INDUCED-TRENCH METHOD OF CULVERT INSTALLATION

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The induced-trench (imperfect-trench) method of culvert installation is used to reduce the loads on a culvert under a high fill. Although the method has been used successfully with concrete pipe under some unusually high fills, the magnitude of the reduction in load achieved by the induced trench has not been clearly established. This research project was initiated to evaluate the settlement ratio and to compare the measured loads acting on the culvert with theoretical values. The results of this research indicate that the range of empirical values that have been recommended for the settlement ratio for the induced trench is reasonable for a 48-in. reinforced concrete-pipe culvert under 30 ft of fill. A comparison of the measured loads acting on the culvert with theoretical loads indicates that the load theory is somewhat conservative.

•THE CONSTRUCTION of underground drainage structures in accordance with high safety standards such as those developed for the Interstate Highway System has led to increased costs for culvert installations. The relatively flat highway profiles result in high earth fills, which require longer culverts capable of supporting heavier overburden loads. Ways are continually being sought to reduce the cost of the culverts while adequate structural performance is maintained.

One proposed method of reducing culvert costs is the induced-trench procedure, also known as the imperfect-trench method. Although the induced trench has been successfully used with concrete pipe under some unusually high fills, opportunities to evaluate the settlement ratio under field conditions have been limited. Because current knowledge of the settlement ratio is based on limited experimental proof, an evaluation of the ratio from a number of field installations would greatly help to establish design criteria for the induced-trench method of construction.

The primary objective of this research was to determine the settlement ratio used in estimating the loads on conduits installed by the induced-trench method of construction. From settlement data collected during this study, realistic values of settlement ratios were determined for the induced trench constructed under the specific conditions present at the test site. Those data, in addition to other information from a number of similar installations with varying fill heights and different culvert sizes, will eventually provide the means for more accurately predicting the settlement ratio for the design of culverts constructed by the induced-trench method.

THEORETICAL CONCEPTS

The purpose of the induced trench is achieved as the column of soil above the culvert settles downward relative to the adjacent compacted soil. The relative movement generates shearing forces that act upward on the interior prism of soil as shown in Figure 1. The shearing forces support part of the weight of the column of soil above the conduit, thereby reducing the load on the culvert.

If the embankment is sufficiently high, the shearing forces may terminate within the embankment at a horizontal plane, termed the plane of equal settlement. Above that plane, no relative settlements occur and no transfer of load takes place. If the embankment is not sufficiently high, no plane of equal settlement will develop beneath the top of the embankment. In that case, differential settlement will occur throughout the height of fill above the culvert. That situation, which is termed the complete-ditch condition, could possibly result in a localized sag in the roadway. When considering the use of the induced trench, an engineer is primarily concerned with the possibility of an eventual settlement of the roadway above the culvert.

When the induced trench is analyzed, an important parameter to be considered is the settlement ratio. That ratio is an indication of the magnitude of the relative movements of the prism of soil directly above the conduit and the adjacent soil and is used in computing the design loads on the culvert. The settlement ratio for the induced trench is calculated by the following formula:

$$r_{sd} = \frac{S_g - (S_d + S_f + d_c)}{S_d} \qquad (1)$$

where

r_{sd} = settlement ratio,
S_g = settlement of compacted embankment at level of top of trench and adjacent to sides of trench,
S_d = deformation of fill from top of pipe to top of trench,
S_f = settlement of flow line of conduit, and
d_c = shortening of vertical dimension of pipe.

During this study, all factors in the formula were measured directly in the field with the exception of S_d. S_d was determined by subtracting the measured values of S_f and d_c from the total settlement of the critical plane measured as $(S_d + S_f + d_c)$.

Once the settlement ratio is established, charts developed by Spangler (9) facilitate the computation of the theoretical loads on the conduit as determined by the following formula:

$$W_c = C_n w B_d^2$$

where

W_c = load/lin ft of conduit;
C_n = load coefficient, which is a function of ratio of height of fill to width of ditch H/B_d, of projection ratio p', of settlement ratio r_{sd}, and of coefficient of internal friction μ;
w = unit weight of backfill, and
B_d = width of trench.

In his derivation of the load theory for underground conduits, Marston pointed out that the influence of the coefficient of internal friction μ of the fill material is relatively minor, and, therefore, the product of Rankine's lateral pressure ratio K and the coefficient of internal friction may be safely assumed to equal 0.13 for the induced trench. Based on that assumption, Spangler's charts relate the load coefficient to the parameters used to analyze the induced trench (Fig. 2). A different chart is used for each value of the projection ratio. Only the chart for a projection ratio of 1.0 is included in this report because the condition represents the case under study. Once the projection ratio and the H/B_d ratio are determined and the settlement ratio is estimated, the proper value of the load coefficient is found from the chart.

RESEARCH INSTRUMENTATION

The instrumentation used to measure the required settlements consisted of settlement platforms with vertical reference rods located in groups of three beneath the median and under each outside shoulder (Figs. 3 and 4). All settlement plates were placed in the plane of the top of the induced trench 6 ft above the top of the culvert pipe. The platforms consisted of 24-in.-square steel plates $^1/_4$-in. thick and 5-ft lengths of $^1/_2$-in. steel pipe welded to the center of the plates. As the fill height was increased, additional 5-ft extensions of $^1/_2$-in. pipe were added.

Changes in culvert diameter were measured with an extensometer consisting of an Ames dial graduated in 0.001-in. increments and fastened securely to one end of a steel

Figure 1. Settlements that influence loads on induced-trench conduits.

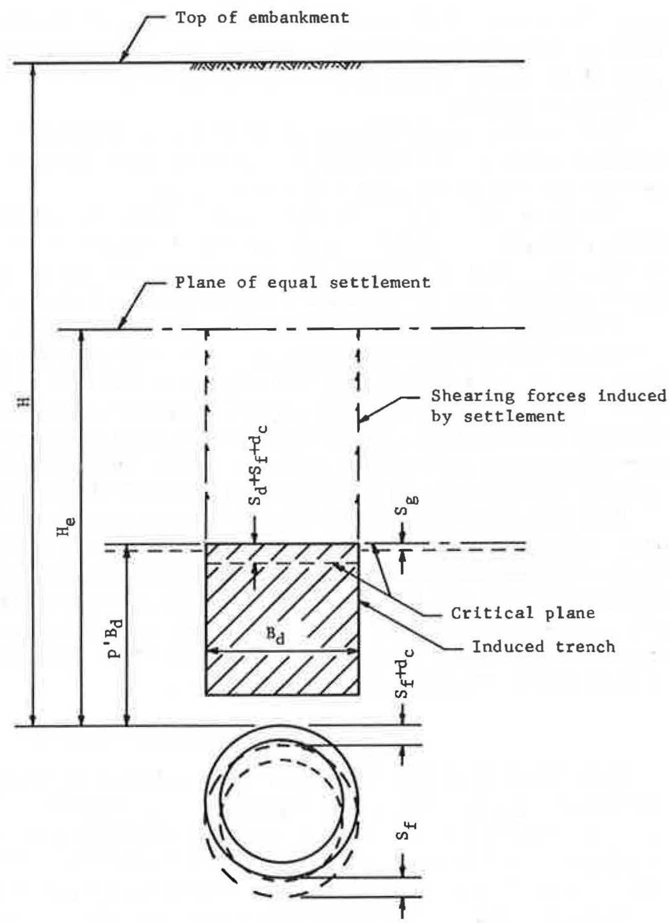
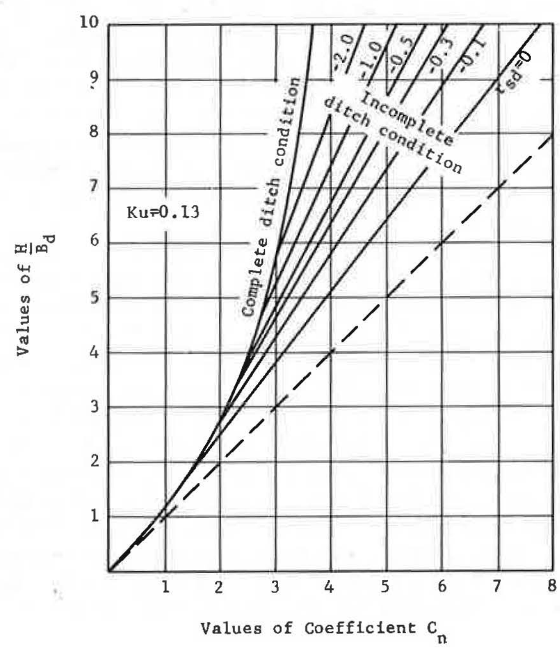


Figure 2. Coefficient C_n for induced-trench conduit when p' = 1.0.



rod. To ensure that the extensometer would be at the same precise location each time that the pipe deformation was measured, reference points were established inside the pipe at the same locations along the culvert where the settlement plates and pressure cells were placed.

To measure invert elevations at the 3 locations of instrumentation required that a vertical angle be turned with a transit because the grade of the culvert was too steep to permit the use of a horizontal line of sight.

The pressure cells used to measure the earth pressure against the pipe were originally designed to measure pore pressures under earth dams. Their selection for use in this research was based on their resistance to damage from moisture; that makes them suitable for an extended study of pressure under a high fill.

Each cell is a sealed hollow plastic dish about 8 in. in diameter (Fig. 5). The hollow cell is filled with low-viscosity oil. The sides of the cell are sufficiently flexible so that soil pressure applied to the outside of the cell is transmitted to the oil inside the cell. Within the oil is a thin plastic envelope about 4 in. in diameter. Gas is pumped through the envelope, which is held closed by the oil pressure until sufficient gas pressure develops to open the envelope. Each cell was calibrated to give the external pressure if the applied gas pressure and the rate of flow of gas through the cell are known.

The pressure cells were attached to the outside of the culvert pipe when the top of the compacted embankment was 1 ft above the top of the pipe. Small pits were dug down to the cell locations at the top and spring lines of the pipe. A flat mortar pad was formed at each cell location, and the cell was attached to the flat surface by an epoxy glue. The exposed face of each cell was covered with a 2-in. layer of AM-9 chemical grout. After installation of the pressure cells, the pits were carefully backfilled and compacted with pneumatic hand tampers.

CONSTRUCTION

Construction of the induced-trench installation began in May 1961 and was completed in October 1961. Work was interrupted several times by wet weather. The culvert is a 48-in. ASTM C-76 class 4 reinforced concrete pipe located on a local channel change parallel to and under the base of a 30-ft high ridge. The entire culvert length of 324 ft is in cut except for the extreme downstream end, which meets the natural channel.

The soil material is generally a compact clay till and has a few stone fragments as wide as several inches in diameter. The uphill shoulder of the cut consists of a mottled yellow silty clay loam over gravelly clay till. The downhill shoulder of the cut contains some black organic soils associated with the valley floor.

The maximum depth of cut at the centerline was about 8 ft; the average depth was about 6 ft. The average width of excavation in the plane of the top of the pipe was about 11 ft; the average width at the flow line was about 8 ft.

A 6-in. compacted bed of sand was placed throughout the bottom of the cut to provide a firm base over the slightly muddy and gravelly bottom (Fig. 6). After the pipe was placed, sand backfill was carried up to the spring lines and compacted with pneumatic hand tampers.

The backfill material from the spring lines to the top of the pipe consisted of cut material mixed with sand. The use of pneumatic hand tampers was continued as much as 6 in. below the top of the pipe. From 6 in. below to 6 in. above the top of the pipe, compaction was effected by driving a rubber-tired 4-wheel tractor back and forth along the pipe. After the compacted cover over the pipe reached 6 in., conventional sheepsfoot rollers were used. When the compacted cover reached 1 ft, construction operations were halted to permit installation of the pressure cells.

After the pressure cells were installed and the installation pits were refilled and compacted by pneumatic hand tampers, the fill was completed to a level 6 ft above the top of the pipe. At that point, a 5-ft wide by 5-ft deep by 280-ft long trench was excavated by backhoe directly over the culvert pipe. The trench was refilled by bulldozer with loose topsoil containing some sod and a few cornstalks (Fig. 7). Density of the trench material varied from 51 to 56 percent of the maximum density obtained by AASHO Method T 99. After the trench had been filled loosely, it was blanketed with a foot of

Figure 3. Location of pressure cells and settlement plates with reference rods.

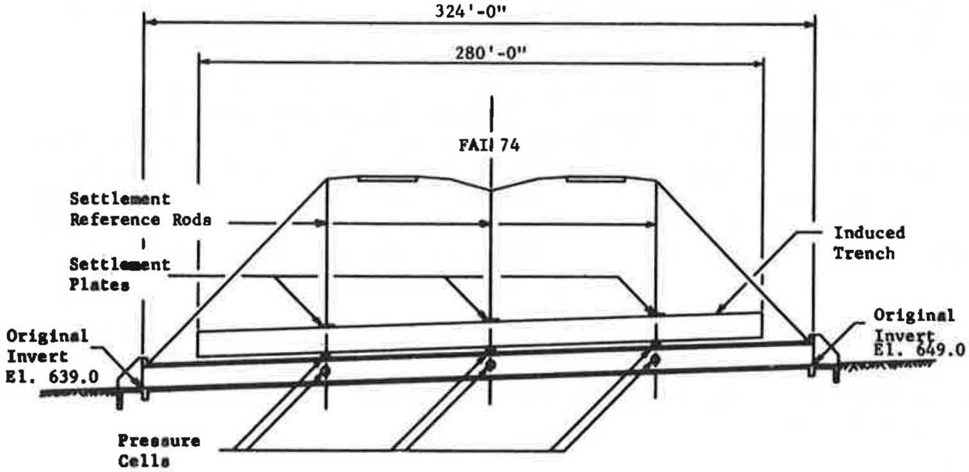


Figure 4. Typical cross section of induced trench.

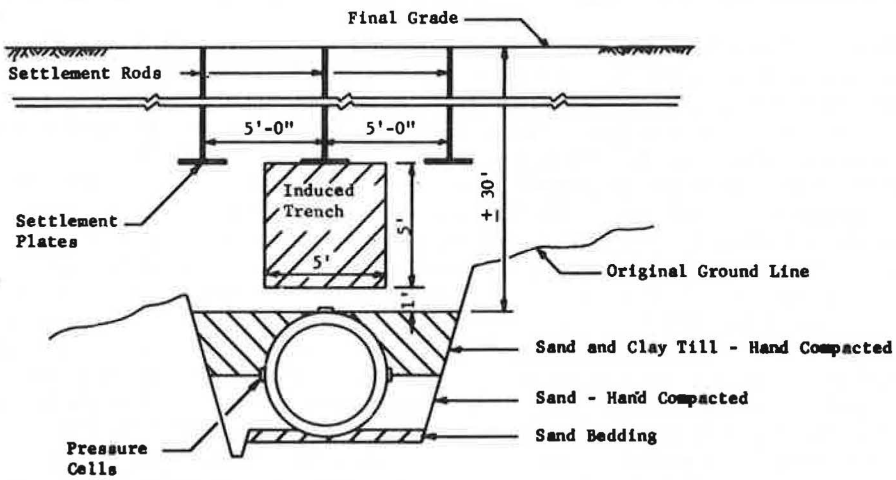


Figure 5. Pressure cell before installation.

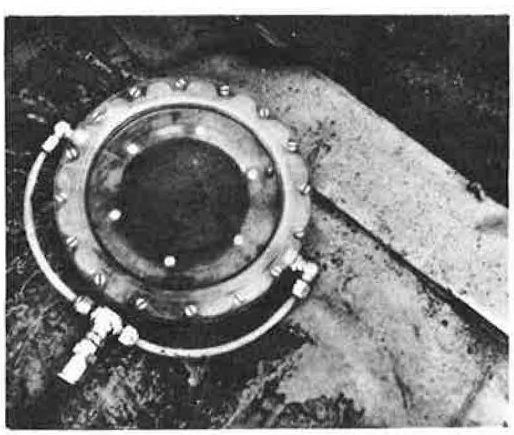


Figure 6. Six-inch compacted sand bed.

silty clay bulldozed from the uphill side of the cut. The settlement plates were then installed, and the remainder of the embankment was constructed in the usual manner. Compaction was by self-propelled scraper haul traffic and crawler-pulled sheepsfoot rollers.

Results of density tests of samples taken near the spring lines, near the top of the pipe, and at approximately 5-ft increments of fill height varied from 97.1 to 105.1 percent of the maximum density obtained by AASHO Method T 99. The percentage of moisture as determined by the same method varied from 46 to 114 percent of the optimum moisture content. Borings taken near each of the 3 transverse instrumentation locations at completion of the embankment indicated that the moisture content varied from 14 to 25 percent, and unconfined compressive strengths varied from 0.9 to 3.8 tons/ft^2.

FIELD TEST RESULTS

The settlement and pressure data were analyzed in this report for the 500 days from May 1, 1961, to September 12, 1962. Data collected beyond that period, although not complete, indicate that little change took place in the settlement ratio or the soil pressures acting on the pipe.

Settlement Ratio

Because the induced trench ensures that the column of soil over the culvert will settle more than the adjacent compacted soil, the settlement ratio for the induced trench will always be a negative quantity. The ratio is currently assumed to lie between -0.3 and -0.5.

Figure 8 shows a plot of the settlement ratios derived from this installation at the north, center, and south locations for the period from May 1961 to September 1962. The settlement ratio after 1 year varied from about -0.25 at the center location to approximately -0.45 at the north location. The ratio at the south location continued to increase in the negative direction and reached a value of -0.80 after 500 days.

Because of the variation in the settlement ratio, the individually measured parameters used in computing the ratio are presented and discussed below.

S_g = settlement of compacted soil adjacent to the trench. The values used for this parameter were the average measured settlement of the side plates installed on the compacted fill at an elevation 6 ft above the top of the pipe. At all 3 locations, the east and west side plates settled different amounts (Figs. 9, 10, and 11). The magnitude of the settlement of the west plates is fairly consistent at the center and the south locations but is about 0.26 ft less at the north location after 500 days. The magnitude of the settlement of the east plates varied from 0.85 at the north location to 0.81 at the center location and 0.52 at the south location after 500 days. The variation in settlement of the side plates at the 3 locations possibly was caused by differences in the natural soil deposits on the uphill and downhill shoulders of the cut as previously described in the construction section of this report.

$(s_d + s_f + d_c)$ = settlement of critical plane. The measured settlement of the center plate located at the top of the trench directly over the culvert centerline was used as the total settlement of the critical plane. The settlement was consistent at the north and center locations but was considerably less at the south location. The variation in settlement is possibly partly due to the varying amount of fill over the different plate locations. The final amount of fill varies from a maximum of 30.5 ft at the north location to a minimum of 27.5 ft at the south location. Measurements indicate unreasonably that the west plate at the south location settled more than the center plate. Only the settlement of the east plate was used in calculating the settlement ratio at the south location.

s_f = settlement of the pipe invert. The pipe invert settlement was consistent at all 3 locations as shown in Figure 12. The average magnitude of the settlement after 500 days was approximately 0.4 ft.

d_c = deformation of culvert pipe. The inside vertical diameter of the conduit decreased an average of about 0.010 ft after 500 days (Fig. 13). The erratic change in pipe deformation during the construction of the embankment is possibly due to temperature changes within the pipe and not due to changes in load. However, data were not collected during this research to confirm the effect of temperature change on the pipe.

Figure 7. Refilling trench with compressible material.

Figure 8. Settlement ratio versus time.

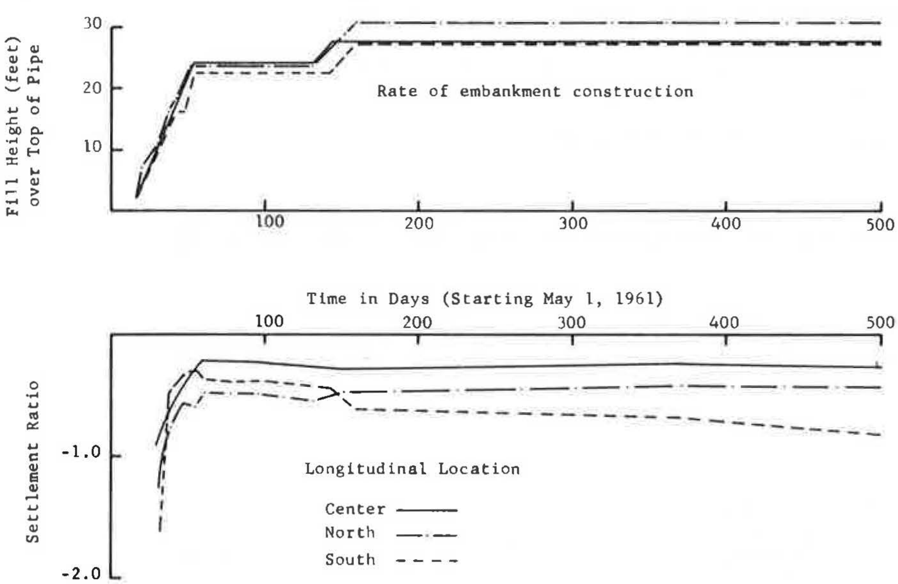


Figure 9. Settlement versus time at north location.

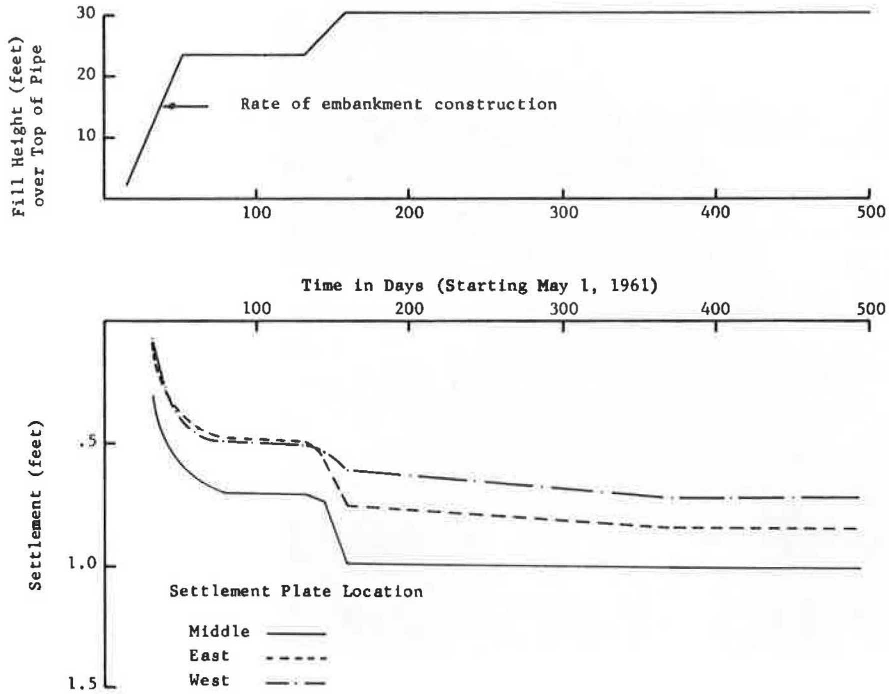


Figure 10. Settlement versus time at center location.

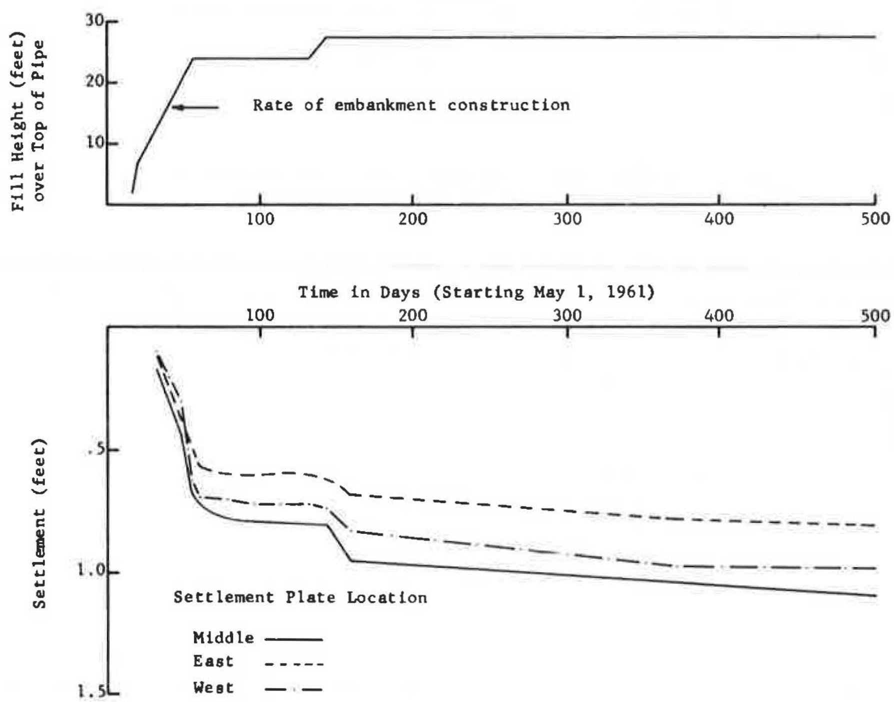


Figure 11. Settlement versus time at south location.

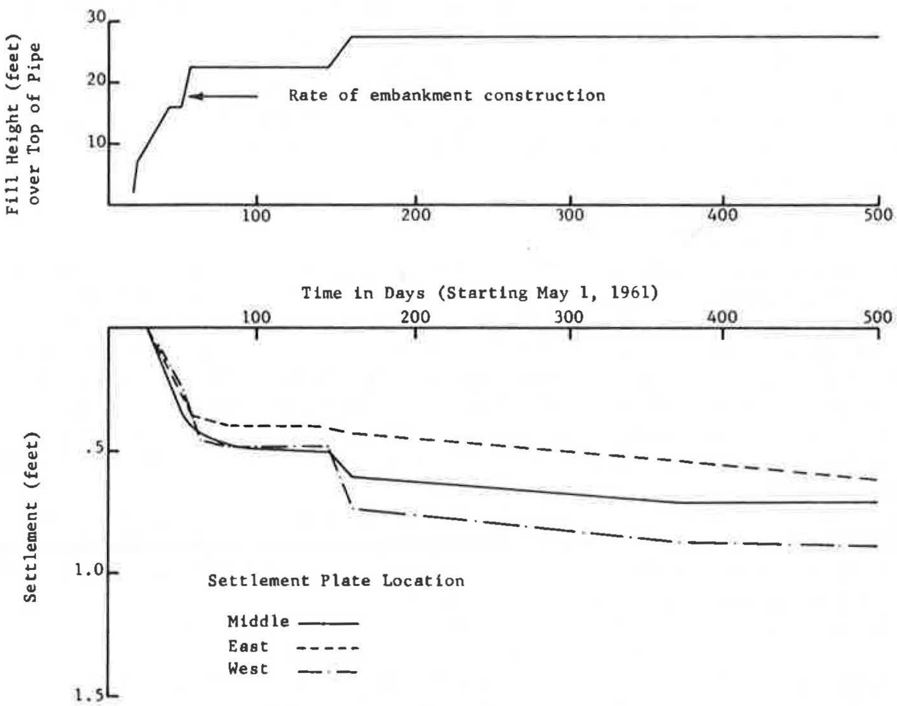
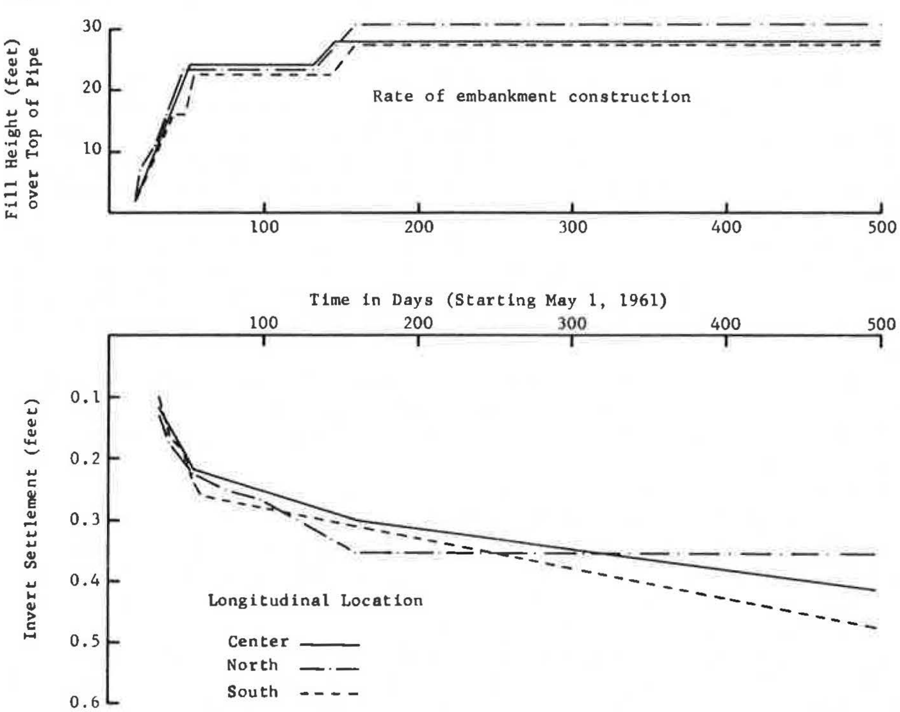


Figure 12. Invert settlement versus time.



In addition to measurements of the change in vertical pipe diameter, changes in the horizontal diameter and each diameter at 45 deg from the vertical were measured. The indicated decrease in all diameters of about 0.01 to 0.02 ft does not appear to be consistent with the loads measured on the sides of the pipe.

Except for the south location, where settlement data were not consistent with data collected at the north and center locations, the values for the settlement ratio were near the limits of the range of values of -0.3 to -0.5 that have been recommended for the induced trench.

Measured and Theoretical Loads on Culvert

Although the theory used to determine the loads on this type of conduit is considered reasonably accurate, the pressures acting on the top and the sides of the culvert were measured during and after construction in order to confirm the theory. The recorded pressures, as shown in Figures 14, 15, and 16, indicate a large variation in pressure on the top cells during the first 150 days after construction began. The reason for the sharp drop in pressure after 60 days at all 3 locations is not apparent, especially since the fill height was constant during this period. It is possible that the heavy rainfall that occurred during the period may have had some effect on the pressures, although the degree of influence is not known.

After 150 days the pressures on the top cells at the north and center locations were fairly consistent and equal to about 7 $lb/in.^2$ The drop in pressure at the south location appears to indicate a possible malfunction in the pressure cell, for the pressure is not consistent with measurements at the other 2 locations.

The measured pressures at the side of the culvert as shown in Figures 14, 15, and 16 were in the order of 1 to 2 $lb/in.^2$ Those values appear to be extremely low for that type of installation, although the arching action of the soil above the culvert could conceivably transmit a large proportion of the load to the sides of the ditch above the pressure cells. Also, it is possible that after the holes were excavated to install the pressure cells, desiccation of the adjacent soil may have formed a hard inflexible crust in front of the cells, and that crust did not permit typical pressures to be transmitted to the cells.

The low recorded pressures also may have been caused by drying out of the AM-9 grout used to fill the spaces between the soil and the pressure cells. The grout may have hardened if the soil became desiccated. Literature from the manufacturer of the chemical grout indicates that the AM-9 gels shrink if they are allowed to dry. Although the shrinking process is understood to be reversible with the addition of water, once the gel had dried, sufficient moisture may not have been present in the soil to swell the dry gel to its original shape.

Pressure cell readings taken in 1963 and in 1967 were consistent with the readings taken in September 1962, except for the west cell at the south location. The pressure recorded at that cell increased from 1.0 psi in 1963 to 6.5 psi in 1967. Clogging of the lines is believed to be responsible for the relatively large increase in the pressure recorded at that location.

The theoretical loads that would act on this conduit were compared with actual measured loads by converting the measured pressures to load per linear foot of pipe. The measured loads corresponding to the rate of embankment construction are shown as curve 1 in Figures 17, 18, and 19.

For a unit weight of soil of 120 lb/ft^3, the theoretical loads that would act on the induced-trench installation based on Marston's formula are as shown by curve 2.

A comparison of curves 1 and 2 at the north and center locations indicates that the measured loads were not greater than 50 percent of the theoretical loads after the embankment was completed. The curves for the south location show the inherent inconsistencies of the pressure charts and are neglected.

In addition to a comparison of the theoretical and measured loads acting on the induced trench, Figures 17, 18, and 19 also show as curves 3 and 4 the theoretical loads that would act on this culvert if the induced-trench method of construction were not used. Two hypothetical conditions were used for comparison with the induced-trench

Figure 13. Change in vertical pipe diameter versus time.

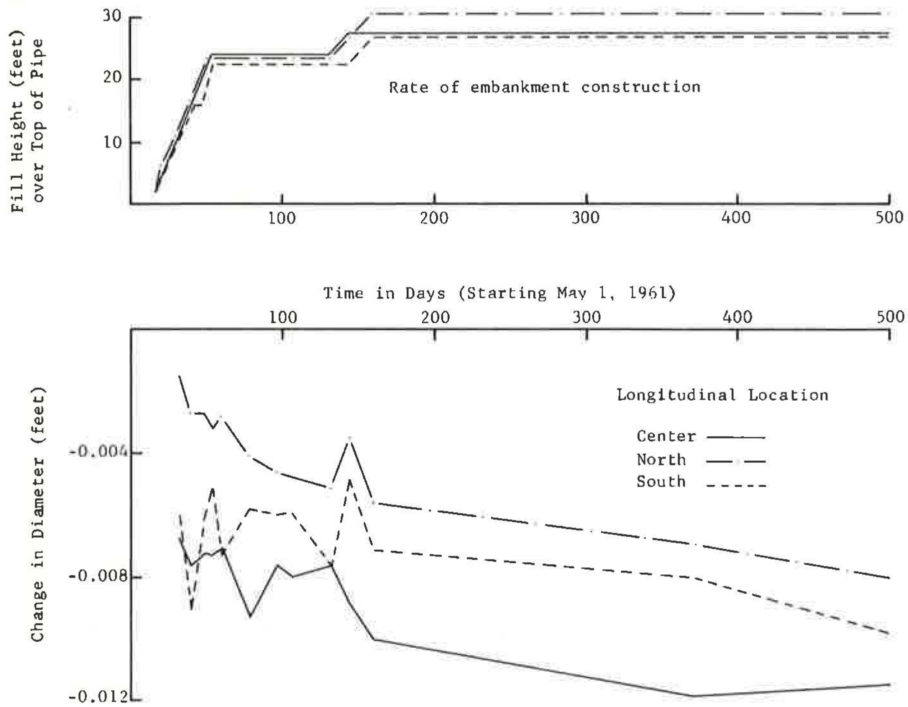


Figure 14. Pressure cell readings versus time at north location.

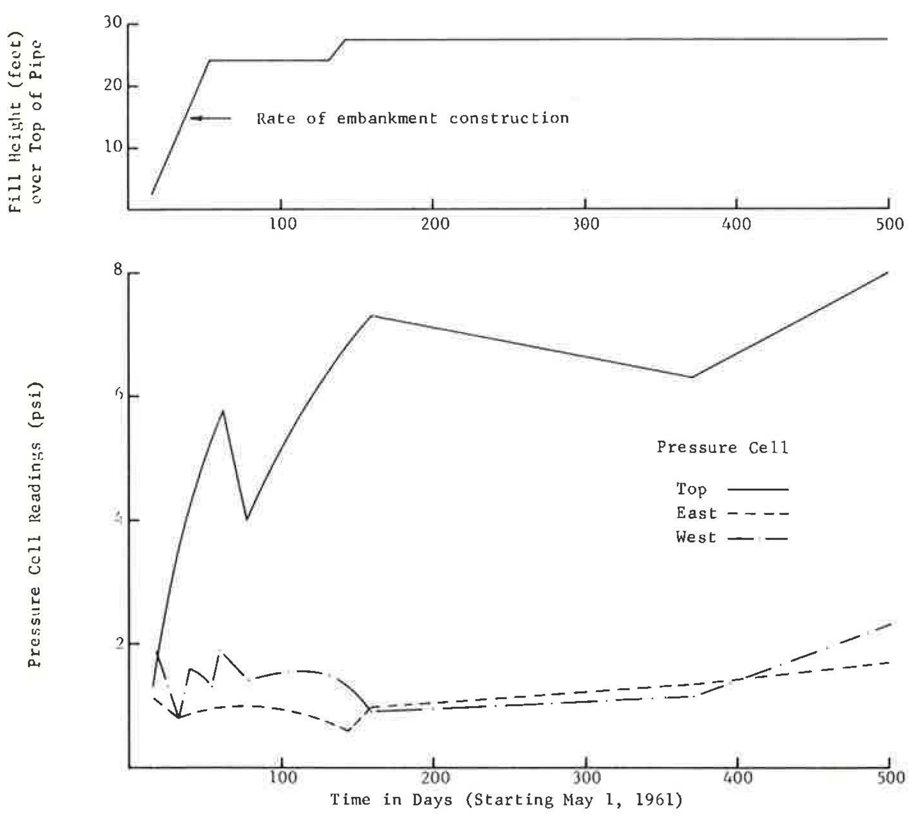


Figure 15. Pressure cell readings versus time at center location.

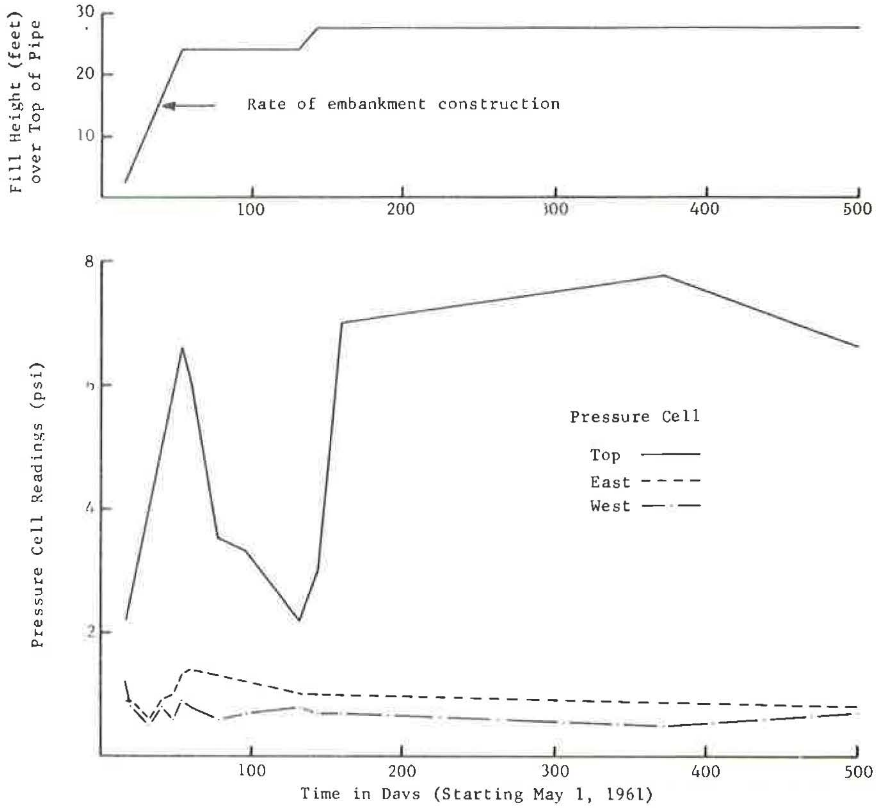


Figure 16. Pressure cell readings versus time at south location.

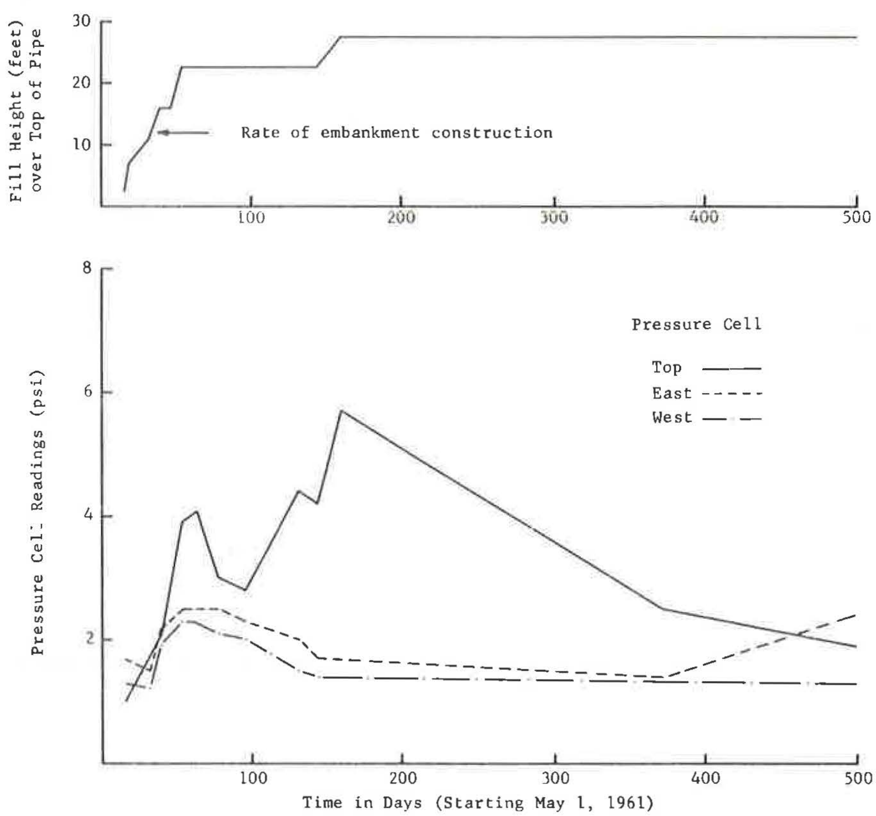


Figure 17. Theoretical and measured vertical loads at north location.

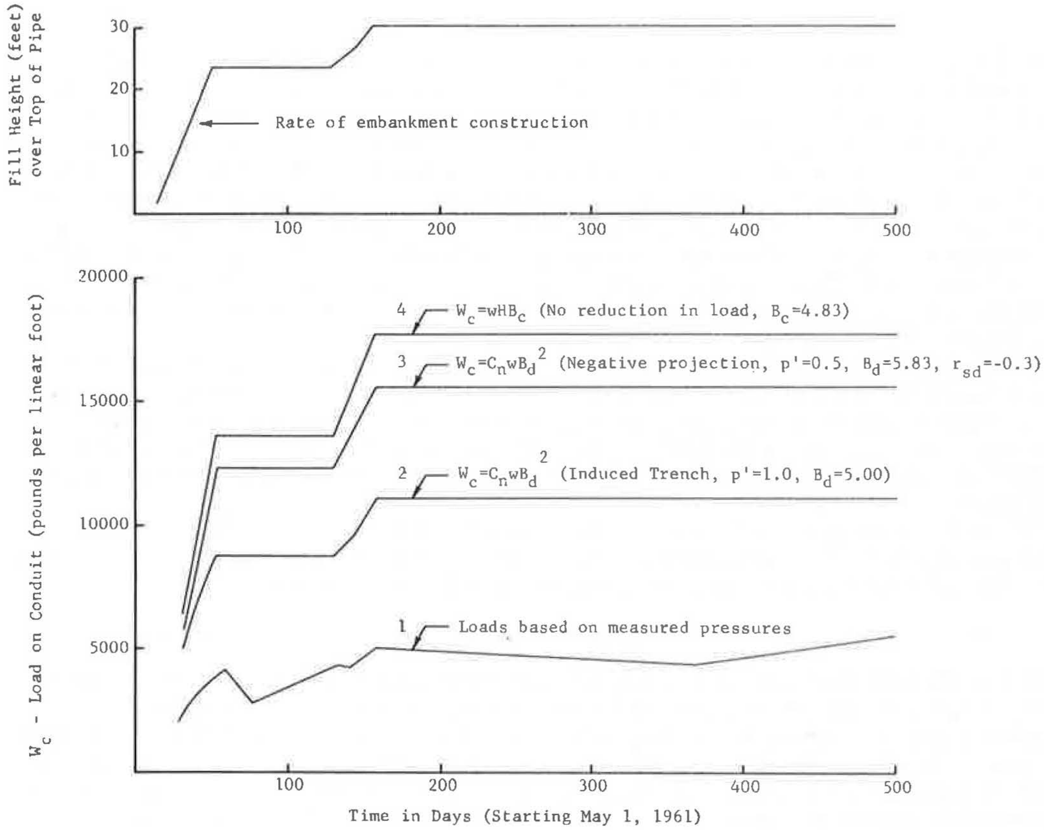
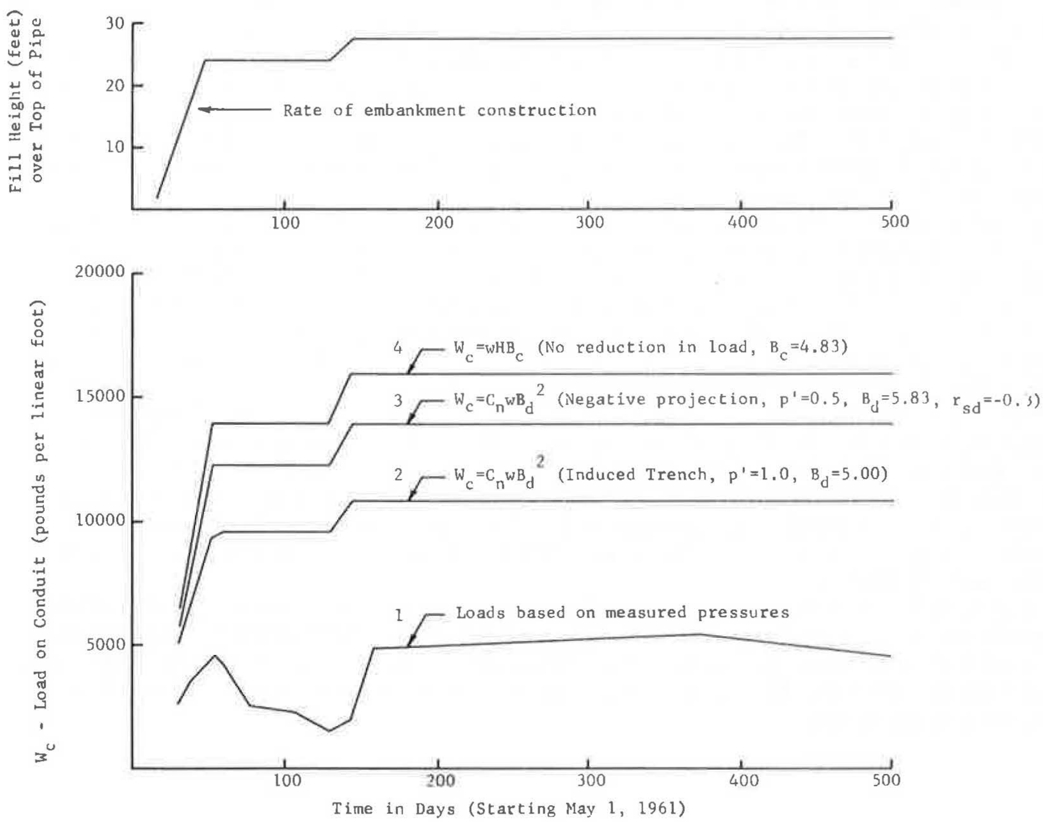


Figure 18. Theoretical and measured vertical loads at center location.



installation. Because the depth of the trench varied from about 4 to 8 ft along the length of the culvert, cases I and II in Figure 20 represent the approximate range in trench depth and were used to estimate the range in loads acting along the length of the culvert.

In case I the width of the trench was assumed to be equal to the width of the conduit plus 1 ft or 5.83 ft, and the depth of the trench below natural ground was assumed to be equal to 8 ft. Because the top of the pipe is placed below natural ground, this case corresponds to a negative projecting conduit and has a projection ratio of about 0.5. The recommended range of values for the settlement ratio for a negative projecting conduit and an induced trench is about the same. For the settlement ratio value of -0.3, the theoretical loads on the culvert computed by Marston's formula are as shown by curve 3 in Figures 17, 18, and 19.

For case II the top of the conduit was assumed to be level with natural ground; that would result in a projection ratio of zero and correspond to a trench depth of about 5 ft. If no relative movement takes place between the soil prism above the pipe and the adjacent soil, i.e., $r_{sd} = 0$, there would be no reduction in load on the conduit, and it would support the total weight of the above column of soil. That situation is shown by curve 4 in Figures 17, 18, and 19.

The unit weight of the fill material above the culvert for curves 2, 3, and 4 was assumed to be 120 lb/ft.[3] Comparing curves 3 and 4 with curve 2 reveals the advantage of using the induced-trench method of construction at this installation.

CONCLUSIONS

The settlement ratios for the induced-trench method of installation as determined by this research project correlate well with the range of values that have been recommended by others. Empirical values of the settlement ratio recommended for use with the induced trench range from -0.3 to -0.5. After initial variations during construction of the induced-trench installation, values of the settlement ratio at 2 of the 3 locations where settlement measurements were made ranged from -0.25 to -0.45. At the third location, a settlement ratio of -0.8 was considered unreliable because of discrepancies in the settlement data.

No change from current recommendations regarding values to be assumed for the settlement ratio is proposed on the basis of the research described in this report. Before definite conclusions are reached concerning the precise value of the settlement ratio for this type of construction, other similar tests must be conducted on culverts of different sizes placed under various fill heights.

At this installation there has been no indication of any settlement of pavement over the top of the induced trench. That indicates that a plane of equal settlement has formed beneath the top of the embankment.

At all 3 locations where pressure cells were located at the top and sides of the culvert, the measured pressures appeared to be low for this type of installation. After initial variations, loads based on measured pressures level off about 5,000 lb/lin ft. That represents a load level equal to about 50 percent of the theoretical loads. The sharp drop in load after initial variations at the south location apparently is due to a malfunction of the pressure cell because the load is not consistent with measurements at the other 2 locations.

The measured pressures of 1 to 2 psi at the sides of the pipe at all 3 locations also appear to be low for this type of installation, although the arching action of the soil above the pipe could conceivably transmit a large portion of the load to the sides of the ditch above the lateral pressure cells. Also, it is possible that, after the holes were excavated to install the pressure cells, desiccation of the adjacent soil in front of the cells may have formed a hard inflexible crust that did not permit typical pressures to be transmitted.

Although the loads based on measured pressures were fairly consistent at 2 of the 3 instrumented locations, much more data from this type of installation are required before final conclusions are drawn on the accuracy of the theory. At the present time, it is recommended that the theory, which appears to be conservative, continue to be used without adjustment.

Figure 19. Theoretical and measured vertical loads at south location.

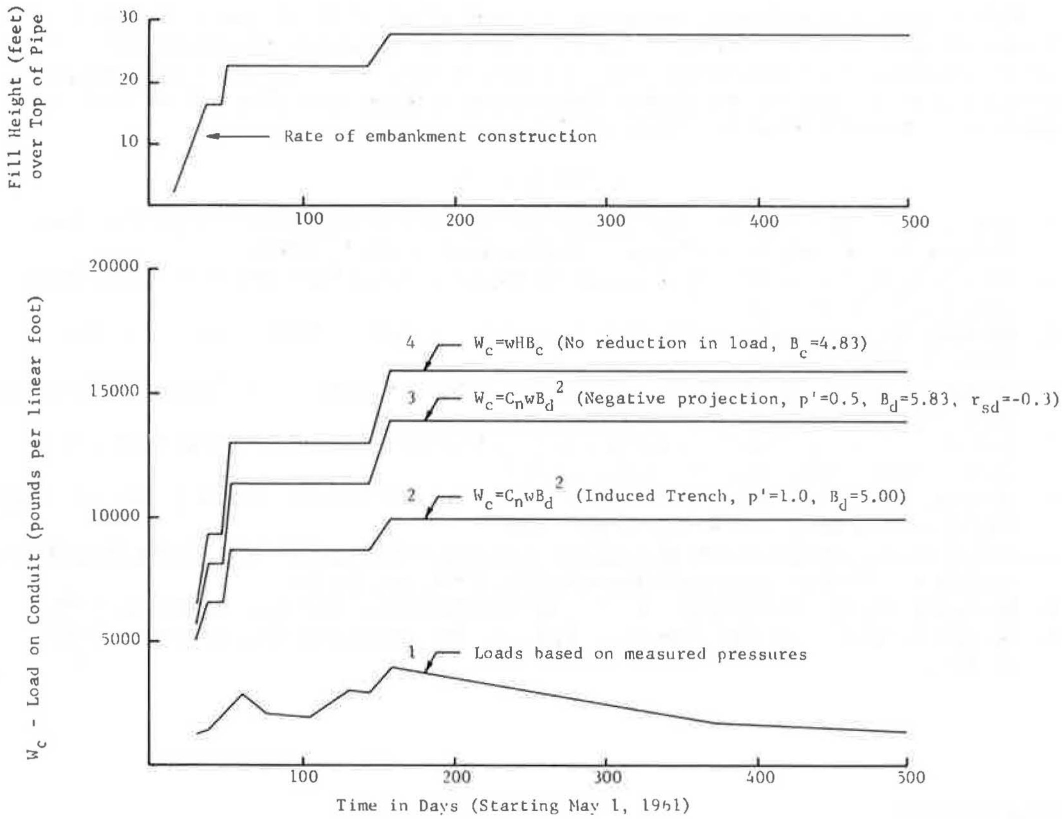
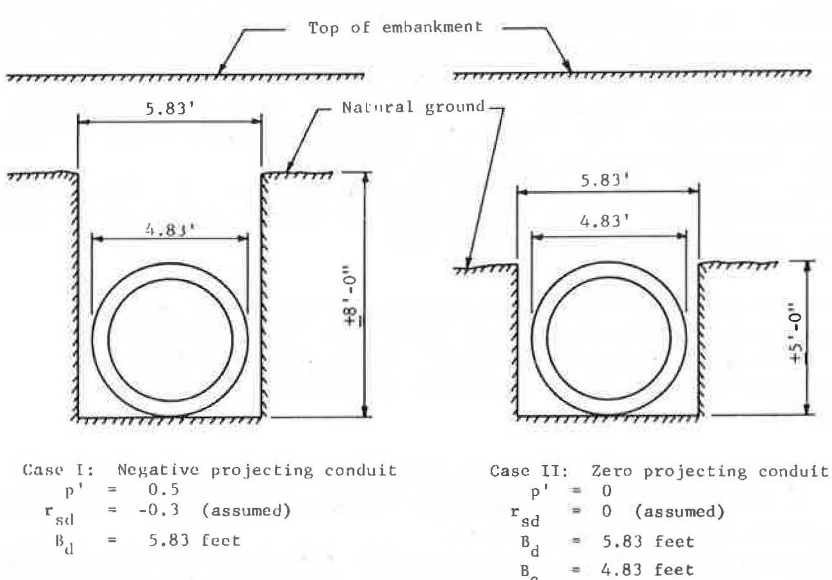


Figure 20. Limits of culvert projection without induced trench.



ACKNOWLEDGMENTS

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DISCUSSION

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This paper constitutes an excellent addition to the literature on the technology of culvert design and construction. It serves to underline and reemphasize the possibilities for greater economy in the installation of cross-drainage conduits under medium to high fills by the imperfect-ditch procedure, which was first introduced and recommended by Marston more than 50 years ago. No matter how reliable laboratory and analytical developments may appear to be, the value of evidence obtained in connection with the performance of actual field installations cannot be overestimated.

The measurements of settlements at several points in the critical plane of the Illinois embankment, which indicated values of the settlement ratio ranging from -0.25 to -0.45, are of special interest to this writer who stated in 1960:

> Research directed toward the determination of loads on negative projecting (and imperfect ditch) conduits has not progressed so far as it has in connection with the other classes of conduits. In the absence of factual data relative to probable values of the settlement ratio for conduits of this class, it is tentatively recommended that this ratio be assumed to lie between -0.3 and -0.5 for the purpose of estimating loads.

The author's findings go a long way toward eliminating the word "tentatively" from the above quotation. It is hoped that other state highway departments will conduct similar studies to add to basic knowledge in this field.

In the matter of load on the structure, pressure-cell measurements indicated a load equal to approximately half of the load calculated by the Marston-Spangler procedure. This, of course, is in the right direction from the standpoint of structural design and safety. Nevertheless, it is of interest to speculate on possible causes of this divergence. One influential factor may have been a difference between the actual coefficient of friction of the embankment soil and the value used to calculate the load.

It is a basic principle of all the conduit-load analyses of the Marston type that the load on the structure is considered to be the resultant of 2 forces: (a) the weight of the prism of soil that lies above the conduit plus or minus the frictional shearing forces that are generated along the sides of this central prism by differential movement or tendency for movement between the central prism and (b) the adjacent soil masses. If the adjacent soil settles more than the central prism, as in the case of the projection condition of positive-projecting conduits, the shear forces are directed downward and are additive to the weight of the central prism to produce the resultant load. If the reverse is true, that is, if the central prism settles more than the adjacent soil, as in the case of ditch conduits, negative-projecting and imperfect-ditch conduits, and the ditch condition of positive-projecting conduits, the shear forces are directed upward and are subtractive from the weight of the central prism.

The magnitude of the unit shear force is a function of the product $K\mu$, where K is Rankine's lateral pressure ratio and μ is the coefficient of friction of the soil (tangent of angle φ). Because K is a function of μ, it develops that the product $K\mu$ varies over a relatively narrow range for all soils: from about 0.13 for $\varphi = 10$ deg to a maximum of 0.19 for $\varphi = 30$ deg or more. It is not considered to be practical to measure the friction angle for the embankment soil of a specific proposed culvert installation. Therefore, in accordance with the principle that the estimated design load should be the probable maximum to which the culvert may be subjected in service, the load calculation diagrams have been constructed by using the value of $K\mu$ that gives the maximum load on the structure. Thus, for conditions wherein the shear forces are directed upward, the calculation diagrams (such as shown in Fig. 2) are based on $K\mu = 0.13$; whereas, for the opposite case of shear directed downward, the diagrams are based on $K\mu = 0.19$.

If the soil of the embankment in the author's research actually had a $K\mu$ value near the maximum of 0.19, the calculated load indicated by the C_n value taken from Figure 2 could have been approximately 40 percent greater than the measured load. That would go a long way toward accounting for the observed divergence between calculated and actual load.

Another circumstance that might have influenced the divergence is the statistical relation between the area of the pressure cells by which the load was measured and the total area of the structure. The pressure cells were 0.67 ft in diameter, and there were 2 cells that gave results considered to be reliable. Thus, the total area over which pressures were measured was approximately 0.7 ft^2. The total area of the pipe projected on a horizontal plane through its top and for the length between the shoulders of the 4-lane roadway was approximately 750 ft^2, or about a thousand times greater than the area of the pressure cells. If one considers the heterogeneous character of soil, it is not surprising that the measured pressures may not have equaled the theoretical loads.

In view of the above possibilities, the author's recommendation that the theoretical approach for estimating design loads on imperfect-ditch conduits continue to be used appears to be justified, even though the results may be somewhat conservative.