Predicting Performance of Buried Metal Pipe Arches

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ABSTRACT

The effects of the state of compaction of the soil backfill and of inclusions around the haunches on the fundamental response characteristics of closed pipe arches are summarized. Typical results of finite-element analyses presented in this paper include (a) the deflected shape of the conduit and (b) the distributions of thrust, bending moment, and soil pressure on the conduit wall. Finally, the results are compared with some design recommendations from the American Iron and Steel Institute handbook.

An extensive study of the performance of buried conduits has been conducted at Purdue University during the past decade (1-5). Although the essential aspects involved in predicting conduit behavior are treated in a companion paper by Leonards et al. in this Record, the response of closed pipe arches, which is the subject of this paper, has not been considered previously. In particular, the effects of the state of compaction of the soil backfill and of inclusions around the haunches of the pipe arch are examined. The results are compared with some design recommendations from the American Iron and Steel Institute (AISI) handbook (6). The aim is to provide a better basis for understanding the advantages and limitations of conventional design procedures for buried steel pipe arches.

PROBLEMS STUDIED

The soil-conduit system studied was a buried steel pipe arch. A general scheme of the finite-element mesh representing typical geometry and boundary conditions of a two-dimensional model of this system is shown in Figure 1. The mesh was generated automatically once the six parameters that define the pipe arch were defined. All problems described here were analyzed by using the CANDE code (7) as modified by research done at Purdue University (3).

The first group of problems was selected to study the effects of different states of compaction of the soil backfill. The backfill was restricted to granular soil because long-span pipe arches are almost always constructed with select backfill materials. The states of compaction selected are moderately loose sand and dense sand. The parameters used to define the Duncan-Chang soil model for the two types of soil backfill are given in Table 1. The relevant parameters defining the geometry, sectional properties, and material properties of the steel pipe arch studied are given in Table 2.

The second group of problems was selected to investigate the effects of inclusions at the haunches of the pipe arch; that is, comparisons were made be-

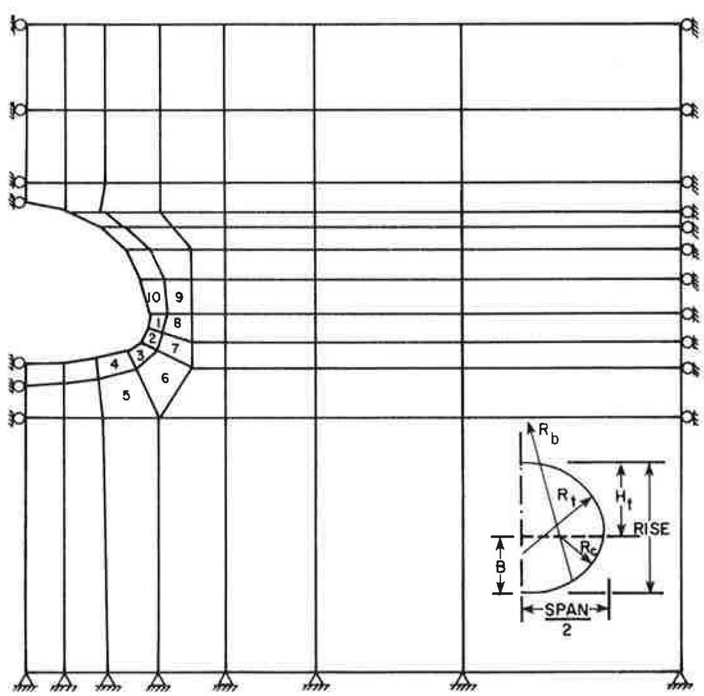

FIGURE 1 Finite-element mesh and parameters defining pipe arch geometry.

TABLE 1 Parameters for Duncan-Chang Soil Model

Parameter	Dense Sand[a]	Moderately Dense Sand[b]	Moderately Loose Sand[c]
Friction angle (degrees)			
ϕ	45	35	30
Modulus number (K)	1,200	920	280
Modulus exponent (n)	0.48	0.79	0.65
Failure ratio (R_f)	0.85	0.96	0.93
Poisson's ratio parameters			
G	0.50	0.37	0.35
F	0.23	0.12	0.07
D	11.70	10.5	3.50
Unit weight (pcf)	130	120	112

[a]Relative compaction (RC) compared with the optimum density in the standard AASHTO T-99 test = 100 percent.
[b]RC = 97 percent.
[c]RC = 92 percent.

TABLE 2 Input Parameters for Pipe Arches Studied

Parameter	Group 1 and 2 Problems	Group 3 Problems
Geometry (Figure 1)		
Span (in.)	246	300
Rise (in.)	154	168
R_b (in.)	378	379
R_t (in.)	124	179
R_c (in.)	32	53
B (in.)	43	68
Sectional properties		
Area (in.^{2}/in.)	0.2282[a]	0.2660[b]
Moment of inertia (in.^{4}/in.)	0.1080[a]	0.1270[b]
Section modulus (in.^{3}/in.)	0.0989[a]	0.1150[b]
Material properties		
E (psi)	30×10^6	30×10^6
μ (Poisson's ratio)	0.30	0.30
Yield stress (psi)	33×10^3	33×10^3

[a]Section 7-gauge 6 x 2.
[b]Section 5-gauge 6 x 2.

tween the conduit responses with and without relatively hard or soft inclusions around the haunches. The parameters that define the pipe arch used in this group of problems are given in Table 2. The soil backfills used are the same as those used in Group 1 problems except that hard or soft inclusions are used around the haunches of the pipe arch. The soil parameters that represent hard and soft inclusions are given in Table 3. The zone of the inclusions is indicated in Figure 1 as the area covered by elements 1, 2, and 3.

The third group of problems was analyzed to investigate further the effects of relatively hard inclusions at the haunches. The parameters defining the pipe arch used in this group are also given in Table 2. The soil backfill is a moderately dense sand the parameters of which are listed in Table 1. The zone of the inclusions for this group of problems is more substantial; it is indicated in Figure 1 as the area covered by elements 1 through 10. The soil parameters that represent hard inclusions used in this group of problems are also given in Table 3.

The sample problems have been selected from a much larger number of computer simulations to demonstrate fundamental response characteristics of buried pipe arches under different backfill conditions. The backfill was added in layers beginning at the pipe invert, and a friction coefficient of 0.5 was used at the soil-conduit interface. Discussions of other essential aspects of the problem, such as (a) effects of using different soil models in the analysis, (b) effects of different soil-conduit interface conditions, (c) importance of the sequence of soil layer placement, and (d) yielding and buckling of the conduit wall, may be found in the companion paper by Leonards et al. in this Record.

TABLE 3 Soil Parameters Representing Relatively Hard and Soft Inclusions

Parameter	Soft Inclusion (Duncan-Chang)	Hard Inclusions: Group 2 Problems	Hard Inclusions: Group 3 Problems
E (psi)	n.a.	10,000	100,000
μ	n.a.	0.30	0.45
c (psi)	2.1	n.a.	n.a.
ϕ (degrees)	20	n.a.	n.a.
$\Delta\phi$	0	n.a.	n.a.
K	60	n.a.	n.a.
n	0.62	n.a.	n.a.
R_f	0.61	n.a.	n.a.
G	0.58	n.a.	n.a.
F	0.33	n.a.	n.a.
D	2.30	n.a.	n.a.

Note: n.a. = not applicable.

RESULTS AND INTERPRETATIONS

Group 1 Problems

Figures 2 and 3 show the effect of backfill conditions on the deflected shape of the conduit. With a moderately loose backfill the crown initially rises while the invert settles; then both the crown and the invert settle considerably as the soil cover above the crown reaches 16.5 ft (Figure 2). At this fill height the conduit wall at the haunch has partially yielded. With dense backfill (Figure 3) there is virtually no settlement at the invert; the conduit essentially retains its initial shape and yielding of the conduit wall is not even approached.

The distribution of thrust in the conduit wall is shown in Figure 4. The thrust distribution at this fill height is comparatively uniform, but it is less uniform at shallower soil cover above the crown. Densifying the backfill does not alter the thrust loads appreciably; it appears that the increased weight of the dense sand is offset by a corresponding increase in arching.

The maximum thrust in buried circular and elliptical conduits can be reliably predicted by using a

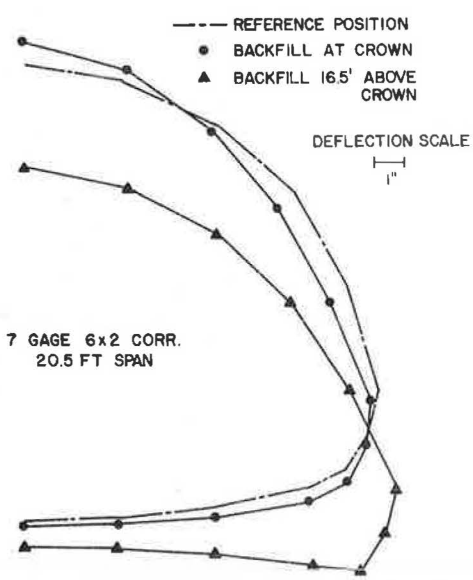

FIGURE 2 Deflected shapes of pipe arch with moderately loose sand backfill.

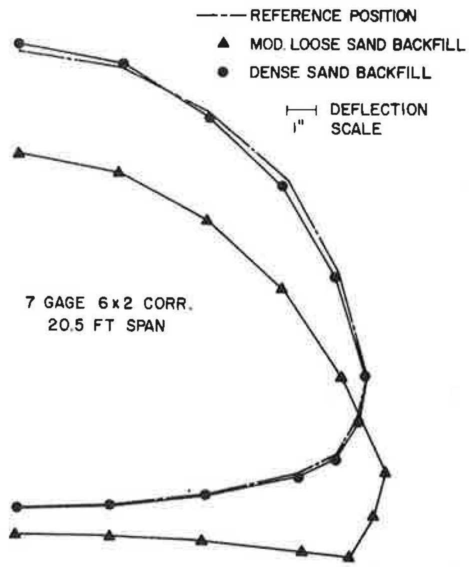

FIGURE 3 Deflected shapes of pipe arch at 16.5 ft of cover above crown.

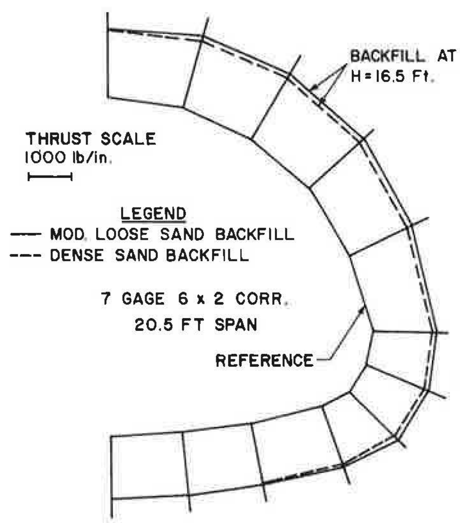

FIGURE 4 Thrust distribution around conduit at 16.5 ft of cover above crown.

diagram presented by Leonards et al. in the companion paper in this Record (Figure 14), which resulted from a study made for the Ontario Ministry of Transportation and Communications (4). By using this diagram, the maximum thrust in the buried pipe arch at a fill height above the crown of 16.5 ft would be 1,700 lb/in., whereas the finite-element analysis gave a value of 1,715 lb/in. On the basis of limited data obtained in this study, the diagram for estimating the maximum thrust appears to be applicable also to closed pipe arches. A comparison was also made with results obtained by using the AISI procedure (6), which uses a load factor along with ring-compression theory to calculate the maximum thrust. For moderately dense sand, the load factor (k) is 0.65 and the maximum thrust would be 1,100 lb/in. with the AISI procedure, which is 35 percent less than the value obtained from finite-element analyses. For shallower cover the discrepancy would be even larger. Because finite-element analyses have generally yielded reliable values of the maximum thrust (5; paper by Leonards et al. in this Record), these discrepancies cast doubt on the advisability of applying the load factors recommended in the AISI handbook.

The distribution of normal stress at the soil-conduit interface is shown in Figure 5. The contact pressure distribution is in reasonable agreement with that calculated by using the AISI procedure. The maximum soil pressure at the haunch for the moderately loose sand is 45.1 psi from the finite-element analysis. Because the maximum ratio of shear stress to shear strength in the soil around the haunches is 0.70 and 0.33 for the relatively loose and dense backfills, respectively, there is no danger of a bearing-capacity failure if the sand backfill is well compacted around the haunches.

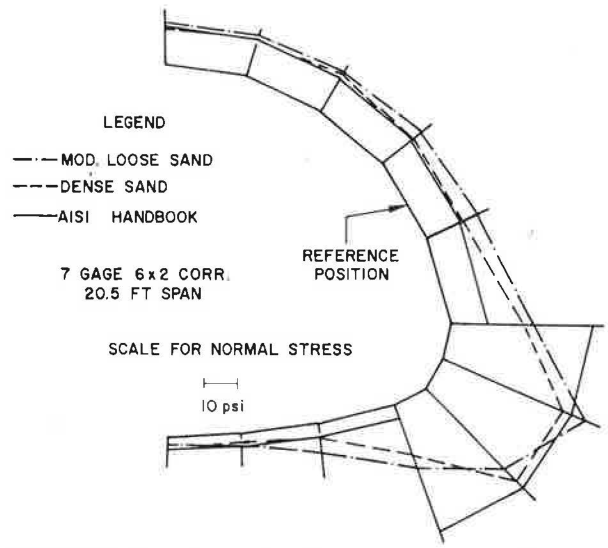

FIGURE 5 Normal stress distribution around soil-conduit interface at H = 16.5 ft above crown.

The distribution of bending moment around the conduit is shown in Figure 6. For the moderately loose backfill, the bending moments at the crown, quarter points, and haunches are nearly equal when the backfill is at the crown; thereafter, the moments at the underside of the haunches increase rapidly and at H = 16.5 ft a fully plastic hinge has almost developed. It is noted that the bending moments in the floor of the pipe arch subject it to tension on the inside, a condition conducive to snap-through buckling. For the dense backfill the maximum moments are smaller by a factor of 5; moreover, there is little change in bending moment as the backfill rises from 0 to 16.5 ft, and there is virtually no tension due to bending of the floor in the vicinity of the invert.

In summary, the predicted performance of a 7-gauge, standard-shape steel pipe arch with a span of 20.5 ft buried in dense granular backfill to a height of 16.5 ft above the crown is excellent. However, if the backfill was moderately loose, a fully plastic hinge would almost develop at the haunch and there would be danger that the floor would buckle inward.

Group 2 Problems

Figure 7 shows the change in rise versus height of backfill for different backfill conditions and in cases when hard or soft inclusions are placed in a limited zone around the haunches. Hard inclusions in

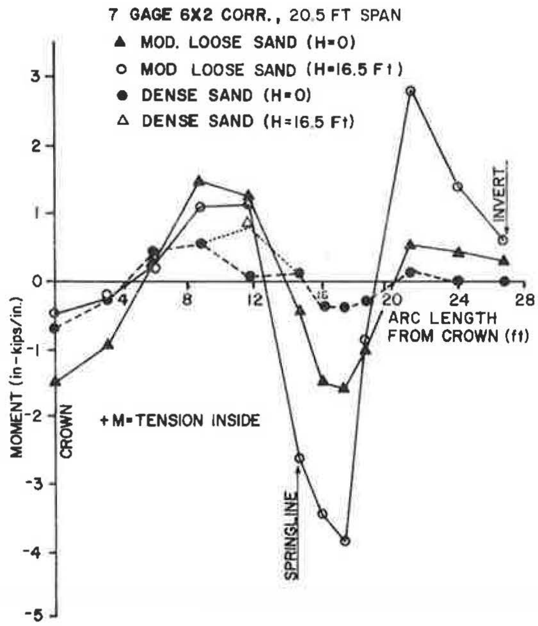

FIGURE 6 Bending moment distribution around conduit.

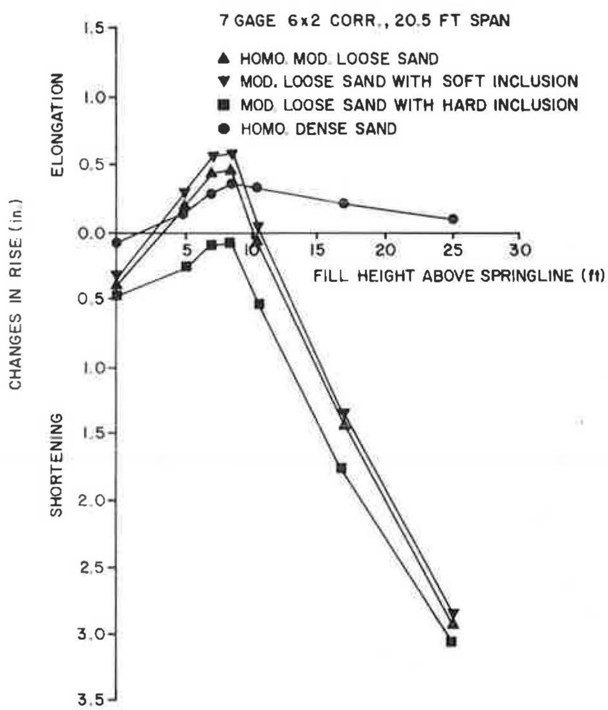

FIGURE 7 Effect of inclusions on change in rise versus fill height above springline.

the moderately loose sand inhibit peaking of the crown, but the ultimate shortening of the rise is barely affected; the soft inclusion has little effect on the change in shape of the conduit. Figure 8 shows the effects of inclusions on the bending moment at the springline. The effects of soft inclusions are of little consequence for the problem studied, whereas hard inclusions in the moderately loose sand cause concentrations in bending stress at points in the conduit wall at which the inclusion abuts the main backfill.

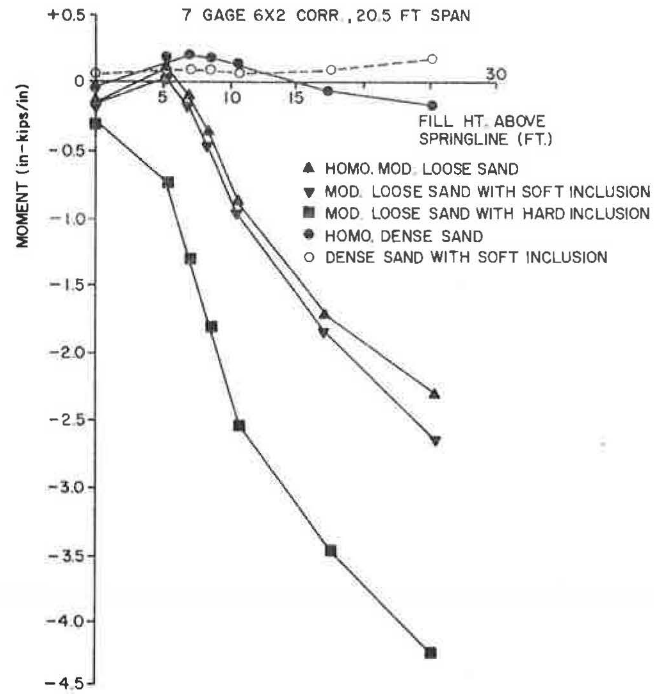

FIGURE 8 Effect of inclusions on bending moment at springline.

The superior performance of homogeneous dense backfill over all other combinations is clearly evident.

Group 3 Problems

Figures 9 and 10 compare the distribution of thrust and bending moment for homogeneous backfill and for backfill with much harder inclusions in a more substantial zone around the haunches. As shown in Figure 9, the hard inclusion at the haunches reduces the thrusts in the conduit wall by about 6 percent, which is a modest benefit. The effect of hard inclusions at the haunches on bending-moment distribution is significant (Figure 10), but it is not necessarily beneficial. For example, the bending moment

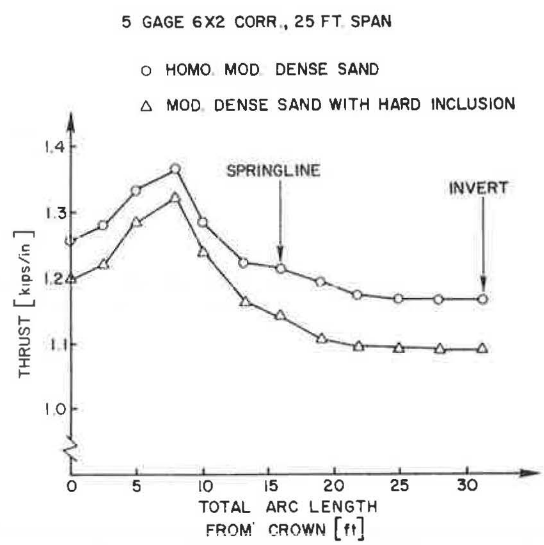

FIGURE 9 Effect of inclusions on thrust distribution around conduit at H = 10 ft above crown.

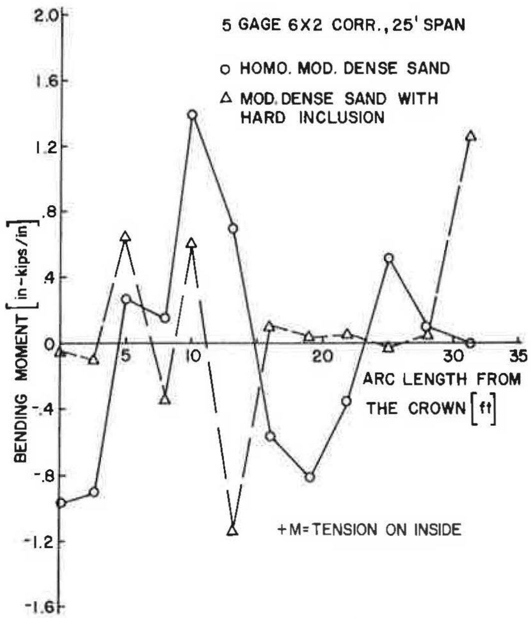

FIGURE 10 Effect of inclusions on bending moment around conduit at H = 10 ft above crown.

at the invert increases from 0.06 in.-kips/in. to 1.27 in.-kips/in., which is an adverse change conducive to snap-through buckling at the invert of the pipe arch. Therefore, hard inclusions are not beneficial to the overall performance of buried steel pipe arches.

CONCLUSIONS

A diagram for estimating the maximum thrust in circular and elliptical conduits has been presented (Leonards et al., companion paper in this Record). Thrusts estimated from this diagram compared favorably with those calculated by using finite-element analyses for the closed pipe arches reported in this paper. Additional studies are needed to verify the general applicability of the diagram.

A comparison was made between the calculated maximum thrusts and soil pressure distributions on a closed pipe arch in a homogeneous backfill with those that would be obtained by using recommendations from the AISI handbook. The soil pressure distributions compared favorably; agreement in the maximum thrust was poor, especially for shallow cover.

When embedded in dense granular backfill, the closed pipe arch is an efficient structural shape for buried conduits supporting overburden loads. Extra effort to densify the backfill around closed pipe arches will pay large dividends in improved performance.

In general, a homogeneous dense backfill is to be preferred over backfills with any of the combinations of inclusions considered in this study, from the standpoint of overall performance of closed pipe arches.

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