piles and Related Comments (JSSMFE).

Measured results after driving the test and reaction piles are shown in **Table 4**. The difference in rebound value between the test loading pile and the reaction pile is attributed to the difference in rigidity between the two piles. The ultimate bearing capacity calculated from the driving data and pile driving formulae (1. Specification for Highway Bridges, 2. Construction Ministry Notification Formula, and 3. Hiley's Formula) and the results of dynamic loading tests after driving and redriving are shown in **Table 5**. Values calculated by the pile driving formulae were 0.75 to 1.17 times the static loading results, and all the calculated results satisfied the designed ultimate bearing capacity (939 tf). The dynamic penetration resistance at the end of driving by the CAPWAPC method was 0.23 times the static ultimate pile capacity and, 47 h later, reached 2.4 times the dynamic penetration resistance and 0.54 times the static ultimate pile capacity. The toe resistance was underestimated, and this is considered an effect of inadequate driving energy.

In the past, the penetration and rebound that would satisfy design values were calculated from the pile driving formula, and after comprehensively judging the values, pile driving was controlled by the standard shown in **Table 6**. In this paper, the authors propose calculating the relationship between the dynamic penetration resistance and the penetration by using the results from the CAPWAPC method and the piling simulation based on stress wave theory (**Fig. 7**). From this figure, we used the ratio between static ultimate bearing capacity and dynamic penetration resistance as 0.3. The designed ultimate bearing capacity was multiplied by this ratio, and further multiplied by a safety factor of 1.2 by taking into consideration the variation in ground conditions. Using the result of this calculation, we obtained the required penetration (6.5 mm) to suit the necessary dynamic penetration resistance. This result is similar in value to the ultimate penetration value (6 mm) shown in Table 6, thereby confirming that the pile driving control standard that was obtained by the stress wave theory could provide the same control standard as that by the conventional method.

Table 6 Proposed criterion for permanent pile installation

Penetration into bearing stratum	l	>4 times of pile diameter (3.2 m)
Final penetration	S	≦6 mm
Final rebound	K	≧25 mm
Blow count for last 1 m	N	≧200
Bearing capacity R_d by pile dynamic formula		$R_d \geqq P_S$

$R_{d1}=\frac{1}{3}\times\frac{ef\cdot W_H\cdot H}{S+(K/2)}$ $R_{d2}=\frac{F}{5S+0.1}$

P_S: Design allowable capacity

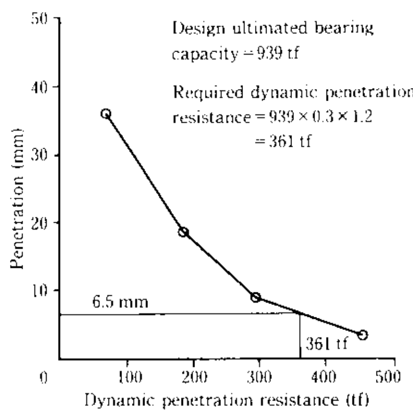

Fig. 7 Proposed criterion for permanent pile installation based on stress wave theory

3.3 Example of Artificial Ground Construction Work at Omiya

The Omiya artificial ground construction project partially used piling based on the STEP method[22] in view of the special nature of the construction site which is located above a retarding basin. This STEP method involves the pile driver being mounted on the piles which have already been driven, so that the driven piles must be able to directly bear the distributed load of a mounted pile driver weighing about 350 t only one day after being driven due to the piling cycle. For this work, steel pipe piles with a diameter of 600 to 800 mm were used, and in the most severe case, one pile of 600 mm in diameter had to bear a maximum mounted load during piling work of 122 t. In order to confirm the safety of the piling work, therefore, it was necessary to properly evaluate the bearing capacity of the pile one day after it had been driven.

The conventional pile capacity control method is based on the pile driving formula, and the formula itself was not meant for estimating the bearing capacity one day after driving a pile; hence, with the Omiya piling work the authors combined the piling simulation program based on stress wave theory with PDA measurements and analysis, and produced a bearing capacity control chart showing the relationship between the penetration and dynamic penetration resistance to more accurately estimate the bearing capacity of the pile one day after driving. The procedure for producing the bearing capacity control chart and the method of bearing capacity control on site are shown in **Fig. 8**. As an example of the bearing capacity control chart, the case of a pile with a diameter of 600 mm is shown in **Fig. 9**. The conventional method frequently involves producing a control chart by setting up empirical input parameters. When preparing the present control chart, however, values for the dynamic penetration resistance, soil characteristics, etc., which were obtained by the CAPWAPC analysis of actual pile driving data were fed back as input data, thereby improving the reliability of this new control chart compared with what is possible by the conventional method.

Bearing capacity control graphs ② and ③ in Fig. 9 were used to control the bearing capacity at the site. For instance, if value © of the bearing capacity in graph ② that was evaluated by the driving data at the end of initial driving fell short of the maximum loading weight of 122 tf during STEP construction, it was possible to evaluate bearing capacity Ⓓ of the pile one day after by graph ③, showing that this bearing capacity control method could confirm the safety of the construction work. In this PDA application on site, a comparison was also made between the results of the static loading test done on site and the PDA analysis results in order to verify the validity of the method being used.

In an example of the STEP method used with Kawasaki Steel's Urayasu quay construction work, a vertical loading test was conducted in order to confirm the elapsed time increase in bearing capacity. The Omiya job proved the capability of the present method for achieving reliability and safety in the construction work,

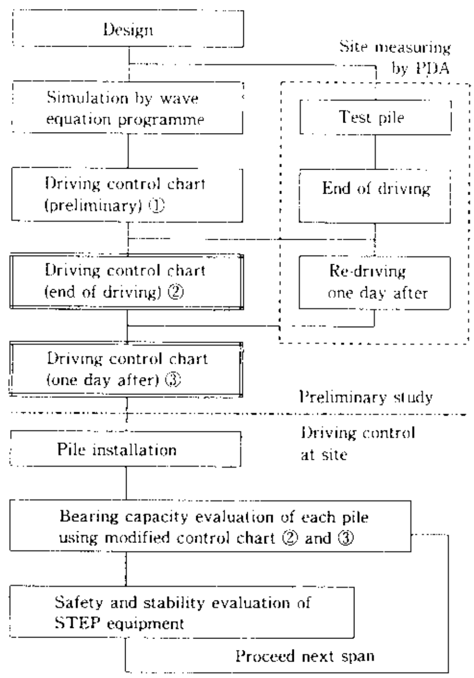

Fig. 8 Pile driving control flow chart for STEP

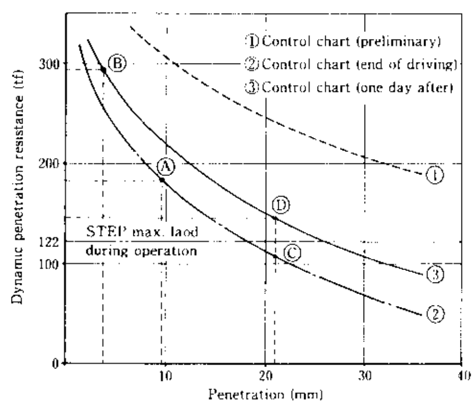

Fig. 9 Pile driving control chart

and introduced PDA as an effective method in terms of both ease of use and economy of construction period.

4 Conclusions

The PDA (pile driving analyzer) method has been described for estimating the pile bearing capacity based on stress wave theory, its applicability has been examined, and application examples of bearing capacity control for actual pile driving have been presented. As a result, the following results were obtained:

(1) The values for the dynamic penetration resistance estimated by re-driving and the ultimate bearing capacity by load testing agreed with each other to an error range of 5 to 10%. Considering other comparative results, it is possible to estimate the ultimate bearing capacity comparatively free of error by a

systematical re-driving test.

(2) In estimating the resistance by PDA, it was found that when the driving energy was low, the bearing capacity was also calculated low, and when driving energy was too high, the pile began to penetrate again, thereby making impossible an accurate calculation of the maximum dynamic penetration resistance. Therefore, setting of an appropriate input energy is necessary.

(3) In calculating pile bearing capacity setup by re-driving, attention should be paid to the elapsed time after pile driving, and depending upon the soil conditions, re-driving must be made after an appropriate period.

(4) The use of the PDA system as a method of bearing capacity control on site is beneficial for improving the accuracy of bearing capacity control. Especially, in the case of the STEP method, in which the load from the piling equipment is applied within a few days after pile driving, this is a useful means for enhancing the safety and reliability of the method.

The features of PDA are: the simplicity of site measuring work and equipment, especially the effectiveness for offshore piling; and the ease of analysis made possible only by measurements at the pile head to estimate the stress on the pile and the soil resistance to the shaft and toe. Actually, the evaluation of pile bearing capacity by the stress wave theory has been a field of rapid progress in Japan, with various proposals being made and researches being carried out currently. With these methods, however, the relationship between parameters to be used in analyses and the soil constants are not clear, making a soil mechanical evaluation of the analytical results difficult. Kawasaki Steel incidentally has installed pore water pressure transducers in the ground around a pile, to study the relationship between changes in pore water pressure and shaft friction force. The authors intend to continue these studies to contribute to the future construction of safer and more reliable foundations by establishing a method that will permit a more accurate evaluation of the bearing capacity of a steel pipe pile.

In conclusion, the authors express their deep appreciation to those concerned who have rendered their valuable cooperation with measurements and analyses, and also to those organizations who have kindly permitted quoting of their data.

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