MEMORANDUM

TO: W. B. Drake, Assistant State Highway Engineer
Chairman, Kentucky Highway Research Committee


The report submitted herewith succeeds a previous report bearing the same title and concerning the same subject. As additional background information, it may be of interest to recall that state-wide surveys of the performance of culvert pipe, conducted in 1950-51*, revealed numerous instances of sagging in the flow lines of culverts. Inquiries into design and construction practices and technical literature disclosed only evasive recommendations to the effect that pipe should be constructed to a cambered grade or slope. Further, it may be recalled that the Bureau of Public Roads issued a revised criterion for the design and installation of concrete pipe culverts, April 4, 1957 (CM 22-40)*.


and that paragraph 3.4, therein, stipulated camber "... by an amount sufficient to prevent the development of a sag or back slope ...." Our proposed revisions of Kentucky specifications (now Amendment 15b), first drafted and submitted under the date of September 24, 1957, noted...
that provisions for cambering pipe had not been included therein because "... we do (did) not have enough information to properly deal with it at the present (that) time." A subsequent submission, October 18, 1957, stated:

After giving pipe camber more consideration, I believe that the amount of camber for any situation will have to be an individual design problem and could not be specified in construction specifications. We will be prepared to make recommendations of a general or specific nature concerning factors that determine the desirable camber design. The subject of camber could be developed for presentation in a design manual.

A scheme for estimating camber (settlement) was outlined in detail by R. C. Deen in a memorandum dated October 24, 1957. This outline was submitted with additional revisions of the specifications, November 21, 1957. Although this scheme was rooted in theory, several simplifying assumptions were made. According to theory, most soils exist in a somewhat precompressed state - that is, as if they have been compacted under a load which has since disappeared - whereas, more intense loading at any subsequent time will induce additional densification of the soil and subsidence. Of course, the amount of subsidence depends upon the intensity of the impressed load, the depth of the underlying soil, and the character or nature of the soil. The first two of these affecting factors are presumed to be of known magnitude; hence, only the affecting parameter of the soil remains to be deduced. In our simplifying assumptions, we surmised that compressible soils are typically plastic silt-loams and that a prudent selection of void ratio values \( e_1 \) and \( e_2 \) describing the load-density relationship of a prevailing type of soil would suffice for approximate determinations of settlement. Of course, the application of such a scheme would be limited to types of structures and foundations which would not require highly accurate settlement analyses. For preliminary guidance, values of \( e_1 \) and \( e_2 \) were abstracted from consolidation tests reported in the literature. These preliminary calculations yielded results which were in the same order of magnitude as the sagging previously observed in the field. However, to further validate this approach to the problem, an extensive field study was undertaken in 1958 in conjunction with the construction of the Simpsonville interchange on I-64 between Louisville and Frankfort. Undisturbed soil samples were taken at several culvert sites; consolidation tests were performed; and settlement analyses
were made prior to the installation of the pipe. The pipe were installed according to a cambered grade which, theoretically, was sufficient to compensate for the expected settlement. Most of the pipe were placed in the Fall of 1958, but the fills were not completed until the 1959 construction season.

Our report of February, 1960, by Aubrey D. May, bearing the subject title, covered the laboratory work, construction, and early settlement measurements. The current report, by R. C. Deen, summarizes the earlier work on the project and includes recent settlement data. These reports largely substantiate the criterion as it was originally conceived.

While the field work at Simpsonville was in progress, and as an outgrowth of an informal report of progress which was presented at a meeting of the Research Committee in February, 1959, Mr. T. H. Baker, Director of Construction, requested an advance guide for use by construction personnel. The guide offered (by memorandum dated February 26, 1959) was based on the average void ratio-pressure data determined from the soils taken from the I-64 project. Subsequently, nomographs were prepared and issued for the convenience of construction engineers. Field parties were also instructed to take soundings to rock at intervals along each proposed line of pipe. Presumably, the guide has been and is being followed by construction personnel.

Figures 10 thru 15 of Deen's report illustrate how effectively the guide (nomograph) would have been if it had been used exclusive of other methods, to predict settlement at the Simpsonville interchange. Some of the culverts would have been cambered excessively, while others would not have been cambered adequately. Therefore, it seems appropriate to suggest that the use of the guide be tempered with judgement - specifically from the standpoint of judging the character of underlying soils. Hard pans, gravels, etc. should not be expected to settle as much as fat clays. In any case, we are recommending continued use of the guide - that is, for mid-range soils; however, clayey and shaley soils, if known or suspected, should be compensated doubly or more.

I am confident that this method of estimating settlement has meaningful applications in the area of faulting at bridge approaches and also to other situations involving embankment settlement.

I do not believe that this report requires any action by the Research Committee at this time. Copies are being
furnished for informational purposes only; but, of course, comments and criticisms are invited. Informational copies will be forwarded to the Bureau of Public Roads also.

Mr. Deen presented this report before a session of the Highway Research Board earlier this month; and it will, presumably, be published by the Board during the year.

Respectfully submitted,

Jas. H. Havens
Director of Research
Secretary, Kentucky Highway Research Committee

Attachment

cc: Research Committee
R. O. Beauchamp
R. L. Campbell
T. J. Hopgood
A. O. Neiser
Research Report

CAMBER DESIGN STUDY
FOR
CONCRETE PIPE CULVERT

By

Robert C. Deen
Assistant Director of Research
DEPARTMENT OF HIGHWAYS
Commonwealth of Kentucky

Highway Research Laboratory
132 Graham Avenue
Lexington, Kentucky
November, 1964
ABRIDGEMENT


Descriptors: Concrete Culvert Pipe; Camber; Settlement; Consolidation, Deen, R. C.

When a pipe culvert is constructed on or near the natural ground surface and covered by a highway fill or embankment, the weight of the embankment compresses and consolidates the foundation soil, settlement occurs, and the culvert subsides and sags below the original grade line. Experience has shown that culverts which become clogged with silt and debris, become disjointed and faulted, leak, become undermined, and endanger the stability of the embankment. These and other damages attendant to settlement restrict the flow of water, prevent adequate inspection of the structure, and may eventually require extensive maintenance or complete replacement of the structure. Some of this damage may be avoided by placing the culvert on cambered grades—that is, by installing the culvert with its flow line somewhat above its normal or desired elevation along the central portion of its length. This idea anticipates that settlement under the load of the embankment will, in time, lower the flow line to the desired straight grade.

The project reported in this paper was undertaken to develop a simplified criterion which would permit the inclusion of camber as a routine design feature in highway culvert installations. The work was based on the theory of consolidation and consisted of consolidation tests and prediction of settlement profiles under proposed embankments, the installation of these culverts cambered according to the predicted settlement profiles, and the observance of the settlements during and following the completion of the embankments. Fairly close agreement between the predicted and observed settlements invited serious speculation as to the possibility of estimating camber, within reasonable limitations, from typical void ratio-pressure curves obtained from typical or average soils.
INTRODUCTION

When a pipe culvert is constructed on or near the natural ground surface and covered by a highway fill or embankment, the weight of the embankment compresses and consolidates the foundation soil, settlement occurs, and the culvert subsides or sags below the original line as illustrated in Figure 1. The amount of settlement depends, of course, upon the fill height or load, the depth of foundation soil, and the susceptibility of the foundation soil to consolidation. In addition, and because there may be movement of the foundation soil outwardly and toward the toes of the embankment, the structure may tend to lengthen. It may also lengthen slightly, however, simply because the distance along the sag or settlement curve is greater than the straight grade distance. These movements are damaging to the drainage structure and should be minimized or otherwise compensated in design insofar as practicable.

Experience has shown that culverts which settle excessively below their original straight grade frequently become clogged with silt and debris, become disjointed and faulted, leak, become undermined, and endanger the stability of the embankment. These and other damages attendant to settlement restrict the flow of water, prevent adequate inspection of the structure, and may eventu-
ally require extensive maintenance or complete replacement of the structure. Some of this damage may be avoided by placing culverts on cambered grades—that is, by installing the culvert with its flow line somewhat above its normal or desired elevation along the central portion of its length, as illustrated in Figure 2. This idea anticipates that settlement under the load of the embankment will, in time, lower the culvert to approximately the desired straight grade.

Some engineering specifications (1), handbooks (2) and treatises suggest the desirability of cambering culvert pipe, but the literature which has been reviewed does not seem to offer any generally accepted criterion or formula for predicting even approximately the magnitude of the camber to be used. Spangler (3) suggests that the proper amount of camber could be determined rather precisely in advance of construction by application of some of the present knowledge of soil mechanics, such as the Terzaghi theory of consolidation (4), but favors a more empirical approach to the problem. While it is well recognized among soils engineers that extensive consolidation data and foundation settlement analyses are necessary in the design of large and costly structures, it would not be practical to require these analyses for each culvert installation on a highway. To avoid such an expensive and time-consuming procedure, a short,
Fig. 1. Settlement of Culvert below Straight Grade.

Fig. 2. Cambered Culvert and Desired Straight Grade.
fairly accurate, simple method is desired, whether it be rational or empirical.

The ultimate objective of this investigation, therefore, was to develop a simplified criterion which would permit the inclusion of camber as a routine design feature in highway culvert installations. In reality, the work was founded on the theory of consolidation and consisted of consolidation tests and predictions of settlement profiles under proposed embankments, the installation of culverts cambered according to the predicted settlement profiles, and the observance of settlements during and following the completion of the embankments. Fairly close agreement between the predicted and observed settlements invited serious speculation as to the possibility of estimating camber, within reasonable limitations, of course, from typical void ratio-pressure curves obtained from typical or average soils.
PROJECT DESCRIPTION

Six locations on a section of Interstate Route 64 near Simpsonville, Kentucky, shown in Figure 3, were selected for study. Plans for the proposed highway were inspected, auger borings were made, and the respective sites chosen on the basis of embankment heights and soil depths available. A summary of culvert dimensions and installation data is presented in Table 1. All the pipe culverts on this section of highway consisted of reinforced concrete pipe.

Every effort was made to avoid interference with the regular construction of the culverts and embankments other than to establish the cambered grade line elevations. Preliminary work began on the camber project in July, 1958. Rough grading and embankments were completed in August, 1959. The bituminous pavement on the undivided roadway which crosses the interstate route and which overlies Pipes B and D was constructed in the fall of 1959 while the mainline of I 64 was paved in the fall of 1960.
Fig. 3 Sketch Showing Culvert Locations.
### TABLE 1. CULVERT DIMENSIONS AND INSTALLATION DATA

<table>
<thead>
<tr>
<th>Culvert Designation</th>
<th>Station No.</th>
<th>Diameter (in)</th>
<th>Actual Length (ft)</th>
<th>Number of Pipe Sections</th>
<th>Slope (%)</th>
<th>Foundation Soil Depth (ft)</th>
<th>Embankment Height* (ft)</th>
<th>Max. Camber** (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>983 + 90</td>
<td>18</td>
<td>227.25</td>
<td>56</td>
<td>1.89</td>
<td>3-11</td>
<td>23</td>
<td>.19</td>
</tr>
<tr>
<td>B</td>
<td>74 + 00 Veechdale Rd.</td>
<td>24</td>
<td>169.75</td>
<td>42</td>
<td>0.60</td>
<td>0-5 1/2</td>
<td>33</td>
<td>.18</td>
</tr>
<tr>
<td>C</td>
<td>1000 + 50 Interstate</td>
<td>30</td>
<td>201.70</td>
<td>50</td>
<td>1.90</td>
<td>0-6</td>
<td>13 1/2</td>
<td>.14</td>
</tr>
<tr>
<td>D</td>
<td>70 + 00 Veechdale Rd.</td>
<td>18</td>
<td>150.05</td>
<td>37</td>
<td>4.39</td>
<td>0-5 1/2</td>
<td>27</td>
<td>.23</td>
</tr>
<tr>
<td>E</td>
<td>10 + 70 Ramp I</td>
<td>36</td>
<td>146.15</td>
<td>36</td>
<td>0.90</td>
<td>2-2 1/2</td>
<td>28 1/2</td>
<td>.26</td>
</tr>
<tr>
<td>F</td>
<td>1057 + 35 Interstate</td>
<td>30</td>
<td>214.10</td>
<td>53</td>
<td>0.99</td>
<td>6-6 1/2</td>
<td>19</td>
<td>.43</td>
</tr>
</tbody>
</table>

* Represents average of values measured at center of each pair of lanes for 4-lane divided highway or value measured at center of roadway for undivided highway. Includes pavement thickness.

** Did not necessarily occur at point where embankment height was measured.
tested samples was either 2 or 4 tons per square foot. The resulting void ratio-pressure curve from each consolidation test was used in the camber computations.

The foundation soil profiles were superimposed upon the pipe culvert section sheets included in the highway plans. The depth of soil beneath the culvert flow line and the height of embankment above the flow line were determined at 24-foot intervals along each culvert site. This interval was selected because the construction crew chose to set their batter boards every 24 feet, which is the length of six pipe sections.

Using the respective void ratio-pressure curves and Equations 1 and 2, the expected settlement was calculated for each of the 24-foot intervals. All embankment material was assumed to have a unit weight of 120 pounds per cubic foot. Often, in settlement calculations, the distribution of the vertical stress within the foundation produced by the weight of the embankment is determined by use of influence charts, which are solutions of the Boussinesq, Westergaard or similar equations (5). However, the depths of foundation soils encountered in this project were so shallow in relation to the widths of the embankments at the base that stresses produced by the embankment weights diminished very little with depths of foundation soils. For this reason, the midplanes of the foundation soils were assumed to carry the full stresses produced by the embankment loads. Also, because the foundation soils were
relatively thin, the pressure produced upon the midplane of the foundation soil - due to its own weight - was neglected. Total settlements for Pipes A and F were based upon two dominating layers of compressible soil in the profile. For the other pipes, the entire depth of soil beneath the flow line was assumed to be compressible. The straight-grade elevations originally shown on the plans were corrected to include the camber desired for each installation.

As construction of the culverts progressed, elevations were obtained at the 24-foot intervals within the culverts. Masonry nails were driven into the mortared joints in the culvert inverts. Elevations were obtained on the nail heads to check the accuracy to which the culverts were placed and also to provide initial readings before any settlement occurred. Where the culvert flow lines were sufficiently flat to permit a horizontal line of sight, elevations were determined with a level mounted on a special tripod as shown in Figure 4. Readings were obtained on a short section of a standard level rod as shown in Figure 5. A 6-volt hunter's lantern served as means of illumination within the culverts. Where the grades were too steep to use this technique, the straight grade line of the culvert was extended and a hub was driven 2 feet from each end of the culvert so
Fig. 4  Use of Level to Obtain Elevations within Culverts Laid on Relatively Flat Grades.

Fig. 5  Section of Standard Level Rod used in Settlement Measurements.
that its top was on the grade-line extension. By using a transit, a line of sight could be obtained which was parallel to the straight grade line. A variation in a rod reading within the culvert from the height of the instrument above the straight grade line indicated the magnitude of camber or of settlement. This method is illustrated in Figures 6 and 7.
Fig. 6 Sketch Illustrating use of Transit in Measuring Settlement within Culverts Laid on Steep Grades.

Fig. 7 Short Section of Level Rod used in Conjunction with Transit to Measure Culvert Settlement.
RESULTS AND DISCUSSION

From the twelve undisturbed samples obtained at the culvert sites, ten fixed ring and six floating ring consolidation samples were trimmed and tested. It was not possible to perform the floating ring consolidation test on Pipe E and F samples because they were too soft to support the weight of the ring. Averages of the fixed and floating ring test values were used in settlement calculations when available for the same soil. Table 2 presents the void ratios and pressures obtained from each test.

To provide a simplified guide for estimating camber, a nomograph has been prepared. First, an average void ratio-pressure curve was plotted from the average of all consolidation data accumulated in this study. The void ratio scale was then converted to a settlement scale by use of the equation:

\[
S = \frac{e_1 - e_2}{1 + e_1} \cdot D
\]

\[
\frac{S}{D} = \frac{e_1 - e_2}{1 + e_1}
\]

Where \( S \) = total expected settlement, 
\( D \) = thickness of compressible layer, 
\( e_1 \) = initial void ratio, and 
\( e_2 \) = final void ratio.
<table>
<thead>
<tr>
<th>Culvert Designation</th>
<th>Sample Number</th>
<th>Void Ratio</th>
<th>Pressure (T/ft²)</th>
<th>0</th>
<th>1/4</th>
<th>1/2</th>
<th>1</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1 Fixed</td>
<td>1.037</td>
<td>1.022</td>
<td>1.005</td>
<td>.968</td>
<td>.918</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 Floating</td>
<td>1.045</td>
<td>1.032</td>
<td>1.022</td>
<td>.998</td>
<td>.959</td>
<td>.900</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Fixed</td>
<td>.672</td>
<td>.659</td>
<td>.651</td>
<td>.640</td>
<td>.625</td>
<td>.610*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Floating</td>
<td>.608</td>
<td>.585</td>
<td>.576</td>
<td>.563</td>
<td>.549</td>
<td>.535*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1 Fixed</td>
<td>.722</td>
<td>.712</td>
<td>.702</td>
<td>.684</td>
<td>.653</td>
<td>.620*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1 Floating</td>
<td>.765</td>
<td>.739</td>
<td>.728</td>
<td>.710</td>
<td>.671</td>
<td>.623</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Fixed</td>
<td>.680</td>
<td>.673</td>
<td>.665</td>
<td>.651</td>
<td>.629</td>
<td>.598</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Floating</td>
<td>.720</td>
<td>.708</td>
<td>.697</td>
<td>.679</td>
<td>.650</td>
<td>.610</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1 Fixed</td>
<td>1.058</td>
<td>1.009</td>
<td>.985</td>
<td>.932</td>
<td>.864</td>
<td>.799*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Fixed</td>
<td>.933</td>
<td>.922</td>
<td>.907</td>
<td>.859</td>
<td>.791</td>
<td>.727*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Floating</td>
<td>.692</td>
<td>.675</td>
<td>.662</td>
<td>.636</td>
<td>.600</td>
<td>.565*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>2 Floating</td>
<td>.741</td>
<td>.717</td>
<td>.710</td>
<td>.689</td>
<td>.648</td>
<td>.609*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>1 Fixed</td>
<td>.783</td>
<td>.753</td>
<td>.736</td>
<td>.702</td>
<td>.653</td>
<td>.607</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Fixed</td>
<td>.846</td>
<td>.773</td>
<td>.745</td>
<td>.700</td>
<td>.642</td>
<td>.583</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1 Fixed</td>
<td>1.107</td>
<td>1.041</td>
<td>.997</td>
<td>.943</td>
<td>.866</td>
<td>.784*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2 Fixed</td>
<td>.903</td>
<td>.790</td>
<td>.777</td>
<td>.757</td>
<td>.716</td>
<td>.665</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>--</td>
<td>.826</td>
<td>.801</td>
<td>.786</td>
<td>.760</td>
<td>.718</td>
<td>.672</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Extrapolated values from void ratio-pressure curves.
PIPE B

This 24-inch culvert was installed using a B₁ bedding as called for by Kentucky Highway Department Specifications. The construction of the B₁ bedding is similar to that of the "imperfect trench" method. Loose hay was used as the compressible material in backfilling the trench. As shown in Figure 11, the measurements indicate a favorable trend—that is, the settlement curve has approached the predicted curves.

PIPE C

This culvert is under a relatively low embankment and the foundation soil is relatively shallow. It was included in the investigation because of its nearness to other culverts studied. Figure 12 shows that the inlet portion was laid close to the solid rock; camber and settlement data are shown for the outlet portion of the culvert. Significant settlement was observed at the outlet and near the centerline of survey where the culvert was close to rock. This is partially explained by the fact that earthmoving equipment passed over the culvert before the pipe was covered adequately.

PIPE D

Figure 13 reveals a good comparison between actual and predicted settlement for this 18-inch
Fig. 11. Actual and Theoretical Settlement Curves for Pipe B.
Fig. 12. Actual and Theoretical Settlement Curves for Pipe C.
Fig. 13. Actual and Theoretical Settlement Curves for Pipe D.
culvert which was also constructed using a $B_1$ bedding. It will be noted that actual settlement along the inlet portion of the culvert has already exceeded the predicted ultimate value. Again, this may be attributed to the frequent passage of heavy equipment along a haul road over the culvert immediately after construction of the backfill.

**PIPE E**

This culvert had the largest diameter, 36 inches, in the group and also required $B_1$ bedding. The foundation soil was rather shallow throughout the culvert site but was one of the more compressible soils tested. The actual settlement curves, Figure 14, conform in a general way with the shape of the predicted settlement curve, but they do not yet agree in magnitude.

**PIPE F**

This 30-inch culvert, the first one constructed, was placed upon a foundation soil which was rather uniform in depth. When construction was started, the resident engineer decided to remove a portion of the undesirable foundation soil and to replace it with a more suitable material. Settlement calculations were not corrected for this change; and, of course, this accounts, in part, for the fact that actual settlements have not been as great as the predicted values. This fact is illustrated by the curves in Figure 15.
Fig. 14. Actual and Theoretical Settlement Curves for Pipe E.
Fig. 15. Actual and Theoretical Settlement Curves for Pipe F.
CONCLUSIONS

Insofar as the soils involved in this study might be considered to be typical of many areas in Kentucky and perhaps elsewhere, it may be inferred that the camber and settlement data offered herein would provide a reasonable approximation of the settlement expected in many pipe culvert installations. In assuming the soils to be typical, it is implied that the decreases in the void ratios for each increment of load determined for these soils are more-or-less average. On this basis, then, the settlement of the midplane of the foundation soil, which is also taken as the settlement of the culvert, is directly proportional to the decrease in void ratio occurring within the foundation soil. A composite expression of the decrease in void ratio in terms of the fill height and depth of foundation soil should provide the best generalization obtainable from the data available. It is believed that such a generalization is satisfied by the camber guide, presented in the form of a nomograph, since it does take into account the initial void ratio of a foundation soil produced by its own weight above its midplane and also the change in the void ratio as a result of the additional load produced by the weight of fill. The nomograph was
prepared on the assumption that the foundation soil would have a submerged unit weight of 65 pounds per cubic foot and that the embankment material would have a unit weight of 120 pounds per cubic foot. More precisely, if the soils involved in this study are assumed to be typical, the nomograph satisfactorily performs the same operations as the more general settlement calculations with the exceptions that it does not allow for any stress distribution through the foundation soil, nor does it apply to a compressible layer of soil at great depths.

Of course, it is recognized that no truly average or typical soil exists and, therefore, the nomograph will yield varying degrees of accuracy (as shown in Figures 10 through 15) depending upon the variance from the so-called typical soil and its associated void ratio-pressure curve. It should be remembered that the soils encountered in this study consisted predominantly of silty clays and some clay silts and clays. Sands, gravels, and non-plastic soils would have consolidation characteristics different from the soils studied and would be obvious exceptions from the typical soil upon which the nomograph is based. It is implied, moreover, that the field engineer must determine the depth of foundation soil and height of fill expected at each culvert site and make a cursory
appraisal of the soil. Exceptional soils and exceptional depths of soils and fill heights may merit special investigation. Thus, use of the nomograph should be tempered with judgement.

Although the culverts studied in this project consisted of reinforced concrete pipe, it may be inferred that the guide developed therefrom would apply equally well to other situations. The nomograph has been based on Terzaghi's theory of primary consolidation, and the nomograph is thus applicable to those situations in which settlement is likely to occur by this process. There is no reason to think that the nomographic guide would not apply equally well to corrugated metal pipe culverts as well as box culverts.

It is suggested that this method of estimating settlement may find useful application in other situations involving subsidence of embankments. The differential settlement occurring between bridges and their approach embankments (see Figure 16) is a serious problem in highway maintenance (6,7,8). On modern roads, this defect has become a hazard to high-speed traffic, and remedial work is expensive and causes considerable inconvenience to road users. There is, as yet, no confirming data to show whether or not the difficulty arises from consolidation within the foundation soil or to show that it can be attributed largely to volume changes within the embankment material.
Fig. 16. Settlement of Bridge Approach
A typical example of such a situation is illustrated in Figure 17. It will be noted that the abutment of the bridge is placed on piles which are bearing on firm rock at significant depth. Generally, there is a considerable depth of relatively compressible material between the rock level and the natural ground line. It is not unreasonable to expect that the placement of significant embankment material over the foundation soil will cause a differential settlement between the approach embankment and the bridge deck since the embankment can settle as a result of consolidation occurring within the original ground and the abutment cannot because it is founded on piles bearing on rock. According to the nomograph presented in Figure 8 of this paper, differential settlement between the approach slab and the bridge deck of approximately one foot may be expected. This entire amount of settlement may not occur after the pavement has been completed and, therefore, may not be manifestly apparent in the final grade because some of this settlement will, of course, occur during the construction period as the embankment is placed. The differential settlements which have been noted at bridge approaches in the State of Kentucky appear to be typically on the order of four to six inches. Although the possibility of volume changes occurring within the embankment itself should not be overlooked, it must be recognized that
Fig. 17. Example of Conditions which Might Contribute to Settlement of Bridge Approaches
embankment loadings of as much as 15 or 20 feet on the natural soil may induce significant settlement. The nomograph presented in this paper might serve as a guide to estimate the order of magnitude of such settlements, and to suggest the possible need for special provisions to account for or minimize these unwanted settlements.
LIST OF REFERENCES

1. Standard Specifications for Road and Bridge Construction, Kentucky Department of Highways, 1956 (Section 5.11.3).


EXAMPLES OF CANNER CALCULATIONS

APPENDIX I
Example 1, 2-Lane Highway

TO DETERMINE EXPECTED SETTLEMENT:

Lay straight-edge from 20 feet on D line to 50 feet on H line and read settlement of 1.29 feet on S line (Figure 8).

Note: In no case should camber be installed to the extent that a downstream elevation is higher than some upstream point of elevation. This problem may occur if a culvert has a small difference in inlet and outlet elevations. In such a case, the maximum camber permitted by these limiting elevations should be installed. Occasionally, the inlet portion of a culvert may have to be placed on a straight horizontal grade line at an elevation equal to that of the inlet.
Example 2, 4-Lane Divided Highway

TO DETERMINE EXPECTED SETTLEMENT:

Centerline Of Roadway Over Outlet Portion Of Culvert

Lay straight-edge from 24 feet on D line to 21 feet on H line and read settlement of 0.81 feet on S line.

Median

Lay straight-edge from 18 feet on D line to 17 feet on H line and read settlement of 0.52 feet on S line.

Centerline Of Roadway Over Inlet Portion Of Culvert

Lay straight-edge from 17 feet on D line to 19 feet on H line and read settlement of 0.54 feet on S line.