

LTBASE: A Computer Program for the Analysis of Laterally Loaded Piers Including Base and Slope Effects

MOHAMMED A. GABR AND ROY H. BORDEN

An improved model for the analysis of laterally loaded piers is presented. The model is based on the subgrade reaction concept and incorporates base shear and moment springs. The model is capable of accounting for the presence of a sloping ground surface. The computer code, LTBASE, which implements the model, is described. A comparison between the predicted and measured response of 16 load tests shows the inclusion of the base resistance in the conventional subgrade reaction approach to be desirable. The ability of the model to predict the behavior of piers on slopes is indicated by a favorable comparison between the predicted and measured response of five test piers.

Rigid pier foundations are commonly used to support a variety of structures subjected primarily to lateral loads. Highway overhead signs, light pole structures, and electrical transmission towers are all examples of situations in which the lateral loads transferred to the piers from the superstructure generally result in high overturning moments and relatively insignificant vertical loads. Although the majority of piers are constructed on horizontal ground surfaces, it is not uncommon to see them constructed in cut slopes or compacted embankments.

In general, the load-deflection analysis of laterally loaded piers is conducted without consideration for the influence of base resistance. Although it can be shown that this assumption is valid for piers with relatively large length/diameter (L/D) ratios, for the case of short rigid piers, the inclusion of base resistance can be significant.

Two theoretical approaches have generally been employed for predicting the lateral movement of piers. The elastic approach (1), which assumes the soil to be an ideal elastic continuum, and the subgrade reaction approach (2-8), in which the soil reaction at a point is related to the pier deflection at that point through a constant of subgrade reaction referred to as K_{ho} .

A model incorporating base resistance contribution to the lateral response of rigid piers has been presented (9). The authors used a linear 3-D finite element parametric study to define numerical values for the base subgrade moduli. Three different L/D ratios were used in the analysis in order to define base spring stiffnesses as a function of L/D ratio. Spring stiffness expressions for the base resistance were formulated by

fitting empirical equations to the results obtained from the parametric study.

Using the subgrade reaction approach, the soil-pier interaction mechanism is modeled by treating the pier as a linear elastic beam and the soil reaction as a line load. Using a finite number of elements in a numerical solution, the interaction is represented by discrete nonlinear springs, with the spring stiffness varying as a nonlinear function of pier lateral deformation. The subgrade reaction concept provides a rational approach that permits the description of the nonlinear behavior of the soil-pier interaction system readily, if only approximately.

Presented in this paper is the computer program LTBASE, which was developed for the nonlinear analysis of piers subjected to lateral loads. The analysis is based on the subgrade reaction approach and incorporates the mobilized base resistance (4). The program is capable of analyzing cases where the piers are constructed on slopes (10).

BASE RESISTANCE MODEL

For rigid piers having relatively small L/D ratios, it has been shown that the soil at the base provides significant moment and horizontal shear resistance (4). Considering this effect, a difficulty would arise from the fact that the determination of such boundary condition is dependent on both the soil reaction and the pier response or, in a more commonly used term, is dependent on the soil-structure interaction mechanism. The interaction behavior is explained by the dependence of the magnitude of the base resistance on the amount of deformation at the base; the determination of such deformation requires the knowledge of the amount of the base resistance.

Referring to Figure 1, and assuming rigid body motion, the vertical and horizontal displacements of the base could be correlated to the angle of rotation of the pier, θ_r , as follows (1):

$$w_o = 2 * \sin(\theta_r/2) * \text{SQRT}[C^2 + (D/2)^2] \quad (1)$$

$$W_o = (\pi/2) - (\theta_r/2) - \text{ARCTAN}[C/(D/2)] \quad (2)$$

$$y_o = w_o * \cos(W_o) \quad (3)$$

$$v_o = w_o * \sin(W_o) \quad (4)$$

where

C = distance from the base to the center of rotation,

M. A. Gabr, Norwegian Geotechnical Institute, P.O.B. 40 Tasen, N-0801, Oslo 8, Norway. R. H. Borden, Center for Transportation Engineering Studies, Box 7908, North Carolina State University, Raleigh, N.C. 27695.

- D = pier diameter,
 θ_r = angle of rotation of the pier,
 y_o = horizontal displacement of the base as a result of rotation, θ_r , and
 v_o = vertical displacement of the base as a result of rotation, θ_r .

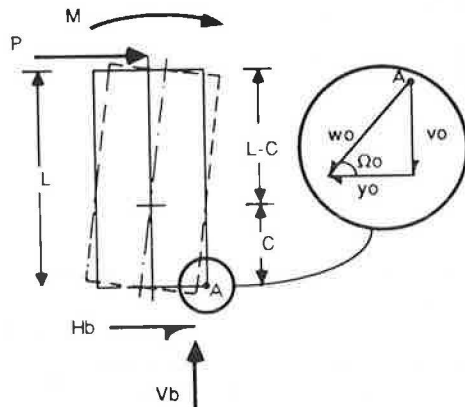


FIGURE 1 Base deformations as a function of pier rotation.

The horizontal shear resistance, H_b , and moment resistance, M_b , mobilized at the base as a result of rotation angle θ_r , are expressed as functions of horizontal and vertical deformations developed at the base. The normal reaction caused by the soil at the base will be a function of the vertical displacement resulting from pier rotation.

The base load-vertical displacement curve is shown in Figure 2. A linear relationship is assumed to exist between base vertical resistance and vertical deformation up to the failure of the soil under the base (11-13). Similarly, the shear force-lateral displacement relationship (Figure 2) is also assumed to be linear up to the mobilization of the full lateral shear force (11-13). Experiments have revealed that the ultimate shear resistance will develop at a shear movement of approximately 0.2 in., whereas a downward movement of about 5 percent of the pier diameter is necessary to mobilize the ultimate vertical base resistance (11).

However, because of the coupled pressure-deflection dependence at the base, the shear spring stiffness is defined as a function of the shear deformation, as well as the normal force developed at the base. The mobilized normal soil resistance is formulated as a function of the pier rotation angle, θ_r , in Figure 1. Accordingly, the resisting moment and lateral shear force

developed at the base because of pier rotation, θ_r , were developed as follows (4):

$$V_b = \beta(v_o) * K_v * v_{ult} * (D^2/6) \quad (5)$$

$$H_b = \alpha(V_b, y_o) * V_b \tan(\delta) + Ca (\pi D^2/8) \quad (6)$$

$$M_b = V_b * (3\pi D/32) \quad (7)$$

where

- K_v = vertical modulus of subgrade reaction;
 V_b = normal soil reaction mobilized at the base as a result of rotation, θ_r ;
 H_b = horizontal shear resistance mobilized between the base and the soil as a result of rotation, θ_r ;
 δ = angle of friction between the base and the soil;
 v_{ult} = vertical displacement required to mobilize the ultimate vertical base resistance;
 M_b = mobilized resisting moment at the base as a result of rotation, θ_r ;
 $\alpha(V_b, y_o)$ = ratio of the lateral base deformation as a result of rotation angle, θ_r , to the lateral deformation required to mobilize the full lateral shear resistance. This coefficient is a function of the lateral base displacement, y_o , and the magnitude of the normal force, V_b , at the base;
 $\beta(v_o)$ = ratio of vertical base deformation as a result of rotation angle, θ_r , to the vertical base deformation required to develop the ultimate vertical base resistance; and
 Ca = undrained shear strength \times adhesion factor at the base.

ULTIMATE RESISTANCE INCLUDING SLOPE EFFECT

An ultimate lateral resistance expression for piers constructed in cohesionless soil deposits with horizontal ground surface was presented by Reese (14). In this formula, two mechanisms of soil resistance are assumed to exist. Near the ground surface, a passive wedge is assumed to provide the lateral resistance. At

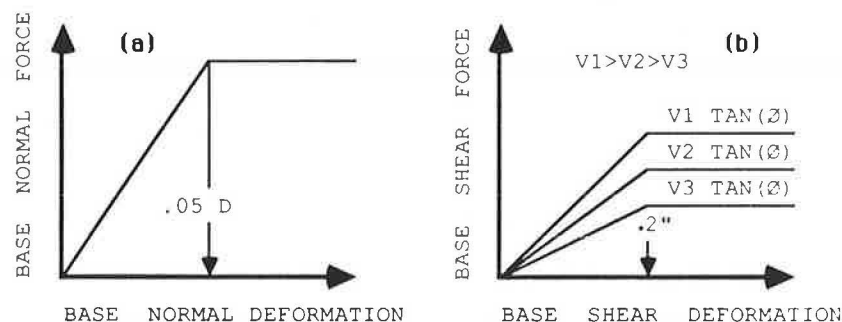


FIGURE 2 Base and shear normal springs.

used in the analysis gets larger, the computational time increases and could be as long as 15 minutes for an analysis using 100 elements, using a computer instrumented with an Intel 8087 numeric data coprocessor that has a clock speed of 4.77 MHz.

OUTPUT INFORMATION

For each successful execution, the program output is directed to three output files. The output files are saved on the default drive (i.e., the drive from which the program is loaded and executed). The name under which each output file is stored and the contents of each are described as follows:

- **OUTPUT.PRN.** This file contains information about critical input data and the output results for all the loading increments used in the analysis. If the option for internally increasing the length is specified, this file is expected to be relatively large and comprehensive. The size of this file might be as large as 300 K. This is approximately equivalent to the size of a double-density, double-sided floppy disk. During the preliminary analysis, if the option for the search of the appropriate length is selected, it is recommended that the user specify the option to suppress the printout of this file.

Once the appropriate length is found, a single run is executed using this length and the output file OUTPUT.PRN can then be printed. It would be beneficial to glance through this file to verify the input data. The information about the distribution of lateral deflection, moment, shear, and soil modulus, as a function of depth, is printed to this file. Also, the maximum shear and maximum moment in the pier, corresponding to each loading increment, are printed.

- **SUMMARY.PRN.** This file contains a summary of the applied loads, input soil properties, and the pier dimensions. The computed factor of safety, based on the predicted capacity, is printed whenever applicable. The factor of safety is printed each time the analysis is performed using a new length. A brief glance through this file would help the user to decide upon the appropriate pier length to be used.

- **PLOT.PRN.** This is a special file prepared for using the output results in association with any graphics software package to create a load-deflection plot. The output to this file consists of three columns. The third column represents the pier top deflection, y , corresponding to different loading increments. The first and second columns represent the lateral load, PT , and the value of the second boundary condition, $BC2$, applied at the top of the pier. In general, $BC2$ will be an applied moment or a specified pier top rotation. Short headings are used to help the user to identify the results.

EXAMPLE PROBLEM

An example problem is presented to demonstrate LTBASE capabilities. The example also serves to illustrate the ease of creating a batch input data file when a simple soil profile is encountered. The soil profile and the pier dimensions are given in Figure 4. The profile consists of a uniform sand deposit that has an angle of internal friction of 30 degrees. The ground surface is horizontal and the water table is located at a depth of 5 ft. The pier is 30 in. in diameter. The initial estimated length

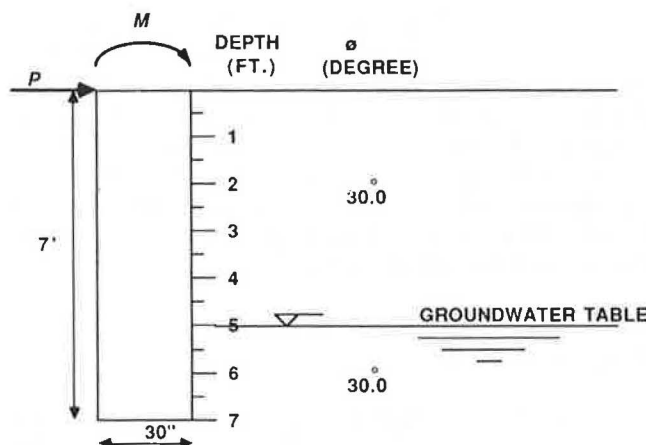


FIGURE 4 Example problem: soil profile and pier dimensions.

is chosen equal to 7 ft. The pier length is divided into seven increments, each increment having a length of 1 ft. In cases where part of the pier is extended above the ground surface, the choice of the element size should satisfy the following conditions:

$$N \times H = L \quad (21)$$

$$NU \times H = Le \quad (22)$$

where

- N = number of elements,
- NU = number of elements above ground surface,
- H = element length,
- L = pier length, and
- Le = exposed pier length, above the ground surface.

The tolerance of convergence is chosen equal to 1×10^{-3} in. The maximum deflection criterion, at the top of the pier, is taken equal to 3.0 in. The applied design loads at the pier top are assumed to equal 2 kips lateral load, and 60 K-ft applied ground moment. This simulates a condition where a lateral load of 2 kips is applied at the top of a 30-ft column supported by the pier being analyzed. The pier head is assumed to be free to rotate. The limiting factor of safety criterion is chosen to equal 1.5. Once this value is achieved, the program execution is ended and the results are printed.

Because of the groundwater table, the soil profile is divided into two sublayers. The first layer is 5 ft thick (from the ground surface to the groundwater level) and the second layer is 2 ft thick (from the groundwater level to the bottom of the pier). The existence of the water table is accounted for by using the submerged unit weight for the soil below the groundwater level. The unit weight of the soil above and below the water table is taken to equal 120 pcf and 57.6 pcf, respectively. The values of the coefficient of lateral subgrade reaction, K_{ho} , were chosen according to the values given by Reese et al. (7).

The vertical subgrade reaction coefficient, K_v , used at the base of the pier was obtained by assuming that the full base

normal resistance will be mobilized at a downward movement of 5 percent D , and equal to 90 psi, according to the bearing capacity expression by Kulhawy (19). Based on the assumption of a linear relationship between normal base resistance and downward movement to failure, K_v was computed to be approximately 60 pci. The option for internally increasing the pier diameter ratio was selected. The printout of the output file OUTPUT.PRN was suppressed because of space limitations. Problem input data are shown in Figure 5.

OUTPUT RESULTS

The output file SUMMARY.PRN, given in Figure 6, provides the computed factor of safety as a function of pier length. The pier length was incremented by two elements, each 1 ft long. When the pier length reached 9 ft, the computed factor of safety was found to be 1.98, which is higher than the specified minimum of 1.5. The execution of the program was then automatically terminated and the results printed.

It is clear from the output file SUMMARY.PRN that the length that satisfies the factor of safety criterion is approximately 8 ft. Once this length is found, a single run is executed

using the length of 8 ft, and the output file OUTPUT.PRN is created. The file OUTPUT.PRN contains comprehensive information about the input data as well as the analysis results. The input data are printed for user verification. The pier deflection, moment, shear, and soil modulus are printed as a function of depth. Lateral pier top deflection is plotted versus the applied ground moment in Figure 7. The data required to produce such a plot are written to the file PLOT.PRN.

SIGNIFICANCE OF BASE RESISTANCE

The results of a parametric study indicating the significance of base resistance on the predicted ultimate capacity of 2.5-ft-diameter piers are shown in Figure 8. In this study, the ultimate capacity is defined as the moment resistance corresponding to 2 degrees pier rotation. The vertical subgrade reaction coefficient, K_v , at the base of the pier was obtained by assuming that the ultimate base normal resistance, q_{ult} , will be mobilized at a downward movement of 5 percent D and equal to 150 psi. Based on the assumption of a linear relationship between normal base resistance and downward movement up to the deformation corresponding to failure, K_v was taken to equal 100 pci. The surrounding soil was chosen to consist of a

```

1. LTBASE
2. EXAMPLE RUN
3. NCSU
4. M. A. GABR
5. 5/18/87
6. 1
7. 2.0 60. 1 1.5
8. 30.0 1.0 .001 3. 7 0 1 0 0
9. 30.0 60. 00.0
10. 00.0 0.
11. 2
12. 5.0 30. 120.0 30.0 100. 00. .000 0
13. 7.0 30. 57.60 30.0 60.0 00. .000 0
14. 1
15. .293E+11 7.

```

Notes Added for Explanation:

1. Job title
2. Job number
3. Job location
4. Operator
5. Date
6. Option to specify single run or multiple runs using incremented length
7. Lateral load Moment Code to indicate that the applied load is a Moment F.S. Criteria
8. Diam. Length increment Convergence tolerance Deflec. limit
- No. of elements Option to internally generate P-y curves Option to printout P-y curves
- No. of elements above G.S. Option to generate output file "output.prn"
9. ϕ at the base K_v at the base C_u at the base
10. Ground surface slope angle in the front Ground surface slope angle in the back
11. No. of soil sublayers
- 12,13. Soil properties, pier diameter and option to generate P-y curves
14. No. of different pier EI's
15. $E I_p$

FIGURE 5 Data for the sample run.

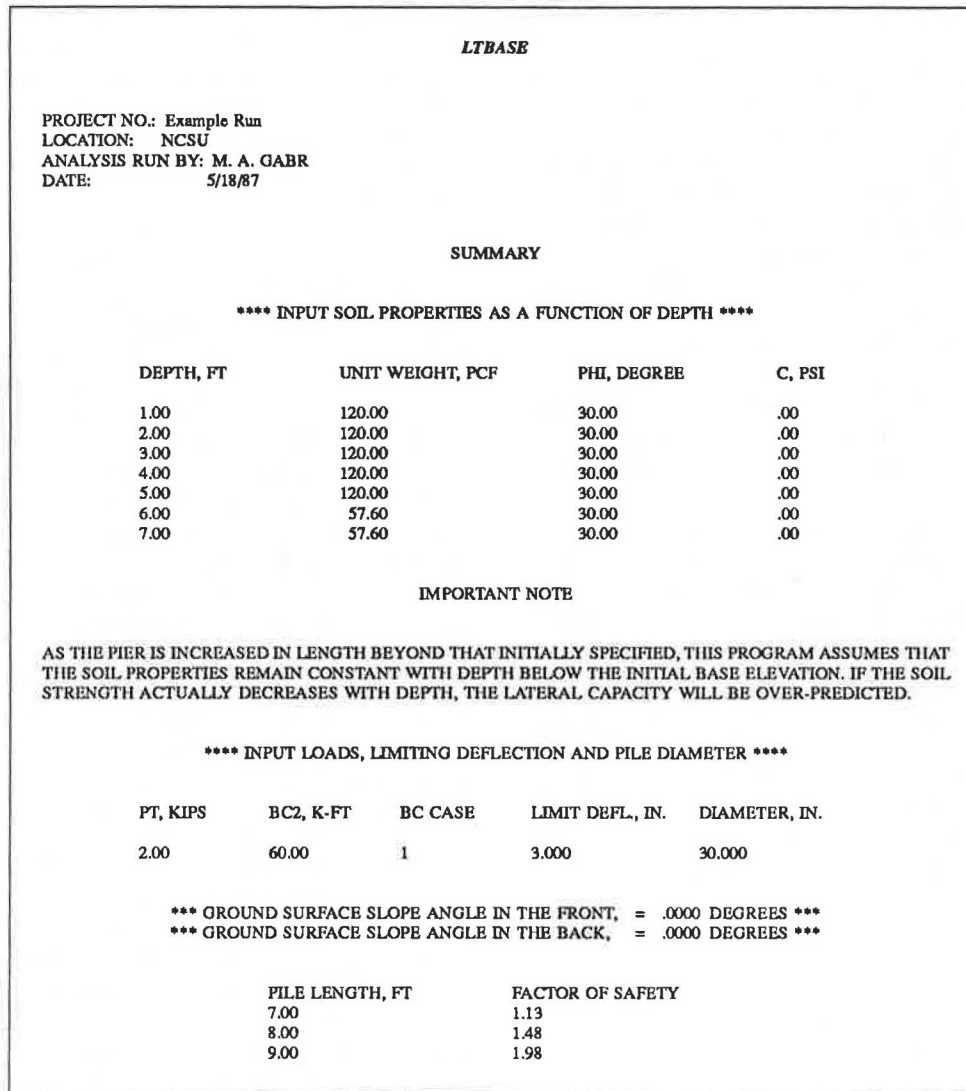


FIGURE 6 Output file, SUMMARY.PRN.

uniform sand deposit with angle of internal friction ϕ of 30 degrees.

For L/D ratios greater than four, Figure 8 indicates that the base resistance accounts for an increase in capacity of approximately 10 percent. However, as the L/D ratio decreases, the

importance of the base resistance is obvious. For an L/D ratio of 2.5, the model indicates that the capacity of a pier could be underpredicted by slightly more than 25 percent if the base resistance is not included. For L/D ratios less than 2.5, the significance is even greater.

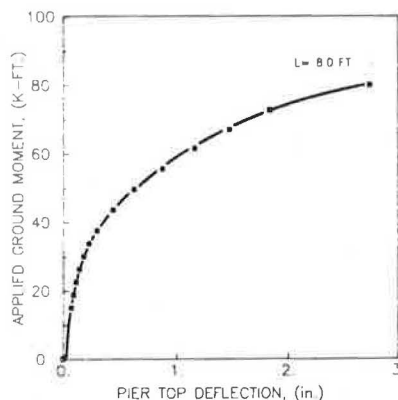
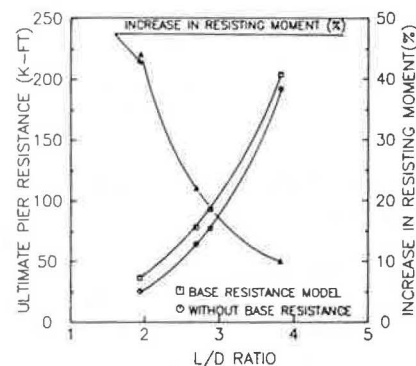


FIGURE 7 Lateral load-deflection response, sample problem.

FIGURE 8 Increase in capacity as a function of L/D ratio.

EFFECT OF SLOPING GROUND SURFACE

An analysis performed by the authors (10) indicated that the percent reduction in lateral capacity due to the presence of a sloping ground surface was essentially independent of pier dimensions and soil properties. The ratio of sloping ground surface capacity to horizontal ground surface capacity was found to be simply a function of the value of the ground surface slope angle, θ . A parametric study performed on a 2.5-ft-diameter and 7-ft-long pier is shown to illustrate the influence of the slope presence on the overall capacity. An idealized subsurface sand deposit with ϕ equal to 30 degrees was used. The p - y curves were internally generated by LTBASE using the procedure described by Reese et al. (8). However, the ultimate lateral resistance, used in the construction of the p - y curves, was computed using the developed expressions that account for the slope.

A significant decrease in capacity was observed as a result of the slope presence. Figure 9 shows that for a ground surface slope angle, θ , of 15 degrees, a 32 percent reduction in capacity is predicted for a pier rotation of 2 degrees. The reduction is somewhat less for smaller deformations. At a pier rotation of 0.1 degrees, the 15-degree slope angle resulted in only a 5 percent reduction in capacity. The smaller reduction in capacity at the 0.1-degree rotation level is a result of using the same K_{ho} values for both horizontal and sloping ground surface cases. As mentioned earlier, it remains to be investigated whether the slope presence would have an effect on the values of the coefficient of lateral subgrade reaction, K_{ho} .

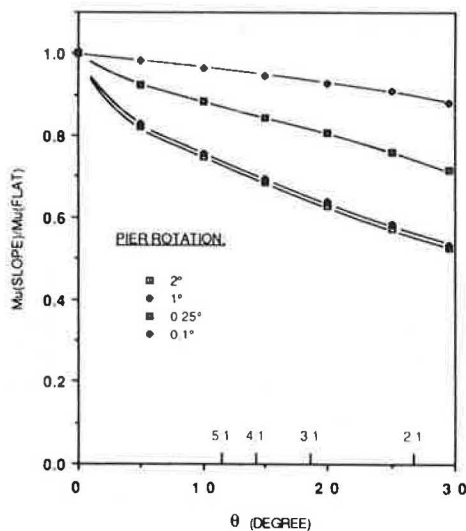


FIGURE 9 Moment capacity ratio as a function of ground slope angle.

COMPARISONS OF PREDICTED AND OBSERVED FIELD BEHAVIOR

Predictions of the lateral response of 16 load tests performed by GAI and ITT (9) were performed using LTBASE. An extensive documentation of the load test procedures, soil properties, idealized profile of each site, and the corresponding organization can be found elsewhere (9). The soil properties used as input data were those reported by the test performers. The p - y

curve procedure developed by Reese et al. (15) was used whenever a sand profile was encountered and the procedure developed by Sullivan (7) was used for clay. The base load-deformation relationships were developed following the procedure described previously in this paper.

To summarize the results and aid in evaluating model predictive capability, the measured versus predicted capacities are plotted for 1 and 2 degrees of pier rotation in Figure 10. Tests for which pier rotation as a function of applied moment was not provided were evaluated assuming that the pier rotated about a point two-thirds of the pier length down from the top. Rotations of 1 and 2 degrees correspond to pier top lateral deflections of 1.4 and 2.8 in., respectively, for a pier length of 10 ft.

The data are shown in conjunction with a 45-degree line, indicating perfect agreement between measured and predicted responses. Lines representing predicted values equal to 1.25 and 0.75 times the measured response are also shown. Linear regression analyses were performed on the data and resulted in slopes of 0.82 and 0.83 for the 1- and 2-degree rotation plots, respectively. It is shown from the foregoing statistics that the predictions are generally conservative and tend to somewhat underestimate the pier capacity. However, it should be noted that, at small deformation, the predicted response would be dependent, mostly, on the coefficient of lateral subgrade reaction and its distribution with depth. As the deformation increases, the predicted response becomes more governed by the ultimate lateral soil resistance and the base resistance.

For comparison, the measured versus the predicted capacities, using the computer program COM624 developed by Reese, are shown in Figure 11. The slope of the regression lines, standard error of the slopes, and the regression coefficients are given in Table 1. The standard error values indicate the variation of the data points around the slope of the best fit line. Using COM624, it was found that approximately 68 percent of the predicted responses were less than 0.75 times the actual measured field behavior, as shown in Figure 11.

TABLE 1 STATISTICAL PARAMETERS EVALUATED AT 1- AND 2-DEGREE ROTATION

	LTBASE		COM624	
	Degrees			
	1	2	1	2
Slope of regression line	0.83	0.82	0.64	0.56
Standard error of slope	0.04	0.04	0.04	0.04
Coefficient of correlation, R^2	0.87	0.85	0.59	0.56
Percent predictions exceed 1.25 the measured capacity	0	0	0	0
Percent predictions less than 0.75 the measured capacity	13	13	68	68

PIERS CONSTRUCTED ON SLOPES

The predicted and measured field behavior of five field load tests of drilled piers constructed in profiles with sloping ground surfaces are presented (Figure 12). One of the test piers was embedded in a cohesionless soil with a 3.5:1 sloping ground surface, whereas the other four were in a residual soil profile with a 2.2:1 sloping ground surface. All the piers were loaded

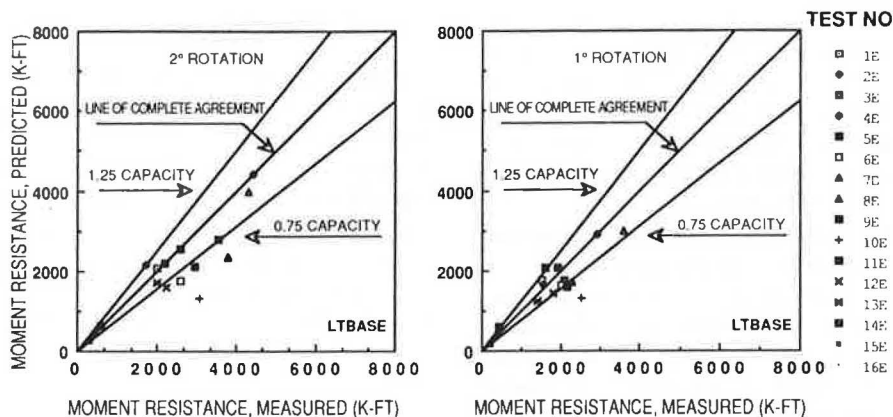


FIGURE 10 Predicted versus measured moment resistance at 1 and 2 degrees rotation: LTBASE.

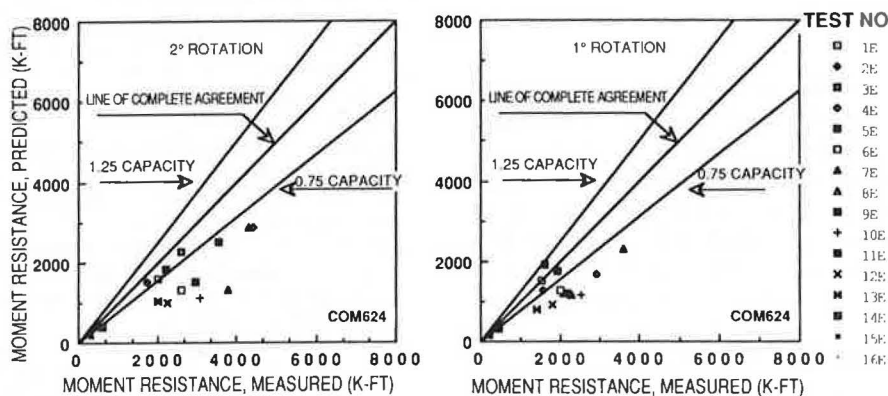


FIGURE 11 Predicted versus measured moment resistance at 1 and 2 degrees rotation: COM624.

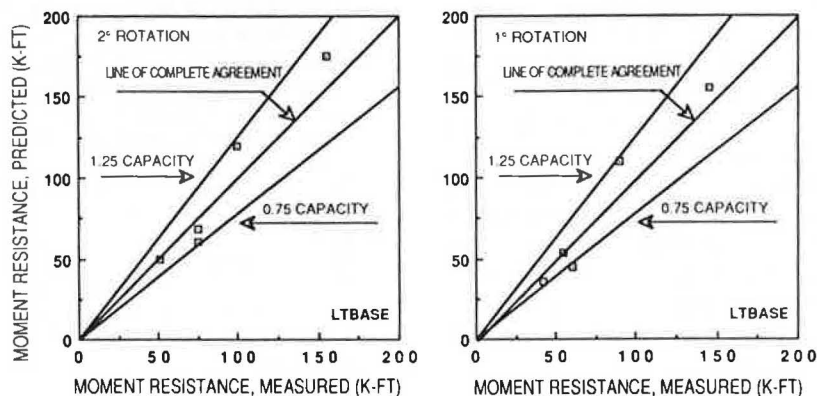


FIGURE 12 Predicted versus measured moment resistance at 1 and 2 degrees rotation for laterally loaded piers on slopes.

in the down slope direction. Detailed descriptions of the test procedures, site soil properties, and load test results can be found elsewhere (20).

In general, the measured responses were in reasonably good agreement with those predicted. It should be noted that at the early stage of the moment-deflection curve (for small deflections) the predicted response is highly dependent on the value of the coefficient of subgrade reaction, K_{ho} . This establishes

the need of a procedure for the evaluation of K_{ho} in residual soils.

In three of the five piers tested, the measured capacity was somewhat underestimated at large deformations, although the other two predictions overpredicted the capacity by a nearly equal percentage. Nevertheless, it should be noted that the ultimate resistance values, P_u , computed using the developed slope expressions (10, 20), are modified using an empirical

ultimate capacity adjustment parameter introduced by Reese et al. (7). This parameter, which is a function of pier diameter and depth, was developed to force P_u from theory to match test results. However, this parameter was developed on the basis of test data from piles constructed in a horizontal ground surface profile. It remains to be seen if this parameter is influenced by the presence of a sloping ground surface.

Moreover, the formulation of the theoretical expression included the effect of the active force developed behind the pier (10, 20). It has been observed that, at least for partially saturated soil deposits, this active force does not develop in the field (9, 10, 20). This active force ultimately has an influence equal to about 5 to 10 percent of the passive resistance. However, for generality it was deemed desirable to include the active force effect. In the final analysis, a solution including this effect is conservative and therefore acceptable at this time.

SUMMARY

This paper presents the capabilities of the computer program LTBASE, which has been developed to evaluate the nonlinear lateral load-deflection response of laterally loaded piers. A procedure to account for the influence of mobilized resistance at the base of the piers on the predicted lateral response is described. Also, a methodology supported by theoretical formulation is implemented in the program for the analysis of cases where the laterally loaded piers are constructed on slopes.

The importance of considering base resistance effects and sloping ground surface has been presented. For a 30-in.-diameter pier with an L/D ratio of 2.5, in loose sand, the base resistance is shown to increase the predicted ultimate moment capacity by more than 25 percent. The corresponding capacity at any design deflection level is also increased, although to a lesser degree for smaller rotations. On the contrary, the presence of a sloping ground surface decreases the pier capacity. For the same pier constructed in a 15-degree slope, 3.7:1, the predicted capacity corresponding to 2-degree rotation is shown to decrease by approximately 32 percent.

The capability of LTBASE to predict the measured field behavior of 16 piers constructed in horizontal ground surface profiles and 5 piers constructed in sloping ground surface profiles was also demonstrated. In general, the predictions obtained from LTBASE agreed reasonably well with the measured field behavior, with all but one prediction within ± 25 percent of the measured response.

LTBASE is capable of running on an IBM-compatible PC. Storage required for the sum of the code, data, and constants blocks is about 300 K. Minimum amount of random access memory (RAM) required to run the program is about 200 K. Maximum number of nodes and elements corresponding to this capacity is 101 and 100, respectively. The program is coded in FORTRAN77 computer language. The source code was compiled using the Microsoft FORTRAN77 version 3.2 compiler. The compiled code is linked to MS-FORTRAN runtime library, FORTRAN.L87, which supports an 8087 math coprocessor. The Microsoft 8086 object linker version 3.02 was used in the linking process. Double precision arithmetic is used throughout the program to enhance the accuracy of the solution.

ACKNOWLEDGMENTS

This research was sponsored by the North Carolina Department of Transportation and Highway Safety (NCDOT) in cooperation with the FHWA, U.S. Department of Transportation. A technical advisory committee chaired by W. G. Marley and including R. Martin, J. Ledbetter, and P. Strong of the NCDOT, and D. D. Rhame of FHWA aided in the coordination of the research and are gratefully acknowledged. The authors also wish to thank the NCDOT personnel who supported the geotechnical investigation and lateral load testing.

REFERENCES

1. H. G. Poulos. Behavior of Laterally Loaded Piles: I—Single Piles. *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 97, No. SM5, May 1971, pp. 711–731.
2. F. Bagueline, R. Frank, and Y. H. Said. Theoretical Study of Lateral Reaction Mechanism of Piles. *Geotechnique*, Vol. 27, No. 3, Nov. 1977, pp. 405–434.
3. J. Briaud, T. Smith, and B. Meyer. Laterally Loaded Piles and the Pressuremeter: Comparison of Existing Methods. *Laterally Loaded Deep Foundations: Analysis and Performance*, STP 835, ASTM, 1984, pp. 97–111.
4. M. A. Gabr and R. H. Borden. Influence of the Base Resistance on the Lateral Load Deflection Behavior of Rigid Piers. *Proc., International Conference on Soil-Structure Interaction*, Paris, France, May 1987, pp. 219–226.
5. H. Matlock. Correlation for Design of Laterally Loaded Piles in Soft Clay. *Proc., 2nd Annual Offshore Technology Conference*, Houston, Texas, American Institute of Mining, Metallurgical, and Petroleum Engineering, 1970, pp. 577–594.
6. F. Parker, Jr., and L. C. Reese. *Experimental and Analytical Studies of Behavior of Single Piles in Sand under Lateral and Axial Loading*. Research Report 117-2. Center for Highway Research, The University of Texas at Austin, Nov. 1970.
7. L. C. Reese and J. D. Allen. *Handbook on Design of Piles and Drilled Shafts Under Lateral Loads*. Office of Research and Development, FHWA, U.S. Department of Transportation, July 1984.
8. L. C. Reese. Laterally Loaded Piles: Program Documentation. *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 103, No. GT4, April 1977, pp. 287–305.
9. H. L. Davidson. *Laterally Loaded Drilled Pier Research*. Final Report: Vol. I and II. Electrical Power Research Institute, 1982.
10. R. H. Borden and M. A. Gabr. *LTBASE: Lateral Pier Analysis Including Base and Slope Effects*. Research Report No. HRP 86-5. Center for Transportation Engineering Studies, North Carolina State University, Raleigh, July 1987.
11. L. C. Reese, F. T. Touma, and M. W. O'Neill. Behavior of Drilled Piers under Axial Loading. *Journal of the Soil Mechanics and Foundations Division*, ASCE, Vol. 102, No. GT5, May 1976, pp. 493–510.
12. H. G. Poulos and E. H. Davis. *Pile Foundation Analysis and Design*. John Wiley & Sons, Inc., New York, 1980.
13. J. Focht and C. Drash. Behavior of Drilled Piers in Layered Soils on Texas Barrier Islands. *Drilled Piers and Caissons II*, ASCE, May 1985, pp. 76–98.
14. L. C. Reese. Ultimate Resistance Against a Rigid Cylinder Moving Laterally in a Cohesionless Soil. *Journal of the Society of Petroleum Engineers*, Dec. 1962, pp. 355–359.
15. L. C. Reese, W. R. Cox, and F. D. Koop. Analysis of Laterally Loaded Piles in Sand. *6th Annual Offshore Technology Conference*, Vol. 2, Paper 2080, Houston, Tex., May 1974.
16. J. M. Murchison and M. W. O'Neill. Evaluation of P–Y Relationships in Cohesionless Soils. *Analysis and Design of Pile Foundations*, ASCE, San Francisco, Calif., Oct. 1984.

17. R. F. Scott. *Analysis of Centrifuge Pile Tests; Simulation of Pile Driving*. Research Report: OSAPR Project 13. American Petroleum Institute, Pasadena, Calif., June 1980.
18. F. Baguelin, J. F. Jezequel, and D. Shields. *The Pressuremeter and Foundation Engineering*. Trans Tech Publications, Aedermannsdorf, Switzerland, 1978.
19. F. H. Kulhawy. Limiting Tip and Side Resistance: Fact or Fallacy. *Proc., ASCE National Convention*, San Francisco, Calif., 1985.
20. M. A. Gabr. Load-Deflection Analysis of Laterally Loaded Piers. Doctoral thesis. North Carolina State University, Raleigh, 1987.

The contents of this paper reflect the views of the authors, who are responsible for the fact and accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the North Carolina Department of Transportation and Highway Safety or the Federal Highway Administration. This paper does not constitute a standard, specification, or regulation.

Publication of this paper sponsored by Committee on Foundations of Bridges and Other Structures.