Measured Performance of 4.4-Meter Diameter Multiplate Keyhole-Slotted Conduit Under 20-Meter Earthfill

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The need for information on the performance of large buried conduits was the catalyst for an instrumentation program for the Ohio Department of Transportation. A corrugated steel, multiplate keyhole-slotted conduit 4.4 m in diameter, 249 m long, under 20 m of earthfill was instrumented to obtain readings of earth pressures and measurements of changes in diameter as well as slip between the conduit plates. Eight pneumatic total pressure cells were installed at the springline with three more placed just above the crown. Near-field stresses have deviated by 15 to 40 percent from stresses calculated free of arching effects. Stresses in most cells have been decreasing slowly, indicating stress relief in the long-term behavior of the conduit. Diametral deformation stations were established at 7.62-m intervals throughout the length of the conduit. Four readings of diameter were made at each station (vertical, horizontal, and the two 45-degree diagonals). Excellent agreement with expected behavior of conduit geometry has been observed. A significant amount of plate slip occurred during the first few days following construction of the fill, but slippage has slowed with time. Measurement of earth pressures near the conduit wall has shown that slotted joints do permit greater burial depths than would conventional bolted joints.

A corrugated steel conduit 4.4 m in diameter and 249 m in length was constructed in June 1991 at the site of Ramp R of the Ronald Reagan Cross County Highway, Hamilton County, Ohio for the Ohio Department of Transportation (ODOT). ODOT engineers wished to validate the design concepts, numerical modeling, and construction procedures for such large, flexible structures. Of special interest was the action of slotted joints. Katona and Akl (*1*) indicated that

> . . . bolt holes slotted in the circumferential direction . . . permit relative circumferential contraction of the plates. As the culvert circumferentially contracts from joint slippage, the surrounding soil envelope is forced into a compression arch, which in turn carries a greater portion of additional loading. When all joint slippage is complete, the culvert again acts as a continuous unit so that further loading will be carried by both the structure and the soil arch. Ultimate failure in thrust typically occurs by seam failure, but at a burial depth significantly greater than that of a standard culvert without slotted joints. (*1*)

This case appeared to be an ideal beginning for the necessary data base. The authors referred to Selig et al. (*2*) for concepts related to measuring the performance of the conduit. Whereas Selig et al. (*2*) established instrumentation at one location, these authors gathered data over the entire length of the conduit and under more than double the fill height of the system tested by Selig et al. (*2*).

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INSTRUMENTATION AND MEASUREMENT

Instrumentation Plan

The first author established an instrumentation plan that was accepted by ODOT engineers. The plan involved frequent reading of earth pressure cells, measurement of the deformed conduit geometry with backfill loading and time, measurements of the slip of the keyhole-slotted joints, records of the soil backfill characteristics and compaction data, and surveyed elevations as the fill depth increased. The elevation view of the conduit and the profile of the overlying fill at Ramp R are shown in Figure 1. The instrumentation layout in elevation view is depicted in Figure 2, while the layout in plan view is shown in Figure 3.

The pressure cells chosen were Slope Indicator Company Pneumatic Total Pressure Cell Model 51482. These cells are an extremely sensitive and economical means for determining static total pressure on a plane surface. Eight earth pressure cells were installed (June 19) at the springline of the conduit, and the final three cells were placed (June 24) just above the crown. An excavation 4.6 × 2.4 × 1.22 m deep was made to accommodate the cluster of springline cells. The base of the excavation was then backfilled with layers of clean sand and compacted to at least the same degree of compaction as the surrounding earthfill and leveled. The cells were individually installed in small excavated pockets, each approximately twice the size of the cell. Each cell was positioned in its pocket and checked for correct functioning, alignment, and level. The pocket was then backfilled using clean sand to a density similar to that of the surrounding soil, taking care that no particles large enough to damage the tubing or cell performance were present. Tubing was run from the cells through 50-mm diameter holes cut in the conduit wall at the springline. The tubing was then connected to a terminal pipe mounted on the inside wall of the conduit at its midlength and approximately 3 m above the invert. Slack was provided in the tubing to avoid stressing or shearing of the polyethylene at the soil-conduit wall as the backfill soil consolidated.

Deformation points were established at 7.62-m intervals along the 249-m length of the conduit. Each point was marked with white fluorescent paint so that the locations could be seen easily when working in the conduit with flashlights. A total of 33 stations were marked. Four readings of diameter were taken at each observation point: vertical, horizontal, and two diagonals at 45 degrees from vertical. Permanent marks were established to ensure that the readings were taken at consistent positions with successive monitoring. Measurements were made using an aluminum rod that could be dismantled for easy transport. The three-piece rod had a section that moved against a scale. The outer two sections were of known

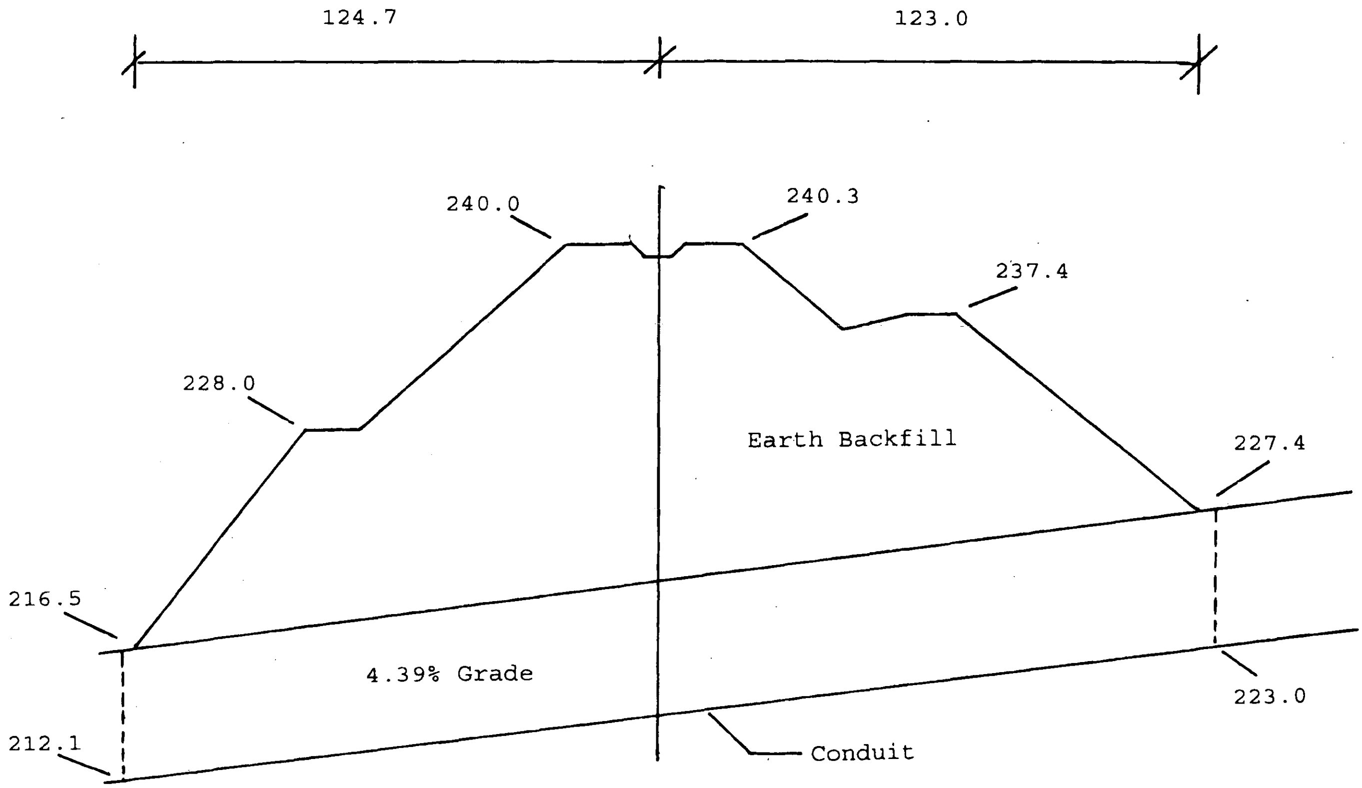

FIGURE 1 Elevation view of conduit with overlying fill (numbers represent elevations and lengths in meters).

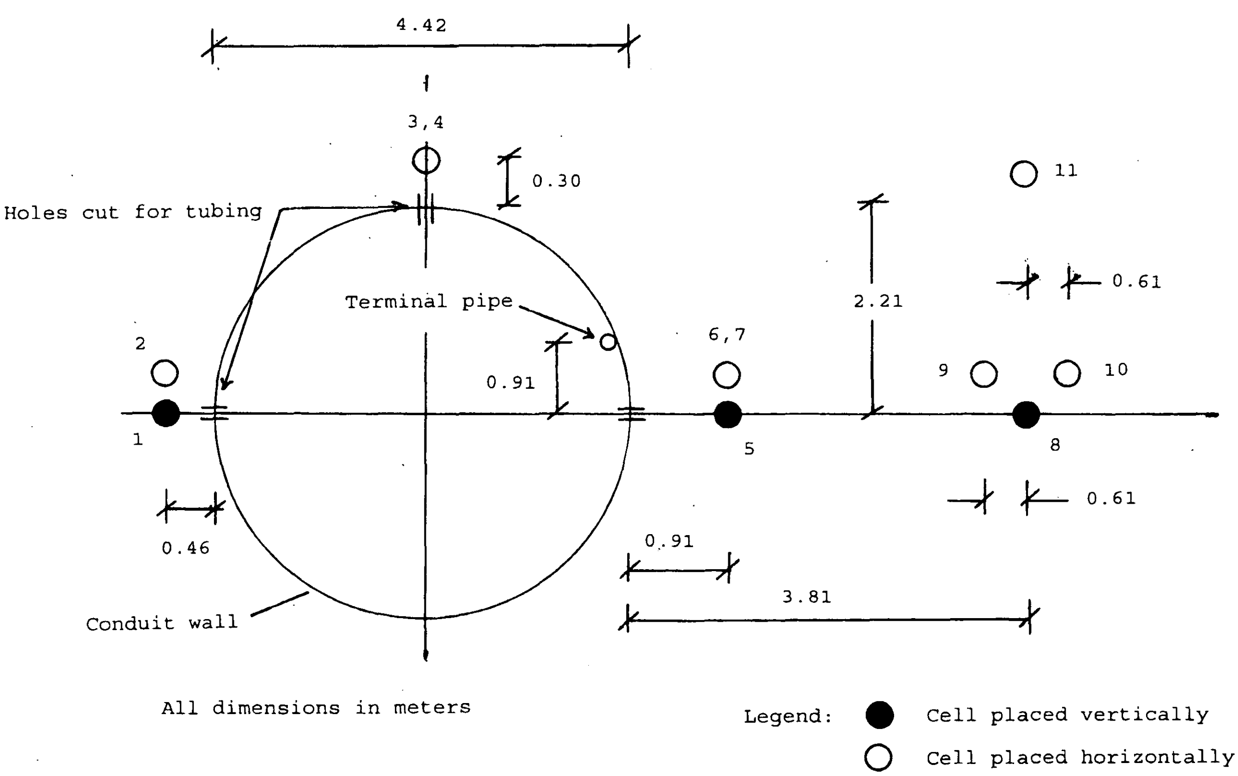

FIGURE 2 Elevation view of instrumentation layout for conduit (looking upstream).

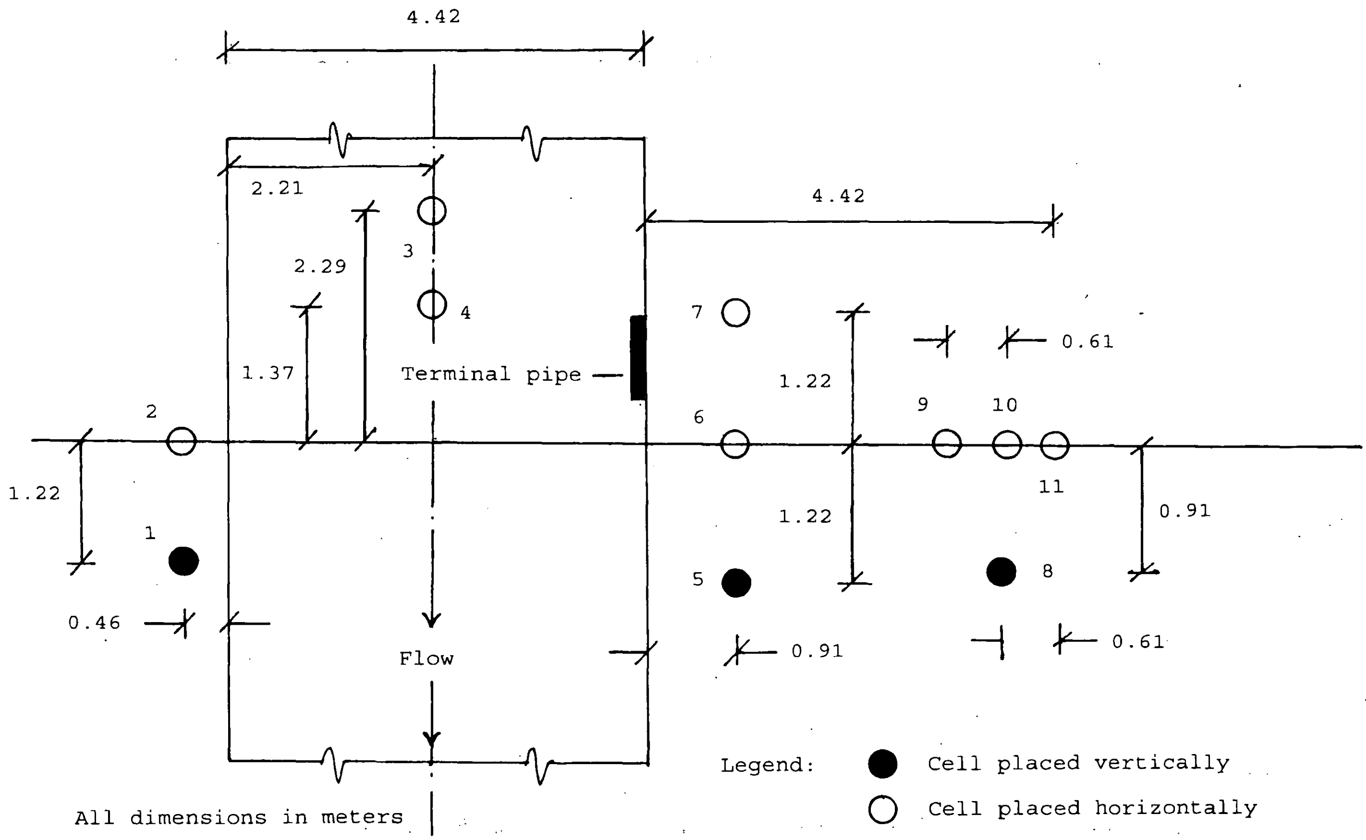

FIGURE 3 Plan view of instrumentation layout for conduit.

length. Hence, the field team merely had to place the needled ends of the rod against the permanent marks on the conduit walls and read the scale to obtain the diameter at a particular station. Care was taken to ensure that minimum flexure was present in the rod. The change in the rod length caused by temperature changes was insignificant. Repeatability to within 1 mm was obtained. All the data gathered in the field was transferred to computer data files for processing.

Regular monitoring of the keyhole-slotted joint slippage was undertaken. A simple procedure was adopted for this purpose. Using a steel punch, two distinctly visible sharp punch marks were made on either side of the multiplate bolt connection in the conduit wall. As the maximum amount of earthfill was near the midlength of the conduit, the keyhole connections in that area were monitored. A total of 16 observation points (eight points upstream and eight downstream of the centerline) 7.62 m apart were established. Slippage along the springline connections to the right and left of the conduit were monitored. The 10th and 20th bolt connections downstream and upstream of the centerline were also monitored. For the latter locations, the springline and invert bolt connections to the right and left of the conduit were measured, using time and fill placement as variables.

Earth Pressure Cell Measurements

Backfilling operations commenced on June 24, 1991; construction activity was temporarily suspended (contractor choice) from June 27 to August 29, 1991 just after the crown was covered. The earthfill was completed by October 17, 1991. All 11 earth pressure cells have functioned properly through early 1994.

A comparison between measured and calculated earth pressures has been made. The calculated earth pressures are the product of the unit weight of the compacted backfill material and the depth of fill at a particular cell location. Reports of compaction tests using the nuclear method were obtained from ODOT at regular intervals. The wet unit weight of the compacted fill varied from 19.8 to 21.7 kN/cu.m. The calculated earth pressures do not consider any effect of arching or other soil-structure phenomenon. Horizontal earth pressures were calculated by multiplying the vertical earth pressure by an average earth pressure coefficient of 0.37 (given the soil backfill type and compaction characteristics). The variation of the measured and calculated earth pressures with increasing fill height at the location of Cell 9 (free field, measuring vertical stress) is shown in Figure 4. The Cell 9 pressure readings compare quite well with the calculated pressures. The pressure is seen to steadily increase as fill placement continued. The measured pressures are about 34.5 kPa (5 psi) lower than the calculated pressures during most of the fill placement. The final recorded pressure was 412.3 kPa (59.8 psi) which is about 24.1 kPa (3.5 psi) lower than the calculated pressure for that fill height. This difference is reasonable given the average data from the compaction of the backfill.

The variation in the measured and calculated earth pressures with increasing fill height near the conduit wall at Cell 5 (near field, measuring horizontal stress) are depicted in Figure 5. While the recorded stresses increase in a near linear manner, the measured

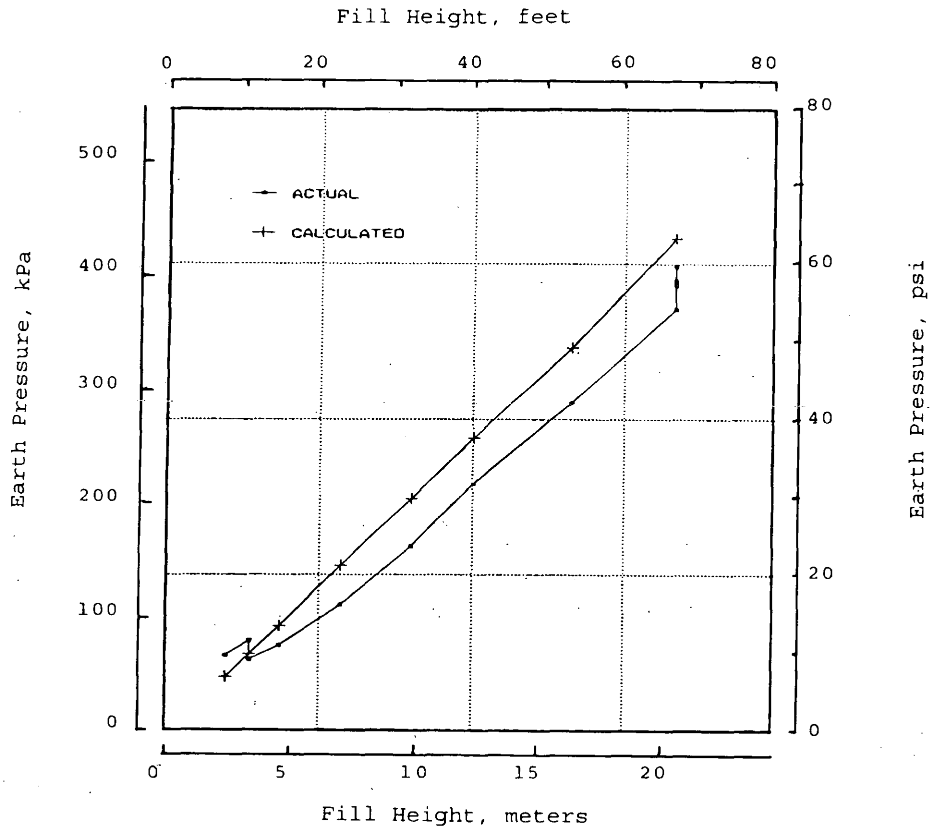

FIGURE 4 Variation of Cell 9 measured and calculated earth pressures with increasing fill height.

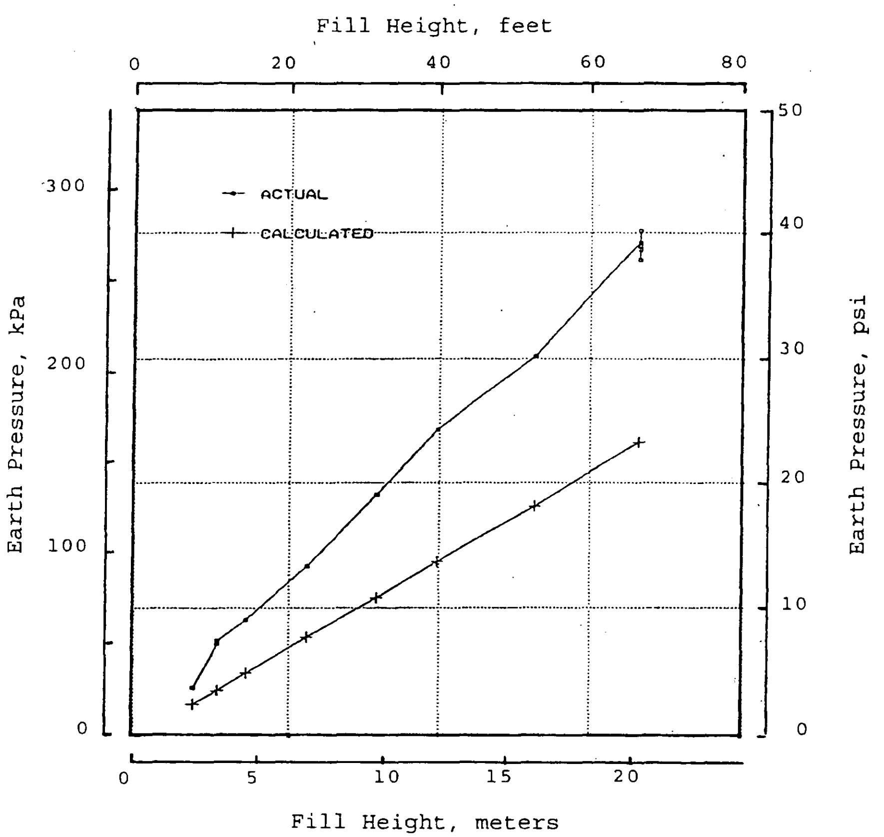

FIGURE 5 Variation of Cell 5 measured and calculated earth pressures with increasing fill height.

stress was found to always exceed the calculated stress. This makes sense given the lateral bulging of the conduit and the induced horizontal thrust against the soil backfill.

The measured and calculated vertical stresses at the crown of the conduit are shown in Figures 6 and 7. Replicate pressure Cells 3 and 4 were placed 1 m apart and 0.3 m above the conduit within the sand backfill. In each case the measured vertical pressure is less than the calculated pressure after the first 3 m of fill had been placed. The difference in this case is caused by arching within the soil backfill.

Excellent agreement between vertical free field measured and calculated stresses is indicated in Figure 8. The difference between the two is less than 13.8 kPa (2 psi).

Conduit Deformation Measurements

Thirty-three observation points at 7.62-m intervals were established along the entire length of the conduit. Horizontal, vertical, and two quarter-point measurements were made. The following designations apply to subsequent figures.

- 1-1 = Vertical Measurement Line
- 2-2 = Horizontal Measurement Line
- 3-3 = Quarter Point (right side) Measurement Line
- 4-4 = Quarter Point (left side) Measurement Line

The orientation scheme for the diameter deformations is depicted in Figure 9. Deformations along the length of the conduit as measured 20 January 1992 (3 months after the fill was completed) are shown in Figure 10. In the figure, positive deformation indicates elongation, while negative deformation represents shortening relative to the baseline measurements. Deformations have been plotted on a magnified scale to provide better understanding of the behavior of the conduit. The maximum vertical flattening is 96.5 mm (3.8 in.) at a point 137 m (450 ft) into the conduit. Horizontal elongation at the same location is 40.1 mm (1.58 in.), while the maximum elongation of 44.5 mm (1.75 in.) occurs 7.6 m (25 ft) further into the conduit length. The maximum shortening along quarter point (3-3) is 50.0 mm (1.97 in.) at a point 160 m (525 ft) into the conduit, and 49.0 mm (1.93 in.) along quarter point (4-4) at a point 122 m (400 ft) into the conduit. Maximum deformations occur between 61 to 183 m from the upstream mouth of the conduit where the fill height is greatest. Deformations increase from the upstream end towards the midlength of the conduit then gradually decrease as one approaches the downstream end.

Vertical Deformation Along the Conduit

The variation of the vertical shortening (squash) along the length of the conduit at various stages of fill placement is illustrated in Fig-

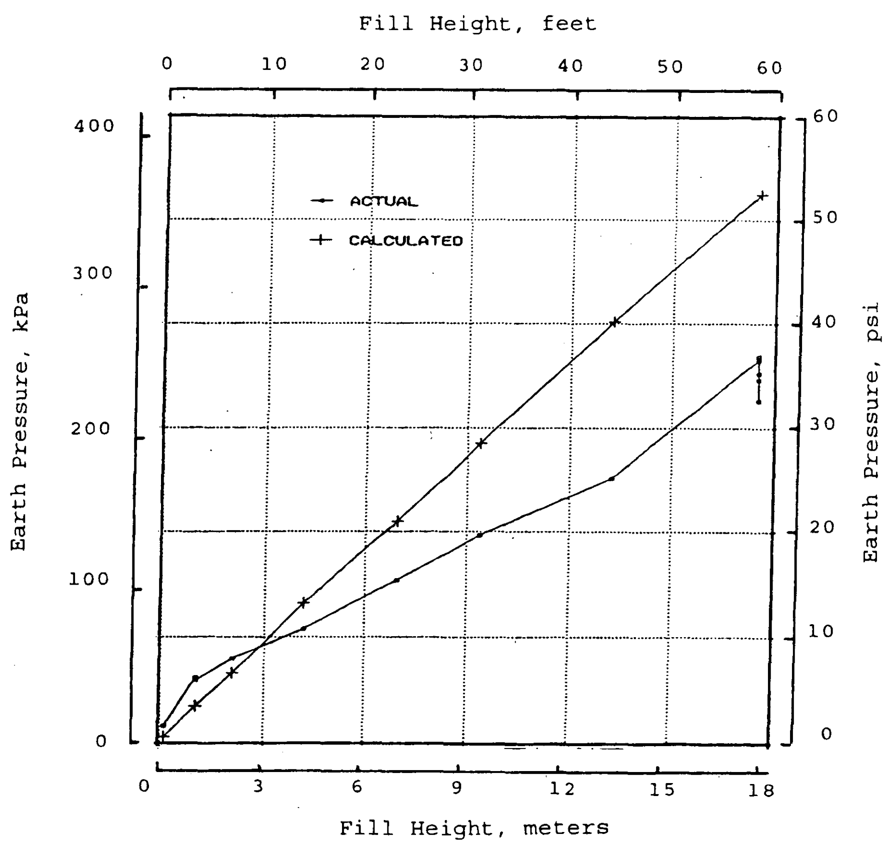

FIGURE 6 Variation of Cell 3 measured and calculated earth pressures with increasing fill height.

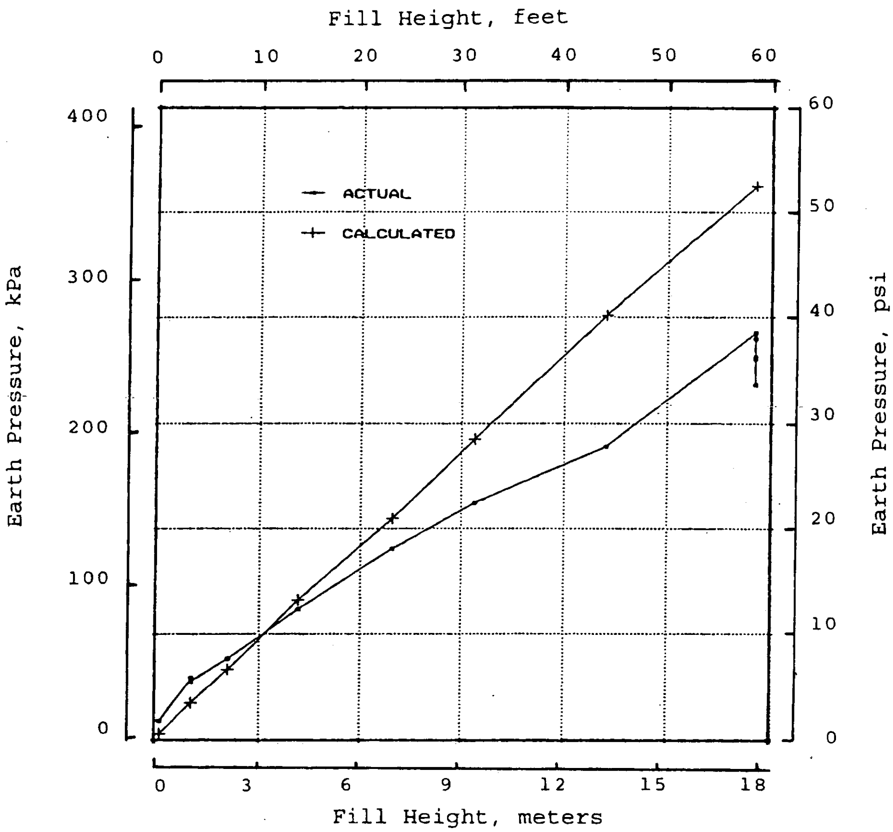

FIGURE 7 **Variation of Cell 4 measured and calculated earth pressures with increasing fill height.**

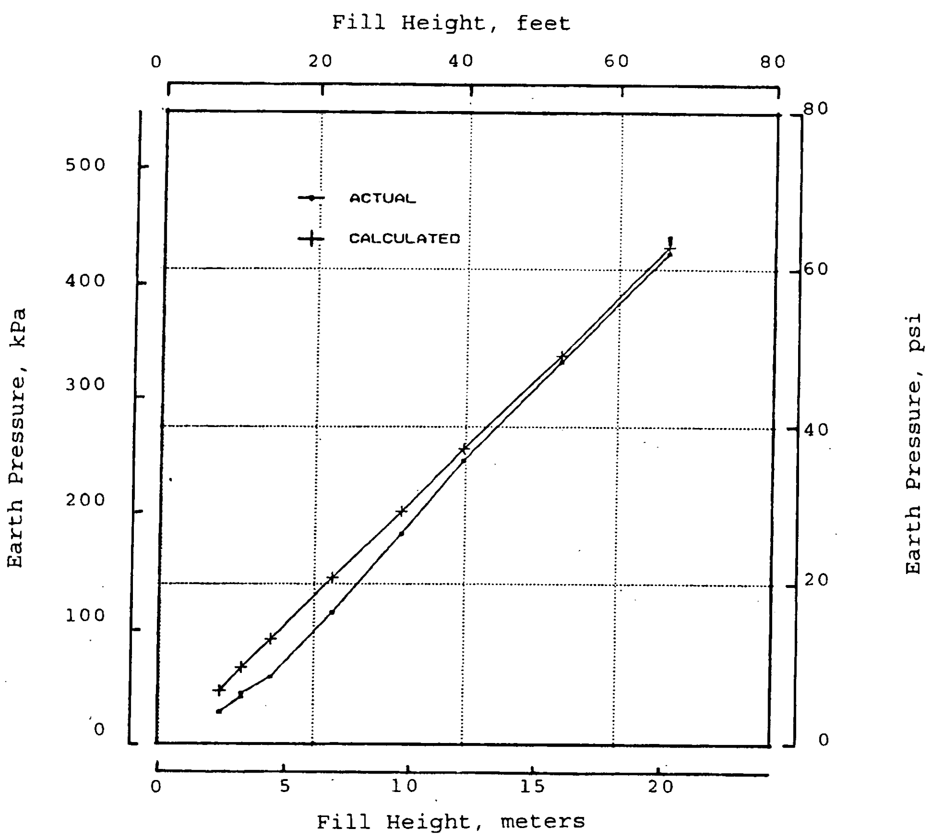

FIGURE 8 **Variation of Cell 11 measured and calculated earth pressures with increasing fill height.**

ure 11. Vertical flattening increases in a similar pattern as backfill placement increases. Maximum flattening occurs between 125 to 168 m in from the upstream end of the conduit. The maximum vertical flattening at the end of fill placement was 82 mm or approximately 1.9 percent of the as-built diameter.

Deformation measurements were continued for two years after completion of backfill construction. The objective was to observe the behavior of the culvert geometry with the passage of time. Conduit deformations at midlength as a function of time following the completion of the fill are shown in Figure 12. In the first 30 days the vertical flattening increased by 9.9 mm (0.39 in.); in the next 64 days the increase was only 4.1 mm (0.16 in.). Similarly, the horizontal elongation increased by 2.0 mm (0.08 in.) in the first 30 days and then by 1 mm (0.04 in.) in the next 64 days. Quarter point (3-3,4-4) measurements changed but slightly in the first 8 days and since then have been constant.

Keyhole-Slotted Joint Movement

Slippage of the keyhole-slotted joints between plates was monitored at numerous locations. As the fill reached its maximum height, the slippage was closely monitored. Slippage along the springline and the invert on both sides of the conduit was recorded. Stations were established as follows:

- C-20 = 20 bolts upstream of center;
- C-10 = 10 bolts upstream of center;
- C = mid-length (124 m into the conduit);
- C+10 = 10 bolts downstream of center; and
- C+20 = 20 bolts downstream of center.

The movement of the right and left abutment plates at the conduit midlength are noted in Figure 13. The decrease in slot movement following the completion of the fill is evident. To indicate how much slip occurs along the length of the conduit, 16 locations in the central 122 m were monitored. A graphical representation of this data is given in Figure 14.

Replication of Measured Pressures

Replication of earth pressure cells was completed at three locations to check the accuracy of stress cell measurements. Cells 3 and 4 placed at the crown have shown very comparable values. Readings have been within 14 kPa (2 psi) at all times (Figure 15). Cells 6 and 7 located at the springline have also shown excellent agreement (Figure 16).

CONCLUSIONS

The conduit geometry undergoes constant change with changing fill height. During backfilling up to the crown of the structure, the culvert flexes upward at the crown and inward at the springline, and the magnitude of these movements increases as the height of backfill

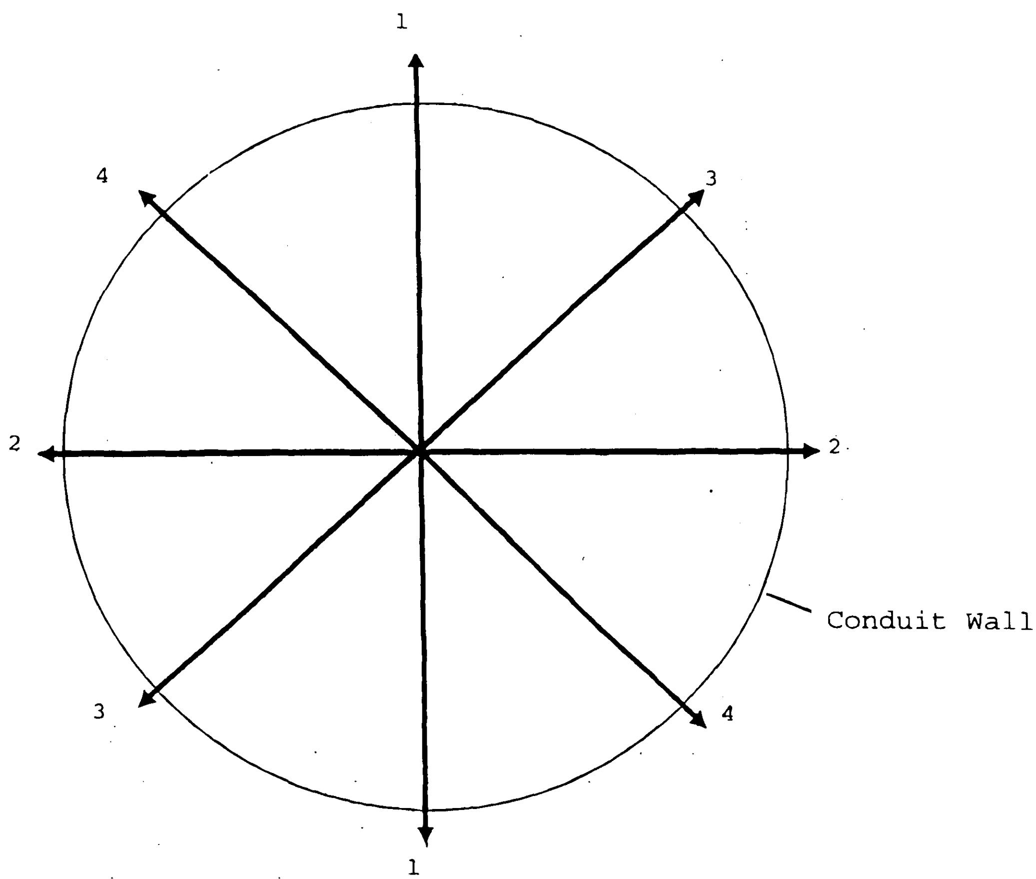

FIGURE 9 Orientation scheme for measurement of deformations in diameter of the conduit (looking downstream).

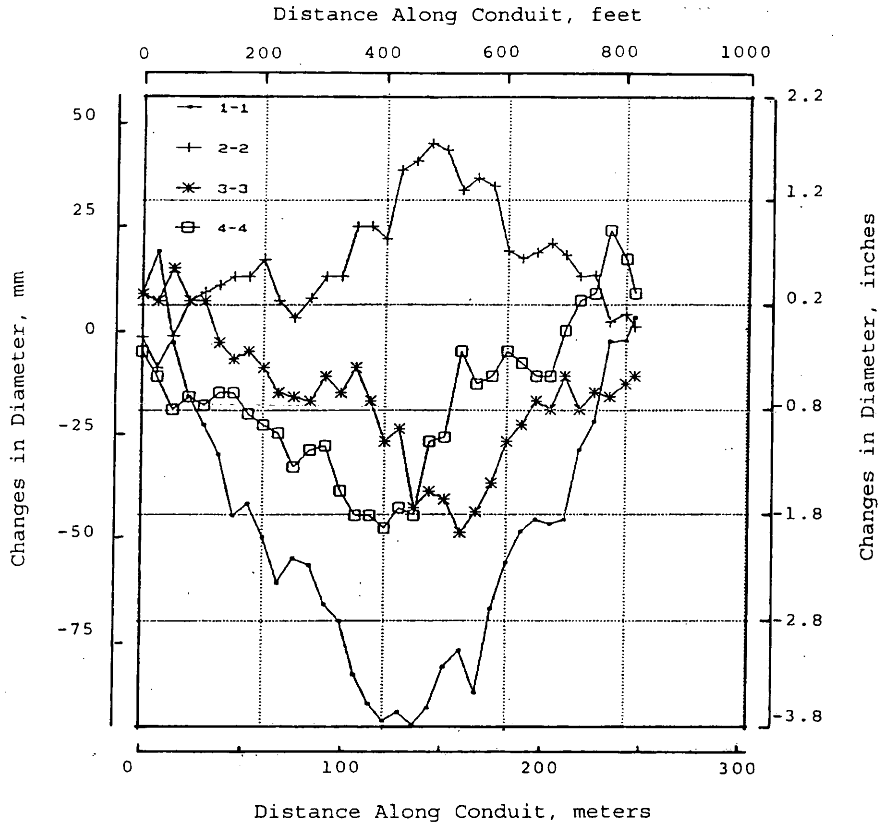

FIGURE 10 Accumulated changes in diameter of conduit 3 months after the fill was completed.

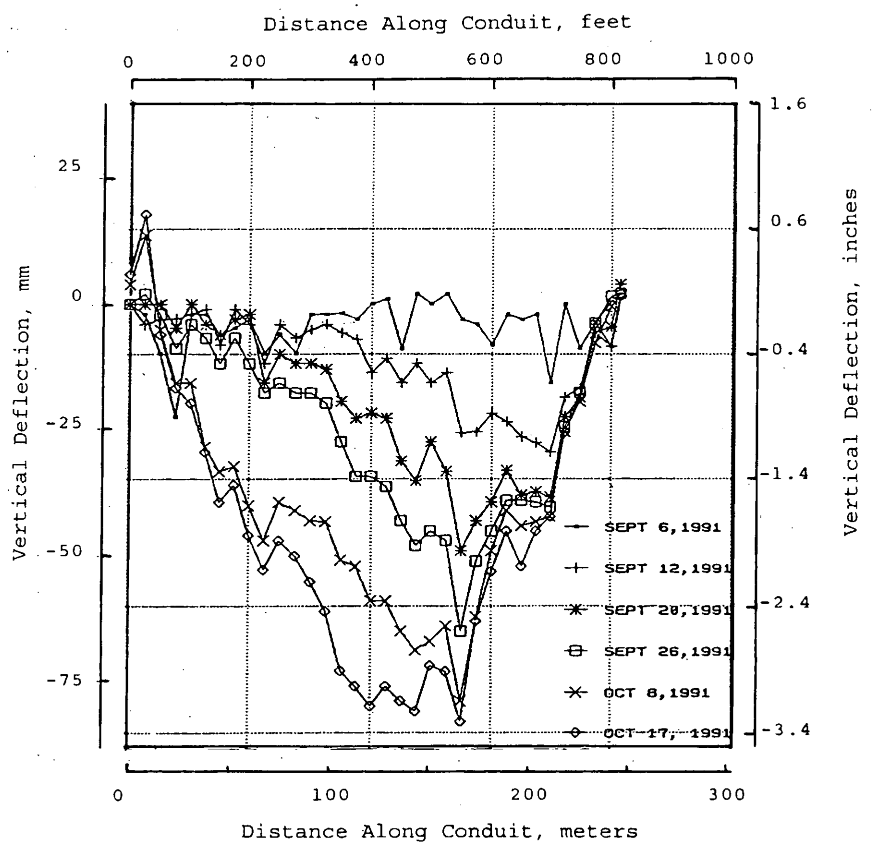

FIGURE 11 Variation in crown movement along entire length of conduit at different stages of fill placement.

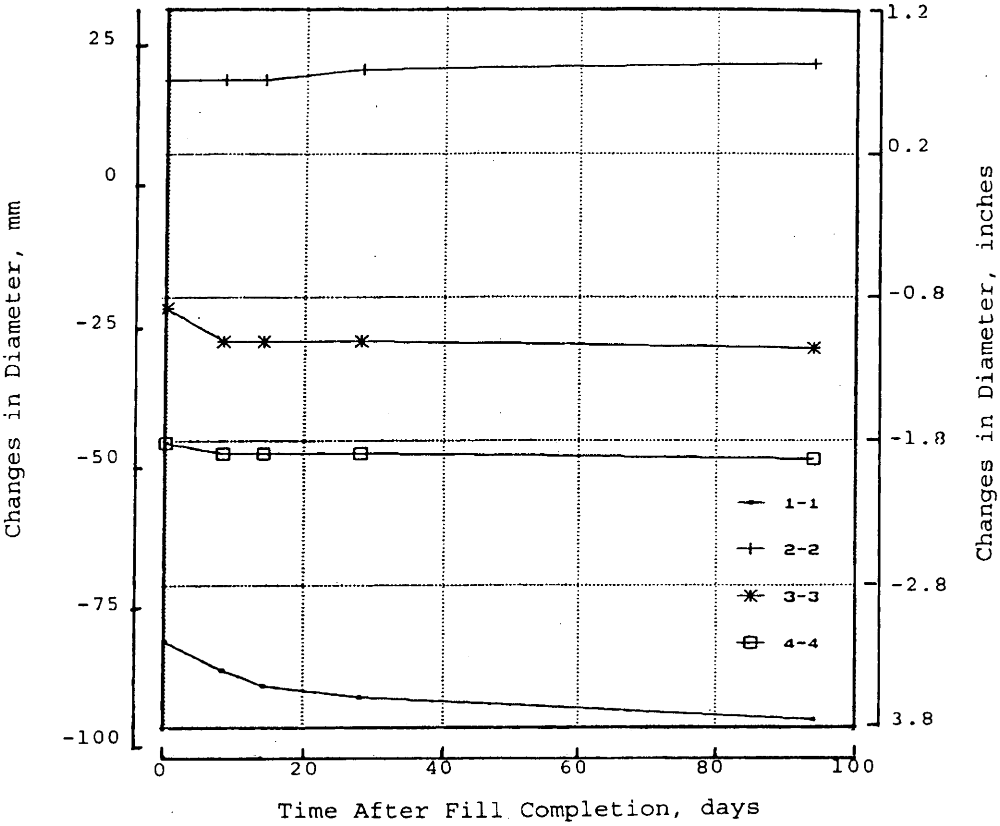

FIGURE 12 **Long-term deformation of conduit measured at midlength (124 m into the conduit).**

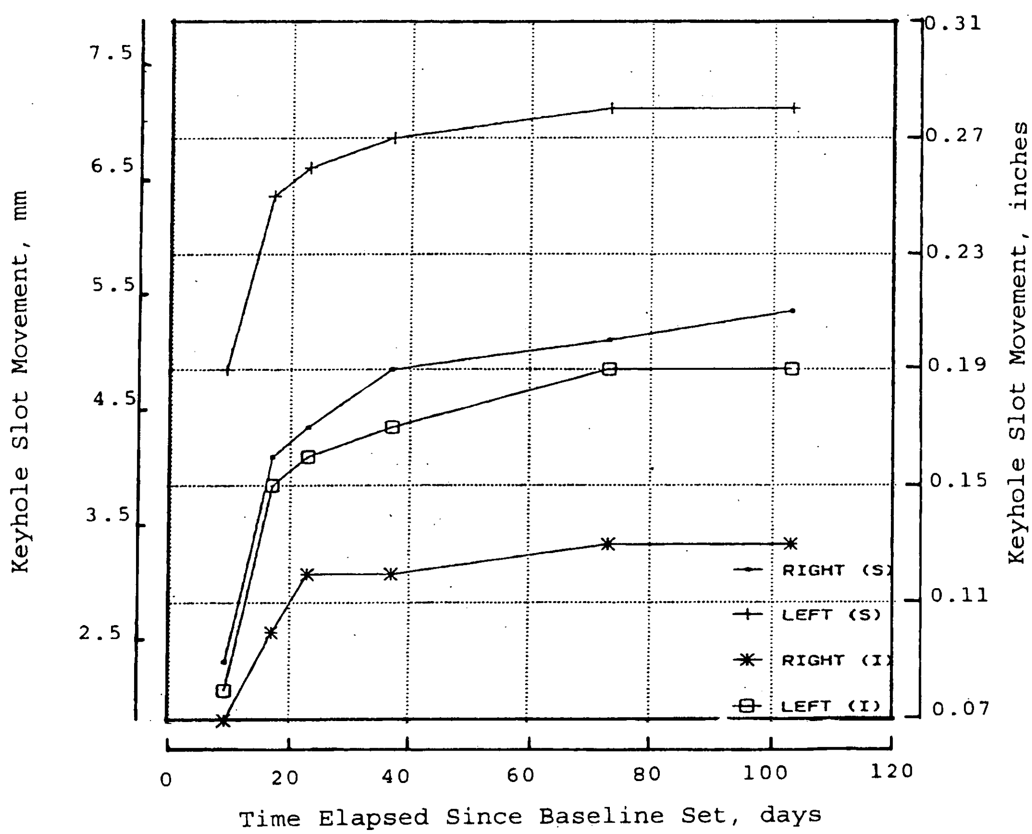

FIGURE 13 **Keyhole slot movements at right and left walls of conduit at midlength (both springline (S) and invert (I)).**

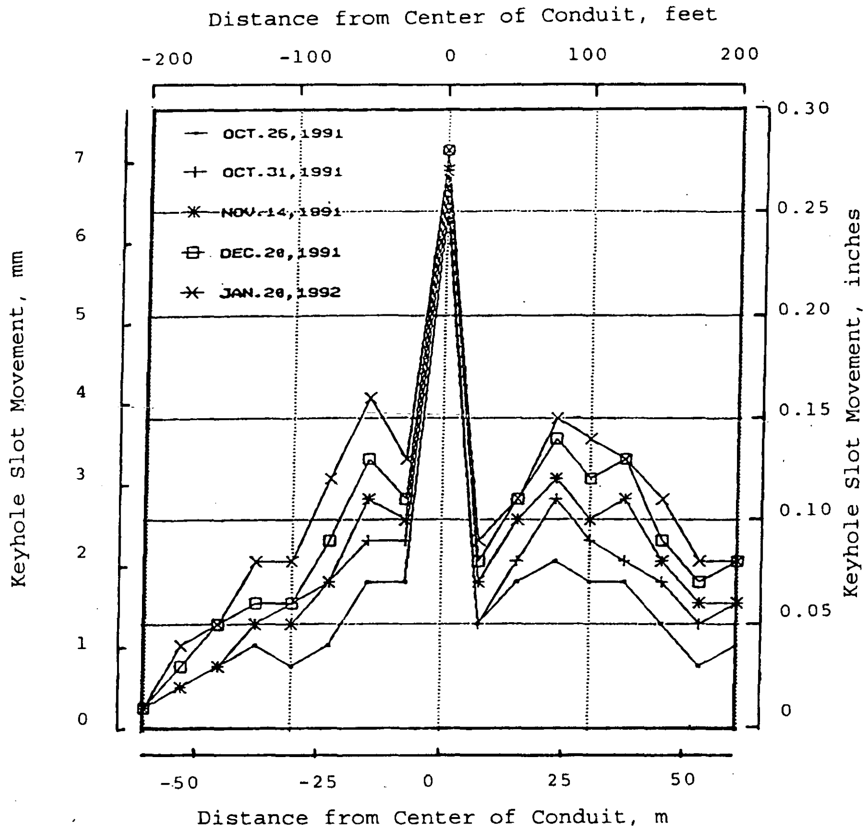

FIGURE 14 **Keyhole slot movement of springline along left side of conduit (looking downstream) over time.**

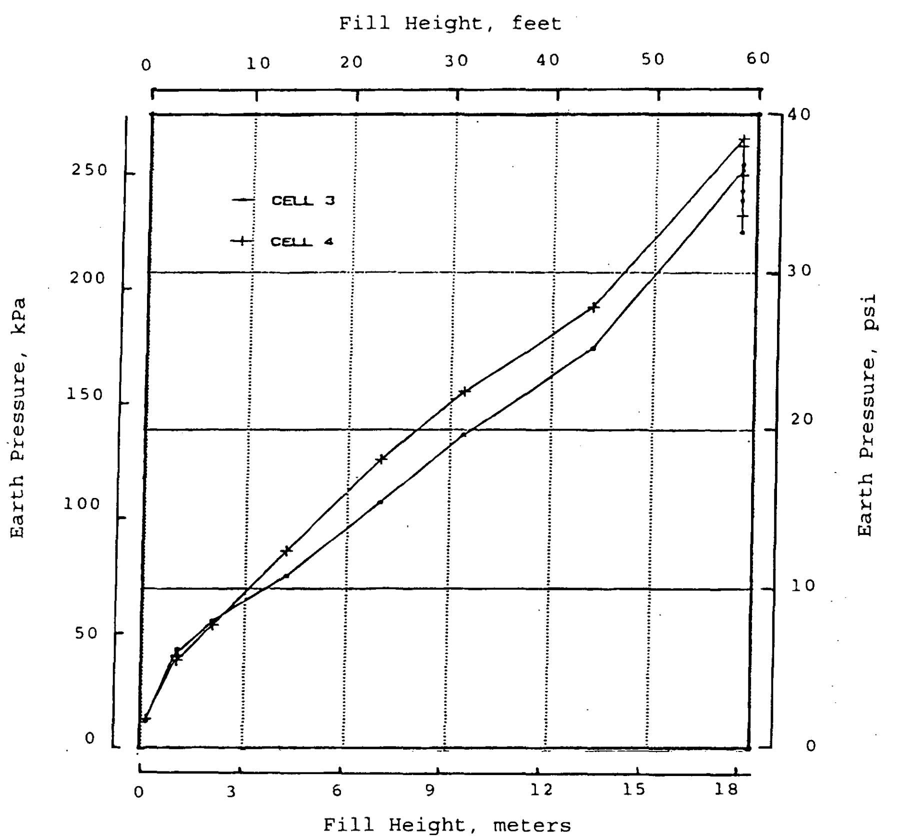

FIGURE 15 **Comparison of earth pressure readings for Cells 3 and 4 with increasing fill height.**

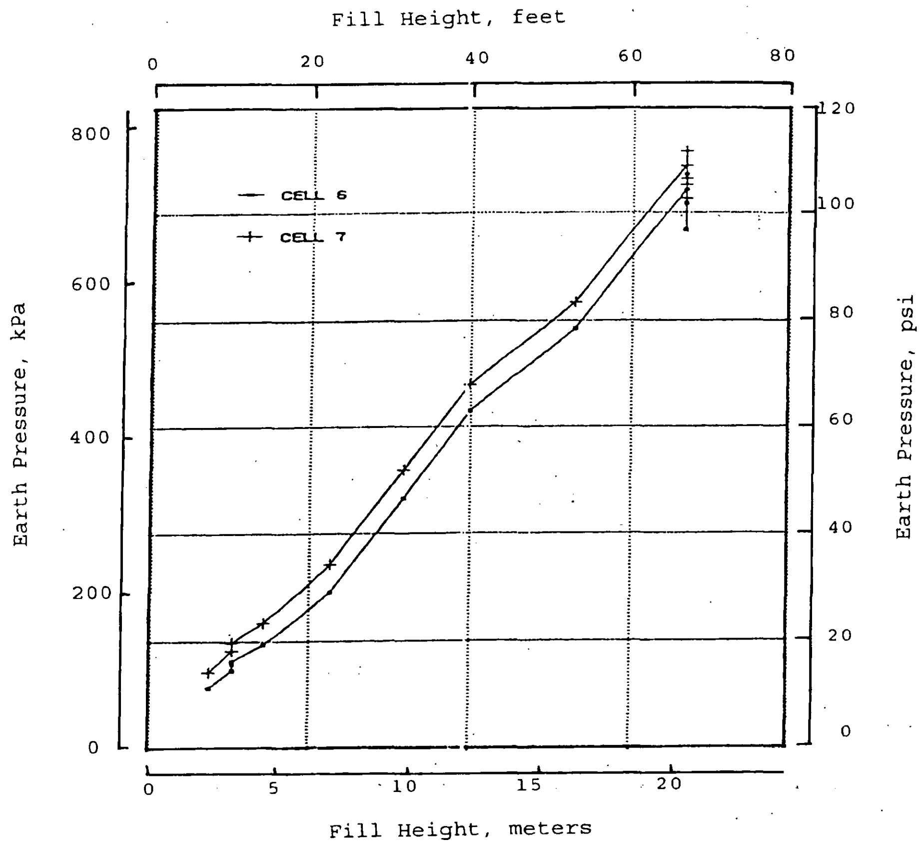

FIGURE 16 Comparison of earth pressure readings for Cells 6 and 7 with increasing fill height.

increases. As the backfill is placed on top of the structure, the magnitude of the movement decreases. Eventually, with a sufficient depth of cover over the structure, the movements reverse so that the crown of the structure flexes downward, and the conduit flexes outward at the springline.

The maximum movement during fill construction on the monitored conduit was at the crown, which moved inward about 96 mm (3.78 in.); this is just about the allowable crown deflection of 2 to 3 percent of the span considered in culvert design. The maximum elongation was 44.5 mm (1.75 in.). Fill placement sequence and compaction pressures had a significant impact on deformation. Both the quarter point measurements reflected inward flexing. As the conduit was founded on rock (with shallow sand bedding), settlement of the conduit from fill placement was considered minimal and not taken into consideration. No significant changes from temperature variations were found.

The measured lateral soil pressure near the conduit wall was within 25 percent of the overburden stress at the end of construction. The lateral stress near-field (within one pipe diameter of the conduit wall) was not too different from the far-field pressure. This could be from lateral compression of the soil near-field as the conduit elongated in the horizontal direction.

The vertical soil pressure in the structural backfill at the springline was in excess of the overburden stress at the end of construction just as found by Selig et al. (*2*). This increase is believed to be caused by load transfer from the more compressible embankment soil. Although both the vertical and horizontal soil pressures at the springline are greater than the free-field stresses, the ratio of the horizontal to vertical stress at the end of construction was about 0.40.

Positive soil arching at the crown was demonstrated. The measured vertical soil pressure at the crown at midlength was less than 60 percent of the overburden pressure at that elevation, but at free-field distance the vertical soil pressure was very comparable to the overburden pressure.

Long-term observations have indicated a slight decrease in recorded earth pressures. Decrease in cell pressures has not been significant. Conduit deformations have shown little change after 90 days following completion of the fill.

Keyhole slip at the springline of 8.1 mm (0.32 in.) was measured. Slip at the springline was higher than that at the invert. Most of the slip occurred within 15 days of fill completion. Long-term slip measurements have revealed a decrease in movement between the plates. Slippage could be responsible for larger crown flattening and hence increased positive arching over the crown. Load transfer (arching) caused by the slotted joint slip makes deeper burial of the conduit possible.

ACKNOWLEDGMENTS

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