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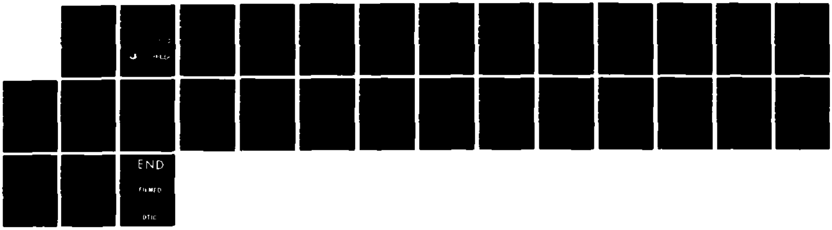

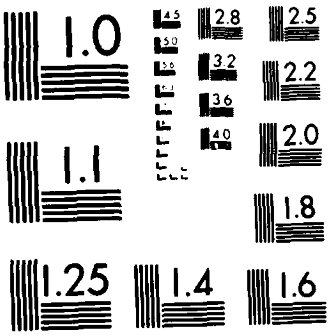

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Constitutive Modeling for Blast-Induced Wave Propagation

ERIC C. DRUMM

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110 C Perkins Hall
Knoxville, TN 37996

MARCH 1985

FINAL REPORT
JUNE 1984 — SEPTEMBER 1984

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The description of the stress-time history acting on a buried structure is a major source of error in the analysis of underground structures subjected to weapons loadings. The stress wave propagating spherically from the weapon is attenuated as it travels from the source. This attenuation is a function of the inelastic response of the soil, and results in an increase in the loading rise time or decrease in the loading rate. Since the inelastic soil response is a function of the loading rate, a wave propagation analysis should be conducted to determine the stresses on the structure. At the interface between the soil and structure, the stress is modified further by soil-structure interaction effects. Thus, the stress on the structure is a function of both the structural and soil properties as well as the distance traveled by the stress wave. These related phenomena can be included in a numerical analysis, but the accuracy depends on the constitutive representation of the materials. One-dimensional wave propagation experiments and impact tests with various soils are reviewed, and the attenuation as a function
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of the soil stress-strain response is discussed. The stress-strain response may change from "hardening" to softening" when the loading rise time is less than 1 second. Several elasto-viscoplastic models capable of representing this response are discussed, and recommendations are made regarding the use of existing numerical codes to perform soil-structure interaction alalysis of buried structures. Future research suggestions are offered.

PREFACE

This report was prepared by Dr. Eric C. Drumm, Engineering Science and Mechanics Department, College of Engineering, University of Tennessee, 110C Perkins Hall, Knoxville, TN 37996-2010 under the Summer Faculty Research Program sponsored by the Air Force Office of Scientific Research (AFOSR) and the Southeastern Center for Electrical Engineering Education (SCEEE).

This report covers work done between June 1984 and Sep 1984. Lt Thomas J. Hilferty was the AFESC/RDCS project officer.

This report discusses stress wave propagation analysis, inelastic soil response and soil-structure interaction. Recommendations are made regarding the use of existing numerical codes to perform soil-structure interaction analysis of buried structures.

This report has been reviewed by the Public Affairs office (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be available to the general public including foreign nationals.

This technical report has been reviewed and is approved for publication.

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SECTION I

INTRODUCTION

The stresses acting on a buried structure due to the effects of a weapon blast depend on the type, size, and orientation of the weapon, the distance between the weapon and structure, and the stress-propagation behavior of the surrounding soil. For a given weapon loading, the response of the structure depends on the stresses in the surrounding soil, while the stresses in the soil depend on the structural response. This coupling of effects is termed soil-structure interaction. Depending on the mass and stiffness of the structure and the behavior of the surrounding soil, the stresses acting on the structure may be greater than or less than the free-field stresses (stresses that would exist if the structure were not present).

Current Air Force design procedures (References 1-3) recognize the existence of soil-structure interaction effects, but a rational method of including these effects in the analysis procedure has not been implemented. For a complete soil-structure interaction analysis, the soil and structure should be analyzed as a system with appropriate material constitutive models.

Unlike the dynamic loads from machines, earthquakes or water waves, blast loads may result in stresses of large magnitude with short rise times and duration. As the stress wave propagates through the soil, the stresses are attenuated and the rise time of the stress history increases (or the loading rate decreases). Since the propagation and attenuation of the stress wave depends on the inelastic stress-strain behavior of the surrounding soil, and the response of soil may depend on the rate at which the load is applied, the wave propagation and loading rate effects are closely linked. Thus, for an accurate numerical analysis of the soil-structure system, the constitutive characterization of the soil is of utmost importance.

The objective of this research is to investigate the wave-propagation and constitutive behavior of geologic media subjected to blast-induced stresses from conventional weapons. This study is to consist of the following three tasks:

1. Review previous experimental investigations of wave propagation through geologic media. This study should address the effect of the inelastic stress-strain response on the stress propagation behavior.

2. Review existing constitutive models that may describe nonlinear, inelastic, rate-dependent behavior. Of significant importance in the choice and implementation of a model is the ability to determine numerical values for the model parameters from laboratory tests.

3. Provide recommendations regarding the implementation of constitutive models with loading rate effects into numerical codes available to the Air Force. These recommendations should include applications of numerical techniques to problems of interest to Air Force research and analysis personnel. Suggestions with respect to additional laboratory testing programs and additional instrumentation in currently scheduled field tests will be offered.

The resulting "state-of-the-art" report should give Air Force personnel a better understanding of the wave propagation of blast-induced stresses and how loading rate effects may be included in analysis procedures. These analytical methods may be useful when performing survivability/vulnerability analyses and in providing geotechnical guidance for the siting of buried and partially buried structures. In addition, a numerical analysis prior to the field-testing of structures may be helpful in optimizing the test with respect to instrumentation and weapon placement.

SECTION II

PREVIOUS WAVE PROPAGATION RESEARCH

The determination of the free-field stresses acting against a buried structure is essentially a problem of wave propagation through the surrounding soil. The sudden release of energy by a detonated weapon results in a stress wave that propagates through the soil in a spherical wave front. The stress wave is geometrically or spatially attenuated as it travels from the source since the detonation energy is being distributed over an increasing volume of material. In addition to the spatial attenuation, the stress wave is attenuated by the dissipative properties of the soil. This attenuation effect is a material property which is included in the constitutive model and should not be confused with the spatial attenuation. The spatial attenuation will not be considered further as it is included automatically in the analysis procedure.

Most of the early wave propagation and dynamic stress-strain testing was conducted to determine the effects from nuclear air-blast loading, but the loadings due to conventional weapons are similar in many respects. As described by Wilson and Sibley, (Reference 4) the classical air-blast wave from a nuclear weapon results in a loading history at a given point in the soil that rises sharply and is followed by an exponential decay in the positve phase of the pressure. This positive phase is followed by a negative phase frequently ignored in analysis procedures. Since the radial extent of the loaded area is large with respect to the thickness of the soil layer, the soil is laterally constrained and the resulting deformation is essentially one-dimensional. The assumption of one-dimensional loading may not be appropriate for the analysis of conventional weapon effects against buried structures because of the spherical wave front that is generated. Also, the stress-time history of a nuclear weapon has a slightly longer rise time and lasts longer than loadings usually associated with conventional weapons. In spite of these differences, many similarities exist and an understanding of one-dimensional wave propagation is instructive and may be an appropriate assumption for some loadings and geometries.

The shape of the stress-strain relationship has been recognized as the most important factor affecting the wave propagation response of soils (Reference 4-7). As indicated in Figure 1(a), in an infinite column of an elastic, homogeneous, material, a one-dimensional stress wave propagates with a velocity proportional to the elastic modulus, M_e, with little attenuation or change in shape. In one-dimensional compression, many soils exhibit the familiar "s-shaped" response, Figure 1(b). Since the unloading modulus, M_u, is larger than the loading modulus, M_l, the unloading wave propagates more rapidly, interacting with the loading wave and resulting in an attenuation with distance from the source. As indicated in Figure 1(b), the form of the stress pulse changes shape as it propagates through the soil, resulting in an increase in the rise time, a decrease in the peak stress, and an increase in the total duration of the pulse at low stress levels, the relatively large value of initial modulus, M_i, Figure 2, results in a stress wave propagation at about the seismic velocity, while at higher stress levels, the smaller value of M_L, results in a propagation velocity less than the seismic velocity. This explains the high velocities obtained from seismic surveys in which relatively low stress levels are applied and indicates the importance of testing at appropriate stress levels.

A review of wave propagation can be considered to include two related areas of study. First, experimental studies of the propagation and attenuation of stress waves through soils will be reviewed. In these tests a one-dimensional compression wave is applied to one end of a long soil specimen and the stress and/or velocity recorded as the wave propagates along the specimen. Since the wave propagation depends on the stress-strain behavior of the soil in which the wave is propagating, the second review area will consist of efforts to measure the dynamic stress-strain response directly. To measure this response a shock wave is applied to a short specimen. The shock wave will travel through the specimen and be reflected several times during the duration of the pulse, resulting in essentially a uniform stress state.

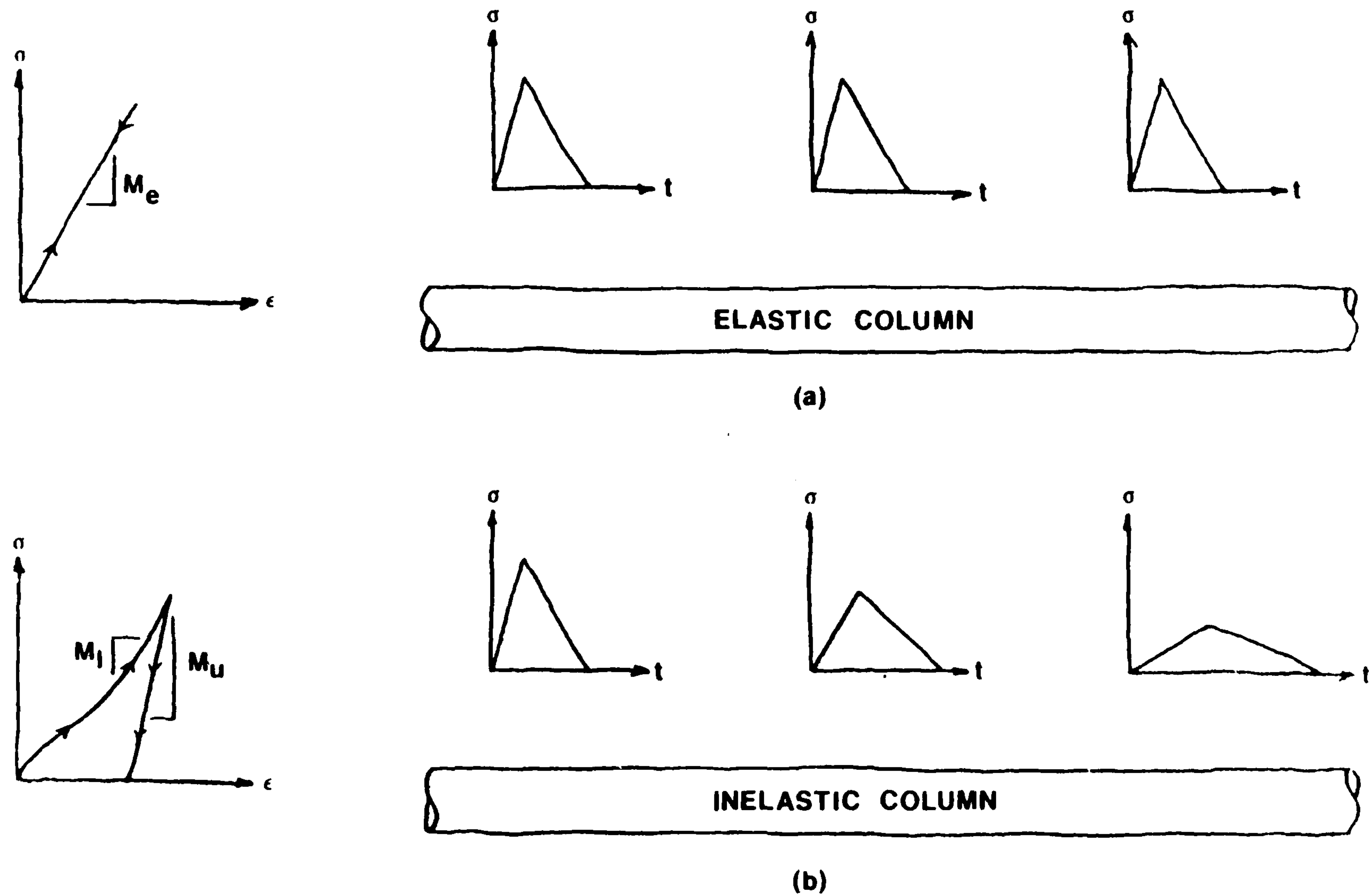

Figure 1. One-Dimensional Wave Propagation Along an Infinite Bar

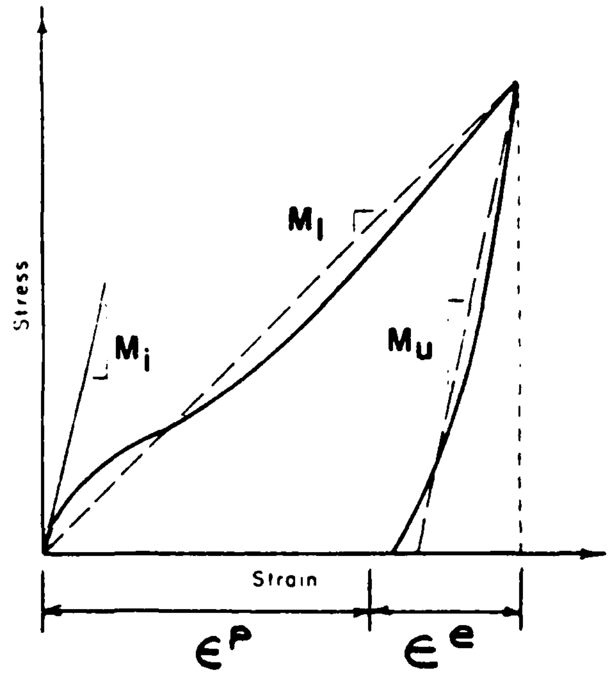

Figure 2. Typical Stress-Strain Response Under Uniaxial Conditions

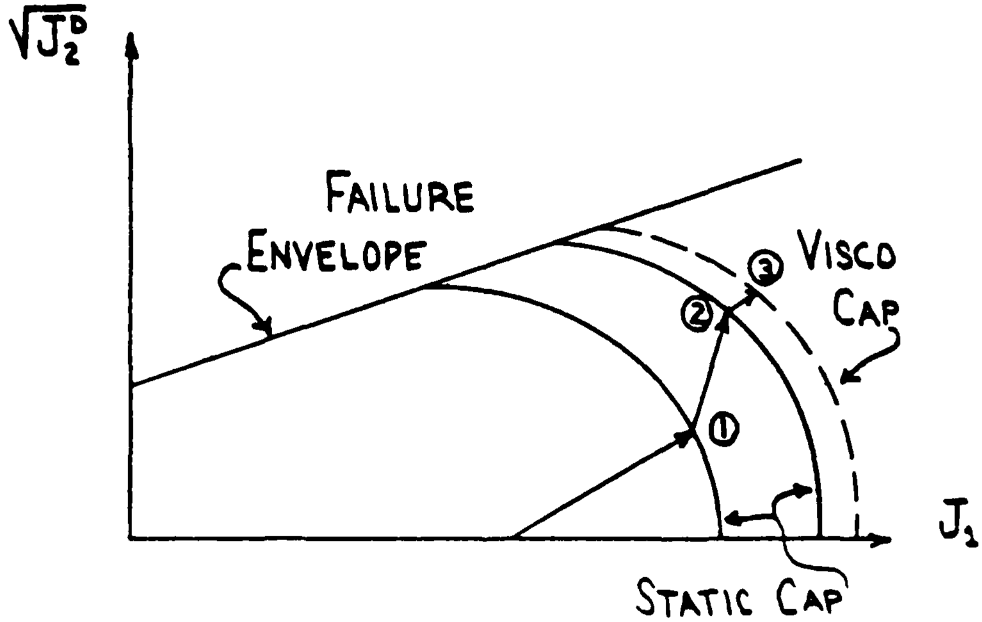

Figure 3. Plasticity Surfaces for Visco-Plastic Cap Model

The propagation of air shock waves through cylindrical specimens of soil has been reported by several investigators (Reference 5-10). The common features in these tests are the radial confinement of the specimen and the application of a stress pulse which propagates one-dimensionally along the specimen. The radial confinement is provided by rigid rings or spiral reinforcing in a rubber membrane such that the longitudinal transmission of the stress wave is not significantly impeded. The stress and displacements are measured at various locations along the specimen by embedded stress and/or strain gauges. While questions may arise as to the accuracy of stress-strain measurements taken in this manner, the overall wave propagation and attenuation response can be effectively observed as functions of soil type and input wave form. The "s-shaped" stress strain response has been recorded in shock tests on sand specimens confined by spiral windings (Reference 7). It was concluded that the formation of a steady shock wave in sand is influenced by the characteristics of the stress-strain curve, and that the attenuation depends on the material properties and boundary conditions.

Measurements of the pore air pressure in samples of sand, silt and pea gravel (Reference 8) indicate that pore air pressure is affected by the peak overpressure, shape of the shock wave, permeability of the material, and depth of penetration. Significant pore pressures can develop in coarse-grained uniform soils, but are of little consequence in well-graded soils. The attenuation rate is independent of the overpressure and depends on the pore size, depth of penetration and positive shock duration.

Shock wave tests on Ottawa sand confined in segmental rings (Reference 9) indicate materials that exhibit strain-softening display an increase in the rise time and decrease in the magnitude of the stress and particle velocity pulse. Strain hardening materials tend to "shock-up" or show a decrease in the rise time as the wave propagates through the soil.

Samples of Ottawa sand and Kaolin clay (Reference 10) have been subjected to shock waves and the stress-strain curves for the sand found to be of the familar "s-shape," while those of the clay were essentially linear during the loading phase. As might be expected, the attenuation rate in the clay was found to be greater than that of the sand, due to the greater hysteresis loss and lower wave velocity.

Shock wave studies have been performed on soil samples without rigid lateral confinement in which confining stresses up to 15 psi were applied by vacuum. Triaxial specimens of Ottawa sand (Reference 11) and clay (Reference 12) 2.8 inches in diameter by 64 inches long were subjected to air shock waves. The results indicate that the stress wave in sand undergoes the least amount of change in shape for high densities, high confining pressures, and small amplitudes of shock pressure with long duration. Because these conditions approximate the conditions under which an elastic wave would exist, not much change is expected. With an increase in the peak shock and decrease in duration, the attenuation was found to increase, with corresponding increases in peak shock and duration.

A good review of wave propagation studies is presented by Hampton et al. (Reference 13). A series of tests on laterally confined specimens of Kaolin is described in which rise time of the load was reported as "instantaneous" or about 1 msec. Measurements from embedded stress and strain gauges indicated "softening" behavior or stress-strain curves that were concave downward towards the strain axis. This is a departure from the "hardening" behavior or "s-shaped" response typical of uniaxial strain. These results were discussed with respect to uniaxial strain tests conducted with the WES device (Reference 14) and the differences were attributed to a difference in boundary conditions, sample size, method of confinement, and the difference in loading rate. The effects of submillisecond rise times on the stress-strain response will be subsequently discussed.

The increase in strength of soils due to the rapid application of load has been recognized since the 1840s. The effect of nuclear weapons loading provided the impetus for many experimental studies during the early 60s. Although much of the early data consist of only the rate effects on the soil strength and initial modulus, this provides an understanding of the general behavior of soils under impact loads. Of additional interest is the apparatus used to apply the impulsive load to the specimen, since the form of the applied stress pulse is a function of the loading apparatus. Stress histories with a short rise time and duration typical of conventional weapons may be difficult to obtain with some test devices, but the stress strain response must be measured over the range of anticipated loading rates.

Sample geometry is an important consideration when determining constitutive parameters since the knowledge of the complete state of stress is required if the results are to be properly incorporated into a general model. The propagation and reflection of stress waves in the sample also depend on the geometry.

The importance of sample configuration, specifically, lateral constraint, has been discussed by Wilson and Sibley (Reference 4). It was suggested that the value of the constrained modulus M_c, is bounded below by triaxial compression tests due to sampling disturbance and the lack of lateral constraint. The value of M_c is bounded above by the modulus calculated from the seismic velocity. This value is high due to the effects of preconsolidation and the low applied stress levels. The actual value of M_c should be between the value computed by a hydrostatic test and a uniaxial strain test. A series of uniaxial strain, hydrostatic compression, and triaxial shear tests on samples of tuff were reported by Ehrogott (Reference 15). The relationship between dynamic and static strength was found to depend on the state of stress in the sample, although it was not clear what these effects are. It is clear that loading rate effects, as well as general stress-strain behavior, depend on stress path. A review of impact tests under various stress paths follows.

Triaxial tests on dry and undrained saturated sands were conducted by Whitman and Healy (Reference 16) with time to failure ranging from 5 msec to 5 minutes and the results indicated little increase in strength for dry and dense saturated sands. Loose saturated sands tend to develop lower values of excess pore pressure when loaded rapidly, resulting in a strength increase of about 40 percent for a decrease in failure time from 5 seconds to 0.025 seconds.

A similar study on the rate effects on a saturated remolded clay was reported by Richardson and Whitman, (Reference 17) and it was suggested that the rate effects are due to the internal migration of pore water causing larger excess pore pressures at low rates.

An extensive series of tests on Goose Lake clay (Reference 18) at various water contents was conducted with a pneumatic device producing failure times ranging from 2 msec to 1 hour. An increase in dynamic strength was observed for all water contents, but a smaller strength increase was found for samples with low water contents. The increase in secant modulus at 1 percent strain was found to be more dependent on strain rate and water content than was the strength. Increases in dynamic strength and modulus have also been reported by other researchers (Reference 19-21).

Dynamic direct shear tests (Reference 22 and 23) using compressed air to create loading rise times ranging from 1 to 5 msec have been conducted on specimens of sand, clay, and sand-clay mixtures. The dynamic impact strength envelopes were compared with those of "rapid static" tests with time to failure of 30 to 50 seconds. The results indicate little increase in strength for the sand samples in both dry and saturated conditions, while the clay and clay-sand mixtures exhibit an increase in apparent cohesion. The increase in cohesion appears to be independent of the moisture content and grain size for specimens with a degree of saturation, S, greater than 85 percent.

The split Hopkinson pressure bar (Reference 24) or Kolsky (Reference 25) apparatus was developed for the testing of metals and has been used to investigate the loading rate effects on the behavior of geologic materials (Reference 26-29). Although the Hopkinson bar is convenient for dynamic testing and the impact velocities can be accurately controlled, the rate of strain is not constant and cannot be determined directly. This apparatus and the analysis of the test data have been well documented (Reference 30-33) and will not be discussed further.

Perhaps the best data on loading rate effects have been obtained from tests conducted on thin specimens in uniaxial strain devices (Reference 5,14,34,35). Since the sample length is small, the stress wave may propagate across the sample and be reflected from the ends many times during the duration of the load. Thus, a relatively uniform stress distribution throughout the sample can be assumed. This assumption, known as the "multiple-reflection theory," is probably appropriate, provided the rise time is greater than 0.1 msec for sand and 1.0 msec for clay, (Reference 36) but reflections and rarefactions may affect the actual state of stress in the sample (Reference 37). In addition, the complete state of stress is unknown due to the inability to measure the radial stresses.

Schindler (Reference 14) describes the development of a uniaxial device by WES in which a cold-gas expansion is used to apply the impact loading. This device was modified by Jackson et al. (Reference 35) to duplicate the effects of a conventional weapon by using a loading initiated by a hot gas expansion (explosion) resulting in rise times less than 1 msec. The stress-strain responses of three sands have been measured with this device under transient pressures ranging from 10 mPa to 80 mPa. It is reported that the response changes from "stiffening" behavior to "softening" behavior when the rise time is less than 1 msec. A numerical analysis was performed to show that these effects were due to rate effects rather than a change in the state of stress due to reflections. This distinct change in behavior with submillisecond rise times is similar to that reported by Hampton (Reference 13). It has been suggested (Reference 38) that this softening is due to a decrease in strain rate after the initial rapid loading. This change in behavior is significant and should be investigated more closely under different states of stress. Further testing with rise times less than 1 msec should be conducted to assure that this measured response is, in fact, representative of the material and not a function of the testing device.

Table 1 summarizes the rate effects on strength and initial modulus. Although a complete description of the stress-strain response is needed for a wave-propagation analysis, the general trends are informative. The stress-strain behavior of the soil is highly dependent on the type of soil, lateral confinement, state of stress or stress path, stress level, and the rate at which the load is applied. Laboratory tests should be conducted under conditions approximating those in situ. Some existing mathematical models that represent the constitutive response of geologic materials will now be discussed. Of particular interest are models which incorporate the effects of rate of loading.

TABLE I. SUMMARY OF EFFECTS ON STRENGTH AND INITIAL MODULUS DUE TO INCREASE IN LOADING RATE*

SOIL TYPE	STATE		STRENGTH INCREASE	INITIAL MODULUS INCREASE	COMMENTS
CLAY	All S		less than increase in modulus	great	lower excess pore pressures function of OCR
	Low S		moderate		function of moisture content
	S [illegible] 85%		great		independent of moisture content and grain size
SAND & GRAVEL	Dry	loose dense	slight	slight	dependent on density
	Saturated	loose	great		lower excess pore pressures
		dense	slight	slight	

*NOTE: General trends are indicated only. The effect of loading rate is a function of many variables, such as the applied stress level, the stress state, the loading history, the grain size distribution, density, water content, porosity, and overconsolidation ratio, amoung others. The properties of a given soil should be determined in the field or laboratory under <u>in situ</u> conditions, and should be determined under various states of stress and over the range of expected loading rates.

SECTION III

CONSTITUTIVE RELATIONS

Numerical wave propagation (Reference 39-41) and soil-structure interaction modelling for blast loadings (Reference 42-43) have been conducted with elastic material representations in which the stress is related directly to the strain. Due to the inelastic response and the stress-path dependence of most soils, an incremental plasticity formulation such as that conducted by Goudreau et al. (Reference 44) for a combined air blast and ground shock loading is preferred.

Incremental plasticity type models, in terms of stress invariants, can represent material behavior over multiple-stress paths and will assure uniqueness of the stress-strain relation. Space does not permit a complete discussion of plasticity, but, in most formulations used to represent geologic materials, the strain is assumed to consist of an elastic part, e^e, and a plastic part, e^p, as shown in Figure 2. To include the frictional response common to most geologic media, a failure envelope such as that shown in Figure 3 is used. When the stress state (plotted in an invariant space as shown in Figure 3) is below the envelope, only elastic strains can occur. Since most geologic materials experience plastic strains at stresses below the linear envelope, or due to stress paths, as shown in Figure 3, an additional yield criterion or cap, is defined. As the stress state moves from Point 1 to Point 2 the cap also moves as a result of strain hardening. This results in the change in the elastic limit of the material response. While many plasticity formulations exist, (Reference 45 and 48) formulations that can represent the loading rate effects are of interest in blast loadings. A trade-off must often be made between sophistication of the model and the ability to determine the material parameters from laboratory or field tests.

Although many of the elasto-viscoplastic models are formulated to model creep behavior, the formulation should be general enough to include the change in behavior due to rapidly applied loadings. Variations of the Sandler Cap model (Reference 46) have been proposed (Reference 38,49,50) in which the flow rule is written in terms of a viscous parameter. Under slow rates of loading, the cap moves with the stress state as in a conventional plasticity model, and the hardening or stiffening behavior expected for a uniaxial stress state may occur. Under rapid rates of loading, the cap lags the stress state indicated by Point 3 producing the "apparent softening" (Reference 49) behavior measured by Jackson (Reference 35). Additional strains accumulate in the visco-plastic domain until the cap "catches up" to the stress state. A model of this type has been formulated by Rubin and Sandler (Reference 49) for high-pressure and high-temperature equations of state, and modular subroutines are provided for use in explicit integration codes. A model formulated in terms of the third stress invariant has been used by Schreyer (Reference 51). Other models (Reference 38, 49-51) have all been used to predict the laboratory tests of Jackson (Reference 35) and appear to represent the rate effects adequately. It should be kept in mind that due to the lack of experimental data, only the behavior under the uniaxial state of stress has been predicted for rise times less than 1 msec. A true test of these models awaits laboratory data under different stress paths.

SECTION IV

RECOMMENDATIONS

Existing numerical techniques are available to perform dynamic soil-structure interaction analyses for weapons effects on buried structures. For many soil conditions such as clays and partially saturated sands, a rate-dependent constitutive model may be required. Since an explicit time integration scheme is usually recommended for blast loadings, (Reference 33,52) a large deformation code such as DYNA3D (Reference 53) may yield good results.

To indicate how such a code may be used, the full-scale buried HYPAR structure tests to be conducted at Tyndall AFB should be analyzed. Soil samples from the test site should be tested under quasi-static loading conditions and the analysis performed with constitutive models currently implemented in DYNA3D. The ground motions and interface pressures will be compared with those measured in the field tests to illustrate the importance of the soil model. While a better solution is likely to be obtained if a rate-dependent model is used, the analysis will demonstrate the laboratory determination of the rate independent constitutive parameters and the analysis with soil-structure interaction effects. With rate-dependent properties from future tests at high loading rates, a better solution may be obtained.

Future Air Force research should be directed towards development and implementation of rate-dependent constitutive models. The severe shortage of quality laboratory test data under high loading rates hinders this development, therefore both tasks should be considered concurrently. Stress states other than uniaxial strain are important for the localized stress conditions existing near conventional weapons. Data on soils for which full-scale structural tests have been conducted or are planned should be considered to verify the models. Numerical analyses of field test structures prior to testing can permit parametric studies of test variables such as weapon location and orientation, as well as assist in the determination of instrumentation location. A rational approach to the design of field tests will permit more effective use of test structures and weapons to maximize the data obtained. Testing can then follow to determine if the structure behaves as predicted. Numerical analyses can also be useful in isolating the effects of stress wave reflections in laboratory and centrifuge tests at high loading rates.

Additional areas of research in soil structure interaction research include the development of appropriate interface models to permit relative motions between the soil and structure. These relative motions may be particularly important for surface and partially buried structures. Although interface models exist, these models cannot include the effects of soil arching. Soil arching is the tendency for the soil to transfer stress from the more flexible portions of the structure to the portions of greater stiffness. Tests simulating nuclear weapons have shown that current analysis methods underpredict the strength of the structure due to these effects (Reference 3). Arching effects may be enhanced with the rapid application of load associated with conventional weapons. Special interface elements can be developed to include these effects, with the constitutive parameters determined from field or laboratory tests.

The analysis of buried structures subjected to conventional weapon loadings is complex, but existing methods are available to obtain reasonable solutions. With the implementation of rate-dependent material models, the quality of the solutions should improve. Numerical solution procedures interpreted in conjuction with the results of centrifuge and field tests will result in an improved understanding of the soil structure interaction and wave propagation effects in these problems.

REFERENCES

1. Crawford, R.E., Protection From Nonnuclear Weapons, Technical Report, AFWL-TR-70-127, Air Force Weapons Laboratory, Kirkland, AFB, NM, Feb 1971.

2. Fundamentals of Protective Design for Conventional Weapons, USAE Technical Manual 855-1 (Draft), USAE WES, Vicksburg, MS., Jun 1982.

3. Kiger, S.A., Slawson, T.R., and Hyde, D.W., A Procedure for Computing the Vulnerability of Shallow-Buried Flat-Roof Structures, USAE WES Tech. Report SL-84-5, Vicksburg MS., 1984.

4. Wilson, S.D. and Sibley, E.A., "Ground Displacement from Air Blast Loading," J. Soil Mech. Div. ASCE Vol. 88, SM6, pp. 1-31.

5. Heierli, W., "Inelastic Wave Propagation in Soil Columns," J. Soil Mech. and Found. Div. ASCE, Vol 88, No. SM6, Dec 1962, pp. 33-63.

6. Hendron, A.J., Auld, H.E., "The Effect of Soil Properties on the Attenuation of Airblast-Induced Ground Motions," Proc. Int'l Symp. on Wave Prop. and Dyn. Prop of Earth Mat'ls, Albuquerque, NM 1967, pp. 29-47.

7. Stoll, R.D., and Ebeido, I.A., "Shock Waves in Granular Soil," J. Soil Mech. and Found. Div., ASCE, Vol. 91, No. SM4, July 1965, pp. 107-125.

8. Hampton, D., "Pore Air Pressure in Soil Subjected to Shock Waves," J. Soil Mech. and Found. Div., ASCE, Vol. 91, No. SM6, Nov. 1965, pp. 41-56.

9. Baker, W.J. and Triandafilidis, G.E., "Kinematics of Wave Propagation in Laterally Confined Columns of Sands," Proc. Int'l Symp. on Wave Prop. and Dyn. Prop. of Earth Mat'ls, Albuquerque, N.M., pp. 411-422.

10. Hampton, D. and Wetzel, R.A., "Stress Wave Propagation in Confined Soils," Proc. Int'l. Symp. on Wave Prop. and Dyn. Prop. of Earth Mat'ls, Albuquerque, N.M., 1967, pp. 433-442.

11. Selig, E.T., and Vey, E., "Shock Induced Stress Wave Propagation in Sand," J. of Soil Mech. and Found. Div. ASCE Vol. 91, No. SM3, May 1965, pp. 19-50.

12. Vey, E. and Strauss, L.V., "Stress-Strain Relationships in Clay due to Propagating Stress Waves," Proc. Int'l. Symp. on Wave. Prop. and Dyn. Prop. of Earth Mat'ls, Albuquerque, N.M. 1967, pp. 575-585.

13. Hampton, D., Huck, P.J., Selig, E.T., "Wave Propagation in Confined Clay," J. of Soil Mech. and Found. Div. ASCE, SM4, 1970, pp. 1391-1410.

14. Schindler, L., "An Improved Facility for Testing Soils in One Dimensional Compression," Proc. Int'l Symp. on Wave Prop. and Dyn. Prop. of Earth Mat'ls, Albuquerque, N.M., 1967, pp. 847-859.

15. Ehrgott, J.Q., "Constitutive Property Tests on Tuff to Determine Rate Effects," USAE WES, Misc. Paper S-73-59., 1973.

16. Whitman, R.V. and Healy K.A., "Shear Strength of Sands During Rapid Loadings," J. Soil Mech. and Found. Div. ASCE Vol. 88, No. SM2, April 1962, pp. 99-132

17. Richardson, A.M., and Whitman R.V., "Effect of Strain Rate Upon Undrained Shear Resistance of a Saturated, Remolded Fat Clay," Geotechnique, Vol. 13 1963, pp. 310-324

18. Olson, R.E., and Parola, J.F., "Dynamic Shearing Properties of Compacted Clay," Proc. Int'l Symp on Wave Prop. and Dyn. Prop. of Earth Mat'ls, Albuquerque, N.M., 1967, pp. 173-182.

19. Selig, E.T., and Vey, E., "Impact Tests on Constrained Sand Specimens," ASTM Materials Research and Standards, March 1965, pp. 111-118.

20. Yong, R.N., and Japp, R.D., "A Flow Law for Clays in Dynamic Compression," Proc. Int'l Symp. on Wave Prop. and Dyn. Prop. of Earth Mat'ls, Albuquerque, N.M., 1967, pp. 183-188

21. Knott, R.A., "Effect of Loading Rate on the Stress-Strain Characteristics of a Clay Shale in Unconsolidated-Undrained Triaxial Compression," USAE WES, Misc. Paper, S-73-68, 1973.

22. Schimming, B.B., and Saxe, H.C., "Inertial Effects and Soil Strength Criteria," Proc. Soil-Structure Interaction Conf., Tuscon, AZ. 1964, pp. 118-128.

23. Schimming, B.B., Haas, H.J., and Saxe, H.C., "Study of Dynamic and Static Failure Envelopes," J. Soil Mech. and Found Div., ASCE, Vol 92, No. SM2, March 1966, pp. 105-124.

24. Hopkinson, B., British Ordnance Board Minutes 13565, 1915.

25. Kolsky, H., Proc Phys. Soc B, 62, 676, 1949.

26. Fletcher, E.B. and Poorooshasb, H.B., "Response of a Clay Sample to Low Magnitude Loads Applied at a High Rate," Proc. Int'l. Symp. on Wave Prop. and Dyn. Prop. of Earth Mat'ls, Albuquerque, N.M., 1967, pp. 781-786.

27. Hakalehto, K.O., "Brittle Fracture of Rocks under Impluse Loads," Int'l J. of Fracture Mech., Vol 6, No 3, Sept 1970, pp. 249-256.

28. Janach, W., "The Role of Bulking in Brittle Failure of Rocks under Rapid Compression," Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., Vol. 13, 1976, pp. 117-186.

29. Lundberg, B., "A Split Hopkinson Bar Study of Energy Absorption in Dynamic Rock Fragmentation," Int. J. Rock Mech. Min. Sci. and Geomech. Abstr., Vol 13, 1976, pp. 187-197.

30. Kolsky, H., Stress Waves in Solids, Dover Publications, Inc, New York, 1963.

31. Davies and Hunter, "Dynamic Compression Test of Solids in Hopkinson Bar," J. Mech Phy. Solids, Vol II, 1963, pp. 155-179.

32. Bertholf, Karnes, "Two-Dimensional Analysis of Split Hopkinson Bar System," J. Mech. Phy. Solids, Vol 23, 1975, pp. 1-19.

33. Zukas, J.A., Nicholas, T., Swift, H.F., Greszczuk, L.B., and Curran, D.R., Impact Dynamics, John Wiley and Sons, New York, 1982.

34. Whitman, R.V., Miller, E.T., and Moore, P.J., "Yielding and Locking of Confined Sand," J. of Soil Mech. and Found. Div. ASCE, SM4, July, 1964, pp. 57-84.

35. Jackson, J.G., Ehrgott, J.Q., and Rohani, B., Loading Rate Effects on Compressibility of Sand, USAE WES Report SL-79-24, Vicksburg, MS, 1979.

36. Seaman, L., "Evaluation of WES One-Dimensional Dynamic Soil Testing Procedures," USAE WES Misc. Paper SL-83-8, 1983.

37. Carter, W.J., "Laboratory Test Facility for Static and Dynamic Loading of Structures and Components," Symp. on the Int. of Non-Nuclear Munitions with Structures, Part 2, 1982, pp. 59-61.

38. Baladi, G.Y., and Rohani, B., An Elastic-Viscoplastic Constitutive Model for Earth Materials, USAE WES Tech Report SL-82-10, Vicksburg MS, 1982.

39. Parkin, B.R., "Impact Waves in Sand: Theory Compared with Experiments on Sand Columns," J. of Soil Mech. Div, ASCE Vol 87 No. SM3, June 1961, pp. 1-32.

40. Stoll, R.D., "Essential Factors in a Mathematical Model of Granular Soil," Proc. Int'l Symp. on Wave Prop. and Dyn. Properties of Earth Mat'ls, Albuquerque, NM, 1967, pp. 201-209.

41. Curtis, J.O., "A One-Dimensional Plane Wave Propagation Code for Layered Rate-Dependent Hysteretic Materials," USAE WES Misc. Paper SL-81-25, 1981.

42. Khatua, T.P., Pattanayak, A.K., and Gupta, A.K., "Dynamic Analysis of Buried Structures subjected to Shock Loads," Trans. of the 5th Int'l Conf. on Structural Mechanics in Reactor Technology, Berlin, Germany, 1979, pp. 2-8/ M6/6.

43. Dutertre, J.C., and Yong, R.N., "Analysis of Impulse Stress Propagation in a Visco-Elastic Medium," McGill Univ., Montreal, Que. Report for Defence Research Estb., Ottawa, Def. Res. Bd., Oct 1973.

44. Goudreau, G.L., Bailey, R.A., Hallquist, J.D., Murray, R.C. and Sackett, S.J., Proc. Symp. Impact of New Computing Systems in Computational Mech. ASME, Boston, MA, 1983, pp.141-154.

45. Schofield, A.N. and Wroth, C.P., Critical State Soil Mechanics, McGraw Hill, London, 1968.

46. DiMaggio, F.L., and Sandler, I.S., "Material Model for Granular Soils," J. Engr. Mech. Div., ASCE EM3, 1971, pp.935-950.

47. Baladi, G.Y., "An Elastic-Plastic Constitutive Relation for Transverse Isotropic Three-Phase Earth Materials," USAE WES Misc. Paper S-78-14., 1978.

48. Baladi, G.Y., An Effective Stress Model for Ground Motion Calculations, USAE WES Tech Report SL-79-7, Vicksburg MS, 1979.

49. Rubin, D., and Sandler, I., "Development of a High Pressure Cap Model for Use in Computations of Ground Shock from Subsurface Explosions," Contract Report S-77-2, Prepared for Defense Nuclear Agency by Weidlinger Associates, 1977.

50. Katona, M.G., "Evaluation of Viscoplastic Cap Model," J. of Geotech Engr, Vol 110, No. 8, August 1984, pp.1106-1125.

51. Schreyer, H.L., and Bean, J.E., "A Third Invariant Viscoplasticity Theory for Rate-Dependent Soils," Proc. Fifth Engr. Mech. Div. Specialty Conf., Laramie, WY, 1984, pp.953-956.

52. Cook, R.D., Concepts and Applications of Finite Element Analysis, 2nd Edition, John Wiley and Sons, New York, 1981.

53. Halquist, J.D., "DYNA3D Users Manual," Univ. of California, Lawrence Livermore National Laboratory Rept. UCID-19592, 1982.

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