Prediction of Lateral Movement of Bridge Abutments on Piles

H. J. SIRIWARDANE, L. K. MOULTON, and RAN-JAY CHEN

ABSTRACT

An investigation of the horizontal movement of perched bridge abutments founded on end bearing piles driven through the bridge approach embankment and underlying compressible foundation soils is described and discussed in this paper. The finite element method of analysis was used to predict the horizontal movements of perched abutments in a parametric study and for two actual bridges, where observations of the abutment movements were available. The results of the parametric study led to the conclusion that most perched abutments founded on end bearing piles driven through approach embankments underlain by soft compressible foundation soils tend to rotate and move laterally away from the bridge superstructure. The magnitude of this movement is dependent on the relative stiffness of the embankment and foundation soils, the depth of the compressible foundation soils relative to the height of the approach embankments, and the nature of the pile support provided. The magnitude of the backward movement of the perched abutments tends to be greater as the softness and depth of the foundation soils increase. The presence of the pile support for this type of abutment appears to have little effect in preventing the backward rotation and horizontal displacement of the abutments. The use of the simplified method of analysis employed in the parametric study to predict the movement of the abutments of two actual bridges produced mixed results. The direction of the movement of the abutment of one of these bridges was predicted correctly, but the magnitude of the predicted movement was slightly less than observed. For the second bridge, the analyses failed to correctly predict either the direction or magnitude of the abutment displacements. However, it was determined that the construction sequence used at this structure could not be adequately modeled with the simplified analytical procedures used, and that a more sophisticated method of analysis might have to be adopted for future studies of this type.

A great deal of data has been collected over the years relative to the effect of differential foundation movements on buildings and industrial structures. These data have been used to establish limits on the movements that are considered tolerable (1-4). These tolerable movement criteria have been used in conjunction with appropriate geotechnical and structural analyses to decide how the structure should be designed and founded in order to tolerate any anticipated movements safely and economically. Unfortunately, similar tolerable movement criteria and the accompanying design methodology have not been fully established for highway bridges.

It was the recognition of the need for the development of criteria for determining whether a proposed bridge can tolerate the estimated total and differential movements to which it may be subjected that led the Federal Highway Administration to sponsor research programs designed to fulfill this need. This comprehensive program of study was performed in the Department of Civil Engineering at West Virginia University. The research was initiated in 1978 and was completed in 1982 (5-7).

As a part of this study, data were collected on 314 bridges that had experienced some type of foundation movements. The bridges were distributed across 39 states, the District of Columbia, and 4 Canadian provinces. These data were analyzed to determine (a) the effect of a variety of substructure variables on the type and magnitude of foundation movements, (b) the influence of these bridge foundation movements on the various components of the bridge structures, and (c) the tolerance of the various bridges studied to the foundation movements to which they had been subjected.

The results of this study indicated that the largest number of substructure units that experienced movements were the bridge abutments. A total of 439 abutments exhibited some type of movement, with 379 moving vertically, 138 moving horizontally, and 77 moving both vertically and horizontally (6,7). Although the magnitude of the vertical abutment movements was often substantially greater than the magnitude of horizontal movements, the horizontal movements tended to be more damaging to the bridge superstructures. It was found that, depending on type of spans, length and stiffness of spans, and type of construction material, many highway bridges can tolerate significant magnitudes of total and differential vertical movements without becoming seriously overstressed, sustaining serious structural damage, or suffering impaired riding quality. In particular, it was found that a longitudinal angular distortion (differential settlement/span length) of 0.004 would most likely be tolerable for continuous bridges of both steel and concrete, whereas a value of angular distortion of 0.005 would be a suitable limit for simply supported bridges. However, it was concluded that horizontal movements of abutments would have to be limited to less than 1.5 in. to prevent damage to bridge superstructures, bearings, and joints.

To use these tolerable movement criteria in design, it is necessary that a means be available for predicting both the vertical movements of abutments and piers, and the horizontal movements of abutments. Although it has been demonstrated that reasonably reliable predictions of the settlements of bridges can be obtained as long as adequate subsurface information and laboratory test data are available (6-8), to date, little attention has been devoted to the prediction of horizontal abutment movements. The purpose of this paper is to describe a preliminary study that was undertaken as a first step in the development of a methodology for the prediction of the horizontal movement of abutments.

Guided by the results of field observations (6-7), a parametric investigation was undertaken to determine the effect of the geometry and soil properties on the horizontal movements of perched abutments founded on end bearing piles driven through approach embankments and an underlying layer of compressible foundation soil. In addition, data from selected case histories were used to determine if the simplified method of analysis selected for this preliminary study could produce reasonable predictions of the abutment movements or if a more sophisticated method of analysis would be required.

FIELD OBSERVATIONS

A general summary of the field observations of the type and magnitude of abutment movements is presented in Table 1 (6,7). The frequency of occurrence of the various ranges of vertical and horizontal movements is shown in Figure 1. These data indicate that, as noted earlier, the majority of abutments

TABLE 1 General Summary of Abutment Movements *(6, 7)*

	Frequency of Movements		Magnitude of Movements	
Movement Type	Number of Abutments	Percent Moved	Range in Inches	Average in Inches
All types	439	100.0		
Vertical	379	86.3	0.03-50.4	3.7
Horizontal	138	31.4	0.1 -14.4	2.6
Vertical and	77	17.5	0.1 -50.4	6.9
horizontal			0.1 -14.4	2.2

Note: 1 inch = 25.4 mm.

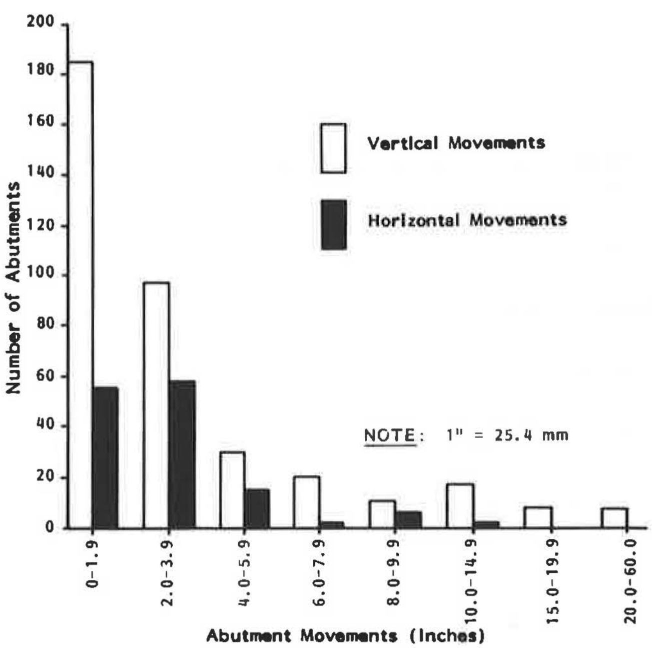

FIGURE 1 Frequency of occurrence of various ranges of vertical and horizontal abutment movements *(6, 7)*.

that moved experienced vertical movement, less than one-third moved horizontally, and a substantial number moved both vertically and horizontally. Although many of the abutments that experienced horizontal displacement moved inward, many becoming jammed against the beams or girders, as shown in Figures 2

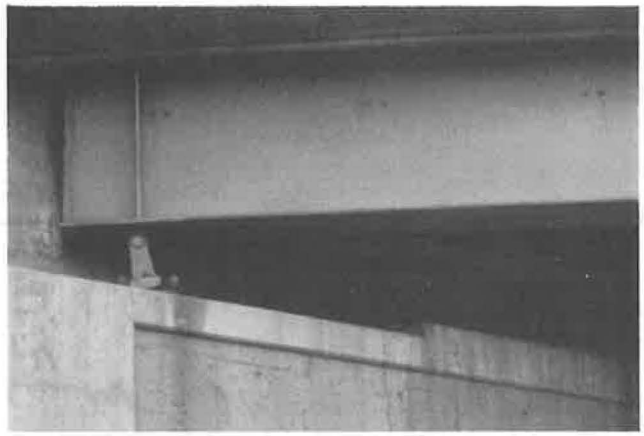

FIGURE 2 Illustration of inward horizontal displacement leading to abutment being jammed against beams.

and 3, a substantial number of abutments (a total of 39) moved outward away from the bridge superstructure and toward their approach embankments, as shown in Figures 4 and 5. These were almost invariably perched abutments founded on piles driven through approach fill placed over deep compressible soils.

Of those abutments with sufficient field data to be included in the analysis, substantially more

FIGURE 3 Backwall of abutment jammed against beam as result of inward horizontal movement of abutment.

FIGURE 4 Tilted rocker caused by backward horizontal displacement of abutment.

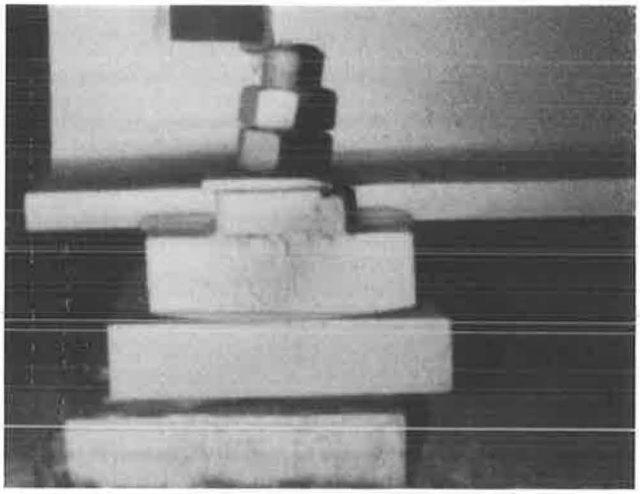

FIGURE 5 Displaced bearing and tilted anchor bolt caused by backward horizontal displacement of abutment.

perched abutments were reported than either full-height or spill-through abutments, as shown in Figure 6. Although these data indicate that more full-height abutments experienced movements than spill-through abutments, both the range and average magnitude of the movements of the spill-through abutments were greater than for the full height abutments. This was true with respect to both vertical and horizontal moments. However, both the range and magnitude of the horizontal movements of the perched abutments were substantially greater than those observed for either full-height or spill-through abutments. For those 93 perched abutments that experienced horizontal movements, the displacements ranged up to 14.4 in., whereas the corresponding ranges of horizontal movements for the 32 full-height abutments and 13 spill-through abutments that moved were 8.0 and 8.8 in., respectively.

The relatively large number of perched abutments that moved suggests that greater attention needs to be directed to the design and construction of the foundation systems for this type of abutment. Consequently, the initial attempts to predict the horizontal movements of bridge abutments concentrated on this type of abutment. Because the great majority (80 percent) of the perched abutments that experienced horizontal movements were founded on piles (6), this type of foundation was selected for the abutments considered in the analysis.

PARAMETRIC STUDY

To investigate the influence of the various factors believed to control the horizontal displacement of abutments, selected parameters were systematically varied and the abutment displacements were calculated. These parameters included: (a) the relative stiffness of the embankment and its underlying foundation, that is, the ratio of elastic moduli or the modular ratio (E_H/E_h); (b) the depth of the foundation, H, relative to the height of the approach embankment, h, that is, the depth ratio (H/h); and (c) the nature of the pile support, in terms of the ra-

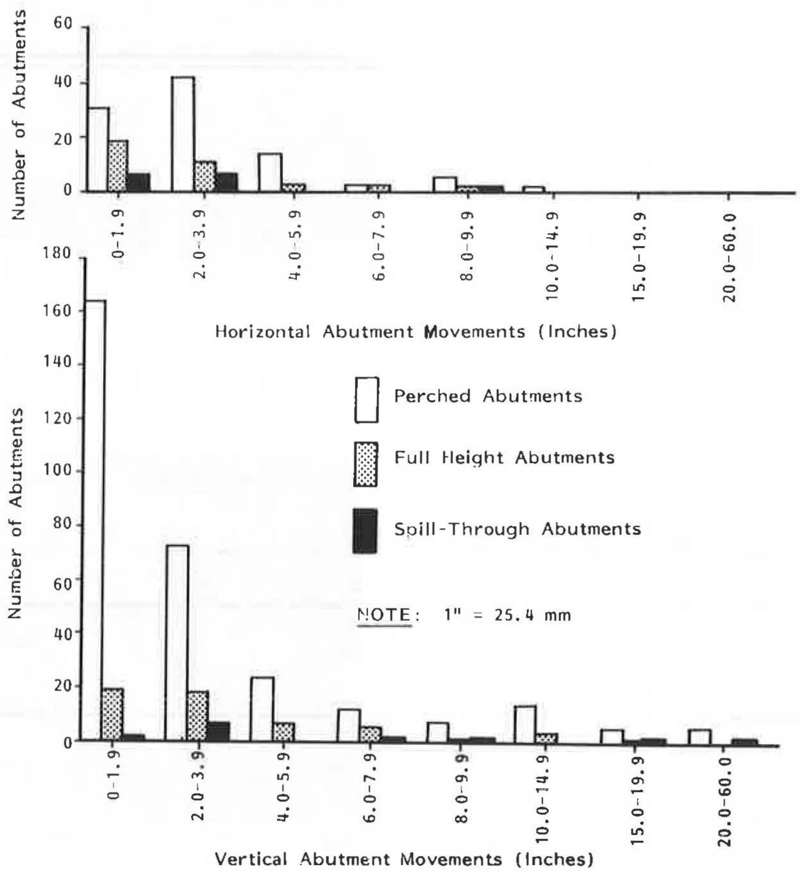

FIGURE 6 Frequency of occurrence of various ranges of vertical and horizontal abutment movements in terms of abutment type (6,7).

tio of the number of batter piles, B, to the number of vertical piles, V, as well as the effects of the removal of pile support and the removal of fixity at the pile tips.

The geometry of the embankment, abutment, and foundation system selected for analysis, and the imposed loading conditions were based on an average of the conditions that were observed to have existed for those perched bridge abutments on piles that experienced horizontal movements (6,7). The piles selected were 12-in., 53-lb, steel H-piles driven to rock, except for the case where the lack of fixity of the pile tips was investigated by stopping the pile tips just short of the rock surface. The front row of piles was battered 4 in. horizontally for each foot of vertical penetration. The basic center-to-center spacing of the rear row of piles, which was vertical, was selected as 5 ft 8 in., and the spacing of the front row of piles was changed as the ratio of the number of batter to vertical piles (B/V) varied. The slopes of the approach embankment were assumed to be 2:1.

Method of Analysis

The analysis of the abutment movements was performed using the finite element method, assuming linear elastic material behavior and plane strain conditions. The computer code used in the analysis (9) was developed for handling geotechnical problems and has the capability of simulating sequences of construction and excavation and material nonlinearities with a number of constitutive models. The program can also handle plane stress/plane strain and axisymmetric idealizations with four- and eight-node isoparametric elements. The accuracy of the program has been verified by solving a number of problems over the past few years.

It is understood that the problem under consideration would generally be affected by the construction sequence and the time-dependent nonlinear behavior of the structure and particularly its foundation. This nonlinear behavior can be modeled by using a piecewise linear approximation together with an incremental analysis. This procedure is referred to as the tangent stiffness method. Alternately, a secant modulus can be defined in terms of total stresses and strains to model the nonlinear material behavior. For the sake of simplicity, this latter procedure was adopted for the preliminary study reported here. There appear to be ample precedents for the adoption of this methodology (10) in studies such as this.

A typical finite element mesh used in the parametric study is shown in Figure 7. This particular mesh is for the case where the depth of the foundation soil is twice the height of the embankment, that is, the depth ratio, H/h, is two. The bottom boundary (rock) was assumed to be fixed in horizontal and vertical directions, while the two lateral boundaries were assumed to be free for vertical movement.

The unit weight of the embankments and the elastic properties of the embankment and foundation materials used in the analysis, that is, the secant moduli and Poisson's ratio, were assumed based on published data (11,12) and the results of in situ measurements made on comparable embankments and their foundations by the various highway agencies that supplied data for the tolerable bridge movement study described earlier (5-7).

The superstructure loading was based on the weight of a typical concrete deck with a span of 60 ft, a width of 42 ft, and a thickness of 0.6 ft along with eight steel rolled beams of the type

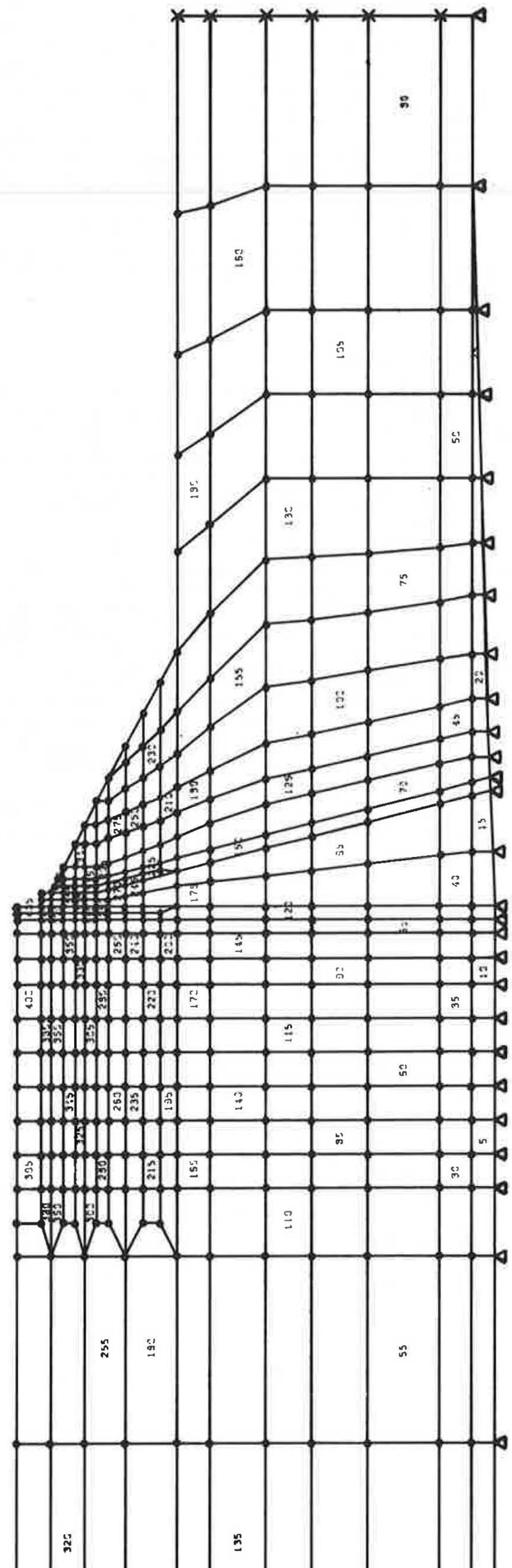

FIGURE 7 Typical finite element mesh used in the parametric study for H/h = 2.0.

33WF130. The superstructure loading on the abutment used in the parametric study was equal to 3,443 lb/ft. First, the deformations resulting from the embankment fill were computed by performing a gravity turn on analysis. Then the superstructure loading was applied to the abutment.

Each row of piles was idealized as a continuous pile in the two-dimensional analysis. Here, the bending stiffness provided by each row of piles was modeled by using an equivalent elastic modulus for the pile material so that the total bending stiffness of the actual piles in each row would be equal to the bending stiffness of the idealized pile section.

Results of the Analysis

The analyses described earlier produced a large quantity of data. For the sake of brevity, only a limited portion of the results are presented here. However, the large volume of computer output produced has been retained at West Virginia University, and additional results can be made available for interested readers.

The results of the analysis of the effect of the relative stiffness of the embankment and its underlying foundation are shown in Figure 8. In this particular series of analyses, the embankment modulus was held constant at $E_h = 15 \times 10^5$ lb/ft², and the foundation modulus, E_H, was varied. The results shown in Figure 8 are for the case where the foundation depth was taken as twice the embankment height, that is, H/h = 2, and the number of batter and vertical piles were considered to be equal, that is, B/V = 1. Similar trends were also observed for other cases of H/h ratios.

It is clear from Figure 8 that the effect of the relatively soft foundation is to produce a backward rotation and displacement of the abutment. The softer the foundation soil relative to the embankment, the more pronounced this effect appears to be. This type of behavior was described by Stermac et al. (13) in 1969, and it is notable that the mechanism associated with this type of displacement, that is, the "bulging" motion of the lower portion of the piles as a result of the foundation displacements, was also correctly identified by these authors.

The effect of the depth of the soft foundation soil relative to the fill height on abutment movements is illustrated for two typical cases in Figure 9. In this instance, depth ratios of H/h = 2 and 4 have been used with a modular ratio of $E_H/E_h = 0.08$. These data indicate that the deeper the soft foundation soil is relative to the height of the bridge approach embankment, the greater the tendency is for backward rotation and displacement of the abutment. The combined effect of the variation of modular ratio, E_H/E_h, and depth ratio, H/h, is given in Figure 10, which shows the horizontal displacements of the beam seat as a function of these parameters. It should be noted that even when the modular ratio approaches one the calculations indicate that there is still a slight tendency for backward movement of the abutment, although these small movements may have little practical effect on abutment performance.

The effect of the nature of the pile support on abutment displacement is shown in Figure 11 for a depth ratio of H/h = 2 and a modular ratio of $E_H/E_h = 0.08$. The data in Figure 11 clearly indicate that increasing the ratio of batter piles to vertical piles, B/V, has relatively little effect on the horizontal displacement of the abutment. In fact, doubling the number of batter piles caused only a slight reduction in the backward displacement of the abutment. However, Figure 11 shows that eliminating the piles entirely did produce a significant change

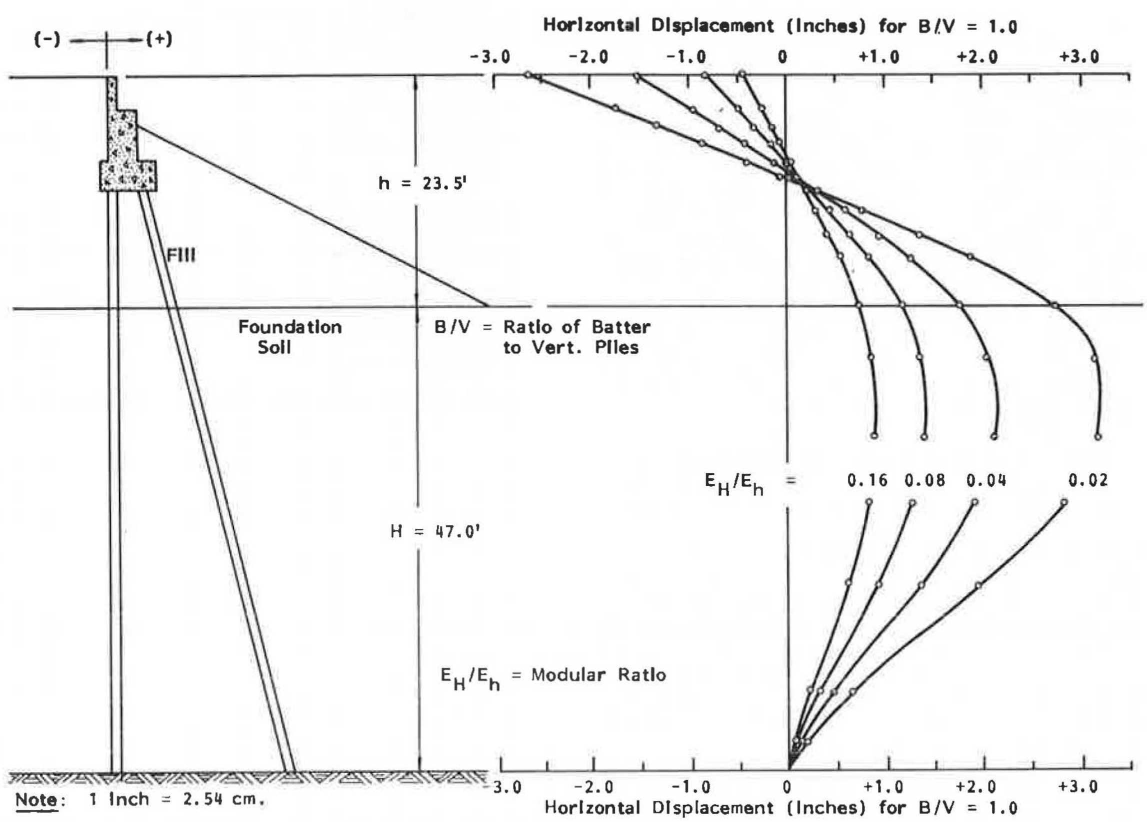

FIGURE 8 Effect of modular ratio on abutment displacement.

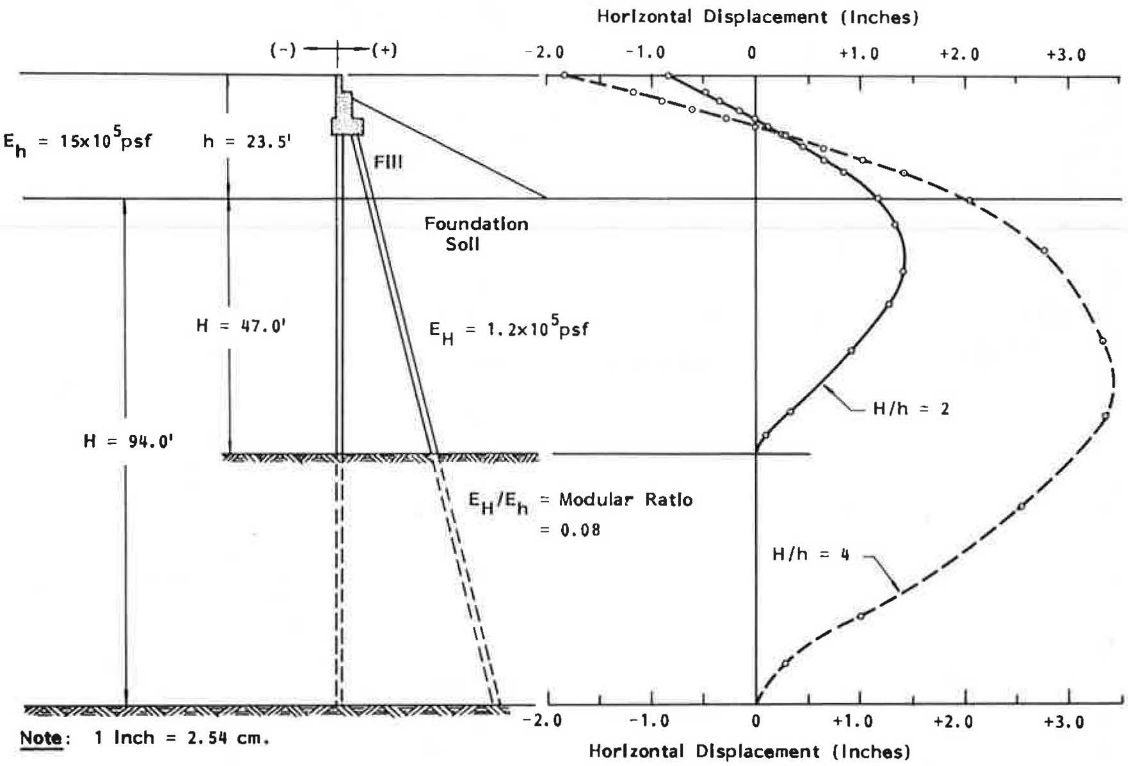

FIGURE 9 Effect of depth ratio, H/h, on abutment displacement for modular ratio of 0.08.

in the calculated abutment displacement. Although the abutment did rotate backward as a result of differential foundation settlement, there was practically no horizontal displacement of the beam seat. These same general trends with respect to the effect of the nature of the pile support were observed regardless of the depth of the foundation soil, except that the backward displacement of the abutment increased with an increase in the depth ratio, H/h. This is shown in Figure 12.

The effect of the fixity of the pile tips on horizontal abutment movements is shown in Figure 13 for

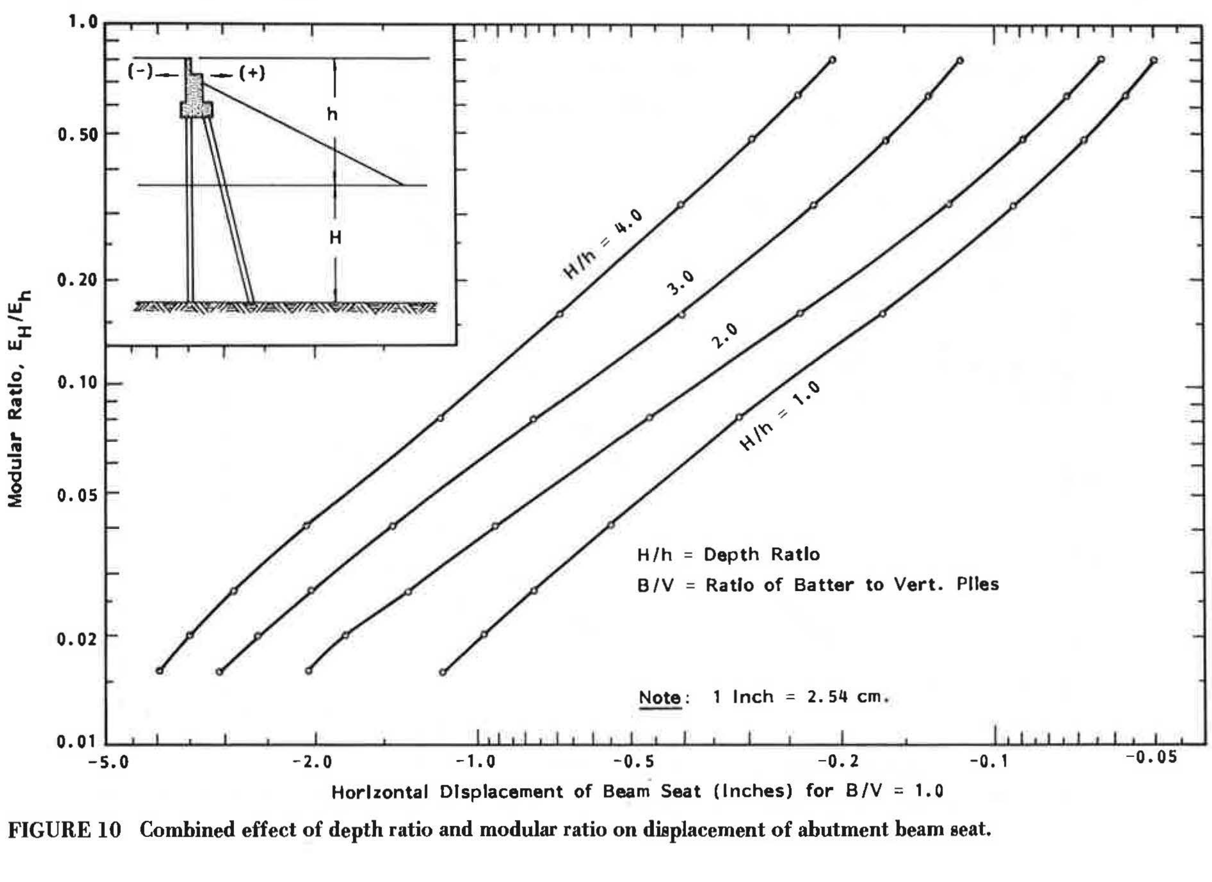

FIGURE 10 Combined effect of depth ratio and modular ratio on displacement of abutment beam seat.

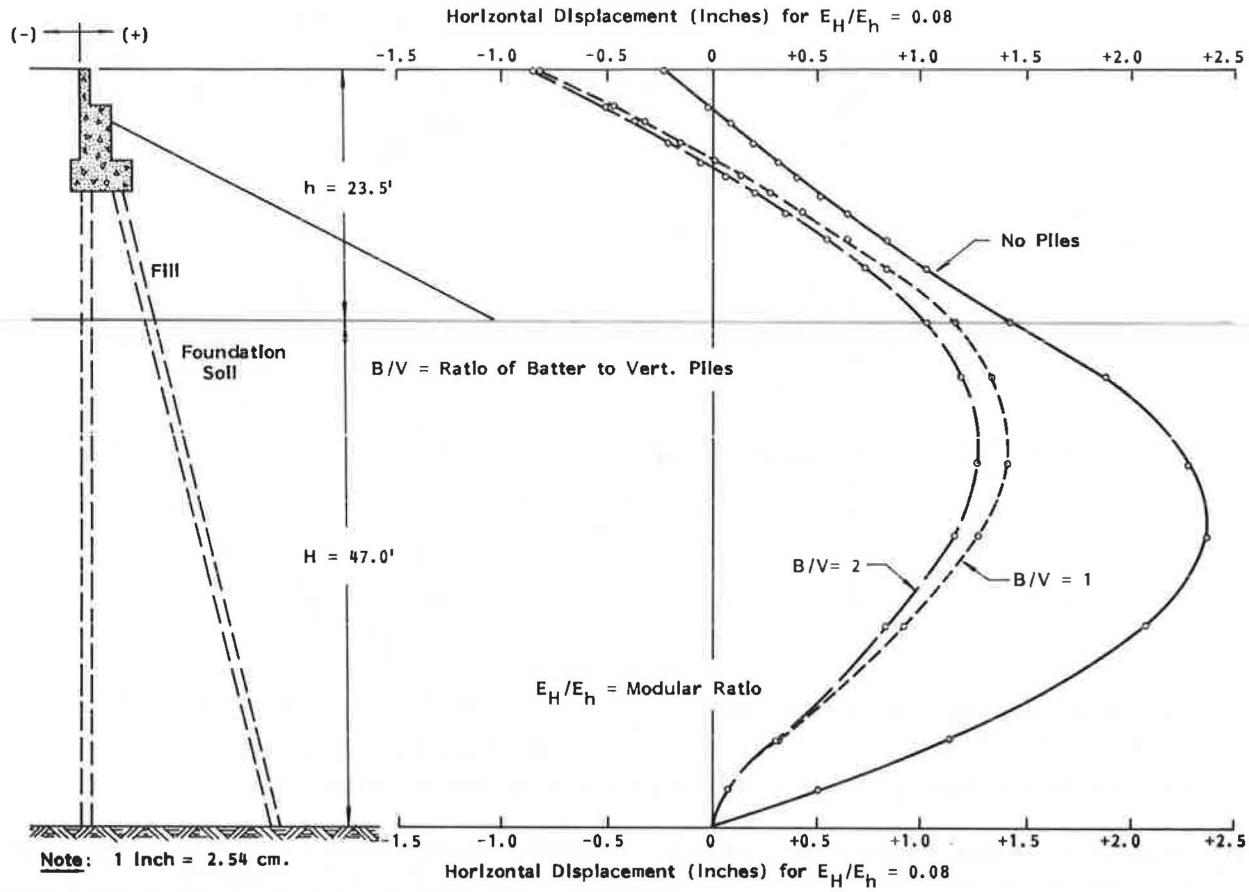

FIGURE 11 Effect of nature of pile support on abutment displacement.

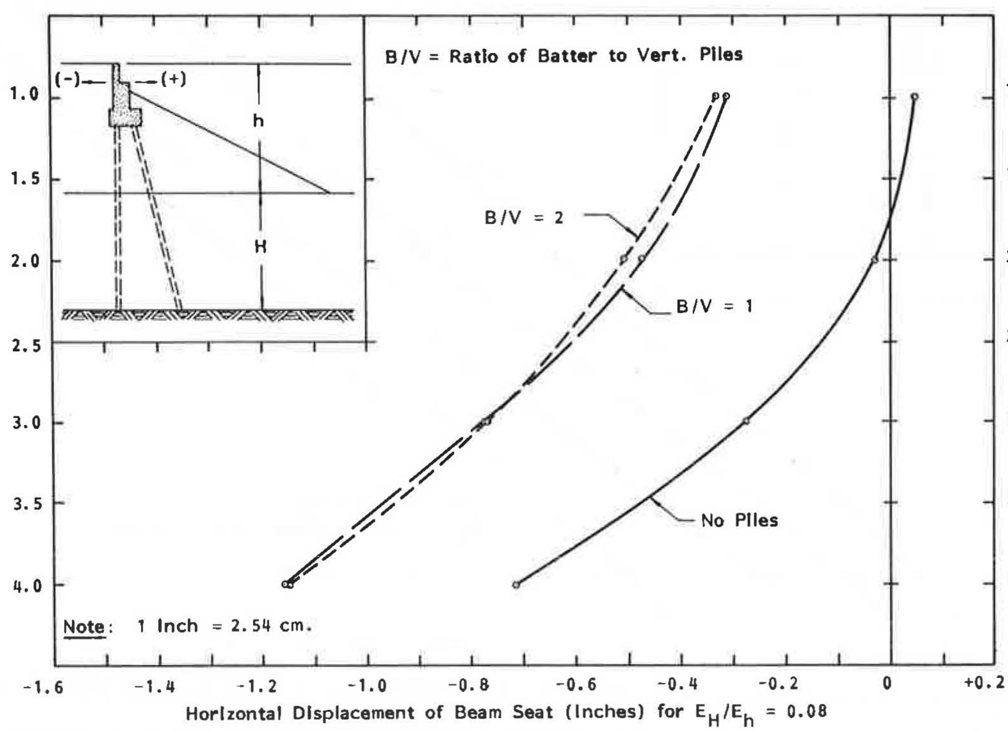

FIGURE 12 Combined effect of nature of pile support and depth ratio on displacement of abutment beam seat.

a depth ratio of H/h = 2, a modular ratio of E_H/E_h = 0.08, and a pile ratio of B/V = 1. The data in Figure 13 indicate that the lack of fixity associated with not achieving end bearing on rock can tend to allow the lower portion of the piles to displace in a forward direction, causing increased backward rotation and displacement of the abutment. The practical significance of this finding should not be overlooked.

MOVEMENT PREDICTIONS FOR ACTUAL BRIDGE ABUTMENTS

Two bridge case histories were studied to determine if the simplified analytical technique used in the parametric study would produce predictions of horizontal abutment movements that would show reasonable agreement with the observed abutment movements, or if more sophisticated techniques would be required.

Both of the bridges selected were located in Maine and consisted of two-span, continuous steel structures with perched abutments, founded on end bearing steel H-piles driven through granular approach embankments and soft compressible foundation soils. Initially, the method of analysis used for both of these structures was the same as described for the parametric study. However, for these bridges the secant moduli and Poisson's ratios were estimated using published data (11,12) aided by judgment based on the results of in situ measurements made at the bridge sites, including standard penetration tests and vane shear tests, and the results of laboratory testing, including classification, consolidation, laboratory vane shear tests, and unconfined compression tests. To simulate long-term deformations resulting from loads of the fill and the superstructure, consolidated drain properties need to be used in the analysis. The complete listing of all the material properties used in this study has been omitted here, but has been documented elsewhere (14).

The first of the two bridges studied was the structure carrying the Route 1 Connector over Route 703 in the city of South Portland in Cumberland County. The north abutment was selected for analysis because both measurements and observational data were available for this unit of the substructure. The geometry of this abutment, its pile foundation, the embankment, and foundation soils are shown in Figure 14, along with the soil moduli used in the analysis.

The computed horizontal displacements of the abutment are also shown in Figure 14. These data indicate a backward horizontal displacement of 1.82 in. at the top of the abutment backwall and a backward displacement of 1 in. at the beam seat. The observed tilt of the rockers for this abutment, shown in Figures 4 and 15, and reference to the bridge plans for this structure, suggest that the actual backward movement of the abutment at the bridge seat was slightly greater than 2 in. Consequently, although the predicted abutment movements were in the right direction, they were somewhat smaller than the observed movements. This is not surprising considering the simplified method of analysis used and the assumptions that were required to select the soil parameters used in the analysis.

The second of the two bridges studied was the structure carrying the U.S. Route 1 westbound ramp over Interstate Route 95 in Brunswick in Cumberland County. The west abutment was selected for analysis

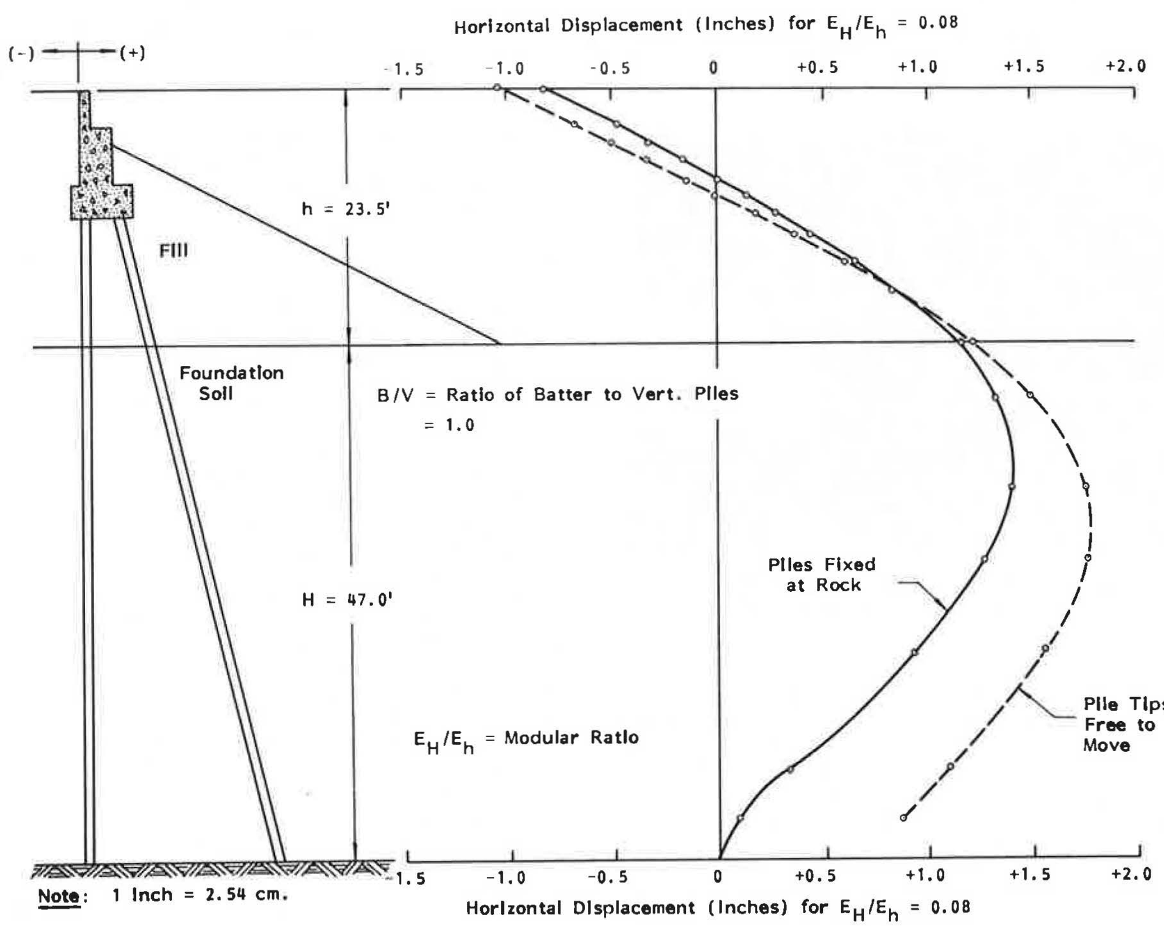

FIGURE 13 Effect of fixity of pile tips on abutment displacement.

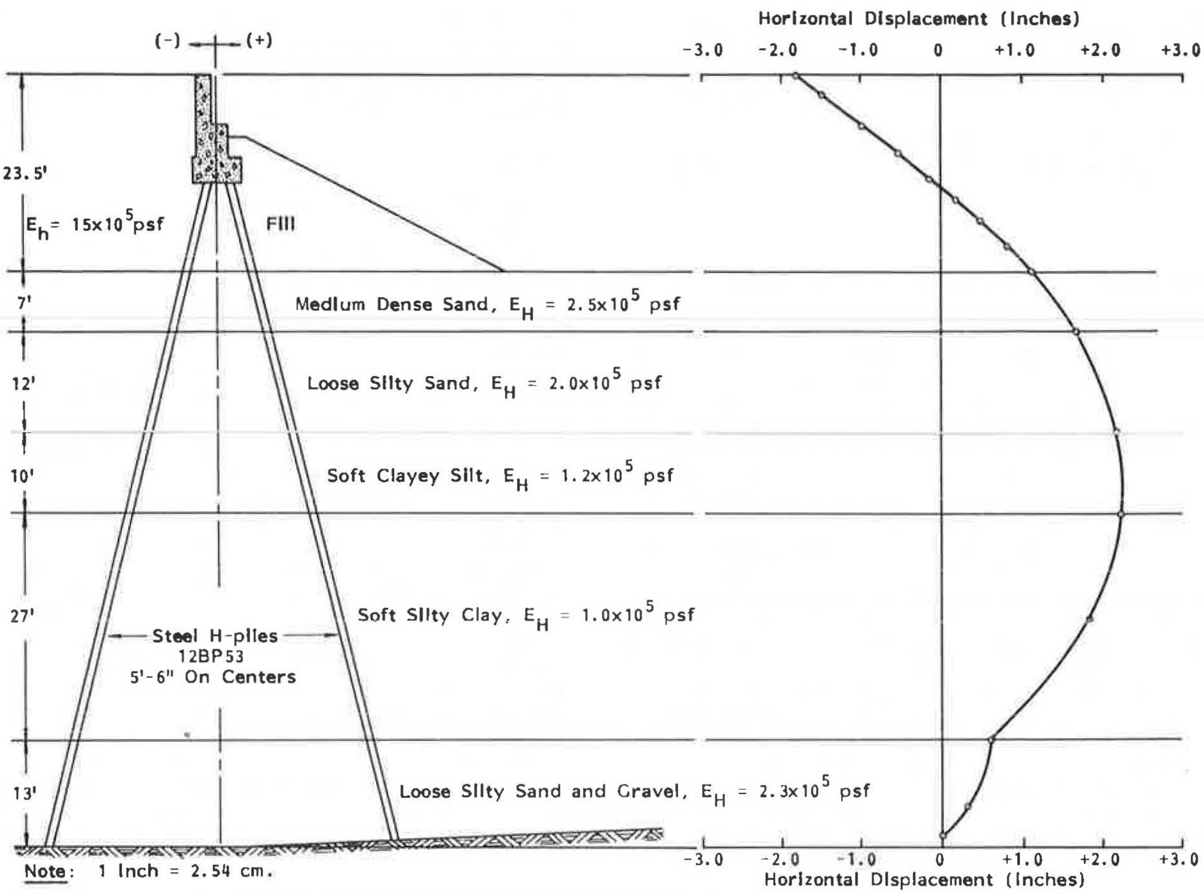

FIGURE 14 Computed horizontal displacements at the north abutment of the Route 1 connector over state Route 703–South Portland, Maine.

FIGURE 15 Tilted rockers at the north abutment of the South Portland bridge, caused by the backward rotation and displacement of the abutment.

because the soft foundation soil was the deepest beneath that abutment and because field observations indicated that this abutment had experienced the most horizontal displacement. The geometry of this abutment, its pile foundation, the embankment, and foundation soils are shown in Figure 16, along with the original soil moduli used in the analysis.

The computed horizontal displacements of the abutment and its foundation system, based on these initial assumptions, are shown by the solid curve in Figure 16. These data indicate a backward movement of the top of the abutment backwall of 4.53 in. and a backward displacement of the beam seat of 3.70 in. Actually, the abutment moved forward approximately 3 in. at the beam seat (see Figure 2) and the front face of the abutment, shown in Figure 17, is tilted forward between 2 and 2.25 in. in a vertical distance of approximately 7.5 ft. This type of forward motion was reportedly quite surprising to the cognizant officials of the Maine Department of Highways (DOH), who would normally expect backward movement of a bridge abutment under the circumstances existing at this site. However, there were some circumstances surrounding the design and construction of the bridge at this site that might have had a bearing on the abutment performance.

First, it should be noted that, although it was considered that the abutment in question was a perched abutment, this abutment is actually about 21 ft high, which approaches the height of some full-height abutments. This difference can be observed by comparing the front face of this abutment, as shown in Figure 17, with that of the abutment of the South Portland bridge, shown in Figure 15. Consequently, it is possible that the effect of lateral earth pressure behind the abutment might have played a much more significant role in the control of the horizontal displacements than might be expected for a normal perched abutment.

Second, the construction sequence at this site first required the placement of I-95 fill, followed by the bridge approach embankment, as shown by the dashed fill surfaces indicated in Figure 16. Although the exact timing of the subsequent construction sequence is unclear, the best judgment of the

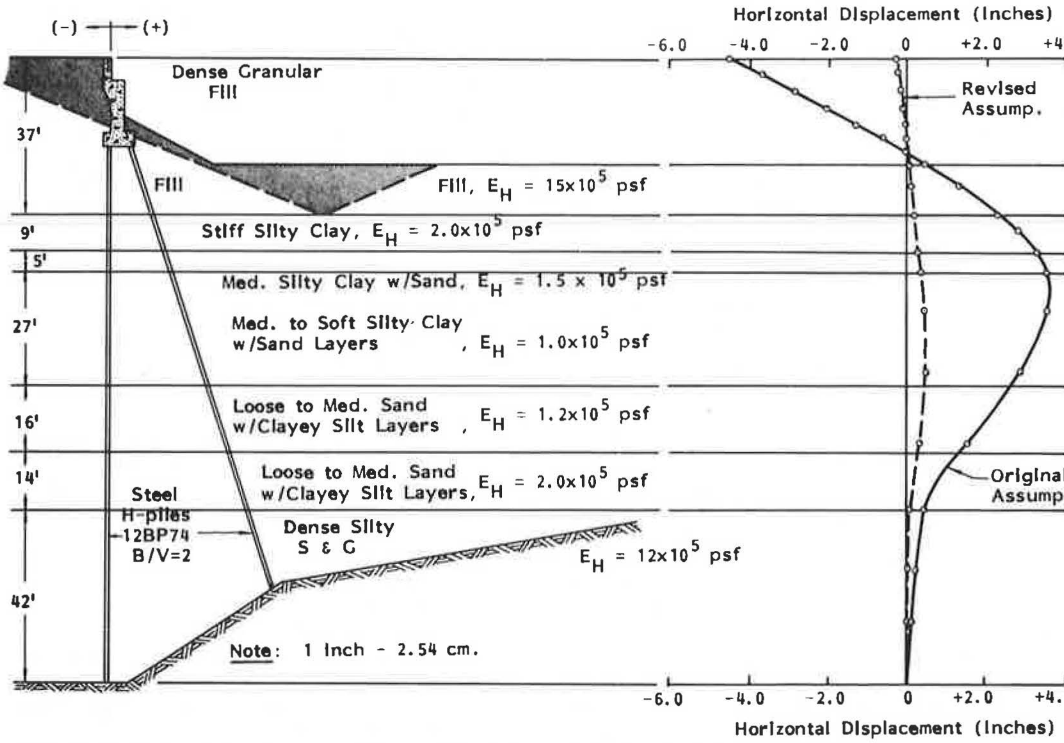

FIGURE 16 Computed horizontal displacements at the west abutment of the U.S. Route westbound ramp over Interstate 95—Brunswick, Maine.

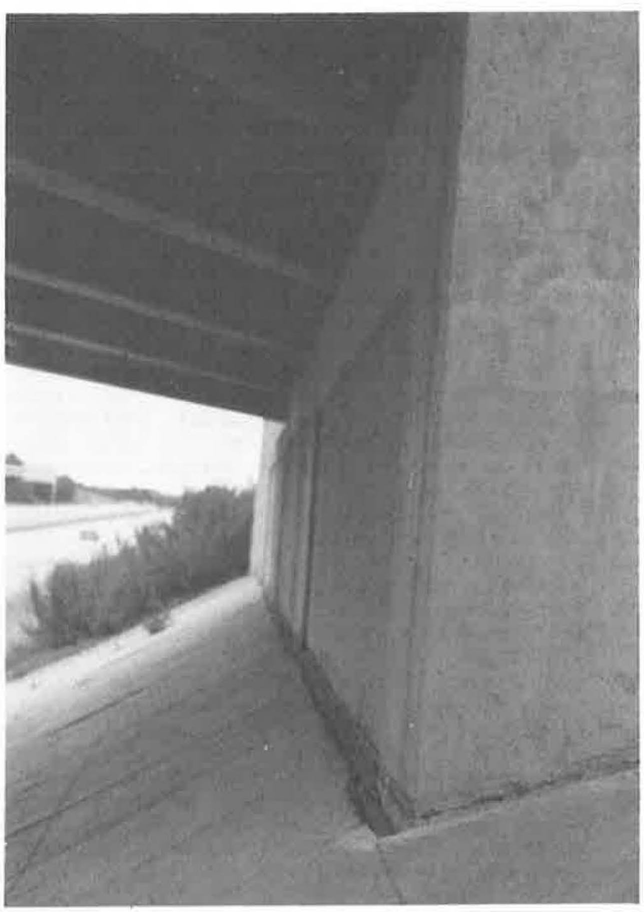

FIGURE 17 The exposed front face of the rather high west abutment of the Brunswick bridge.

Maine DOH officials was that these embankments were allowed to settle until the following construction season before abutment construction was undertaken. Following the completion of the abutment, select granular backfill was placed in the areas indicated by the shading in Figure 16. This was reportedly a well-compacted material required to have a dry density equal to or in excess of 90 percent of modified proctor density.

To simulate the circumstances resulting from this construction sequence, a new analysis was performed on the basis of a revised set of assumptions. It was assumed that consolidation of the foundation soils that took place before the beginning of the abutment construction resulted in (a) a substantial (threefold) increase in the secant moduli of the soft foundation soils behind the bridge foundation, that is, behind the vertical row of piles, and (b) a decrease in the effective weight of the original embankment material to 30 percent of its original density. That is, the fill and the foundation have already deformed (consolidated) by 70 percent before the abutment was placed, and only 30 percent of the fill weight had an influence on abutment movement.

It was also assumed that the densely compacted granular backfill had a unit weight of 140 lb/ft^2 and an elastic modulus twice that of the original fill. This revised set of assumptions led to the computed horizontal displacements shown by the dashed curve in Figure 16. Although this resulted in a marked decrease in the backward horizontal displacement of the abutment, it still did not account for the relatively large forward displacement observed. This suggests that much more detail may have to be obtained about the material properties and construction sequence at this site, and that a more sophisticated method of analysis may be required to model the behavior of abutments under circumstances such as those at this site.

SUMMARY AND CONCLUSIONS

Based on the results of the parametric study described in this paper, it can be concluded that most perched abutments founded on end bearing piles driven through approach embankments underlain by soft compressible foundation soils tend to rotate and move backward away from the bridge superstructure. The magnitude of this movement is dependent on the relative stiffness of the embankment and foundation soils, as expressed by the modular ratio, E_H/E_h; the depth of the compressible foundation soils, relative to the height of the approach embankments, as expressed in the depth ratio, H/h; and the nature of the pile support provided. The magnitude of the backward movement of the perched abutments tends to be greater as the softness and depth of the foundation soils increase.

The presence of the pile support for this type of abutment appears to have little effect in preventing the backward rotation and horizontal displacement of the abutments. In fact, the parametric study demonstrated that eliminating the piles actually reduced the tendency for backward rotation and horizontal displacement of the abutment. Furthermore, it was found that increasing the number of batter piles had little effect in reducing the tendency for backward displacement of the abutments. However, the fixity of the pile tips at the surface of rock did make a significant difference in the predicted horizontal displacement of the abutments. The data suggest that, if the piles are not driven to refusal on the rock surface, so that fixity is obtained, then forward horizontal displacement of the pile tips can occur, leading to a greater tendency for backward displacement of the abutment.

The use of the simplified method of analysis employed in the parametric study to predict the movement of the abutments of two actual bridges produced mixed results. The direction of the movement of the north abutment of the South Portland bridge was correctly predicted, but the calculated magnitude of horizontal displacement was less than observed. In the case of the west abutment of the Brunswick bridge, the initial analysis indicated that the abutment should move backward rather substantially. However, field observations indicated that the abutment had rotated and moved forward about three in. A second analysis was performed with a revised set of assumptions that were designed to more closely model the construction sequence and material properties that actually occurred at this site. Although the results of this analysis indicated only a slight backward displacement of the abutment, they were still far from being in agreement with the observed movements.

Consequently, it was concluded that more sophisticated methods of analysis will be required to more accurately predict the abutment movements of actual bridges. Moreover, this will require a more detailed knowledge of the properties of the embankment and foundation materials. It is anticipated that this study will be continued and expanded in the future to produce a practical methodology for the prediction of the horizontal movement of highway bridge abutments that can provide some guidance to bridge designers in making decisions on abutment design.

ACKNOWLEDGMENTS

The study described in this paper was the outgrowth of findings obtained during an earlier study designed to develop criteria for tolerable movements of highway bridges. That research was sponsored by FHWA, U.S. Department of Transportation, and much of the field data referred to in this paper was supplied by the many highway agencies throughout the United States and Canada that contributed information for the tolerable movement study. The authors wish to express their appreciation to the many individuals and agencies that cooperated in that effort. In particular, the authors are especially grateful for the cooperation of Albert F. DiMillio, of the Federal Highway Administration; and Theodore Karasopolous and Guy Baker of the Maine Highway Commission, whose extraordinary efforts constituted an important contribution to this paper.

REFERENCES

1. A.W. Skempton and D.H. MacDonald. Allowable Settlements of Buildings. Proc., Institute of Civil Engineers, Part III, Vol. 5, London, Dec. 1956, pp. 727-768.
2. D.E. Polshin and R.A. Tokar. Allowable Non-Uniform Settlement of Structures. Proc., Fourth International Conference on Soil Mechanics, Vol. 1, London, Aug. 1957, pp. 402-405.
3. R. Grant, J.T. Christian, and E.H. Vanmarcke. Differential Settlement of Buildings. Journal of the Geotechnical Engineering Division, ASCE, Vol. 100, No. GT9, Sept. 1974, pp. 973-991.
4. J.B. Burland and C.P. Wroth. Settlement of Buildings and Associated Damage. State-of-the-Art Review. Proc., Conference on Settlement of Structures, Cambridge, Pentech Press, London, 1974, pp. 611-654.
5. L.K. Moulton, H.V.S. GangaRao, and G.T. Halvorsen. Tolerable Movement Criteria for Highway Bridges, Volume 1--Interim Report. FHWA/RD-81/162. FHWA, U.S. Department of Transportation, Dec. 1981, 127 pp.
6. L.K. Moulton, H.V.S. GangaRao, and G.T. Halvorsen. Tolerable Movement Criteria for Highway Bridges, Final Report. FHWA/RD-82/112. FHWA, U.S. Department of Transportation, Dec. 1982.
7. L.K. Moulton. Tolerable Movement Criteria for Highway Bridges. Report FHWA-TS-83. FHWA, U.S. Department of Transportation, Dec. 1983.
8. H.E. Wahls. Reliability of Settlement Predictions. Presented at 63rd Annual Meeting of the Transportation Research Board, National Research Council, Washington, D.C., Jan. 1984.
9. H.J. Siriwardane. A Computer Program for Nonlinear Finite Element Analysis of Two-Dimensional Soil-Structure Interaction Problems. Computer Program, Department of Civil Engineering, West Virginia University, Morgantown, 1982.
10. C.S. Desai (ed.). Application of the Finite Element Method in Geotechnical Engineering. Proc., Symposium held at the U.S. Army Engineers Waterways Experiment Station, Vicksburg, Miss., 1982.
11. J.E. Bowles. Foundation Analysis and Design, 3rd edition. McGraw-Hill, New York, 1982.
12. J.K. Mitchell and W.S. Gardner. In Situ Measurement of Volume Change Characteristics. Proc., Conference on In Situ Measurement of Soil Properties, ASCE, June 1975, Vol. II, pp. 279-345.
13. A.G. Stermac, M. Devata, and K.G. Selby. Unusual Movements of Abutments Supported on End-Bearing Piles. Canadian Geotechnical Journal, Vol. V, No. 2, May 1969.
14. H.J. Siriwardane, L.K. Moulton, and R.-J. Chen. Prediction of Lateral Movement of Bridge Abutments Supported on Piles. Department of Civil Engineering, West Virginia University, Morgantown, Jan. 1984.

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