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# Behaviour of Laterally Loaded Piles - A Case Study

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## Introduction

Piles are commonly used to support bridge structures, tall buildings, transmission line towers etc. where poor subsoil conditions are encountered. The safety of such structures depends on the ability of the supporting piles to resist large amount of lateral forces. These lateral forces may come from movement of vehicles, wind action, earthquake forces etc. Extensive theoretical and experimental studies were carried out on laterally loaded piles to determine their ultimate resistance and the deflection under working loads (Matlock and Reese, 1960, 1961, Meyerhof and Ranjan, 1972) Poulos and Davis, 1980, Narasimha Rao and Mallikarjuna Rao, 1997). Matlock and Reese (1960) developed design curves for predicting the deflection in laterally loaded piles using the subgrade reaction approach. Meyerhof and Ranjan (1972) described methods for finding out the bearing capacity of rigid vertical piles and pile groups under inclined loads in sand. Poulos and Davis (1980) developed a method for analysis of pile response based on modified boundary element approach. Narashima Rao and Mallikarjuna Rao (1997) indicated that though the modulus of subgrafe reaction is simple, the method is only applicable if the deflection of piles is within the range of elastic compression of the soil. The disadvantage of this approach is the lack of continuity and is dependent on the size of foundation. In spite of these drawbacks the subgrade reaction approach is widely used due to its simplicity (Poulos and Davis, 1980). In present practice, laterally

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loaded piles are analyzed using nonlinear load transfer approach using "p-y" curves. The relationship between pressure and deflection at any point along a pile is nonlinear. The method models the soil as a set of nonlinear springs that are defined by load transfer functions or "p-y" curves. The curve represents the soil resistance at a particular depth in terms soil resistance per unit length versus deflection. Experience in determining the soil properties used in analytical methods is also reflected in the accuracy of analysis. Therefore, there exists a need for comparison of results of large-scale lateral tests with analytical prediction (Anderson et al., 2003). Results presented in this paper are in the above direction and are obtained from comprehensive analysis of a case study in Taiwan.

## Case Study

The Taiwan High Speed Rail Project consists exclusively of a viaduct track supporting structure. The viaduct consists of a prestressed concrete girder element supported by reinforced concrete piers, pile cap and bored reinforced concrete piles. Bored piles of diameter 1500 mm to 2000 mm have been used.

The location of the project is situated in part of the Chin-Nan plane. The plane is 145 km long and 40 km wide, and it is relatively low and flat. The ground surface elevation ranges from 5 to 20 m above sea level, with slopes of 1 in 800 to 1 in 1000. The area is covered by Quaternary Periodween alluvium, which consists of a lagoon deposit and terrace alluvial deposit.

For the sake of verification of assumptions in pile design, six numbers of test piles (TP-1 to TP-6) have been tested. The location and length of test piles have been chosen in such a way that they can cover all conditions of pile type, pile capacity as well as soil conditions. More details are given in Samsung et al. (2003). This paper presents the results of comparative study of laterally loaded pile response. Three design methods have been used and the results are compared with measured response. The summary of soil profiles determined from the boreholes and laboratory test data at each of the test pile site is presented in Table 1. Table 2 presents general information of the lateral loaded piles.

## Analytical Approaches

The analytical approaches adopted to calculate the lateral displacements along the length of pile are discussed in the following sections. They are I) Japanese Road Association (JRA) method (linear modeling) II) JRA method (bilinear modeling) and III) "p-y" curve method JRA methods in general are based on the subgrade reaction analysis suggested by Poulos and Davis (1980).

**TABLE 1 : Summary of The Soil Profiles**

| Soil type | Description | Material characteristics | Remarks |
|---|---|---|---|
| 1 | Very loose to dense becoming very dense silty sand | 9-49% fine content<br>SPT range 4-50 but can be >50 | Found at all test locations |
| 2 | Very soft to stiff becoming very stiff silty clay or clayey silt. | 55-100% fine content with clay fraction on the order of 13% to 58%, minimal sand content, SPT range 1-30 and some times more than 30. | Found at all test locations |
| 3 | Loose to very dense slight sandy clayey silt | <13% clay fraction<br><46% sand content<br>SPT range 8-50 | Found in TP-3, TP-6 locations |

**TABLE 2 : General Information on Lateral Pile Load Test**

| Test Pile No. | Test Pile Diameter | Test Pile Length |
|---|---|---|
| TP-1 | 1500 mm | 58 m |
| TP-2 | 1500 mm | 50 m |
| TP-3 | 2000 mm | 50 m |
| TP-4 | 2000 mm | 50 m |
| TP-5 | 1800 mm | 58 m |
| TP-6 | 1800 mm | 50 m |

***JRA Method***

Horizontal Spring constant of pile is derived based on the horizontal reaction coefficient of the soil according to elastic beam theory. The horizontal spring constant, $k_l$ is defined as follows:

$k_l$ = horizontal force that causes pile head a unit movement

$$= 4\,\mathrm{EI}\,\beta^3$$

where, $$b = \sqrt[4]{\frac{K_h D}{4EI}} \quad (m^{-1}) \qquad (1)$$

$K_h$ = coefficient of horizontal subgrade reaction

$$= D_E e_g K_{HO} \left(B_h/30\right)^{-3/4}$$

$D_E$ = sub grade reduction factor due to liquefaction

$e_g$ = reduction factor to sub grade modulus due to pile group effect

$K_{HO} = \alpha E_o/30$

$B_h = \sqrt{D/\beta}$

$E_o$ = 25 N as per JRA

N = SPT, N-value

$\alpha$ = 1 (for normal loads)

= 2 (for seismic loads)

D = pile diameter

E I = bending stiffness of pile

Lateral displacement ($\delta$) of pile head is given by

$$\delta = \frac{(1+\beta h)^3 + (1/2)}{3EI\beta^3} H \quad (2)$$

Lateral displacement of single pile above the ground level ($y_1$) is given by,

$$y_1 = \frac{H}{6EI\beta^3}\left[\beta^3x^3 + 3\beta^3hx^2 - 3(1+2\beta h)\beta x + 3(1+\beta h)\right] \quad (3)$$

Lateral displacement of single pile below the ground level ($y_2$) is given by,

$$y_2 = \frac{H}{2EI\beta^3} e^{-\beta x}\left[(1+\beta h)\cos\beta x - \beta h \sin\beta x\right] \quad (4)$$

where, h = length of pile above ground level

H = lateral load

$\beta$, EI are as described earlier.

***Japan Road Association Method (Bilinear Modeling)***

Design has been performed based on the bilinear approximation (Fig.1) of soil behaviour in which the soil parameters, such as elastic soil stiffness and yield strength for each stratum of a given soil profile have been computed according to JRA specifications that are given as follows.

$$K_h = 0.2\alpha E_o D^{-3/4} \tag{5}$$

where $K_h$ = Coefficient of subgrade reaction (kg/cm$^3$)

$E_o$ = Elastic modulus of soil (kg/cm$^2$)

$D$ = Diameter of pile

$\alpha$ = the modified factor for $E_o$

= 1 for normal condition

= 2 for earth quake condition

In the present study value of $\alpha = 1$ is used.

The lateral restraint of soil has been calculated by assuming that the soil is elasto-plastic and the effective resistance of the soil has been calculated depending on the type of soils:

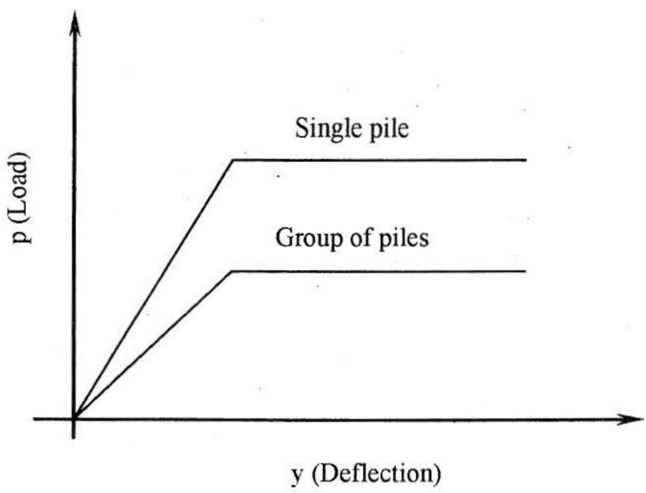


**FIGURE 1 : Bilinear Curve for Soil Stiffness for the Analysis of Lateral Loaded Piles**

*a) Sand*

$$P_e(z) = f_{rp}\alpha\gamma_e z K_p \tag{6}$$

where $P_e(z)$ = Effective resisting soil stress at depth z (kN/mm²)

$\alpha$ = Shape factor of front face of the pile (usually $\alpha = 3$)

$\gamma_e$ = Average effective soil unit weight up to depth z (kN/m³)

$K_p$ = Coefficient of passive earth pressure

$f_{rp}$ = Coefficient of soil resistance (usually 1.0)

*b) Clay*

$$P_e(z) = f_{rc}(1+z/2D)(\gamma_{ez}+2c) \leq 9c \tag{7}$$

where D = Pile diameter

C = Cohesion intercept of clay

$f_{rc}$ = Coefficient of soil resistance (generally 1.0).

Calculations have been done in the spreadsheet program, MS Excel using the formula function. The quantities are automatically evaluated for every soil layer in 'Excel' sheets. The computed soil stiffness ($K_h$) and effective soil resistance ($P_e$) at various depths in the 'Excel' sheets (Eqns. 5, 6 and 7) are used as input data for structural analysis of soil pile model using finite element analysis using SAP (2000). The pile is divided into finite number of elements and the forces and displacements are calculated at each nodal point by using the computed soil stiffness in analysis. The two parameters $K_h$ and $P_e$ are used to generate the bilinear soil spring for each layer.

***"p-y" Curve Method***

The lateral resistance of the piles under lateral loading has been analyzed by using "p-y" curve method. In this method, a non-linear load (p) versus horizontal displacement (y) of soil layer for given pile diameter is estimated based on input soil parameters, such as

i) SPT-N values

ii) Undrained shear strength of cohesive soil

iii) Undrained modulus of cohesive soil

iv) Friction angle of sandy soil

The "p-y" relationships are constructed for various points along the pile using the method given in Matlock (1970). Once these load-displacement curves are established for the soil layers, Winkler beam theory is applied to analyse the problem. Since each spring has a non-linear behaviour, numerical approach, such as finite difference method, has been adopted to solve this problem. The major difference in this method compared with other conventional approach is the assumption of stress-strain behaviour. Conventional approach assumes that the soil behaves elastically without consideration of ultimate soil resistance. The basic input of soil parameters is horizontal coefficient of subgrade reaction or modulus and soil resistance or strength. Generally, the non-linear "p-y" curve approach yields higher movement than elastic approach at high stress level and small difference at small stress level. Therefore, large difference in lateral displacement may be expected if the stress level is high, however this method does produce predictions of pile displacement that are closer to that experienced under applied load.

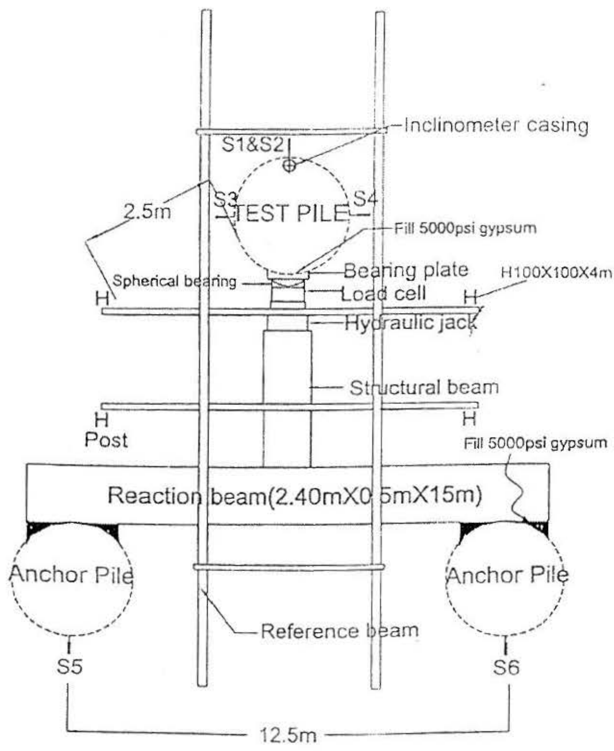


**FIGURE 2 : Typical Load Testing Arrangement for Lateral Testing of Pile**

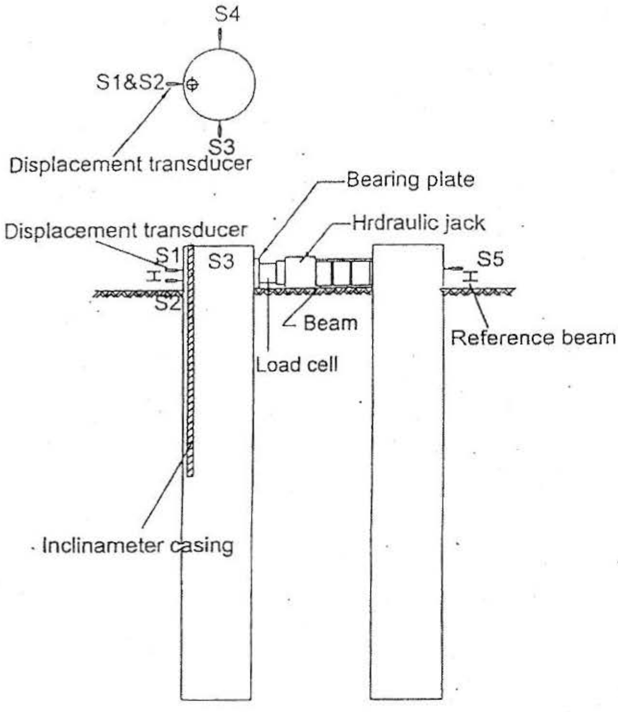


**FIGURE 3 : Typical Arrangement for Lateral Load Test and Instrumentation**

## Laterally Loaded Pile Test Results

Six numbers of test piles have been constructed to get actual lateral deflection up to a depth of 40 m from pile top. Figures 2 and 3 show typical load testing arrangement and instrumentation for the lateral testing of pile. To construct the test piles casing-drilling method is adopted. The test piles are projected 0.3 m above the ground surface for the purpose of mounting displacement transducers. Two piles are used as a reaction system to counteract lateral forces. A hydraulic jack is arranged horizontally to apply the lateral load on the test pile. Displacement transducers have been used to measure the pile head deflection and inclinometers have been used to measure the deflections along the length of pile. Results are given in Table 3.

## Results and Discussion

Results of the lateral pile load test are compared with the predicted values as shown in Figs.4 to 9.

**TABLE 3 : Pile Load Test Results**

| Test Pile No. | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| Diameter (m) | 1.5 | 1.5 | 2.0 | 2.0 | 1.8 | 1.8 |
| Maximum test load (kN) | 2200 | 3000 | 4200 | 5000 | 3800 | 3500 |
| Maximum head displacement (mm) | 163.23 | 116.38 | 157.9 | 141.44 | 188.16 | 153.5 |
| Residual displacement (mm) | 62 | 52 | 61 | 55 | 97 | 65 |

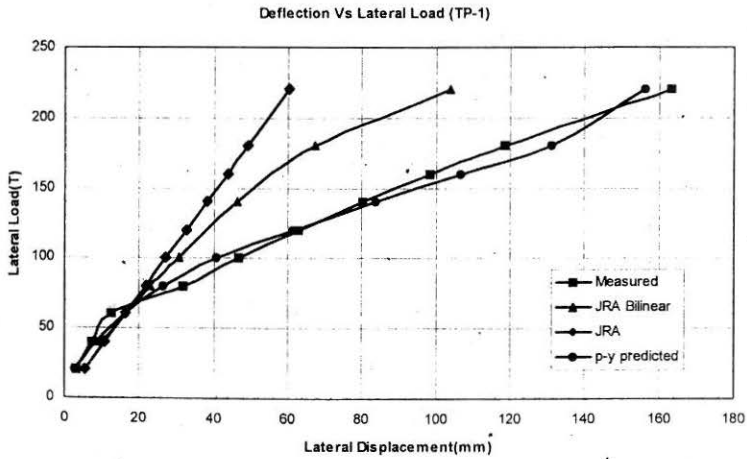


**FIGURE 4 : Load-Displacement Curve for TP-1**

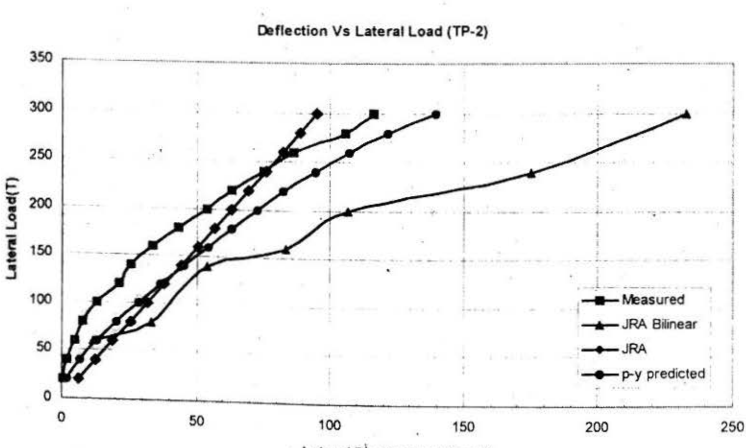


**FIGURE 5 : Load-Displacement Curve for TP-2**

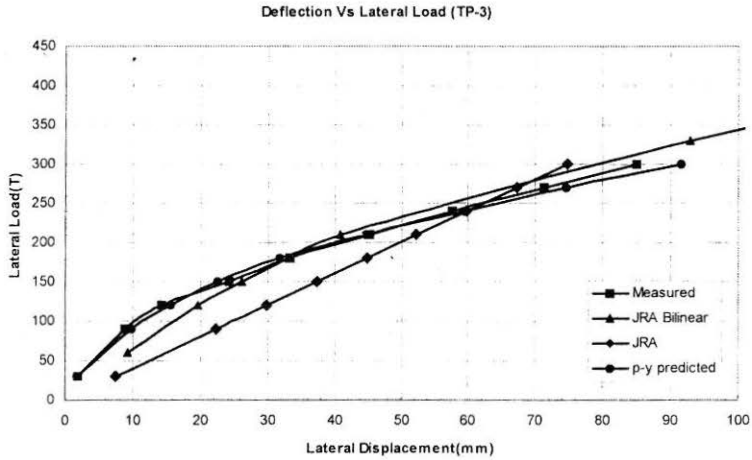


**FIGURE 6 : Load-Displacement Curve for TP-3**

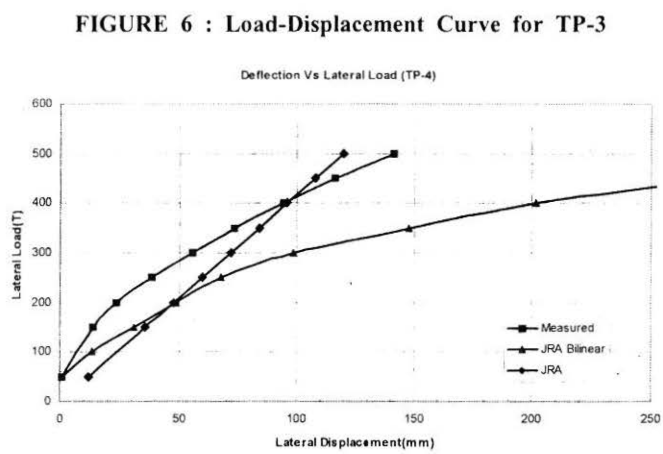


**FIGURE 7 : Load-Displacement Curve for TP-4**

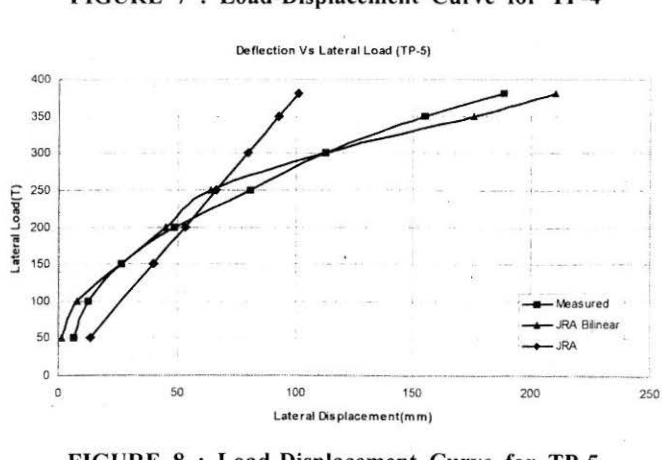


**FIGURE 8 : Load-Displacement Curve for TP-5**

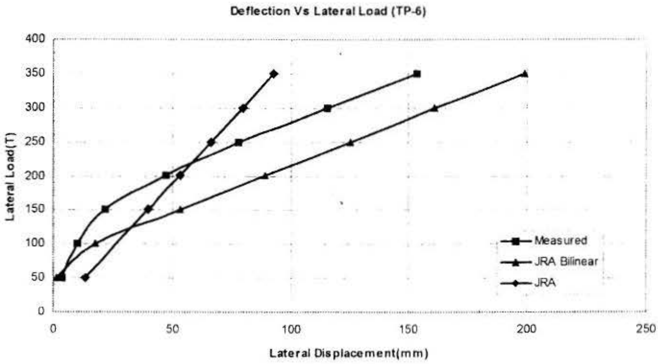


**FIGURE 9 : Load-Displacement Curve for TP-6**

### *"p-y" Curve Method*

From the results of lateral load versus pile top movement, the predicted curves based on "p-y" method are closer to the measured value from the pile load test results. Over a displacement range of 160 mm for TP-1 and 90 mm TP-3, the predicted displacement values are almost same as measured values. However, for test pile TP-2, predicted deflections at different loads are in the higher side than measured response. It is likely that the difference is due to lower values of stiffness used in the analysis and this lead to under-prediction of response. Results of test piles (TP-1 to TP-3) are satisfactory, so no further analysis has done for remaining test piles.

### *JRA with Bilinear Modeling*

The results of estimated deflections from JRA method considering bilinear modeling have been superimposed on the measured deflections to compare the results. In this method, soil resistance has been modeled as series of non-linear springs, which follow the bilinear load-deflection behaviour. The results show that the predicted curve closer to the measured value. At the initial stage of loading, the predicted curve shows a conservative trend for all test piles, i.e., predicted values are marginally higher than the measured values at the same loading level. In test piles TP-1, TP-3, the predicted responses under higher loading are lower than the measured values.

### *JRA Method*

Besides the above two methods, JRA method (subgrade modulus) is used to estimate the displacement along the single pile. Estimated displacements are superimposed on the plots to compare with the measured values. It can be noted that JRA method is conservative for initial loading cases. It is observed that the predicted displacements are higher than the measured for almost all test piles.

Among the three analytical approaches, prediction by "p-y" method is more satisfactory. From the above plots it is clearly seen that predicted curve by "p-y" method almost follow the measured values. Prediction by JRA-Bilinear approach is also similar to measured values, but it is not as good as "p-y" predicted value. The predicted curves are closer to the measured values for all test piles except TP-2. It is expected that the difference may due to the soil input parameters of TP-2, that is used in the analysis are somewhat underestimated. The JRA approach (linear) for the entire test piles is not as accurate as the more non-linear approach or bilinear or "p-y" curve method.

Considering that 50mm and 100mm as maximum allowable lateral displacements of pile head, the deviations of predicted lateral load from measured value are calculated for each test pile and percent deviations are reported in Table 4.

From the above analysis it is easily seen that percentage deviation of predicted values are within acceptable range for "p-y" curve approach. For the test piles TP-1 and TP-3 the deviations are negligible (0-15%) for "p-y" predicted values. But in case of other approaches the deviation is too high for test piles TP-1, TP-2 and TP-4 (31-63%). By lowering the acceptable range of deflection, deviation for JRA-Bilinear and JRA can be reduced, but that will lead to more conservative prediction. The predicted responses are calculated on the basis of soil parameters that are determined from laboratory

**TABLE 4 : Deviation of Predicted Lateral Load From Measured Value**

| Test Pile | Percent Deviation from Measured Value | | | | | |
|---|---|---|---|---|---|---|
| | 50 mm Allowable Displacement | | | 100 mm Allowable Displacement | | |
| | "p-y" Predicted | JRA-Bilinear Predicted | JRA Predicted | "p-y" Predicted | JRA-Bilinear Predicted | JRA Predicted |
| TP-1 | 0 % | +36 % | +63 % | 0% | 38% | 88% |
| TP-2 | −15 % | −31.5 % | −15 % | 9% | −27% | 18% |
| TP-3 | 0 % | +7 % | −7 % | 7% | 8% | 23% |
| TP-4 | - | −31 % | −31 % | - | −31% | 2% |
| TP-5 | - | +10 % | −10 % | - | 2% | 38% |
| TP-6 | - | −25 % | −5 % | - | −20% | 36% |

+ ve: Predicted values are higher than measured values.

- ve: Predicted values are lesser than measured values test results. Soil parameters may differ from in-situ value due to remolding or disturbance of soil and that will reflect on predicted response. Though predicted response never matches perfectly with actual response, but it gives some idea about anticipated response, and that depends upon proper choice of approach.

## Conclusions

Six test piles (TP-1 to TP-6) are constructed and lateral pile load tests are carried out. Three design methods have been used to evaluate the test results. The objectives are to analyze and interpret the lateral pile load test results and verify the appropriateness of design assumptions. It should be noted that even though the methods are quite different and different models have used, the results of all design approaches are consistent. The predicted behaviour of the pile to the action of lateral load is reliable for low levels of soil strain and once the soil strain increases the accuracy of the results is such that the displacements are overestimated. The degree of overestimation is affected by the sophistication of the model but the non-linear approach like "p-y" method gives closer results compared to other methods.

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