EVALUATION OF BENDING LOAD IN BATTER PILES SET IN SOFT CLAY

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Abstract

In this study, we conducted centrifuge tests to evaluate the bending load. The parameters are depth of clay layer, angle of skew, and others. We evaluated the bending load occurring in batter piles from these experimental results and observed the results in actual bridges. We propose a method of estimating the bending load in batter piles in soft ground. The proposed method makes more accurate predictions than the equations proposed in the 1960s.

Introduction

Batter pile foundations are believed to have a larger horizontal bearing force than vertical piles. Thus, the use of batter pile foundations is expected to reduce the cost of highway bridge structures. However, problems exist in the design and construction techniques for batter pile foundations. So, the design method is not shown in Specifications for Highway Bridges.

We suggest a way to evaluate the consolidation load acting on batter piles, which are sometimes used in soft ground. In soft clay ground, long-term consolidation settlement occurs; a consolidation load acts on batter piles with the settlement, and a bending load occurs in the piles. In the 1960s, equations for evaluating the bending load occurring in batter piles were proposed. However, they are believed to overestimate the load. To use batter pile foundations for bridges, we must correctly evaluate the load.

Bending transformation occurs in piles with consolidation settlement in soft ground. In the pile foundation design handbook(Japan Road Association, 2007.), a method of estimating this bending transformation was introduced. This method was proposed on the basis of the results calculated for the Tomei/Kuno highway bridge by the former Japan Highway Public Corp(Japan Highway Public Corp, 1970.). Fig.1 shows the conceptual diagram of this method. In this method, we have an assumption that a batter pile is cantilever beam. By this method, the distributed load, *P*, can be calculated using next equation.

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$$P = \alpha DU\Sigma\gamma h \sin\theta$$

In which, α = a coefficient that defines the load with < 3, D = pile diameter, U = degree of consolidation, γ = unit weight of a soft clay consolidation layer, h = depth of load acts, θ = angle of the piles. Usually αD = the distance between adjacent piles. This equation is called as Sato's equation.

They proposed that soft ground covering 80% of the area in all ground layers acts on the batter piles as a distributed load. However, this is based on very few results, so, we think the scope for application is limited. In fact, when we tried to design batter piles with this method, unrealistically large deformation occurred in the piles. Therefore, we think that evaluations by this method are overly cautious. Other researchers have examined construction methods for reducing negative friction by using asphalt coating for piles. However, some experimental results show that these methods can increase the bending deformation in piles, so this method cannot be a fundamental solution.

The deformation of batter piles by consolidation settlement is a function of the thickness of the layer and the rigidity of the pile and the ground. In retrospective research, some have tried to (i) replicate the experiment by changing the action area or magnitude of the consolidation load or (ii) predict the bending deformation of the piles with a response displacement method that considers the deformation of the ground and the piles. However, the parameters, for example the extent of the impact, the consolidation load, the deformation of the ground, and the rigidity of the spring between the pile and the ground, are considered individually, and we have no integrated information. In method (i), we know that we can replicate the experimental data by supposing a triangular consolidation load and adjust the area of the load, but we do not know how to determine the area of the load. In method (ii), the area of the load is determined uniquely, but if we set the elasticity spring on the entire length of the piles, we cannot replicate the experimental results.

We conducted experiments to evaluate the bending deformation occurring in batter piles in consolidated ground for certain conditions: the thickness of the soft ground layer, the angle and diameter of the batter piles, and so on. On the basis of these experiments and retrospective research, we propose a method for evaluating the bending deformation of batter piles caused by consolidation in soft ground.

Experimental setup

Fig. 2 shows the experimental setup. This experiment was conducted in a centrifugal field of 50G. We used a soil box 1500 mm wide, 500 mm high, and 300 mm deep. The ground used in the experiments consisted of a supporting layer of sand and a soft clay consolidation layer. First, we deposited the sand layer in the gravitational field with a target Dr of 85%. The sand layer was compacted by hand. Next, we pour slurry of kaolin-clay into the soil box. We then set the soil box in the centrifuge and increased the acceleration to 50G. We let the box stand for two or three days to consolidate the kaolin-clay to achieve normally consolidated clay, with a target degree of consolidation of 90%. We moved the soil box to the gravitational field and set up the pile model (Photo 1) and measurement instruments. Finally, we placed the soil box in the centrifuge again and poured water, as a vertical load, onto the surface of the clay after setting an impermeable bed on the surface of the clay to keep the water from permeating the clay.

Table 1 shows the experimental conditions. The parameters are the diameter of the piles (16.0 or 19.0 mm), the angle of the piles (0, 8, or 15 degrees), the thickness of the clay layer (200, 250, or 300 mm), and the strength of the clay layer (poor or semi-firm). The pile diameters are equivalent to 800 mm or 1000 mm in the gravitational field; these are common screw piles sizes in highway bridge foundations. Fifteen degrees is a construction limit. The thicknesses of the clay layer are 10–15 m in the gravitational field. To make a semi-firm clay layer, we put a steel board on the clay surface when we consolidated the clay layer. As a result, the effective cohesion c' of the poor clay is about 6.0 kN/m^2, and that of the semi-firm clay is 8.5 kN/m^2.

We aimed to measure the settlement of the clay layer, the strain on the piles, the settlement and displacement of the footing and pier model, and the water pressure. The water pressure was measured to evaluate the degree of consolidation of the clay. The settlement of the clay layer was measured at four points. The strain was measured at two batter piles and one straight pile. The strain on the batter piles was measured at seven points along the depth direction. Two strain gauges were set at each depth mounted face to face. To evaluate the strain, we smoothed the measured strains because the data contained considerable noise.

After this, we show all parameter in prototype scale.

Experimental results

Fig. 3 shows the settlement of the clay at each depth. The frame of the distribution of the settlement is triangular, so the displacement distribution in this experiment is approximately the same as the theoretical distribution. This indicates that not all layers act as the consolidation load. In the equation shown in JRA (2007), the span of the clay layer acting as the consolidation load is 80% of the entire consolidation layer.

Fig. 4 shows the distribution of the bending strain moment on the piles for four cases, which consist of the same pile diameters and different clay layers and batter pile angles. The bending moment was calculated using the axial direction strain measured by face-to-face mounted gauges. For example, we call the axial direction strain measured with a strain gauge ε_1; the axial direction strain measured with the corresponding face-to-face strain gauge is ε_2. The bending strain ε_m at this depth is calculated using ε_1, ε_2, and the following equation.

$$\varepsilon_m = (\varepsilon_1 - \varepsilon_2)/2$$

The bending moment M was calculated using ε_m and the following equation.

$$M = E\,Z\,\varepsilon_m$$

In which, E is the elastic coefficient, 7.3×10^{-7} (N/m^2), and Z is the modulus of the section 1.7×10^{-7} (m^3).

This figure shows that larger bending moments occurred in the clay layer and at the top of the piles. These results are the same as the retrospective results, but the value of the bending moment calculated in this experiment was smaller than that in the retrospective results. Furthermore, the moment at the top of the piles was positive, and that in the clay layer was negative. In addition, the moment near the bearing layer was almost zero, indicating that the consolidation layer acting as the consolidation load existed in all the layers. This is clear from the settlement of the clay layer (Fig. 3). Therefore, these experimental data indicate that the bending moments of the batter piles varied with the depth of the clay layer, the angle of skew, the settlement of the clay layer, and so on. Thus, the consolidation load can change with these parameters. In JRA (2007), the span of the consolidation layer is 80% for all cases. From this experimental result, we may be able to rationalize this value.

Fig. 5 shows the bending moment occurring on the batter pile measured in this experiment, that observed on the Tomei/Kuno highway bridge, and that observed in a real-scale test by the Port and Airport Research Institute (Takahashi, 1985(b)). In addition to the measured or observed bending moments, two calculated ones are shown, one calculated by Sato's equation and the other by our proposed equation. Our proposal equation is based on that proposed by Takahashi (Takahashi, 1985(a)). Takahashi's equation is next.

$$\frac{EI}{D}\frac{d^4y}{dx^4} = k_h\left(\delta_v(z)\sin(\theta) - y(z)\right)$$

In which, EI = rigidity of piles, y = flexure of the piles, x = distance from pile cap, p = subgrade reaction, D = pile diameter, k_h = coefficient of subgrade reaction, d_v = settlement of the ground surface, θ = angle of the piles. Takahashi's method is to input the ground settlement through an elastic spring. By setting this spring, the deformation of both the ground and the pile are considered. In our proposed equation, the passive earth pressure defined in the Pile Foundation Design Memorandum (JRA, 2007) is applied to the upper limit of the load. Put simply, our proposal equation is next,

$$\frac{EI}{D}\frac{d^4 y}{dx^4} = k_h\left(\delta_v(z)\sin(\theta) - y(z)\right) \leq \alpha D\Sigma(\gamma h)\sin\theta$$

The ground spring is a perfectly elastic-plastic model, and we set the springs on the consolidation layer and the bearing layer. If the deflection of the piles is larger than the deformation of the ground, the springs act as a subgrade reaction. That is, the load span is fixed in Sato's equation; on the other hand it is flexible in our propossal equation. The movement of the piles (rotation and horizontal displacement) is fixed at the top of the piles.

As Fig. 4 shows, for the Tomei/Kuno highway bridge and our centrifuge results, the moments calculated by Sato's equation are almost the same as the observed moments. However, for the real-scale test by PARI, the moment calculated by Sato's equation is considerably larger than the experimental or observed results. This indicates that Sato's equation has an applicability limit. On the other hand, the results of our proposal equation are in better agreement than those of the Sato's equation with the results for the Tomei / Kuno highway bridge and our centrifuge experiment. Our proposed equation also agrees with the observed results in the real-scale test by PARI(Takahashi, 1985(b)). From this, the load span can change under the condition. So, it is grate that to be able to evaluate flexible load span in our proposal equation.

Conclusions

We conducted centrifuge tests to evaluate the bending moment acting on batter piles with consolidation settlement. On the basis of these test results and retrospective observed or measured results, we proposed an equation for evaluating the moment acting on batter piles in a soft clay layer. We conclude the following.

- The older equation, Sato's equation, may overestimate the moment acting on batter piles.
- Our proposed equation can suitably evaluate the moment occurring on the batter piles.
- From our calculated results, we show why our proposed equation is more accurate than Sato's and can suitably evaluate the moment: The load span is fixed in Sato's equation even if the actual load span changes.

Reference

Japan Road Association(JRA). 2002. Specifications for Highway Bridges.Japan Road Association (JRA). 2007. Pile Foundation Design Memorandum.(in Japanese)

Sato, A., Akai, K., Funabashi, T. 1970. A study on the negative friction and the calculation method on the bending of a battered pile, Japan Highway Public Corporation technical report(in Japanese).

Takahashi, K. 1985(a). Bending of a batter pile due to ground settlement, Soils & Foundations, Vol. 25, No. 4, pp.75-91.

Takahashi, K. 1985(b). Behavior of Single Piles in Subsiding Ground, Technical Note of The Port & Harbour Research Institute Ministry of Transport(in Japanese).

Tab. 1 condition of the experiments by PWRI

<table>
<tr><td rowspan="3">Case</td><td colspan="3">Pile model</td><td colspan="3">Ground model</td></tr>
<tr><td rowspan="2">Pile diameter ϕ (mm)</td><td rowspan="2">Thickness of the pile t (mm)</td><td rowspan="2">Angle of the batter piles (degree)</td><td colspan="2">Clay layer (consolidation layer)</td><td>Sand layer (bearing layer)</td></tr>
<tr><td>strength of the clay layer</td><td colspan="2">thickness of the layer (mm)</td></tr>
<tr><td>A</td><td>19.0 [950]</td><td>1.5 [23.2]</td><td>15</td><td rowspan="3">poor</td><td rowspan="5">200 [10000]</td><td rowspan="5">150 [7500]</td></tr>
<tr><td>B</td><td rowspan="6">16.0 [800]</td><td rowspan="6">1.0 [16.1]</td><td>0</td></tr>
<tr><td>C</td><td rowspan="2">8</td></tr>
<tr><td>D</td><td rowspan="4">semi-firm</td></tr>
<tr><td>E</td><td rowspan="3">15</td></tr>
<tr><td>F</td><td>250 [12500]</td><td>100 [5000]</td></tr>
<tr><td>G</td><td>300 [15000]</td><td>50 [2500]</td></tr>
</table>

- Right number is model scale, and [left number] is prototype scale.

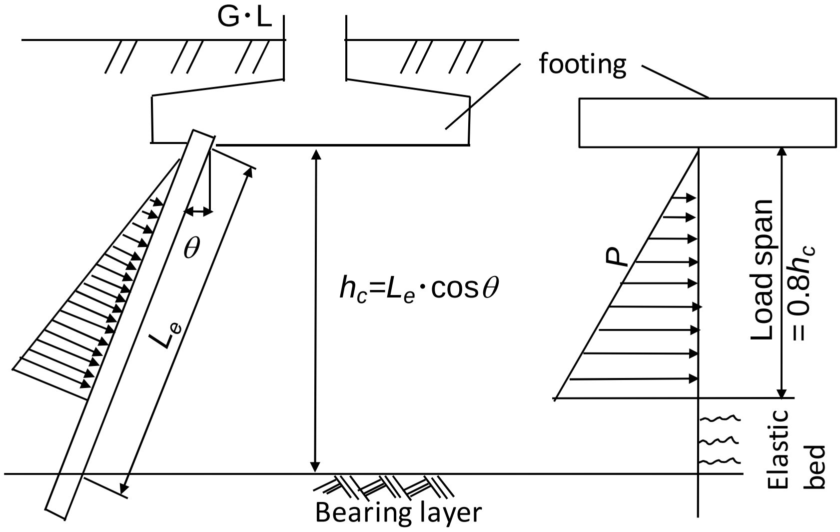


Fig. 1 Conceptual diagram of Sato’s equation

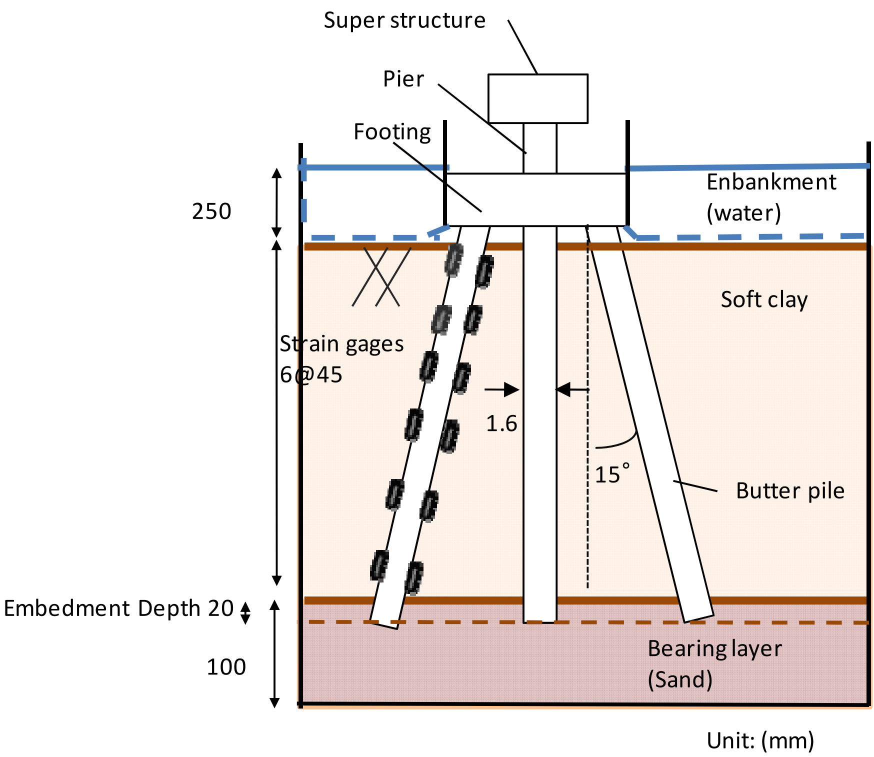


Fig. 2 Experimental setup for consolidated load centrifuge experiment

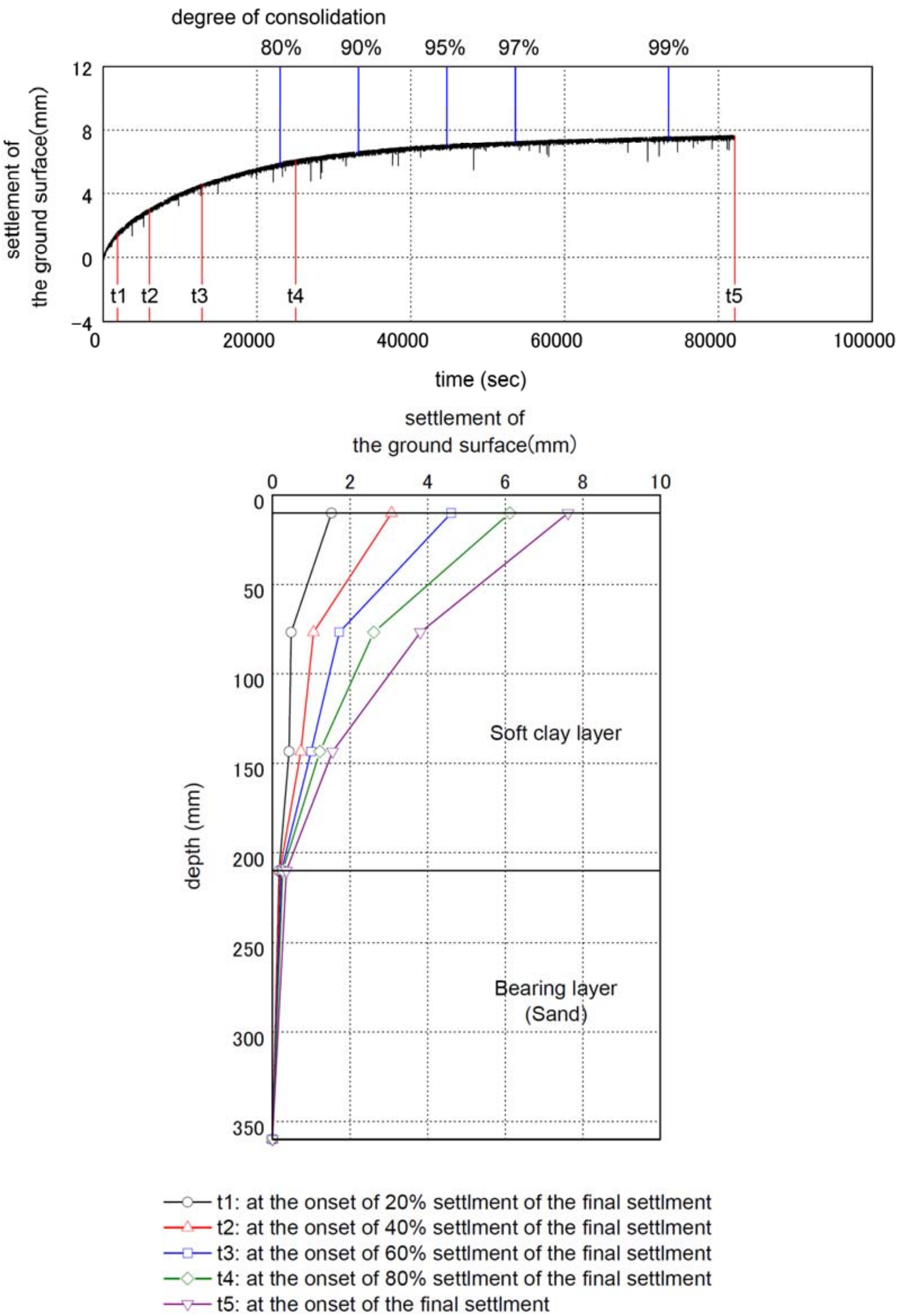
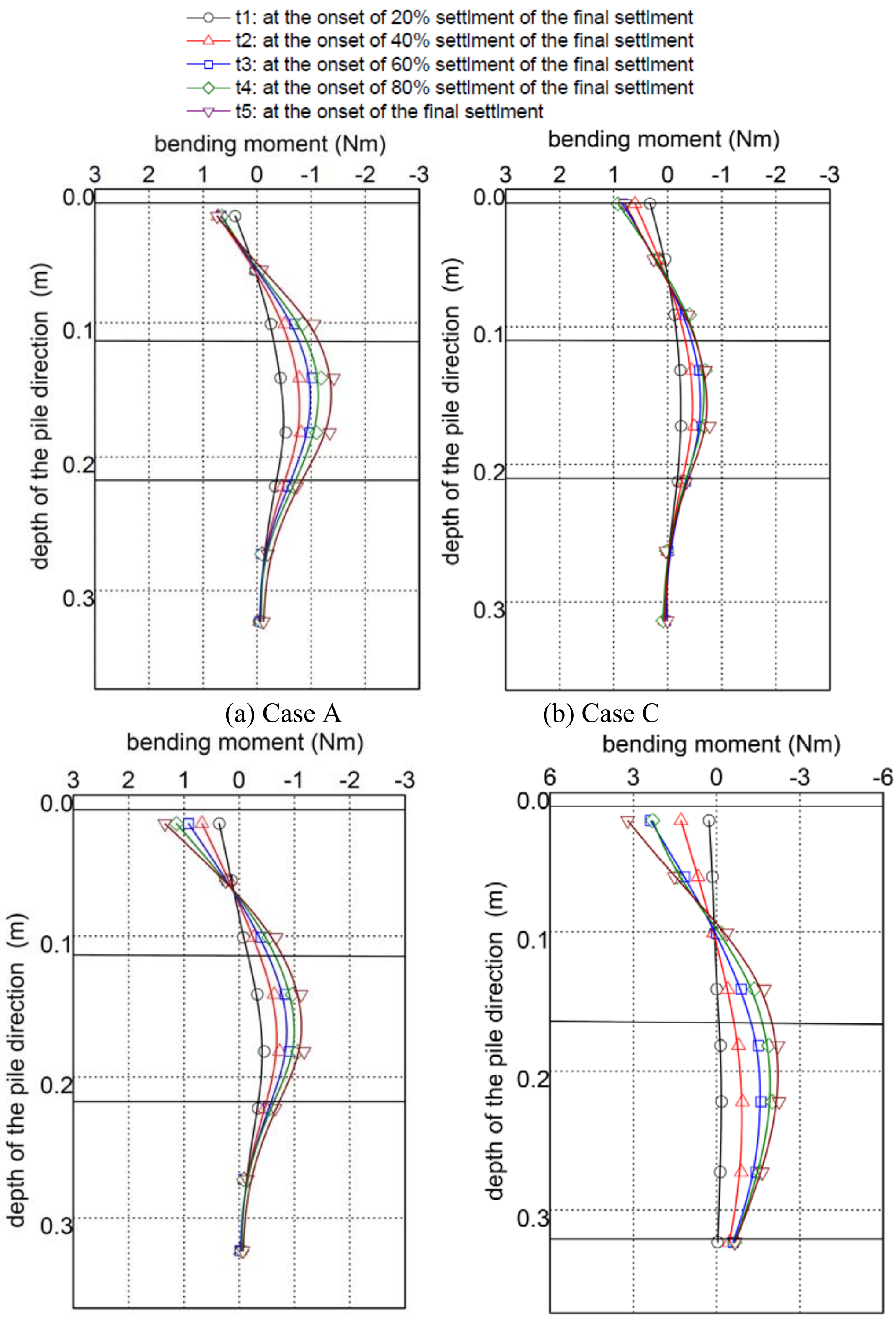


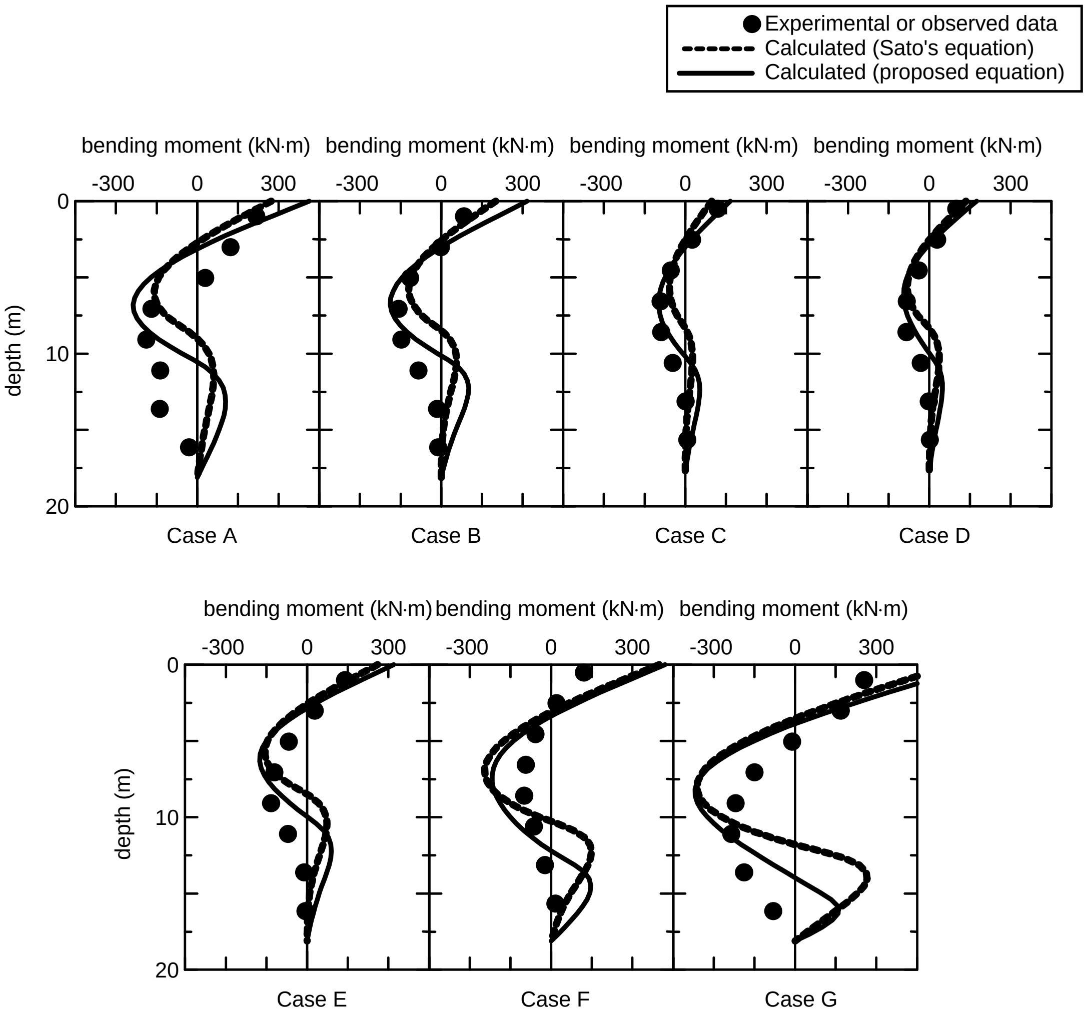
Fig. 3 Histories of the settlement of the soft clay layer’s surface and the distribution in the depth direction



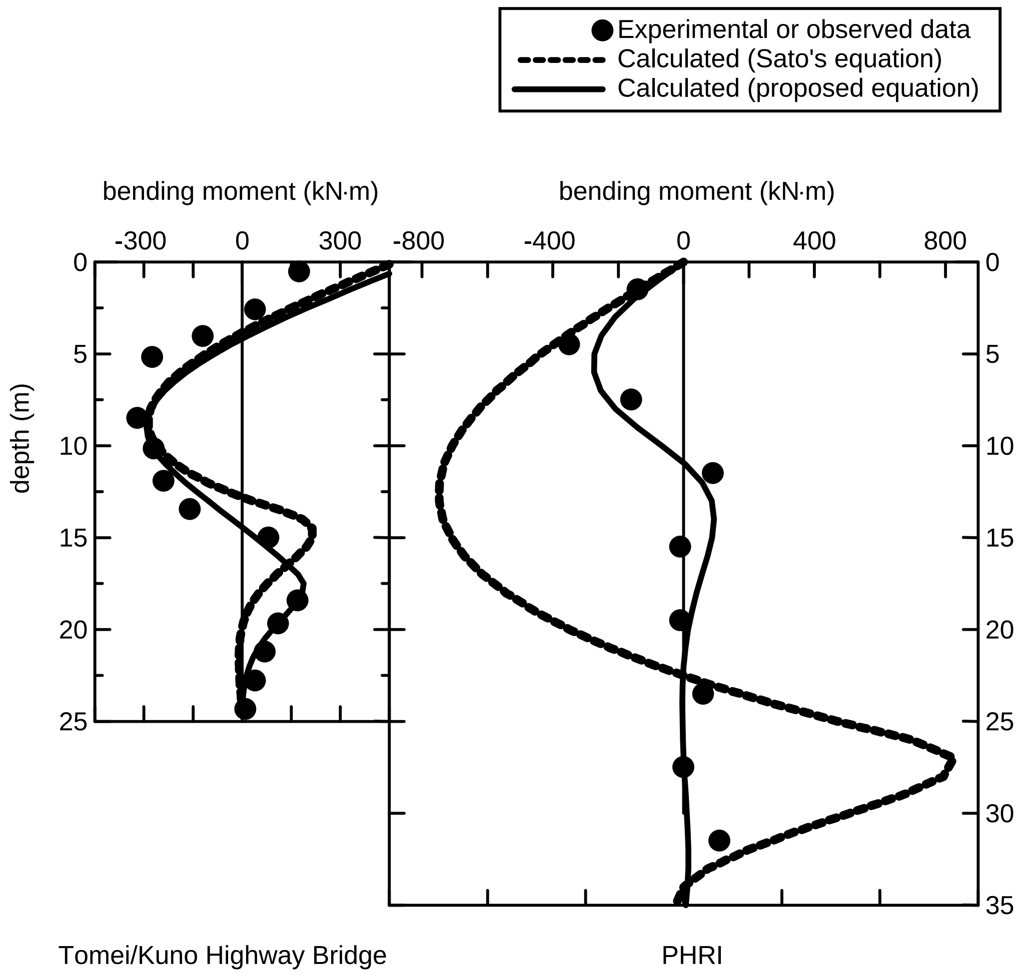
(a) Case A (b) Case C

(c) Case E (d) Case G

Fig. 4 Distribution of the bending moment(experimental data)



(a) Experimental data by PWRI and calculated data



(b) Observed data by Japan Highway Public Corp(Tomei/Kuno highway Bridge), experimental data by PHRI, and calculated data

Fig. 5 Distribution of the bending moment (experimental data, observed data and calculated data)