

Figure 13. Comparison of approach slab settlements.

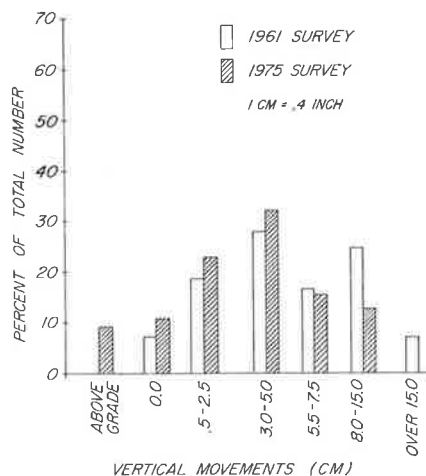
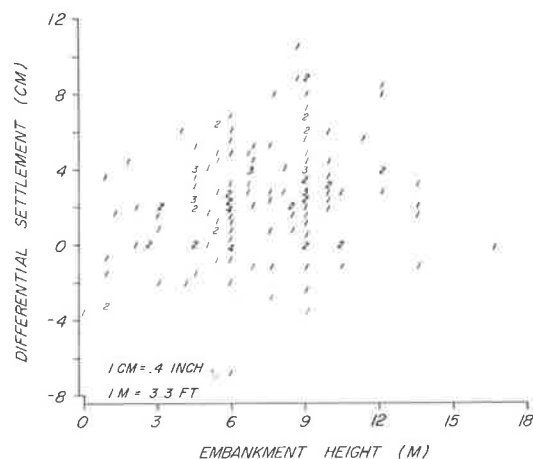


Figure 14. Differential settlements versus embankment height.

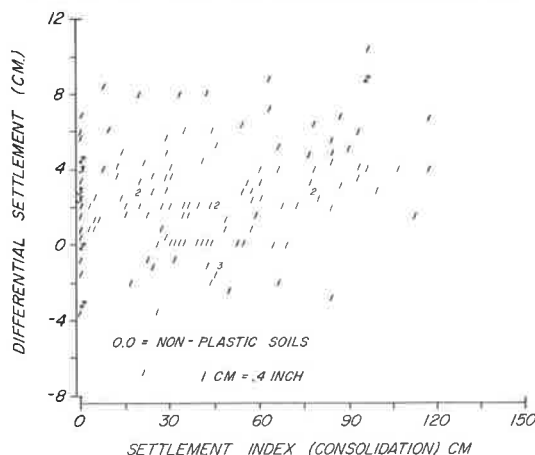


moving vehicle, but only minor damage, if any, will occur to the structure.

The vehicle response to settlements of 10 cm (4 in) or more will undoubtedly 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.

#### REFERENCES

1. Report of Survey of Settlements in Bridge Substructures and Approach Pavements. Bureau of Bridges, Ohio Department of Highways, Sept. 1961.
2. Report of Survey of Vertical Movements in Bridge Abutments and Approach Pavements. Bureau of Bridges, Ohio Department of Transportation, Sept. 1975.
3. D. H. Timmerman. An Evaluation of Bridge Approach Design and Construction Techniques. Univ. of Akron. Ohio Department of Transportation, and Federal Highway Administration, Research Rept., Dec. 1976.

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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.

In 1975 the Transportation Research Board Committee on Foundations of Bridges and Other Structures conducted a performance survey of existing bridges in the United States and Canada to determine the foundation movements that could be tolerated by a structure. A questionnaire, which was similar to one used in a 1967 survey, was sent to all highway departments, bridge departments, public works agencies, and research organizations in every state and province in these two countries. The following information was requested for each case: type of bridge, description of the foundations for the abutments and piers, description of the subsoils, the magnitude and description of foundation movements, the kind of maintenance required, and whether or not the movements were tolerable. The satisfactory response to the survey yielded a considerable amount of information covering most of the bridge, foundation, and soils combinations in North America.

### SURVEY INFORMATION

On this continent there are literally thousands of bridges of all sizes, designs, and ages, which are supported on various foundations and soils. Only a limited number of meaningful measurements of foundation movements and assessments of the performances of the structures were obtained from the survey; however, it was clear from the answers given that where little maintenance was required, the performance was rated tolerable, no matter how little or great the movements. Where considerable maintenance or repairs were required, all movements were rated not tolerable. A detailed discussion of these movements is reported by Keene in a paper in this Record.

The engineering performance of the bridges was directly related to the extent and kind of movement to which the abutments, piers, and foundations were subjected after construction. As there were three basic foundations, the performance ratings were studied separately under the following headings:

1. Abutments and piers on spread footings—all footings placed on fills, natural ground, or bedrock.
2. Abutments and piers on friction piles—all friction piles including steel H, pipe, concrete, and wood, whether driven through fill or natural ground.
3. Abutments and piers on end-bearing piles—all piles bearing on rock or in a resistant soil formation.

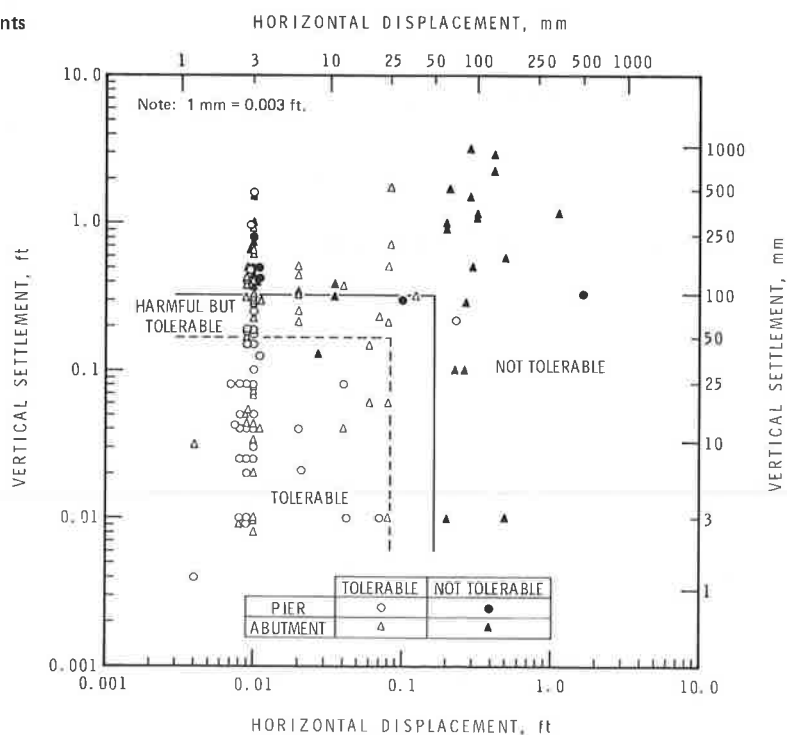
In some cases movement was not recorded or was reported as zero. For presentation in figures in this report, zero movement, whether vertical or horizontal, was assumed to be equal to or less than 3 mm (0.01 ft).

### Abutments and Piers on Spread Footings

Vertical and horizontal movements of about 120 abutments and piers and their rated performance with respect to whether they were tolerable or not tolerable are shown in Figure 1. Vertical settlements ranged from 0 to more than 1000 mm (3 ft), and the horizontal movements ranged from 0 to 510 mm (1.6 ft). Some of the movements were uniform; others were differential or rotational. About 28 percent of the cases were rated not tolerable.

The most common cause of movement was consolidation of earth fills and underlying foundation soils. Other causes included instability of embankment fills and valley slopes, soil creep, and active earth pressures behind abutments. Seasonal temperature variation was also listed as one of the causes. For example, Dillon and Edwards (1) report that abutments were affected by freezing of bridge bearings. As the bridge deck contracted in winter, the abutments were pulled together. In summer, the bearings behaved normally, but the subsequent expansion of the bridge deck did not push back the abutments. Over a number of years this process closed all expansion joints and caused heavy damage to the bridge.

Figure 1. Engineering performance of bridge abutments and piers on spread footings.



### Abutments and Piers on Friction Piles

About 60 cases involving friction piles were reported. Vertical and horizontal movements of abutments and piers and their effects on the performance of the bridges are plotted in Figure 2. The vertical settlements ranged from 0 to over 1220 mm (4 ft), and the horizontal displacements ranged from 0 to 460 mm (1.5 ft). In permafrost areas, vertical heaving of the piles of 50 to 1070 mm (0.17 to 3.5 ft) was observed due to frost action. About 40 percent of the cases were judged not tolerable and the remainder were tolerable. Some of the differential or rotational movements that were less than some of the tolerable ones were not tolerable; the tolerable movements were mainly uniform. The causes for these movements were instability of natural slopes, soil creep, settlement of embankment fills, and downdrag or negative skin friction.

### Abutments and Piers on End-Bearing Piles

About 90 cases that describe the performance of abutments and piers on end-bearing piles were reported. The magnitude of the vertical and horizontal movements and their effects on the performance of the bridges are shown in Figure 3. Vertical settlements ranged from 0 to a maximum of 1100 mm (3.6 ft); the horizontal movements ranged from 0 to 550 mm (1.8 ft). About 60 percent of the cases were judged not tolerable. Some large movements were judged tolerable because they were uniform and did not interfere with the performance of the bridge, whereas some small differential or rotational movements were not tolerable.

The major causes for these movements were instability of natural slopes, soil creep (2), and consolidation of the compressible soils around piles due to the weight of embankment fills. When the subsoils consolidated, batter and vertical piles were forced to bend and caused the superimposed abutments and piers to settle, rotate, and translate horizontally (3). In numerous cases large settlements of the piles were attributed to downdrag or negative skin friction as the surrounding foundation soils consolidated around the piles. At one bridge site, negative skin friction was identified as the cause of failure of 17 end-bearing piles.

Large uniform settlements usually did not affect the performance of the bridges. For example, a bridge supported on end-bearing piles on bedrock was subjected to settlements of from 300 to 600 mm (1 to 2 ft). General subsidence of the underlying bedrock was caused by a solution of a thick salt formation 82 m (250 ft) thick at a depth of 426 m (1300 ft) at the site. This was responsible for large movements that were considered tolerable.

### CLASSIFICATION OF BRIDGE FOUNDATION MOVEMENTS

Examination of the performance ratings of foundation movements plotted in Figures 1, 2, and 3 showed that horizontal movements affected the structures more than did the vertical movements. It was possible, nevertheless, to delineate the tolerable and not tolerable movements from which the proposed classification of bridge foundation movements was developed. It is shown on each of the figures and is given as follows:

Tolerable or acceptable:  
 $S_v < 50 \text{ mm (0.16 ft)}$   
 $S_h < 25 \text{ mm (0.08 ft)}$   
 Harmful but tolerable:

$50 \text{ mm (0.16 ft)} \leq S_v \leq 100 \text{ mm (0.33 ft)}$

$25 \text{ mm (0.08 ft)} \leq S_h \leq 50 \text{ mm (0.16 ft)}$

Not tolerable:

$S_v > 100 \text{ mm (0.33 ft)}$

$S_h > 50 \text{ mm (0.16 ft)}$

where

$S_v$  = vertical movements (settlement or heave), and  
 $S_h$  = horizontal movements.

To demonstrate how this classification applied to the performance ratings obtained from the field survey, all the cases plotted in Figures 1 through 3 were compared statistically in Tables 1 and 2 according to this classification.

In Table 1, 110 cases were assessed, covering spread footings, friction piles, and end-bearing piles where the abutment and pier movements were judged not tolerable. The percentage distribution of the field ratings for each of the foundations was relatively consistent with the proposed classification. When they were grouped, 85 percent agreed with the proposed classification, 12 percent came within the harmful but tolerable range, and 3 percent fell within the tolerable zone.

For the field-rated tolerable movements, the percentage distribution was different, but the agreement was satisfactory (Table 2). Of the 157 cases, 56 percent agreed with the proposed classification, 22 percent came within the tolerable but harmful range, and 22 percent fell into the not tolerable range. The results are shown in Figure 4.

The movements rated not tolerable in the field were in excellent agreement with the proposed classification, but agreement for the movements rated tolerable in the field was only satisfactory. The reason for the differences was that the performance of foundations was governed not only by the magnitude of the movements but also by the kind of movements. Large vertical and horizontal movements were acceptable if they were uniform, as shown by the statistical distribution of tolerable cases. On the other hand, vertical and horizontal movements can be very harmful and can damage the structures severely if they are differential or of a rotational nature. Most of the movements judged not tolerable were of the latter type, hence the good agreement with the classification. Since the engineering profession is more concerned with harmful or not tolerable movements, the proposed classification of foundation movements for bridges was considered satisfactory.

### SUMMARY AND CONCLUSIONS

In 1975 a questionnaire circulated throughout the United States and Canada requested information on the engineering performance of all bridges whose abutments or piers were supported on either spread footings, friction piles, or end-bearing piles. The response to the survey showed that bridge foundations were affected by slope instability, consolidation of embankment fills and underlying subsoils, soil creep along valley slopes, frost action, and seasonal temperature variations. In addition, pile foundations were affected by soil settlements and negative skin friction or downdrag.

An analysis of the reported foundation movements and performance ratings showed that

1. Large vertical and horizontal uniform movements were often tolerated.
2. Differential or rotational movements were more damaging than uniform movements, and their effect on

the performance of the structure was often rated not tolerable.

3. Bridge structures were more sensitive to large horizontal movements than to large vertical movements.

4. Based on the available data, a classification of movements for bridge foundations was proposed that applied adequately to most of the cases reported in the survey.

5. All bridge foundations move.

## ACKNOWLEDGMENTS

Appreciation is expressed to all those in the United States and Canada who took the time to answer the questionnaire and made their information available to the engineering profession. Many members of the TRB Committee on Foundations of Bridges and Other Structures helped collect this information and their assistance is gratefully acknowledged. This paper is a contribution from the Division of Building Research, National Re-

Figure 2. Engineering performance of bridge abutments and piers on friction piles.

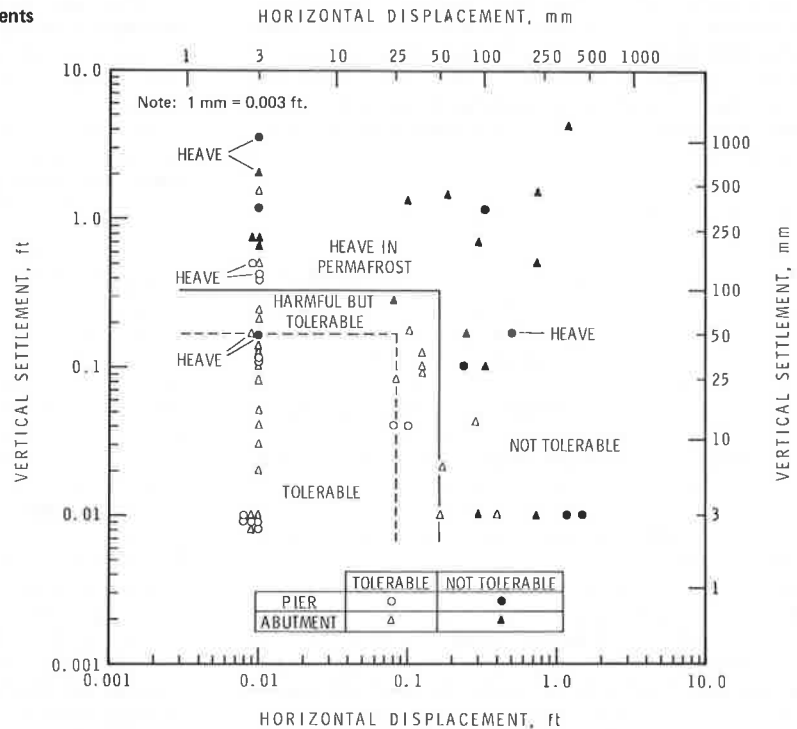


Figure 3. Engineering performance of bridge abutments and piers on end-bearing piles.

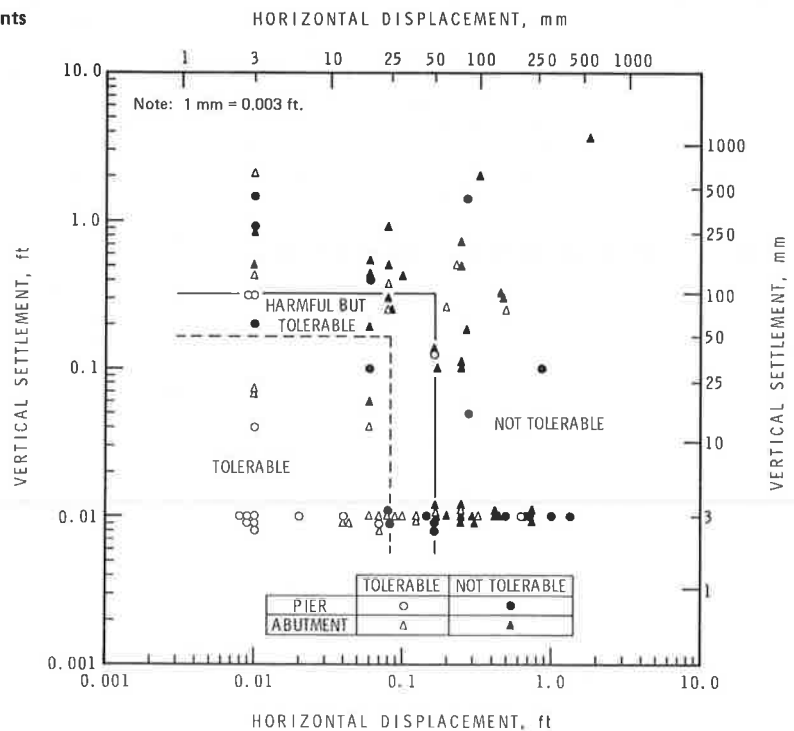


Table 1. Application of suggested classification for bridge foundation movements to field-rated not tolerable performance of bridges.

Type of Foundations for Piers and Abutments	Survey Points (number)	Classification of Bridge Foundation Movements					
		Not Tolerable		Harmful but Tolerable		Tolerable	
		Points (number)	Distribution (%)	Points (number)	Distribution (%)	Points (number)	Distribution (%)
Spread footings	33	30	91	2	6	1	3
Friction piles	24	21	88	3	12	0	0
End-bearing piles	53	43	81	8	15	2	4
Total	110	94	85	13	12	3	3

Table 2. Application of suggested classification for bridge foundation movements to field-rated tolerable performance of bridges.

Type of Foundations for Piers and Abutments	Survey Points (number)	Classification of Bridge Foundation Movements					
		Not Tolerable		Harmful but Tolerable		Tolerable	
		Points (number)	Distribution (%)	Points (number)	Distribution (%)	Points (number)	Distribution (%)
Spread footings	86	19	22	18	21	49	57
Friction piles	36	7	19	8	22	21	58
End-bearing piles	35	8	23	9	26	18	51
Total	157	34	22	35	22	88	56

search Council of Canada, and is published with the approval of the director of the division.

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2. M. Bozozuk. Mud Creek Bridge Foundation Movements. Canadian Geotechnical Journal, Vol. 13, No. 1, 1976, pp. 21-26.
3. A. G. Stermac, M. Devata, and K. G. Selby. Unusual Movements of Abutments Supported on End-Bearing Piles. Canadian Geotechnical Journal, Vol. 5, No. 2, 1968, pp. 69-79.

## Discussion

A. G. Stermac, Materials Office, Ontario Ministry of Transportation and Communications

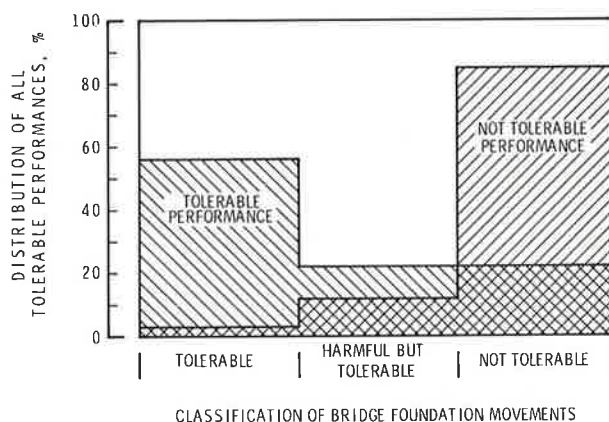
The author is to be complimented for his review, sorting, and tabulation of such a vast amount of information. It is certainly an interesting presentation.

When so many results start to form a pattern, one is tempted to draw certain conclusions. The author has obviously succumbed to this temptation and has suggested values beyond which bridge movements become harmful but still tolerable and beyond which they become not tolerable. What constitutes tolerable or intolerable movements of a bridge can be considered from a number of viewpoints, such as

1. Structural integrity,
2. Maintenance, and
3. Public perception of ride comfort.

There is no question that, by far, the most important consideration is the structural integrity of the bridge because it most directly affects the safety of the travel-

Figure 4. Assessment of foundation performance ratings.



ing public. It is, though, only the designer, the structural engineer, who can determine what type and amount of movement a particular bridge can safely tolerate.

It is well known that, basically, only differential movements will have a bearing on the structural integrity of a bridge. These, however, are a function of the bridge type, width, length, and span length. To lump all bridges together amounts to saying that all bridges are the same and behave in the same way. This, of course, is not the case. Not differentiating between uniform and differential movements and settlements amounts to saying that this does not matter. This also is not the case.

In view of the above, the value of criteria developed without reference to type, length, or width of bridges and type of movement or settlement is seriously questioned. The author's last conclusion that "all bridge foundations move" is also questioned since there is ample evidence that some did not.

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