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GRAVITY EFFECTS IN SMALL-SCALE STRUCTURAL MODELING

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Experimental research involves exposing both full- and small-scale structures to live weapon effects. Small-scale testing is more economical than full-scale testing, but is subject to data interpretation problems caused mainly by similitude criteria violation, i.e., model distortion. One of the most troublesome causes of distortion in dynamic tests of model structures is gravity. The objective of this effort was to develop concepts and procedures that compensate for gravitational effects without using a centrifuge. The concept is to use Froude scaling which accepts a gravitational acceleration scale factor of unity, but requires the ratio of the stress and mass density scale factors to equal the length scale factor. Model material must therefore be weaker than prototype materials. A survey of potential simulants for soil and concrete was conducted. A proof-of-principle experiment designed to assess the validity of Froude scaling, and three proposed small-scale experiments on shallow buried arches are described.

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PREFACE

This report was prepared by personnel of Applied Research Associates, Inc. (ARA), Albuquerque, New Mexico 87110, under Contract Number F08635-87-C-0426 for the Air Force Engineering and Services Center, Engineering and Services Laboratory (HQ AFESC/RD), Tyndall Air Force Base, Florida.

This report summarizes work done between October 1987 and may 1988, and discusses the application of the Froude scaling technique to simulate the behavior of underground structures subjected to conventional weapon effects. The HQ AFESC/RDCS project officer was Capt Isaac Schantz.

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SECTION I
INTRODUCTION

A. OBJECTIVES

The objectives of this study are to develop concepts and procedures that compensate for gravitational effects without using artificially induced gravity, i.e., without using a centrifuge. The approach is to use Froude scaling (References 1, 2, and 3), which accepts a gravitational acceleration scale factor of unity, but requires the use of a simulant material for which the ratio of the stress scale factor, σ, and mass density scale factor, ρ, equals the desired length scale factor, ℓ, i.e.,

$$\frac{\sigma}{\rho} = \ell$$

Simulant (or model) materials must therefore be weaker than prototype materials, which may be difficult but not impossible to achieve.

B. BACKGROUND

To develop design criteria for structures that will withstand the effects of conventional (nonnuclear) weapons, the Air Force conducts both analytical and experimental research. Some experimental research involves exposing both full-scale and small-scale structures to live weapon effects. Small-scale testing is usually more economical than full-scale testing, but is subject to problems with data interpretation caused mainly by violation of similitude criteria, i.e., model distortion. When significant model distortion exists, application of model test data to prototype design involves interpolation or extrapolation, which creates uncertainty and decreases confidence in prototype behavior predictions. One of the most troublesome causes of distortion in dynamic tests of model structures is gravity. Gravity causes the shear strength of granular soils to increase with depth, which is important when considering issues related to the effects of conventional weapons, e.g., weapon penetration resistance and the strength of buried structures.

When dynamic structural tests use replica scaling, similitude analysis indicates that the model gravitational acceleration scale factor should be the reciprocal of the length scale factor (Reference 4). This similitude requirement is often violated, with generally uncertain consequences. The requirement can be satisfied by using a centrifuge, provided the body in question remains in contact with the centrifuge; however, this is difficult and expensive.

C. SCOPE

The study described in this report covers the development and application of Froude scaling techniques to simulate the behavior of dynamically loaded underground structures. The main emphasis in this study is the application of these techniques to two problems of interest to the Air Force, namely, the behavior of shallow buried structures and pile foundations subjected to conventional weapon effects. These two problems are discussed in detail. Three potential small-scale experiments are discussed and preliminary designs are accomplished to assess the validity of the proposed techniques.

The use of models in small-scale tests and Froude scaling techniques is discussed in Section II. The application of Froude scaling techniques to simulate the behavior of shallow buried structures and pile foundations subjected to conventional weapon effects is covered in Section III. A survey of potential simulant materials for soil and concrete was conducted and the results are described in Section III. A proof-of-principle experiment, designed to assess the validity of Froude scaling, and three potential small-scale experiments on shallow buried arches are described in Section IV. Conclusions and recommendations on the applicability and limitations of Froude scaling techniques are presented in Section V.

SECTION II
SCALING LAWS

A. EXPERIMENTAL RESEARCH

Experimental research is essential for understanding the behavior of complex systems and should be viewed as a complement to, analytical research. The behavior of structures (or structure components) is best evaluated by full-scale testing. However, such testing is expensive and time-consuming. As a result, experimental research is typically conducted on small-scale models. The results from experimental research can be used to develop and/or verify a mathematical model for predicting the response of the prototype structure; to predict quantitatively the response of the prototype structure; and to establish confidence levels with which the results can be applied. The interpretation of test data can be simplified if modeling techniques, or similitude requirements, which account for all the variables governing the response of the structure, are developed and adhered to during the experiment.

The theory of models is employed to develop the similitude requirements, or scaling laws, between model and prototype. When all scaling laws are satisfied, the model is said to be a true model, and the results are directly applicable to prototype behavior. In certain instances, it is not possible to satisfy all the scaling laws. Whenever one or more of the scaling laws are not satisfied, the model is said to be distorted. When significant model distortion exists, application of model test data to prototype design will involve interpretation, which creates uncertainty and decreases confidence in prototype behavior predictions.

The theory of models used to accomplish the objectives of this study and the resulting scaling laws that need to be satisfied by a true model are derived in this section.

B. SCALING METHODS

The starting point in any investigative model is the determination of the set of variables that influence the problem. The number of variables in this set can be quite extensive. Dimensional analysis can be used to reduce the effective number of variables appearing in the problem. The basic approach is to express the physical dimensions of any variable in terms of a set of dimensionally independent fundamental units such as mass, M, length, L, and time, T.

The important variables affecting the behavior of shallow buried structures and pile foundations are shown with their scale factors and dimensions in Table 1. The scale factor for a variable is defined as the ratio of its model to prototype values. For example, the scale factor for length, ℓ, is given by ℓ_m/ℓ_p where the subscripts m and p refer to model and prototype, respectively.

The scale factor for each variable can be obtained by using the fundamental scaling law:

> "The scale factor for any variable is obtained by replacing the variable's dimensions by their scale factors."

TABLE 1. IMPORTANT VARIABLES WITH THEIR SCALE FACTORS AND DIMENSIONS

Variable	Scale Factor	Dimensions
length	ℓ	L
mass density	ρ	ML^{-3}
acceleration	a	LT^{-2}
time	t	T
stress	σ	$ML^{-1}T^{-2}$
strain	ϵ	-
Poisson's ratio	ν	-
friction angle	ϕ	-
velocity	v	LT^{-1}
force	f	MLT^{-2}
unit weight	γ	$ML^{-2}T^{-2}$
impulse	i	$ML^{-1}T^{-1}$
energy	W	$ML^{2}T^{-2}$

The similitude requirements or scaling laws governing the relationships between model and prototype can then be derived by: (1) choosing a set of dimensionally independent base variables, (2) expressing the scale factors for the fundamental units M, L, and T, in terms of the scale factors for the base variables, and (3) deriving the scale factors for the remaining variables.

Scaling methods differ in the choice of base variables. The two most common scaling methods are replica scaling and Froude scaling. In replica scaling the set of base variables consists of length, mass density, and stress. When tests are designed using replica scaling, the scaling laws indicate that the acceleration scale factor should be the reciprocal of the length scale factor (References 1 and 4). This requirement can be satisfied by using a centrifuge.

In Froude scaling the set of base variables consists of length, mass density, and acceleration. The acceleration is chosen as a base variable and is assigned a scale factor of unity. For systems in which gravity effects are important this method can be employed to design model tests without requiring the use of a centrifuge. The Froude scaling laws which govern the relationships between model and prototype are derived in the following section.

C. DERIVATION OF FROUDE SCALING LAWS

Froude scaling uses the following set of dimensionally independent base variables:

length, ℓ with dimensions L
mass density, ρ with dimensions ML^{-3}
acceleration, a with dimensions LT^{-2}

The application of the *fundamental* scaling law to the three base variables yields the following scale factors:

$$\ell = \ell \qquad (1)$$
$$\rho = m\ell^{-3} \qquad (2)$$
$$a = \ell t^{-2} \qquad (3)$$

The scale factor for the fundamental unit of length, L, is given by Equation (1). The scale factors for the fundamental units M and T in terms of the scale factors of the base variables are obtained from Equations (2) and (3):

$$m = \rho \ell^3 \quad (4)$$

$$t = \sqrt{\frac{\ell}{a}} \quad (5)$$

Once the scale factors for the base variables are chosen, the scale factors for all other variables are fixed. Application of the fundamental scaling law yields the scale factors for the remaining variables shown in Table 1 in terms of the scale factors for the fundamental units.

The stress scale factor is given by

$$\sigma = m \ell^{-1} t^{-2} \quad (6)$$

Substitution of the scale factors for m and t from Equations (4) and (5), yields

$$\sigma = \rho \ell^3 \times \ell^{-1} \times \frac{a}{\ell} = \rho a \ell \quad (7)$$

The velocity scale factor is given by

$$v = \ell t^{-1} \quad (8)$$

which can be combined with Equation (5) to yield

$$v = \ell \times \sqrt{\frac{a}{\ell}} = \sqrt{a \ell} \quad (9)$$

The force scale factor is given by

$$f = m \ell t^{-2} \quad (10)$$

Substitution of Equations (4) and (5) into (10) yields

$$f = \rho \ell^3 \times \ell \times \frac{a}{\ell} = \rho a \ell^3 \quad (11)$$

The unit weight scale factor is given by

$$\gamma = m \ell^{-2} t^{-2} \quad (12)$$

Substitution of Equation (4) and (5) into (12) yields

$$\gamma = \rho \ell^3 \times \ell^{-2} \times \frac{a}{\ell} = \rho a \quad (13)$$

The impulse scale factor is given by

$$i = m \ell^{-1} t^{-1} \quad (14)$$

which, combined with Equations (4) and (5), yields

$$i = \rho \ell^3 \times \ell^{-1} \times \sqrt{\frac{a}{\ell}} = \rho \sqrt{a \ell^3} \quad (15)$$

The energy scale factor is given by

$$W = m\,\ell^2\,t^{-2} \tag{16}$$

which, combined with Equations (4) and (5), yields

$$W = \rho\,\ell^3 \times \ell^2 \times \frac{a}{\ell} = \rho\,a\,\ell^4 \tag{17}$$

The scale factor for dimensionless quantities, such as strain, Poisson's ratio, and friction angle, is unity. The scale factors for all the variables from Table 1 are summarized in Table 2.

TABLE 2. FROUDE SCALING FACTORS

Variable	Scale Factor	Froude Scale Factor	Replica Scale Factor
length	ℓ	ℓ	ℓ
mass density	ρ	ρ	$\rho = 1$
acceleration	a	$a = 1$	$a = 1/\ell$
time	$t = \sqrt{\frac{\ell}{a}}$	$t = \sqrt{\ell}$	$t = \ell$
stress	$\sigma = \rho\,a\,\ell$	$\sigma = \rho\,\ell$	$\sigma = 1$
strain	ϵ	$\epsilon = 1$	$\epsilon = 1$
Poisson's ratio	ν	$\nu = 1$	$\nu = 1$
friction angle	ϕ	$\phi = 1$	$\phi = 1$
velocity	$v = \sqrt{a\ell}$	$v = \sqrt{\ell}$	$v = 1$
force	$f = \rho a \ell^3$	$f = \rho\,\ell^3$	$f = \ell^2$
unit weight	$\gamma = \rho\,a$	$\gamma = \rho$	$\gamma = 1/\ell$
impulse	$i = \rho\sqrt{a\,\ell^3}$	$i = \rho\sqrt{\ell^3}$	$i = \ell$
energy	$W = \rho\,a\,\ell^4$	$W = \rho\,\ell^4$	$W = \ell^3$

In Froude scaling, the three base variables are the length, mass density and acceleration. Since gravity cannot be scaled outside a centrifuge, the acceleration scale factor is chosen as unity. The resulting scale factors that govern the variables of interest are summarized in Column 3 of Table 2.

In replica scaling, the three base variables are the length, mass density and stress. The same procedure used to derive the scale factors for Froude scaling can be applied to derive the scale factors for replica scaling (Reference 4). Since the same material is used for model and prototype, the scale factors for mass density and stress are equal to one. The resulting scale factors that govern the variables of interest are summarized in Column 4 of Table 2.

The consequences of violating the scaling law for a particular variable can only be determined by testing at several scales (interpolation or extrapolation) or by analysis. Dimensional analysis determines how variables should be scaled for model testing, but not how important any given variable is to the physical behavior being studied.

D. DISCUSSION

Since gravitational acceleration cannot be scaled without using a centrifuge, the acceleration scale factor has to be chosen equal to unity. In this case the scale factors for the remaining variables are as shown in the third column of Table 2. An examination of these scale factors shows that, while allowing true modeling of gravitational acceleration, Froude scaling places additional constraints on the material properties and loading conditions.

1. Materials Similitude

When replica scaling is used to design a small-scale experiment, test models are usually constructed of the same material as the prototype structure. When Froude scaling is used, the properties of the model or simulant material need to satisfy the following scaling laws:

stress	:	$\sigma = \rho\ \ell$
strain	:	$\epsilon = 1$
Poisson's ratio	:	$\nu = 1$
friction angle	:	$\phi = 1$

As a result, the prototype materials cannot be used to construct small-scale models; instead simulant materials should be substituted for prototype materials. Because the product of the length and mass density scale factors is usually less than one, the simulant materials need to be weaker than the prototype materials. Although, in principle, one may arbitrarily select the length scale factor, the choice is generally dictated by the properties of the available simulant material.

2. Loading Similitude

To completely simulate loading conditions, the following conditions need to be adhered to in the design of small-scale experiments using Froude scaling:

time : $t = \sqrt{\ell}$

velocity : $v = \sqrt{\ell}$

peak pressure (or stress): $\sigma = \rho \ \ell$

impulse : $i = \rho \sqrt{\ell^3}$

For a laboratory experiment in which the load is applied with a hydraulically driven actuator, the pressure (or stress) scale factor does not present any special problem as long as the rate of application and magnitude of the load stay within the limits of the machine. All of the above conditions can be satisfied simultaneously.

For field experiment in which an explosive charge is used for loading, it may not be possible to satisfy simultaneously all the above similitude requirements since they are different from cube root scaling applicable to the source. However, these requirements can be satisfied in part; the similitude requirement for either peak pressure or for impulse, but not both can be satisfied. This violation of similitude requirements for loading is not very critical. If the maximum response of the system occurs early, peak pressure should be properly scaled. If the maximum response of the system occurs after overpressure has decayed substantially, the impulse should be properly scaled. This subject will be discussed further in Section III.

SECTION III

SMALL-SCALE MODELING OF BURIED STRUCTURES

A. INTRODUCTION

The Air Force is interested in developing concepts for small-scale testing of buried structures subjected to conventional weapon effects. While the scaling laws discussed in Section II can be applied to any structural system, specifically one in which gravity effects are important. The main emphasis in this study is the application of these techniques to two problems of interest to the Air Force, namely, shallow buried structures and pile foundations.

Previous experimental work performed on small-scale models of shallow buried structures and pile foundations will be briefly described. The description is followed by a discussion of potential application of Froude scaling to these problems. The identification of model materials (or simulant materials) for soil and concrete to satisfy Froude scaling laws is discussed. Finally, the simulation of loading conditions is covered.

B. APPLICATION OF FROUDE SCALING

For small-scale tests conducted on buried structures and various types of foundation in which test models have been subjected to static and dynamic loading conditions, gravitational effects influence the response of the soil, the structure, and soil/structure interaction. As a result, gravitational effects should be considered during test design. Previous experience and potential application of Froude scaling to these problems is discussed in this section.

1. Small-Scale Modeling of Buried Structures

Since the early 1960s, the Air Force has supported several research programs aimed at developing theoretical and experimental techniques for use of models (References 5, 6, 7, and 8) to simulate the behavior of underground structures subjected to blast loading. Dimensional analysis and model theories have been used to derive the similitude requirements that govern the relationships between prototype and model behavior. Typically, the same combination of materials was used for model and prototype. In this case, similarity requirements show that a true model can be obtained only if the test is performed in a centrifuge. Under a 1-g condition, distortion is inevitable. Results from distorted models are useful to examine the behavior of underground structures (References 7 and 9). However, these results are subject to data interpretation.

It is common to assume that gravitational effects are negligible, and thus to try to satisfy all similitude requirements except the requirement related to gravity. The soil/structure interaction phenomenon is complex. The behavior of soil is stress-dependent, making it necessary to simulate the stress level in the soil if the soil/structure interaction is to be properly simulated. Test results on shallow buried structures show that the soil around the structure has a stiffening effect which tends to limit lateral deflections of the structure (Reference 9). The stiffening effect is due to the development of passive pressures produced by shear stresses in the soil. This phenomenon is generally referred to as soil arching and is responsible for most of the increased structural hardness for buried structures. Gravity causes the shear strength of granular soil to increase with depth, an important factor when considering the hardness of buried structures. As a result, the validity of neglecting gravity effects is questionable.

The alternative to 1-g simulation is to use a centrifuge. In centrifuge testing the increased forces generated in the model make it possible to simulate the self-weight-induced stresses that control the stiffness and strength of the soil. The similitude requirement for stress is:

$$\sigma = \rho a \ell$$

When the same material is used for model and prototype, the stress scale and mass density scale factors are unity. As a result, to obtain a true model the acceleration scale factors should be equal to the inverse of the length scale factor, i.e., $a = 1/\ell$. For example, a centrifuge test at 50 g will correspond to a 1/50 scale model of a prototype structure.

Centrifuge testing of buried structures has become increasingly popular in the last several years. Several tests have been conducted at the University of Colorado (Reference 10), the University of San Diego (Reference 11) and the University of Florida (References 12 and 13) with support, in part, by the Air Force. To investigate the importance of gravity, tests have been conducted at several gram levels. Results from tests at 1 and 60 g at the University of Florida (Reference 13) showed significant differences in the response of the buried structures, while test results at 60 and 80 g showed close correspondence. These results indicate that gravity effects are important and should not be dismissed as negligible without investigation. Another consideration is that the response of underground structures subjected to dynamic loading may be significantly altered as the type of soil varies from a dry non-cohesive material to a highly cohesive material. The effect of gravity on the soil/structure interaction is expected to change depending on the type of soil. The importance of gravity is thus problem-dependent, and its significance should be decided separately for each problem.

The use of a centrifuge to conduct tests on small-scale models of buried structures has proved to be valuable. It allows the testing of a true model at a reduced cost as compared to full-scale testing. However, centrifuge testing presents some problems for structural modeling. These problems are related mainly to the size of the model. Typically, the length scale factor for centrifuge testing of buried structures is around 1/50 or smaller. These small-scale factors are needed because of limits on the size of the centrifuge. The soil bin must be large enough and the structure small enough so that boundary effects are minimized. For dynamic loading, the simulation time is controlled by the relative size of the bin and structure since wave reflections from the walls of the bin will interfere with the structure response. Another major difficulty is related to maintaining material properties while satisfying geometric scaling laws. For example, in the case of reinforced concrete, aggregate size and reinforcing steel size must be scaled to construct a model, while material strength and deformation characteristics need to be maintained. This requirement can be satisfied relatively easily for a scale factor around 1/8 or 1/10, but becomes very difficult to satisfy for a geometric scale factor of 1/50 or smaller.

The problem related to bin size and geometric scale can be eliminated if the testing is conducted outside a centrifuge. To satisfy gravity scaling outside a centrifuge, Froude scaling laws should be used. In this case the same material cannot be used in model and prototype. The problem is to find a simulant material to construct the model. For simulant materials, the ratio of the stress scale factor to the mass density scale factor is equal to the geometric scale factor. As a result, different simulant materials are needed for different geometric scale factors. For buried structures, the materials of interest are soil and concrete. Candidate simulant materials for soil and concrete are discussed in Section III, C.

2. Small-Scale Modeling of Piles

The dynamic response of pile foundations has received considerable interest in recent years (References 14, 15, 16, and 17). The research involved experimental and theoretical investigations of the response of single piles and pile groups subjected to static and dynamic loading. The dynamic loading is usually due to either a vertical or lateral excitation at the top of the pile cap. The experiments are usually performed on small-scale models of piles. However, some data are available from full-scale tests. The test data are used to derive and calibrate mathematical models. The small-scale tests are performed either in the field or in the laboratory under 1 gram condition. The materials used in the tests are the same for model and prototype. The result is a distorted model due to the violation of the similarity requirements for gravity.

The distortion could be very significant, especially for friction piles. The friction between the pile and soil is due to the inherent cohesion of the material and a term sometimes referred to as apparent cohesion. Inherent cohesion is due to cementation and is a property of the material. It is equivalent to the shear strength of the material when the normal stress is zero. Apparent cohesion is due to the effect of gravity-induced confining stresses acting through an angle of friction. When replica scaling is used to design a small-scale test (i.e., the same material is used for model and prototype), the similitude requirement for gravity is violated. The inherent cohesion which is a material property is preserved. However, apparent cohesion is not preserved since it is a function of gravity. In Froude scaling the overburden stress is properly scaled and, as a result, the apparent cohesion is perserved. This problem is very significant for long-buried structures, such as poles and vertical shelters (References 18 and 19).

Most testing of piles has been conducted on small-scale models either under static loading conditions or under dynamic loading simulating earthquake excitation. At present, a series of experiments on pile in a centrifuge are being conducted at Cambridge, England (Reference 20). This effort is supported by the Air Force and is aimed at evaluating pile response in a blast environment. The tests are being conducted at 1/60 scale. Preliminary test results show that the centrifuge can be used to assess the response of pile foundations subjected to blast loading. These results need to be verified with full-scale field tests or with tests at several scales. Since tests at scales much larger than 1/60 cannot be conducted in a centrifuge due to size limitations, field tests are needed. Froude scaling should be used to design the field tests because for this problem gravity effects are important and they cannot be neglected.

C. IDENTIFICATION OF SIMULANT MATERIALS

1. Material Behavior and Scaling Requirements

At low stress levels, only elastic deformation occurs. As stress increases, the material exhibits nonlinear behavior, i.e., elastic and inelastic deformation generally take place simultaneously. Accordingly, the mechanical behavior of a material can be fully described with a stress-strain relationship for elastic deformation, a yield surface that defines states of inelastic shear deformation, a loading hydrostat that defines states of inelastic hydrostatic deformation, and an incremental relation between stress and strain under conditions of inelastic deformation. An example of a material model commonly used to calculate soil response is the Air Force Weapons Laboratory (AFWL) engineering model shown in Figure 1.

At the start of an investigation the properties of the prototype material need to be defined. This is usually done by laboratory testing of samples of prototype material. Subsequently, the parameters for a material model, such as the AFWL engineering model, are derived to fit the laboratory data.

In replica scaling the same material is generally used in model and prototype. Material similitude presents no special problem. This is, however, not possible in Froude scaling. An examination of the scale factors summarized in Table 2 shows that, while allowing true modeling of gravitational acceleration, Froude scaling places constraints on the simulant

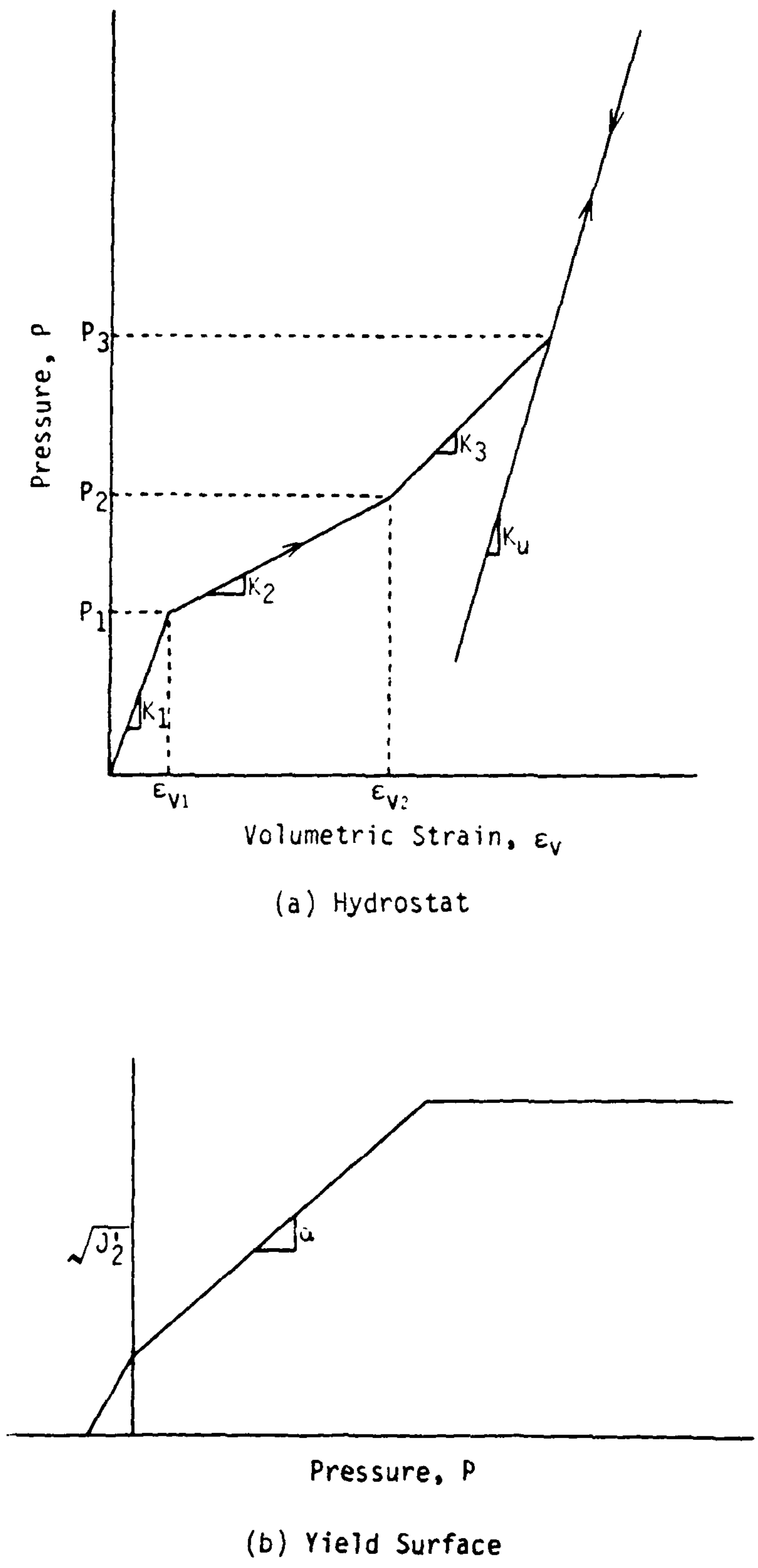


Figure 1. Air Force Weapons Laboratory Engineering Model.

material used to model the prototype material. The properties of the simulant material need to satisfy the following requirements:

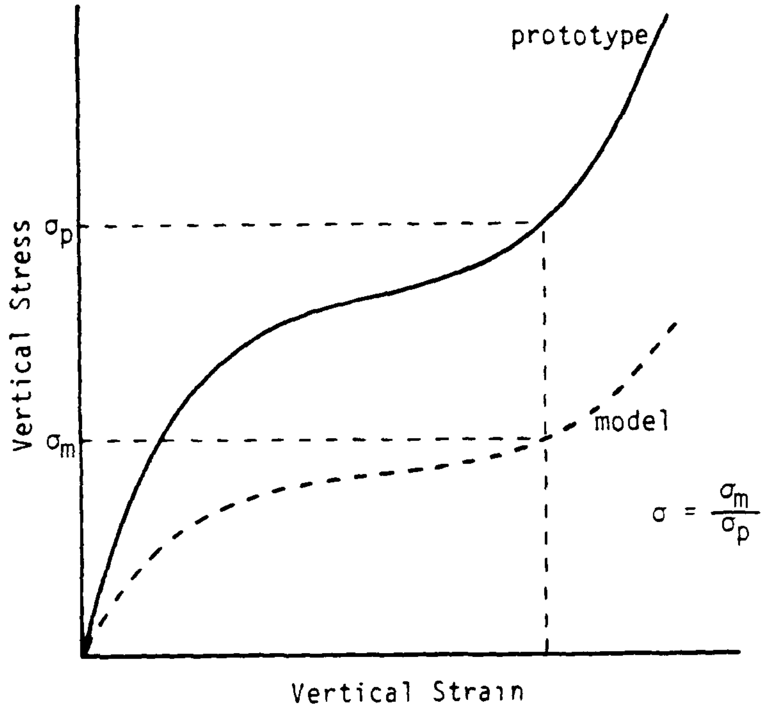
stress	:	$\sigma = \rho\, \ell$
strain	:	$\epsilon = 1$
Poisson's ratio	:	$\nu = 1$
friction angle	:	$\phi = 1$

The scaling law for stress implies that once the geometric scale factor, ℓ, is decided upon, the ratio of the required stress to unit weight of the simulant material is fixed. The scaling laws for stress and strain imply that there is only a change of scale on the stress axis and no change of scale on the strain axis. These conditions need to be satisfied in the linear and nonlinear stress space, but only up to the stress level of interest. For example, the uniaxial stress-strain characteristics and yield surface for prototype and simulant materials are shown in Figure 2.

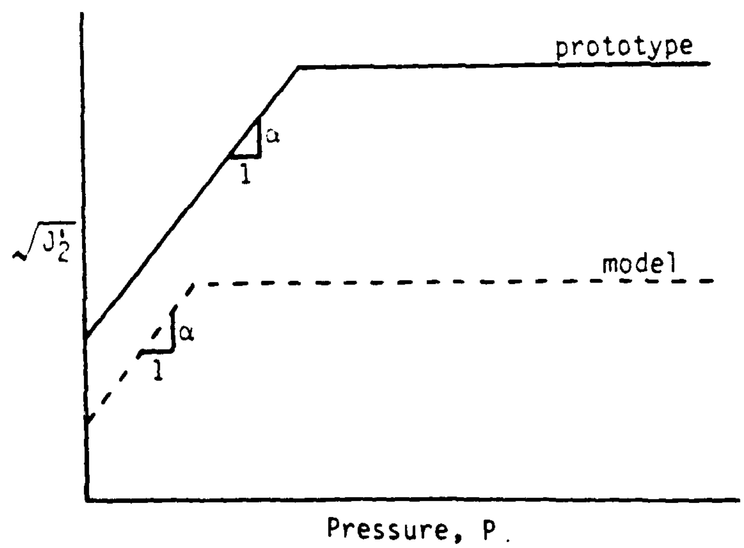
The stress-strain curve has an associated value of Poisson's ratio. Poisson's ratio is dimensionless and thus has a scale factor of unity. This condition implies that the model and prototype materials should have the same Poisson's ratio. The slope of the yield surface is related to the friction angle of the material which is dimensionless and thus has a scale factor of unity. This condition implies that the model and prototype materials should have the same friction angle.

When sufficient information about the stress-strain response of candidate simulant materials is unavailable, initial screening can be conducted on the basis of wave speeds. For buried structures, the interface normal stresses on the structure surface can be estimated based on the acoustic impedance of the soil (Reference 21). The acoustic impedance is equivalent to the product of the mass density and seismic wave speed of the soil. As a result, the wave speed in the material can be used for initial screening. However, full laboratory testing of the candidate simulant materials should be undertaken before a decision is made on which simulant material should be used in an experiment.

The above discussion is general and applies to the derivation of a simulant material corresponding to any prototype material. For shallow buried



(a) Uniaxial Stress-Strain Surface



(b) Yield Surface

Figure 2. Characteristic Curves for Prototype and Simulant Materials.

structures and pile foundations, the prototype materials of interest are soil and reinforced concrete (or concrete and steel). As such, the main emphasis in the remainder of this section is on identification of simulant materials for soil and concrete.

2. Soil Simulant

a. Screening Procedure for Granular Materials

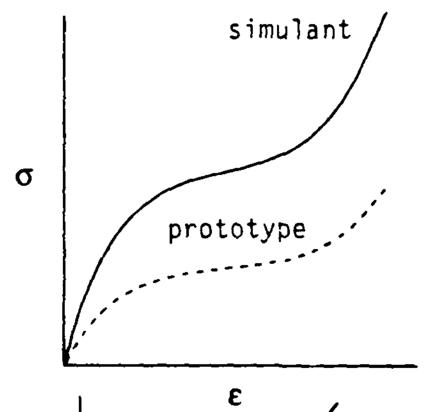
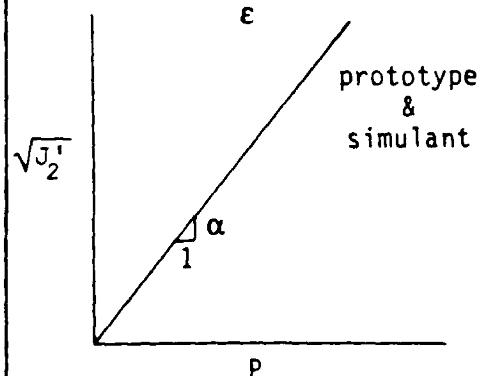
The discussion in the previous section covered the behavior of soils in general. Here the attention is limited to granular materials. The applications of interest are shallow buried structures and pile foundations. For a buried structure subjected to conventional weapon effects failure can occur either in the structure or in the soil. The type of soil failure observed in a granular material is either sinking of the structure or a bearing capacity failure. Sinkage typically occurs in loose sand. This type of behavior is not of interest and it is prevented by imposing a requirement on relative density of prototype and simulant soil material. A further restriction should be imposed on grain size and grain size distribution if one is interested in the response of coarse, medium, or fine granular material.

The requirements and limitations on the properties of granular materials that exhibit the type of behavior of interest are summarized in Table 3 along with the scale factor for each property. This table is used for screening purposes, i.e., each of the properties of the prototype and simulant materials need to fall within the acceptable range. It should be noted that the yield surface has a zero intercept along the vertical stress axis, i.e., the material has no inherent cohesion. As a result, the requirement for the yield surface is that the simulant and prototype material have the same friction angle.

b. Survey of Candidate Materials

Early in this effort, it was decided to concentrate the search on simulants for granular-type material. An examination of the stress scale factor revealed that the simulant material needs to be weaker than the prototype material. With these guidelines in mind, a survey of potential simulants was conducted.

TABLE 3. SCREENING OF SIMULANTS FOR GRANULAR MATERIAL

Significant Properties	Requirements and Limitations for Granular Material	Scale Factors for Simulant Materials
Granular	Spherical or Angular Shapes (Rough Surface For Friction)	-
Gradation	Well Graded (Excellent Shear Strength)	-
Relative Density	65 - 100%	1
Air Voids Content	10 - 30%	1
Dry Unit Weight	85 - 115 pcf	ρ
Friction Angle	27 - 40 degrees	1
Poisson's Ratio	0.2 - 0.35	1
Wave Speed		$\sqrt{\ell}$
Seismic	500 - 2500 ft/s	
Loading	400 - 2000 ft/s	
Stress-Strain Characteristics (relationship needs to hold up to the stress level of interest)		$\sigma = \rho\ell$ $\epsilon = 1$
Failure Surface		$\alpha = 1$

The literature search started with a review of work done at U.S. Army Waterways Experiment Station (WES) on shock-attenuating materials (References 22 and 23). The candidate materials for shock attenuation exhibit a behavior similar to concrete, except that they are weaker. These materials may be used as a simulant for concrete and will be covered in more detail in the next section. The mix for these materials includes beads manufactured by plastic companies. The beads may be used as soil simulants. Several plastic companies were contacted to obtain properties for the beads. The companies contacted include BASF Wyandotte Corporation, Dow Chemical Company, and Koppers Company, Inc. The beads manufactured by these companies are made of polystyrene and are used primarily for insulation and packaging. The beads have a bulk density around 640 kg/m^3 (40 pcf) and are available in a size range of 0.5 to 1.5 mm (0.02 to 0.06 in) which is equivalent to U.S. Mesh Sieve Numbers 10 to 40. The engineering properties, such as wave speeds, friction angle and Poisson's ratio, are unavailable. These materials have compressive strengths of a few hundred psi, depending on the size of the bead, with the largest size beads having the lowest compressive strength. Samples of these materials were obtained from the manufacturers. An examination of the samples showed that the friction angle of this material is very low. Based on these observations and available data, this material may be used as a simulant for undrained clay, but not for sand.

A study was conducted on the effects of vacuum on the shearing resistance of ideal granular systems (Reference 24). In this study, crown barium glass spheres, manufactured by Potters Brothers, and carbonyl nickel shot, manufactured by the International Nickel Company, were used as a simulant for granular material. The International Nickel Company could not be located. Potters Industries manufactures glass spheres for application in highway and industrial projects and for use as filler material. Properties of individual spheres are available. For example, soda lime glass spheres have a density of 2.5 - 4.5 g/cm^3 (150 - 300 pcf), a modulus of elasticity of about 5×10^6 psi, a compressive strength of 70,000 psi, and a Poisson's ratio of 0.21. It is available in sizes greater than 100 micrometers. This type of glass spheres is strong and is unlikely to be useful as a simulant material.

Several other manufacturers of glass spheres, including JAYGO, Inc., OHARA Corporation, Air-Blast Company, and Sinclair Mineral and Chemical, were contacted in an attempt to obtain engineering properties for their products. Samples of the various products were obtained, but properties other than size and density are unavailable. Some of these materials are potential simulants for granular materials. Laboratory testing is needed before a final decision can be reached.

Other potential simulants are pellets and plastic beads. Companies contacted about these types of materials include Green Plastics Corporation, Composition Materials Company, Engineering Laboratories, Dow Chemicals, Huntsman Chemicals and Chevron Chemicals. The engineering properties of interest are unavailable for these materials. The manufacturers had information on size and density of final products. As a result, without laboratory testing, no decision on the potential application of these materials can be made.

The survey of materials led to P-Q Corporation, a manufacturer of sodium silicate micro-spheres. Some engineering properties of this material were available. Two of P-Q the products have the following properties:

Commercial Name	Compressive Strength (Hydrostatic Pressure)	Size Range	Density
Q-Sell 600	200-300 psi	10-120 μ	0.43g/cm^3
Q-Sell 400	200-250 psi	20-150 μ	0.21g/cm^3

The estimated initial loading wave speed of this material is in the range of 100 to 1000 in/s. Information about the frictional properties of this material is unavailable. This material is a potential simulant. However, further testing of this material is needed.

Several chemical companies were contacted in an effort to get additional properties on polystyrene beads. Texstyrene Plastic has three different grades with the following properties:

Name	U.S. Mesh Sieve No.
T grade	40-45-50 (300-425 μ average size)
C grade	30-35-40 (mostly 35)
B grade	20-30 (50% of each size)

The density is about 640 kg/m³ (40 pcf) before expansion and can drop to about 32 kg/m³ (2 pcf) after expansion. The expansion also results in a weaker material. The expansion is due to either hot air expansion or steam expansion. Hot air expansion allows more control on the amount of expansion, thus a material with the desired strength can be obtained. Additional engineering properties are unavailable for this material. Samples of this material were obtained. Based on the available information, this material may not be a good candidate for sand because of its low friction angle, but it could be used to simulate other materials. Its main advantage is that its expansion can be controlled, thus resulting in a simulant with the desired strength.

In further review of material properties, three candidate materials were identified. These materials are pumice, perlite, and vermiculite. Pumice is a porous, froth-like volcanic glass. Powdered or ground pumice is used in plaster and lightweight concrete and pozzolanic cement. Contacts with pumice distributors and their testing facilities revealed that no testing is typically done on pumice products such as pumice block. The information available on the raw material relates to size and density. Pumice can be obtained in several sizes ranging from fine to coarse, and its density is around 720 kg/m³ (45 pcf). While no testing has been conducted to obtain the friction angle, this material rests at a high angle and thus is expected to have a friction angle comparable to that of sand. As a result, pumice is thought to be a promising candidate for use as a simulant for granular material.

Perlite is a siliceous volcanic rock which, when heated in a specially designed furnace in excesss of 1600°F, is transformed into lightweight, glass-like particles containing countless sealed cells. This structure accounts for its good insulating characteristics. It is mainly used as an aggregate in light weight insulating concrete. Contacts were made with GREFCO, Inc. to obtain data on their perlite based products. Two of their products are known by the commercial names Dicaperl® "CS - Series" and Dicaperl® HP-510. The products in the "CS-Series" consist of ceramic glass spheres with a light tan color and a density of 400 kg/m^3 (25 pcf). The particle size for three products in the series are:

	Particle Size of Dicaperl®		
	CS-10-100	CS-10-200	CS-10-400
range (micrometers) average (micrometers)	10-100 80	10-200 125	10-400 175

The Dicaperl® HP-510 is a free-flowing white powder with a density of 200 kg/m^3 (13 pcf). The particle size ranges between 20 and 210 micrometers (U.S. Mesh Sieve Number 30-325) and an average size of 70 micrometers (Sieve Number 200 U.S. Mesh). The compressive strength of these products varies from under 100 to several hundred psi. Preliminary estimates of the wave speed for these products ranges between 100 to 500 ft/s. The frictional properties for these products are unavailable. In summary, the data available indicate that these products are good candidates for soil simulants.

Vermiculite is a micaceous mineral (chemically hydrated magnesium - aluminum - silicate) which is found in nature as a multilayer crystal. When subjected to sufficient heat or certain chemical reactions, vermiculite will increase in volume approximately 15 times. Vermiculite is employed in making plasters and board for heat, cold and sound insulation, as a filler in caulking compounds, and for plastic mortars and refactory concrete. Zonolite is the commercial name for vermiculite product of W.R. Grace & Co. Vermiculite ore concentrate can be mechanically ground to various degrees of fineness. It is available commercially from W.R. Grace & Co. in five grades with bulk density and sieve analysis as shown below:

Grade	U.S. Mesh Sieve No.	Bulk Density (pcf)
#1	3 - 12	50 - 65
#2	8 - 16	50 - 65
#3	12 - 40	50 - 65
#4	30 - 70	45 - 65
#5	- 40	40 - 50

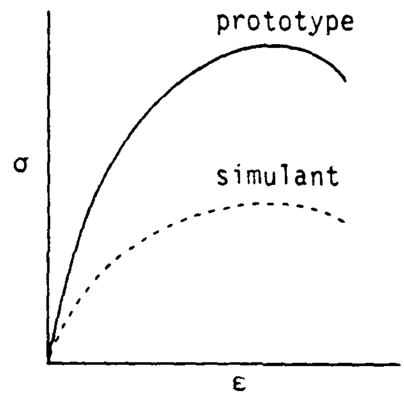
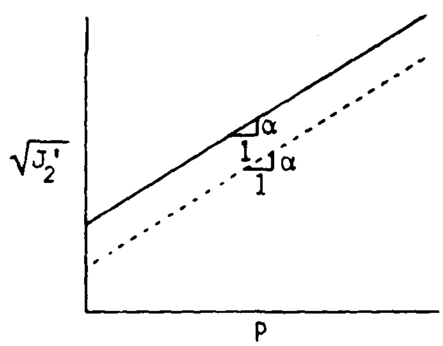
The ore can be thermally exfoliated in specially designed furnaces to provide various products. Expanded vermiculite is commercially available in five grades. Each grade is comprised of a different range of sieve sizes and the density ranges from 4 to 10 pcf. Preliminary estimates of the loading wave speed for one grade of vermiculite is 140 ft/s. No additional data on the material properties for the various grades is available from the manufacturer.

In summary, several potential candidates for use as simulants for granular materials have been identified in this survey. The most promising are pumice, perlite, vermiculite and Q-Sell of the P-Q corporation. Additional laboratory testing is recommended before any of these materials can be used in an experiment.

3. Concrete Simulant

The foregoing discussion of Froude scaling has defined the requirements to be met by the simulant material. The material properties which govern the behavior of concrete, the range of values for each property, and the scale factors relating the properties of the prototype and simulant materials are summarized in Table 4. If it is assumed that an experiment is to be conducted at 1/20 scale and that the prototype concrete has 4000 psi unconfined compressive strength, the properties of the prototype and simulant are listed in Table 5. The problem is to develop a simulant with half the unit weight of regular concrete, a Young's modulus of 100,000 psi and a compressive strength of 100 psi.

TABLE 4. SCREENING OF SIMULANTS FOR CONCRETE

Significant Properties	Requirements and Limitations for Concrete	Scale Factors for Simulant Materials
Unit Weight	135 - 150 pcf	ρ
Unconfined Compressive strength	3000 - 5000 psi	$\rho \ell$
Elastic Modulus	$3.0 - 4.0 \times 10^6$ psi	$\rho \ell$
Tensile Strength	150 - 500 psi	$\rho \ell$
Poission's Ratio	0.15 - 0.22	1
Stress-Strain Characteristics		$\sigma = \rho \ell$ $\epsilon = 1$
Failure Surface		stress = $\rho \ell$ $\alpha = 1$

A family of cellular concrete has been designed for use as a shock-attenuating material (Reference 23). The materials tested were cellular concrete with fly ash, expanded polystyrene concrete with fly ash, foamed polyurethane, foamed sulfer and molded expanded polystyrene. The studies showed that with proper adjustments in the cement content, water-cement ratio and foam content, concrete can be proportioned to meet the yield stress requirements.

TABLE 5. MATERIAL PROPERTIES FOR PROTOTYPE AND SIMULANT CONCRETE

Property	Assumed Prototype Concrete	Target Simulant Concrete
Unit Weight (pcf)	150	75
Young's Modulus E (psi)	4×10^6	1×10^5
Ultimate Strength (psi)		
Compression ($\sigma_{u,c}$)	4000	100
Tension ($\sigma_{u,t}$)	400	10
$E/\sigma_{u,c}$	1000	1000
$\sigma_{u,c}/\sigma_{u,t}$	10	10

Further analysis of the properties of expanded polystyrene concrete with fly ash has been conducted by Applied Research Associates, Inc. (Reference 25). The mixtures were designed to meet certain strength requirements, and laboratory tests were performed to characterize the material properties. These tests showed that mixtures can be designed to meet specified requirements.

Adjustments in the mix designs are required before these materials can be used as concrete simulants in the construction of small-scale models for underground structures.

Concrete simulants have been developed in the past to study the earthquake safety of dams (References 26 and 27). Materials used in the initial development of these simulants were plaster, celite and water. The ratio of water to plaster was found to be the most important parameter in controlling the mechanical properties of the simulant. The amount of celite used in the mixture was adjusted to provide good workability and consistency. Sand was later added to the mixture. It was found that the addition of sand did not increase the strength of the simulant, but it did increase the modulus. Since the ratio of modulus to strength is dimensionless, it should be the same for the simulant and prototype materials. Sand can be used to adjust this ratio to the desired value. As a result, this mixture of plaster, celite, sand and water is a good simulant for concrete.

Other candidates for concrete simulant are permalite perlite concrete and vermiculite concrete. Typical properties of different permalite perlite concrete mixes are shown below:

Cement to Aggregate Ratio	Dry Density Range, pcf	Minimum Compressive Strength, psi 28 days
1:4	36 - 42	300
1:5	30 - 36	200
1:6	24 - 30	125
1:8	18 - 24	80

By varying the cement to aggregate ratio from 1:4 to 1:8, the compressive strength is reduced from 300 to 80 psi, and the unit weight is reduced from 42 to 18 psi. The density can be increased if necessary by addition of lead powder to the mixture.

Vermiculite concrete used in construction applications has a compressive strength between 125 and 500 psi and a unit weight between 22 and 40 pcf. The Young's modulus varies between 5,000 and 15,000 psi. These two materials are versatile and, with proper adjustments in the mix proportions, simulant concrete with desired strength and deformation requirements can be obtained.

D. SIMULATION OF LOADING CONDITIONS

To completely simulate the applied load, not only the magnitude, but also the time and space distribution of the load must be properly scaled. The similitude requirements governing loading conditions are:

time	:	$t = \sqrt{\ell}$
velocity	:	$v = \sqrt{\ell}$
peak pressure (or stress)	:	$\sigma = \rho \quad \ell$
impulse	:	$i = \rho \sqrt{\ell^3}$

These similitude requirements impose different constraints on the experiment depending on whether the experiments are conducted in the laboratory or in the field.

1. Laboratory Experiments

The scale at which a prototype structure can be tested in the laboratory is generally controlled by loading conditions. The magnitude of the applied load generally dictates the size of the model and thus the geometric scale between model and prototype. If the load is applied using a hydraulically driven actuator, the peak magnitude of the applied load is controlled by the size of the machine. Other considerations related to loading conditions are the rise time to peak stress and the duration of the applied load.

The scale factor for stress is unity in replica scaling and is proportional to the length scale factor in Froude scaling. As a result, in Froude scaling the magnitude of the applied stress is reduced. The reduction implies that, for a given machine, an experiment can be conducted at a larger scale than permitted by replica scaling. Generally, experiments are preferably conducted at the highest scale permitted by cost.

The scale factor for time is equal to the length scale factor in replica scaling and is equal to the square root of the length scale factor in Froude scaling. The result is the Froude scaling requirement for time is less stringent than the replica scaling requirement. This is important especially when scaling a pressure load with a small rise time. If the rise time becomes very small, it will be impossible to apply the load within the time constraints using a machine driven with hydraulic actuators.

In summary, for laboratory experiments in which the load is applied using a hydraulically driven machine (or a similar machine), the size of the experiment is controlled, in part, by the magnitude and rate of application of the load. Froude scaling imposes less stringent constraints on the loading conditions than replica scaling and thus allows laboratory expermiments to be conducted at a larger scale then permitted by replica scaling.

2. Field Experiments

In the field, the pressure loading is due generally to an explosive charge detonated at a certain distance from the model. The size of the charge is determined by the scale of the experiment. Unlike replica scaling in which the weight of the explosive charge follows cube root scaling, Froude scaling imposes different requirements on loading conditions. The similitude requirements on the applied stress and the impulse (the area under the stress-time history) are:

stress : $\sigma = \rho \ \ell$

impulse : $i = \rho \ \sqrt{\ell^3}$

These requirements have to be satisfied in both time and space.

It is apparent from the above expressions that cube root scaling cannot be used to calculate the explosive charge if Froude scaling is used to design the experiment. As a result, all the similitude requirements for loading conditions cannot be satisfied simultaneously in a field experiment when a single explosive charge is used. These requirements can be satisfied in part, i.e., when an explosive charge is used either the similitude requirement for peak stress or for impulse can be satisfied, but both requirements cannot be satisfied simultaneously. This violation of similitude requirements is not very critical. If the maximum response of the system occurs early, the response will be sensitive to peak pressure. As a result, the similitude requirement for peak stress should be satisfied while the requirements for impulse is violated. If the maximum response of the system occurs after the overpressure has decayed to zero, the response will be sensitive to impulse.

In this case, the similitude requirement for impulse should be satisfied first, while the requirement for peak stress is violated.

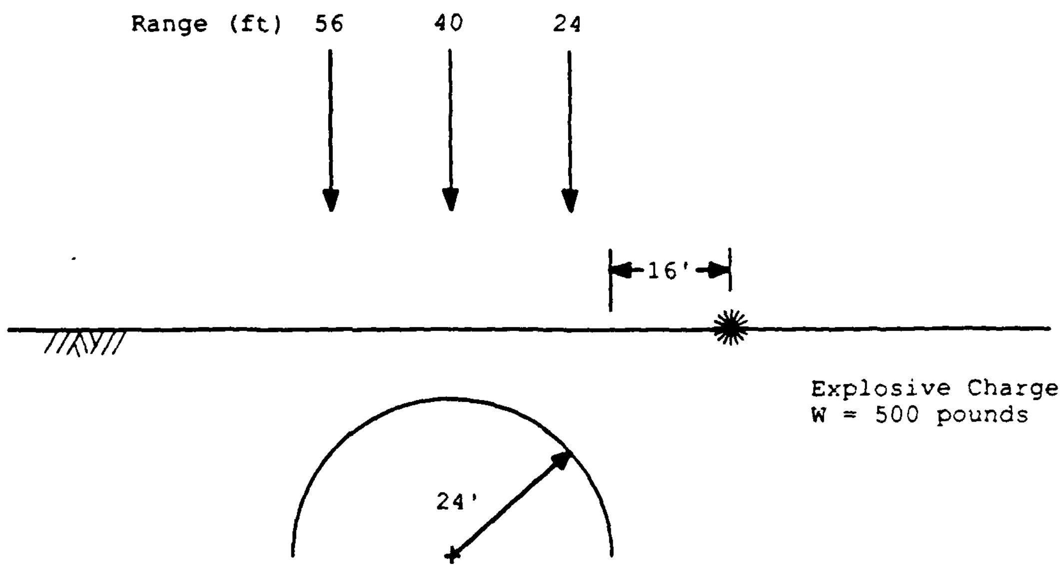
In the field, the load is usually due to an explosive charge either above ground or in a buried configuration. The main parameters in the design of a charge are the size of the charge, its height of burst (or depth of burial), and the stand off distance between the charge and the structure. A trial design for the charge is chosen. For instance, a design based on cube root scaling can be chosen for a start. A trial and error procedure is used to find a final design that provides the best compromise. One of the design parameters is varied at a time and the resulting peak stress and impulse at the range of the structure can be calculated. The set of parameters that most closely satisfies the similitude requirement of interest is chosen as a final design. This procedure is illustrated in the following example. It is of interest to design a 1/5-scale experiment for a buried structure, as shown in Figure 3, subjected to a conventional weapon. The weapon is equivalent to a 500-pound TNT surface charge at 4.8 meters (16 feet) from the edge of the structure. The structure is a buried arch with a 6 meter (24 feet) inner radius. The objective is to design the charge to be used in the 1/5-scale experiment. The scale factors for stress and impulse depend on the scale factor for the mass density of the simulant material. For the purpose of this example, it is assumed that ρ is equal to one-half. The scale factors for stress and impulse are thus equal to:

$$\text{stress:} \quad \sigma = \rho\, \ell = 1/2 \times 1/5 = 1/10$$

$$\text{impulse:} \quad i = \rho\sqrt{\ell^3} = 1/2 \left[\sqrt{1/5} \right]^3 = 0.045$$

It is further assumed that the response of the structure is more sensitive to the impulse than to the peak overpressure.

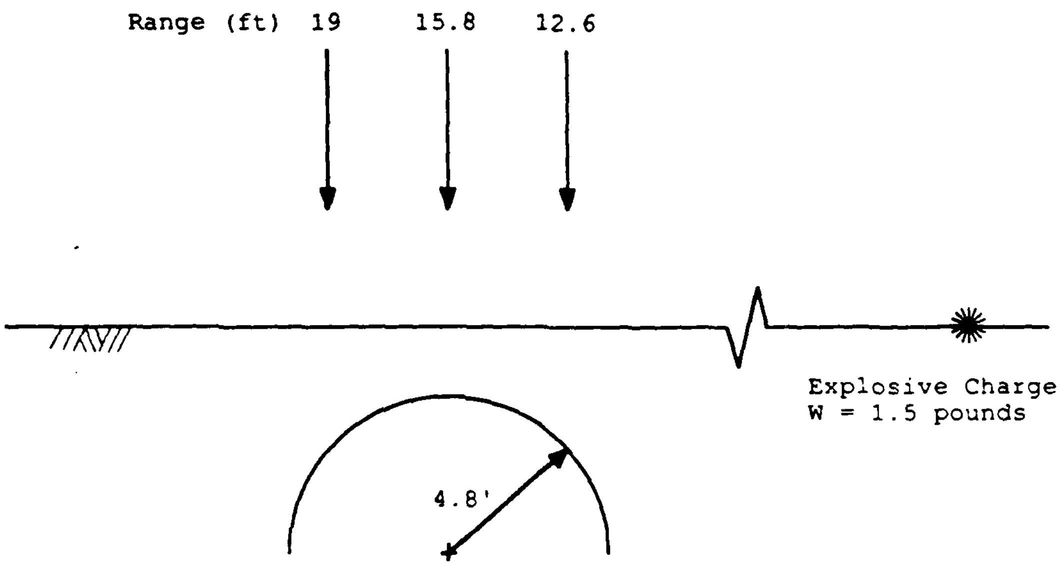
The parameters that need to be determined are the size of the charge and its offset from the structure. The similitude requirements have to be satisfied at all locations. Three locations above are chosen. They correspond to the location of the centerline and two other locations symmetrical about the centerline and at two-thirds of the radius of the arch.



Range (ft)	Peak Pressure (psi)	Impulse (psi-msec)
24	150	200
40	40	136
56	20	96

Figure 3. Buried Arch Subjected to Conventional Weapon.

For the full-scale structure, the peak stress, and impulse at the ground surface and at the three chosen locations are calculated, using the recommendations in the Air Force manual (Reference 28) and are shown in Figure 3. According to cube root scaling, the charge weight for the 1/5-scale experiment should be 4 pounds. However, Froude scaling requires the use of a simulant material weaker than the prototype material. The result is a further reduction in applied stress. A trial and error procedure is used to design the charge for the experiment. The starting point is a 3-pound charge with a stand off distance of 1 meter (3.3 feet). The peak overpressure and impulse at the three locations are calculated and compared to the corresponding required values obtained using Froude scaling laws. The calculated peak stress and impulse are much greater than the required values. As a result, the calculations are repeated for smaller charge yields and larger stand off distances until a satisfactory comparison between actual and required estimates for impulse are obtained. Convergence is obtained after few trials. The results for a final charge design are shown in Figure 4. It is apparent from Figure 4 that the impulse is matched over a wide region above the structure, but not at every location. An alternative procedure using high explosive simulation techniques rather than a single explosive charge is discussed in Section IV. This technique offers better ways to satisfy Froude scaling requirements imposed on loading conditions.



$$\ell = 1/5, \; \rho = 1/2 \;\Rightarrow$$

$$\sigma = 1/5 \times 1/2 = 0.1$$

$$i = 1/2 \times \frac{1}{5\sqrt{5}} = 0.0447$$

Range (ft)	Peak Pressure (psi)		Impulse (psi-msec)	
	Calculated	Required	Calculated	Required
12.6	7.5	15.	8.6	8.9
15.8	4.	4.	6.0	6.1
19.0	3.4	2.	5.7	4.3

Figure 4. One-Fifth Scale Design for Buried Arch.

SECTION IV

DESIGN OF SMALL-SCALE EXPERIMENTS ON BURIED ARCHES

A. GENERAL

The sponsor has indicated an interest in performing small-scale experiments of conventional weapon attacks on buried second generation aircraft shelters. This shelter has an inside radius of 24 feet and a length of 100 feet. The arch wall prototype cross section is shown in Figure 5.

For the purposes of this study it is assumed that the shelter will be buried with approximately 6 feet depth of burial at the crown. Access will be obtained by a ramp located between retaining walls. The threat is assumed to be 500 pounds of encased TNT which can be approximated as a spherical charge. The charge standoff distance of interest ranges from 2 to 8λ, where λ is the ratio of the standoff distance to the cube root of the charge yield in pounds.

Preliminary calculations for Froude scaled model experiments at two different scales are presented in the sections which follow. The first model size was selected to provide as small a scale as practical for a field experiment while maintaining a scaled reinforced concrete cross-section. A minimum thickness of 1 inch for the reinforced concrete was selected as a compromise between economy and practicality. This leads to a length scale of approximately 1/18. The second model size was selected to provide a scale practical for laboratory experiments which could also be tested in a centrifuge, if desired. In this instance the shelter will be constructed of a material which simulates the reinforced concrete gross properties. In the past many investigators have used aluminum for this purpose because of its low modulus and ease of machining. The length scale in this instance will be approximately 1/50. Laboratory experiments could be conducted on a representative length of the shelter or on the entire shelter length, if end wall response is felt to be important. It is highly desirable to conduct model experiments at three separate scales to demonstrate the correctness of the scaling laws. Although the third scale has not been investigated in this study, the same principles that are applied in the following sections can be used to develop a model with a length scale between 1/18 and 1/50.

Before an experiment can be conducted, the most promising simulant materials identified in the previous section need to be fully characterized.

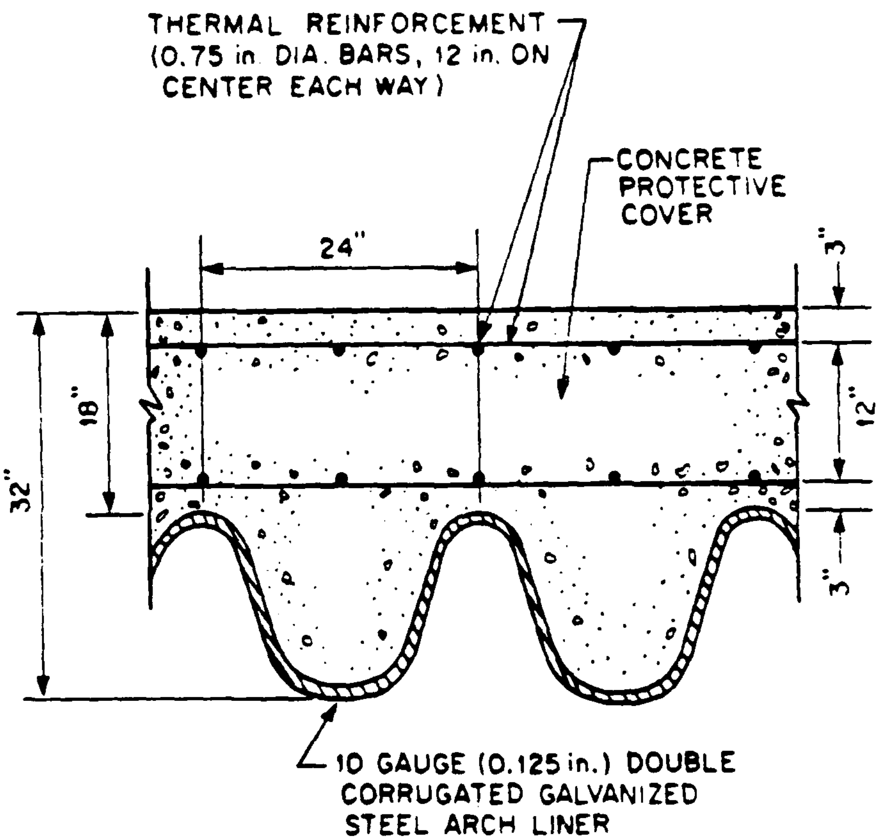


Figure 5. Arch Wall Cross Section.

The laboratory experiments required to fully describe the mechanical response of the simulant materials are described in the next section.

The behavior of a buried structure is a complex phenomenon which involves the response of the soil, the arch, and soil/arch interaction. It is recommended that proof-of-principle type experiments be conductd to verify the Froude scaling technique and its application before the more complex problem of buried structure is investigated. A typical proof-of-principle experiment is discussed in Section IV, C.

B. LABORATORY TESTING OF SIMULANT MATERIALS

Before an experiment is conducted, the potential soil and concrete simulants need to be fully characterized. The objectives of this characterization is to compare the mechanical properties of the simulant and prototype materials, and to identify the simulant that best satisfies the scaling requirements. This characterization is necessary because the engineering properties for the candidate simulants identified in the previous section are not fully known since these simulants are typically used for different applications.

The laboratory tests required to characterize the mechanical behavior of a material are uniaxial strain tests, triaxial compression tests, unconfined compression tests, and tests for physical properties. Uniaxial strain tests can be conducted in a triaxial vessel under K_o conditions. Zero radial displacement is maintained by controlling the confining pressure. The material properties defined by the K_o triaxial test include uniaxial load-unload response, volumetric response, moduli at various stress levels, Poisson's ratio, strain path and the shear stress versus volumetric strain relationship.

Triaxial compression tests and unconfined compression tests are needed to determine the failure properties of a material, i.e., the shear strength of the material as a function of confining pressure. Triaxial compression tests are performed at several confining stress levels. A hydrostatic loading is applied up to the confining stress level of interest, then an additional axial load is applied up to the ultimate shear strength of the sample. Unconfined compression tests are conducted on samples of concrete simulant, but not soil simulant. In this test an axial load is applied on a sample and gradually increased until shear failure occurs. The friction angle of the material is obtained from the plot of the failure surface.

The required physical properties of a granular material include the unit weight, seive analysis and relative density. For concrete and concrete simulants, only the unit weight of the material is required.

C. PROOF-OF-PRINCIPLE EXPERIMENT

Once the physical and mechanical properties of the simulant materials have been obtained, it would be extremely useful to conduct a simple, inexpensive, proof-of-principle experiment. The primary purpose of this experiment would be to demonstrate that a small structure, where gravity effects are important to the response, can be adequately modeled in the laboratory using Froude scaling techniques.

A friction pile subjected to a vertical static or dynamic load satisfies the requirements of a proof-of-principle experiment, i.e., it is simple and inexpensive, and gravity effects are important to the response. A pile model at the same scale as the proposed buried arch experiments can further be used to verify the response of the simulant materials since these same simulants will be used in both experiments.

These models can be conveniently tested in a soil bin using the ARA gas loader to provide the dynamic load. The actual pile model dimensions can be varied based upon the outcome of the laboratory testing conducted on the simulant materials. The results of these experiments can then be compared with theoretical results for a prototype friction pile, or with experimental results from the literature.

D. SMALL-SCALE EXPERIMENTS ON BURIED ARCHES

1. Choice of Scale for Experiments

For the purpose of illustration, the arch is a first generation (TABVEE) aircraft shelter. This arch is semicircular in cross section with radius and length of approximately 24 feet and 100 feet, respectively. The concrete protective cover is placed on a 10-gage double-corrugated galvanized steel arch liner as shown in Figure 5. The minimum concrete cover is 18 inches in thickness. This shelter can be additionally hardened by placing earth cover over the shelter in either a buried or bermed configuration.

Small-scale tests on this shelter configuration are recommended at three different scales. The smallest "responding model" that is physically and economically possible is on the order of 1/18 scale. This model would have an inside diameter of 32 inches and a 1-inch cover of concrete simulant. This experiment would require a test bed approximately 20 feet in width to accomodate explosive standoff distances on the order of 2 to 8λ. Smaller scale models such as 1/50 scale will not be constructed of concrete simulant. Instead the gross properties, such as the bending and axial capacity, of the section will be calculated and an equivalent section made out of material such as aluminum will be designed. This test would provide data on the gross response of the arch section. The test bed will be filled with simulant material to provide Froude scaled results. The results from 1/50-scale model can then be compared with centrifuge test data. The third scale recommended for an experiment will be betweeen 1/18 and 1/50 scale. The actual scale will be dependent on the results of the simulant material properties characterization.

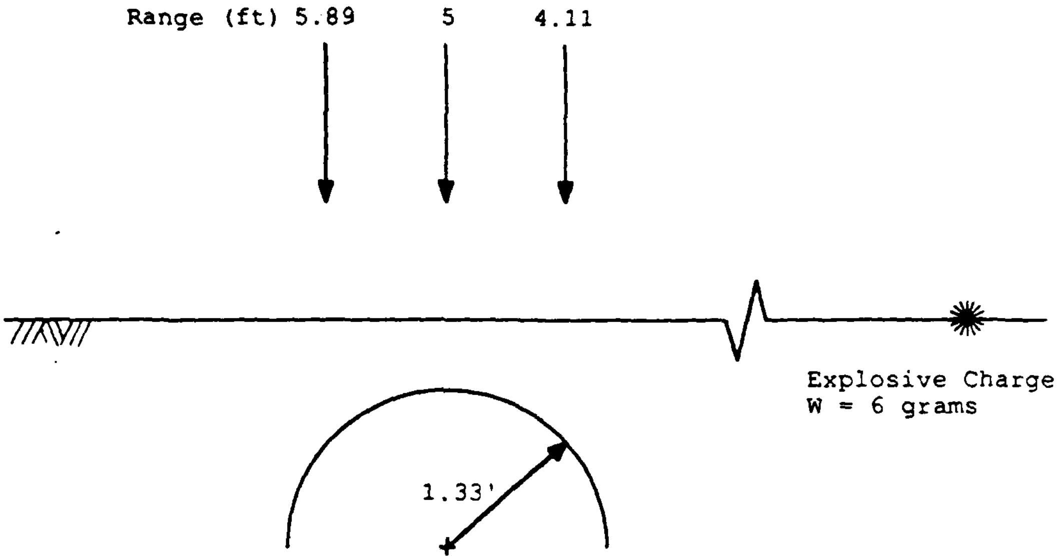
Field tests could be conducted with the explosive detonated either above ground or in a buried configuration. As discussed in the previous section, Froude scaling and cube root scaling of the explosive charge yield provide conflicting requirements for peak pressure and impulse at the test articles. For the recommended experiments, it is assumed that the threat is due to a surface burst from 500 pounds of explosives at about 2λ from the edge of the structure. The peak overpressure and impulse at three locations above the structure are summarized in Figure 3. For the small-scale experiments, charge weight and its standoff distance are varied and the peak overpressure and impulse at the same three locations above the structure are calculated. The final design is obtained when the calculated and required (i.e., scaled) peak overpressure and impulse are within an acceptable range. In the recommended experiment the response of the arch is more sensitive to impulse than to peak overpressure and, as a result, the effort was to match the impulse better than peak overpressure. The calculated and required values for peak overpressure and impulse for the 1/18 and 1/50-scale experiments are summarized in Figures 6 and 7. It is apparent that at these small scales the charge weight is very small, i.e., 6 grams for the 1/18 scale and 0.25 grams for the 1/50 scale. As the scale of the experiment decreases, the peak overpressure at the ground surface above the structure does not exhibit the fast decay seen for the full-scale experiment. At these small scales, this type of scaling for the explosive charge may not be appropriate. High explosive simulator technology may be applicable for modifying both peak pressure and impulse and for simulating airblast and source-related ground shock in a manner consistent with scaling requirements. This approach is discussed in more detail in a following section.

2. Instrumentation Requirements

Instrumentation of a scaled experiment requires that scaling rules be either adhered to or understood to avoid misinterpretation of data. Scale factors of primary importance for 1/18 and 1/50-scale experiments are shown below:

	Scale of Experiment	
	1/18	1/50
Time	0.24	0.14
Frequency	4.2	7.1
Density	1/4 to 1/2	1/4 to 1/2
Acceleration	1	1
Velocity	0.24	.14
Displacement	0.056	.02
Stress	0.014 to 0.028	0.005 to 0.01
Strain	1	1

The kinds of measurements an experimenter may wish to have are listed below under three categories, free-field environment, structure loads, and structure response.

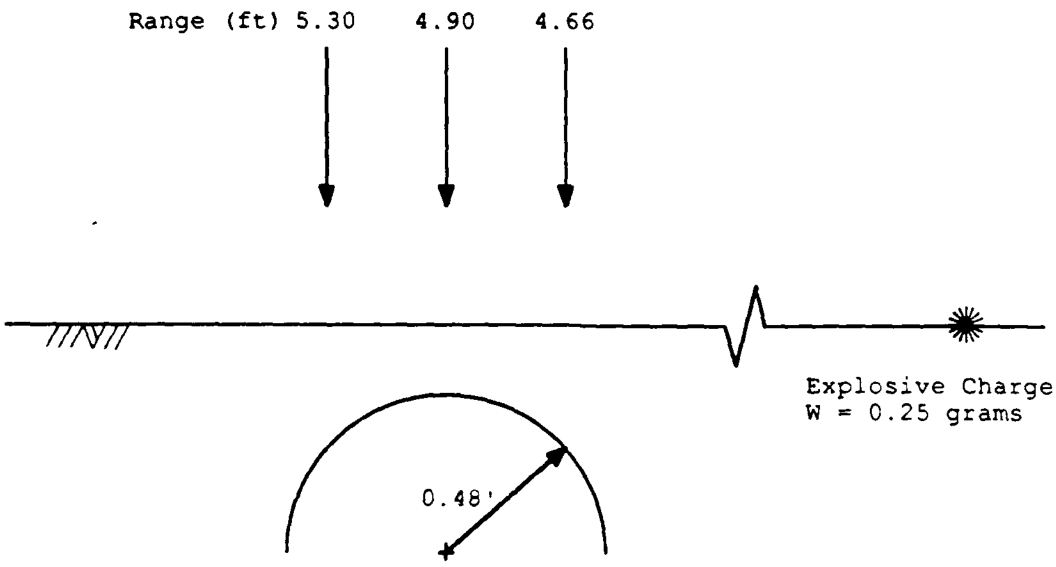


$\ell = 1/18,\ \rho = 1/2 \Longrightarrow \sigma = 0.0278$

$i = 0.00655$

Range (ft)	Peak Pressure (psi)		Impulse (psi-msec)	
	Calculated	Required	Calculated	Required
4.11	3.5	4.17	1.13	1.31
5.	2.8	1.11	0.95	0.89
5.89	2.2	0.56	0.83	0.63

Figure 6. One-Eighteenth Scale Design for Buried Arch.



$\ell = 1/50, \ \rho = 1/2 \Longrightarrow \sigma = 0.005$

$i = 0.0071$

Range (ft)	Peak Pressure (psi)		Impulse (psi-msec)	
	Calculated	Required	Calculated	Required
4.66 4.90 5.30	0.80 0.70 0.65	0.75 0.20 0.10	0.15 0.12 0.12	0.14 0.10 0.07

Figure 7. One-Fiftieth Scale Design for Buried Arch.

	Free Field	Structure Loads	Structure Response
Motion			
Acceleration	✓		✓
Velocity	✓		✓
Displacement	✓		✓
Stress			
Overpressure	✓	✓	✓
Soil	✓		
Interface		✓	
Strain			✓
Relative Displacement			✓

Motion measurement requirements can be reasonably met with commercially available accelerometers such as the Endevco 7270. Single and double integration of accelerometer data should provide acceptable estimates of velocity and displacement. The size and frequency response of this gage are compatible with small-scale experiments. However, this gage is much denser than the proposed soil simulant, and would need to be repackaged for use in the free field.

Mutual Inductance Particle Velocimeter are attractive for measurement of particle velocity in the free field and can be integrated to provide displacement over the gage length. These gages can be designed to present less of a density mismatch problem than accelerometers. They are very useful in severe environments. There are no other known available velocity or displacement gages are of appropriate size and density for use in the free field.

There are several gages or gage concepts which have potential for overpressure, stress and normal interface stress measurement. The Kulite LQ-080 is of reasonable size and has a range of 200 psi. This gage is designed for air pressure measurements, and has potential for soil stress measurements and structure interface stress measurements. Piezo electric materials such as tournaline and polyvinylidene fluoride are attractive for soil stress and structure interface stress measurements. Problems of impedance mismatch with soil simulant would have to be overcome by building a gage with a large diameter compared to thickness. There are no known interface shear stress gages that would be useful at these scales.

Commercially available coupon and solid state strain gages should be fully compatible with structural response measurement requirements. Their dimensions should not be a problem at the proposed scales.

Relative displacements in the test structures can be measured with Linear Variable Differential Transformer (LVDT) linear potentiometers or theta strain gages. ARA is currently working under contract to the Defense Nuclear Agency on a light sensing gage for tunnel ovaling measurements which could be applicable. Frequency response may be a problem with LVDTs, and performance under acceleration may be a problem with linear potentiometers.

Time of arrival measurements can be very useful in analysis of blast and shock experiments. Time of arrival in air or in a well-characterized soil simulant can be used to obtain shock, velocity, particle velocity and pressure or stress at the shock front. Small inexpensive peizo electric crystals are typically used and time of arrival can be resolved to fractions of a μ second.

Small-scale experiments will require small-scale instrument cables to avoid perturbation of the free-field environment and the structure response. Small-scale experiments can be conducted at small distances from data acquisition equipment which is consistent with higher frequency response requirements. A typical layout of instrumentation for an experiment is shown in Figure 8.

3. Explosive Simulation

The previous sections have illustrated the compromises in environments which must be made because of the conflicting requirements of using Froude scaling for the structure and soil and the cube root scaling which governs the airblast environment. Simulation techniques are available which may allow for the development of environments which more closely match the scaling requirements. The development of simulation techniques have received considerable attention for the past 25 years (Reference 29). Although these techniques were originally developed to simulate large yields from much smaller high explosive sources, many of the techniques for modifying the shock parameters

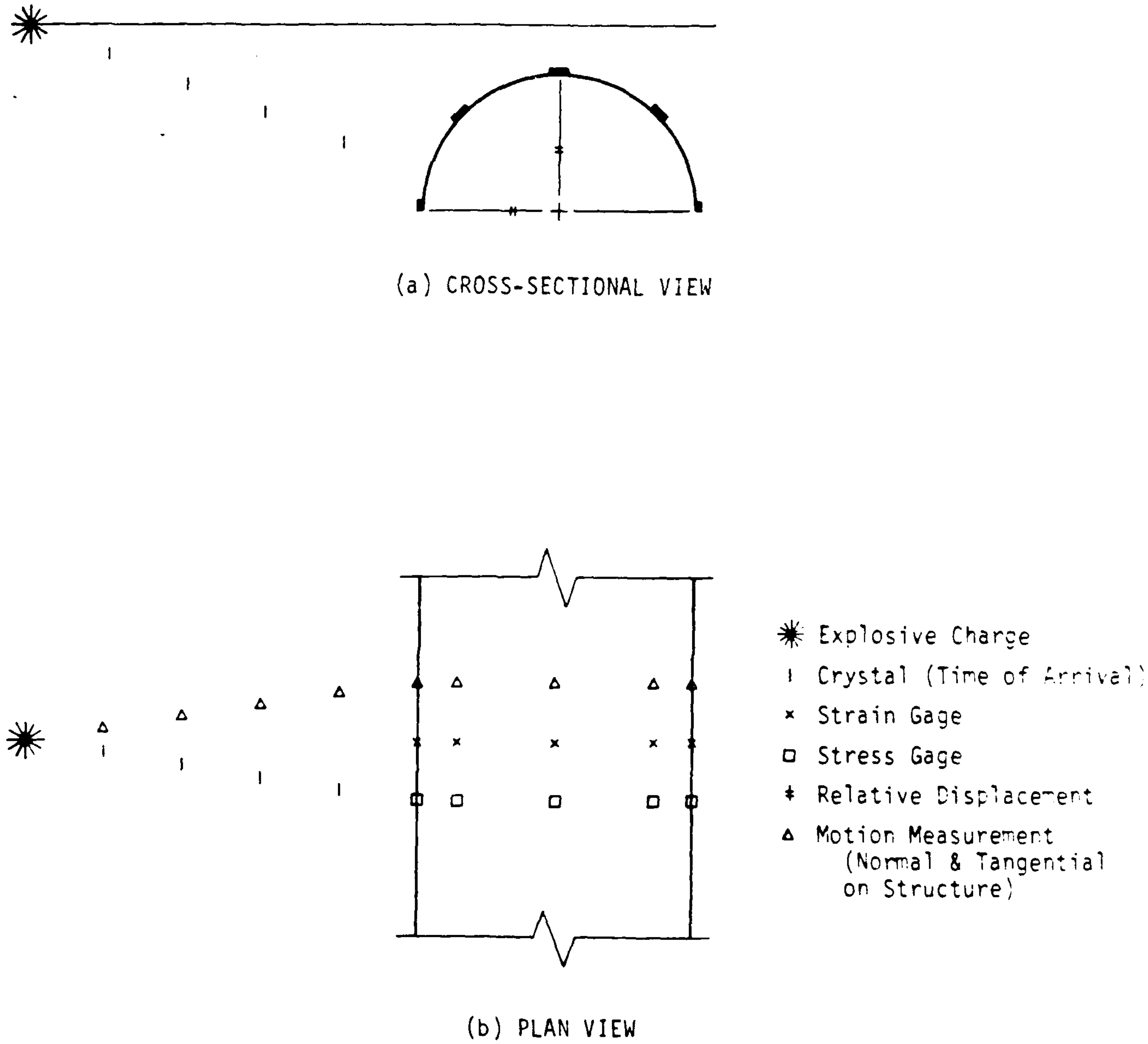


Figure 8. Instrumentation Layout.

are of general applicability. For example, the airblast environment could be simulated by using a distributed energy source, placed over the entire test bed. This source would be selected to have the correct properties to provide the desired shock front velocity, peak overpressure, and impulse. In general, the peak overpressure will be a function of the charge density and the standoff distance while the impulse will be a function of the charge thickness.

The total energy requirements for laboratory experiments are low enough such that around 1/50-scale electrical sources may be an attractive alternative to an explosive source. In addition, using gases other than air may be possible. This approach would provide additional flexibility in modifying shock parameters in a manner consistent with the modeling requirements.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This study covered the development and application of Froude scaling techniques to simulate the behavior of dynamically loaded underground structures. Froude scaling allows true modeling of acceleration without using artificially-induced gravity, i.e., without a centrifuge. It should be used in the design of small-scale experiments outside a centrifuge in which gravity effects influence the response of the system.

While allowing true modeling of gravitational acceleration, Froude scaling places constraints on the material properties and loading conditions. Simulant rather than prototype materials should be used in small-scale experiments. A survey of potential candidates for soil and concrete simulants has been conducted. For granular material, it has been found that the most promising simulants are pumice, perlite, vermiculite and Q-sell of the P-Q Corporation. For concrete, a mixture of plaster, celite, sand and water is the most promising candidate. In addition, perlite concrete and vermiculite concrete are potential simulants. The loading can be simulated either with a single explosive charge or using simulation techniques. For experiments at 1/50 scale the total energy requirements are low enough that electrical sources may be an attractive alternative to an explosive charge.

To prove the validity of Froude scaling, a potential proof-of-principle experiment has been designed. Small-scale experiments on buried arches can be designed to meet Froude scaling requirements.

B. RECOMMENDATIONS

To choose a simulant for use in small-scale experiments the potential simulants identified in the survey need to be fully characterized. Laboratory testing on samples of these materials need to be conducted.

Once the simulants are fully characterized, proof-of-principle experiments should be conducted to verify the applicability of Froude scaling. This proof-of-principle experiment should be simple and inexpensive and should involve a soil/structure system in which gravity effects are important. Experiments on piles would satisfy all the requirements.

After successful completion of the proof-of-principle experiment, it is recommended that small-scale experiments on buried structures be conducted. These experiments should be conducted at least at three different scales. The data from the small-scale test should be correlated with data on full-scale structure, if available. These experiments are relatively low cost and as such several experiments can be conducted at each scale to investigate the response at different load levels and/or different structural configurations. These experiments can serve as a basis for a comprehensive study of the response of buried structures subjected to conventional weapon effects and the developments of design criteria for these structures.

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