Abridgment

Effects of Frictional Slippage of Soil-Structure Interfaces of Buried Culverts

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A simple friction-contact interface element is used to simulate frictional slippage, separation, and rebonding along a soil-structure interface. The application is to a long-span buried culvert with incremental soil layering and it is solved by the finite-element method. It is concluded that interface elements, which permit relative slippage between soil and structure, are necessary in order that the predicted structure deformations conform with experimental data.

Although the ever-popular finite-element method (FEM) has been used extensively for the structural analysis and design of buried pipe culverts as well as for other soil-structure interaction problems, it is, of course, simply a numerical-solution methodology. The real challenge is to construct mechanistic models that behave something like the real world while at the same time to strike a balance between rigorous mechanics and engineering simplicity. For the buried-culvert problem, this challenge extends to almost every aspect of the soil-structure system, e.g., soil constitutive model, structural constitutive model, simulation of incremental soil layers, boundary conditions, and geometrical nonlinearities. One aspect of particular interest is the treatment of the culvert-soil interface. Typically, FEM models assume that the soil is bonded to the culvert during deformation.

Katona has introduced (1) a simple friction-contact interface element that simulates frictional slippage, separation, and rebonding of two bodies that initially mate at a common interface and subsequently deform with an arbitrary static loading schedule. Constraint equations between initially mating node pairs and the general principle of virtual work are used to formulate the interface element for an FEM solution procedure. This interface element is operational in the FEM program Culvert Analysis and Design (CANDE) (2,3).

CANDE is a special-purpose design and analysis program for buried culverts and includes capabilities for incremental construction and nonlinear material representations for structural and soil elements as well as the above-mentioned interface element. Plane strain geometry and small deformations are assumed. The culvert structure is modeled with a sequence of beam-column elements, and the soil is modeled with continuum quadrilateral or triangular elements.

With the aid of the CANDE program, the objective of this paper is to illustrate that the inclusion of interface elements helps to simulate the observed structural responses of long-span culverts during field installations.

LONG-SPAN CULVERT MODEL

Long-span arch culverts, which infers spans that range from 5 to 15 m, are constructed by bolting together curved structural plates of corrugated metal into the shape of an arch with the ends anchored into concrete footings. Backfill soil is compacted in a sequence of symmetrical layers on both sides of the arch. During this process, lateral soil pressure moves the arch sides inward and the crown upward (peaking). Subsequent soil layers placed above the crown reverse this trend by pushing the crown downward and the sides outward, which mobilizes passive soil resistance. Field experience indicates that the relative crown movement is a major performance criterion for assessing the structural integrity of the soil-structure system (4). Generally, it is considered desirable to maintain the relative crown movement (peaking and flattening) within 2 percent of the total arch rise.

The following example demonstrates that the soil-structure interface assumption significantly influences the crown movement prediction during the backfilling process. Moreover, a frictional slipping interface appears to be a better representation of observed behavior than a completely bonded interface.

Figure 1 is an FEM representation of a high-profile, long-span arch in which symmetry is assumed about the vertical centerline. Top rise is 3.4 m; half-span is 4.8 m. Sixteen beam-column elements (line segments) form half of the arch periphery; an additional element composed of four quadrilateral elements is embedded in the concrete footing. Interface elements connect the culvert nodes above the footing to corresponding soil nodes. Three separate interface conditions are to be considered: bonded ($\mu = \infty$), frictional slip ($\mu = 0.5$), and frictionless slip ($\mu = 0.0$), where μ is the coefficient of Coulomb friction. In all cases, the initial reference system includes the concrete footing, the metal arch, and the soil raised to the level of the springline. Loading consists of seven incremental layers of soil and includes body weight plus temporary compaction pressures (5 psi), which squeeze each soil layer to simulate the effects of the compaction equipment (5). For the purposes of this study, linear constitutive properties are assumed for all material as noted in Figure 1; effects of nonlinear material models are presented elsewhere (5).

DISCUSSION OF RESULTS

Figure 2 shows the resulting crown-displacement histories as a function of fill height for the three interface conditions. We observe that maximum crown peaking increases by nearly a factor of 3 for the frictionless case as compared with the bonded case. Moreover, for the slipping cases ($\mu = 0.0$ and 0.5), the crown does not return to the zero reference until the fill height is greater than 2.0 top-rise units above the springline, whereas the return to the zero reference occurs at a fill height of 1.3 top-rise units for the bonded case. The term "peaking range" will be used to refer to the fill-height level at which the crown returns to zero reference.

Also shown in Figure 2 is a typically observed crown-deflection history based on averaging experimental data from four different long-span arch installations (5), none of which conforms exactly to the model represented in Figure 1. Although not shown, the individual experimental curves exhibit a rather wide variation in the magnitude of crown peaking that ranges from 0.5 to 3.0 percent deflection of the total rise. However, one common trait is that the peaking range of the individual experimental curves is fairly consistent; it measures slightly more than 2.0 top-rise units, as illustrated by the averaged-data curve.

In comparing the analytical deflection histories with the averaged experimental curve, it is apparent that the slipping conditions ($\mu = 0.0$ and 0.5) provide a more reasonable representation of the averaged data than does the completely bonded condition. This conclusion is based on the observation that peaking ranges are in good agreement, not the

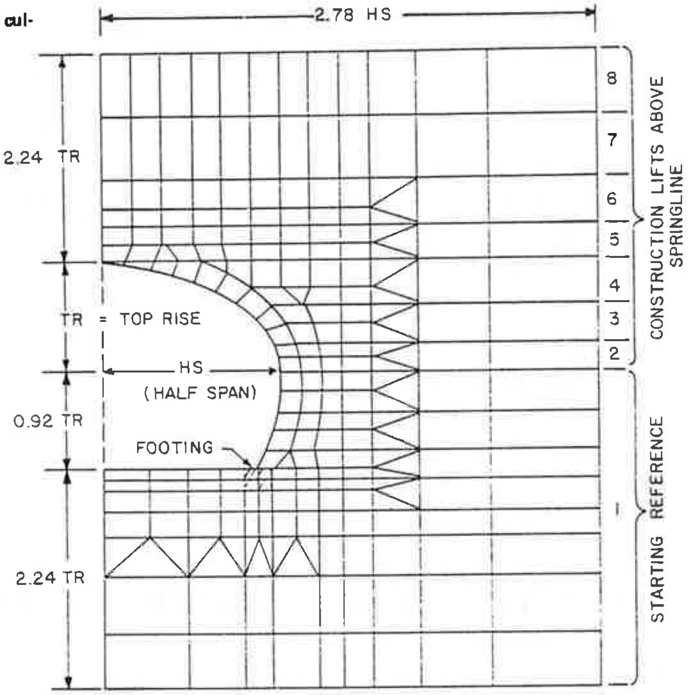

Figure 1. Dimensions of FEM model of arch culvert and soil system.

MATERIAL	YOUNG'S MOD. kPa	POISSON RATIO
SOIL	13.8×10^3	0.35
FOOTING	20.7×10^6	0.20
STEEL ARCH 5 GAGE, 6 x 2-INCH	20.7×10^7	0.30

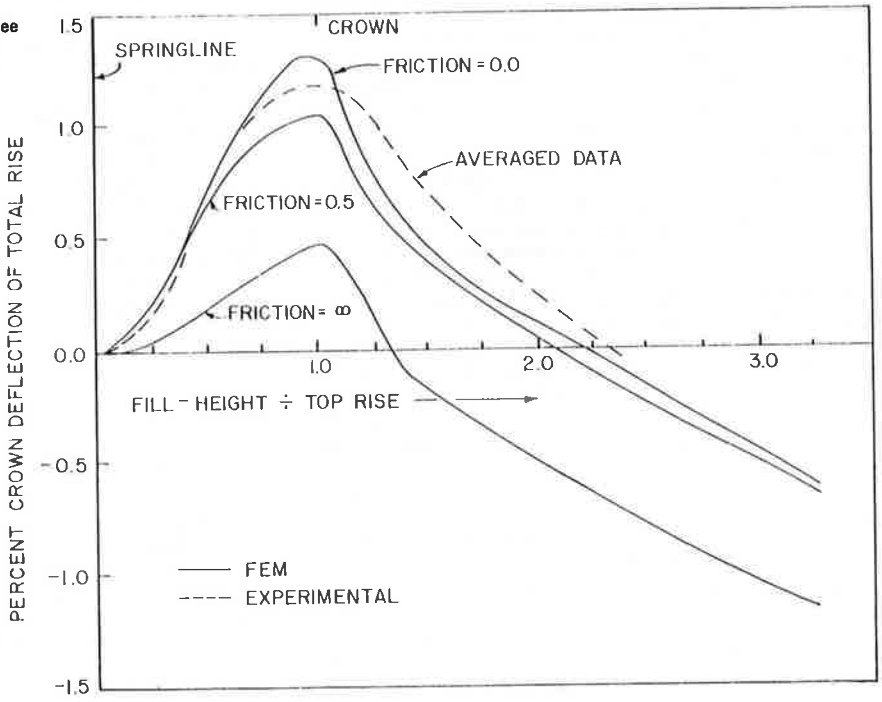

Figure 2. Crown-displacement histories for three friction values and averaged experimental observations.

observation that the peaking amplitudes also happen to be in good agreement. The observation that the peaking amplitude of the averaged data is bracketed by the two slipping conditions is incidental because amplitudes are easily changed by the assumed soil stiffness. However, the peaking range is unaffected by soil stiffness (5).

In summary, it is concluded that FEM models of long-span culvert installations should incorporate slipping interface conditions in order to properly predict deformation histories.

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Deflection of Flexible Culverts due to Backfill Compaction

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A detailed study was made of the effects of compaction on the long-span aluminum culvert structure in Tice Valley, California. Finite-element analyses were performed to simulate field behavior. Measurements showed that the deflections due to compaction were very significant. The analysis procedure appeared to model the effects of compaction reasonably accurately.

Experience with flexible metal culverts has shown that the loads applied by rollers and other heavy construction equipment during compaction of the backfill can cause considerable deflection of a culvert. If heavy construction equipment is permitted to operate close to the sides of a flexible culvert, considerably more "peaking," or upward movement of the crown, may occur than if heavy equipment is kept away from the structure.

In an analytical study of these effects, Katona (1) performed finite-element analyses in which the application of temporary compaction loads was simulated. He found that temporary loads applied to the surface of each new layer of backfill resulted in additional amounts of peaking, and his results were therefore in agreement with field experience.

Thus it is clear from both field experience and analytical studies that compaction loads can induce appreciable deflections in flexible metal culverts. Although the experience and the analytical studies are in qualitative agreement, no data have been available that could serve as a basis for quantitative comparisons of field measurements with analytical results in any particular case.

The purpose of the study described in this paper is to make a detailed evaluation of the effects of compaction for the long-span aluminum culvert structure in Tice Valley, California. Deflections of the haunch, the crown, and the quarter point were measured before and after compaction of each new layer of backfill, and analyses were performed to simulate the field behavior. It was thus possible to determine the magnitude of the compaction load appropriate for the equipment used on the job, and it was also possible to determine the effect of the compaction loads on the bending moments in the culvert.

TICE VALLEY CULVERT STRUCTURE

The Tice Valley culvert structure is located in Walnut Creek, California, about 20 miles east of San Francisco. A cross section through the structure is shown in Figure 1. It is a horizontal ellipse with a span of 25 ft 1 in and a rise of 12 ft 11 in. The culvert is constructed of aluminum structural plate 0.15 in thick and has aluminum bulb angle stiffener ribs spaced at 2 ft 3 in across the crown.

The backfill is a sandy clay classified CL by the Unified Soil Classification System. It was compacted to a minimum of 95 percent of the maximum dry density determined by the standard compaction test of the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO 799, ASTM D698). The final depth of cover over the crown of the structure was 4.0 ft. The backfill was spread in layers about 1.0 ft thick and was compacted by using a 16 500-lb bulldozer and a 3500-lb vibratory roller.

INSTRUMENTATION

Deflection gages were installed at two sections in the culvert located 6 ft 9 in apart. Four measurements were made at each section. As shown in Figure 2, these were (a) change in span, (b) change in rise, (c) deflection of quarter points relative to invert, and (d) vertical movement of quarter points relative to haunch.

The vertical movements of the quarter points were