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HISTORICAL DEVELOPMENT OF THE SOIL-STRUCTURE INTERACTION PROBLEM

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The term "soil-structure interaction" refers to the general phenomena involved in the behavior of buried structures as a result of the properties of both the structure and the surrounding medium in response to loading imposed on this system. This subject has been of technical interest for many decades, and some of the basic concepts and design methods in use today were initiated in the early 1900s. More recently, as the cost and importance of buried structures have increased, new information has been accumulated through research, analysis, and testing. However, much of this knowledge has still to be adapted to design practice. This paper traces the historical development of the subject of soil-structure interaction.

• THE subject of earth pressure and its application in engineering design have been discussed since the time of Rankine and Coulomb. Since that time considerable effort has been expended in the determination of loads on retainment and underground structures. The term "soil-structure interaction" is used because of the indeterminate effects of the interaction between a structure and the soil. This indeterminancy is the result of the distribution and magnitude of earth pressure varying with the amount and type of deflection of the structure. The phenomenon of an earth pressure that is related to soil deformation was recognized by Rankine and is referred to as the active and the passive Rankine state in the analysis of horizontal earth pressures. It is, of course, obvious that the general phenomenon is not adequately defined by this definition. The soil properties and condition, the structural geometry and rigidity, and the characteristics of the loading all affect the magnitude and distribution of earth pressure on a structure. All of these characteristics are combined into the very complicated, indeterminate problem of soil-structure interaction.

Until recently the design of buried structures was based primarily on the loading produced by the overburden material on the structure, with only the shallow buried structure receiving any significant live load. The advent of nuclear weapons and the resulting need for protective structures brought a new dimension to the study of loads on buried structures with loadings that are orders of magnitude greater than earlier loadings. Almost simultaneously, the development of the Interstate highway program began requiring more and larger highway culverts with greater fill heights and culvert loadings than ever before.

The increase in highway construction and the national defense requirements renewed the interest in underground structures. This interest has resulted in large-scale research and development projects directed at the problem of soil-structure interaction. It has also made us aware of the shortcomings and unknowns in the design of underground structures.

Most important, however, this increased research effort has resulted in a corresponding increase in the level of knowledge on the subject. Moreover, the subject has received so much attention that it is difficult to keep abreast of the technical advances. As a result of these great strides in research, development, and design knowledge of

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soil-structure interaction, it is important to occasionally review the status of what we know, or think we know, about the subject. The objective of this symposium is to review the state of the art of soil-structure interaction knowledge in order to stimulate current research and development on this subject.

The soil-structure interaction symposium has been broadly divided into the subjects that generally provide the topical areas for design and research. Each of these broadly defined subjects has been discussed in detail by the other authors contributing to this symposium. However, it is the purpose of this paper to present a comprehensive coverage of the historical background on the subject of the design of underground structures, a subject often referred to as the soil-structure interaction problem.

For convenience, the subject has been divided into two major areas: the development of concepts in classical culvert design and the development of phenomenological concepts in the response of buried structures. These two subject areas are intimately related because both deal with the same subject. However, this division allows the reader to follow the development of soil-structure interaction with a clearer perspective of the research and development efforts.

The first area, classical culvert design concepts, traces the development of an approach that has attained a level of acceptance that is characteristic of traditional earth pressure theories. The improvements and refinements in this approach are significant and have formed the basis for the design of buried conduit. These theories are still applicable and are used currently in design.

The second area, phenomenological concepts, traces the various studies that have made significant developments in the understanding of the soil-structure interaction problem. Many of these studies have been milestones in the understanding of the phenomenon, but the application of the results of these studies is sporadic and often lost in the confusion of technical advances.

The references discussed in this paper are not inclusive. An extensive bibliography concerning the period 1900 to 1968 was compiled by Krizek, Parmelee, Kay, and El-naggar (1).

DEVELOPMENT OF CONCEPTS

Not enough is known about soil-structure interaction to predict with any degree of accuracy the ultimate load-carrying capacity of buried structures. In the design of underground structures, the loading is usually based on empirical relations that are not fully understood. If the loading on the underground structure is determined from classical earth pressure theory, large variations can be expected between the actual and the theoretical loadings. These variations can result from the underground structure deflecting more than the adjacent soil and thereby causing a reduction in the pressure transmitted to the structure with a corresponding increase in the pressure carried by the adjacent medium. Conversely, under load, the structure may not deform as much as the adjacent soil, and the resulting redistribution can produce an increase in load on the structure and a decrease in the pressure carried by the adjacent medium. These two opposite conditions are similar to the active and passive earth pressure conditions defined by Rankine more than 100 years ago. The difference in the conditions is determined by the direction of the soil stress produced by the soil movement along some slippage plane. Because of the elegance of the classical earth pressure theory, it is understandable that the earliest approaches to the loading of buried structures should take a form similar to the Rankine earth pressure theory. The two opposite conditions of soil-structure interaction loading are characterized by the soil-structure systems shown in Figures 1 and 2.

The amount of pressure redistribution is very difficult to quantify and depends on the degree to which the relative deflection along the shearing plane has mobilized the soil shear strength. From this it is apparent that identifying the location of the shearing plane and the amount and type of stresses induced along the shearing plane is an important part of defining the problem. .

In the case of a large underground structure deflecting under load, the soil at the center of the roof span of the structure displaces with respect to the soil over the supports and also with respect to the adjacent soil in which it is buried. Because of the

differential deflection of the various parts of the structure and the relative flexibility of the soil and the buried structure, the soil-structure interaction phenomenon will occur as a redistribution of pressure among various segments of the structure in addition to the redistribution of load from the structure to the adjacent soil. This simplification of a very complicated problem is shown in Figure 3.

Classical Concepts

Marston was the first to recognize that the loading on an underground structure is dependent on the interaction of the structure and the surrounding soil. In 1913 he published the Marston theory on soil loads on drainage pipes (2). This theory was based on a prism of soil whose movement developed the forces shown in Figure 4 as it imposed a load on the underground structure. This theory clearly took into account the relative deflection of the pipe and the settlement of the soil. However, the design of the buried pipe was based on vertical loads only and was only applicable in the design of buried rigid pipes such as clay tile or concrete pipes.

The earliest development of flexible conduit design criteria was based on empirical equations developed by using the results of the 1926 American Railway Engineering Association investigation (3). Tables were developed for the necessary pipe thickness and diameter for various heights of fill. The design tables were based on the assumption that failure occurred when the pipe deflection reached 20 percent of the diameter. For design, the deflection was limited to 5 percent, thus providing a safety factor of 4. It is interesting to note that no attempt was made to correlate the load-carrying capacity with soil characteristics, and therefore there was little evidence of any understanding of soil-structure interaction. It is also interesting to note that the original fill height versus pipe requirement table was the forerunner of the gauge tables commonly used today.

As highway construction increased during the 1930s, the use of larger and more costly drainage structures also increased. The need for a more rational concept for the design of flexible pipes was observed by Spangler, a former student of Marston. Consequently in 1941, Spangler (4) published his Iowa formula for predicting the deflection of buried flexible pipe. Spangler introduced the first well-defined soil-structure interaction concept (Fig. 5). This concept recognized that a passive type of soil pressure is developed by the horizontal expansion of the pipe, which allowed the pipe to carry more load with less deflection than in the unrestrained condition. Moreover, he proposed that the deflection might be used as a basis for determining the magnitude of the horizontal pressure developed on the sides of the pipe. He defined the proportionality constant between the pipe deflection and the developed pressure and proposed limiting values for use in design. This method was the first procedure that required an evaluation of the necessary soil properties for application in design.

In 1960, White and Layer (5) proposed the ring compression theory for the design of flexible buried pipes as shown in Figure 6. This theory assumes that the ring deflection of the structure is negligible and that the failure occurs by the crushing of the pipe walls. Model tests were conducted separately by Meyerhof (6) and Watkins (7) to evaluate the ring compression theory. The results of these studies showed that failure could result from an additional parameter, that of the buckling of the culvert wall (Fig. 7).

Further studies by Watkins (8), Meyerhof and Baikie (6), and Meyerhof and Fisher (10) resulted in the further refinement of structural response in terms of the deflection, crushing, and buckling aspects of the buried structure. However, in some of these studies, loosely defined soil terms such as "good backfill," "compressible soil," and "plastic soil" appear in the description of formulas and coefficients.

It is apparent that by the middle 1960s extensive studies had defined the problem and isolated the important parameters, but a complete definition of the parameters did not exist. In 1967, in an attempt to further clarify the interaction of the soil characteristics and the deflection of the structure, Nielson presented a theory for determining loads on buried conduit by an arching analysis (11). The proposed method used an adaptation of the Spangler deflection equation, but, despite the apparent good agreement with the experimental data studied, little use has been made of this novel

diversion from the classical Marston procedure. The proposed arching condition is shown in Figure 8.

An interesting aspect of the research and design procedures is the way in which generally accepted methods treat either rigid structures or flexible structures, with adequate procedures being available for each. However, only limited research has been directed toward development of a comprehensive design procedure covering the full range of pipe stiffnesses.

Phenomenological Concepts

Even though soil-structure interaction phenomena are still not completely understood, it was recognized during the early studies that the overall compressibility of the structure relative to the soil it replaces is important. Terzaghi treated this phenomenon in considerable detail in his trapdoor tests (12). This was one of the first papers to comprehensively evaluate the stress distribution on a structure in a fully buried condition. Terzaghi discusses the fundamental assumptions of the researchers who contributed to an understanding of the problem (13): Engesser (1882), Bierbaumer (1913), Coquot (1934), and Vollmy (1937). The principal contribution of these studies was to delineate the formation of the soil surface along which the soil arching stresses were mobilized (Fig. 9).

One of the next major milestones was a paper by Whitman, which reported on the results of a buried dome study in which the soil was simulated by a uniformly placed granular backfill (14). These tests were a part of a program that set an example for many of the tests that followed in the study of buried structure responses.

The requirements for buried structure design criteria resulted in a unique conceptual approach developed and presented by Newmark and Haltiwanger (15). This publication advanced many new ideas and provided the impetus for much of the research that followed.

In 1964, the state of the art of soil-structure interaction was reviewed at a symposium held at the University of Arizona (16). The participants at this symposium discussed in detail the various aspects of the phenomenon. A paper by Triandafilidis et al. (17) delineated the important variables of soil-structure interaction in a series of tests performed on vertical cylindrical and disk structures designed to separate arching stresses from sidewall friction effects. The results of this study provided the necessary quantitative data to enable researchers to make an analytical relation between structure stiffness and medium stiffness and the load on the structure.

At this symposium, Luscher and Hoeg (18) presented the results of a study that discussed the uncertainty in the lateral pressures acting at the sliding surface. Considerable attention was given by these authors to the assigned values of the at-rest and active pressure coefficients used by other investigators. The results of a study by Donnellan (19) were reported, which demonstrated the effect of depth of burial on the load-carrying capacity of a cylinder. Donnellan's study defined the shallow and deep burial conditions and the effect of burial depth on the deflection behavior of rigid and flexible cylinders. An example of these results is shown in Figure 10.

Additional studies reported at this symposium by Selig (20) defined the methodology for the measurement of soil pressures and deformations with great accuracy. This was an important step forward in the research on soil-structure interaction. It was this aspect that implied that soil tests could be used to evaluate and define the necessary properties for the design of soil-structure systems. Researchers were quick to begin studies of the effect of soil characteristics on the response of buried structures. A notable example of this effort was one of the studies of Allgood (21). This research presented a method for determining deflections and critical buckling loads based on the one-dimensional confined compression modulus of the soil. From this research, it was apparent that we had a handle on the problem of the interaction of the structure and the soil. The next obvious step was to develop the means of modifying the pressure on the structure by modifying the characteristics of the surrounding soil. This approach had been tried by Spangler (22) with considerable success but without any quantified design criteria.

Figure 1. Active soil pressure condition.

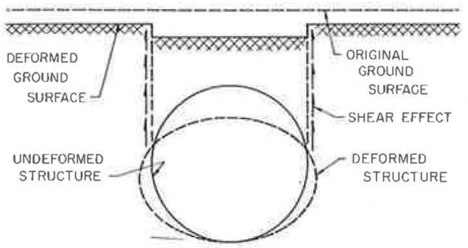


Figure 2. Passive soil pressure condition.

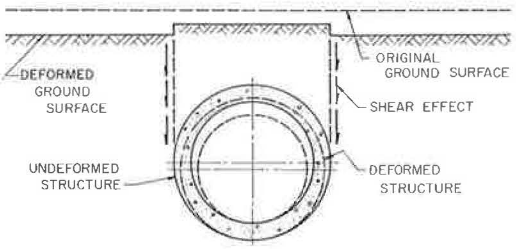


Figure 3. Soil pressure redistribution.

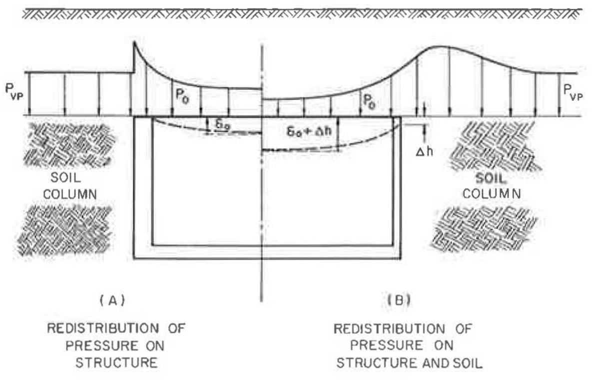


Figure 4. Marston theory of soil loads on rigid buried pipes.

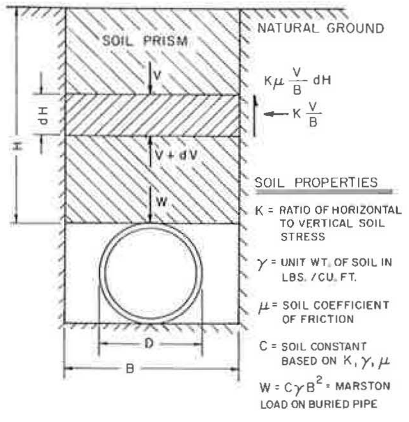


Figure 5. Loading assumptions for the Iowa formula.

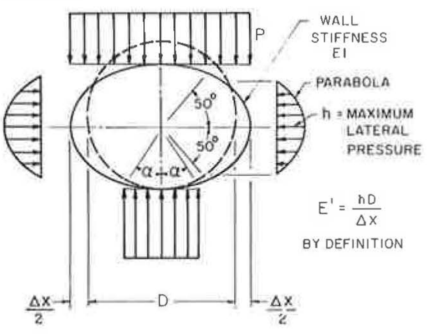


Figure 6. Ring compression theory for design of flexible pipe embedded in dense soil.

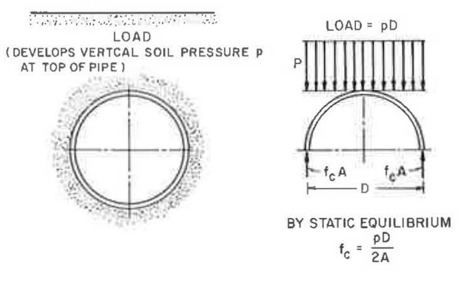


Figure 7. Ring buckling curves for buried flexible pipes.

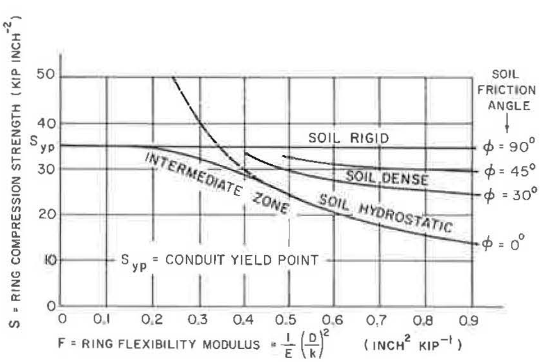


Figure 8. Free-body diagram for arching analysis.

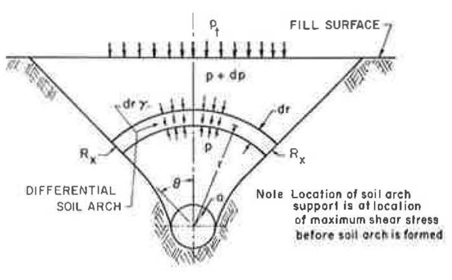


Figure 9. Formation of soil arching stresses.

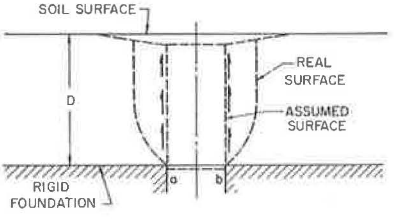


Figure 10. Normalized radial displacement of horizontal cylindrical structure (diameter/thickness = 114).

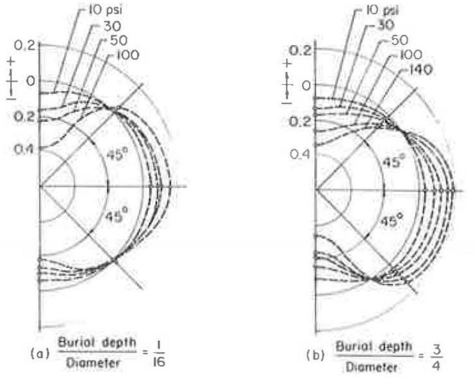


Figure 11. Effective density profile for standard backfill.

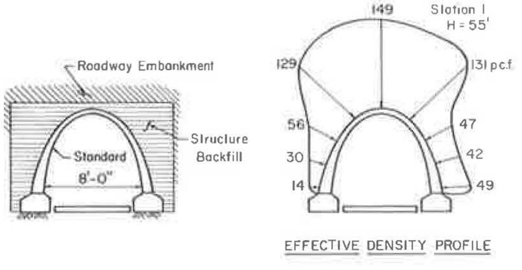


Figure 12. Effective density profile for uncompacted backfill over culvert.

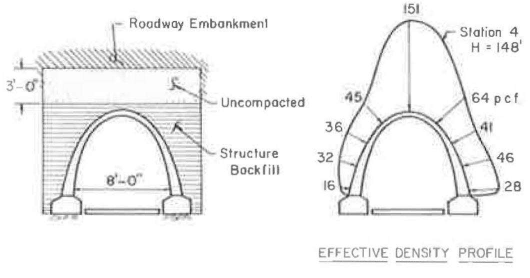
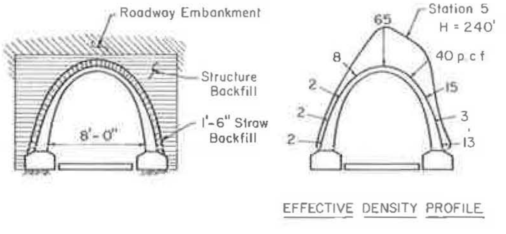


Figure 13. Effective density profile for straw backfill adjacent to culvert.



After the state of the art was advanced further, this procedure was explored once again by the California Division of Highways in an extensive research program that included the measurement of soil pressures on several large full-scale culverts with various conditions of the surrounding media. These results were reported by Davis and Bacher (23) and present an interesting characterization of the changes that occurred during the development of further insight into the soil-structure interaction phenomenon. The changes produced in the soil-structure interface pressure in this study by using the soft "backpacking" material are evident in Figures 11, 12, and 13.

SUMMARY

The problem of soil-structure interaction is illustrated by the design requirements for culverts to carry tremendous overburden fill heights and for complex buried structure systems to resist large surface loadings. The problem is further complicated by the scarcity of failures attributable to design shortcomings and the difficulty in evaluating a failure when it does occur.

Current design practice is based largely on work conducted in the 1920s and 1930s, and, despite the success of these practices, they are empirical in nature and depend heavily on experience and engineering judgment. However, recent refinements in these procedures have made possible much more daring uses of soil-structure interaction concepts.

Design engineers now have enough confidence to construct soil-structure systems in which the soil pressures are controlled by the backfilling techniques or the backfilling materials. This concept seems to have great potential, but the irony of this "breakthrough" is that it was first presented by Spangler and Marston as a result of their first tests on buried conduit, and it was called the "imperfect ditch method."

REFERENCES

1. Krizek, R. J., Parmelee, R. A., Kay, J. N., and Elnaggar, H. A. Structural Analysis and Design of Pipe Culverts. NCHRP Rept. 116, 1971, 155 pp.
2. Marston, A., and Anderson, A. O. The Theory of Loads on Pipes in Ditches and Tests on Cement and Clay Drain Tile and Sewer Pipe. Eng. Exp. Sta., Iowa State College, Bull. 31, 1913.
3. American Railway Engineering Association. Culvert Load Determination. Bull. 284, 1926.
4. Spangler, M. G. The Structural Design of Flexible Pipe Culverts. Eng. Exp. Sta., Iowa State College, Bull. 153, 1941.
5. White, H. L., and Layer, J. P. The Corrugated Metal Conduit as a Compression Ring. HRB Proc., Vol. 39, 1960, pp. 389-397.
6. Meyerhof, G. G., and Baikie, L. D. Strength of Steel Culvert Sheets Bearing Against Compacted Sand Back Fill. Highway Research Record 30, 1963, pp. 1-19.
7. Watkins, R. K. Failure Conditions of Flexible Culverts Embedded in Soil. HRB Proc., Vol. 39, 1960, pp. 361-371.
8. Watkins, R. K. Structural Design of Buried Circular Conduits. Highway Research Record 145, 1966, pp. 1-16.
9. Meyerhof, G. G. Composite Design of Shallow Buried Steel Structures. Proc. 47th Canadian Good Roads Assn. Conf., 1966.
10. Meyerhof, G. G., and Fisher, C. L. Composite Design of Underground Steel Structures. Eng. Jour., Vol. 46, No. 9, 1963.
11. Nielson, F. D. Soil Structure Arching Analysis of Buried Flexible Structures. Highway Research Record 185, 1967, pp. 36-50.
12. Terzaghi, K. Stress Distribution in Dry and in Saturated Sand Above a Yielding Trapdoor. Proc. Internat. Conf. on Soil Mechanics, Vol. 1, 1936.
13. Terzaghi, K. Theoretical Soil Mechanics. John Wiley and Sons, 1943.
14. Whitman, R. V., Getzler, Z., and Hoeg, K. Static Tests Upon Thin Domes Buried in Sand. Jour. Boston Soc. of Civil Engrs., Vol. 50, 1962.
15. Newmark, N. M., and Haltiwanger, J. D. Air Force Design Manual. U. S. Air Force Special Weapons Center, Rept. AFSWC-TDR-62-138, 1962.

16. Proceedings of the Symposium on Soil-Structure Interaction. Univ. of Arizona, Tucson, Sept. 1964.
17. Triandafilidis, G. E., Hampton, D., and Spanovich, M. An Experimental Evaluation of Soil Arching. Proc. Symp. on Soil-Structure Interaction, Univ. of Arizona, 1964.
18. Luscher, U., and Hoeg, K. The Beneficial Action of the Surrounding Soil on the Load-Carrying Capacity of Buried Tubes. Proc. Symp. on Soil-Structure Interaction, Univ. of Arizona, 1964.
19. Donnellan, B. A. The Response of Buried Cylinders to Quasi-Static Overpressures. Proc. Symp. on Soil-Structure Interaction, Univ. of Arizona, 1964.
20. Selig, E. T. A Review of Stress and Strain Measurement in Soil. Proc. Symp. on Soil-Structure Interaction, Univ. of Arizona, 1964.
21. Allgood, J. R., Ciani, J. B., and Lew, T. K. Influence of Soil Modulus on the Behavior of Cylinders Buried in Sand. U.S. Naval Civil Eng. Laboratory, Port Hueneme, Calif., Tech. Rept. R-582, 1968.
22. Spangler, M. G. A Practical Application of the Imperfect Ditch Method of Construction. HRB Proc., Vol. 37, 1958, pp. 271-277.
23. Davis, R. E., and Bacher, A. E. California's Culvert Research Program—Description, Current Status, and Observed Peripheral Pressures. Highway Research Record 249, 1968, pp. 14-23.