COMPOSITE CONDUIT CONSTRUCTION FOR LOWER COST INSTALLATIONS AND IMPROVED PERFORMANCE

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Substantial reductions in material costs of conduits may be obtained by partially or fully surrounding specially designed thin-shelled core units with structurally bonded concrete or with a combination of concrete and soil-cement. Analyses are made of composite concrete conduits with side support varying from undisturbed trenches through recompacted soil to those with no lateral support. Analyses are made of controlling moments, shears, and thrusts for various angles of encasement at the bottom and sides or for encasement fully surrounding the core units. From these values, comparisons are made of allowable loads on unreinforced concrete composite conduits and of relative amounts of tensile reinforcement required in reinforced conduits. Tests are described in which performance and installations of conventional pipe sections are compared with those of composite sections under similar loads to verify previously described analyses.

•THERE is a continuing search for ways to improve conduits and to reduce costs simultaneously, if possible. Shortages of construction materials and of construction funds have accelerated this search.

This paper will describe new soil-structure systems as a means of obtaining both improved costs and improved performance of pipelines.

The concepts involve specially shaped and designed preformed core units used in the field with structural stiffening and supporting materials bonded to selected areas around the core's periphery. This assembly is installed in specially designed trenches or embankments, as shown in Figure 1.

One can obtain more than the sum of the advantages of precast and cast-in-place pipeline construction by combining advantageous features of each. Design analyses showed substantial savings in reinforcing steel and concrete. Construction cost analyses showed additional savings and a superior, more reliable conduit.

The preformed core can be thin and light in weight or thin only where thickness is not required. The composite conduit would then have special tensile and compressive characteristics in essential areas. Cores could incorporate flexible joints, preformed joints, corrosion-resistant linings, pressure linings, velocity reducers, or numerous other features. Thin, light cores made under controlled conditions can be manufactured, transported, and assembled at much lower cost than today's conventional conduits. A machine (U.S. Pat. 3,830,606), which doubles as a trench shield, can be used to install and surround core units in narrow or wide trenches to further reduce installation costs.

The medium or mediums between the core and the earth itself are essential components of the system. The medium might be conventional soil backfill, select dense sand, soil-cement, structural concrete, a spongy cushion, or combinations of these in selected areas. This paper deals primarily with theories and tests of round rigid concrete type conduits, although many adaptations are obtainable for other types of conduits

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that depend on lateral support for installed strength. Primary analyses concern rigid structural in situ mediums structurally bonded to at least portions of the core and comparative tests with other mediums. Besides the structural advantages, a concrete medium obviates the need for select bedding. Grade maintenance and core support are interdependent, and minimum trench widths reduce loads and avoid wasting concrete backfill. Thus, the concept is somewhat self-governing in ensuring that construction will comply with design and thereby avoid major disputes about compliance with trench width, bedding, and backfilling specifications and high bedding-termination stresses (1).

This paper focuses on installations in narrow trenches formed in undisturbed supportive soil or in dense backfill. These trenches are shaped to the general configuration of the lower periphery of the core.

The advantages of a narrow trench are manifold (2, 3). Less excavation backfill and restoration are required as is less right-of-way. Earth loads are smaller because of the narrow trench.

This paper then deals primarily with the structural cost-related advantages of using thin, preformed, round concrete core units with a rigid surrounding medium bonded to selected areas of the core to act structurally with it in a narrow trench.

ECONOMIC ANALYSIS OF STRUCTURES

Hydro Conduit Corporation undertook economic analyses of composite construction a few years ago. It appeared that savings of up to 30 percent of the then current installed costs of concrete pipe conduits could be realized. Obviously savings varied as conduit diameters and the evaluated depths and types of installations varied. Rigorous structural analyses and field testing appeared to be justified and were undertaken.

Structural composite action depends on shear transfer between bonded elements of nonlaminated and laminated beams (bottom and top respectively, Figure 2). This transfer differentiates composite conduits from encased conduits. Effective shear transfer increases the load-carrying ability by a factor of 4 for the same deflection or by 2 for the same unit stress in Figure 2. Before testing full-scale pipe, extensive tests of beams were conducted in 1971 to determine the reliability of various bonding agents in transferring shear between new and hardened concrete. Results (4) indicated, as expected, that mechanical keys were the most effective but that various lesser degrees of tensile strength and shear transfer could be developed between roughened surfaces or at the interface by using certain chemical agents or chemical agents and mechanical keys.

These beams were tested by applying concentrated loads at the midpoint. Field loading on conduits is actually imposed more uniformly as shown by classical pressure distributions in Figure 3. So that reliable bond and shear values can be established, the criterion of bond or means of shear transfer and related moment resistance should be further verified by tests of composite beams of design thickness that are loaded uniformly to produce the desired moments. Thus, one can determine the effectiveness of various bonding means such as portland cement, chlorinated rubber, epoxies, spiked or roughened surfaces, and keyed surfaces.

COMPARATIVE ANALYSES

Several configurations of composite construction can be compared analytically with one another and with conventional construction for degrees of efficiency. Eight types of conduits with 60-in. (1524-mm) internal diameters are shown in Figure 4; a conventional 60-in. (1524-mm) conduit is shown in Figure 4a; composite conduits are shown in Figure 4b, c, d, e, g, and h; and a thin-walled conduit with a soil-cement encasement is shown in Figure 4f. At the left of each figure are moments at the top, sides, and bottom. At the right are values of t^2W/M [in inches (1 in. = 25.4 mm)], which is proportional to the maximum load that can be supported safely by an unreinforced conduit, and M/Wd, a nondimensional measurement, which is directly related to the tensile

Figure 1. Composite core with top and bottom bonded encasement in a narrow trench.

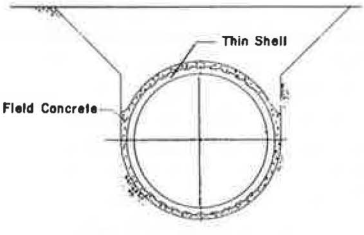


Figure 2. Nonlaminated and laminated beams.

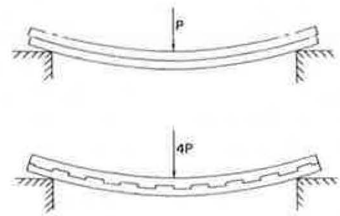


Figure 3. Assumed distribution of earth loads and support on buried composite conduit.

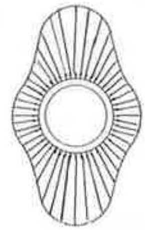
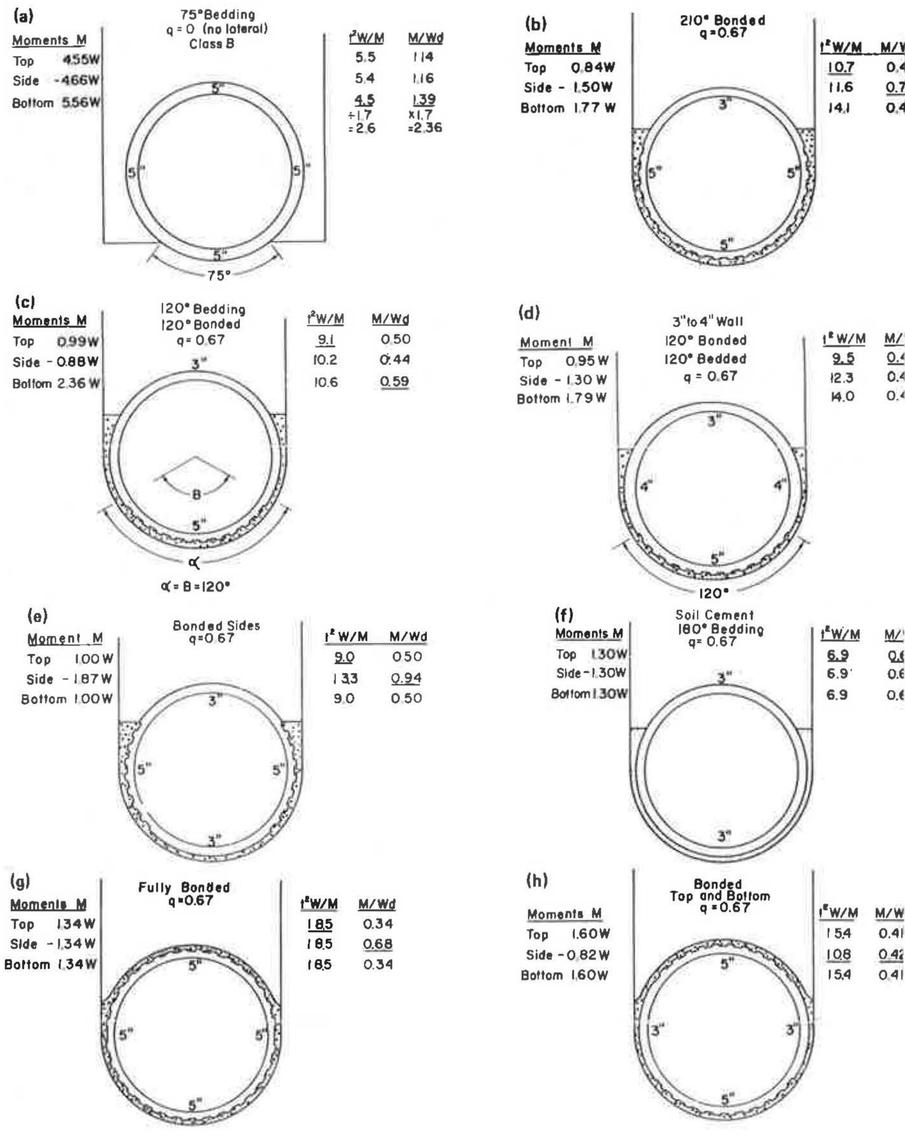


Figure 4. Eight types of conduits with 60-in. (1524-mm) internal diameters.



steel required in a reinforced conduit, where t is the wall thickness of either the core or the bonded composite section, M [in pound-force-inch (1 lbf-in. = 0.1130 N•m)] is the moment at the section being analyzed, W is the load on the conduit, and d is the effective moment resisting lever arm from the compressive face to the tensile steel in reinforced sections. For unreinforced conduits controlled by flexural strength, the extreme fiber stress f_t is equal to the moment M at the section times c, half the wall thickness, divided by I, the moment of inertia of the section. Rearranged,

$$M = f_t I/C = (f_t bd^3/12)/(d/2) = f_t 2d^2 \quad (1)$$

If f_t is set equal to an allowable value of $5\sqrt{f_c'}$, where f_c' is the 28-day compressive strength at the extreme fiber and K is a coefficient which, when multiplied by W, computes the moment at that section (M = KW), then the maximum load is

$$W = (2)(5)\sqrt{f_c'}\, t^2/K \quad (2)$$

Thus, for a given cross section t^2/K, the values of Wt^2/M are directly proportional to W. The lowest value will determine W_{max} for a conduit.

Similarly, for reinforced conduits

$$A_s = M/f_s jd = (KW/f_s jd)\, K/d \quad (3)$$

Therefore, M/Wd is proportional to the tensile steel required at reinforced sections, and the highest value controls the tensile steel requirements. (Probable controlling values are underlined in Figure 4.)

Moments, thrusts, and shear are based on arch theory analysis modified to reflect certain differences between pipe and arches (5). Earth loads W are assumed to act over the top 180 deg of the conduit. Bedding in Figure 4b, c, d, e, f, g, and h is assumed to be 180 deg, and the ratio of passive lateral support to vertical load q is assumed to be 0.67 in the undisturbed firm soil trenches.

Originally, side support for composite conduits was assumed to be 33 percent of the vertical load. A subsequent study was conducted to determine more accurate values of q for undisturbed trench sides with soil-cement backfill, dense sand backfill, and concrete encasement. From known loads on the pipe tested in Phoenix and reported later in this paper, Smith (6) determined analytically what lateral support would be required to restrict deflection of the pipe sections to the measured values. These were determined to be 0.33 for dense sand in a trench 2 ft (0.6 m) wider than the pipe, 0.60 for soil-cement, or 0.67 for concrete as side backfill in a narrow trench. The coefficient of lateral to vertical load for embankment culverts is not known but would logically lie between 0 and 0.6. The two-band criteria (established by California Department of Transportation) for pipe culverts specify values between 0.30 and 1.0. A value of 0.33 would seem to be conservative.

The composite designs used are variations of a 3-in.-thick (76-mm) core section or a core of variable wall thickness with 1 or 2 in. (25 to 51 mm) of exterior concrete bonded to selected areas. Bonding is indicated by the staggered interface between the core and envelope. Figure 5 (5) shows the general arrangement of segments in a composite section somewhat similar to Figure 7b, in which the top 240 deg are thin and the lower 120 deg are thick and there is a transition segment between.

Earth load W for trench conduit designs may be determined from Marston-Spangler formulas. Coefficients for moment, thrust, and shear in terms of W for unit diameters were computed at 15-deg increments from top to bottom for 180-deg bedding and various lateral support values.

Analyses should first be made of flexural strength of nonreinforced conduits for maximum economy. Comparisons in this paper are based on allowable flexural stress in the extreme fibers of $5\sqrt{f_c'}$. Obviously, no steel or steel for handling only is required in these designs. When imposed loads induce higher stresses than are allowed in the unreinforced composite section, the design control shifts to reinforced concepts.

Water in the conduit and pipe-weight effects have been neglected in these comparisons. Moments due to pipe weight may reasonably be disregarded because the nature of installation tends to hydrostatically load the pipe externally and, thereby, relieve such stresses.

Open-Topped Conduits

In Figure 4a, the lowest value of t^2W/M, 4.5, governs the allowable load W. If f_c' = 5,500 psi (37.9 MPa) and there is no reinforcement,

$$W_{max} = 2\ (5)\sqrt{5{,}500}\ (4.5) = 3{,}337 \text{ lb/ft } (48\ 690 \text{ N/m}) \tag{4}$$

With 120-lb/ft^3 (1920-kg/m^3) material in a 9-ft-wide (2.7-m) trench, the fill would be less than 3 ft (0.9 m), and the effective value of t^2W/M would be 2.6. This figure is used for later comparisons (the 1.7 divisor represents W_{wide}/W_{narrow} for trenches).

Considering a reinforced section, W for a 9-ft-wide (2.7-m) trench conduit is about 1.7 times W for a 6-ft-wide (1.8-m) composite conduit. The resisting moment arm d is about 4 in a 5-in. (127-mm) wall. Therefore, the critical value of M/Wd is 5.56 at the bottom times 1.7/4 = 2.36, the highest value of M/Wd. These numbers will be used for comparisons to determine relative steel areas required in composite conduits.

Figure 4b is basically a 3-in. (76-mm) core with idealized shear transfer notches and bonded concrete somehow encasing the lower 210 deg. The lowest value of t^2W/M, 10.7, governs the design used to compute the maximum safe load on the conduit. (Note this is 4 times the value in Figure 4a. Figure 4b also takes into account the narrow trench.)

Assuming f_c' = 5,500 psi (37.9 MPa) and f_t = 371 psi (2.56 MPa), W = (2)(371)(10.7) = 7,935 lb/ft (115 770 N/m) [versus 3,337 lb/ft (48 690 N/m) in Figure 4a]. If the 120-lb/ft^3 (1920-kg/m^3) material is used for backfill, the allowable height of fill is 16 ft (4.9 m) in a 6-ft-wide (1.8-m) trench. It is evident not only that the composite section can take a much greater load but also that the allowable height of fill is increased dramatically with the narrower trench.

For reinforced core units of Figure 4b with a steel cover of 1 in. (25 mm), the maximum value of M/Wd, 0.75, would control the steel design of an elliptically placed cage because the effective value of d is only 2 in. (51 mm). However, 0.75 is still only 32 percent of 2.36 for the class B installation of Figure 4a.

It may not be possible to obtain composite action at the sides at a reasonable cost. The direction of forces at the top and bottom enhances composite performance at the notched interface, but these forces are reversed at the sides. Therefore, in Figure 4c only the lowest 120 deg are bonded, and the design is balanced for nonreinforced sections.

The allowable load on nonreinforced sections in Figure 4c is 15 percent less than that of the fully bonded conduit in Figure 4b, but the reinforcement requirements are theoretically reduced another 21 percent, and the core is probably less costly to manufacture. Inadvertently decreasing the thickness of the composite section to $4\frac{1}{2}$ in. (114.3 mm) at the bottom makes 8.5 the controlling value of t^2W/M at the top, a reduction of 7 percent in W_{max}. However, the controlling value of the reinforced section becomes 0.61, which is almost unchanged.

The composite action at the bottom is beneficial for the reinforced section in Figure 4c, in which an effective d-value is 4 in. (102 mm). However, d at the sides is still only 2 in. (51 mm), and this results in the controlling value of 0.59. This can be improved further if the side walls are thickened or if steel is placed in the envelope at the sides. The use of a thickened section is shown in Figure 4d. This thickening results in a balanced reduced design in which 0.47 becomes the controlling value that is only 20 percent of 2.36 required in the trench conduit in Figure 4a. In addition, the total concrete in the core and envelope is only 75 percent of that in the ASTM A-wall pipe (U.S. Pat. 3,812,884). Thickened sides and notched tops or bottoms are principal novel features of this construction and may well be the most economical construction for conduits over 6 ft (1.8 m) in diameter.

Figure 4e shows the effect if bond and shear transfer are obtained at the sides but are not obtained at the bottom. Excessive stiffness and moments are redistributed such that, at side portions, steel requirements increase by 60 percent over those in Figure 4c.

Soil-Cement Medium

A thin-walled pipe made of soil-cement or unbonded concrete is shown in Figure 4f. Encasement provides 180-deg support but no provisions for bond. Moments are equal as indicated, and t^2W/M is 6.9, which is 25 percent less than in Figure 4c. Inasmuch as W is proportional to the square of t for unreinforced, uncracked sections, uniform thin sections are less desirable. In comparison, the thickened bottom of the composite pipe in Figure 4c attracts moment from the other quadrants and makes them all more effective.

M/Wd in Figure 4f is 0.66, which is 12 percent less efficient than the 120-deg bonded unit of Figure 4c and 40 percent less efficient than the unbalanced unit in Figure 4d. Without a bond, there is no structural benefit given to the core by soil-cement. The principal benefit is in construction when a reduced trench width and improved lateral support are used. Soil-cement bedding may not perform as predicted unless foundation conditions are known. For example, line bearing may occur on a rigid foundation if the core is placed directly on the subbase. Conversely, soil-cement will not afford improved rigidity on softer foundations.

One might suggest increasing the soil-cement bedded core uniformly to 4 in. (102 mm) in thickness, but this starts the cycle again because there would be similar structural benefits with 1-in. (25-mm) thicker walls in each previously analyzed design. Thus an ideal balance is desired among costs of cores, envelopes, reinforcing, and installation after moments and shear have been considered in the installed condition. In summary, for open-topped sections, the best combination appears to be a 120-deg bottom bonded with soil-cement at the sides to provide 180-deg support. Thickened sides would gain considerably more for reinforced larger diameters.

Full Encasement

Figure 4g shows 360-deg encasement that is bonded and rigid and that results in excellent flexural values and in low steel requirements for the top and bottom. Full encasement also allows formation of joints and bends in forming the conduit and preformed flexible joints. If full advantage is taken of balanced moments for reinforced sections, the sidewall thickness has to be increased to at least 5 in. (127 mm) to make d equal 4 in. (102 mm). An effective value of 4 for d at the sides might also be obtained by reinforcing the envelope, potentially reducing M/Wd to 0.34. This would be practical for large-diameter conduits.

If a bond cannot be readily obtained at the sides, the design of Figure 4h would apply in which only the top and bottom are bonded. With a 3-in. (76-mm) wall and a 2-in. (51-mm) envelope, the values are as shown in Figure 4h. This is a reasonably balanced design that has low steel areas.

Other Shapes

Consideration might also be given to greatly exaggerated differing wall thicknesses. Consider a pipe with a 60-in. (1524-mm) internal diameter and with top and bottom walls as shown in Figure 6. Figure 6a shows a pipe with uniform wall thickness; Figure 6b a pipe of unbalanced design.

Controlling moments and values of t^2W/M and M/Wd for 180-deg load, 180-deg bedding, and 0.67 lateral support based on Figure 6 are given in Table 1.

The values in Table 1 indicate an advantage of about 0.30 percent in reduced reinforcement, and a small increase in flexural strength will be obtained by unbalancing wall thicknesses.

Cases should also be considered in which lateral support will be removed because of subsequent adjacent excavations. Comparisons similar to those in Figure 4a, c, f, and h are shown in Figure 7a, b, c, and d respectively. In Figure 7, moment, shear, and thrust values have been computed assuming a 180-deg load but only 120-deg bedding and no lateral support.

There are many other possible variations of core and encasement construction. Off-center core units could be made on existing machines; the thick side could be down for light fills, and the soil-cement backfill could be reversed with a composite bottom section for greater loading.

ALLOWABLE FILLS

For economy, the same equipment should be used to make plain or reinforced core units. Thus, units of a specific diameter may be designed both for closed- and open-topped construction. Several factors beyond the scope of this paper such as normal fill heights, joint types, and joint spacings also determine the basic core unit to be used.

The following example shows use of the concepts in design. Consider a conduit with a 60-in. (1524-mm) internal diameter and a 3-in. (76-mm) core used in a trench with 120-lb/ft^3 (1920-kg/m^3) saturated top soil as backfill.

In an open-topped composite conduit, and in Figure 4c, if $f_c' = 6{,}000$ psi (41.4 MPa), the maximum W would be

$$W = 2\,(5)\,\sqrt{6{,}000}\,(9.1)/1.2 = 5{,}874 \text{ lb/ft } (85\,700 \text{ N/m}) \tag{5}$$

This represents 13 ft (4 m) of cover. No structural reinforcement would be required because the section is designed not to crack.

If reinforced pipe is specified and a design stress of 40,000 psi (275.8 MPa) is used,

$$A_s = M/0.875\,(40{,}000)\,d = (2.36)\,(1.2)\,(5{,}874)/35{,}000\,(5 - 1) = 0.12 \text{ in.}^2\text{/ft } (2.6 \text{ cm}^2\text{/m}) \tag{6}$$

For class B bedded pipe, in an $8\frac{1}{2}$-ft (2.6-m) trench,

$$W = 1.2\,(9{,}899) = 11{,}879 \text{ lb/ft } (173\,000 \text{ N/m}) \tag{7}$$

For the test pipe,

$$\text{load} = 142{,}548 \text{ lb/ft/60-in.-diameter/1.9 load factor} = 1{,}250 \text{ D } (173\,000 \text{ N/m/1524 mm/1.9} = 59.8\, D_{SI}) \tag{8}$$

Figure 5. Finite element model of conduit in which top 240 deg are thin and bottom 120 deg are thick.

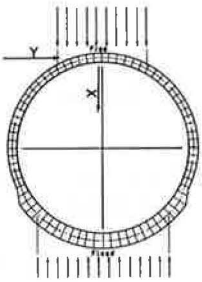


Figure 6. Uniform-wall pipe (a) compared with pipe of unbalanced design of similar total weight (b).

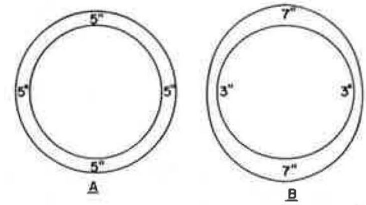
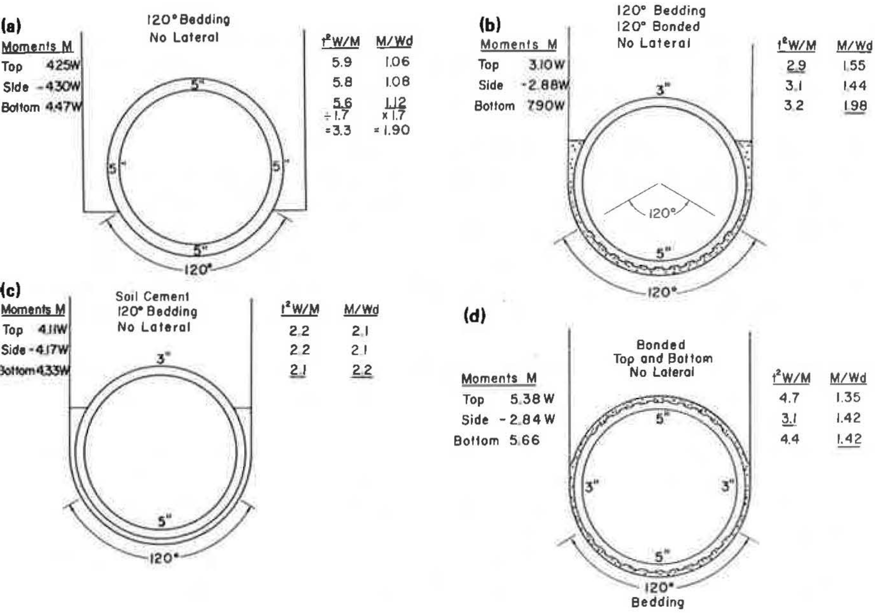


Table 1. Controlling moments and values of t^2 W/M and M/Wd for 180-deg load, 180-deg bedding, and 0.67 lateral support based on Figure 6.

	Controlling Moment		t^2W/M		M/Wd	
Item	Uniform Thickness	Unbalanced Design	Uniform Thickness	Unbalanced Design	Uniform Thickness	Unbalanced Design
Top	1.35W	1.49	18.5	33.0	0.34	0.25
Sides	-1.35W	-0.44	18.5	20.0	0.34	0.22
Bottom	1.35W	1.49	18.5	33.0	0.34	0.25

Note: Underscored numbers are probable controlling values.

Figure 7. Four types of construction without lateral support.



A_s is about 0.47 in.^{2}/ft (10 cm^2/m). Checking by moments gives

$$A_s = (5.56)\,(11{,}879)/(0.875)\,40{,}000\,(4) = 0.47 \text{ in.}^2/\text{ft } (10 \text{ cm}^2/\text{m})$$

Savings are 79 percent in steel and 27 percent in concrete when composite construction is used. Soil-cement backfill could be used from the bonded bedding termination to the spring line.

Dramatic savings may be realized for larger conduits. Consider a pipe. In a narrow trench, a conduit with a 5½-in. (140-mm) core and 120 deg of bonded bedding 3½ in. (89 mm) thick should support more than 13 ft (4 m) of 110-lb/ft^3 (1762-kg/m^3) backfill without reinforcement. For 13 ft (4 m) of fill, conventional design of the C 76 B-walled pipe with class B bedding would need 1,100-D (52.7-D_{SI}) pipe that has a steel area of at least 0.59 in.^{2}/ft (12.7 cm^2/m). Composite construction even in a reconstructed trench with a lateral support value of 0.33 would only require 0.44 in.^{2}/ft (9.5 cm^2/m) of steel. If q were 0.67, A_s would be 0.22 in.^{2}/ft (4.7 cm^2/m).

The lighter cores can be transported and hauled at less cost. There would be savings in excavating and backfilling less material, less even than in most conventional pipe trenches, and savings in materials and labor when select bedding is prepared. Partially offsetting these savings is the cost of pouring about 0.1 yd^3 (0.076 m^3) of soil-cement/ft of conduit. For a simple comparison, the excavation and backfill and the total concrete and steel required for the 108-in. (2743-mm) composite pipe would be about the same as for the ASTM C 76, 84-in. (2134-mm) class I-walled B pipe.

TESTS

To verify many of these theories, field tests were conducted by Hydro Conduit Corporation in Phoenix in 1973 on eight sections of pipe that represented the five designs shown in Figures 8, 9, 10, 11, and 12. Figure 13 shows a sectional view of the installation (7).

Construction of the pipeline is shown in Figures 14, 15, and 16.

On January 8, 1973, 20 days after installation field loading, tests were conducted on the eight sections of the pipeline in the order shown in Figure 13. The method of loading was to center a 126-in.-wide (3200-mm) by 20-ft-long (6.1-m) steel cylinder over the section to be tested and to fill the cylinder with sand as shown in Figure 17. Measurements were taken and recorded of horizontal and vertical deflection of the pipe simultaneously at both ends of the section being tested after each 2 ft (0.61 m) of overburden were placed.

Each pipe had approximately 2 ft (0.61 m) of backfill to ground level before the cylinder was placed over the pipe except for pipe D-1 (Figure 13) in test 2, which started with about 4 ft (1.2 m) of initial cover.

Test sections had a maximum fill of about 23 to 25 ft (7 to 7.6 m). The steel cylinder weighed approximately 6 tons (5443 kg) so that the total maximum load on each test section area was about 106 tons (96 200 kg). The unit stress at the top of the pipe itself was about 2,450 lb/ft^2 (117 kPa). The total load on an 8-ft (2.4-m) length of pipe was 58.5 tons (53 000 kg) and the D-load was 2,930 (140 D_{SI}). Test section 2 (pipe D-1) had 2 ft (0.61 m) more fill or a total load of 115 tons (104 000 kg) and a D-load of 3,200 (153 D_{SI}).

The diameter changes were measured by reading the scales of Ames dials. These were attached between telescoping rods, which were held continuously by springs to marbles that were attached to the walls of the pipe about 1 ft (0.3 m) from each end as shown in Figure 18.

Micrometer readings were also taken between marbles before and after each test, but alignment problems probably made them less reliable than the Ames readings.

Figure 8. Thin-walled pipe with soil-cement backfill used in Phoenix test installation.

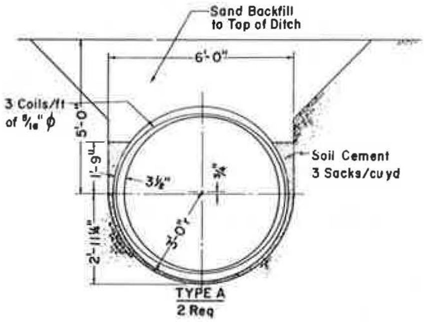


Figure 9. Grooved composite test pipe bonded at top and bottom with 1¾-in. (44.5-mm) overlay bonded at top and bottom.

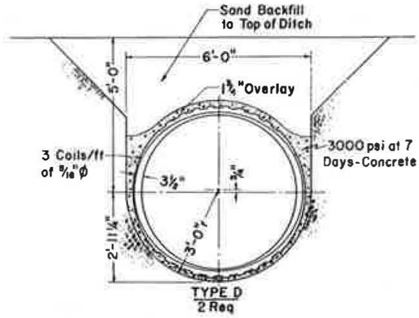


Figure 10. Grooved composite test pipe bonded at top and bottom with 3½-in. (89-mm) overlay bonded at top and bottom.

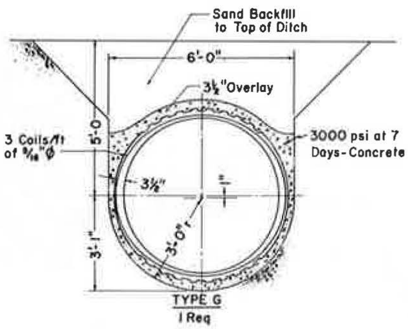


Figure 11. Overlays of 3½ in. (89 mm) on ungrooved thin-walled test sections.

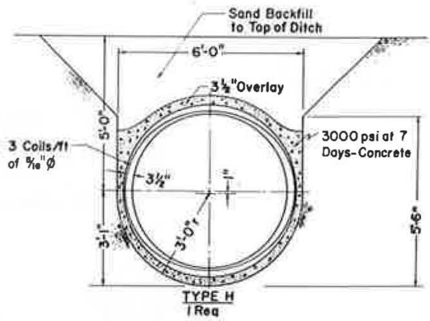


Figure 12. Control test section with 5¼-in. (133.4-mm) wall and sand backfill.

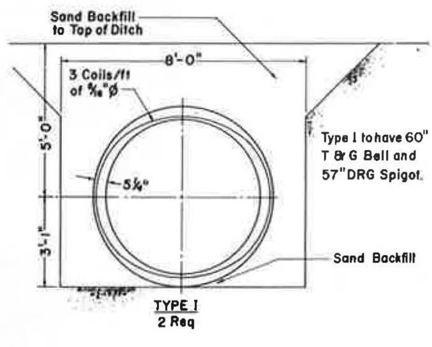


Figure 13. Flexible joint details and test pipeline profile.

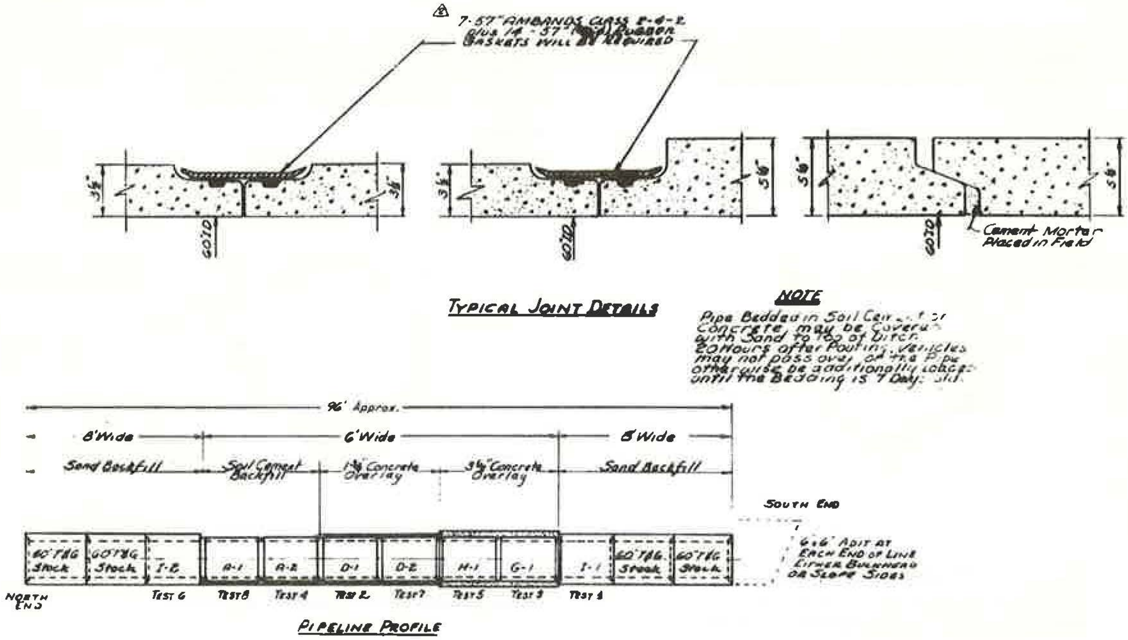


Figure 14. Template for rounded trench bottom for Phoenix tests.

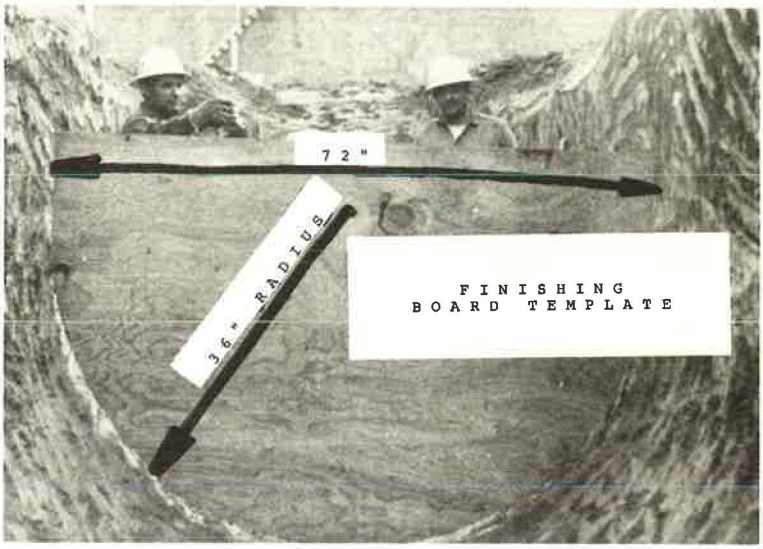


Figure 15. Concrete blocks used to position test sections in narrow trench.

Figure 16. Phoenix test sections with bulkheads separating segments prior to backfilling.

Figure 17. Sand being dropped into 126-in. (3200-mm) cylinder centered over alternate test sections to simulate field load.

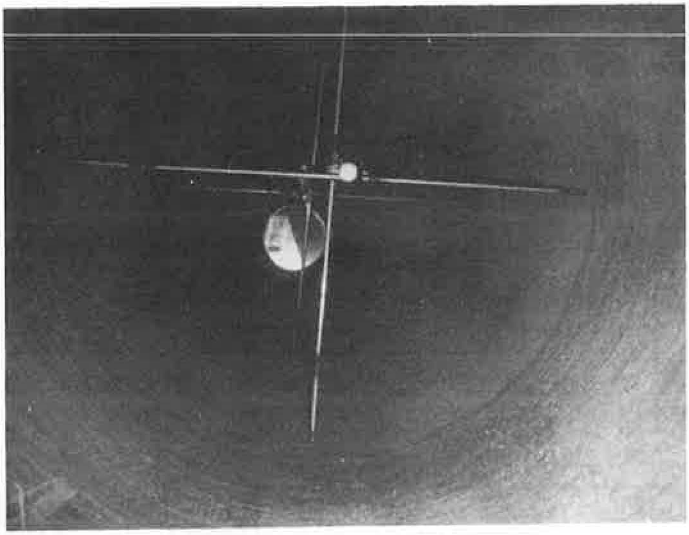


Figure 18. Dial gauges used to measure horizontal and vertical deflections of each test section during loading sequence.

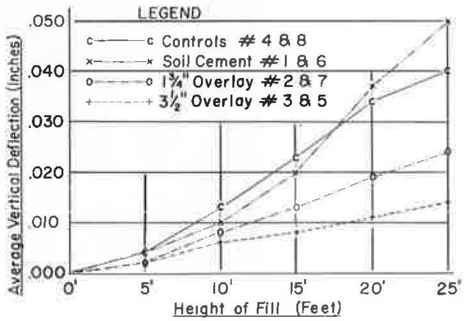


Figure 19. Average vertical deflections of four conditions of test pipes under various heights of backfill.

Table 2. Vertical deflections of test conduits under 20 ft (6.1 m) of fill.

California DOT Test	Δ[a]	Other Tests	Δ[a]
Zone 7	0.0012	ACPA trench	0.0019
Zone 8	0.0008	ACPA embankment	0.0008
Zone 9	0.0025	Phoenix control	0.0006
Zone 10	0.0015	Phoenix soil-cement	0.0006
Zone 11	0.0009	Phoenix 1¾-in. overlay	0.0003
Zone 12	0.0034	Phoenix 3½-in. overlay	0.0002

Note: 1 in. = 25.4 mm.

[a]Deflections in inches (millimeters) are divided by pipe diameter in inches (millimeters) and thus are nondimensional for comparisons.

Vertical deflections are shown in Figure 19 for incremental loadings. The values have been averaged for ease of comparison.

These tests prove that composite as opposed to conventional construction will greatly limit deflections. Just how small these deflections are is more apparent when they are compared with deflections measured in the California DOT 84-in. (2134-mm) test pipeline at Mountainhouse Creek (8) and the American Concrete Pipe Association (ACPA) test lines in Ohio. Table 2 gives deflections divided by diameter for 20 ft (6.1 m) of fill.

Table 2 data indicate that the dense sand backfill used for the control section at Phoenix was about as favorable a material as could be chosen. Therefore, deflections were only 17 to 80 percent of any of the other conduits. These comparisons are relative because the Phoenix tests were in a trench although most of the others were in embankments.

Compared with this most favorable trench installation, the composite conduits deflected only 22 and 44 percent as much under 20 ft (6.1 m) of backfill.

CONCLUSIONS

Composite construction can offer economic savings in concrete pipe type conduits. Many such conduits, even under high fills, do not require structural reinforcement when installed in narrow trenches. Even in formed trenches and in designs without lateral support, composite conduits can greatly reduce required concrete and steel.

Designs for unreinforced and reinforced conduits differ. Thickened walls in selected areas of unreinforced conduits stiffen these sections and attract moments, but the ability of the section to resist moment is proportional to the square of the wall thickness. However, steel areas in reinforced conduits vary directly with moment arms.

Conduits bonded at the bottom for open construction and at the top and bottom for closed construction currently seem to be the most feasible to manufacture and install. Consideration should be given to thickening side portions of core units or to applying reinforced structural concrete at the side portion of the envelope for further economic savings.

Analyses and field tests of thin-cored composite conduits in narrow, natural, or artificial trenches verify theories that will be useful in obtaining more reliable and economical composite conduits for almost any fill of normal height.

ACKNOWLEDGMENT

I am indebted to numerous people who have contributed to these efforts including C. Mack Albertson; E. D. Dowden, Jr.; K. K. Kienow; L. M. Johnson; J. Devine; M. W. Piché; J. P. Zicaro; W. Franz; and, in particular, Wayne W. Smith, who developed the computer program for the analyses.

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DISCUSSION

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The thesis of this paper and the ideas expressed are the most innovative that I have encountered in approximately 50 years of activity and observation in the field of buried conduit design and installation. Although I may have some mental reservations relative to the practical aspects of both the manufacture and installation of the composite structures, nevertheless it is refreshing and valuable to have these ideas laid out and made available for discussion. This is particularly true since Breitfuss has wide experience in the concrete pipe manufacturing industry and has the point of view of a businessman and a competent engineer.

I have had occasion to investigate the structural failure of several dozen buried pipelines and, in each case, have attempted to pinpoint the most probable cause or causes of the failure. Each individual case had its own peculiar circumstances that might have contributed to the difficulty, but two conditions are predominant: (a) the case of ditch conduits in which an actual width of the ditch at the elevation of the top of the pipe was greater than the width for which the pipe was designed and (b) the case of both ditch and projecting conduits in which a bedding condition produced a highly concentrated upward reaction on the bottom of the pipe and thus increased the bending moment in the pipe wall and decreased the supporting strength of the pipe.

The methods of pipe manufacture and installation depicted by Breitfuss in Figure 1 would go a long way toward alleviating the detrimental influence of both these adverse circumstances. For example, with respect to load on a pipe, it is widely recognized that the actual width of ditch at the elevation of the top of the pipe has an important influence on the load to which the pipe is subjected and which it must support without evidence of structural distress. The Marston equation, which is used extensively for determining loads on ditch conduits, is

$$W_c = C_d w B_d^2 \tag{9}$$

where

W_c = load on conduit in pounds/linear foot (newton/meter),
C_d = a load coefficient = $[(1 - e)^{-2K\mu'}(H/B_d)]/2K\mu'$,
w = unit weight of soil,
H = height of fill above top of pipe,
B_d = width of ditch at elevation of top of pipe,
K = lateral pressure ratio (Rankine),
μ' = coefficient of soil friction, and
e = base of natural logarithms.

Since the width of the ditch has such a great influence on the load on the buried structure, the installation of a pipe in a ditch having the same width as the outside diameter (OD) of the pipe, as shown in Figure 1, represents the minimum possible load situation in a given soil and under a given depth of cover. This can be demonstrated by calculating the load on 60-in. (1524-mm) pipes under 15 ft (4.6 m) of cover in ditches of various widths ranging from that of the 72-in. (1829-mm) pipe to that of the OD pipe plus 60 in. (1524 mm). The latter width provides a $2\frac{1}{2}$-ft (0.8-m) clearance on each side of the pipe. The results of such calculations are shown in Figure 20. They indicate that the load on a 72-in. (1829-mm) OD pipe in a ditch that is the same width as the pipe is only 47 percent of the load on the same pipe in an 11-ft-wide (3.4-m) ditch—a dividend certainly worth striving for.

Generally, the vertical earth load on the top of a buried pipe is approximately uniformly distributed over its full width. In contrast, the distribution of the equal and opposite reaction on the bottom of the pipe is influenced by the character and quality of the pipe bedding. Therefore, the stress in the pipe wall and its ability to support load vitally depend on the bedding. To illustrate this principle, consider a simple beam loaded variously as shown in Figure 21. For a load concentrated at the midspan, the bending moment is a maximum and equal to

$$M = 0.250\ Pl \tag{10}$$

where

M = maximum moment at centerline of span,
P = load, and
l = span length.

If the same magnitude of load is distributed uniformly over the span length, the maximum moment is

$$M = 0.125\ Pl \tag{11}$$

or only one-half the concentrated load moment.

For an intermediate distribution of load, say, over the middle third of the span, the moment is

$$M = 0.208\ Pl \tag{12}$$

This example from sophomore engineering mechanics of a simple beam is pertinent because exactly the same principle applies to a circular structure, such as a pipe, and the stress in the pipe wall is directly related to the distribution of the upward reaction on the bottom of the pipe. The function of good-quality bedding is to distribute the reaction as widely as possible and thereby reduce the bending moment stress.

To demonstrate further, I can indicate the bending moment at the bottom of the pipe when the width of bedding is expressed in terms of the central angle subtended by the effective bedding contact, as shown in Figure 22. The moment at the bottom is a maximum when the reaction is a concentrated load, e.g., when $\phi = 0$. It decreases rapidly as ϕ and the width of bedding increase, up to a value of about $\phi = 90$ deg. The benefit derived by increasing the bedding angle from 90 to 180 deg is relatively minor.

The importance of good distribution of the bottom reaction was brought to my attention in a recent investigation. A large-diameter sewer line constructed of reinforced concrete pipe had failed extensively in the invert. Interviews with the contractor and the engineer revealed that the pipe bedding consisted of 6 in. (152 mm) of compacted coarse, harsh gravel overlying shale bedrock. This bedding material was not shaped to fit the contour of the pipe. Rather, the pipe was laid on a flat surface of the gravel. There is little doubt that the bottom reaction was concentrated over a very narrow longitudinal element of the pipe and thus caused high bending moment and failure in the invert.

Figure 20. Load on 60-in. (1524-mm) pipe in ditches of various widths.

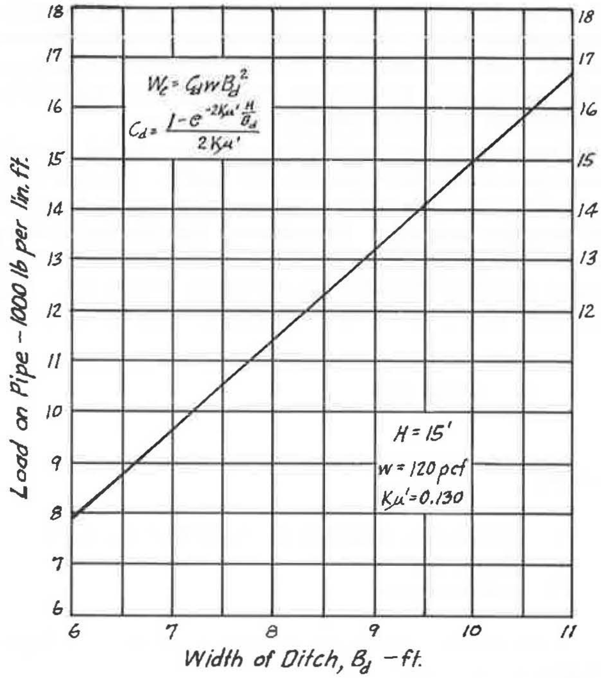


Figure 21. Influence of load distribution on bending moment.

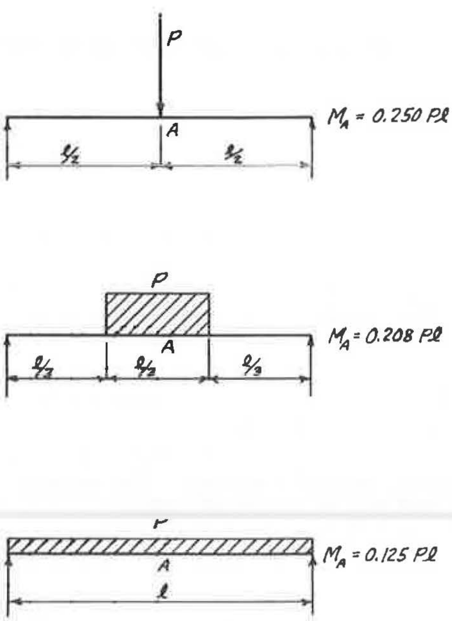
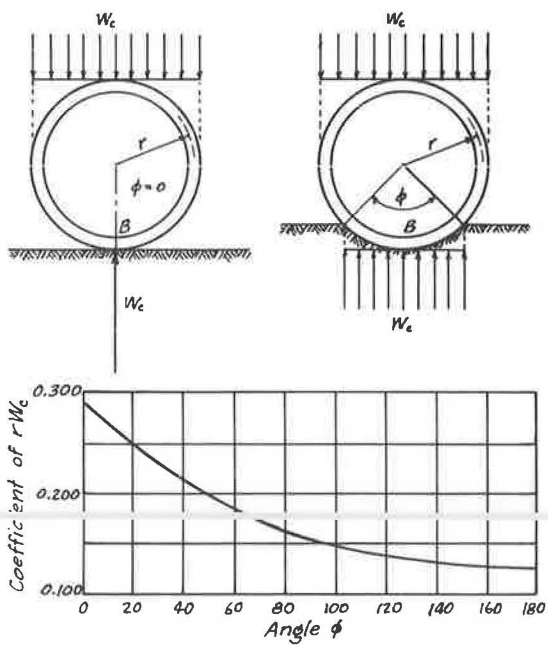


Figure 22. Influence of width of bedding on bending moment at B.



The foregoing discussion indicates that the prospective dividends, in terms of reduced stress in the wall of a buried conduit, brought about by the method of manufacture and installation recommended by Breitfuss are great. However, although I am not an expert in conduit construction, I have seen enough jobs being installed to be somewhat skeptical of the practicality of the proposals under current conditions of contractual relations in this field. All too often, a general contractor does not have the knowledge or appreciation of the importance of accurate control of excavation, adequate bedding, and good backfilling practices and is understandably cost conscious and much interested in maintaining a satisfactory production schedule. Furthermore, guidance and direction by the engineer in charge often leave much to be desired. In some instances when a pipeline gets in trouble, the contractor and the engineer may get their heads together and jump to the conclusion that faulty pipe was the cause of a failure, when nearly always it is poor-quality installation that is the culprit.

There is need for major upgrading of installation practices in the field of conduit engineering, and the proposals outlined by Breitfuss would appear to go a long way toward that end, if such proposals are faithfully carried out. In this connection, Breitfuss suggests that a distinct advantage might accrue if pipe manufacturers accepted responsibility for the installation of a buried pipeline and its manufacture and delivery to a site. Some type of turnkey contract between the manufacturer and the contractor might be worked out, and the result would be that installation crews in the employ of the manufacturer would install the pipe and backfill it to the top. Or as an alternative, the manufacturer might furnish expert supervision of the bedding and backfilling operations. In either case, it is believed that better results would be attainable than under the current system of divided responsibility between the supplier and the contractor.

AUTHOR'S CLOSURE

I value and agree with the comments by Spangler. I appreciate his expanded discussion on two important aspects of the concept: the reduced load on the pipe and the practical application of this type of construction.

My paper may be said to deal primarily with design and economic comparison for lower costs; Spangler's discussion is more related to improved performance.

Spangler offers a good simple illustration of load and moment reductions when an ensured wider supporting base is used. Although it is true that increasing the bedding angle from, say, 120 to 180 deg decreases invert moments only 8 to 10 percent, continuous support for 180 deg prevents high stresses from developing where bedding changes abruptly from rigid to yielding [series C (1), zone 10 (6)]. The reader must also realize the importance of ensured lateral support when 180-deg bedding is used. Increasing side support from, say, 33 to 67 percent of the vertical load decreases moments about 50 percent. The composite pipe in the Phoenix tests (7) should support more than 40 ft (12.2 m) of fill without cracking.

Spangler has some reservations on the manufacture and installation of composite structures. In relation to manufacture, there are probably minor economic advantages in a small pipe, but there are now several methods of making larger concrete cores. Cores can be made on packerhead or dry-cast machines with slightly thinner walls, standard joints, and much less reinforcement. Slots or ridges can be formed in the core units when they are made. Much thinner walled cores can be made by the centrifugal or wet-cast process. With certain modifications these processes can also make cores with thicker sides to maximize the advantages of composite construction. For example, tunnel liners with thickened side walls can be reinforced elliptically so that moments will be balanced in the composite structure after grout backfilling in a much smaller tunnel than is currently required [4 in. (102 mm) in a 10-ft (3-m) tunnel represents 7 percent less excavation]. Another major application is an alternative to large monolithic or box culverts.

Three factors for additional development as mentioned by Spangler are economical joints, reliable side support verification, and machinery to install composite conduits.

One machine mentioned in the paper is under development to hold cores in position while concrete or other types of backfill are placed beneath or around them. The ingenuity of contractors and construction machinery manufacturers should result in more efficient installation machines. However, Spangler appropriately suggests more defined responsibilities for installation. A composite conduit is decidedly a soil-structure system whose success depends on both components of the system. Correct construction is somewhat self-governing in that, if the subgrade and invert are correct, the composite wall at the bottom will be correct. Besides, the installer wants the narrowest possible trench to save materials. Forming and holding that trench may cause disputes between the trenching contractor and the conduit installer acting as a subcontractor, but these disagreements can probably be resolved contractually.