increase in traffic over the years, was in very good condition when observed in 1961 (16). Interest in and use of superstructures tied to flexible piers and stub abutments has continued to grow and is essentially limited only by the lack of suitable design criteria (17, 18, 19, 20).

Preboring for abutment piling is now commonly used. The paper reports that the possibility of consolidation apparently was recognized because 23 of the 32 (reported) abutments are on pile foundations. It is unfortunate that the respondents did not identify whether or not the pilings were prebored so that a comparison of abutment movement could be made. It also would be interesting to know whether the abutments are rigid high abutments or the spill-through type. It is believed that the influence of preboring, type of abutment, and superstructure-substructure interaction (connection), if known, would be reflected in modifications to Walkinshaw's recommendations.

In structural considerations, the effects of differential vertical movement and the restraint of horizontal movement should be compared and interrelated to thermally induced stresses [which may be significant (21, 22, 23)] in addition to the live-load stresses. Such analyses can be readily calculated by any highway bridge design group.

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Movements of Bridge Abutments and Settlements of Approach Pavements in Ohio

Raymond A. Grover, Ohio Department of Transportation

The Ohio Department of Transportation experienced intolerable movements of bridge abutments and adjacent approach slabs within a short time after construction of a new highway facility. Two accurate field surveys measured the extent and magnitude of the settlements against the data on embankment heights, subsoil conditions, type of abutment design, and other conditions. The first study, in 1961, indicated that 90 percent of the surveyed bridge abutments had settlements of 10 cm (4 in) or less and only 20 percent of the settlements were 2.5 cm (1.0 in) or less. In most cases, the abutments were supported on spread footings, without piles, in the approach embankment. Major revisions were incorporated in the design and construction specifications. The two most important ones were the use of piles at the abutments and the increase of compaction requirements for the embankments. The second survey was conducted in 1975 to evaluate the revised policies. These data indicated that 70 percent of the surveyed bridge abutments had no measurable settlements and 20 percent had minor settlements even though supported by piling. Generally, the measured settlements were within tolerable limits. In 1961, the average approach slab settlement was 6.5 cm (2.5 in) and in 1975, the average approach slab settlement was 5.0 cm (2.0 in).

By the end of 1960, the Ohio Department of Transportation had completed a large portion of their Interstate highway system as well as the construction of other major highway facilities. This construction program included hundreds of kilometers of new highways and hundreds of new bridges. Over 90 percent of the bridges were steel beams or girders of multiple spans with continuity over the piers, as shown in Figure 1.

Within 1 to 3 years after construction intolerable movements (vertical settlements and horizontal displace-

Figure 1. Steel beam bridge—continuous over piers.

ment) occurred at many bridge abutments and the adjacent approach pavements. The movements were considered intolerable because of the magnitude of the vertical settlements and the resulting dangerous and uncomfortable riding characteristics to the trucking industry and the private automobile. These settlements also caused an undesirable increase in the stresses of the superstructure, particularly over the pier area nearest the abutment. The horizontal movements decreased the efficiency of the temperature expansion joints at the abutments, often to a value of zero. When the expansion joints closed completely, additional compression stresses were transmitted to the superstructure, physical damage occurred to the abutment backwall, beam or girder bearing devices were distorted, and approach slabs were cracked. Maintenance costs and problems such as these so soon after construction of the highway were a serious concern.

The most extreme example of vertical settlement occurred on a structure where the approach embankment height was 17 m (58 ft), the overburden soils were soft wet silts and clays that had a thickness of 3 m (10 ft), and the underlying bedrock was a hard shale. The plans required the removal of all soil overburden such that the embankment would be built and supported directly on the shale bedrock. The plan requirements were fulfilled and the embankment fill was constructed of materials from an adjacent shale and sandstone roadway cut section. The bridge abutment was supported by spread footings (no piles) seated in the approach embankment. Before completion of the construction project, the abutment bearings needed to be shimmed 4 cm (1.5 in) due to consolidations within the rock embankment. During the next 15 years, the settlements continued; total accumulated amounts were more than 30 cm (12 in) in the roadway pavement and the bridge abutment. Three maintenance projects were needed in this time period to correct the settlements and repair the abutment (the last project removed the damaged abutment and rebuilt a new abutment supported on caissons drilled through the embankment into bedrock). This experience is objectionable and expensive.

In general, the field construction procedures for all projects were in reasonable conformance with the plan and specification criteria. This included the construction of the embankment, the controlled rates of embankment construction, the specified waiting periods between the completion of the embankment and the construction of the abutment, and the time relation between placing superstructure concrete versus the concrete abutment backwall.

STATEWIDE SURVEY: 1961

To define the extent and causes of the problem more clearly, a statewide survey was conducted in 1961 (1). The survey included accurate measurements of actual vertical settlements, lateral movements, abutment damage, and condition of expansion joints where significant settlements had occurred at bridges completed between the years 1955 and 1960.

The 12 district offices conducted the survey and no criteria were given to define significant settlement. Probably, noticeable or undesirable responses to a person riding in an automobile over the bridge approach area determined which bridges in the district would be included in the survey. In other words, the riding characteristics were probably tolerable or intolerable to a particular individual.

The existing (measured) roadway approach and bridge profiles were compared with the plan profiles to determine the amounts of settlement. These data were related to embankment heights, existing subsoil conditions, length of waiting periods, type of abutment design (piles, no piles, pile type), amounts of lateral movements, or other unusual conditions. Figures 2, 3, and 4 show typical data and plotted survey profiles.

During this 5-year period, Ohio constructed over 1500 bridges. The abutments of approximately 500 of these bridges were located in a roadway approach embankment that had a height of 5.5 m (18 ft) or more. The survey reported 75 bridges that had significant settlements, but profiles were furnished for only 68 bridge sites (133 abutments); most of the abutments were located in embankment fills of more than 5.5 m (18 ft) in height. Figure 5 shows these data and whether the abutments were designed with or without piles.

At the time of the 1961 survey, about 90 percent of the 133 abutments were below plan grade by 10 cm (4 in) or less and about 20 percent were below plan grade by 2.5 cm (1.0 in) or less.

Prior to the survey, steel shims had been placed at 28 of 133 abutments under the abutment bearing devices to correct settlements that occurred during or shortly after construction. Figures 6 and 7 show the two common bearing devices used in Ohio, one consisting of sliding steel bars and the other consisting of a fabricated rocker, but the sliding device has been shimmed 6.5 cm (2.5 in). When the bearing devices were shimmed, an unsightly differential displacement between the abutment and the superstructure was the end result, as pictured in Figure 8.

Often when vertical settlements occur at the abutments, the abutments will also have horizontal displacements. These horizontal movements will be toward the superstructure. In certain instances, especially when the abutments are supported on spread footings, the horizontal movements will be so severe that the steel beams will contact the concrete abutment backwall, and the backwall will sustain structural damage. When long-term and significant settlements are anticipated during the design stages but will not occur until after the highway is opened for traffic, the steel beams in the end spans can be hinged to avoid superstructure damage from settlements. These hinges probably will not accommodate horizontal movements. Figure 9 indicates a bearing device that has moved 7.5 cm (6 in) vertically and 5 cm (2 in) horizontally.

For the 28 above-noted abutments, 15 had total settlements (including thickness of shims) of 10 cm (4 in) or less, 9 had total settlements of 10 to 30 cm (4 to 12 in), and 4 had total settlements of more than 30 cm (12 in). Below is a tabulation of settlements, which includes settlements corrected prior to the 1961 survey (1 cm = 0.4 in).

Amount Below Plan Grade in 1961 (cm)	Number of Abutments
0 to 2.5	28
2.5 to 7.5	79
7.5 to 15.0	22
15.0 to 25.0	4
Total	133

Total Settlement (includes shims) (cm)	Number of Abutments
0 to 2.5	0
2.5 to 7.5	9
7.5 to 15.0	9
15.0 to 30.0	6
Over 30.0	4
Total	28

The results from the survey clearly indicated the magnitude of the maintenance problems and the probability where the problems would occur. The maintenance costs and the number of areas requiring mainte-

Figure 2. Typical profile, embankment height 11 m.

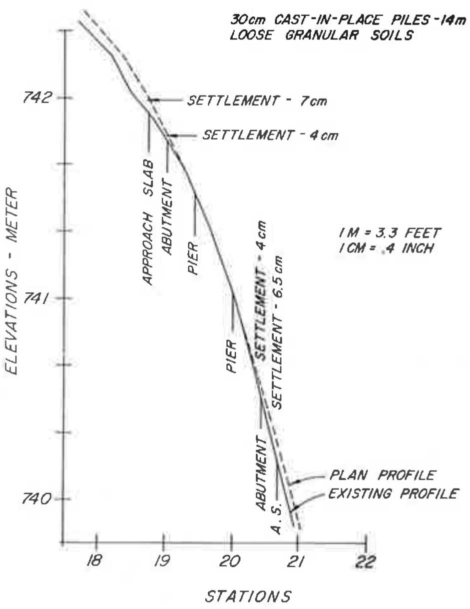


Figure 3. Typical profile, embankment height 5.5 m.

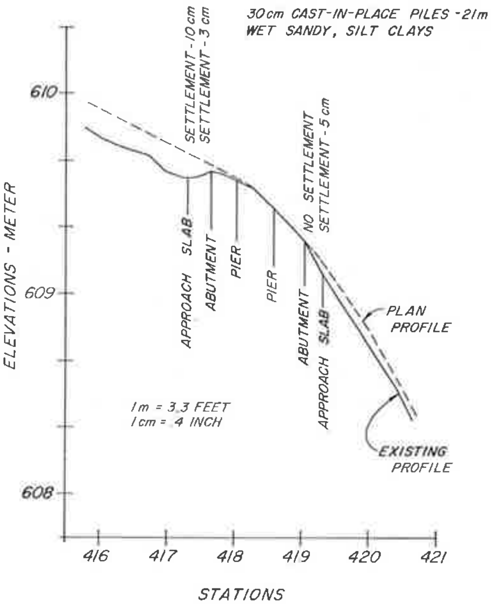


Figure 4. Typical profile, embankment height 12 m.

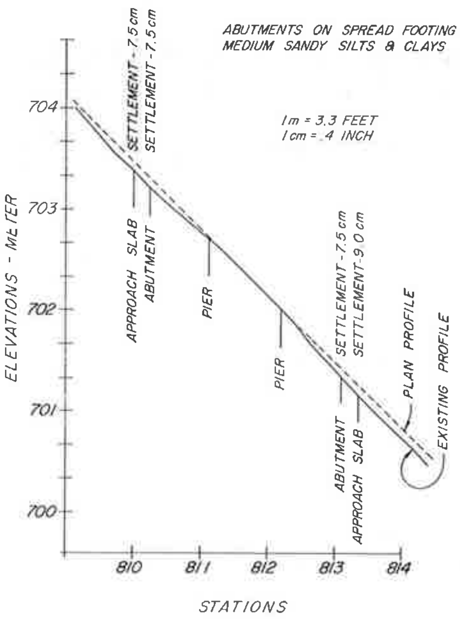
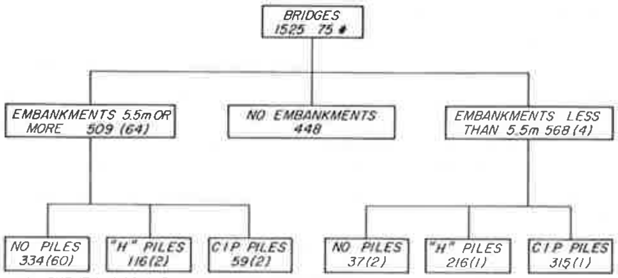


Figure 5. Bridges with measured settlements.



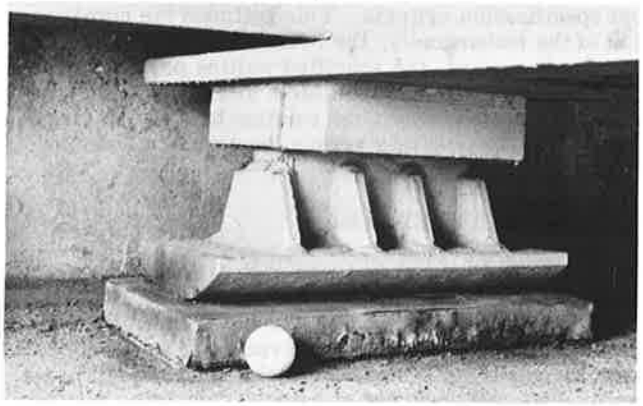
* SURVEY PROFILES FOR ONLY 68 BRIDGES

FIRST NUMBER INDICATES THE TOTAL NUMBER OF BRIDGES BUILT IN THE FIVE-YEAR PERIOD

SECOND NUMBER, IN PARENTHESIS, INDICATES THE NUMBER OF BRIDGES, FOR WHICH PROFILES WERE FURNISHED, INDICATING ABUTMENT SETTLEMENTS

Note: 1 m = 3.3 ft.

Figure 6. Fabricated rocker bearing.



nance were extensive. Revisions to the construction specifications and design policies were mandatory. Several recommendations were offered to improve the design and construction procedures. The department adopted the most important ones.

The design revisions would dictate the use of piles at all abutments located in embankment fills. The piles must penetrate through the fill into a firm subsoil stratum even if preboring of holes was necessary. The plans would require a more positive lateral drainage system behind the abutment and a greater use of settlement platforms and piezometers for monitoring the approach embankment when the underlying soil strata were compressible with anticipated consolidations.

Figure 7. Sliding plate bearing.

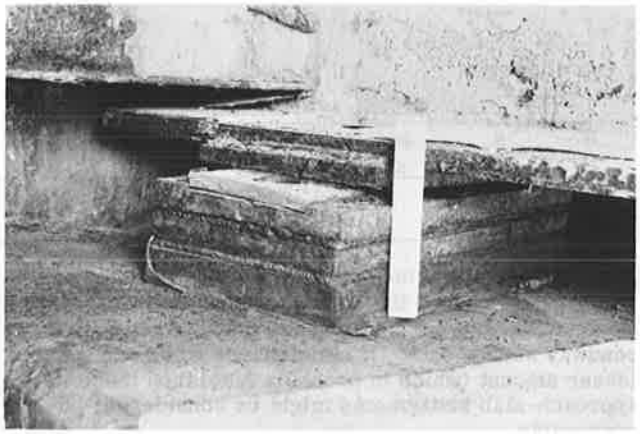


Figure 8. Differential displacement in curb and railing.

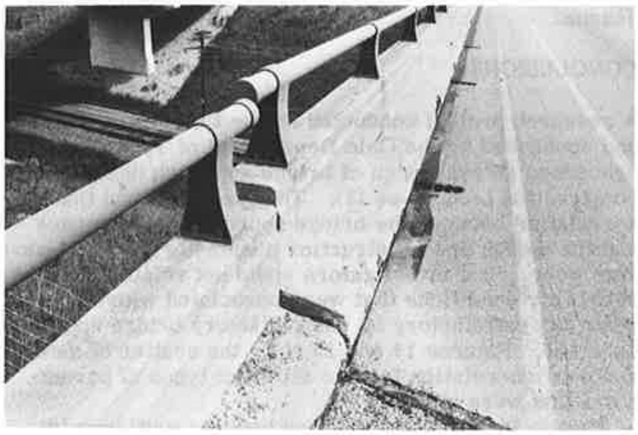
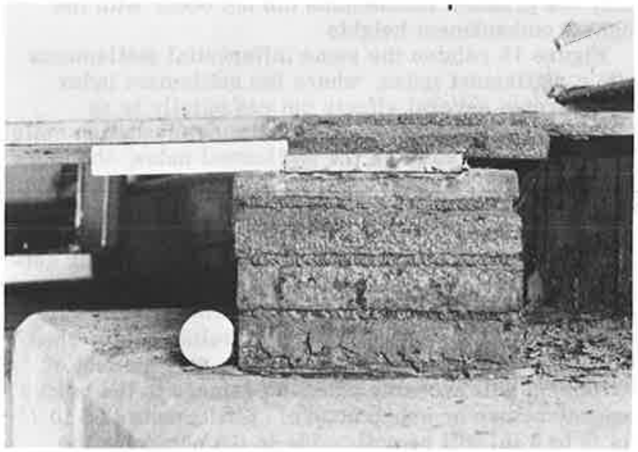


Figure 9. Horizontal and vertical movements.



The revision to the construction specifications was to increase the compaction efforts in constructing the embankment. For soil, the compactive density would be based on a laboratory dry weight as high as 102 percent of AASHTO T99. For shale and rock materials, the required loose-layer thickness would not exceed 20 cm (8 in), the moisture content would be controlled, and each layer would have six coverages of a fully ballasted roller.

STATEWIDE SURVEY: 1975

In 1975, another survey of all parts of the state was conducted to evaluate the revised design and construction policies (2). Each district was requested to furnish a profile of several bridges and adjacent approach pavements whether or not settlements were noticeable. The given conditions were (a) the bridge should have been completed between 1964 and 1974, (b) the approach embankment height was 4.5 cm (15 ft) or more, (c) the abutments were supported by piles, and (d) the extent of lateral or rotational movements should be indicated.

Profiles for 79 bridges were submitted where the abutments were supported by either cast-in-place reinforced concrete piles or steel H-piles. For these 158 abutments, 71 percent had no measurable settlements and 19 percent had measurable settlements even though supported by piles. Of the 19 percent, 22 abutments were supported by friction piles and 8 were supported by steel H-bearing piles driven to bedrock. Only 6 percent of the abutments had settlements of more than 2.5 cm (1 in) and only one abutment had a settlement of more than 5 cm (2 in). In the 1961 survey, 55 percent of the abutments had settlements greater than 5 cm. An interesting observation should be carefully noted here but is seldom believed by most engineers: The use of piles at abutments located in a roadway embankment is not an assurance that there will be no settlement of the abutment. In Ohio, piles will considerably reduce the amount of abutment settlement versus an abutment design that does not include piles. Even when settlement of a pile-supported abutment occurs, the actual amount is probably within tolerable limits.

A phenomenon was measured in the 1975 survey that did not appear in the 1961 survey. At 10 percent of the abutments, the profiles showed that the existing field elevations were above plan grade from 1.0 to 4.0 cm (0.5 to 1.5 in). No rational explanation can be offered to explain these data. Two districts noted the occurrence of a few rotational or lateral movements of approximately 5 cm (2 in). Figure 10 shows a comparison of abutment settlements between the 1961 and 1975 surveys.

The difference in performance of the two abutment types (supported by piles or spread footings) can also be seen by a comparison of Figures 11 and 12. Deviations from the 1:1 slope line indicates differential settlements between the abutment and the end of the approach slab. Differential settlements are more common for the pile-supported abutments—63 percent of the cases exceeded 2.5 cm (1 in). In the differential settlements for abutments supported by spread footings, only 31 percent of the cases exceeded 2.5 cm.

This aspect of fewer differential settlements may appear desirable from a rideability aspect but is unsatisfactory from other aspects such as total settlements, lateral movements, and maintenance costs. Although

Figure 10. Comparison of abutment settlements.

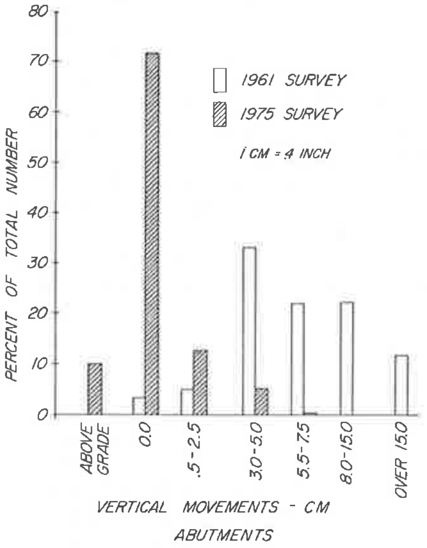
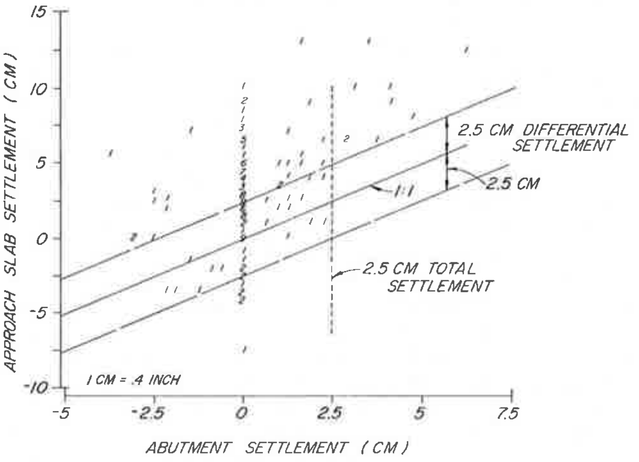


Figure 11. Performance of pile supported abutments.

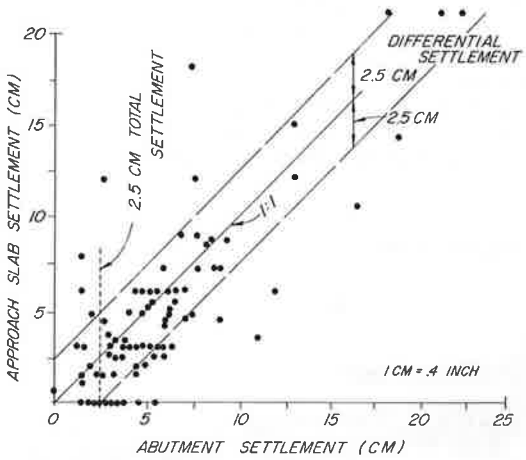


the differential settlements between the abutments on spread footings and the approach slabs were less than the abutments on pilings, the total settlements of the abutments on spread footings were of a much greater magnitude.

The improvement of the settlements at the end of the 158 approach slabs away from the abutments was not nearly as striking as the improvement of the abutment settlements. The data indicate that 10 percent of the approach slabs had no settlement in 1975 and 8 percent had no settlement in 1961. In 1975, 68 percent of the approach slabs had settlement from 2.5 to 7.5 cm (1 to 3 in); in 1961, 62 percent were in this range. In 1975, 12 percent of the approach slabs had settlements of more than 7.5 cm whereas in 1961, 31 percent had settlements of more than 7.5 cm. The 1975 survey measured a maximum approach-slab settlement of 14 cm (5.5 in), but the maximum measured amount was 23 cm (9 in) in 1961. Figure 13 shows a comparison of the approach-slab settlements for the two surveys.

The average approach-slab settlement was 5 cm (2 in) in 1975, but the average settlement was 6.5 cm (2.5 in) slabs having settlements of more than 2.5 cm (1 in), in the 1961 survey. With about 70 percent of the approach this may seem unreasonable. No assessments have been made between the cost of plan requirements to significantly reduce the amount of approach-slab settlements versus the maintenance costs to repair these roadway settlements. If maintenance costs are the lesser amount (which is probably true) then these approach-slab settlements might be considered reasonable.

Figure 12. Performance of abutments on spread footings.



Like the abutments, 10 percent of the approach slabs were above the plan profile in the 1975 survey. Perhaps this phenomenon may be attributed to frost heave because the field measurements were made during the winter season.

CONCLUSIONS

A research project conducted by the University of Akron and sponsored by the Ohio Department of Transportation concerned an evaluation of bridge approach design and construction techniques (3). This project found that the correlation between the bridge approach performance and the design and construction parameters studied were very poor. The investigators could not relate with any reliability conditions that were associated with either generally satisfactory or unsatisfactory bridge approach behavior. Figures 14 and 15 show the scatter of data and poor correlation for two different types of parameters that were studied.

Figure 14 shows the relation between settlements (differential settlement between the end of the approach slab and the abutment) and the height of the approach embankment. There is no general correlation, and, in fact, the greatest settlements did not occur with the highest embankment heights.

Figure 15 relates the same differential settlements with a settlement index, where the settlement index incorporates several effects but essentially is an anticipated consolidation of the existing foundation soils. The greater the value of the settlement index, the more plastic the subsoils. The data of the graph are random: Nonplastic soils indicate settlement distress as great as that with cohesive soils.

After several years of observing and measuring settlements at bridge approaches, I believe that settlements of 2.5 cm (1 in) or less can be classified as tolerable and will hardly be noticed by the traveling public when tempered by an approach slab. Also, this amount of settlement will probably cause no damage to the bridge superstructure or substructure. Settlements of 5 to 7 cm (2 to 3 in) will be noticeable to the person in the

Figure 13. Comparison of approach slab settlements.

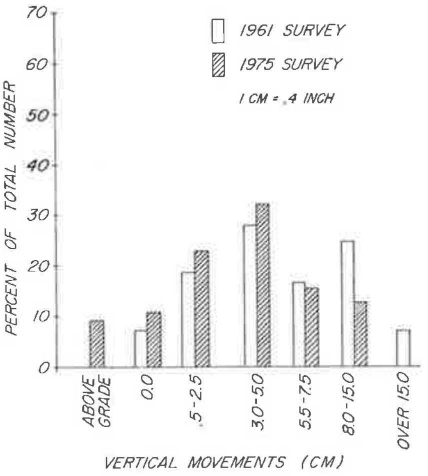
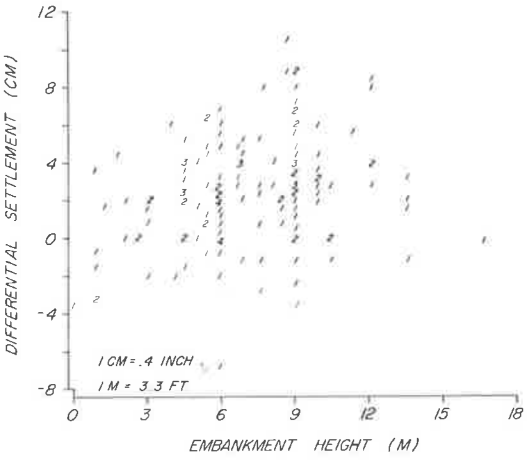


Figure 14. Differential settlements versus embankment height.

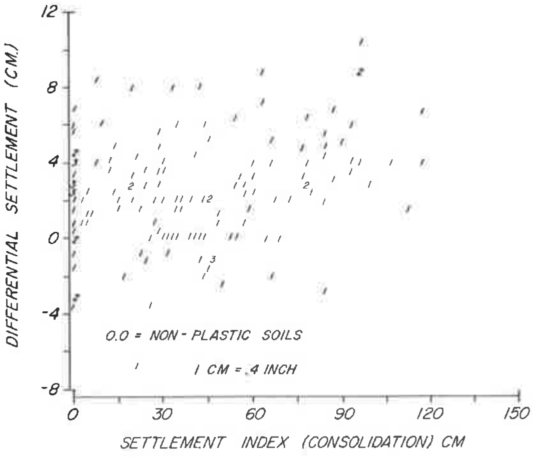


moving vehicle, but only minor damage, if any, will occur to the structure.

The vehicle response to settlements of 10 cm (4 in) or more will undoubtly be objectionable to a vehicle passenger and physical damage will likely occur in the bridge superstructure and abutments. Settlements of this amount should be classified as intolerable.

Little or no maintenance will be done and may not be necessary for settlements of 2 to 5 cm (1 to 2 in) or less.

Figure 15. Differential settlement versus settlement index.



Maintenance may not be furnished for settlements of 7 to 10 cm (3 to 4 in) but should be considered desirable. For settlements of a greater magnitude, maintenance is probably necessary and likely to be completed.

ACKNOWLEDGMENT

These comments on tolerable or intolerable settlements and the related maintenance program are my own feelings and observations. They have no official status of my office or the Ohio Department of Transportation. I have no exact or precise documentation to either substantiate or refute my observations. I do believe rather strongly that this is an appropriate attitude toward tolerable or intolerable settlements.

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Bridge Foundations Move

M. Bozozuk, Division of Building Research, National Research Council of Canada, Ottawa

The postconstruction performance of several hundred bridges in the United States and Canada was related to the measured movements of their foundations. The results, presented graphically, indicate the range of vertical and horizontal movements and consequently provide realistic information for the planning of remedial work and the practical design of new bridges. A classification of movements for bridge foundations is proposed.