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# STABILITY OF PILED BRIDGE ABUTMENTS ON SOFT CLAY DEPOSITS

# STABILITE DES CULEES DE PONT SUR PIEUX DANS L'ARGILE MOLLE

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**SYNOPSIS** Construction of backfills behind piled bridge abutments on soft clay deposits leads to lateral deformation of the soil, resulting in large pile bending moments and the displacements of the abutment. A series of centrifuge in-flight backfilling tests were carried out to investigate the effect of tip fixity and pile pitch on the deformation of clay and the displacement of the abutment and the piles. Normally consolidated clay deposits in which the undrained strength increases linearly with depth were dealt with. An attempt was made to calculate the lateral loads on the piles at the time of failure of the clay deposits by combining the upper bound analysis with the proposals by other research workers concerning the ultimate lateral resistance and the relationship between the lateral resistance and the displacement of the piles. The agreement between the calculation and observation was satisfactory.

## INTRODUCTION

Construction of backfills behind piled bridge abutments on soft clay deposits gives rise to lateral deformation of clay, resulting in large pile bending moments and, in extreme cases, causing serious damage to the bridge structure due to the lateral movement of the entire abutment. Although some research works have been carried out to study the behaviour of piles subjected to lateral deformation of soft clay(Matsui et al., 1982, Springman et al., 1991 and Stewart et al., 1991), there still remain many unsolved problems because of its difficult nature arising from extremely complicated soil-structure interaction. Among them, the problems of lateral loads on the piles exerted by lateral deformation of soft clay is of overriding importance in order to establish reasonable design procedures for the piled bridge abutments.

A series of centrifuge in-flight backfilling tests were conducted to investigate the interaction between soft clay and piles. The effects of pile tip fixity and the pile pitch on the deformation of clay and the displacement of abutment as well as piles were studied. In addition, the lateral resistance of single row pile groups was measured in different series of centrifuge tests. Loads acting on the piles at the time of failure of clay deposits were calculated by combining observed relationships between the lateral displacement of the pile and the lateral resistance with the results of the upper bound analysis on the stability of the clay deposits.

## CENTRIFUGE MODEL TESTS

Model piles were made of aluminum and the diametre and the thickness were 10mm and 0.5mm respectively. They are equivalent to steel piles with the diametre of 1000mm and the thickness of 15.4mm at 100g. A model bridge abutment was also made of aluminum and the model piles were threaded to the abutment. The details of the size of the abutment and the arrangement of the piles are illustrated in Fig.1. The piles supporting the abutment were in two rows. The spacing between the rows was 30mm or 3 times the pile diametre. Two different spacings were employed for the piles in one row; 35mm and 75mm which are 3.5 and 7.5 times the pile diametre respectively. Two of the piles in each arrangement were strain gauged as shown in the figure. The outputs from the strain gauges in this alignment include strains from bending and axial tension or compression. The submerged unit weight of the piled abutment was 13.9kN/m$^3$.

Backfilling tests were carried out for 8 different conditions listed in Table 1. For tests cases with the number "2" and "4" at the last digit, backfilling was performed after inserting a rigid spacer behind the abutment so that the abutment did not receive the horizontal thrust directly from the backfill. The purpose of the tests was to isolate the effect of lateral deformation of clay on the displacement of the piles. The model piled abutment was installed in clay with two different types of tip fixity, either embedded in a bearing sand layer beneath clay or rigidly fixed to the base of a soil box as illustrated in Fig.1. The former represents the case in which the pile tip rotates as in a hinge and the latter corresponds to the case of a long pile with a fixed point at some depth. These conditions at the pile tip are defined as "hinged" and "fixed" hereafter. Conditions for lateral loading tests on pile groups with piles in a single row are shown in Table 2. The number of the piles in one row is identical to that for the models in the backfilling tests. In all the test cases, the piled abutments were installed in soft normally-consolidated clay deposits with identical undrained strength profile which shows a linear increase with depth. The strength at the surface($c_0$) was 3.2kPa and the gradient of strength increase(k) was 300kPa/m. The thickness of the clay deposits was 100mm.

Model clay layers were made by Kawasaki clay with plasticity index of approximately 30 (Takemura et al.,1991). The bearing sand layer was made by Toyoura sand and as a fill material zircon sand was used taking advantage of its high submerged unit weight of 22.0kN/m$^3$. The friction angle $\phi'$ of zircon sand was 34°. A centrifuge strong box used in the tests was made of steel. The length, depth and width were 500mm, 326mm and 150mm respectively. A deaired clay slurry was poured into the strong box and preconsolidation was carried out under a pressure of 5kPa. Prior to pouring the slurry,

**Table 1** Test Conditions: Backilling Test

| Test case | Pile spacing (mm) | Number of piles | Existence of spacer | Pile tip condition |
|---|---|---|---|---|
| LP81 | 35 | 8 | No | Sand layer |
| LP82 | 35 | 8 | Yes | Sand layer |
| LP83 | 35 | 8 | No | Fixed |
| LP84 | 35 | 8 | Yes | Fixed |
| LP41 | 75 | 4 | No | Sand layer |
| LP42 | 75 | 4 | Yes | Sand layer |
| LP43 | 75 | 4 | No | Fixed |
| LP44 | 75 | 4 | Yes | Fixed |

**Table 2** Test Conditions: Lateral Loading Test

| Test case | Pile spacing (mm) | Number of piles | Corresponding test code for filling test |
|---|---|---|---|
| HP4 | 35 | 4 | LP81 - LP84 |
| HP2 | 75 | 2 | LP41 - LP44 |

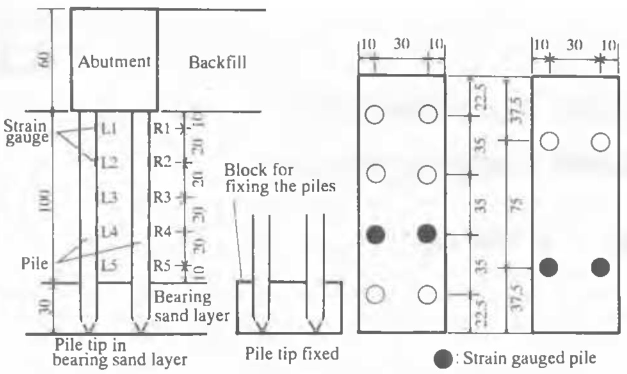

Fig.1 Model piled abutment and arrangement of piles

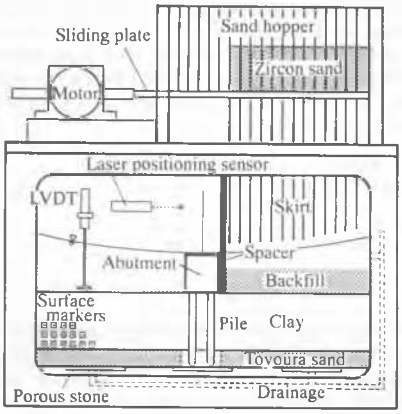

Fig.2 Test setup: Backfilling tests

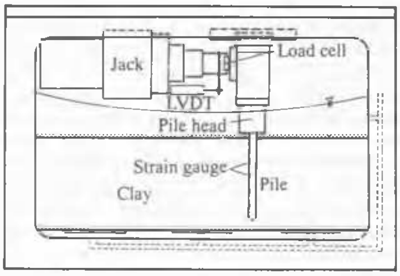

Fig.3 Test setup: Lateral loading tests

for the cases with hinged tip, a 30mm thick bearing sand layer was made by compacting Toyoura sand. For the cases with fixed tip, the model piles were once disconnected from the abutment and only the piles were fixed to a pile holding block placed at the base of the box as shown in Fig.1. Preconsolidation was conducted with the model piles sticking out from the block into clay. Having completed preconsolidation, pore pressure transducers were inserted into clay, surface markers for deformation measurements were placed at the side face of clay and lead shots were placed at the surface to give surcharge pressure of 8kPa. In the cases with fixed tip, noodles were inserted into clay in the direction perpendicular to the side face in order to see the variation of clay deformations along the width of the clay deposit. The box was then covered with a sealing lid and seepage consolidation was conducted by applying water pressure of 75kPa to the surface of clay.

On completion of seepage consolidation, for the cases with hinged tip, small holes were drilled through clay at predetermined locations with a miniature hand auger. The model abutment was positioned by placing the piles in these drilled holes. For the cases with fixed tip, the model abutment was fixed to the piles sticking out of clay. Zircon sand was spread on the surface as a surcharge, a sand hopper was mounted on the strong box, a laser positioning sensor as well as LVDTs were attached and then the box was taken to a centrifuge. Water was introduced so that the abutment was just submerged. The completed model before centrifuge tests is shown in Fig.2. Centrifugal consolidation was performed for 8 hours at 100g until excess pore pressures nearly dissipated. Subsequent to centrifugal consolidation, in-flight filling was conducted by allowing zircon sand to fall freely on to the clay surface behind the abutment. The backfill with the height of 66mm was built in stepwise filling of 8 to 9 lifts. The pile strains, the displacements of abutment, pore pressures in clay and deformations of clay were measured. Since it was not possible to cause failure in tests LP83 and 84, the level of water in the model was lowered to increase the net weight of the backfill in an attempt to cause large deformations in clay. In the lateral loading tests for the group piles, the model clay layer was prepared in a similar manner to that for the case with bearing sand layer. The pile groups were loaded horizontally with a loading device shown in Fig.3 at 100g. Measurements were taken for the displacements of the pile head, lateral forces and pile strains.

## TEST RESULTS AND DISCUSSIONS

The deformations of clay immediately after the completion of backfilling, which were read off from the movements of surface markers recorded on photo films are illustrated in Fig.4. These deformations are in fact considerably smaller in the magnitude than those in the mid plane of clay measured with the noodles. Friction between clay and a plastic plate in the viewing window of the strong box is considered to be responsible for this. However, the overall trend of the deformations is not very different from that of the deformations in the mid plane. In the figure, the displacements of the abutment measured with photographing are also shown. In all the four cases with hinged tip, large deformations appeared in clay as shown in the upper half of Fig.4. Clearly large lateral movements of clay forced the abutment to tilt towards the fore side. On the other hand, for the cases with fixed tip, the deformations in clay are small, particularly for the abutment with 8 piles. This implies that the stability of clay deposits depends very much on the type of tip

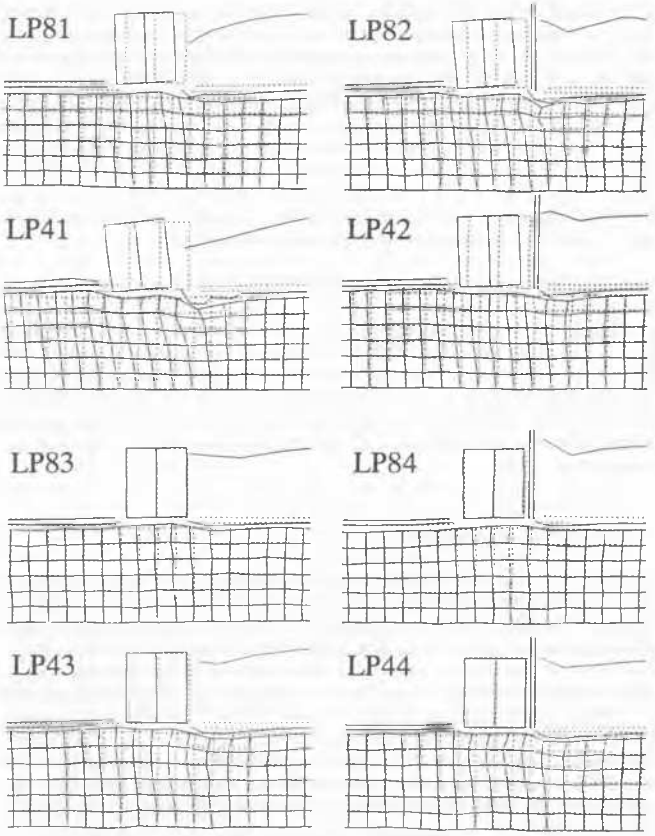

Fig.4 Deformations of clay and movements of abutment after backfilling

fixity. Generally speaking, lateral deformations are dominant in all the cases. This is because the vertical deformations are suppressed by the existence of the abutment. It is seen that the deformations of clay are largest in the vicinity of the surface marker second from the surface and below this level they decrease nearly with depth.

Observed lateral displacements of the centre of the gravity of the abutment are plotted against the average backfill pressures at the clay surface due to the backfill in Fig.5. The lateral displacements for the cases with hinged tip are much larger than those for the cases with fixed tip. This can be easily predicted from the pattern of deformations of clay illustrated in Fig.4. Comparing tests LP81 with LP41 and LP83 with LP43, it is seen that smaller lateral displacements took place for the abutment with 8 piles for the cases without the spacer. On the other hand, for the cases with the spacer, the difference between 8 piles and 4 piles is very small. This can be seen by comparing tests LP82 with LP42 and LP84 and LP44. This leads to a conclusion that by increasing the number of supporting piles the stability of the abutment in soft clay against backfill loads can be increased but the stability against the lateral deformations cannot be increased very much.

The variations of pile strains with the height of backfill observed in test LP84 are illustrated in Fig.6 for the two strain gauged piles. The relationships between the pile strains and fill heights are very linear. As pointed out earlier, the strains from axial tension or compression are included in the outputs shown in Fig.6; axial tension and compression for the pile on the right and the left respectively. Considering this, it can be said that the patterns of strains for the two piles are very similar. As can be seen from Fig.4, the pattern of lateral deformations is more or less symmetrical with respect to the centre axis of the abutment. This seems to have given similar lateral pressures on the two piles.

In order to evaluate the effect of lateral deformation of clay on the displacement of the piles quantitatively, it is necessary to determine the loads acting on the piles taking the stability of clay deposit into account. In this study, an attempt was made to evaluate the stability of clay deposit by using the upper bound analysis. The calculation was carried out for the cases with fixed tip. The failure mechanism used in the analysis was determined as shown in Fig.7 based on the patterns of clay deformations observed in the tests. This is the mechanism with four variables, L, $\omega$, $\eta$ and $\varepsilon$. The angle $\psi$ is the dilation angle of the fill material. For the computation of energy dissipation within the zone III, the mechanism proposed by Randolph and Houlsby(1984) was made use of. The periphery of the piles was assumed to be smooth, as they were made of aluminum. It was postulated that the zone VII can move only vertically because of the constraint by the abutment. The results of calculation are illustrated in Table 3. The height H calculated by assuming the dilation angle to be equal to the angle of friction $\phi'$ is much larger than that observed in the centrifuge tests. As explained later, the clay deposits are in the state of failure even in the cases with fixed tip, although the deformations of clay illustrated in lower half of Fig.4 appear to be not very much. The use of $\phi'$ as the dilation angle is justifiable, when the zone VII moves only vertically as postulated in the analysis. However, it has been confirmed in the tests that the part of backfill corresponding to this zone moved laterally, only slightly though, even in the cases with the spacer. Although this small movement does not alter the overall velocity hodograph in the clay parts, it causes some increase in the downward velocity of zone VII. If the assumption that the zone VII moves only vertically is kept, the effect may be considered to be equivalent to the decrease in the dilation angle. On the basis of this, the calculations were conducted using dilation angles less than 34°. The results are also given in Table 3. As expected the minimum height decreases with the decrease in the dilation angle.

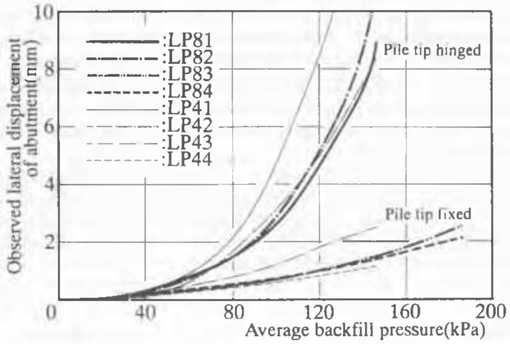

**Fig.5** Lateral displacements of abutment versus backfill pressure

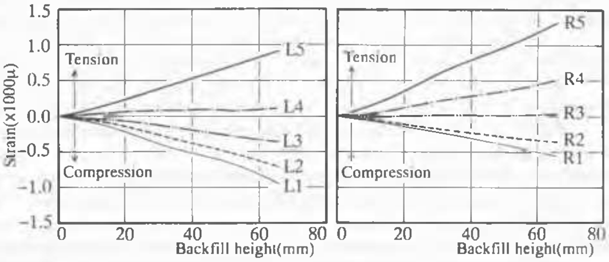

**Fig.6** Variation of pile strains with the height of backfill: LP84

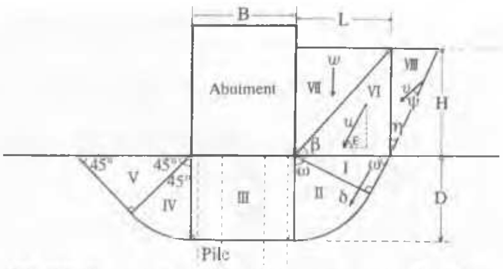

**Fig.7** Failure mechanism used in upper bound calculation

**Table 3** Results of Upper Bound Calculation

| $\psi$ | Number of piles : 4 | | | | Number of piles : 8 | | | |
|---|---|---|---|---|---|---|---|---|
| | L | $\omega$ | H | D | L | $\omega$ | H | D |
| (deg) | (mm) | (deg) | (mm) | (mm) | (mm) | (deg) | (mm) | (mm) |
| 0 | 17 | 71.5 | 37 | 16 | 15 | 71.5 | 43 | 14 |
| 5 | 29 | 42.5 | 41 | 20 | 30 | 36.0 | 49 | 18 |
| 10 | 44 | 31.0 | 45 | 23 | 50 | 24.5 | 55 | 21 |
| 15 | 65 | 23.5 | 52 | 26 | 76 | 18.5 | 64 | 24 |
| 20 | 96 | 18.5 | 62 | 30 | 117 | 14.0 | 78 | 28 |
| 25 | 149 | 14.0 | 78 | 36 | 187 | 10.5 | 101 | 34 |
| 30 | 260 | 10.5 | 112 | 47 | 339 | 7.5 | 147 | 44 |
| 34 | 492 | 7.5 | 178 | 64 | 656 | 5.5 | 241 | 63 |

The lateral deformations of clay beneath the abutment were read off from the movements of the surface marker below the centre axis and second from the clay surface, and they are plotted against the height of backfill in Fig.8. This particular marker was chosen because it was in the areas with largest deformation as pointed out earlier. The general trend is that the deformation is smaller for the cases with fixed tip. For the cases with 8 piles, the points with the greatest curvature seem to exist at the backfill height of about 40mm for the hinged tip and about 65mm for the fixed tip. For the cases with 4 piles these points seem to appear at the height of about 35mm for the hinged tip and

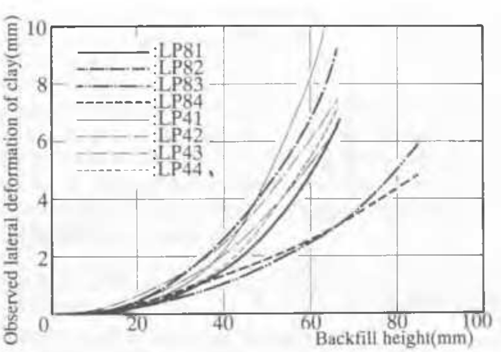

**Fig.8** Lateral deformations of clay beneath abutment versus backfill height

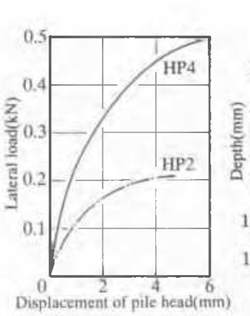

**Fig.9** The results of lateral loading tests

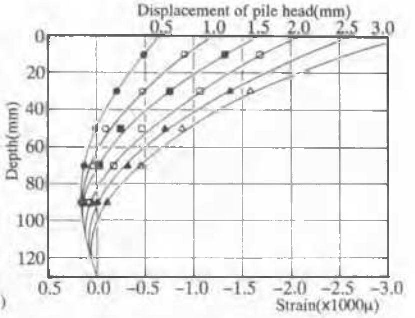

**Fig.10** Piles strains observed in lateral loading tests: HP4

about 45mm for the fixed tip.The results in Table 3 show that the dilation angles corresponding to these values are 0° and 10° to 15° for the hinged tip and fixed tip respectively. It can be concluded from the results in Fig.8 that the stability of clay deposits depend on the number of the supporting piles and the type of tip fixity.

The relationships between the lateral loads and the displacements of the pile head obtained in the lateral loading tests are illustrated in Fig.9 for the two group piles with 2 and 4 piles in one row. The load for the case HP2 is nearly half of that for the case HP4, implying that the load taken by one pile is nearly the same as far as this tests are concerned. The observed strains of the pile in the case HP4 are plotted in Fig.10 up to the stage of 3.0mm of the displacement of pile head. In his elaborate work on the lateral resistance of piles, Kubo(1964) proposed to represent the lateral resistance of a pile in clay in terms of the coefficient of lateral subgrade reaction and the lateral displacement of the pile. In order to use Kubo's equation in this study, some modification is necessary. In this centrifuge tests, not only piles but also clay deposits move. Therefore the lateral displacement of the pile has to be replaced with the relative displacement between the pile and clay. Considering the strength profile of the clay deposits dealt with in this study, the modified equation is given as;

$$p = \alpha(c_0 + kz)y^{0.5} \qquad (1)$$

where p is the lateral resistance at the depth z and α is a constant. Calculating the displacements of piles by integrating the curves in Fig.10 and combining the results in Fig.9, the values of α were obtained as given in Table 4. It is surprising to see that all the values are nearly identical and close to 3.2mm$^{-0.5}$ for different displacements of the pile head. This is another evidence confirming the validity of Kubo's proposal.

**Table 4** Value of α obtained from the Lateral Loading Test: HP4

| Displacement of pile head (mm) | 0.5 | 1.0 | 1.5 | 2.0 | 2.5 | 3.0 |
|---|---|---|---|---|---|---|
| α value (mm$^{-0.5}$) | 4.5 | 3.4 | 3.2 | 3.1 | 3.2 | 3.1 |

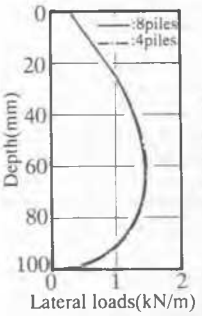

**Fig.11** The calculated variation of lateral loads with depth

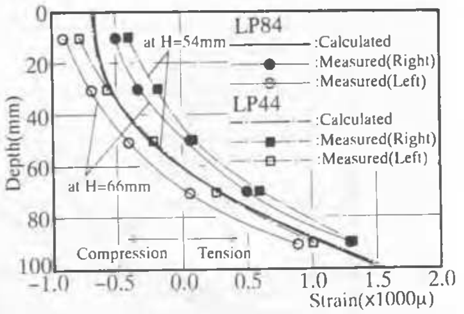

**Fig.12** Comparison between calculation and observation for pile strains

The patterns of clay deformations in Fig.4 indicate that there are two distinctively different zones of deformations; a zone with large deformations near the surface of clay and a zone with deformations decreasing linearly with depth. These two zones are defined as the zone of plastic flow and zone of transition in this study. From Fig.4 the deformations for the cases with fixed tip may appear to be not enough to cause plastic flow, but the maximum deformation observed with the noodles was well over 15mm. The deformation of this amount certainly causes plastic flow in clay. On the other hand the displacements of the piles are not very large. Even at the pile head, they are about 2mm for fixed tip as shown in Fig.5. Considering this with the pile length which is 130mm, it can be assumed that the piles remain fairly straight throughout the tests. Summarizing these, we can reasonably conclude that the patterns of relative displacements between the piles and clay are considered to be very close to those for the deformations of clay. Based on this conclusion, an attempt was made to calculate theoretically the lateral loads on the piles due to the lateral deformation of clay. In the plastic flow zone, the ultimate lateral resistance proposed by Randolph and Houlsby(1984), 9.14$c_u$, was adopted. As the depth of the zone of plastic flow, the depth D indicated in Fig.7, which is equal to $L\sin\omega$, was employed. In the transition zone, the relative displacement y was assumed to decrease linearly with depth, vanishing at the bottom of the clay layer. Putting 9.14$c_u$ in Eq(1), the value of y at the depth D or at the interface between the two zones was obtained. This in turn determines the relationship between y and depth z in the transition zone. The calculated variation of the loads acting on the piles with depth are given in Fig.11. As D, the value at the dilation angle of 15° for which the clay deposits are considered to have failed was used. The pile bending strains can easily be deduced from the calculated loads. The results are shown in Fig.12 together with the observations for the cases LP44 and 84 with the spacer and fixed tip at the backfill height of 54mm and 66mm respectively. The observed strains were derived by subtracting the strains due to frictional stress $c_0$ between the base of the abutment and clay from the actually measured strains. The agreement in the trends for the two results is rather striking, although there is a small difference in the magnitude. This difference is inevitable because the observed strains include the strains due to axial tension or compression. Since the piles on the left and right are subjected to the axial compression and tension respectively, the shifts of the curves for the observed strains are considered to be reasonable.

## CONCLUSIONS

Following conclusions are drawn from this study on the stability of piled abutments subjected to lateral deformations of clay of which undrained strength increases linearly with depth.

1) By increasing the number of supporting piles, the stability of the abutments in soft clay against backfill loads can be increased but the stability against the lateral deformations of clay cannot be increased very much.
2) The stability of clay deposits accommodating the abutments depends on the number of the supporting piles and the type of tip fixity. When the piles are fixed at the tip, the displacements of the abutment as well as the deformations of clay are small.
3) Lateral loads acting on the supporting piles can be calculated theoretically with reasonable accuracy by combining the upper bound analysis with the ultimate lateral resistance proposed by Randolph and Houlsby and with the relationship between the lateral resistance and relative displacement of laterally loaded piles proposed by Kubo.

## REFERENCES

Kubo,K.(1964). A new method for the estimation of lateral resistance of piles. Report of PHTRI, 2(3): 1-37.

Matsui,T., Hong,W.P. and Ito,T.(1982). Earth pressure on piles in a row due to lateral soil movements. Soils and Foundations, 22(2): 71-81.

Randolph,R.M. and Houlsby,G.T.(1984). The limiting pressure on a circular pile loaded laterally in cohesive soil. Geotechnique, 34(4): 613-623.

Springman,S.M., Bolton,M.B. and Randolph,R.M.(1991). Modelling the behavior of piles subjected to surcharge loading. Proc. of Centrifuge 91, Boulder, pp.253-260.

Stewart,D.P., Jewell,R.J. and Randolph,M.F.(1991). Embankment loading of piled bridge abutments on soft clay. Proc. of Geo-Coast '91, Yokohama, pp.741-746.

Takemura,J., Watabe,Y., Suemasa,N., Hiro-oka,A. and Kimura,T.(1991). Stability of soft clay improved with sand compaction piles. Proc. of 9th ARCSMFE, Bangkok, Vol.1, pp.543-546.