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EXPERIMENTAL STUDIES IN SOIL-STRUCTURE INTERACTION

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This paper contains a literature review of certain experimental studies that pertain to soil-structure interaction. It is divided into two parts: model studies and field or full-scale testing. The requirements that govern model studies are reviewed briefly, and examples of applications are presented. A brief presentation is made of several studies that have used model analysis. They cover topics such as effects of soil moisture and density on culvert deflection, effects of differential soil compaction on culvert stresses, imperfect ditch method of construction, stresses on multiple pipe installations, pressure distribution on pipe, and soil properties. The field study portion presents field studies of the imperfect ditch method of construction, full-scale failure tests, and certain Canadian large pipe tests. A circular culvert design method that takes into account most of the significant variables that affect culvert performance is also presented.

•IN reviewing the literature on soil-structure interaction, I found that many researchers had solved buried structure problems by using a field or model study. In spite of all the work that has been done, the field of culvert design is still relatively new. There is a great deal that is not known about the performance of culverts in various situations. Some design tools that have been available for many years have been applied on an experiential basis only. Some of these will be discussed later in this paper.

Only those studies that have been done in the past few years will be presented here. Many topics that are of considerable importance are omitted because of space limitations.

For purposes of discussion, experimental studies are divided into two groups: model studies and field or full-scale tests.

MODEL STUDIES

Model tests have been successfully used to investigate the performance of full-scale culverts. Other soil mechanics problems that can be treated as plane strain problems, such as slope stability, have also been successfully modeled.

Models may be used to solve complex problems that cannot be readily evaluated by using analytic means. The use of models in obtaining solutions related to performance of underground structures is most attractive because of the complexity of the problems involved. Time and money often prohibit the use of full-scale tests to investigate the effect of different variables on a system. Because of the ease with which models can be fabricated and tested, they yield much more information for a given amount of time and money than do full-scale tests. Full-scale tests are useful in verifying results obtained from model tests.

In order to establish reliable similitude requirements for a given model system, we must define all variables that influence the phenomena. Defining the variables involved requires that an investigator have considerable experience within the area of investigation. As experience is gained in an area, model analysis can be applied with confidence to the solution obtained.

SIMILITUDE REQUIREMENTS

Before a brief review of similitude requirements is presented, it might be helpful to give an example of how similitude and model analysis works.

Sponsored by Committee on Subsurface Soil-Structure Interaction.

Most people interested in culvert design are familiar with the Iowa formula; therefore, it will be used to illustrate the modeling concept as follows:

$$\Delta X = K W_c r^3/(EI + 0.061 E'r^3) \tag{1}$$

where ΔX is the change in horizontal diameter; K is a bedding constant; W_c is the load acting on the culvert and is equal to W_c = pD; P is the average vertical pressure acting on conduit; E' is the modulus of soil reaction; r is the radius of the culvert = D/2; E is the modulus of elasticity of the culvert wall; and I is the moment of inertia of the pipe wall per unit length.

A discussion on the use of the Iowa formula and modulus of soil reaction is included later in this report.

If pD is substituted for W_c and both sides of Eq. 1 are divided by D, we derive

$$\Delta X/D = K P r^3/(EI + 0.061 E'r^3) \tag{2}$$

If the numerator and denominator on the right side of the equal sign in Eq. 2 are divided by EI,

$$\Delta X/D = K(Pr^3/EI)/[1 + (0.061 \times E'r^3/EI)] \tag{3}$$

or

$$\pi_1 = K \pi_2/(1 + 0.061 \pi_3) \tag{4}$$

Consider the two following pipes:

1. No. 1 (model): 4-in. diameter; modulus of elasticity, 10×10^6 psi (aluminum); wall thickness (smooth wall), 0.050 in.; moment of inertia = $t^3/12 = 1.0416 \times 10^{-5}$ in.^{4}/in.; $D^3/EI = 0.61443$.
2. No. 2 (prototype): 10-ft diameter; modulus of elasticity, 30×10^6 psi (steel); 8 gauge, 6- × 2-in. corrugation; moment of inertia = 1.15 in.^{4}/ft = 0.0958 in.^{4}/in.; D^3/EI = 0.60106.

Assume that both culverts are embedded in a soil with a modulus of soil reaction of 5,000 psi and that they are subjected to an average vertical pressure of 100 psi. Then, in the case of No. 1, $pD^3/EI = 61.443$ and $E'D^3/EI = 3{,}072.15$. In the case of No. 2, $pD^3/EI = 60.106$ and $E'D^3/EI = 3{,}005.30$.

By substituting the value for each pipe into Eq. 3 and by letting K = 0.083, we get the following:

No. 1

$$\Delta X/D = 0.083\ (61.443)/[1 + (0.061 \times 3{,}072.15)]$$

$$\Delta X/D = 0.02706 = 2.706 \text{ percent}$$

No. 2

$$\Delta X/D = 0.083\ (60.106)/[1 + (0.061 \times 3{,}005.30)]$$

$$\Delta X/D = 0.02706 = 2.706 \text{ percent}$$

Thus Spangler's deflection equation predicts exactly the same percentage of deflection for both the 4-in. pipe and the 10-in. pipe. This is the principle on which model analysis is based. If the individual pi-terms are the same, the results, regardless of size, will also be the same.

The properties of the soil and pipe that govern soil-structure interaction under static load have been defined, so models can be used to predict soil-structure interaction performance.

In most soil-structure interaction problems, the form of the equation is not known. If it were known, there would be little need to use model analysis. Therefore, one must select the primary independent variables that influence the phenomenon and place them in dimensionless pi-terms.

SIMILITUDE REQUIREMENTS FOR DEFLECTIONS UNDER HIGH FILLS

To illustrate the use of model analysis for a specific soil-structure interaction problem, we will use an example for determining culvert deflection under a fill that is high in comparison with the diameter of the culvert. The culvert is assumed to be long enough such that end effects can be neglected and that maximum stress in the culvert wall is below the yield point stress. The primary independent variables and dimensions involved are as follows:

Primary Independent Variable	Dimension
Culvert diameter, D	L
Pipe wall stiffness, EI	$FL^{-2} \times L^4/L = FL$
Constrained modulus of elasticity of the soil or modulus of soil reaction, M_s	FL^{-2}
Pressure applied at the level of the pipe because of the fill or other load above the pipe, P	FL^{-2}
Deflection of some point in the culvert, ΔX (horizontal diameter used)	L

It can be shown that these are all the variables that have a significant influence on the amount of deflection that a culvert will experience. It may be argued that such things as soil density, water content, and other soil properties must be included. The influence of these variables is included in the constrained modulus of elasticity of the soil. The constrained modulus is a function of soil density, water content, plasticity, soil type, grain-size distribution, and all other soil variables plus boundary conditions.

According to the Buckingham pi-theorem, there must be three pi-terms (five primary independent variables minus two dimensions). These pi-terms may be formulated as follows:

$$\pi_1 = \Delta X/D$$

$$\pi_2 = PD^3/EI$$

$$\pi_3 = M_s D^3/EI$$

or

$$\pi_1 = f(\pi_2, \pi_3)$$

If model analysis is to be used to predict the deflection of a full-scale pipe, all the pi-terms must be the same for the model as for the prototype structure, as previously illustrated in the example, or

$$\pi_{1_m} = \pi_{1_p}$$

$$\pi_{2_m} = \pi_{2_p}$$

$$\pi_{3_m} = \pi_{3_p}$$

where m refers to the model and p refers to the prototype or actual structure.

The model must be designed so that each pi-term for the model is the same as for the prototype structure. Sometimes deviations are necessary, but then distorted modeling techniques are encountered that complicate the analysis and will not be considered here. A more complete treatment of soil modeling is given elsewhere (19).

Distorted modeling methods are discussed in various books on engineering similitude. The modeling of soils by using distorted models may lead to unexpected problems because of the nonlinear nature of the soil culvert system.

SIMILITUDE REQUIREMENTS FOR WALL BUCKLING

Similitude requirements for wall buckling are not nearly as easy to satisfy as those for deflection and pressure. The moment of inertia, area of the pipe wall, and the yield point stress of the culvert material must be included. To get an exact model, not a distorted one, is very difficult because the corrugations of a metal culvert preclude the use of plane wall pipe as models. In deflection measurements, the area of the pipe wall has been shown to make very little difference if moment of inertia is constant. This can be seen by the elasticity solution of the problem and from model tests. However, in buckling problems, the area of the pipe wall or the radius of gyration of the pipe wall must be included. Because of the difficulty in obtaining an exact model for a corrugated metal culvert, model studies of wall buckling have not been very rewarding.

MODEL ANALYSIS OF DYNAMIC LOADING

Model analysis of dynamic loading becomes even more difficult in that the inertial properties of the soil-culvert system must also be modeled. When this is attempted, the density of the soil as well as the elastic properties must be modeled. A few investigators have modeled specific situations, but most of these studies have been associated with blast-shelter construction and will not be presented here.

EFFECTS OF SOIL DENSITY AND MOISTURE ON CULVERT DEFLECTION

As examples of what can be done with models, a few results will be presented. Figure 1 shows the results of a study to determine the effects of initial density of clay soil on the deflection that a culvert undergoes (1). As can be seen, the soil density has a considerable effect on the deflection. Figure 2 shows the effects that initial density of sand has on the deflection of the culvert. A decrease in density shows a marked increase in deflection for both sands and clays. Figure 3 shows the influence initial moisture content has on the deflection of the culvert in clay soils. As the moisture content increases, the deflection increases very rapidly. At a load of 50 psi, for example, the deflection at 20 percent moisture is approximately 35 times the deflection at 10.3 percent moisture. This is why density alone (even including grain-size distribution and Atterberg limits) is a poor indicator of soil stiffness in cohesive soils.

EFFECTS OF BACKFILL DENSITY ON STRESSES IN PIPE

In 1964, Watkins (2) presented the idea of differential soil density to release stresses in the pipe and pressures on the pipe. The soil around the pipe is compacted to a high degree of density, and the soil next to the pipe is left in a rather loose state to form a cushion around the pipe. Data were not presented at that time. Figure 4 shows the method proposed by Watkins for achieving the differential density.

Figure 5 shows the results obtained from two different studies (3) that used models. Both studies were made on the same 4-in. diameter 6061-T6 aluminum model. Both studies used the same soil (Ottawa sand) compacted to the same density in the same simulator. The only difference was in the manner in which the models were placed. The soil in Stankowski's study was placed before the model, and then the model was "jacked" into position. Insertion of the model appeared to compact the soil adjacent to the model to a slightly higher density; however, no measurements of density were made after model placement. The soil in Mohammed's study was "rained" around the model pipe. As soil particles fell, those hitting the very edge of the model were deflected away from it. The density of soil adjacent to the pipe was believed to be lower than the soil mass. Therefore, density of the soil immediately adjacent to the model in Stankowski's study is assumed to be higher than in Mohammed's study. As can be seen, there is a significant difference in stress because of the method of soil and culvert placement. The difference in soil density and pipe stress shown points out that a very

Figure 1. Variation in horizontal deflection in clay.

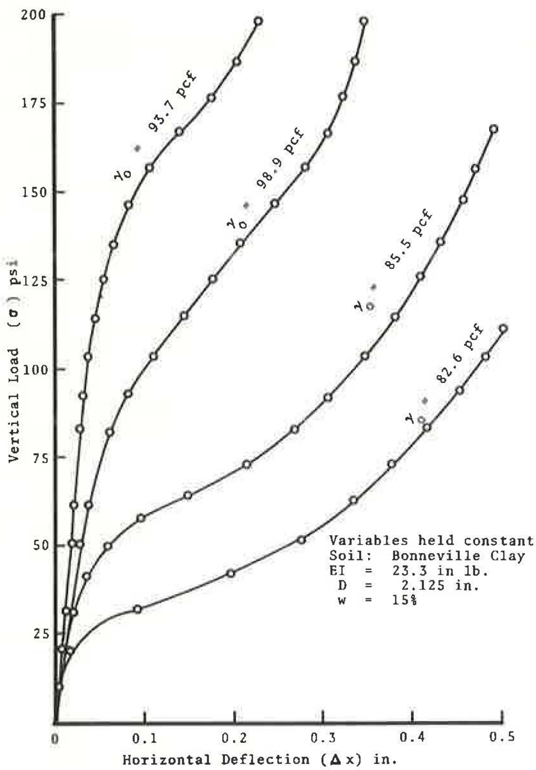


Figure 2. Variation in horizontal deflection in sand.

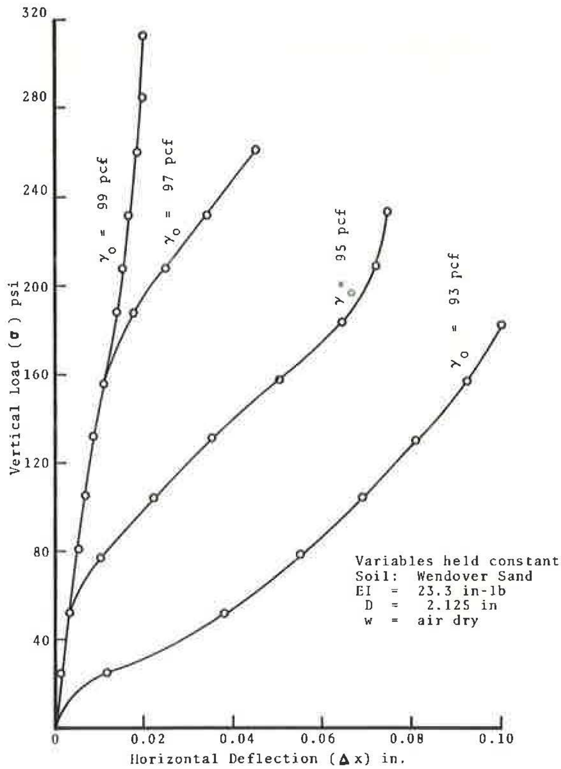


Figure 3. Effect of moisture on horizontal deflection.

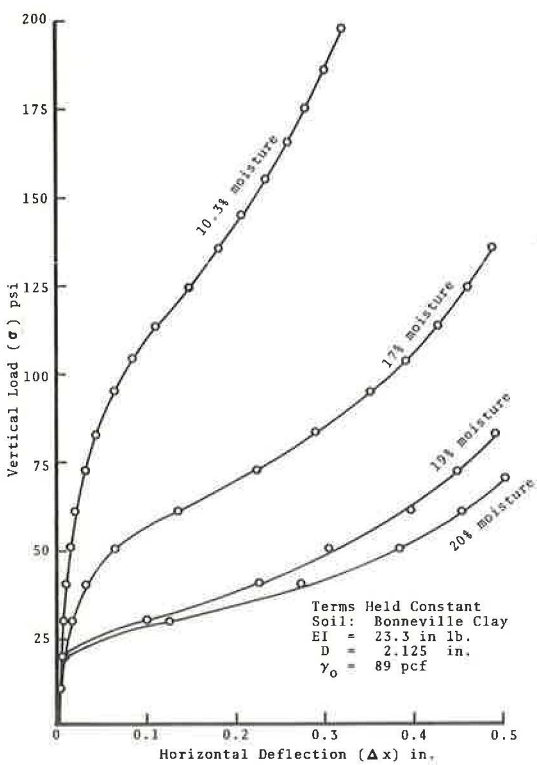
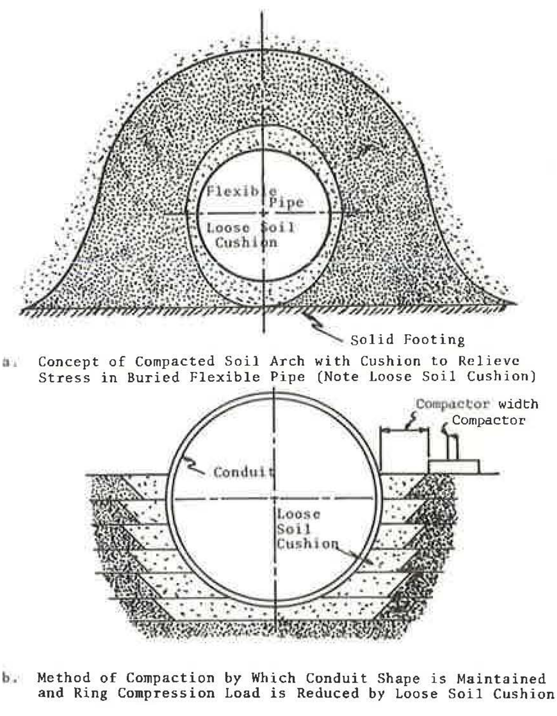


Figure 4. Watkins' method for reducing pressure on buried circular conduits.



a. Concept of Compacted Soil Arch with Cushion to Relieve Stress in Buried Flexible Pipe (Note Loose Soil Cushion)

b. Method of Compaction by Which Conduit Shape is Maintained and Ring Compression Load is Reduced by Loose Soil Cushion easy and economical method of "backpacking" may be achieved by making use of differential soil density; however, much more study is required.

IMPERFECT DITCH METHOD OF CONSTRUCTION

The imperfect ditch method of construction was one of the earliest methods used to reduce the loads exerted on an underground conduit. Figure 6 shows the usual method of installing the conduit by this method. The culverts that have been installed by using this method have used a compressible layer that is the same width as the culvert and placed almost directly above the culvert. Figure 7 shows the results of a study (3) made to determine the effect of the width and height of the compressible layer above the culvert on the stresses in the pipe wall.

The upper limit stress is the average of the absolute value of the stress plus two standard deviations. In this model study, the upper limit pipe wall stress in almost all cases was higher for an installation with a compressible layer than it was for no compressible layer at all. The reason for this is that the pipe tended to deflect upward into the compressible layer instead of flattening into an approximate elliptical shape. Figure 8 shows a summary of the deflections obtained.

The model was a 6061-T6 circular aluminum tube, 4 in. in diameter. The compressible layer was a common household sponge, with a thickness of $^5/_8$ in. and widths of 4, 5, 6, and 8 in.

The data presented in Figure 7 are not intended to discredit the validity of the imperfect ditch method of construction. The figure does, however, serve as a warning that, if the imperfect ditch is not properly designed, stress and deflection conditions can be more severe in a pipe installed by this method than in one installed by normal procedures. The compressibility of the sponge used in the model study was much higher than most material used in actual field construction. The higher compressibility of the imperfect ditch in the model would induce higher stresses because of the vertical elongation that may not be experienced in most field structures.

Several other studies, in which different compressibilities of the compressible layer have been used, have shown that the imperfect ditch is effective in reducing loads on the structure.

MULTIPLE PIPE INSTALLATIONS

Model analysis can also be applied in other ways. Figure 9 (4) shows a photoelastic model that was used to determine the stress concentration caused by multiple culverts. Similitude requirements can be easily established for such studies. Figure 10 shows a plot of the radial pressure-applied pressure versus spacing between the model culverts. The numbers in parentheses are the values obtained for single culverts. This type of soil-structure interaction model is extremely sensitive to "fit" of the culvert model in the plastic. Figure 11 shows a plot of shear stress-applied pressure versus model spacing. Solutions such as those shown in Figures 10 and 11 are plane stress solutions, whereas most model solutions are probably closer to a plane strain solution. The difference is usually insignificant when compared with the accuracy with which such variables as soil properties can be determined.

Figure 12 shows a comparison (1) between stresses and deflections obtained from a model analysis. The values were obtained from the elasticity solution of Burns and Richard. Results shown in Figure 13 were obtained by the technique used to get the data shown in Figure 12. It shows the results of a study to determine the pressure concentration (radial pressure and applied pressure) caused by multiple pipes.

The pressure acting on the outside of the pipe, the stress in the pipe wall, and the deflection of the pipe were obtained by fitting a Fourier series to a general loading distribution as shown in Figure 14. The Fourier series coefficients were determined from measured strains and displacements on the inside of the pipe. No pressure transducers were placed on the outside of the model to disturb the pressure distribution.

Currently, most culverts are designed to carry considerably more load than is actually imposed on them. The designer should not worry about the strength of multiple installation culverts. Even with the increased stress induced by multiple installations,

Figure 5. Effect of placement method on circumferential stress.

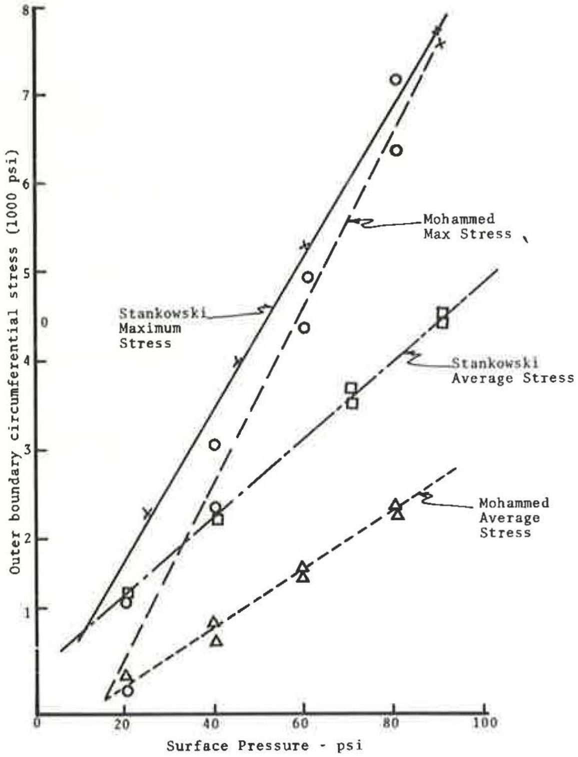


Figure 6. Imperfect ditch construction.

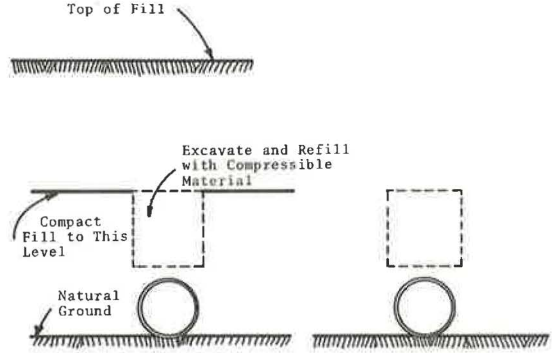


Figure 7. Variation of circumferential stress with compressible layer parameters.

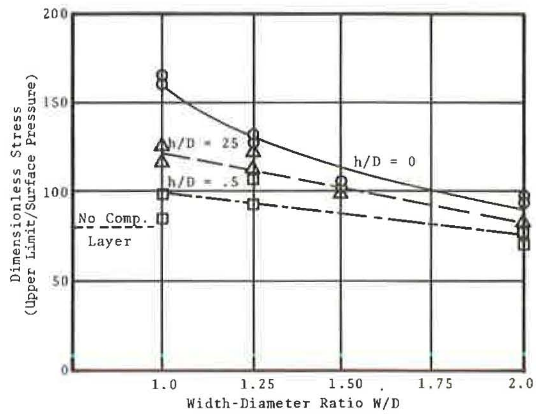


Figure 8. Effect of location of imperfect ditch on deflection of horizontal and vertical diameters (surface pressure = 60 psi).

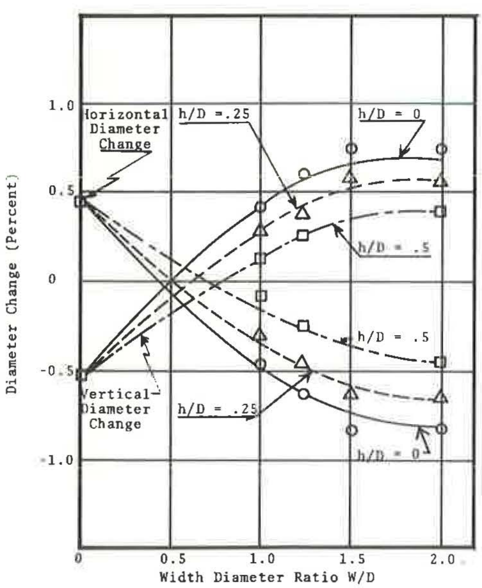


Figure 9. Photoelastic model.

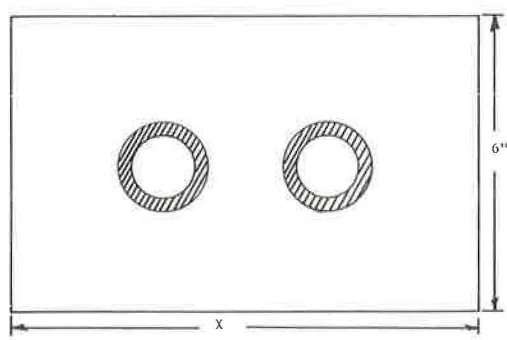


Figure 10. Experimental radial interface pressure concentration factors.

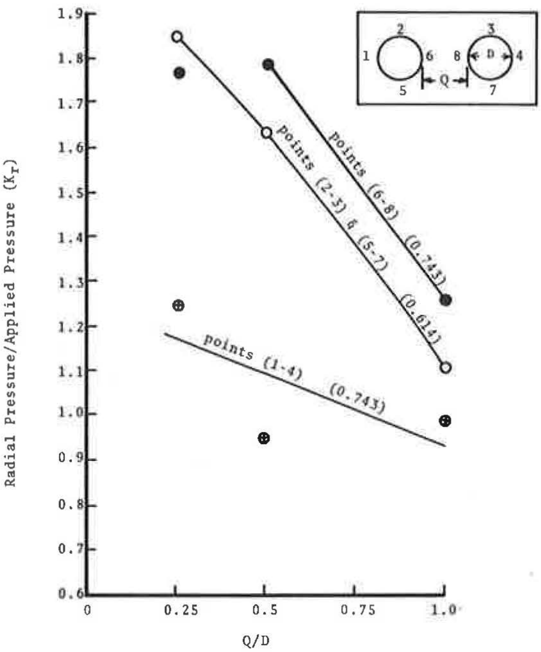


Figure 11. Experimental shear stress concentration factors.

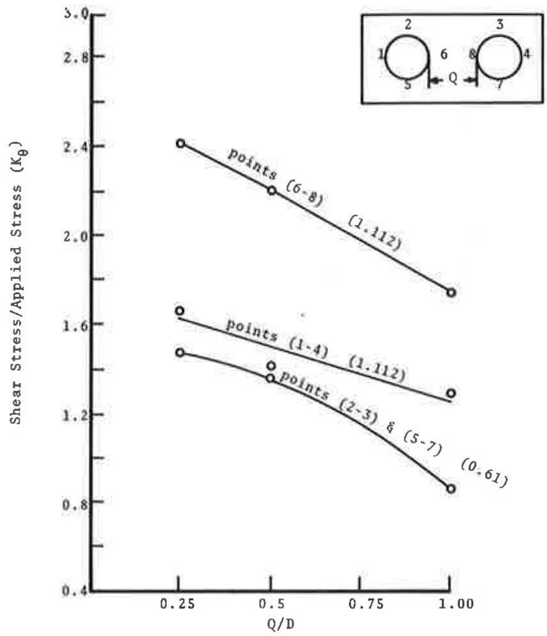


Figure 12. Comparison of predicted and recorded horizontal diameter changes for the single cylinder system.

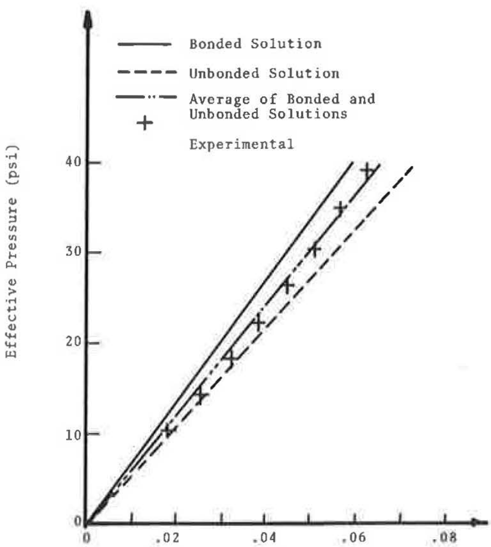
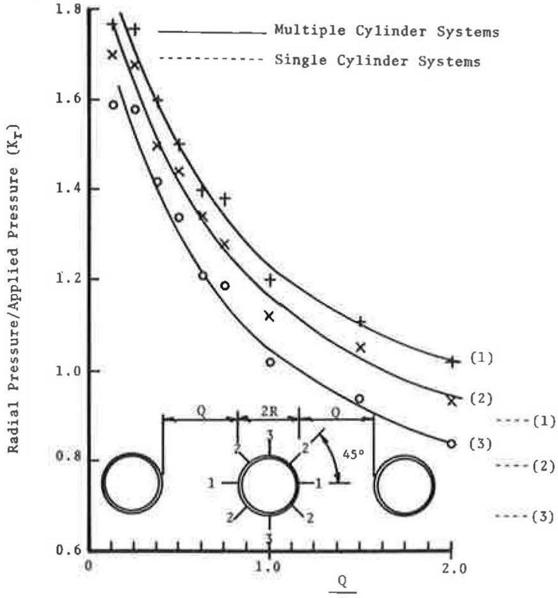


Figure 13. Experimental radial interface pressure concentration factors.



most culverts designed by current methods will carry the load with an adequate factor of safety. However, as research and development continue and more refined and accurate solutions of the loads on pipe become available, the increased stresses due to multiple installations will have to be considered.

PRESSURE DISTRIBUTION ON PIPE

In 1941, Spangler (5) presented the Iowa equation for determining the deflection of a flexible pipe. The pressure distribution used by Spangler was arrived at by measuring the radial pressure on the pipe with friction ribbons. The steel ribbons were placed on the pipe before the fill was placed. After completion of the fill, the ribbons were pulled out from under the fill, and the pressure was assumed to be related to the coefficient of friction and the force necessary to pull the ribbon out from under the fill. The ribbons were calibrated in the laboratory before they were installed on the structure; however, before measurements are made, many things can change the calibration.

It is highly probable that the friction ribbons measured only the radial component of pressure acting on the pipe. The shear component was neglected. This is a common mistake with most field measurements that use some type of pressure transducer on the outside of the pipe. Only the radial pressures are measured.

The pressure distribution used by Spangler is shown in Figure 15. This pressure distribution is adequate for low-density soils that have a high value of Poisson's ratio; however, for high-density granular soils with a low value of Poisson's ratio, the pressure distributions appear to change somewhat. These conclusions are based on a theory presented by Burns and Richard, which involves elastic media. Figures 16 and 17 show the pressure distribution obtained for two different conditions. Figure 16 shows the pressure distribution for a low-density soil (low value of constrained modulus) and a high value of Poisson's ratio. This condition would represent the low-density clay that Spangler did most of his work on. For this case, the pressure distribution obtained from the elastic theory is approximately the same as the pressure distribution measured by Spangler. Figure 17 shows the pressure distribution obtained for a high-density soil (high value of constrained modulus) and a low value of Poisson's ratio. This condition represents a well-compacted granular soil.

To determine whether the pressure distribution acting on the pipe changes for granular soils, we compared data obtained by Stankowski (6) with the data shown in Figure 17. Figure 18 shows the results obtained. They show that the pressure distribution does change from that used by Spangler. The major change is in the horizontal pressure distribution. Spangler's pressure distribution has the horizontal pressure acting only over a 100-deg section of the culvert. The measured pressures shown in Figure 18 act over essentially the entire 180 deg. The measured pressures, therefore, present more resistance to horizontal movement of the pipe than that used in Spangler's pressure distribution. The measured vertical pressure also has a dip in the pressure distribution at the center and at the edge of the pipe. This would reduce the magnitude of the vertical load that is exerted on the pipe. This dip in pressure seems to become more pronounced as the constrained modulus of elasticity of the soil gets higher.

If the modulus of the soil reaction E' is determined by using the calculated values from the theory of elasticity for pressure and deflection at the horizontal diameter, the difference in pressure distribution makes the Iowa formula (Eq. 1) predict too much deflection for soils with a high value of constrained modulus and low value of Poisson's ratio. For example, the Iowa formula predicts approximately 40 percent more deflection than Burns and Richard's (full slippage) elastic theory for a soil with a high constrained modulus (10,000 psi) and low Poisson (0.1).

On the basis of the information presented here, it cannot be said that the Iowa formula should be modified for dense granular soils. It does suggest, however, that more study is needed in this area. Field studies that are made should be instrumented so that shear stresses, as well as radial pressures acting on the pipe, can be measured in order for the necessary verification to be obtained.

Figure 14. General loading components.

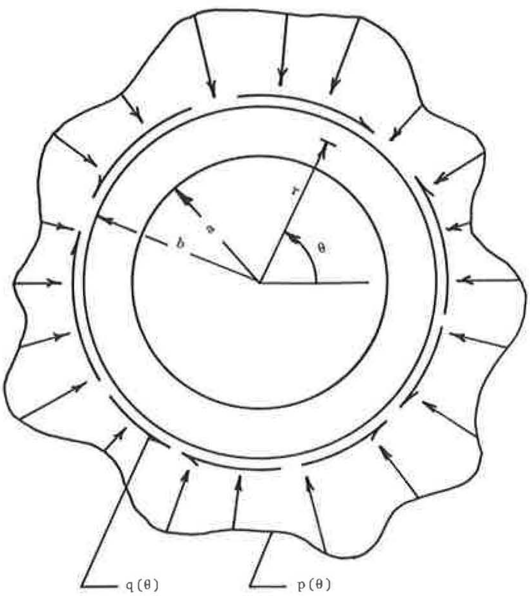


Figure 15. Assumed distribution of pressure on flexible culvert pipe.

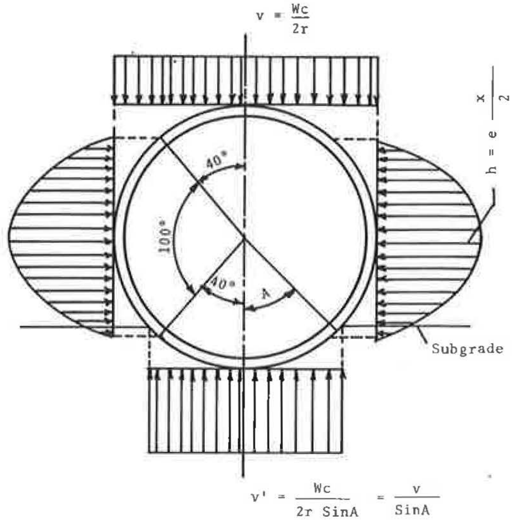


Figure 16. Pressure distribution for a low-density soil.

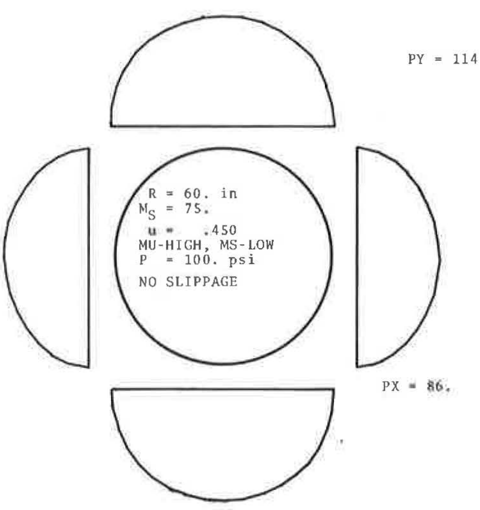
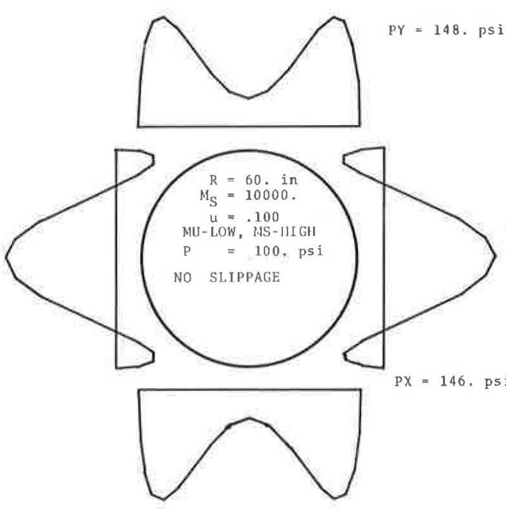


Figure 17. Pressure distribution for a high-density soil.



SOIL PROPERTIES DETERMINATION FROM MODEL STUDIES

The author, in another report (7), established the relation between the modulus of soil reaction and the constrained modulus of elasticity. In establishing this approximate relation, he used the bonded shell equation of Burns and Richard's solution (8) of a pipe embedded in an elastic medium. He concluded that the modulus of soil reaction can be approximated by

$$E' = 1.5\ M_s \qquad (5)$$

If the unbonded shell solution of Burns and Richard had been used, it would have been shown that

$$E' = 0.7\ M_s \qquad (6)$$

It has been shown by Stankowski (6) and Nielson and Statish (9), who used model studies, that the actual modulus of soil reaction of soil is between the predicted modulus of soil reaction by the bonded shell and the unbonded shell solution. Figure 19 shows the results of a confined compression test used to determine the constrained modulus of elasticity. Figure 20 shows how the modulus of soil reaction varies with pressure for this same soil at the same initial density. If an average value of the modulus of soil reaction is used, it can be shown that

$$E' = 0.8\ M_s \qquad (7)$$

Because the modulus of soil reaction is directly associated with Spangler's pressure distribution (Fig. 15), any question concerning the validity of the pressure distribution on the pipe will also be directly applicable to the modulus of soil reaction. If the pressure distribution acting on the pipe is different from that used by Spangler, modification of the modulus of soil reaction may also be needed.

SPECIAL PROBLEMS

Model analysis has been applied to many soil-structure interaction problems. Watkins has applied model studies to determine the minimum necessary height of cover over a conduit for the safe crossing of construction equipment (10), determination of pressures on culverts under stockpiles (2), and determination of the movement of soil around a pipe (11). Linger (12) has applied model studies to determine how the flexibility of a flat-top buried structure affects the redistribution of pressure on the structure.

FIELD OR FULL-SCALE TESTS

Many investigators have made attempts at field studies to determine or verify certain phenomena. Some of these studies have been associated with determining the pressure on the culvert and the corresponding displacement. One variable almost invariably neglected is the shear stress acting on the culvert. Measurements of shear stress are difficult to obtain on an actual field installation, whereas radial pressures acting on the culvert are relatively easy to obtain. A significant part of the load is neglected if only the radial pressures are measured.

Other studies have been made to determine the maximum load that a culvert can carry and to determine how large a culvert can be installed without failure.

One of the earliest applications of the imperfect ditch method of construction reported in the literature (13) involved a 48-in. concrete sewer pipe. Twenty years after the construction of the sewer, the height of an embankment above a ¼-mile section was increased from 60 to 78 ft without making any changes in the pipe.

Davis and Bacher (15) reported on California's culvert research program in which field studies and observations were made on several culverts. Different backfill designs were employed including an imperfect ditch construction and a variation therefrom in which a compressible layer of baled straw surrounded the culvert.

In one case in which a layer of baled straw surmounted a rigid culvert, horizontal and vertical pressures were found to be much less than in another in which no compressible layer was used. When baled straw was placed above a flexible conduit, the profile of the average induced pressure per foot of fill showed super-hydrostatic pressure bulbs at the invert. Effective densities at the crown, sides, and midpoints of the lower quadrants were about one-half that of the embankment. With increasing fill heights, maximum effective densities were observed to decrease and minimal densities to increase "so that some tendency toward a more uniform distribution is indicated." The case where a layer of baled straw surrounded the conduit "showed the most promise, inasmuch as the lateral pressures were almost negligible and vertical (effective) densities were about half that of the embankment."

An 18.5-ft diameter structural plate culvert under 83 ft of cover was reconstructed using the imperfect ditch method (16). The rebuilt culvert and the fill were instrumented such that pressure and deformation measurements could be taken. The behavior of the rebuilt culvert was observed to be significantly different from that predicted by the Marston-Spangler theory. Some of the most important conclusions of this study were as follows:

1. The predicted average vertical pressure, by Marston's theory, at the straw level was almost double the average measured pressure.
2. The shear-plane method may be used between the straw level and the conduit level to predict the average vertical pressure at the top of the conduit.
3. The maximum average vertical pressure on the conduit was approximately one-half of the overburden pressure. This is comparable to the effective densities reported by Davis and Bacher (15).
4. Lateral pressure on the side of the conduit was found to be substantially larger than the average vertical pressure.
5. A reduction in both the horizontal and vertical diameters was observed; however, at certain locations it appeared that the culvert may have deflected upward into the compressible layer.

FULL-SCALE TESTS FOR DETERMINATION OF FAILURE

Watkins and Moser (17) conducted tests on full-size pipe to determine the failure mechanism of pipes. Figure 21 shows a cross section of the test cell used. Spangler stated that the test cell does not represent field conditions and that the data obtained are a function of the test cell as well as the soil and pipe properties. Figure 22 shows some of the data obtained by Watkins and Moser, which are plotted in dimensionless form. If the three points at very low deflections and a PD^3/EI of approximately 400 are neglected, most of the data appear to plot approximately as a smooth curve.

The effect that the test cell would have would be to increase the stress in the σ_1 direction shown in Figure 21. The increase in σ_1 should have the effect of increasing the elastic properties (modulus of elasticity) of the soil. There seems to be a compensating effect in that the length of the test section of the cell was quite short in comparison to an actual field installation. This short section would have the effect of reducing the σ_2 stresses, which would have a decreasing effect on the elastic properties of the soil (modulus of elasticity).

For pipe deflections of less than about 5 percent, the change in elastic properties of the soil causes only small changes in the pressure at which failure occurred (approximately 15 percent change in pressure from failure and no deflection to failure at 5 percent deflection). If the cell boundaries caused as much as 100 percent change in the constrained modulus of the soil, the pressures at which failure occurred in the cell would still be approximately the same as the failure pressure in actual field installation. Placement method, soil friction plus cohesion, moment of inertia, and area of the pipe wall will probably shift the incipient failure line in Figure 22 up or down.

Because of the compensating effect of the stresses on the constrained modulus and the low sensitivity of buckling to the constrained modulus, it is believed that the data for buckling, at least at low deflections, are as good as any that are available.

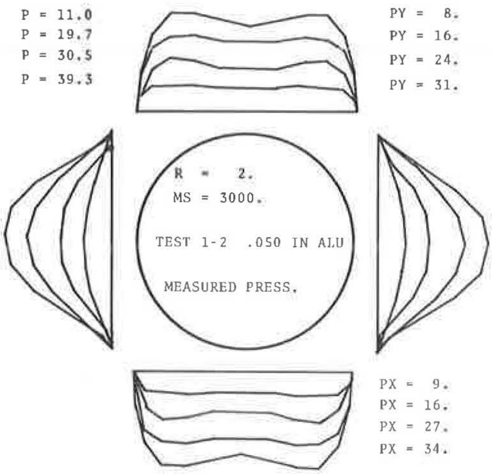


Figure 18. Horizontal and vertical pressures on model culvert.

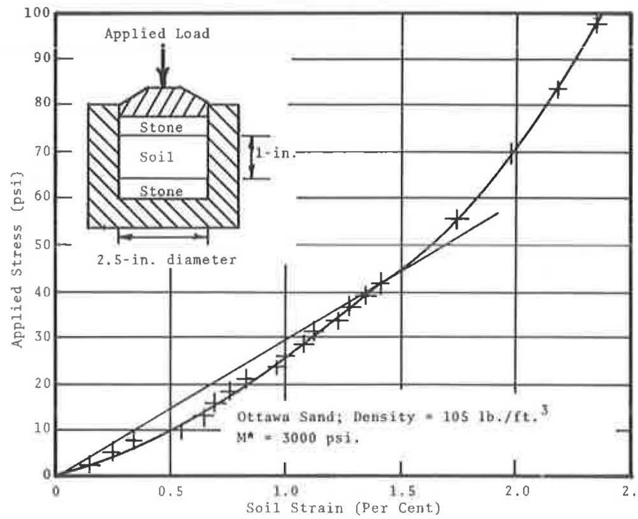


Figure 19. Confined stress-strain curve.

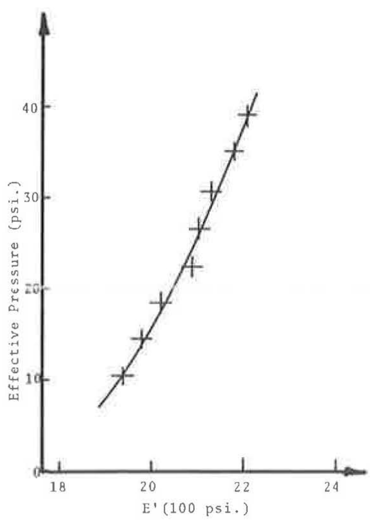


Figure 20. Variation of the modulus of horizontal soil reaction.

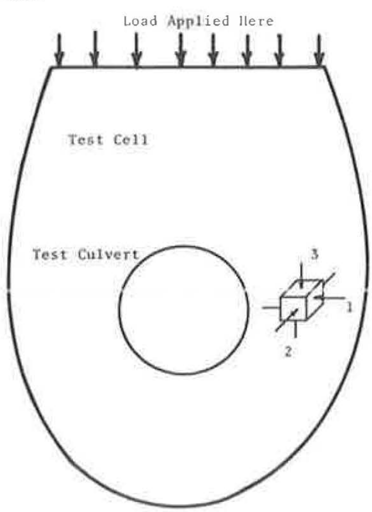


Figure 21. Watkins and Moser's test cell.

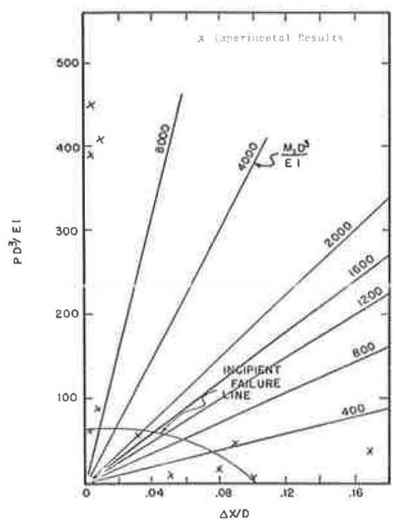


Figure 22. Load deflection obtained from data by Watkins and Moser.

Figure 23. Large culverts in British Columbia (furnished by Chriss Fisher, Armco Corporation).

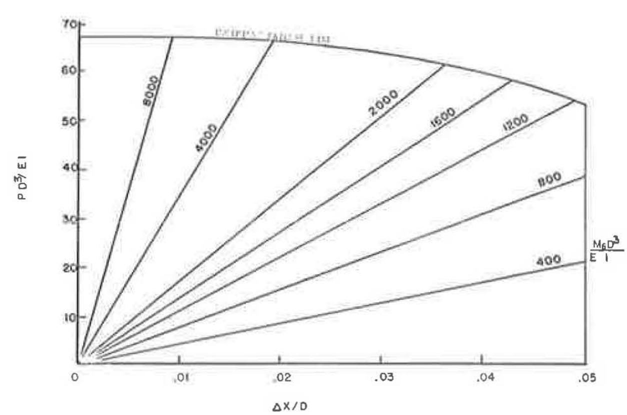


Figure 24. Design chart for circular conduits.

LARGE-SPAN TESTS

Fisher (18) has installed several culverts with 40-ft spans. There have been no failures, and the measured deflections are usually less than 1 in. The secret of the success of these large spans may be in the installation procedure. Fisher used what he calls a thrust beam along the side of the culvert. Figure 23 shows the installation of one of these large culverts.

PLASTIC PIPE

The Bureau of Reclamation in Denver, Colorado, is conducting field experiments on plastic pipe. Because these studies are not complete at this time, no data are available yet.

DESIGN OF CIRCULAR CULVERTS

The way in which Watkins and Moser's (17) large-scale test data are plotted in Figure 22 forms the basis for a possible design procedure. The M^*D^3/EI lines shown in Figure 22 are determined from the elastic theory for analysis of pipe presented by Burns and Richard (8). Most of Watkins and Moser's data plot very close to calculated M^*D^3/EI values from the elastic theory (9). Watkins and Moser's data can be used to delineate an upper boundary. The resulting design chart is shown in Figure 24. As better failure data become available, which take into account all soil and pipe properties, the upper boundary can be adjusted accordingly. Future work may show that one upper boundary is not sufficient to account for all variables. Examples for the use of the design chart can be found elsewhere (9).

SUMMARY

In summary, a great deal of work has been directed toward a better understanding of soil-structure interaction phenomena. Much more research is needed, but an organized approach needs to be made. At the current time, many individuals are conducting research directed toward a better understanding of the performance of underground structures. Much of this research would have been far more valuable if only a few more dollars had been spent for proper instrumentation.

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