Live-Load Response of a Soil-Steel Structure with a Relieving Slab

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ABSTRACT

Data obtained from the field testing of a soil-steel structure with a horizontal elliptical conduit and a reinforced-concrete relieving slab at the embankment level are compared with test data from another similar structure that did not have the relieving slab. The comparison confirmed that the relieving slab does cause a considerable reduction in live-load thrusts and moments in the metallic shell of the structure. A simplified procedure is given to account for the presence of the relieving slab.

The term "soil-steel" is used here for a bridge or a culvert composed of a corrugated steel plate shell embedded in an envelope of engineered soil, and the term "relieving slab" refers to a reinforced-concrete slab provided above the conduit. The purpose of the slab is to reduce live-load effects in the metallic shell of structures with shallow depths of cover.

As reported elsewhere (1), live-load effects in the metallic shell of a soil-steel structure with shallow depths of cover can be substantial as compared with the total load effects. Therefore, it is understandable that efforts are made to reduce these load effects when the depth of cover is limited. Some rudimentary analytical work has been done to account for the reduction in the live-load effects that results from use of a relieving slab. However, the literature appeared to lack test data in this respect. A soil-steel structure with a relieving slab has indeed been tested before (2), but measured responses did not include strains of the conduit wall from which thrusts and moments could be computed.

A soil-steel structure with a relieving slab was tested under vehicle loads, and the response of the structure was monitored through strain gauges on the metallic shell. Results of that test are presented in this paper together with comparisons with corresponding data from a test on a similar structure without the relieving slab.

STRUCTURE WITH RELIEVING SLAB

The structure called the McIntyre River Bridge is located in the city of Thunder Bay in northern Ontario, Canada. The conduit is horizontally elliptical with a span of 8.76 m and a rise of 4.95 m. A relieving slab 0.3 m thick is provided at the embankment level as shown in Figure 1. The slab is reinforced near the bottom face with 19-mm bars at 0.46-m centers in the direction of traffic and with 19-mm bars at 0.28-m centers in the perpendicular direction. The depth of cover under the roadway, including the relieving slab, ranges between 1.49 m and 1.69 m. The conduit wall consists of steel plates 5.54 mm thick of 152 x 51-mm profile.

The bedding consists of a sand cushion 152 mm thick on a 304-mm granular bedding. The soil envelope to within 3.05 m of the conduit consists of the granular B soil, specified by the Ontario Ministry of Transportation and Communications, compacted to a minimum of 95 percent standard Proctor density. The grain size distribution of granular B soil is given in Figure 2. The remaining backfill, as shown in Figure 3, consists of excavated granular material also compacted to a minimum of 95 percent standard Proctor density.

The structure, which is owned by the city of Thunder Bay, was designed by Westeel Roscoe Limited and is identified by the manufacturers as an elliptical K-D steel pipe. It was constructed in 1973, some 10 years before the test.

INSTRUMENTATION AND TESTING DETAILS

Live-load thrusts and moments in the conduit wall were computed from strains that were measured by means of uniaxial resistance gauges installed on the inside of the pipe. The gauges were temperature compensated. Only one section, shown in Figure 1, was instrumented. There were 11 instrumented stations around the section, as shown in Figure 4. At each station, three gauges were installed, also as shown in Figure 4, after the plate had been ground to smooth white metal. A calibrated template was used to mark the positions of the three gauges. Responses from the gauges were recorded by a computer-based data acquisition system, which has been described elsewhere (3). The crown deflection was measured by a displacement transducer.

The live loading was applied by means of two testing vehicles the weights of which can be regulated by concrete blocks. For various load levels, the blocks were so placed on the vehicle that the rear tandem axles were most heavily loaded. Dimensions and weights of the two vehicles are shown in Figure 5. Tests with vehicle 1 were carried out with three load levels. The second vehicle, however, was used with only one level of loading.

For single-vehicle tests, the vehicle traveled along four different longitudinal lines, stopping at seven stations along each line for the recording of strains. For the two-vehicle tests, the two vehicles traveled along one set of longitudinal lines, again stopping at seven stations for data recording.

MEASURED STATIC LOAD RESPONSES

Live-load thrusts and moments in conduit walls at a station were computed from measured strains at the

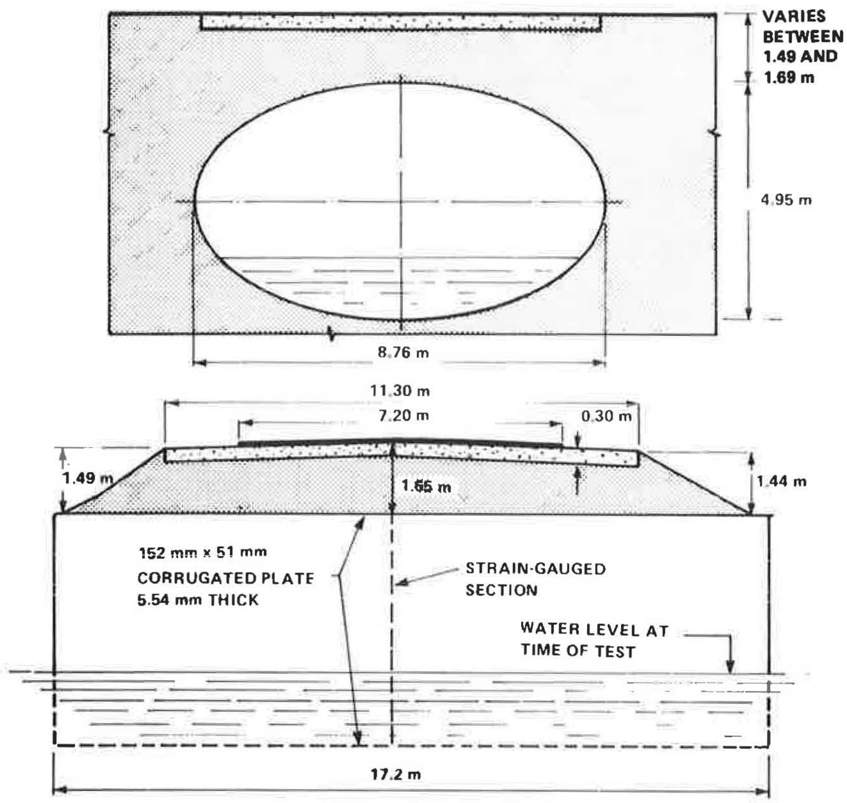

FIGURE 1 Details of McIntyre River soil-steel structure.

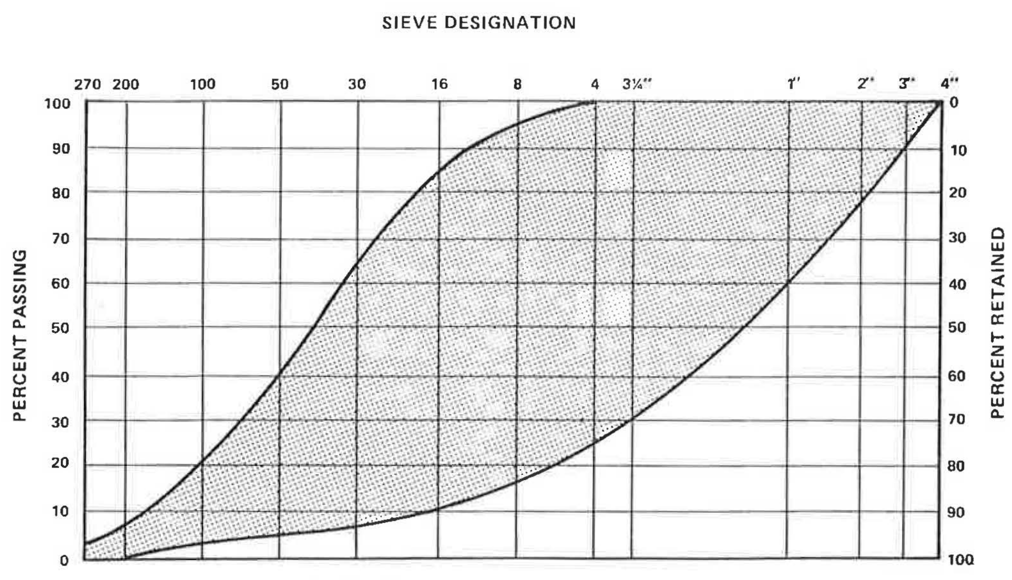

FIGURE 2 Definition of granular B soil.

crest and valley of the corrugation. The gauge at the neutral axis of the corrugation profile was used to check that the variation between the crest and valley strains was linear.

The modulus of elasticity of steel was assumed to be 2.07×10^5 MPa. The moment of inertia of the 5.54-mm-thick corrugated plate was taken to be 2980 mm^4/mm, and the cross-sectional area of the plate was 6.77 mm^2/mm.

Before and after each series of tests along a longitudinal line, readings were taken of all gauges without any load on the structure. In most cases, the two readings for a gauge did not have a difference larger than 3×10^{-6} mm/mm, which is also a measure of the accuracy of the instruments, corresponds to a thrust of 4.2 kN/m.

Thrusts

Live-load thrusts around the conduit due to a single vehicle loaded up to level 3 (see Figure 5) and traveling directly above the instrumented section are shown in Figure 6. Some thrust values were

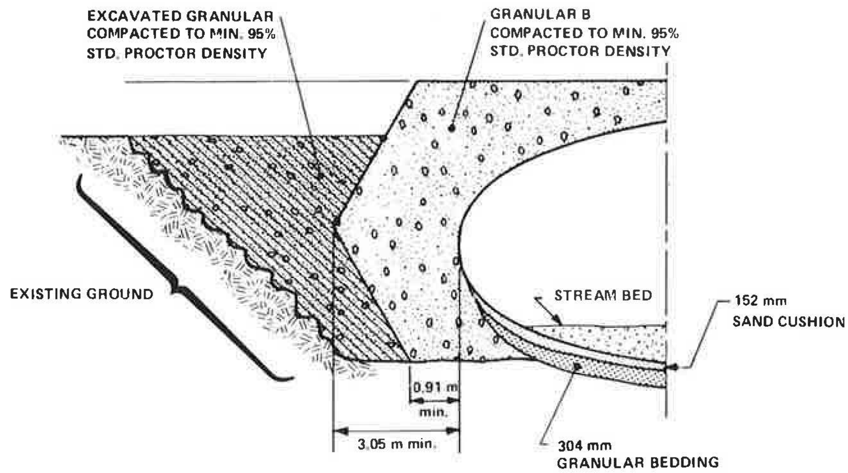

FIGURE 3 Details of backfill.

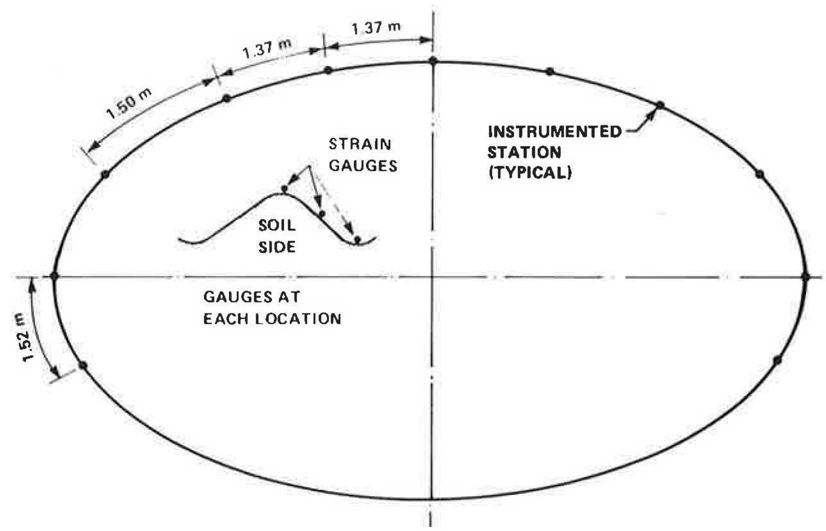

FIGURE 4 Strain-gauge locations.

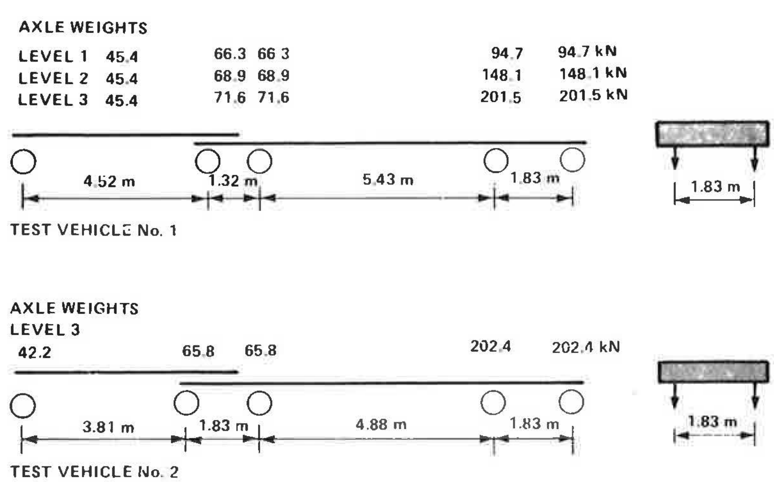

FIGURE 5 Details of test vehicles.

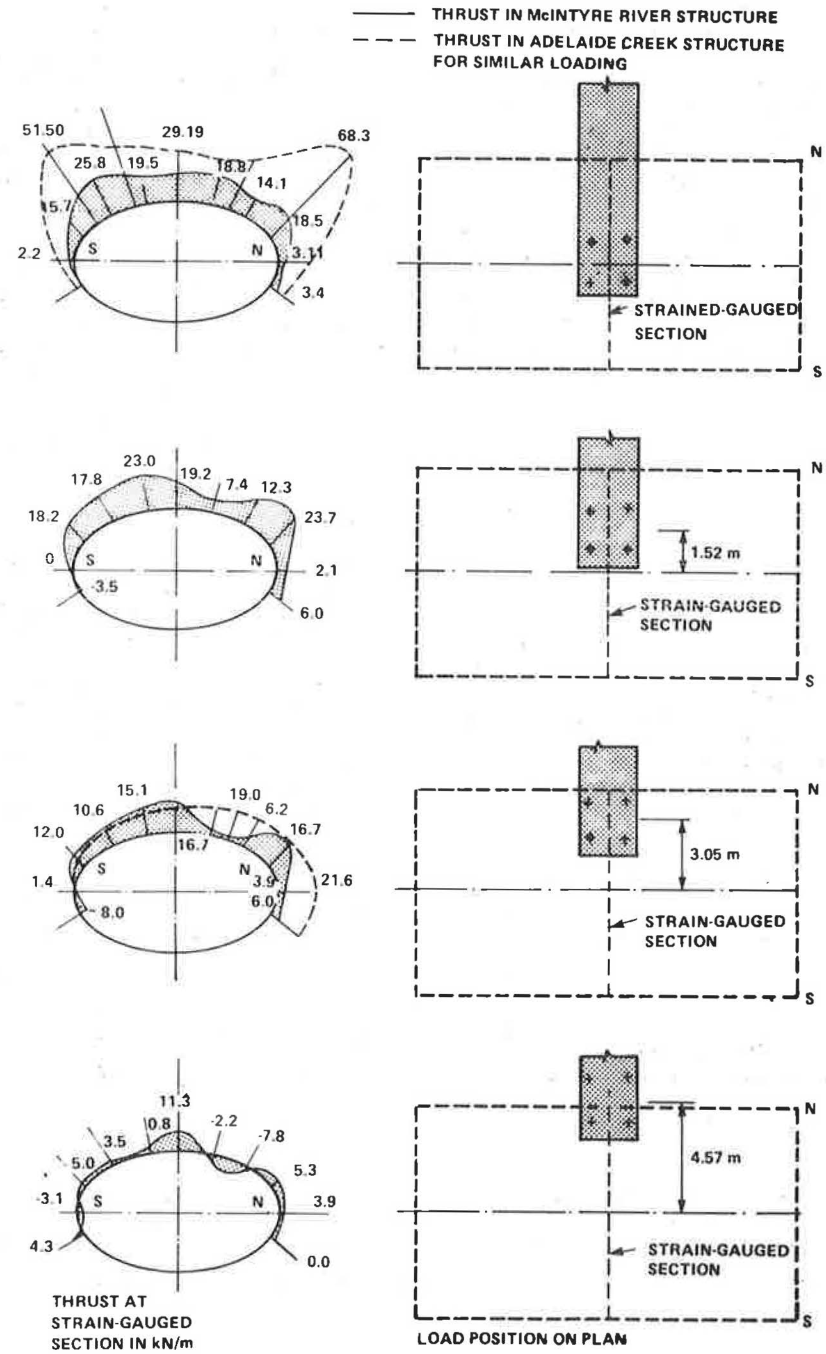

FIGURE 6 Thrust in conduit wall due to test vehicle 1, load level 3.

marginally larger than those shown in Figure 6, but only when one set of wheels of the vehicle was directly above the instrumented section. Other corresponding thrusts, that is, when the vehicle was transversely away from the instrumented section, were always smaller; their details are given in a report by Bakht and Knobel (4). Note that thrusts due to a vehicle well away from the centerline of the conduit or the instrumented section were sometimes less than could be accurately measured by the instruments. In such cases, the plotted values should be taken as representing only the pattern of thrusts rather than the actual values.

Thrusts from two test vehicles were found to be somewhat different than the sum of thrusts from the two vehicles measured separately.

Moments

In most cases, live-load moments were less than the instruments could measure accurately. An idea of the magnitude of the moments can be obtained from the fact that even under the two 400-kN rear tandems of the test vehicles, the maximum flexural stress in the conduit wall was less than 2.0 MPa.

STRUCTURE WITHOUT RELIEVING SLAB

The effect of the relieving slab on live-load moments and thrusts can be best studied by comparing the test data with those corresponding to another similar structure that does not have a relieving slab. Fortunately, such a structure has been tested in the past (1) with the same equipment as that used to test the McIntyre River Bridge.

The structure without a relieving slab, called the Adelaide Creek structure, also has a horizontally elliptical conduit. The span and rise of the conduit are 7.24 m and 4.08 m, respectively. The maximum depth of cover at the time of the test was 1.32 m. The span of this structure is 17 percent smaller than that of the McIntyre River Bridge. However, the comparison of load effects is made meaningful by the similarity of the ratios of span (D_H) to rise (D_V) and depth of cover to span in the two structures (Figure 7). It is noted that for the test on the Adelaide Creek structure, the same vehicles and vehicle positions were used as those for the test on the McIntyre River Bridge. The Adelaide Creek structure is also a Westeel Roscoe Limited K-D steel pipe and has specified backfill similar to that for the McIntyre River Bridge.

COMPARISON OF RESULTS

Conduit wall thrust in the two structures due to the same vehicle at identical locations are compared in Figure 6. It can be seen that in spite of a 17 percent larger span, the structure with the relieving slab has much smaller thrusts than the structure without the slab. The reduction for the maximum thrust is about 50 percent. It is interesting to note that when the tandem is centrally placed above the pipe, the presence of the relieving slab causes the thrust to become more uniform around the pipe than is the case when the slab is absent.

The thrusts due to two vehicles in the two structures are compared in Figure 8. Here again the thrust in the structure with the relieving slab is less in spite of the larger span and a closer transverse spacing of the test vehicles. However, in this case, the reduction of the maximum thrust is about 45 percent.

Note that in the case of a single vehicle, the reduction of the thrust due to the relieving slab was substantial all around the pipe, as shown in Figure 6. In the case of two vehicles, however, the reduction was substantial only where the thrust was the maximum. At other locations, the relieving slab does cause a reduction in the live-load thrusts but not by as large a margin.

The effects of the distance of the load from the reference section on the maximum live-load thrust are compared in Figure 9 for the two structures. Predictably, in the structure without the relieving slab, the thrust diminishes rapidly as the load moves away from the reference section. Note the shape of the curves of thrust versus distance for the Adelaide Creek structure. The curve is convex when the load moves along the traffic direction and concave in the vicinity of the reference section when the load moves along the pipe centerline. This suggests a more uniform distribution of the load in the former direction than in the latter.

For the McIntyre River Bridge, the thrust-distance curves becomes much flatter, which suggests a less rapid diminution of the thrust. The concave curves for a movement of load in both directions

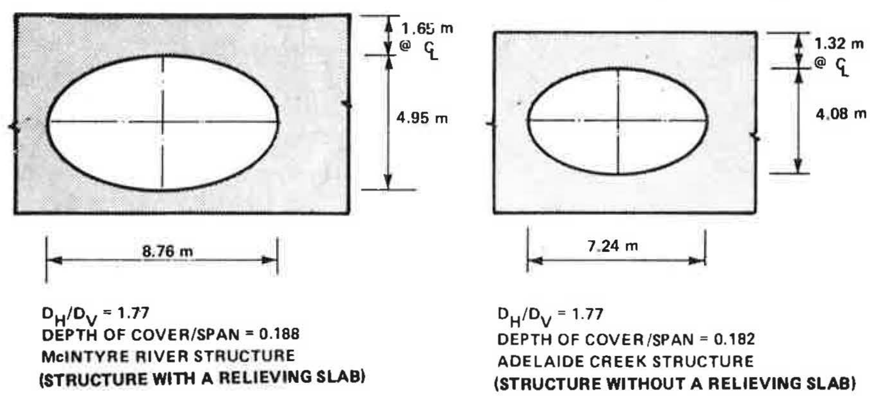

FIGURE 7 Comparison of cross sections of structures with and without relieving slab.

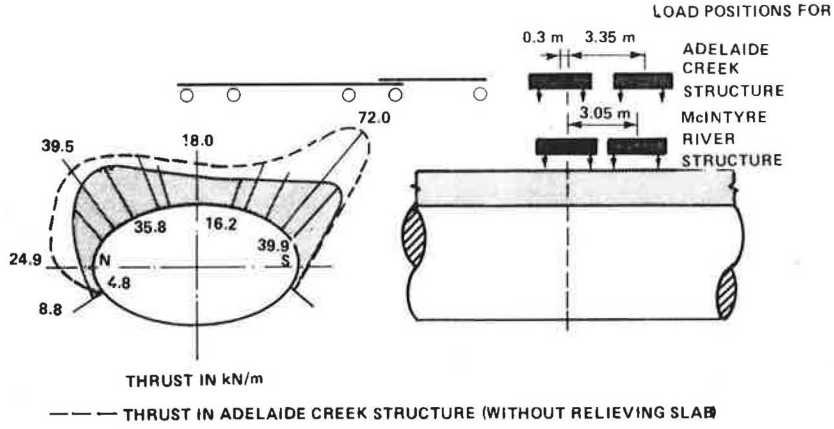

FIGURE 8 Effect of relieving slab on thrust due to two vehicles (load level 3).

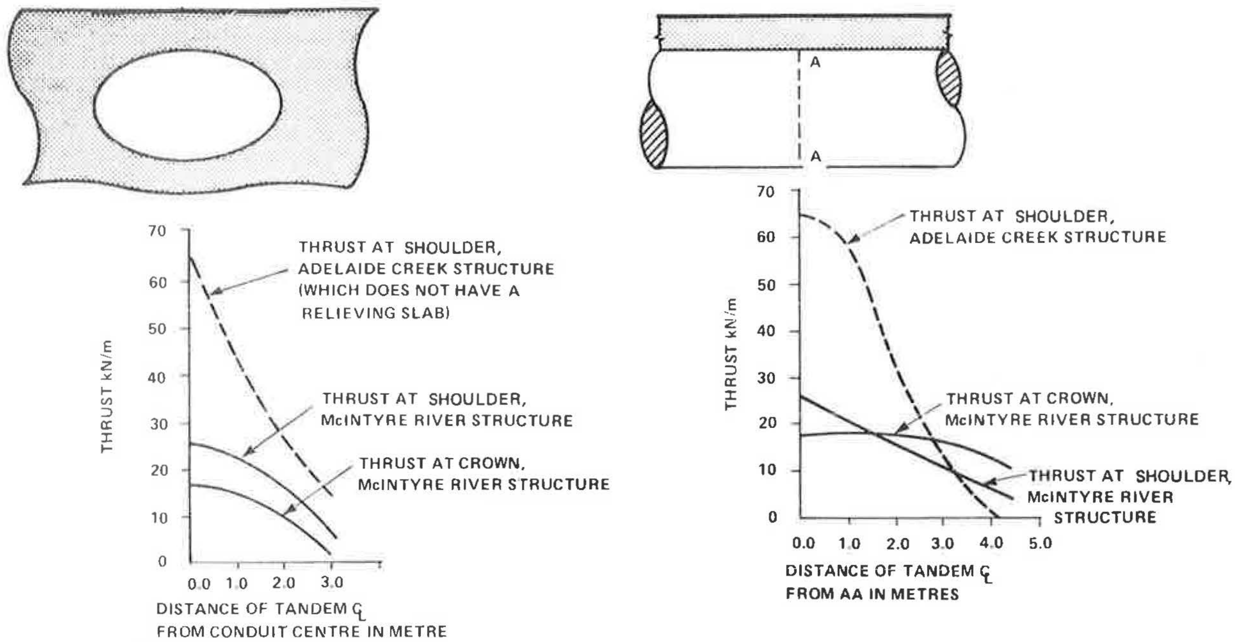

FIGURE 9 Effect of vehicle position on thrust.

imply that the load dispersion through the slab and fill is not strongly influenced by the direction under consideration. Recall that, as noted elsewhere (1), a concentrated load at the embankment level disperses much more rapidly in the longitudinal direction of the conduit than it does in the transverse direction.

Live-load deflections were extremely small. Even under the two 400-kN rear tandems of two side-by-side test vehicles, the vertical crown deflection was only 0.76 mm.

PROPOSED SIMPLIFIED METHOD

It was found that for the vehicle locations that correspond to the maximum thrust in the conduit wall, the following simple procedure could yield fairly accurate values of the maximum thrust.

1. Assume that the vehicle load immediately above the conduit is uniformly distributed on a rectangular area bounded by the extremities of the tire-contact areas on the roadway;
2. Distribute the uniformly distributed load obtained in step 1 to a horizontal plane at the level of the crown of the conduit by assuming that the dispersion through the relieving slab and the fill takes place at a slope of 1 vertical to 1.75 horizontal; let the resulting pressure be designated by q_c; and
3. Obtain the maximum thrust per unit length of the conduit wall by multiplying q_c by the lesser of half the conduit span and half the length of the distributed load at the crown level measured in the direction of the span.

The foregoing procedure, which is illustrated in Figure 10, gave a maximum conduit wall thrust for level 3 of vehicle 1 (shown in Figure 5) of 24.84 kN/m. This value is only 4 percent smaller than the maximum thrust computed from test data, which, as shown in Figure 6, is 25.8 kN/m. Similarly, for the two-vehicle cases shown in Figure 8, this procedure gave a maximum thrust of 44.6 kN/m compared with the

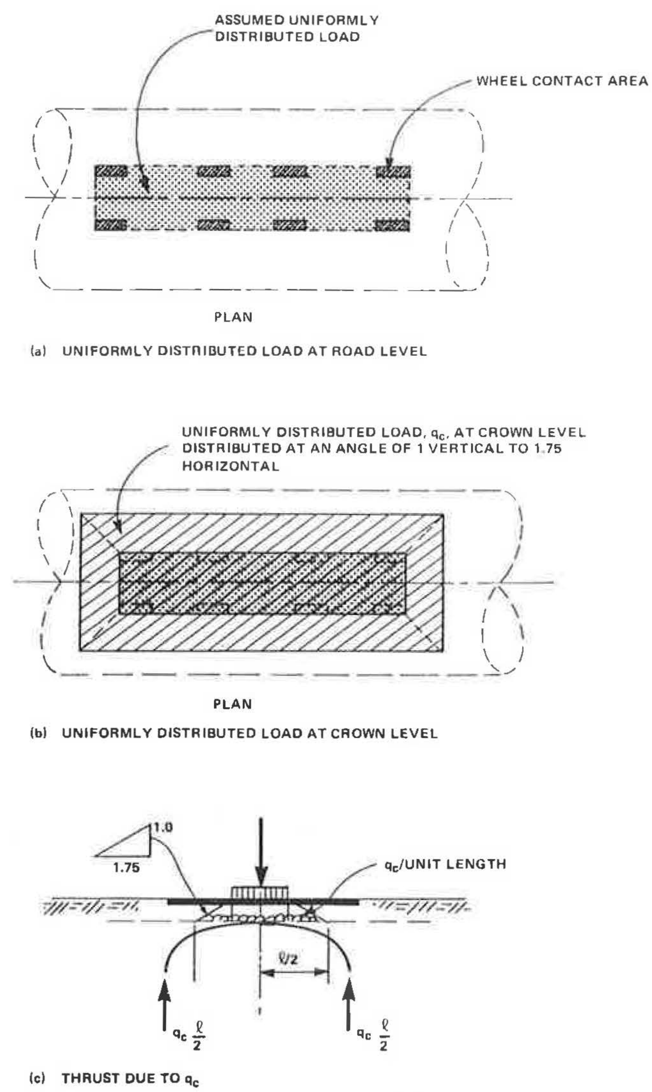

FIGURE 10 Steps in the calculation of thrust.

experimental value of 39.9 kN/m, which corresponds to a safe-side difference of 12 percent.

The live-load effects in a soil-steel structure may not be very sensitive to the soil properties (5,6), but they certainly should be to the flexural stiffness of the relieving slab. Clearly, a structure with a very thin relieving slab will tend to behave more like a structure without a relieving slab than like the McIntyre River structure.

The simple method of analysis just given does not take into account the relative stiffness of the relieving slab as opposed to that of the whole structure. This method should therefore be used as an interim measure for structures similar to the tested one until an analytical method is developed that can rationally take account of the load dispersion in both the longitudinal and transverse directions of the conduit.

CONCLUSIONS

The comparison of test results on a soil-steel structure with a relieving slab with those on an identical but smaller structure without the slab shows that the relieving slab has the effect of considerably reducing the live-load thrusts in the conduit wall. For the structure tested, the maximum thrusts were reduced by about 50 percent. Live-load moments were negligibly small.

The relieving slab of the tested structure appeared to disperse concentrated loads at a slope of 1 vertical to 1.75 horizontal in all directions.

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Inelastic Buckling of Soil-Steel Structures

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ABSTRACT

The buckling of composite soil-steel structures is examined, taking into consideration the formation of plastic hinges in the conduit walls. A structural model is applied in which the soil is replaced by discrete normal and tangential springs acting at the nodal points of a closed polygon of beam elements representing the conduit. The coefficient of the soil springs is taken to be dependent on the type of soil as well as on the direction of displacement and depth of soil at the surface of contact with the conduit. A nonlinear matrix analysis is applied to examine the stability problems in the conduit. Numerical examples show two distinctive modes of failure. A snap-through failure is observed in conduits with relatively large spans or shallow cover or both, whereas short-span conduits with deep cover exhibit no sudden buckling but instead displacements with a higher rate of increase after each loading step. The analyses show reasonable agreement with the results of the failure load obtained from the Ontario Highway Bridge Design Code for the case of cylindrical conduits. However, it is found that the code overestimates the failure load for the horizontal ellipse, whereas it underestimates that for the vertical ellipse.