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ABSTRACT This paper describes field measurements and analysis carried out on the Elkhart Creek soil arch culvert structure in British Columbia, Canada. The structure has a span of 13.4 m, a rise of 7.3 m, and a soil cover of 9.6 m. The original structure collapsed during backfilling in October 1987. A new structure of the same design was built in the Fall of 1989, and because of controversy regarding the design thrust value, it was instrumented to measure thrust, moment, and displacements in the arch. Displacements and stresses in the soil were also measured. The measured thrust values were much lower than expected and indicated that significant positive soil-arching occurred. A nonlinear finite element analysis of the soil-structure system was carried out simulating the construction procedures used, and the computed response compared with the measurements. The computed and observed responses were in reasonable agreement in terms of thrust, moment, displacements and soil stresses provided an allowance was made for slip at the bolted connections.

INTRODUCTION

The Elkhart Creek soil-arch structure is a long-span high cover culvert located on the Okanagan Connector in the interior of British Columbia, Canada. The original culvert collapsed during construction in October 1987 when the soil cover was about 1 m above the crown.

A new structure of identical design and using some of the original steel plates and the same foundations was constructed during the period August 1 to October 5, 1989. Because of a concern regarding the magnitude of the thrust in the metal arch under such a high backfill, the structure was instrumented with 3 "rings" of strain gauges to measure the thrust. Displacements of the arch were also monitored. In addition, load cells and displacement transducers were placed in the soil fill to help obtain a better understanding of the interaction between the soil and the metal arch during construction.

This paper describes these measurements. In addition, a stress and deformation analysis of the structure was carried out using finite elements to model the soil, and structural beam-column members to model the metal culvert. This analysis allows the simulation of the construction procedure as well as the nonlinearities of both the soil and structural elements. In a previous paper, (Byrne et al., 1993), the thrust and the displacement aspects of the problem were examined. Herein, emphasis is placed on the bending moments in the metal culvert. The predictions from the analysis are compared with the field measurements.

DESCRIPTION OF THE CULVERT

A cross-section of the soil-arch metal culvert is shown in Fig. 1. The culvert has a span of 13.4 m, a rise of 7.3 m above the foundation level, and a soil cover of 9.6 m as shown in the figure. The concrete foundations for the arch are founded on rock or very stiff soil. The structure forms an underpass beneath the 4 lane Okanagan Connector Highway with a channel to carry a small stream and a path to allow passage of animals beneath the highway (Fig. 2). The axis of the structure is perpendicular to the highway and the structure has a length of 78 m.

The original structure which failed during construction in 1987 was dismantled and the metal arch rebuilt in August 1989 to the same design and located on the same foundations. The arch comprises 7 mm (0.276") corrugated steel plate with the properties shown in Table I.

TABLE I. Properties of Steel Plate Used

Plate Thickness (mm)	Area (mm^2/mm)	Moment of Inertia (mm^4/mm)	Section Modulus (mm^3/mm)
7.0	8.712	2675.11	92.56

Rib stiffeners were attached to the upper part of the arch extending from the concrete buttress or thrust beam

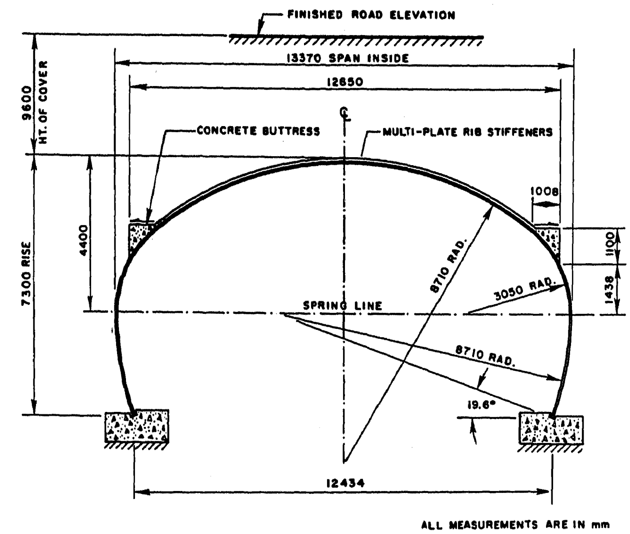

Fig. 1. Culvert cross-section.

and over the crown as shown on Fig. 1. These ribs comprised 0.61 m wide strips of the same 7 mm corrugated plate bolted to the arch and located at 3 m spacing.

The backfill comprised of natural sand and gravel compacted to between 95% and 100% of standard Proctor density. The material at this density had a unit weight of 22.7 kN/m^3 (144 lbs/ft^3). A loose uncompacted cushion of sand was placed above the crown with an approximate unit weight of 16 kN/m^3 (102 lbs/ft^3).

The construction sequence was as follows:

1) The arch was bolted together in place with the bolts tightened to a torque in the range 200 to 340 N.m (150 to 250 lbs.ft.).
2) Granular backfill was placed on either side and compacted. The difference in level from side to side was restricted to less than 0.3 m (1 ft.).
3) When the level of backfill reached the elevation of the concrete thrust beams, these were cast.
4) The sand cushion comprising 1.0 m of loose uncompacted sand was then placed over the crown.
5) Backfilling from either side was then continued until the backfill over the crown reached a height of 2 m. During this stage, great care was taken to insure that heavy equipment did not get too close to the metal arch.
6) Once the backfill exceeded a height of 2 m above the crown, heavy equipment was allowed to cross the crown and backfilling continued until the full 9.6 m height of backfill above the crown was achieved.

INSTRUMENTATION AND MEASUREMENT

The instrumentation comprised of:

1) Strain gauges on the metal culvert allowing axial and bending strains to be measured;
2) Reference points on the culvert and a fixed reference point on the floor allowing the absolute displacements of the culvert to be measured;
3) Earth pressure cells allowing the total stress in the soil to be measured; and

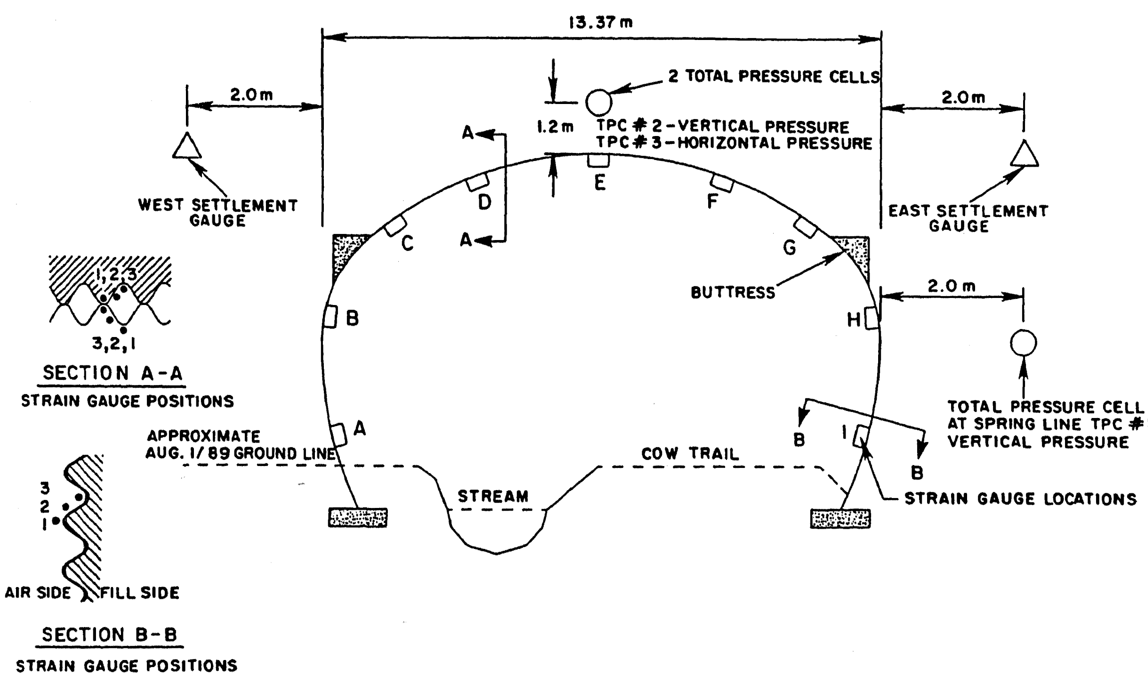

Fig. 2. Instrumentation.

4) Displacement gauges in the soil.

Strain Gauges

Three "rings" of strain gauges comprising a total of 96 gauges in all were used. Each "ring" of gauges was located on a cross-section and comprised of 9 measurement points (A to I) located around the arch as shown in Fig. 2. Each measurement point comprised of 3 strain gauges. One in the hollow of the corrugation, one on the hump and one in between at the neutral axis of the section as shown in Fig. 2. A "ring" of strain gauges therefore comprised of 9(3) = 27 gauges and the 3 rings comprised of 81 gauges. An additional 15 gauges were placed on a rib section. The 3 rings were located near the centre of the culvert approximately 4.6 m apart and are referred to as the north (N), centre (C), and south (S) rings. The centre ring contained the rib section.

The strains measured by the 3 strain gauges show a linear variation with the depth of the corrugation indicating plane sections remain plane. The bending moment was computed from the strain profile knowing the Young's modulus, E, and the section modulus. The axial strain at any location was taken as the average of the 3 strains. The thrust was computed from the axial strain knowing E and the cross-sectional area.

The measured axial strains at the 3 sections at the end of backfill are shown in Fig. 3. The strains measured at the centre ring which contained the rib section are similar to those measured at the north and the south rings. This implies that the stresses are essentially the same in the ribbed and the non-ribbed sections, but that the ribbed sections will have higher load because their effective area is higher.

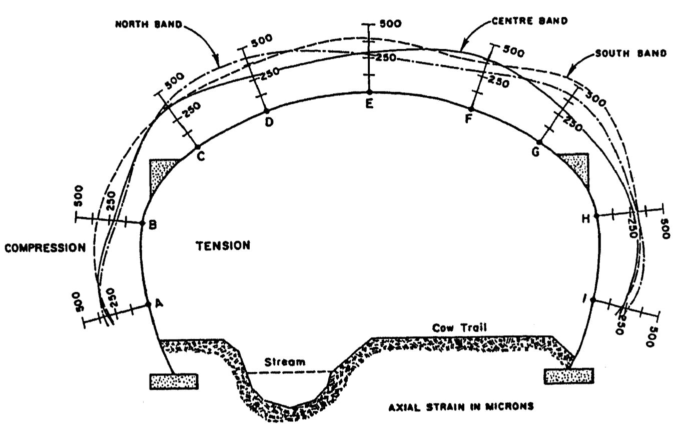

Fig. 3. Measured axial strains in metal arch.

The maximum axial strain is 506 Microns compared with a yield strain for the steel of 1138 Microns. The measured strain implies a maximum axial stress at the centroid of the section of 101 MPa and compares with a yield stress of 227.5 MPa. The axial stress is considerably lower than computed by formulae suggested by Duncan (1977) which gave a value of 272 MPa. This is in excess of the yield stress. His formulae imply negative arching. However, even without arching the axial stress in the culvert from the weight of the overlying soil would be 193 MPa. This value is still almost twice the measured value and implies that significant positive arching occurred.

The low values of the measured axial strains are also in agreement with those measured at the Vieux Comptoir soil-arch structure in Quebec in 1975 (Lefebvre et al., 1975). The structure is very similar in size and shape to the Elkhart Creek structure and the maximum measured axial strains there were also about 500 Microns.

The average axial strain at the crown as a function of height of backfill above the foundation is shown in Fig. 4. It may be seen that the axial strains build up rapidly

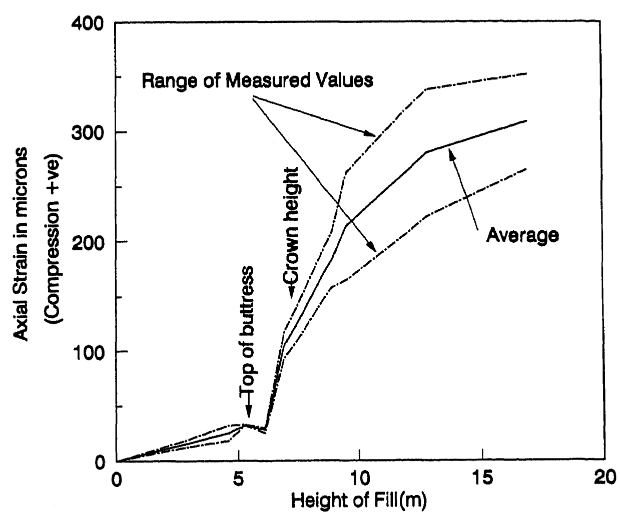

Fig. 4. Axial strain at the crown vs. height of fill.

as the fill height is increased from about 6 m to 13 m, and more slowly thereafter. The reason for the break in the buildup of axial strain or arch thrust with fill height will be discussed later in some detail, and an explanation for the low final thrust values will be offered.

The measured bending moment distribution along the culvert when the fill height is at the level of the thrust beam (fill height = 6 m) is shown in Fig. 5, and the moment at the crown as a function of fill height is shown in Fig. 6. It may be seen from Fig. 6 that the positive or hogging moment at the crown increases with fill until the fill reaches a height of 6 m corresponding to the level of the thrust beams. This is as expected as the side fill pressure causes the crown to rise. At this point the sand cushion was placed over the crown causing the crown to move down (as shown in Fig. 6) with a resulting sharp reduction in moment. Fill was then placed above the sides causing the crown to move up again with a resulting sharp increase in moment. Further placement of fill caused a slight reduction in moment.

Culvert Displacements

Displacements of the metal culvert during construction were observed by measuring the change in distance

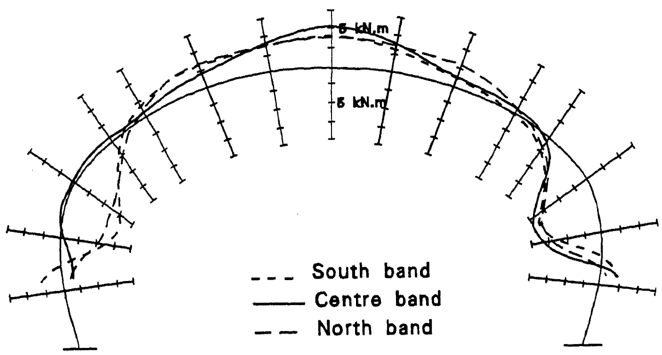

Fig. 5. Bending moment distribution.

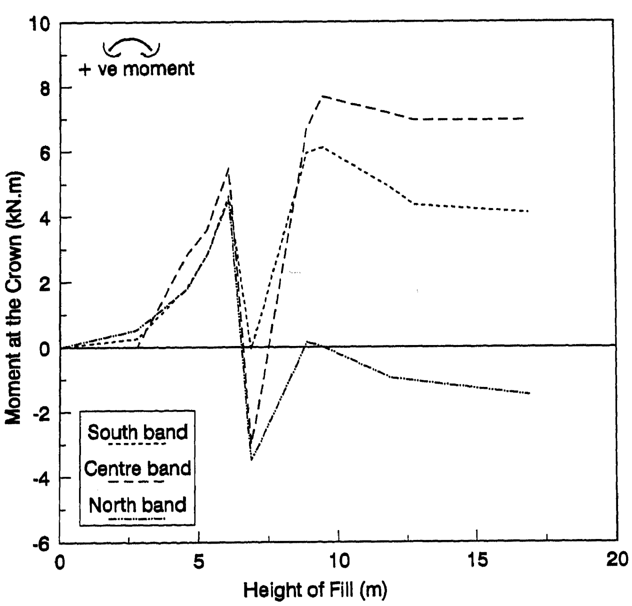

Fig. 6. Bending moment at the crown vs height of fill.

between reference points on the culvert and a fixed reference point at the base of the structure. Measurements were made at 13 cross-section locations within the culvert. The movements of the crown and spring line as functions of the height of backfill are shown in Fig. 7. It may be seen that the crown moved upwards an average of 80 mm until the cushion was placed and thereafter generally moved downwards a similar amount. The spring line point moved inwards at all stages of loading with an average maximum inward movement of about 25 mm.

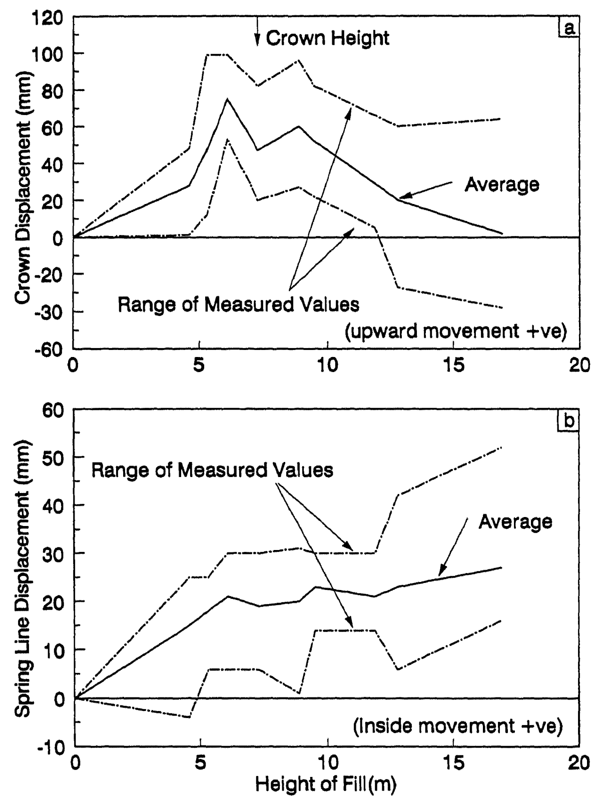

Fig. 7. Culvet displacement vs height of fill.

Earth Pressures

Earth pressure cells were located above the crown at a height of 1.2 m. Two cells were placed, one horizontally and one vertically so as to measure both the vertical and horizontal stresses. An earth pressure cell was also placed at the spring line elevation at a distance of 2 m from the culvert (Fig. 2). At this location only the vertical stress was measured.

The results are described in detail by Byrne et al (1993) and indicate that the stresses above the crown are lower than the corresponding stresses from the weight of the overlying column of soil (overburden stress), whereas adjacent to the spring line, the reverse is true. This indicates that arching is transferring the soil load from the metal arch and to the soil at the sides of the arch. This implies that the surrounding soil is stiffer in the vertical direction than is the arch and is causing positive arching.

Soil Displacements

Settlement gauges to measure the vertical displacements of the soil adjacent to the crown were installed. Each instrument comprised of two boxes filled with oil and connected by a tube. One box was placed on the crown of the metal arch while the other was placed in the soil at the level of the crown but offset 8.7 m perpendicular to the culvert as shown in Fig. 2. By monitoring the difference in oil pressure in the two boxes, the differential movement between the crown and the point in the soil is obtained. The absolute movement of the soil is obtained by adding the absolute movement of the crown to the relative displacement obtained from the gauge.

The measurements indicate that the crown moved down 66 mm compared with the soil, indicating a positive arching situation in agreement with the findings from the strain gauges and the load cells. The absolute displacements indicate that the maximum downward movement of the soil at the offset point was about 10 mm.

ANALYSIS AND PREDICTIONS

Method of Analysis

Analyses of the soil-structure system were carried out using the computer program NLSSIP (Byrne and Duncan (1979)). This is a nonlinear elastic program in which the soil is modelled by finite elements and the metal culvert by beam-column members. The program allows the simulation of the construction procedure in which the soil is placed in layers adjacent to and above the structure.

The nonlinear aspects of the soil are incorporated by considering it to be incremental elastic and isotropic having two elastic parameters: a tangent Young's modulus, E, and a tangent bulk modulus, B, both of which depend on the current stress conditions and change at each step of loading.

Details of the parameters used are described by Byrne et al. (1993) and Duncan et al. (1980).

Modelling of the Soil-Structure System

The finite element and structural modelling of the soil-structure system is shown in Fig. 8. Only half of the system was modelled as the geometry and loading are essentially symmetric. The arch structure was modelled by 8 beam-column members and the soil by 162 finite elements placed in 18 layers.

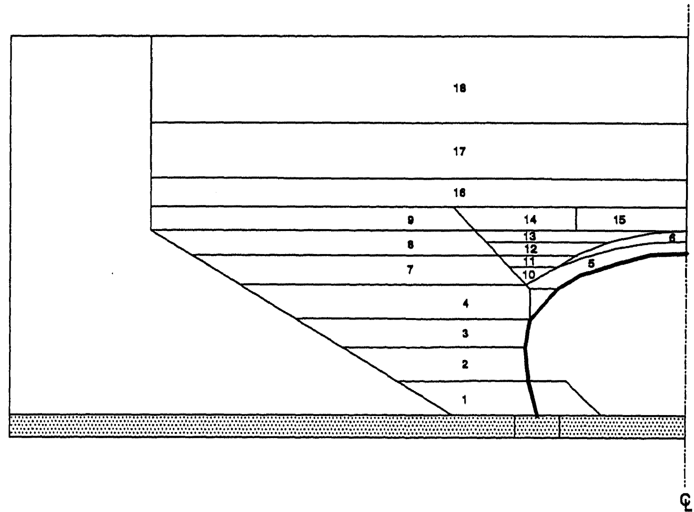

Fig. 8. Finite element modelling of arch and soil.

The concrete foundation strip was also modelled by finite elements. The properties used for the various soils are listed in Table II. These are based on laboratory and field experience with similar soils from Duncan et al. (1980) and Byrne et al. (1987).

TABLE II. Soil Properties Used.

*Soil Type	γ	K_E	n	K_B	m	K_o	ϕ	$\Delta\phi$
1	22.7	600	0.5	360	0.25	0.5	36	2
2	22.7	2000	0.5	1000	0.25	0.5	41	4
3	16	200	0.5	120	0.25	0.5	33	0
4	24	$2x10^5$	0.5	$1.2x10^5$	0.25	0.5	40	0

*(1) pre-existing; (2) backfill; (3) cushion; (4) foundation

The properties used for the beam elements are listed in Table III.

TABLE III. Properties of the Beam Members.

Elements	Without Ribs	With Rib Stiffeners
E_s (kPa)	2 (10^8)	2 (10^8)
I (m^4/m)	2.675 (10^{-6})	3.799 (10^{-6})
A (m^2/m)	8.712 (10^{-3})	10.45 (10^{-3})
α	0.0067	0.0067
β	1.0	1.0
P_y (kN)	1982	2378
M_y (kN.m)	23.9	34.03
M_p (kN.m)	37.7	53.68

The ribs comprised of 0.61 m wide strips of the same corrugated plate bolted to the arch at 3 m spacing. The equivalent properties of the stiffened sections were determined by computing the combined properties for a 3 m length and then dividing by 3.

Axial Thrust

The predicted axial stress in the arch at the level of the crown as a function of the height of fill above the footing level is shown as the solid square symbols in Fig. 9.

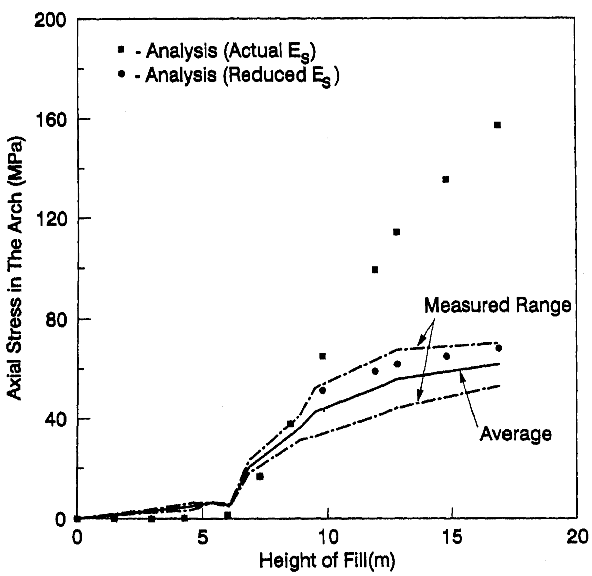

Fig. 9. Axial stress in the arch at the crown vs height of fill.

Also shown on this figure are the measured range of axial stress values together with the average values. As the fill height increases the measured and predicted axial stresses are in reasonable agreement. However, when the fill height exceeds about 10 m above the footing (3m above the crown), further increase in measured stress is small, while the predicted stress continues to increase significantly.

This mismatch between the observed and computed response prompted considerable re-examination of the assumptions regarding the modelling procedure and model values outlined in the previous section and this is discussed in detail by Byrne et al. (1993) and described briefly herein.

A close examination of the measured displacements indicates that the culvert wall shortened significantly during backfilling. Figure 7 showed that filling above the crown caused the crown to come down by about 80 mm while the spring line essentially did not move horizontally. To undergo such a geometry change, the arch must have shortened by about 56 mm.

The shortening of the arch due to the measured strain in the culvert wall is about 1 mm, a very small fraction of the total shortening. A possible explanation is that the remaining 55 mm of shortening took place due to slippage at the bolted connections.

The metal plates of the culvert were bolted together with 19 mm (3/4") diameter bolts inserted in 24 mm (15/16") holes. A section of the arch comprises 16 lines of holes (including the bolts to the foundation bracket). If it is assumed that the plate holes were initially lined up and that the bolt were centered in the hole, then the amount of relative slip that could later take place between the plates is the difference in diameter between the bolt and the hole, namely 5 mm (3/16"). Since there are 16 such locations of possible slip the total amount of arch shortening that could occur due to slippage is 76 mm (3").

Recent laboratory tests carried out for Armtec at McMaster University on a 7 mm bolted connection torqued to field specifications, indicated that slip occurred at an axial stress of 25 MPa with about 5 mm of slippage occurring as the load was increased. Figure 9 indicates a sharp break in the measurements at an axial stress of about 20 MPa. 55 mm of arch shortening arising from slip at the bolted connections is therefore plausible.

Slip at the bolted connections can greatly reduce the effective stiffness of the arch. This was accounted for in the analysis by reducing the axial stiffness of the structural members, while maintaining their bending stiffness. A reduction in stiffness by a factor of 50 was necessary to predict results in reasonable agreement with the measurements as shown by solid circles in Fig. 9. The predicted shortening of the arch due to the reduce stiffness was 50 mm which is in reasonable agreement with the estimated 56 mm from the field measurements.

The measured and computed axial stress distributions in the metal arch are shown in Fig. 10 and are seen to be in close agreement. The computed values shown include a reduction factor of 50 in metal arch stiffness to allow for slippage when the fill height exceeds 3 m above the crown. Without such a reduction the computed values are about 2.5 times higher, which is in close agreement with the prediction from Duncan's equations discussed earlier.

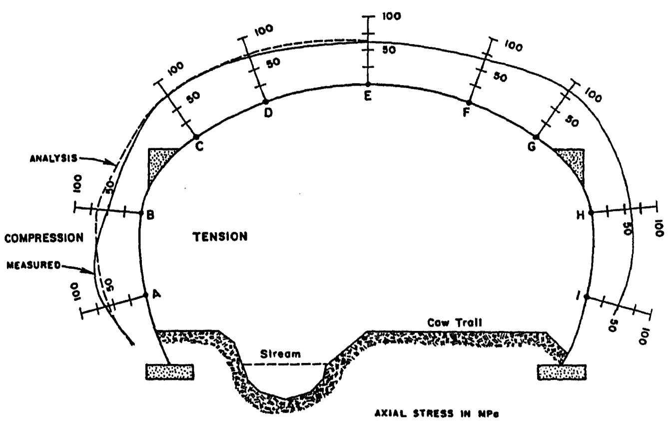

Fig. 10. Predicted and measured axial stress distribution in the arch.

Crown Displacements

The predicted and measured displacements of the crown are shown in Fig. 11. It may be seen that the predictions and measurements are generally in reasonable agreement. The crown first moves up as the side fill is placed, then as backfill is placed above the crown it moves down again. It was found that the predicted displacements just prior to the side fill reaching the thrust block level were very sensitive to the soil parameters chosen. This indicates that great care must be taken to monitor and control displacements during the placement of side fill.

Moments

It was found that the predicted moments were very sensitive to details of the backfilling. The backfilling detail outlined by Byrne et al. (1993) and based on the construction drawings was found not to give the correct pattern of crown moment with fill height. On discussion with the contractor it was discovered that the filling was not as prescribed. While this detail had a significant effect on moments, it had very little effect on predicted thrust.

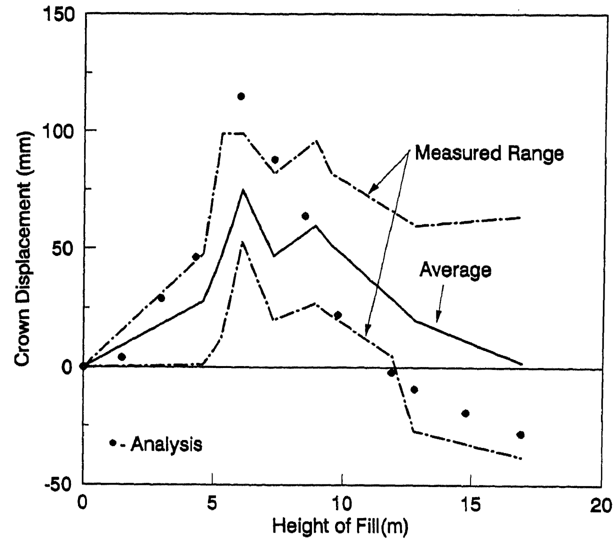

Fig. 11. Measured and predicted culvert displacements at the crown vs height of fill.

The predicted and measured moments at the crown are compared in Fig. 12. It is instructive to first examine the

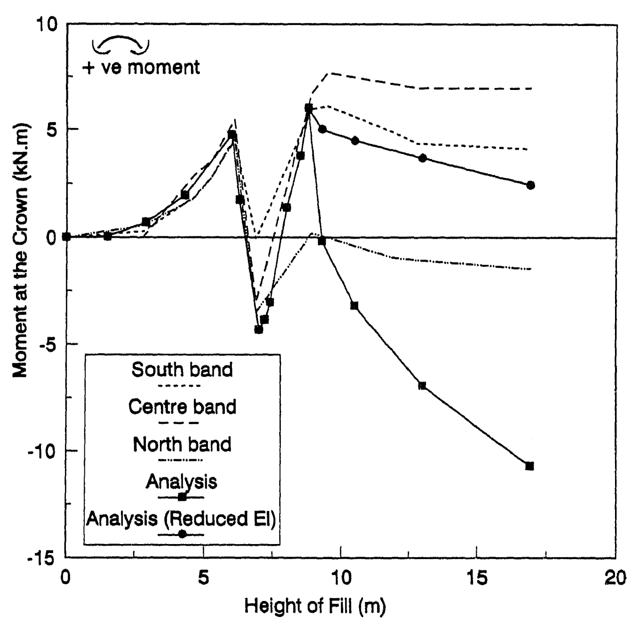

Fig. 12. Measured and predicted moments at the crown vs height of fill.

development of measured moment with fill placement. The actual field fill placement simulation was shown in Fig. 8, and the measured moments are very closely tied to the details of this placement. The moment increases as backfill is placed up to the level of the thrust beam. The cushion is then placed (layers 5 and 6) causing the moment to decrease from about 5 kN.m hogging to about 3.5 kN.m sagging.

Fill was then placed on the sides, away from the steel arch, to a height of about 2 m above the crown (layers 7, 8 and 9). The region in between the cushion and the sidefill was then placed gradually (layers 10, 11, 12, 13 and 14). During this phase of backfilling, the crown moment increased again to about 7 kNm hogging (except in north band). The remaining backfill was completed with horizontal layers covering the whole area. The measured moments in the culvert did not show any appreciable changes during this last phase of filling.

Comparing the predicted and measured moments at the crown (Fig. 12), it can be seen that the predicted moments at the crown are in very good agreement with the measured values up to the filling corresponds to layer 14. After that, the measured moments remain more or less constant, while the predicted moment shows a steady decrease. It should be noted that at this stage, the measured axial thrust also did not show much increase because of the slip at the joints. This slip has been modelled by reducing the axial stiffness of the arch. The flexural stiffness was kept constant since sliding at the joints was not considered to induce a rotary slip.

The measured moments suggest that the flexural stiffness of the arch also reduced. The low axial thrust is due to sliding at the joints which was clearly reflected in the measured displacements in the culvert, and observed in laboratory tests on joints. However, we can offer no substantiated explanation for the apparent reduction in flexural stiffness. Perhaps combined compression-moment tests on joints would show a reduction in flexural stiffness as sliding occurred.

Analyses were also carried out with a lower flexural stiffness (reduced by a factor of 10) and the results are shown in Fig. 12. The moment at the crown now agree very well with the measurements.

The predicted and measured moments along the culvert after the cushion is placed are shown in Fig. 13, and are in good agreement. The measured and predicted moments along the culvert at the end of backfilling are shown in Fig. 14. The results from the analysis with constant flexural stiffness are not in agreement with the measurements, while those with reduced flexural stiffness are in reasonable agreement.

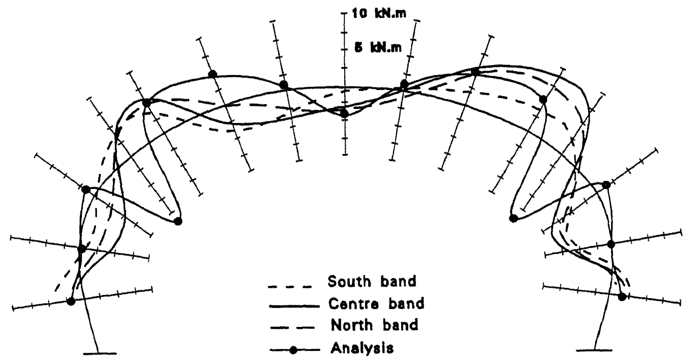

Fig. 13. Measured and predicted moments along the culvert after placement of cushion.

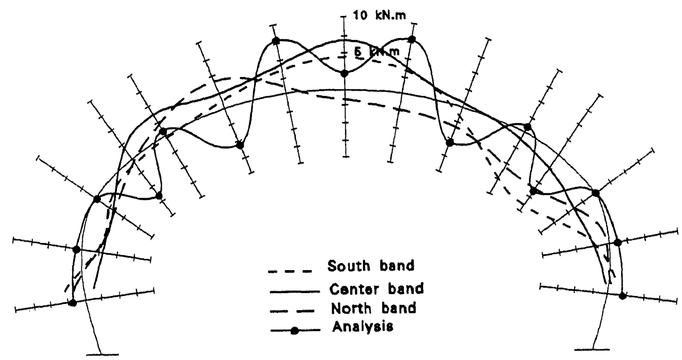

Fig. 14. Measured and predicted moments along the culvert at end of backfilling.

SUMMARY AND CONCLUSIONS

The long-span, high-cover arch culvert at Elkhart Creek in British Columbia, Canada, was instrumented with 3 rings of strain gauges, load cells, and differential movement gauges. In addition, movements of the arch were recorded during and after construction.

The measurements indicate that the axial stress in the arch was much lower than expected from the weight of the overlying soil. The measured low stresses in the soil above the crown, and high stress values outside the arch and adjacent to the spring line indicate that positive arching in the soil was occurring shedding the load from above the arch and out into the side fills.

Finite element analyses of the soil-structure system suggests that the low measured thrust values were caused by slip at the joints when the fill was about 3 m above the crown. Recent laboratory data indicate that the joint slippage does indeed occur. Such slip resulted in a greatly reduced stiffness of the metal arch causing subsequent fill load to be transferred to the soil in "arching action", so that little further increase in axial stress in the metal arch occurred. Joint slippage was also found to significantly reduce bending moments. The predicted moments were greatly influenced by details of the backfill placement procedure.

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