ANALYSIS OF SOIL-STRUCTURE INTERACTION DATA MEASURED IN HIGH EXPLOSIVE TESTS ON BURIED STRUCTURES

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SUMMARY

This paper presents an overview of some recent research in which data measured in high explosive tests on buried structures were used to evaluate two analytical models for interface shear transfer; a Coulomb friction model and an interface impedance model. Results show that while the interface impedance model is generally a better predictor, a more complete representation of the soil shear wave velocity is required for complex environments. The results also indicate that the pseudo interface adhesion term used in the bilinear failure is very sensitive to minor variations in the interface texture, ranging from 0.35 MPa - 1.0 MPa for precast construction.

INTRODUCTION

One of the greatest difficulties faced in the analysis and design of buried structures subjected to ground motions is the definition and modeling of the behavior at the soil-structure interface. This is a highly complex problem due to the interdependency of the ground shock loads experienced by the structure and the resulting response of the structure. Both normal and shear loads are transferred at the soil-structure interface and analytical models for these loads are required in order to adequately represent the interface behavior. While the normal stresses transferred have been investigated extensively, the shear stresses transferred at the soil-structure interface have received only limited attention. These shear stresses, however, are very important loads for certain types of structures and may contribute significantly to structural response and ultimate structural failure.

This paper provides an overview of recent research sponsored by the Air Force on developing and evaluating interface shear transfer (Ref. 1). This research has centered on interface shear stress data measured in recent high explosive tests on buried structures using an interface stress transducer that provides three orthogonal stress measurements (one normal and two shear) at the soil-structure interface. Structural and nearfield velocity and normal stress measurements were also made in order to provide complete sets of data describing the interface behavior. These data have been analyzed and have been used to evaluate analytical models for predicting the interface shear transfer.

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ANALYTICAL MODELS

The analytical models studied in this research are models that have been used by the Air Force in finite element (FE) structure-media-interaction (SMI) and more simplified multi- and single-degree-of-freedom (MDOF and SDOF) analysis codes to predict the interface shear transfer. In the FE SMI approach, the interaction at the soil-structure interface is modeled using slide lines that allow relative slip and separation (Ref. 2). The relative slip phenomenon is characterized using static and dynamic friction, with the dynamic friction characterized by either a Coulomb friction model or an interface impedance model. In the more simplified models, the relative shear transfer is predicted using one of these interface models neglecting the interaction effects on the adjacent soil media response (Ref. 3). The two interface shear models are summarized below.

Coulomb Friction Model

In the Coulomb friction model the shear at the soil-structure interface is calculated according to a simplified adhesion theory of friction that assumes the shear (or friction) stress is proportional to the normal stress and is independent of surface area and velocity of sliding. Thus, the interface shear stress (τ) is given by:

$$\tau(t) = -\mathrm{sign}(\Delta V(t))\mu_d\ \sigma_n(t) \qquad (1)$$

where ΔV = relative velocity parallel to the soil-structure interface, μ_d = the dynamic friction coefficient, and $\sigma_n(t)$ = the normal stress on the interface. The coefficient of friction is a function of several variables (e.g., surface roughness and material strength), but is normally taken as the ratio of shear strength to penetration (compressive) strength of the weaker material. For soil-concrete interfaces, then, the friction coefficient is determined from the internal soil friction angle (ϕ)

$$\mu_d = \tan\phi \qquad (2)$$

Interface Impedance Model

In the interface impedance model, the interface shear is assumed to be related to the shear strain in the adjacent soil and is estimated by

$$\tau(t) = \rho C_s \Delta V(t) \qquad (3)$$

where ρ = mass density of the soil and C_s = shear wave velocity of the soil. The shear wave velocity in the soil varies in time as a function of the state of stress in the soil, however, a constant value derived from the constrained secant loading modulus for the peak soil stress is normally used.

Interface Failure Criteria

Prior research (Refs. 1 and 4) has shown that it is necessary to limit the magnitude of the shear stresses calculated by equations 1-3 by a bilinear failure criteria which accounts for shear failure in the soil and slip at the interface or in the adjacent soil media. This bilinear failure criteria is given by

$$\tau \leq \tau_{max} = \min \begin{cases} c + \sigma_n(t)\tan\phi \\ a + \sigma_n(t)\tan\delta \end{cases} \tag{4}$$

The first expression in equation 4 represents failure in the adjacent soil media while the second expression corresponds to failure at the interface.[1] The soil cohesion (c) and internal friction angle (ϕ) are based on the properties of the soil media. For sand-concrete interfaces, tests indicate that the interface friction angle is approximately 10-12 deg (Ref. 4). The interface adhesion term varies depending on the relative roughness of the structure interface and particle grain size distribution in the soil.

TEST PROGRAM

In the testing program, interface stress and motion data were measured on two generic structures commonly used in hardened construction; a surface flush vertical cylinder and a shallow buried horizontal cylinder. Schematics of these generic structures and the loading sequence experienced in the tests are presented in Figure 1.

For the vertical cylinder, the loading was applied as a uniform surface wave (1). Since the propagation velocity is faster in concrete than soil, the cylinder is in motion earlier at a given depth, causing interface shear stresses that resist the motion of the cylinder (2). As the wave propagates through the soil (3), the soil velocity overtakes the cylinder velocity and the interface shear stresses drag the cylinder down. During all phases of the loading, soil bearing forces (4) at the base of the cylinder resist its downward motion.

The loading mechanisms are similar for the horizontal cylinder except that a transverse loading wave is added to the surface (1a). Due to the timing between this wave and the longitudinal loading wave, the transverse loading wave results in higher confining stresses and preloading of the soil prior to the arrival of the longitudinal stress wave. In addition, the presence of the free surface and an unloaded surface beneath the cylinder result in more rapid attenuation of the longitudinal loading wave.

Interface behavior measurements in the tests consisted of structural and nearfield accelerations, interface normal stresses, and interface shear stresses at approximately the same locations along the length of the cylinder. The interface stress measurements were taken using a triaxial interface stress gage (Fig. 2) developed at the Eric Wang Civil Engineering Research Facility. This gage utilizes a cantilever beam that is strain gaged to provide three

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[1] Equation 4a is a redundant failure criteria for the Coulomb friction model and nonlinear FE analyses with the soil modeled explicitly. It is included here for simplified interaction models where the soil response is not modeled explicitly.

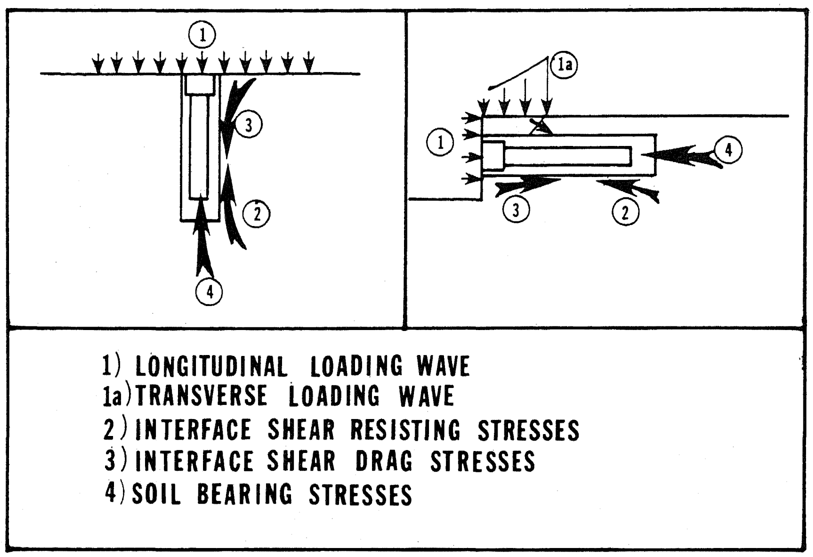

Figure 1. Loading Mechanisms for Test Structures

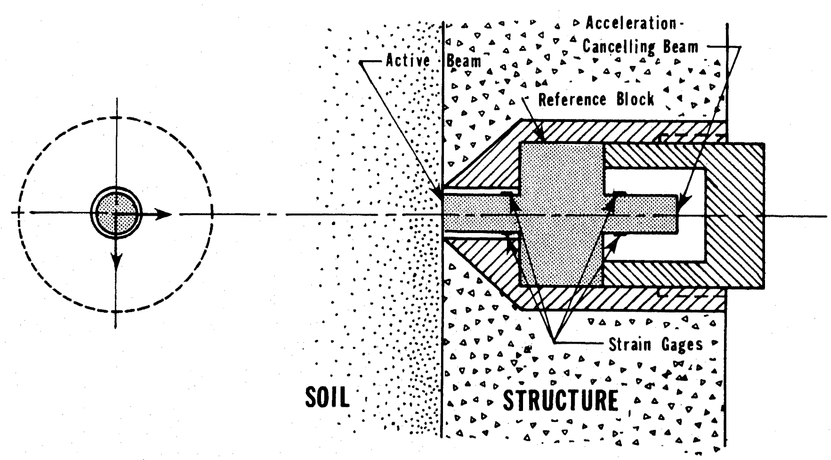

Figure 2. Triaxial Interface Stress Transducer

orthogonal stress measurements, two shear and one normal. A dummy beam is used to cancel undesirable force inputs due to acceleration of the gage and cross-axis sensitivity. The gage is placed in the wall of the cylinder so that it is flush with the surface and in good contact with the adjacent soil media.

RESULTS OF DATA ANALYSIS

In order to evaluate the adequacy of the interface shear algorithms discussed earlier, the interface data measured in the test were used as input into these algorithms and the interface shear stress calculated. These calculated waveforms were then compared to the measured interface shear stresses, and the modeling parameters (e.g., ϕ, a, and C_s) were adjusted to obtain the best fit to the data for each model. Some typical results are shown in Figure 3 for the horizontal cylinder with precast construction. The results of the analysis show that the interface impedance model is generally a better predictor than the Coulomb friction model. The Coulomb friction model overestimates the interface shear at low relative velocities and has an uncharacteristic step reversal. However, when the failure criterion governs the stress transfer, both models provide a reasonable estimate. The results also indicate that a more complex representation of the soil shear wave velocity, C_s, is required to represent the soil behavior for complex loading environments. This is illustrated in Figure 4 where the soil was preloaded by the transverse loading wave. In this case, C_s based upon the initial tangent modulus (instead of the secant modulus as used in Figure 3 and at other locations where the preloading was not significant) provided a better estimate of the shear transfer.

A second emphasis of the research has been to develop guidelines for determining the interface failure modeling parameters (a, c, ϕ, and δ) for two typical construction techniques; precast and cast in place. Since the soil cohesion term for the sand material used in the tests is small, and since the slope of the interface failure line is relatively shallow, this effort has focused on the pseudo interface adhesion term, a, and the internal friction angle in the soil, ϕ. The typical ranges of values for these parameters derived in this study are shown in Figure 5. The results show that the predicted interface shear is sensitive to the soil internal friction angle only for low normal pressures and cast-in-place construction and that an adequate estimate of ϕ can be obtained from the material properties of the soil media. Typical results for the pseudo interface adhesion term, a, show that it is very sensitive to minor variations in the relative roughness of the soil-structure interface. For precast construction against steel, the interface adhesion varied from .36 MPa to 1.0 MPa. This range of interface adhesion is similar to results obtained by Huck (Ref. 4) in an earlier study. For cast-in-place construction, the interface adhesion was higher, ranging from 1.0 MPa to 1.4 MPa. These values may be even higher since the data for cast-in-place construction is somewhat limited and the relative velocity and normal stresses in the tests were not high enough to force failure at the interface over a wide range of pressures.

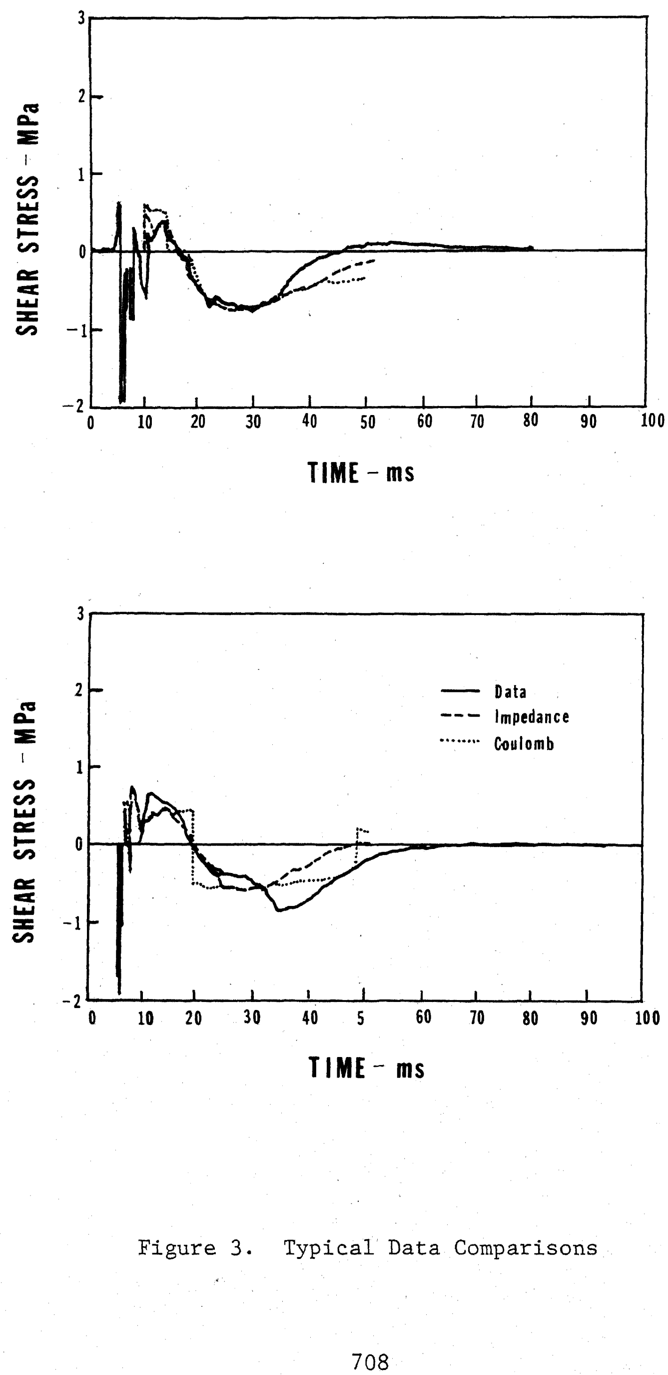

Figure 3. Typical Data Comparisons

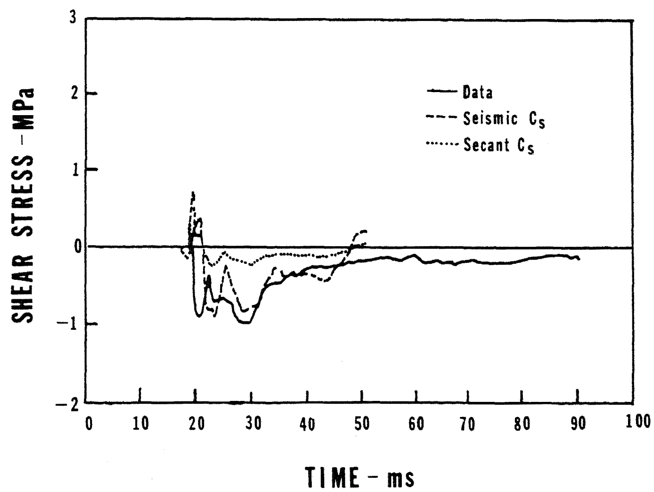

Figure 4. Data Comparison for Region Preloaded by Transverse Loading Wave

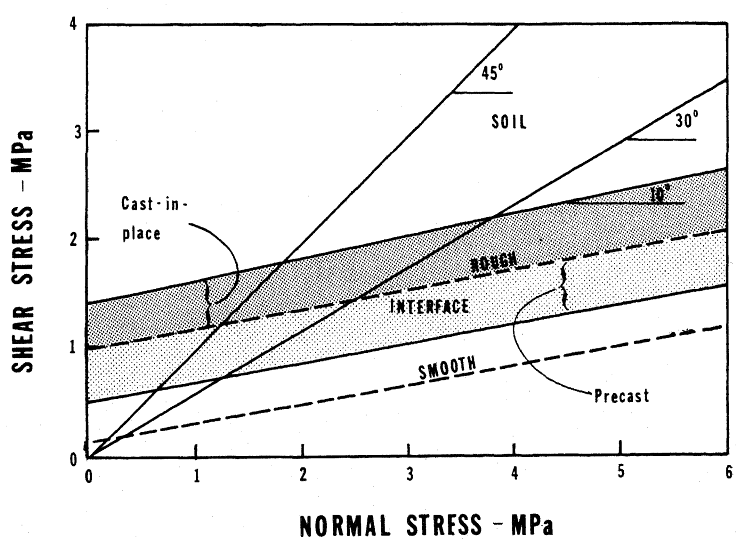

Figure 5. Bilinear Interface Failure Envelope for Precast and Cast-in-place Construction

CONCLUSIONS

In conclusion, the results of this study indicate that the interface impedance model provides a better prediction of the interface shear transfer than does the Coulomb friction model. This model, when coupled with a bilinear failure envelope, provides a fairly accurate prediction of the shear transfer. The parameter inputs to the bilinear interface failure envelope are very sensitive to minor variations in the relative roughness of the soil-concrete interface. Preliminary estimates of the interface model parameters for precast and cast-in-place construction were derived, but additional work is needed in this area. The results indicate that improve correlation with the data can be obtained in the interface impedance model by accounting for the stress-history of the soil media in calculating C_s. Finally, although the triaxial interface stress transducer provides a fairly good recording of the interface shear transfer under transient loads, additional work is needed in evaluating gage performance to improve the analysis and interpretation of the data.

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