ESTIMATION OF PILE BEHAVIOR UNDER HORIZONTAL LOAD

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Abstract

Behavior of foundation pile when it receives horizontal load is generally treated as that of bending beam on elastic bed. In this treatment very important is to know the horizontal reaction coefficient of ground, that is, K-value.

In liner elastic body K-value is constant. In actual ground, however, K-value is not constant and decreases with increase of displacement of pile due to nonlinearity of stress-strain relationship of soil.

The authors developed a new method which allows pursuit of pile behavior through whole process of loading. To be exact, the method enables us to determine K_i for optional desplacement y_i and to determine the horizontal load H_i for y_i from a series of linear solution curves where $K=K_i$. Then, we can draw the behavior curve by connecting all plots on graph.

The authors has studied how to determine K-value for optional displacement according to many results of horizontal load testing of pile. This method was also developed successfully in combination with the results of lateral load test (LLT) in borehole.

Based on the results of LLT measurement to be conducted in borehole for preliminary survey we are now able to forecast behavior of foundation pile under horizontal load with sufficient accuracy.

1 INTRODUCTION

Since developing the LLT (Lateral Load Tester)[1),2)] ten years ago for determination of subgrade reaction coefficient K and evaluation of horizontal resistance of pile foundations, the authors have continued research and experimentation. As a result, in 1970 Imai proposed a simple and effective design method[3),4)] for the estimation of lateral load behavior of piles on the basis of K values obtained from LLT measurements and its practical application. This paper presents results the authors have obtained concerning research on one of the problems not covered by our previous reports, that of a method for calculating equivalent K_0 value in multilayered ground and experimental verification of the method. Thus, this paper concerns results obtained by testing of lateral loading on piles and LLT measurements.

2 THE LLT TEST METHOD

As shown in Figure 1, the LLT apparatus consists of a gas tank, pressure and volume meters, a probe and nylon tubing. Nitrogen gas is used as the pressurizing medium. The nitrogen gas goes from the tank to a regulator, and then to the volume meter. The volume meter is connected to the cell in the probe by a nylon tube. Water is forced into the cell by gas pressure and the cell expands. The volume of water in the cell may be seen by a water level guage connected to the volume meter. Both gas pressure and actual water pressure are monitored. Measurement of loading and of deformation is done by the stress control method. Loading is

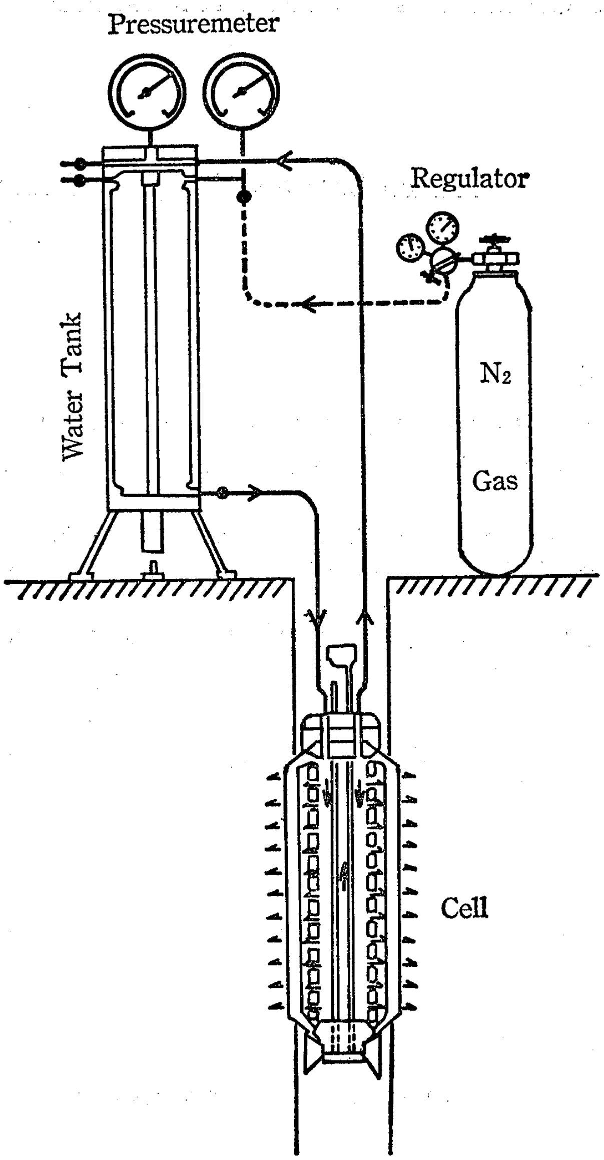

Fig. 1 LLT apparatus

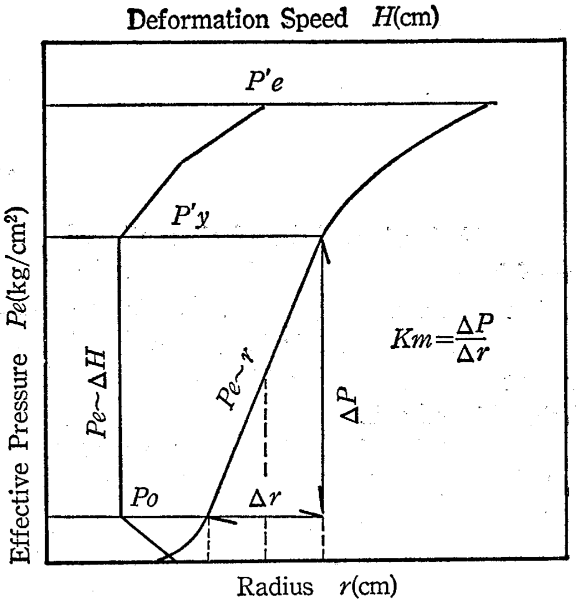

Fig. 2 LLT test results schematically drawn

conducted at intervals of 15 seconds, 30 seconds, 1 minute and 2 minutes at each loading stage. Fig. 2 shows model measurement results. In the figure, r_o is initial borehole radius, that is, that radius of the borehole, which had been contracted by earth pressure at rest, re-expanded by the expanding rubber section of the probe inserted into the borehole. In other words, this is the radius at which earth pressure at rest is cancelled out. Measured K value (K_m) which constitutes a nearly straight $P_e \sim r$ curve following initial radius on the graph, is expressed by the following formula:

$$K_m = \frac{\Delta P}{\Delta r} \qquad (1)$$

Deformation coefficient E is obtained by using elastic theory for 2-dimensional plane strain, K_m, mid-point radius R_m and Poisson's ratio ν in the following formula:

$$E = (1+\nu) \cdot r_m \cdot K_m \qquad (2)$$

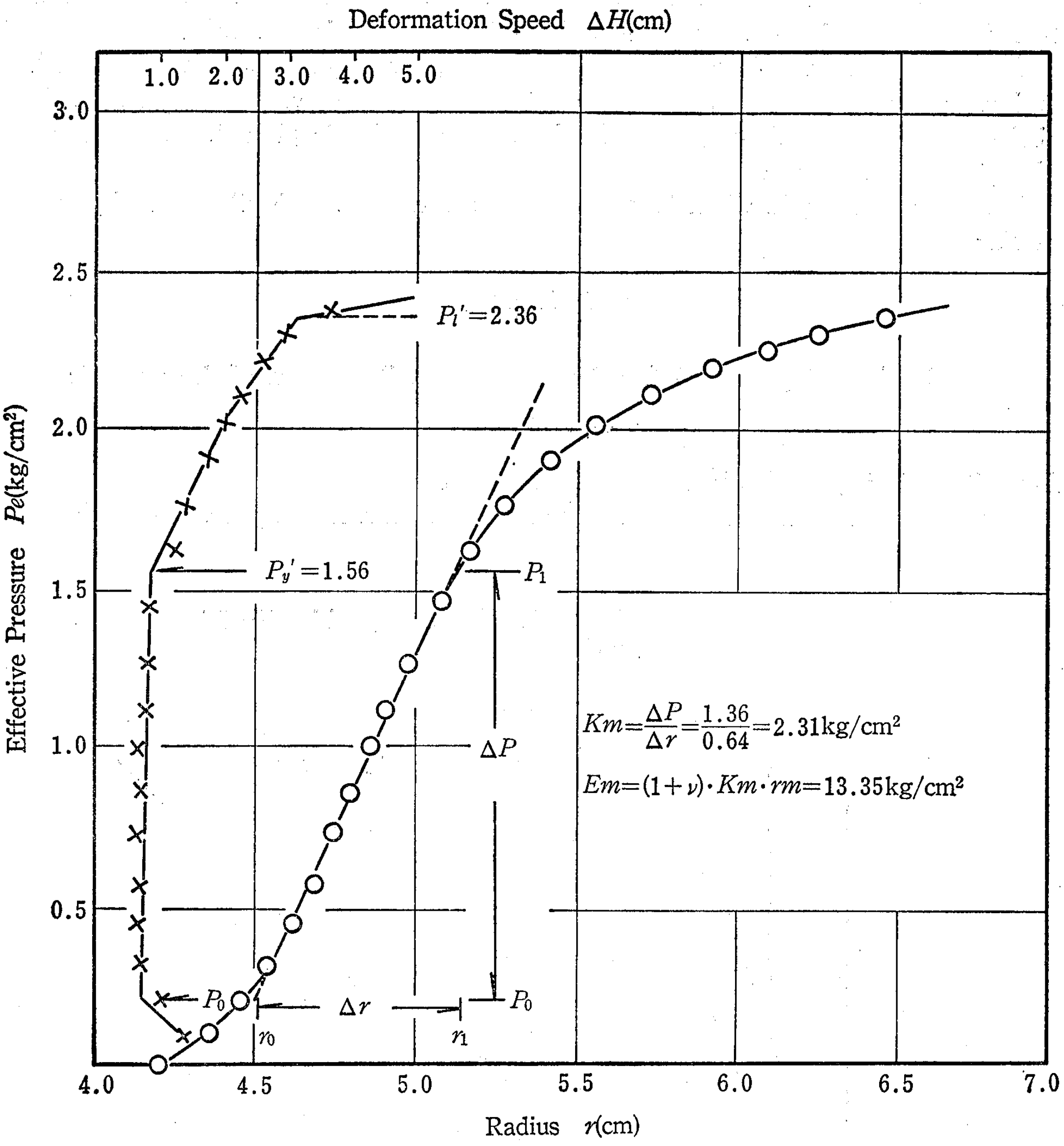

Fig. 3 An example of test result by LLT

In addition, by using the $P_e \sim r$ curve and $P_e \sim \Delta H$ (speed of deformation) curve, such dynamic properties as earth pressure at rest P_o, yield strength P_y and limited pressure P_l are determined. Figure 3 is an example of actual measurements.

3 OUTLINE OF IMAI'S METHOD

When piles are subjected to lateral loads, the resulting load-displacement relationship is not a straight line, but a curve. This can be seen in most of the data obtained from loading experiments. Consequently, when the behavior of a pile subjected to lateral loads is treated as the bending of a beam in an elastic bed, such as in the method proposed by Chang (in which the ground is treated as a linear elastic body) it is difficult to characterize the overall behavior of the pile. In this regard, Imai has adapted Chang's method, which permits relatively easy calculation of pile behavior. Imai's method takes into account the non-linear nature of the ground to describe the behavior of a pile through the entire loading process. In this method, design K_0 value (K value when displacement is 1 ㎝) is used as a basis for determining K value at any displacement (general K value). For each K value thus determined, the required load is calculated. Figure 4 illustrates this. In the diagram, K_i values for all displacement y_i values are plotted. Then, from Chang's behavior curves for $K=K_i$, load H_c for each y_i value is plotted. The curves obtained provide the pile behavior curve.

Behavior of the pile when it is subjected to lateral force is illustrated by the following basic formula:

$$EI\frac{d^4y}{dx^4}+P=0 \tag{3}$$

Here, the following general function expresses soil reaction of the ground:

$$P=\alpha \cdot B^l \cdot x^m \cdot y^n \tag{4}$$

where, B=radius of pile, x=depth and y=displacement

Here, the function expression of K values are shown as apparent K values when the

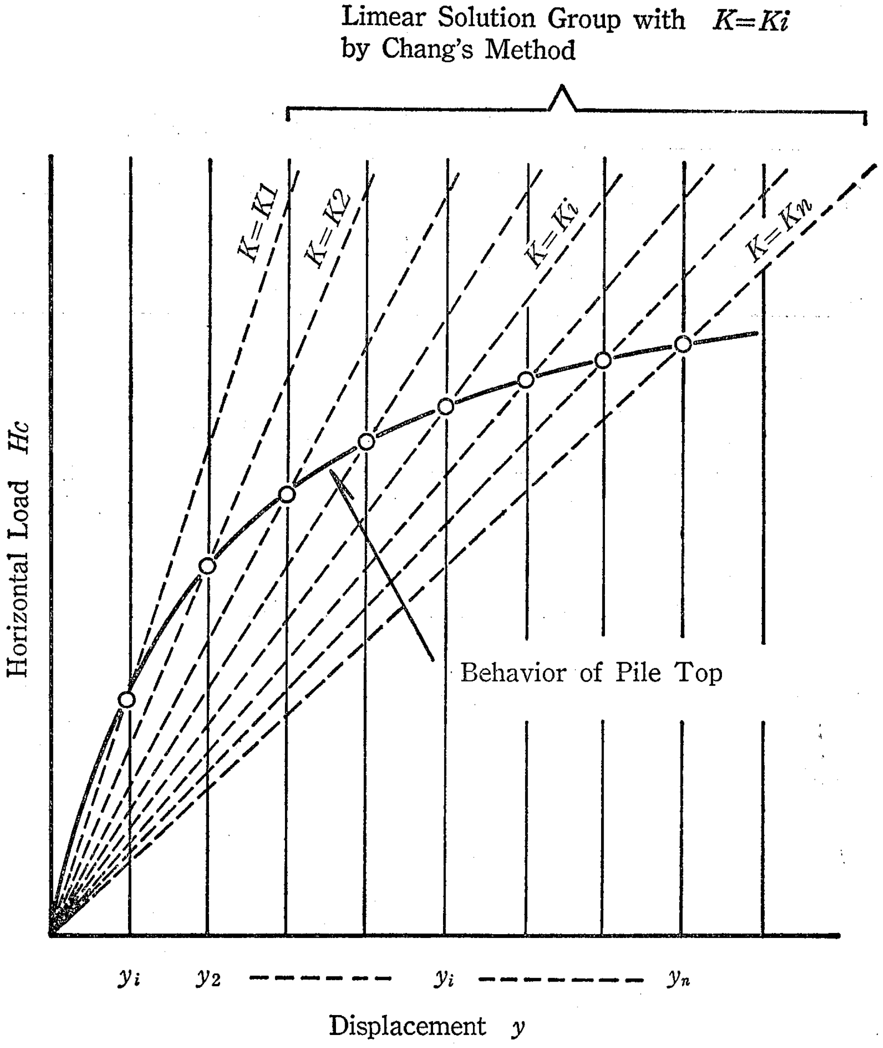

Fig. 4 Schematic expression of assumption of pile behavior

non-linear formula (4) is substituted into the linear model $P=K\cdot B\cdot y$ to produce the following formula:

$$K\cdot B\cdot y=\alpha\cdot B^{l}\cdot x^{m}\cdot y^{n} \tag{5}$$

Consequently,

$$K=\alpha\cdot B^{l-1}\cdot x^{m}\cdot y^{n-1} \tag{6}$$

When each of these indexes is determined on the basis of lateral load test of piles, K value is proportional to a value in the range of $y^{-\frac{1}{2}}$ to $y^{-\frac{2}{3}}$, and proportional to $y^{-\frac{1}{4}}$ of piles radius. In addition, when corrections are made for the difference between loading patterns of the pile and of the LLT, the formula for calculating the design K value required for the pile is shown by the following formula (Please refer to Reference 3 for details concerning Imai's proposal):

$$K=\frac{\pi}{2}\sqrt[4]{\frac{2r_o\,(r_m-r_o)^2}{B\cdot y^2}}\cdot K_m \tag{7}$$

In Formula (7), if displacement y is 1 cm, and K is defined as basic value K_o, K_o is expressed by the following formula:

$$K_o=\frac{\pi}{2}\sqrt[4]{\frac{2r_o\,(r_m-r_o)^2}{B}}\cdot K_m \tag{8}$$

If, in Formula (8), pile diameter B is 1 cm and K value is defined as specific K value, k_o, the following formula is obtained:

$$k_o=\frac{\pi}{2}\sqrt[4]{2r_o\,(r_m-r_o)^2}\cdot K_m \tag{9}$$

where, r_o=LLT initial radius (cm)
r_m=radius at midpoint of range determining K_m, and
K_m=measured K value

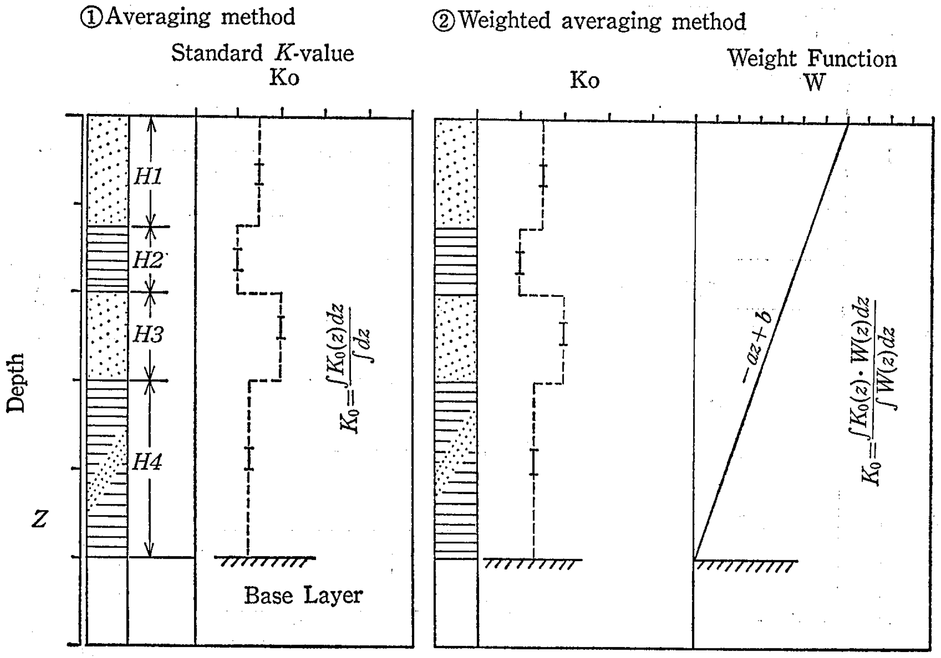

Fig. 5 Basic ideas of calculating equivalent K-value

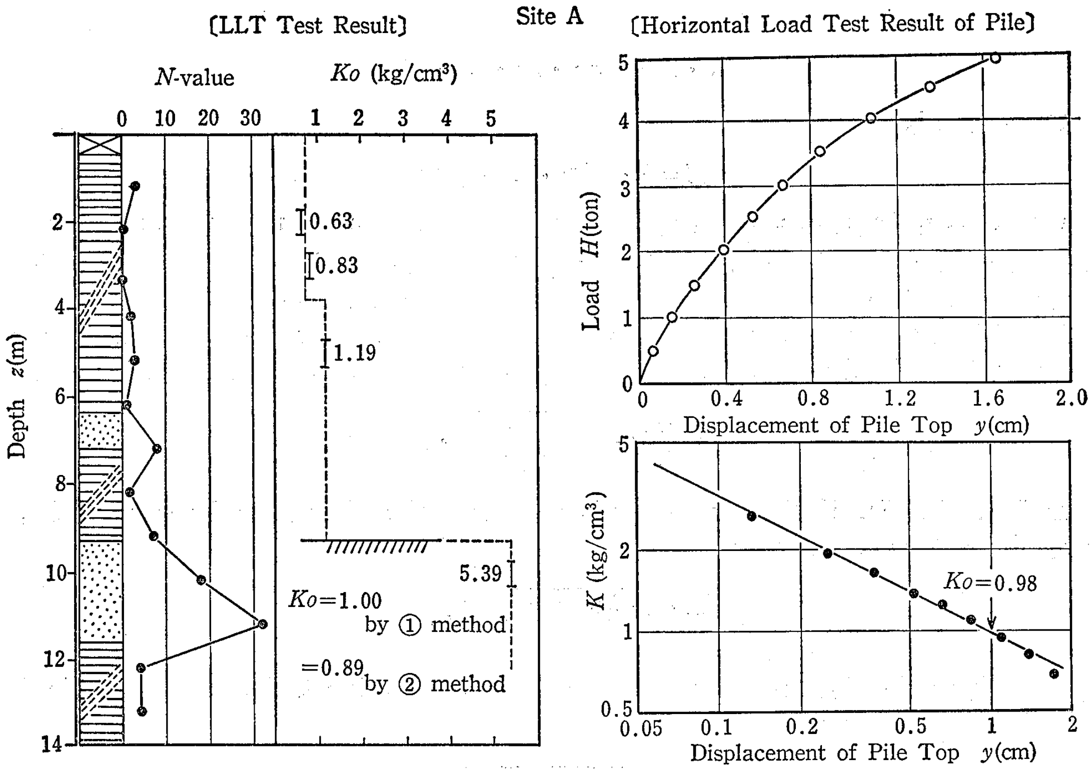

Fig. 6 An example to compare equivalent K-value with measured K-value by pile test

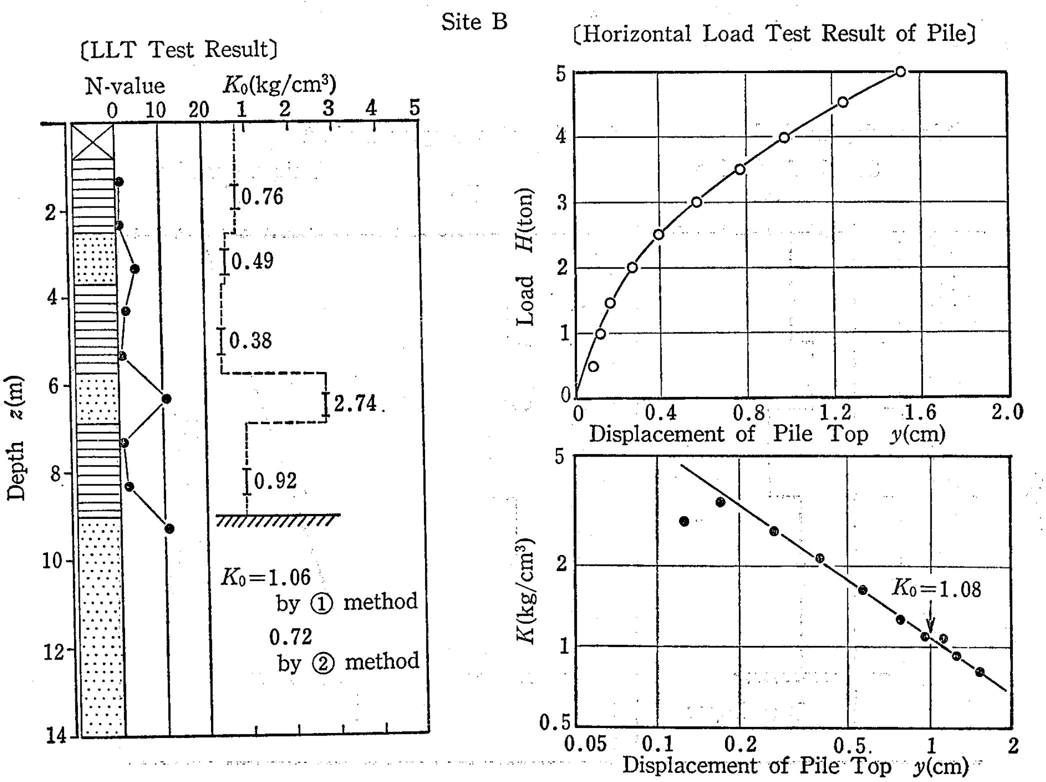

Fig. 7 Another example of comparison

4 EQUIVALENT K_0 VALUE IN MULTILAYERED GROUND

In general, ground is not homogenous in the vertical direction, but, is rather made up of a number of layers. For this reason, ground K values obtained from LLT measurements naturally reflect differences in types of soil, N value, etc. With the availability of computers, even with such complex conditions, it is easy to calculate values of this type. When it comes to the problem of the behavior of piles subjected to lateral forces, it is naturally extremely convenient to be able to calculate design K value (an average value representation of the different K value found in the ground depending on layer depth. etc.)

Thus, we will consider methods for calculation of equivalent K_0 value in multilayered ground. As shown in Figure 5, there are two basic calculation methods. Method 1 takes into account the thickness of the layer by taking a weighted average. Method 2 considers that the main effect of lateral force on K_0 values are towards the top of the pile, while effects fall off with increasing depth. This method takes into account the weight of the layer as depth increases. Equivalent K_0 value is calculated to about 1.5 times the depth that the first bending moment of piles equals zero.

Both methods 1 and 2 are used to calculate equivalent K_0 value. Using these calculated values and the results from lateral load testing conducted at the same point, load displacement curves are made and Chang's formula for the relationship between load and displacement is used to calculate K value. The results of this process are shown for site A in Figure 6 and site B in Figure 7.

Figure 8 shows equivalent K value determined by the two methods, and the equivalent K value calculated on the basis of lateral load test results (when displacement is 1 cm). Although there is a shortage of data, it can be seen that in method 2, equivalent K_0 value determined by

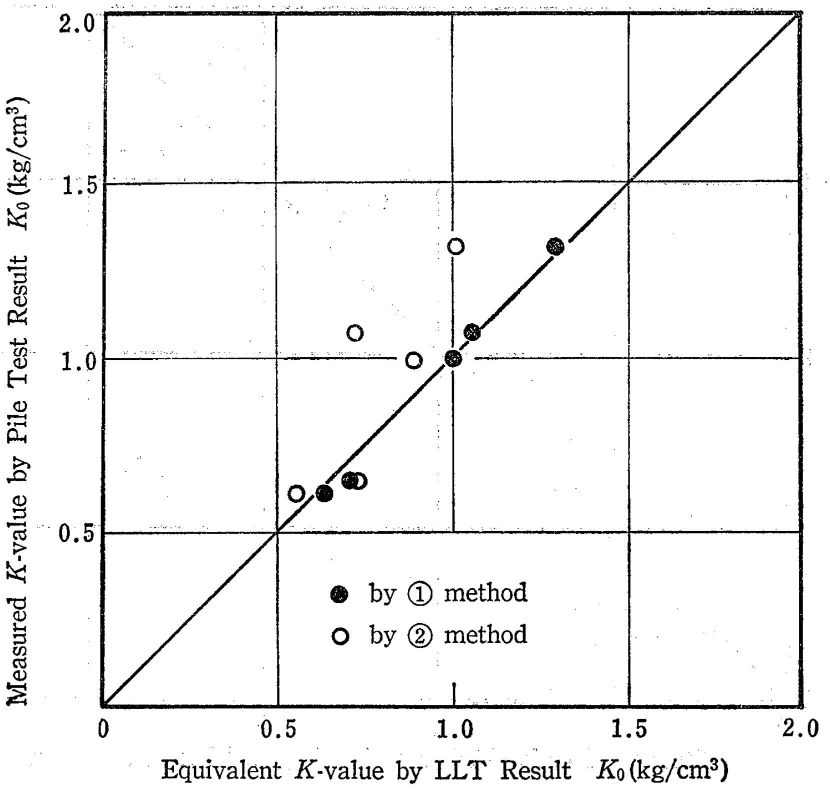

Fig. 8 Comparison of K-values by LLT and pile load test

calculations weighted for variations of K value according to layer thickness and depth is slightly smaller than K_0 value calculated from lateral load tests of piles. Furthermore, in method 2 there is more scatter. However, we see very good correlation with method 1, in which K_0 value is calculated by taking only thickness of the layer into consideration. Thus, in calculation of equivalent K_0 value in multilayered ground on the basis of LLT measurement results, the method that takes only thickness of the layer into account is preferable.

5 VERIFICATION OF IMAI'S METHOD

The K_0 values of Figure 9 were calculated on the basis of 27 LLT measurements and lateral load testing on piles taken at 12 investigation sites. Calculations took into account the thickness of the layer. For every piece of data the basic K_0 value, from lateral load test on piles and the equivalent K_0 value infering for demensions of piles using LLT measurement results were calculated. In addition, the relationship between thickness of the layer and equivalent K_0 value was investigated.

The piles used in the lateral load test included RC, steel pipe and large diameter, cast-

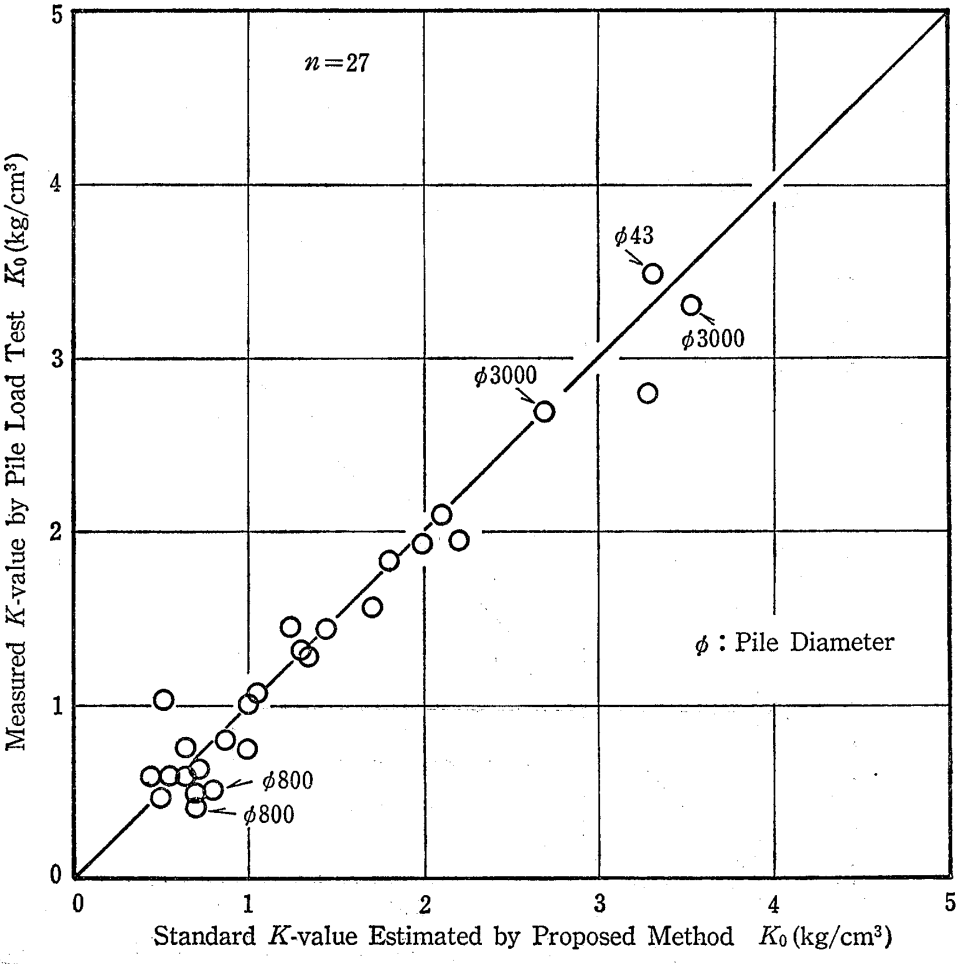

Fig. 9 Comparison between measured and estimated K-value

in-situ piles. With diameters ranging from 4.3 cm to 3 m, there were 10 types of piles. As shown in the Figure, K_0 value calculated on the basis of pile loading test results show a fairly good correlation with equivalent K_0 values determined from LLT measurement results.

As mentioned above, Imai has suggested that K value as determined by Chang's method on the basis of results from lateral load testing becomes smaller as displacement of the head of the pile increases. This value falls off in proportion to $y^{-\frac{1}{2}}$ to $y^{-\frac{2}{3}}$.

Figure 10 shows K values calculated on the basis of recently conducted lateral load tests on piles. The figure shows that the results indeed decrease within a range of about $y^{-\frac{1}{2}}$ to $y^{-\frac{2}{3}}$.

6 PROPOSED PROCEDURE FOR EVALUATION OF PILE TOP BEHAVIOR UNDER HORIZONTAL LOADS

Figure 11 represents a summary of the calculation procedure for application of LLT measurement results to actual design in accordance with the authors' proposal. This procedure permits deduction of deformation of pile top for piles of certain given specifications (E, I, B) and for LLT measurement results.

7 AFTERWORD

In this paper we have considered methods of calculating equivalent K value in multilayered ground. Using recent data from lateral load testing, we have discussed verification of the proposal by the authors for describing the behavior of a pile during the loading process. We have concluded that the best method for calculating K value of multilayered ground is the method

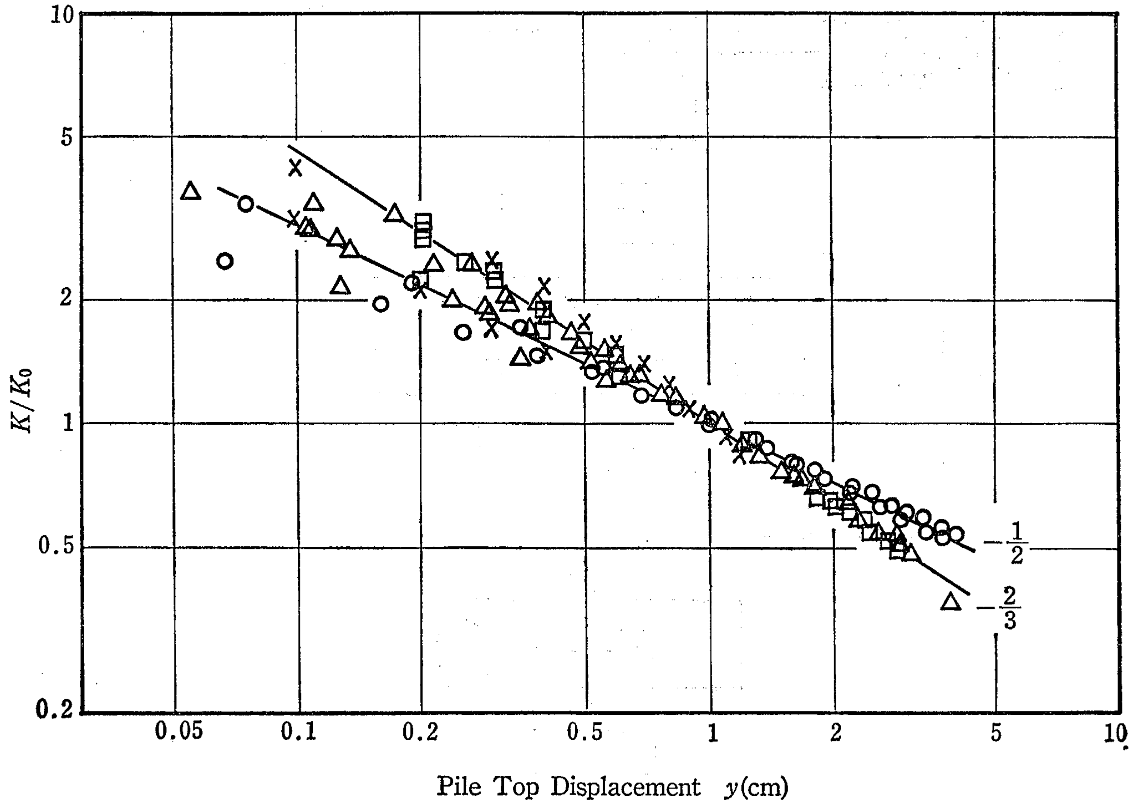

Fig. 10 Relations of K-value with displacement of pile top

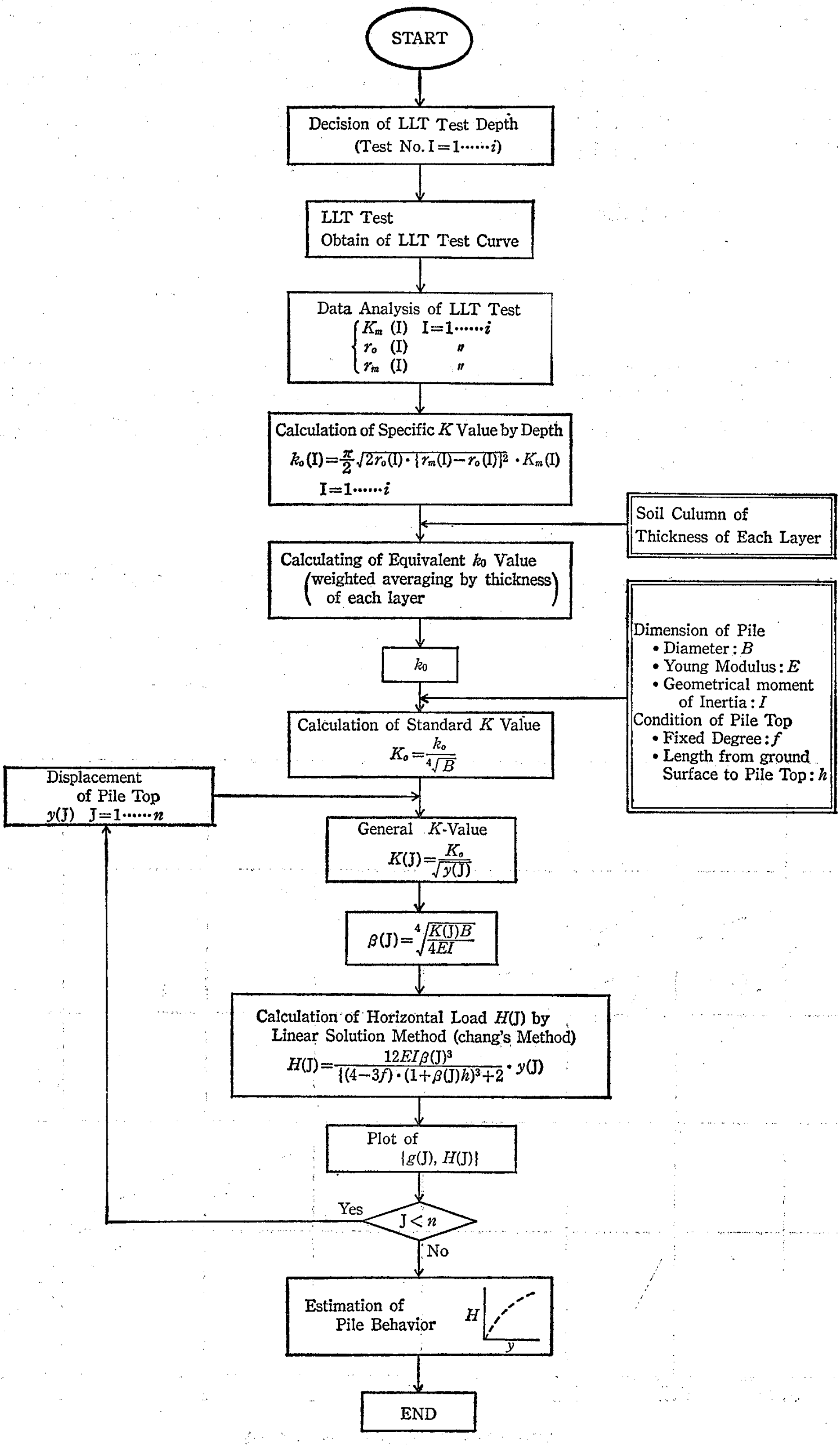

Fig. 11 Calculation procedure for evaluation of pile top behavior under horizontal loads

which takes into account thickness of the layer by averaging values. Also, in the process of verifying the proposal, we have found very good correlations with previous research reports. In conclusion, we have found that by using results from LLT measurements, it is possible to predict the actual behavior of piles under lateral load.

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水平荷重をうけるクイの挙動の予測

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概　要

クイ基礎の設計を行なうに際して，水平力を受けるクイの挙動を把握することは，重要である。しかしながら，実際のクイの水平挙動全体を説明できる簡便で実用的な計算手法は，必らずしも確立されておらず，目安を得る為の簡便法か，あるいは電算による複雑な解法に向っているのが現状である。

約10年前にＬＬＴ (Lateral Load Tester) を開発して以来，研究的，実験的検討を加えて，ボーリング孔内でのＬＬＴ測定結果を用いて，クイの水平載荷挙動の全過程を比較的簡単に推定できる実用的な設計法を提案し（今井，1970），これまで実用に供してきた。

本論文は，これまでの一連の研究報告のうち，課題として残されていた多層地盤における等価 K_0 値の算出方法について検討を行なうとともに，提案した計算法について，その後の実験データによる験証を行なった。さらに，これらのことをまとめ，これまでの提案方法とあわせて，ＬＬＴ測定結果から実際のクイの水平載荷挙動を予測する一連の手法について，とりまとめ示したものである。

図—１は，ＬＬＴの装置図を示す。圧力は窒素ガスを利用し，載荷は時間〜荷重制御方法により行なう。各荷重段階は２分間隔である。図—２は，測定結果を模式的に表わしたものである。測定K値は，図の P_e〜r 曲線の直線部分の勾配として求められる。図—３は，その実測例である。

図—４は，提案した計算法の基本的な考え方を示す。基本的には，計算が比較的簡単な Chang の方法を用いている。クイが水平力を受けた時，結果として得られる荷重〜変位曲線は，一般に曲線形状を示し，Chang が示した弾性床上の梁の曲げ問題としては説明しきれない。そこで，地盤の非線型性を考慮して，変位１cmのときの基準K値 K_0 をもとに，任意の変位でのK値（一般K値）を求め，その変位に見合うそれぞれの所要荷重を算出して，求めた荷重と変位の関係を連続的につらねることにより，クイの全載荷過程の挙動を追跡可能とするものである。なお，クイの所要の設計K値は，ＬＬＴの測定結

果より，(7)式および(8)式によりそれぞれ算出される。

図―5は，地盤が多層から構成されているときの等価K_0値の算出方法について示した。すなわち，一般に地盤は深さ方向に均質でなく，したがって，得られるK_0値も土質やN値の変化に対応した分布を示す。しかし，クイの水平力下の挙動を容易に取り扱うには，変化しているK_0値をならして，代表K_0値とでもいうべき地盤の一つの等価K_0値を求めることができれば望ましい。①の方法は，ＬＬＴ測定で得られたK_0値に層厚分の重みを加えて等価K_0値を求めるものである。また，②の方法は，層厚とともに深さ方向の重みを考慮して等価K_0値を求める方法である。なお，等価K_0値の算出は，一応の目安としてＬＬＴ測定データのうち，クイの曲げモーメント0になる深さの約1.5倍程度としている。図―6および図―7は，この2方法の考え方に基づいた等価K_0値の算出例を示す。図―8は，この2方法により求めた等価K_0値と同じ地点で実施したクイの水平載荷試験結果の荷重～変位曲線から，Chang の式により逆算して求めた基準K_0値（変位1 cmの時のK値）の関係を調べたものである。①の方法による層厚のみ考慮して求めた等価K_0値は，クイの水平載荷試験結果より逆算して求めた基準K_0値と良く一致している。このことから，多層地盤における等価K_0値は，ＬＬＴ測定結果から求めた基準K_0値に，層厚分の重みを考慮することにより得られることがわかった。

図―9は，ＬＬＴ測定と実グイの水平載荷試験を合せて行なっている12調査地27個のデータについて，ＬＬＴ測定結果から層厚を考慮して求めた等価K_0値と，クイの水平載荷試験結果から逆算して求めた基準K_0値の関係を示したものである。かなり良い相関を示す。

図―10は，提案した計算法について，その後のデータによる験証を行なったものである。すなわち，最近得られたクイの水平載荷試験結果から Chang の式により求めた逆算K値と，クイ頭変位の関係を調べたものである。逆算K値は，クイ頭変位が増大するにしたがって減少し，変位の$-\frac{1}{2}$乗～$-\frac{2}{3}$乗に比例する。このことは，以前報告した結果と良く一致している。

以上のことから，実際のクイの水平載荷挙動は，ＬＬＴ測定結果から提案した計算法を用いて十分に予測できることがわかった。

図―11は，これらのことを総括し，ＬＬＴ測定結果を用いて，クイの水平載荷挙動を予測するための一連の計算手順をとりまとめ示したものである。