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SUBSURFACE SOIL-STRUCTURE INTERACTION: A SYNOPSIS

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•THE loads imposed on a structure buried in soil depend on the stiffness properties of both the structure and the surrounding soil. This results in a statically indeterminate problem in which the pressure of the soil on the structure produces deflections that in turn determine the pressure. This soil-structure interaction is a subject that 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 a result of an increase in the cost and the importance of buried structures, new information has been accumulated through research, analysis, and testing. However, much of this knowledge has not yet been adapted to design practice, and there are still many questions to be resolved.

The Highway Research Board Committee on Subsurface Soil-Structure Interaction, which has responsibility for this general topic, has set as its immediate goal a compilation of the essence of current knowledge with the purpose of improving design procedures. Although ultimately the publication of an applications manual may result, the necessary first step is an assessment of the state of the art for the purpose of establishing the known facts, the areas of accomplishment, the subjects of uncertainty, and the problems needing further research.

From the outset of the subcommittee effort, the scope and complexity of the subject caused difficulty in establishing the best method of separating the subject into topics for review. Historically, the design of underground structures has been subdivided into a few general categories based on flexibility, configuration, and size. For example, a structure would be classified as an arch or circular or box culvert based on shape, and the design procedures would be classified as rigid or flexible. The former usually represents corrugated steel pipe, and the latter represents reinforced concrete pipe. Each of these subdivisions had empirical design methods associated with it. One of the obvious limitations of this approach is that structures do not necessarily fit precisely into one of the categories. Furthermore, the existing transition from one group to another is not considered, and the limits of applicability are not clearly defined.

Current design should continue to involve available methods that are backed up by field experience when these methods are applicable. At the same time, however, new approaches are needed that incorporate the fundamental system parameters and that are more suitable to larger structures, greater loads, new materials, and better installation techniques.

At a symposium sponsored by the Committee on Subsurface Soil-Structure Interaction the state of the art was reviewed and past accomplishments and future needs were discussed. The subject was subdivided into the following categories:

1. Historical development: major past efforts and their chronological relation;
2. Material properties: basic properties of the structure and surrounding medium and their influence on performance;
3. Experimental studies: laboratory and field experience that aids in understanding or improving design procedures;
4. Analytic methods: finite element and other procedures for predicting performance; and
5. Design philosophy: methods of design used in practice and their advantages and limitations.

Sponsored by Committee on Subsurface Soil-Structure Interaction.

The paper by Linger briefly traces the history of the major accomplishments on the topic of soil-structure interaction. The earliest work concerned conventional conduit design and had as its focal point the contributions of Marston and Spangler at Iowa State University. Most of the recent analytic and experimental contributions have come from sponsored research dealing with protective construction. In the literature, frequent mention is made of the term "arching," and numerous explanations of the arching phenomenon are given. However, confusion and disagreement still exist as to the meaning and cause of arching.

Arching should be considered as the transfer of load to or away from buried structures as a result of the difference in stiffness properties of the structure, with its adjacent encompassing material, and the surrounding expanse of soil. The stress distribution around the structure is therefore different from that which would exist in the same region of soil if the structure were not present. This latter condition is sometimes referred to as the free field. The paper by Allgood and Takahashi defines arching A as

$$A = 1 - (p_t/p_v)$$

where p_t is the vertical pressure on the structure at the crown, and p_v is the free-field vertical stress at the elevation of the crown. If the deformation characteristics of the structure are the same as those of the soil, then $p_t = p_v$ and $A = 0$; i.e., no change in the state of stress occurs because of the presence of the structure. If the structure is not as stiff as the soil it replaces, then $p_t < p_v$ and $A > 0$, i.e., the arching is positive. Conversely, if the structure is stiffer than the soil, then $p_t > p_v$ and $A < 0$; i.e., the arching is negative. If the structure is surrounded by a zone of material that differs from the free-field soil, the same concept applies as long as the structural unit is taken to be the structure together with the zone of material. For example, a rigid concrete structure encompassed in a layer of polyurethane foam or loose soil may have positive arching rather than negative because the composite system is not as stiff as the free-field soil.

In order to provide a quantitative definition of flexible and rigid structures, we must consider both the properties of the soil and the properties of the structure. Allgood and Takahashi recommend for circular culverts the use of the nondimensional term M_sD^3/EI, where M_s is the secant modulus of the soil in one-dimensional compression, D is the pipe diameter, E is the modulus of elasticity of the structure, and I is the moment of inertia per unit length of the pipe wall. The classification proposed is as follows:

1. Flexible: $M_sD^3/EI > 10^4$,
2. Intermediate: $10^1 \leq M_sD^3/EI \leq 10^4$, and
3. Stiff: $M_sD^3/EI \leq 10^1$.

Structures in the stiff category will experience negative arching, whereas structures in the flexible category will experience positive arching. The transition occurs in the intermediate category for which the most common design methods are least applicable.

The properties of the structure and the surrounding medium must be considered in any rational design. Determination of the important structural parameters is relatively straightforward, and accepted procedures are available for obtaining numerical values with sufficient accuracy. In contrast, measurement of the appropriate parameters for the surrounding medium is much more difficult. This is partly a result of the inherent complexity of soil stress-strain relations, but it also results from a need to incorporate the influence of bedding conditions and variations caused by construction procedures. Most current design methods treat the system properties, particularly those associated with the soil, by grouping them into several broad categories or by using empirical parameters selected by experience and judgment. Few researchers rely on testing to obtain quantitative values. However, the newest computer methods use rational material properties that are more easily defined, and procedures are being prepared for tests to provide direct determination of these properties.

A thorough discussion of the topic of material properties in relation to soil-structure interaction is provided in the paper by Krizek and Kay. In addition, Parmelee and

Corotis review the parameters required in the commonly used Iowa deflection formula for flexible pipe design, indicating the empirical nature of these parameters and the difficulty in relating them to measurable soil properties.

During the past two decades, a variety of laboratory model studies have been conducted as part of research to better understand soil-structure interaction and to improve on the theories. These studies have been very valuable in determining the key parameters and in demonstrating their influence. Model tests are also useful for comparing the effect of new sets of conditions with those for which previous experience exists. Examples are uncommon loading situations, new culvert shapes, or the alteration in load on one culvert by an adjacent one in multiple installations. Model studies on the other hand have serious limitations in quantitative prediction of full-scale performance because of the difficulty in modeling field conditions. For example, the loading is often caused by soil weight, which is not easily scaled, along with depth and stiffness, and details in the construction process such as buildup of backfill in thin layers are hard to represent correctly.

Field observations of buried structure performance are badly needed to prove new theories and refine existing ones. However, few suitable data are available, and the cost of obtaining needed information is substantial.

Papers by Nielson and Statish and by Nielson describe some of the past experimental work on culverts. The major omissions in these papers are the results of studies in protective construction research and studies using other experimental techniques, such as photoelastic models, to investigate soil-structure interaction.

One of the major problems in developing a suitable analytic method for design of buried structures is the difficulty in defining failure. For example, failure may be based on either local or general buckling, seam or bolt rupture, substantial cracking of concrete, or deflections sufficient to cause surface subsidance. The approach taken to analyze for buckling failure, for example, is given in the paper by Chelapati and Allgood.

The elasticity theory has been useful in providing some general trends, but the more versatile finite-element analysis provides the most comprehensive analytic tool available for predicting load distribution on buried structures. For example, nonlinear soil behavior, bedding details, slippage between the soil and the structure, and any desired geometric shape can be analyzed. The paper by Allgood and Takahashi shows the benefits of this method in relation to other methods.

By using the finite-element method we can carry out an analysis of a buried structure to any degree of detail desired. Of course, the greater is the refinement, the greater is the cost. The limiting constraint then is the ability to define the real conditions, particularly the soil properties and bedding conditions, in order to properly simulate them analytically. It is feasible now to establish package computer programs that can analyze common culvert situations at an economical cost.

Design practice in New York State is described in a paper by Butler to illustrate the manner and degree to which past research has been applied. Not only must structural design be considered to resist the soil loads, but handling qualities during construction and durability to withstand adverse environmental conditions must also be incorporated into the design factors. Recommendations for further research to improve design methods are also suggested by Butler.

Following the symposium, a general discussion was held to review the achievements and to establish the steps that should be taken to apply the new information to design practice. The following tasks were identified as the most important steps to be accomplished under the direction of the subcommittee:

1. Define the basic terminology such as arching, backpacking, and bedding;
2. Determine the key parameters and groups of parameters that determine the performance of the structure and the soil, giving recommended standard symbols for their designation;
3. Define and categorize all of the important failure criteria for design, and indicate expected safety factors in current practice;
4. Outline important aspects of installation techniques, and indicate the desired inspection procedures to ensure satisfactory results;

5. Define the requirements for suitable backfill;
6. Describe the important material properties for the soil and the structure, and indicate how they should be measured;
7. List the requirements for field tests to verify design concepts;
8. Recommend steps to be taken for application of research results to design practice; and
9. Prepare educational plans for dissemination of available information.

The plan of action is to complete many of the aforementioned tasks through committee effort, drawing on available information. Needed research and more extensive effort that may be required to develop design procedures will be recommended.

Based on the presentations at the symposium, it may be concluded that (a) information exists from past research, and more is being generated that should be incorporated into design practice; (b) current methods for design of small culverts must be modified or replaced by methods that can accommodate large culverts and new structural materials with proper economy; and (c) agreement is needed on the best methods to describe and measure the relevant properties of the structure and the surrounding media. Further activity directed to the accomplishment of these tasks will be valuable to the profession.