A proposed concept for the rapid field design of protective structures

John Ross Childress

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A PROPOSED CONCEPT FOR THE RAPID FIELD DESIGN
OF PROTECTIVE STRUCTURES

BY

JOHN ROSS CHILDRESS, 1939-

A

THESIS

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[Signatures]
ABSTRACT

This investigation proposes a simplified concept for the rapid field design of protective structures, subject to attack by conventional artillery rounds, mortar rounds and small rockets.

Parameters which should be considered during a rigorous design process are discussed. The number and complexity of these parameters make the rigorous design procedure too unwieldy to be efficiently used, in a limited time period, when materials are not available to comply with Standard Designs.

Since the duration of an explosion pulse is very short and uncompacted soil is capable of absorbing explosive energy, this study investigates the theory that adequate protection can be provided by structures designed by considering only four easily understood and readily determined parameters. These include the radius of destruction of the explosive projectile; the unit weight of the soil to be used in overhead cover; the size of the structure; and the spacing of structural members commensurate with the grade, species and dimensions of available timber.

Tests were conducted using both small-scale and full-scale structures. In each case, the radius of destruction of the explosive charge was measured in the soil used for overhead cover and determined analytically using empirical relationships. The structures were designed to support a depth of earth cover
slightly exceeding the larger radius of destruction. Size and spacing of the structural members were determined by considering the grade and species of lumber used for construction, the unsupported span of the structural member, dimensions and section properties of the timber, and the uniformly distributed load applied to the structure by the soil cover. The results generally support the design concept and warrant further study under actual firing conditions. Conclusions include the following:

1. Consideration of the rigorous parameters involved in dynamic load determination may be replaced by relatively simple field observations and design aids.

2. Because of the nature of the load pulse, for projectiles assumed in this study, the simple and easily understood parameters of required soil cover, the dead load caused by this cover, and the physical and mechanical properties of construction materials are sufficient for the design of protective structures subject to attack by these projectiles.
PREFACE

The general idea for this investigation was conceived during this writer's military service with the U.S. Army's 1st Air Cavalry Division in the Republic of Vietnam, first as Commanding Officer of Company A, 8th Engineer Battalion, and later as the Assistant Operations Officer of that battalion.

Each U.S. Army Division has an organic Engineer Battalion. These military engineers perform a wide variety of tasks in support of military operations. One of these tasks is assisting elements of a division in the construction of protective structures. The Engineer Battalion's organization provides for subordinate elements to actually perform, or at least supervise, construction tasks while planning is done by members of the battalion staff. The design of protective structures and required bills of materials are usually prepared by the Assistant Operations Officer of the battalion.

Each Infantry Brigade, within a division, is normally supported by one Combat Engineer Company from the Engineer Battalion. The mission of the Engineer Company is similar to that of the Engineer Battalion, except on a smaller scale. With regard to construction tasks, the relationship between the battalion and the company might be compared to that of the Architect or Design Engineer to the General Contractor. The Engineer Company actually performs or supervises construction, using plans and specifications prepared at the battalion level.
In an extremely fluid situation, involving redeployment, the Engineer Company, moving with its supported brigade, may be separated from the Engineer Battalion Headquarters by such considerable distances that even radio communications are not possible. In this case field changes in protective structure designs must be made by the engineer officer responsible for construction, based on his experience and engineering judgement.

Standard Designs prove to be little more than a guide unless all of the materials specified by the bill of materials are on hand. Receipt of so many board feet of lumber may not mean receipt of the various sizes of timbers required for the posts or stringers of the protective structure. When this happens, design changes, or a complete redesign, must be made based on materials available. These changes, or redesign, must be accomplished quickly by the officer responsible for the construction or by someone more familiar with the design of protective structures. Time is a factor which must be considered in this situation, as Tactical Commanders usually desire that their Operations Centers, First Aid Stations, etc., be constructed and placed in operation as soon as possible after occupying a new area. Even if the distance to the Battalion Headquarters is relatively short, the Engineer Company Commander may not have time to send back for design changes or a new design, which will utilize his inventory of available construction materials.

The comments of the preceding paragraphs and those contained in the remainder of this thesis are not intended as criticisms of the U.S. Armed Forces
logistics system, nor do they imply a shortage of capable personnel within the Corps of Engineers. They are based upon the experiences of one individual during a one year period. Their only intent is to reflect problems and pressures, which may be encountered by personnel during field construction under adverse conditions. As a result of these experiences, it is believed that a simple and rational method of rapid field design, or revision, to provide desired protection with field available materials would be of value to other military engineers faced with similar problems. This is the basis upon which this investigation was initiated.

The writer wishes to express his appreciation for the financial assistance rendered by the University of Missouri - Rolla during the course of this investigation and to numerous faculty members who have given freely of their time and resources to answer questions or make available reference books and/or necessary equipment during the pursuance of this research.

The writer is extremely grateful for assistance provided by Mr. J. T. Ballard and other personnel at the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi; and by Major Ronald K. Whitlock and other members of the First Advanced Individual Training Brigade, Fort Leonard Wood, Missouri.

The writer would like to express his particular appreciation for the assistance and guidance of his advisor, Dr. Jack H. Emanuel, during the course of this investigation and the preparation of this manuscript.
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I. INTRODUCTION

Having faced the problems of protective structure design and construction as the engineer officer responsible for construction and later as the officer responsible for design, the writer feels that a simplified concept for the rapid field design of protective structures would be extremely useful. The procedure should be sufficiently simple to allow complete understanding by personnel not specifically trained in engineering; it should minimize the variables involved in design; and it should provide for field changes without altering the desired degree of protection. Standard Designs will continue to be useful as a basis for requisitioning construction materials and if the complete list is received, the structure may be built without changes.

Among the parameters to be considered in the rigorous design of protective structures are the size of the enemy projectile which might strike the structure, the type of overhead cover to be used, the desired size of the protective structure, the reaction of its members to dynamic loads, and, of course, available materials.

The size and type of the anticipated enemy projectile introduces the greatest degree of uncertainty in a design of this sort. Projectiles which detonate upon impact cause a particular loading on the structure; those which have delay fusing cause a different type loading, lasting for a longer period of time; and those few that do not detonate, the "duds," cause still another loading condition. The loading caused by exploding projectiles is primarily a function of the pro-
properties of the particular explosive contained in the projectile. These proper-
ties may or may not be available through intelligence channels. Even if
the explosive's properties are known, there are relatively few available
people who have the ability to use them in the determination of a design load-
ing for the protective structure.

The type of overhead cover will require additional considerations. The
unit weight of the soil used for the cover will contribute significantly to the
dead load applied to the structure. The dry unit weight or the saturated unit
weight of most soils is not difficult to determine. Depending on whether or not
materials are available to keep the soil dry, a reasonably accurate determina-
tion of the dead load due to soil cover can be made. The use of coarse rocks,
logs, or steel matting to cause detonation at or very near the top surface of
the final structure will also contribute to the dead load on the structure, but
this contribution is usually very easily determined. However, the energy
absorbing characteristics of these materials and the particular soil, in either
a dry or a wet condition, are not generally known except, possibly, by those
persons whose particular area of interest is in Soil Mechanics or Soil Dynamics.

The size of the structure depends upon its type, the intended use, and,
perhaps most important, the materials available for construction. A statically
indeterminate structure is usually more economical from the standpoint of
materials, but experience and training of the persons responsible for design
or construction may lead to the use of a more easily analyzed statically deter-
minate structure. Also, rigorous consideration of dynamic loads on the structure may be beyond the expertise of the designer.

Protection against aerial bombs, which may contain from one hundred to more than two thousand pounds of high explosives, requires the construction of extremely hardened protective structures. Often constructed of thick, re-inforced concrete, even these structures are deeply buried to afford an acceptable degree of protection. In a situation where the friendly forces enjoy air superiority, or the enemy's capabilities are limited to mortars, conventional artillery and relatively small rockets, the requirement for such hardened and deeply buried structures may be reduced.

It is extremely difficult to make general statements which will apply to every situation in which the military engineer may find himself. For the purpose of this investigation, the following basic assumptions are made:

1. Enemy projectiles are limited to conventional artillery rounds, mortar rounds and small rockets, which contain on the order of fifty pounds, or less, of high explosives.

2. The enemy projectiles used are all fused to detonate upon impact, or the percentage of those with delay fusing is sufficiently small so that the assumption of impact detonation is within the limits of acceptable risk.
3. Construction priorities and availability of materials preclude the use of reinforced concrete and structural steel in the construction of protective structures. Timber will be used as the primary structural members.

The enemy projectile, or design round, against which protection is desired may be specified by the local Tactical Commander, or the size may be determined based on recent enemy activity or intelligence reports as to enemy capabilities within the Area of Operations. Once the design round has been determined, an analysis of craters which this round causes in the local soil, when it impacts and detonates, should be made. If there are no available craters which have been caused by enemy rounds, analysis of craters caused by similar friendly rounds should provide sufficiently accurate information as to the effects of the design round. For example, the effects of a U.S. 81mm mortar round should compare favorably to those of an enemy 82mm mortar round, as should the effects of a U.S. 155mm artillery round compare to those of an enemy 152mm artillery round. The crater analysis will provide the designer with information regarding the effects of the design round on the particular soil he intends to use as cover for the protective structure. The specific items of interest, when making the crater analysis, are the determination of the crater depth and radius. It must be emphasized that it is the true crater depth and radius that should be measured (Fig. 1). The observed crater will have an apparent depth and radius. However, the true depth and radius should be determined by gently excavating the loose soil from the crater. The measured true crater depth and radius gives the designer an idea as to the minimum depth
HA = Apparent Crater Depth
DA = Apparent Crater Diameter
HT = True Crater Depth
DT = True Crater Diameter
RT = \( \frac{1}{2} DT \) = True Crater Radius

Figure 1. Typical Crater, Showing Apparent and True Dimensions.
of soil cover which must be used.

The intent of this investigation is to determine the feasibility of limiting the variables involved in protective structure design to the required depth of overhead cover and the selection and spacing of structural members. By analyzing the true crater caused by the design round, the effects of the exploding projectile and the energy absorbing characteristics of the soil are measured relatively, and the designer need not have specific training in soil mechanics or a complete knowledge of the effects of high explosives.

The true crater depth or radius, whichever is greater, gives an indication of the minimum depth of overhead cover required on the structure. The theoretical radius of destruction, as determined from empirical relationships, and the measured depth or radius of the actual true crater should be compared and the larger value selected. The selected radius of destruction and applied factors of safety will enable the designer to determine the required depth of overhead cover. This depth and the unit weight of the soil, in either a dry or a saturated state, are used to compute the uniformly distributed dead load which will be applied to the structure. Determination of the required size and spacing of structural members may then be done in the usual manner based on available materials and the designer's ability to analyze either statically indeterminate or determinate structures.

Standard Designs should be used for the construction of protective structures
whenever the required materials are available, as they provide maximum protection for personnel and the most efficient use of materials. This investigation is intended only to supplement these designs by providing an easily understood procedure which may be rapidly applied, if materials are not available to comply strictly with the Standard Design.
II. REVIEW OF LITERATURE

Although it is highly unlikely that this investigation can be considered "new work," available information, dealing specifically with protection against conventional artillery rounds or relatively small explosive projectiles, was found to be limited. Information sources range from texts dealing with specific topics related to the investigation, to Field Manuals and Technical Reports published by the Department of the Army, to communications with the writer's military associates, and, finally, the writer's personal experiences and observations.

A. Standard Designs

The U. S. Army's Field Manuals on Field Fortifications (1) and Engineer Field Data (2) contain information and bill of materials for the construction of protective structures. The structures shown, however, are generally too small for use as First Aid Stations or Operations Centers, and anticipate the extremely severe loading of a direct hit of a 155mm, fuse-delay projectile. Both references discuss the use of a cushion-layer, "... of dry untamped earth... to absorb the shock of detonation...," and the use of a burster layer, "... of 15 to 20cm rocks or 20cm logs, wired tightly together, in two layers... to cause detonation of the projectile before it can penetrate to the lower...layers."
B. Parameters for Rigorous Design

As stated previously, to even attempt a rigorous protective structure design would require knowledge of the properties of the explosive charge contained in the design round, knowledge of the particular characteristics of the soil to be used as overhead cover, and some degree of proficiency in the analysis and design of structures subject to dynamic loading.

The writings of Baum (3), which include references to many other worldwide authors, most notably those of Zeldovich and Kompaneyets (4), show that explosion pressures are directly proportional to the density of the explosive and the square of the detonating velocity. The explosion impulse is directly proportional to the cross-sectional area and length of the explosive charge and the density and detonating velocity of the explosive. The time of the pulse is related to the length of explosive charge and detonating velocity, and is given by the following expression (3, p. 503):

\[ t = \frac{2\ell}{D} \]  

(1)

where

- \( t \) = The duration of the pulse, in seconds.
- \( \ell \) = The length of the explosive charge, in feet.
- \( D \) = The detonating velocity of the explosive, in feet per second.

Once the explosion pulse, based on pressure and area of influence, and time of the pulse are determined, analysis of the effects on the soil cover and the actual
structure may be made.

The pressure at some depth below the soil surface may be determined analytically, using the Boussinesq Method for evaluating soil pressure. A discussion of this and other methods is available in almost any text on Soil Mechanics or Foundation Analysis, such as those by Sowers (5) and Bowles (6). It must be noted that these texts are concerned with Soil Mechanics and Foundation Analysis and Design and deal with static loads applied to the soil by foundations, rather than dynamic loads of explosions. In addition, the Boussinesq Theory contains several simplifying assumptions, such as weightless soil—which is elastic, homogeneous, semi-infinite, and isotropic and obeys Hooke's Law—and that stress distribution is symmetrical with respect to the vertical axis. These assumptions greatly simplify the mathematical relationships used in the Boussinesq Theory, but may give inaccurate values in the case of dynamic loads. The pressure at some depth, as determined in this manner could, at most, be used only as a guide. In this case the designer is dealing with a dynamic rather than a static load and this load is rarely applied in a vertical direction, due to the trajectory of the incoming round.

In order to select structural members, the designer needs to know maximum loads and/or deflections to which the members may be subjected. A theoretical determination of the deflection of a structural member caused by an explosion pulse may be made based on procedures shown by Biggs (7), Rogers (8), and
In order to determine the maximum deflection of a member subjected to dynamic loading, the designer must know the magnitude and duration of the pulse, the natural frequency of the structure and, of course, the span length, modulus of elasticity and moment of inertia of the member being deflected. A general expression commonly used indicates that the dynamic deflection equals the product of a Dynamic Load Factor, D.L.F., times the deflection, \( X_{\text{static}} \), caused by a static load equivalent in magnitude to the dynamic load. In equation form:

\[ X = (D.L.F.) \cdot X_{\text{static}} \]  

(2)

The static deflection is determined using common formulas for deflection within the elastic range of the material used. The Dynamic Load Factor for a triangular pulse, which the explosion pulse is ideally assumed to be, may be determined by solving the differential equations of motion for the structure, or may be taken from graphs similar to those shown in Appendix A.

C. Radius of Destruction

Prentiss (10) and Wessman and Rose (11) discuss formulas, used on the European Continent, which give a value for the radius of destruction caused by an impacting and exploding projectile. While the equations are applicable, in the strictest sense, to the effects of aerial bombs which contain one hundred
pounds, or more, of high explosive, some of the factors which must be considered may be extended to this investigation. For aerial bombs, these factors include the weight of the explosive charge, the proportion of the charge below the ground surface, a coefficient for the medium, and a tamping coefficient. Whereas this investigation assumes projectiles which detonate upon impact, at or very near the ground surface, an expression applicable to bombs must consider penetration since the impact velocity of bombs may exceed 1000 feet per second, and some penetration will take place in the few milliseconds between initiation and actual detonation of the projectile. The radius of destruction of a bomb may be calculated from the following expression (10, p. 42 and 11, p. 124):

\[ R = 2.5 \sqrt[3]{\frac{3C}{\alpha \delta}} \]  

(3)

where

- \( R \) = Radius of destruction, in feet.
- \( C \) = Weight of explosive, in pounds.
- \( \alpha \) = A coefficient for the medium in which detonation takes place; for earth it is 0.7.
- \( \beta \) = Proportion of the charge below ground surface.
- \( \delta \) = A tamping coefficient, which varies from 1.0, for complete penetration, to 3.5, for incomplete penetration.

The total depth of destruction is found by combining \( R \), from Equation 3, the depth of penetration, if any, and the distance from the center of gravity of the explosive charge to the nose of the projectile. The minimum depth of cover may then be determined as:
\[ D = R + (h - a) \]  

where

\[ D = \text{Required depth of cover, in feet.} \]
\[ R = \text{Radius of destruction, in feet.} \]
\[ h = \text{Depth of penetration, in feet.} \]
\[ a = \text{Distance from center of gravity of the charge to the nose of the projectile, in feet.} \]

It is important to note that, according to Wessman and Rose (11, pp. 124-125), "...in the development of this formula, the assumption was made that only that part of the bomb, which is below the ground surface is effective in producing a crater."

The Field Manual on Explosives and Demolitions (12) presents the following equation, known as the Breaching Formula:

\[ P = R^3 KC \]  

where

\[ P = \text{Pounds of TNT required.} \]
\[ R = \text{Breaching radius, in feet.} \]
\[ K = \text{Material factor.} \]
\[ C = \text{Tamping factor.} \]

Rearranging in the form of Equation 3:

\[ R = \sqrt[3]{\frac{P}{KC}} \]
For good timber and earth construction, the value of K may be taken as 0.23. Values for C vary from 2.3, for surface detonation, to 1.25, for complete penetration into the overhead cover.

D. Relative Effectiveness of Explosives

It should be noted that the Breaching Formula was derived for the explosive TNT. No mention was made as to the type of explosive used in Equation 3 for calculation of the radius of destruction. However, the time period (1935-1942) would lead one to believe that TNT, or some less powerful explosive, was the assumed explosive in the derivation of this expression. The differences in the effectiveness of TNT and the newer explosives, such as Composition B, may be easily considered, using the Relative Effectiveness of explosives. Notes taken in lectures and handouts distributed by Ash (13, 14) during a course in Explosives Engineering, Mining 307, taken as a part of the writer's graduate course work show that the Relative Effectiveness of one explosive to another may be determined by considering the ratio of the explosives' density and square of their detonating velocity. In other words:

\[
\frac{RE_2}{RE_1} = \frac{\rho_2 D_2^2}{\rho_1 D_1^2}
\]  

(7)

where

\[
\frac{RE_2}{RE_1} = \text{The Relative Effectiveness of Explosive 2 to that of Explosive 1.}
\]
\( \rho_1 \) & \( \rho_2 \) = The density of the respective explosives.

\( D_1 \) & \( D_2 \) = The detonating velocity of the respective explosives.

These handouts included the approximate density and range of detonating velocity for most of the high explosives used by the military, as shown in Table I.

Table I. Density and Detonating Velocity of Common Military Explosives.

<table>
<thead>
<tr>
<th>Explosive</th>
<th>Density, in grams per cubic centimeter</th>
<th>Detonating Velocity, in feet per second</th>
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<tbody>
<tr>
<td>TNT</td>
<td>1.0</td>
<td>20000-23000</td>
</tr>
<tr>
<td>Composition B</td>
<td>1.6</td>
<td>25000-26000</td>
</tr>
<tr>
<td>Composition C-4</td>
<td>1.5</td>
<td>26000-27000</td>
</tr>
<tr>
<td>PETN</td>
<td>1.2-1.6</td>
<td>22000-24000</td>
</tr>
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By using the expression for Relative Effectiveness, one may consider a specific explosive when using either Equation 3 or Equation 6 to determine the radius of destruction. Calculation of Relative Effectiveness is necessary if the explosive contained in the projectile, against which protection is desired, is not TNT, or values may be taken directly from Explosives and Demolitions (12, pp. 83-84).
E. Cratering Effects of 81mm Mortar Rounds and 155mm Artillery Rounds

Cratering effects of 81mm mortar rounds and 155mm artillery rounds, exploded at the ground surface, have been investigated by the U.S. Army Corps of Engineers, Waterways Experiment Station, Vicksburg, Mississippi, as reported by Carre (15). The referenced rounds were statically detonated and their orientation varied from vertical, to forty-five degrees, to horizontal. The soil at the test area was a coarse sand. In a cohesionless soil it would be difficult to determine the true crater dimensions; however, the apparent crater dimensions for these rounds are shown in Table II.

Table II. Apparent Crater Measurements for Surface Detonated 81mm Mortar and 155mm Artillery Rounds.

<table>
<thead>
<tr>
<th>Type</th>
<th>Orientation</th>
<th>Apparent Depth, in feet</th>
<th>Average Apparent Diameter, in feet</th>
</tr>
</thead>
<tbody>
<tr>
<td>81mm</td>
<td>Vertical</td>
<td>0.9</td>
<td>2.7</td>
</tr>
<tr>
<td>81mm</td>
<td>45°</td>
<td>0.8</td>
<td>3.8</td>
</tr>
<tr>
<td>81mm</td>
<td>Horizontal</td>
<td>0.6</td>
<td>3.4</td>
</tr>
<tr>
<td>155mm</td>
<td>Vertical</td>
<td>1.1</td>
<td>4.8</td>
</tr>
<tr>
<td>155mm</td>
<td>45°</td>
<td>1.1</td>
<td>7.4</td>
</tr>
<tr>
<td>155mm</td>
<td>Horizontal</td>
<td>1.4</td>
<td>6.7</td>
</tr>
</tbody>
</table>
Since the trajectory of an incoming round usually causes the angle of impact to be greater than forty degrees, the data obtained for the horizontal orientation might be neglected. The average apparent depth and diameter of the crater caused by the 81mm are then 0.85 feet and 3.25 feet, respectively. The average apparent depth and diameter of the crater caused by the 155mm round becomes 1.1 feet and 6.1 feet, respectively. It is interesting to compare these measured apparent crater data with the theoretical values for radius of destruction, as calculated using Equation 3 and Equation 6. One should certainly expect these values to be less than the calculated values, since these are apparent dimensions. Calculations and comparisons are shown on pages 25-29.

F. Construction Materials

Discussions with the writer's military associates, such as Primmer (16) and Hill (17), confirm that others have used timber as the primary material for protective structures construction. The basic assumption that construction priorities cause timber to be the most readily available material for this type of construction appears valid. In addition, due to the urgency of the situation and priorities established for equipment utilization, the additional fabrication time and equipment required for reinforced concrete or structural steel construction often cause the use of these materials to be less practical than timber.

Wood is an extremely good material for this type of construction due, primarily, to its ability to absorb increased loads which act for short periods of time. A
discussion of the mechanical properties of wood and allowable stresses for various loading conditions is presented by Scofield and O'Brien (18) and Wangaard (19). Of primary importance to the design of protective structures are the allowable stress reductions for unseasoned timber, defects in the wood, or continuous loading due to the earth. According to Scofield and O'Brien (18, p. 11):

> In most wood structures the long time loading induces a stress less than 90% of that permitted for Normal Loading and, therefore, need not be checked separately. Under exceptional conditions such as structures subject to continuous maximum earth or water pressure, the design should be investigated for long time maximum loading using working stresses 90% of those used for Normal Loading.

If knots or other defects are present in members, allowable stress reductions should definitely be made. In the case of continuous earth loading the ten percent reduction in allowable stress is highly recommended by the writer, even if the earth cover does not stress the member to its allowable limit.

G. Experimental Models

To avoid the expense of full-size protective structures and the requirements for artillery pieces, or at least mortars, the use of a model for the initial portion of the investigation was considered. Murphy (20), discusses the use of prediction equations and their application to true and/or distorted models. Particular note is made of the fact that certain difficulties may be encountered if one expects the dead load stresses and distortions to have the same relative effects in both the model and the prototype. Pertinent to this investigation, Murphy (20, pp. 80,
163) states:

If the length scale is to be greater than 1, the material in the model must be proportionately heavier or less stiff or both.

... the duration of the applied impulse in the model must be reduced in comparison with that in the prototype if similarity is to exist. That is, the impulse must be "sharper" in the model.

The first requirement can be met without great difficulty, by proper selection of building materials for the model and proper compensation for weight. The second requirement causes considerable difficulty in that controlling or properly reducing the duration of the impulse on the model is almost impossible. The duration of the impulse on the prototype for the particular type of loading being investigated is extremely short and to obtain even "sharper" impulses would require the use of extremely short lengths of explosive charge, or the use of an explosive with a considerably higher detonating velocity, or both. Thus, the design of small-scale structures, as either true or distorted models, was not attempted.

The Waterways Experiment Station, Vicksburg, Mississippi, was visited as a part of this investigation. Ballard (21) reported that small-scale structures are used in some of the testing conducted at that facility. However, these are used only to observe effects and are not normally used to attempt to accurately predict the action of a prototype. During this visit several segments of high speed photographic films were observed, which showed the effects of explosions on sections of small-scale roof slabs constructed of reinforced concrete. The
observed failure mechanism appeared to be a punching shear failure rather than a flexural failure. This failure mechanism did not occur when adequate depths of soil were used over the slab. For soil depths less than this amount, the explosion pulse caused a failure that, at least initially, could best be described as "someone punching his fist through the slab." Naturally, once the reinforcing bars were cut, the remainder of the slab failed and fell. The true failure mechanism, due to such a short term loading, would have been difficult to observe without the use of high speed photography.

High speed photography supports the comments of Wessman and Rose (11), made in early 1942, that bending of a beam caused by a short duration explosion load would be very localized. They compared the distinct localized action caused by a bullet penetrating glass and the localized deflection of the net of a tennis racket when striking a tennis ball to the effects caused by a projectile upon a beam or slab. Wessman and Rose (11, pp. 101-102) stated:

Original span length has no significance in calculating initial bending moments due to an equivalent static load based on initial deflection. Presumably, the beam would eventually vibrate as a whole and assume a deflection curve associated with the fundamental mode, ... but it is the initial effects which are of major concern to the engineer. Values of \( \ell_1 \) are very small in comparison with actual span lengths. Just what significance may be attached to this beyond emphasizing the initial localized action is a matter for debate.
H. Field Observations

In an effort to obtain actual field data as to the effects of exploding projectiles on protective structures, the questionnaire and cover letter shown in Appendix B were mailed to selected Engineer Battalion Commanders in the Republic of Vietnam. Units were selected in an effort to obtain information from all areas of the country from the Demilitarized Zone to the Mekong Delta. Although response to the inquiries was good, only one contained sufficient information upon which comments could be made or a comparison could be made with theoretical values.

Captain P. B. Hassman (22), Assistant Operations Officer of the 20th Engineer Battalion, 18th Engineer Brigade, reported on the effects of a direct hit by a 122mm rocket. His information is shown pictorially in Figure 2. The cratering effects of this projectile, in rock of 3-in. diameter or less, compare with those observed by the writer during his tour of duty in the Republic of Vietnam. The "funnel tip" phenomenon is peculiar to rockets. This, also, was observed by the writer, although the observed impact areas were limited to compacted areas, such as unsurfaced roads and airstrips. In these cases the "funnel tip" was not as deep as that shown in Figure 2. The average depth was about 12 to 15 inches depending on the degree of compaction. In addition, the angle of the "funnel tip" to the vertical was larger indicating a greater firing range. Application of the basic laws of motion provide an apparent and logical, though not positively established, explanation of this phenomenon. In the case of an exploding mortar or artillery
Figure 2. Cross Section of Overhead Cover on Protective Structure Which Sustained a Direct Hit of a 122mm Rocket.
round, the mass approaches zero almost instantaneously upon detonation. The rocket, on the other hand, does not lose the majority of its mass upon detonation of the high explosive in the warhead. The trailing portion, which contained the now expended propellent charge, is not fragmented and continues to travel until stopped by the material upon which the rocket lands. The effects of the explosive warhead of rockets are similar to those of an artillery projectile with an equivalent amount of explosive; however, the propellant tube must be stopped prior to penetrating the actual structure. Obviously a more impervious barrier, than that formed by small rocks and uncompacted earth, must be provided. Rocks of 6 to 8-in. diameter or tightly bound logs placed near the top of the cover have been suggested (1, chap. 3, pp. 11-12).
A rigorous design of protective structures involves several complex parameters. First, a design round must be selected and the physical properties of the explosive and the geometry of the explosive charge contained therein must be known. Second, soil pressures at the base of the overhead cover, as evaluated by the Boussinesq equation, or similar procedure, are questionable and afford only an approximation of the depth of soil required to reduce the overpressure to a level which would cause deflections within the elastic range of the structural member. Finally, the determination of the deflection caused by the dynamic load becomes very involved, as the solution of the differential equations of motion is not a simple task. The assumption of a triangular pulse probably closely approximates the actual pulse of an explosion. However, for surface detonation of rounds which impact at some angle other than vertical, the percentage of the pulse which may be reflected, rather than transmitted into the cover, and the percentage of explosive energy used to rupture the shell casing affect the selection of the maximum amplitude of the pulse. In addition, this type of structure would certainly be subjected to considerable damping, caused by the earth cover, and this would affect the solution of the equations of motion, and the selection of a Dynamic Load Factor.

The number and complexity of the variables involved would make procedures for rigorous design of protective structures too unwieldy for most military engineers to use quickly and effectively.
The destructive effects of surface detonated explosive projectiles, as applied to protective structures, may be nullified rather simply by using an adequate depth of overhead cover on the structure. Assuming energy dissipation into the atmosphere and utilizing the energy absorbing characteristics of wood and loose earth, determination of the design load for the structure may be greatly simplified by considering only two variables; the minimum depth of cover required and the unit weight of the soil. This minimum depth of cover, in final form, will include the radius of destruction of the explosive charge, an additional amount to absorb metal fragments and perhaps a factor of safety, as specified by the local commander. In any case, it should exceed the measured depth or radius of the true crater caused by the design round in the local soil, and must be sufficiently deep to prevent a possible punching shear failure mechanism.

Theoretical values for the radius of destruction may be obtained from Equations 3 and 6, and, in general, would be expected to be larger than those observed in apparent craters.

In using Equation 3, if surface detonation is assumed the proportion of charge below the ground surface, \( \beta \), would be zero. This would give a value for radius of destruction equal to zero. A value for \( \beta \) of one-tenth should be conservative, especially if the round is fused to detonate upon impact. A value for \( \delta \) may then be determined by interpolation between 1.0 and 3.50. For earth, \( \alpha \) is 0.7. The radius of destruction of an 81mm mortar round, with a charge
weight of 2.1 pounds of Composition B explosive is calculated, using Equation 3, as follows:

\[ \delta = 3.50 - \beta (3.50 - 1.00) \]
\[ = 3.50 - 0.1(2.50) \]
\[ = 3.50 - 0.25 \]
\[ = 3.25 \]

\[ R = 2.5 \sqrt[3]{\frac{\beta C}{\alpha \delta}} \]
\[ = 2.5 \sqrt[3]{\frac{0.1 \times 2.1}{0.7 \times 3.25}} \]
\[ = 1.13 \text{ feet} \]

The total depth of destruction may then be determined based on the assumed depth of penetration, i.e., one-tenth of the charge length, and the distance from the center of gravity of the explosive charge to the nose of the round, as shown in Equation 4. Consideration of these factors will usually give values for the total depth of destruction which exceed the calculated value for R.

As previously stated, the Breaching Formula was derived for TNT. In order to use the revised formula, Equation 6, the Relative Effectiveness of the explosive used to that of TNT must be considered. For Composition B, the Relative Effectiveness is 1.35 (13, pp. 83-84). Assuming surface detonation, \( C = 2.3 \) for an untamped explosive and for good timber/earth construction K may be taken as 0.23 (13, p. 97). The radius of destruction for the 81mm mortar round is
calculated, using Equation 6, as follows:

\[ R = \sqrt[3]{\frac{1.35 \cdot P}{K \cdot C}} \]

\[ = \sqrt[3]{\frac{1.35 \times 2.1}{0.23 \times 2.3}} \]

\[ = 1.75 \text{ feet} \]

A 155mm artillery round contains approximately 15.34 pounds of Composition B explosive. Using the above assumed conditions, the radius of destruction is determined by Equations 3 and 6 to be 2.19 and 3.39 feet, respectively.

There is a relatively large difference between the values for radius of destruction calculated by Equation 3 and those obtained from Equation 6. One reason is that in Equation 3 no specific consideration is given to the Relative Effectiveness of Composition B. It seems reasonable to assume that this equation was based on the effects of the explosive TNT, due to the period (1935-1942) in which it is reported to have been widely used. If the Relative Effectiveness of Composition B explosive is included in Equation 3, the calculated value for R for the 81mm mortar round is increased from 1.13 feet to 1.25 feet and the R for the 155mm round is increased from 2.19 to 2.43 feet. The calculated values for R and the average observed apparent crater depth and radius, for the vertical and forty-five degree orientation from Table II, are shown in Table III.
Table III. Calculated Radius of Destruction and Observed Apparent Crater Radius.

<table>
<thead>
<tr>
<th>Description</th>
<th>81mm</th>
<th>155mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>R, using Equation 3, with no consideration of the Relative Effectiveness of Composition B.</td>
<td>1.13 feet</td>
<td>2.19 feet</td>
</tr>
<tr>
<td>R, using Equation 3, considering Composition B as 1.35 times as effective as TNT.</td>
<td>1.25 feet</td>
<td>2.43 feet</td>
</tr>
<tr>
<td>Observed Apparent Crater Depth and Radius from Table II.</td>
<td>Depth = 0.85 feet, Radius = 1.625 feet</td>
<td>Depth = 1.13 feet, Radius = 3.05 feet</td>
</tr>
<tr>
<td>R, using Equation 6, considering the Relative Effectiveness of Composition B.</td>
<td>1.75 feet</td>
<td>3.39 feet</td>
</tr>
</tbody>
</table>
No definite conclusions can be drawn from the above table, since the observed craters were in a cohesionless soil and the data is for apparent craters rather than radius of destruction, as calculated using Equations 3 and 6. It is interesting to note, however, that the two equations seem to bracket the observed apparent crater radius. Equation 3 gives a theoretical value of $R$, which is about 30 to 40 percent less than the observed apparent crater radius. Equation 6 gives a theoretical value which is about 8 to 11 percent greater than the observed apparent crater radius. This tends to reinforce the idea of making an on-the-spot crater analysis in the field, and selecting the larger value of measured radius and calculated $R$.

The values for $R$, calculated using the two equations, differ by approximately 40 percent. The density and detonating velocity of the TNT, or perhaps even less effective explosive, used in the development of the equation for radius of destruction (Equation 3) may partially account for the differences in material factors and tamping factors used in the two equations. Selection of the tamping factor would, of course, depend on the soil characteristics where development tests were conducted. Selection of the material factor could have been based on the manner in which this factor is used in the two basic equations. In the case of Equation 3, it might be expected that attention was focused on the effects of a single bomb at a time, whereas, in the development of Equation 5, consideration may have been given to the fact that normally several charges, placed in a row, would be used to destroy a timber and earth wall. The combined effects of several charges,
detonated simultaneously, could account for the smaller value of 0.23 used as the material factor in the Breaching Formula. Still another reason for the differences in magnitude of these factors is the geometry of the explosive charge. In the case of bombs or artillery projectiles, one usually visualizes a long, cylindrical charge, whereas in the application of Equation 5, one thinks of making the required size charge by stacking blocks of TNT, or other explosive, against the object to be destroyed. The relatively small cross sectional area of the projectile and longer period of explosion pulse, as compared to the greater cross sectional area and probably shorter period of explosion pulse in the breaching charge, may account for the differences in the material and tamping factors used in the two equations. Finally, the assumption that only that portion of the bomb's explosive charge below the ground surface contributes to the cratering effect is questionable. A tamping coefficient and coefficient for the medium in which detonation takes place, based on this assumption, would differ considerably from those selected in another manner. As a basis for checking experimental results, both Equation 3 and 6 were solved for various values of $P$. The results are shown graphically in Figures 3 and 4. Figure 3 is a plot of Equation 3, where for Composition B:

$$R = 2.5 \sqrt[3]{\frac{1.35 \times 0.1 \times C}{0.70 \times 3.25}}$$

and for TNT:

$$R = 2.5 \sqrt[3]{\frac{1.0 \times 0.1 \times C}{0.70 \times 3.25}}$$
Figure 3. Radius of Destruction versus Explosive Charge, Using Equation 3.

\[ R = 2.5 \sqrt[3]{\frac{8C}{a\delta}} \]
Figure 4. Radius of Destruction versus Explosive Charge, Using Equation 6.
Figure 4 is a plot of Equation 6, where for Composition B:

\[ R = \sqrt[3]{\frac{1.35 \times P}{0.23 \times 2.3}} \]

and for TNT:

\[ R = \sqrt[3]{\frac{1.0 \times P}{0.23 \times 2.3}} \]

Composition B is the explosive commonly contained in many mortar and conventional artillery rounds. TNT was used in this investigation for field testing on full-scale mock-ups.
The experimental procedures of the investigation were divided into two parts. The first part consisted of the design and testing of a small-scale protective structure. In the second part the procedures and results of the first were extended to a full-scale structure.

A. Small-Scale Protective Structures

The first step of this portion was to select a charge and determine its radius of destruction. The selected charge was a Hercules, Number 6, non-electric, blasting cap. This type charge was chosen because its cylindrical shape approximates that of an artillery or mortar round. Its relatively small size, the equivalent of approximately 7 grains of PETN, allowed it to be fired near buildings without endangering people or property. As a safety precaution, however, a firing box (Fig. 5) was constructed. All live firings were conducted in this box and observations were made through the plexiglass side. The inside dimensions of 9 in. by 9 in. were chosen to accommodate either a square baking pan filled with gelatin or a small-scale protective structure.

The first series of live firings involved observation of the cratering effect of an exploding blasting cap on gelatin covered with increasing depths of earth cover. The first shot was made with the blasting cap in direct contact with the
Figure 5. Plywood and Plexiglass Firing Box.
gelatin. As expected, severe cratering and permanent distortion of the gelatin was noted (Figs. 6, 7). For the second shot, a 1/4-in. deep layer of sand was placed on top of a new pan of gelatin and the firing repeated. The resultant true crater in the gelatin measured 2-1/2 in. in diameter and 1-1/2 in. deep. A third shot was made with a 1/2-in. deep layer of sand on the gelatin. The resulting true crater size was determined to be 1-1/2 in. in diameter and slightly less than 1 in. deep. For shot four, 3/4 in. of sand cover was used. The true crater was observed to be 1-1/4 in. in diameter and 1/2 in. deep (Figs. 8, 9). Shots five and six were made with corresponding increases in depths of sand cover. The resulting true crater which followed shot six was 3/8 in. in diameter and 1/8 in. deep for a sand cover of 1-1/4 in. From this it was predicted that for 1-1/2 in. of sand cover, there should be no visible damage to the gelatin. This prediction proved accurate, as shown in Figures 10 and 11. Additional tests were not conducted to determine the absolute minimum depth of sand, between 1-1/4 in. and 1-1/2 in., required to prevent damage to the gelatin, since it is reasonable to assume that an absolute minimum depth of cover will not be used on the prototype. The relationship observed between the depth of true crater in gelatin and depth of sand cover is shown in Figure 12.

There are 7000 grains per pound, so the weight of the explosive charge in the blasting cap may be taken as 0.001 pounds. PETN is 1.66 times as effective as TNT. Using these values with Equation 3:
Figure 6. Blasting Cap in Contact with Gelatin.

Figure 7. Crater in Unprotected Gelatin.
Figure 8. Partially Protected Gelatin.

Figure 9. Crater in Partially Protected Gelatin.
Figure 10. Crater in Protective Cover.

Figure 11. Undamaged Gelatin.
Figure 12. Depth of True Crater in Gelatin versus Depth of Sand Cover.
Using Equation 6 and the Relative Effectiveness of PETN, the radius of destruction is determined as:

\[ R = 2.5 \sqrt[3]{\frac{\beta C}{\alpha \delta}} \]

\[ = 2.5 \sqrt[3]{\frac{0.1 \times 1.66 \times 0.001}{0.7 \times 3.25}} \]

\[ = 0.105 \text{ feet} \]

\[ = 1.26 \text{ inches} \]

This value is 16 percent less than the measured radius of destruction for sand and gelatin, but seems to compare favorably when considering all the assumptions made in order to use the equation.

As observed previously, in Table III, the experimentally determined radius of destruction is bracketed by the theoretical values obtained using Equations 3 and 6.
Based on the sand and gelatin tests and the calculated values of R, small-scale protective structures were constructed and tests conducted to determine whether 1-1/2 in. of sand cover would prevent a punching shear failure when the blasting cap was detonated on top of the structure. The selected structure was assumed to represent a small guard bunker, 9 ft by 9 ft in size. To limit the area of failure to the roof, which seems to be the most critical area, the posts and caps were made of 1-in. by 1-in. balsa wood and the diagonal braces were 1/2-in. by 1/2-in. balsa wood. This substructure had sufficient strength to limit failures to roof sections and was used for all small-scale tests (Fig. 13).

The first series of tests assumed a simple, solid-deck roof of planks laid from cap to cap and covered with sand. With 1-1/2 in. of sand cover, the blasting cap caused no visible damage to the decking (Fig. 14). A failure was observed when the sand cover was reduced to 3/4 in. (Figs. 15, 16). Since the purpose of this test was to establish that failure would not occur with 1-1/2 in. of sand cover, further tests were not performed to determine the limiting protective depth, between 3/4 in. and 1-1/2 in.

The next series of tests assumed a stringer-roof superstructure, upon which decking and sand cover would be placed (Fig. 17). This small-scale bunker is shown before and after the test firing with 1-1/2 in. of cover in Figures 18 and 19. The results of the second shot are shown in Figure 20. For this shot, only 1-in. of sand cover was used on the structure. No damage was observed in this
Figure 13. Substructure Used for Small-Scale Testing.

Figure 14. Undamaged Solid-Deck Roof.
Figure 15. Damaged Solid-Deck Roof.

Figure 16. Damaged Solid-Deck Roof.
Figure 17. Small-Scale Bunker, Stringer-Roof Superstructure.
Figure 18. Bunker With Adequate Cover.

Figure 19. Undamaged Small-Scale Structure.
case. Since the cap was directly over the center stringer, probably that stringer was able to absorb the increased load. In an actual situation, the round cannot be assumed to impact directly over a stringer, therefore, a third shot was made with the blasting cap offset from the stringer. The cover used in this test was 1-1/4 in. and, as anticipated, failure occurred (Fig. 21).

For the final series of tests on small-scale bunkers another stringer-roof superstructure was assumed. The planks and stringers used in this case were much smaller than those previously used and a failure was expected if the cover on this structure was less than 1-1/2 in. In fact, there was some doubt that a failure would be prevented by the 1-1/2 in. of cover, due to the small size of the stringers and the decking. However, as shown in Figures 22 and 23, no damage was done to the structure as long as the cover was 1-1/2 in. This structure was subjected to a total of three shots without an observed failure.

B. Full-Scale Structures

From the results of the first portion of the experimental investigation it was tentatively concluded that failures may be prevented, and adequate protection for personnel assured, by providing a minimum depth of cover equal to or greater than the radius of destruction of the explosive charge. To substantiate the theory that only the uniformly distributed dead load caused by the minimum depth of overhead cover need be considered when determining the size and spacing of
Figure 20. Undamaged Bunker—Blasting Cap Detonated Over a Structural Member.

Figure 21. Damage to Small-Scale Bunker—Inadequate Protective Cover.
Figure 22. Undamaged Small-Scale Structure, With Adequate Cover.

Figure 23. Undamaged Small-Scale Structure--Adequate Cover.
structural members, further tests were conducted at Fort Leonard Wood, Missouri.

These tests were similar to those using the blasting cap, gelatin and small-scale structures. A series of 4-pound charges of TNT were detonated on the surface of the soil at the test site. The true craters had an average depth of 11 in. and an average radius of 21 in. The average unit weight of the soil was determined to be 104.3 pcf. The radius of destruction for a 4-pound charge of TNT was calculated using both equations for R. Using Equation 3, R was calculated to be 17 in., and using Equation 6, R was calculated to be 23.5 in. Again, the theoretical values of R tend to bracket the observed R.

A typical protective structure was assumed. One common size often used for guard bunkers is 8 ft. by 8 ft. Two different roof sections were constructed. The first was designed to support the depth of earth indicated by Equation 3, and will hereafter be referred to as "Bunker 1." The second roof section was designed to support the depth of earth indicated by Equation 6, and will hereafter be referred to as "Bunker 2."

For the first shot on each bunker, the depth of earth used was determined by increasing the calculated values of R by 15 percent. This was based on the assumption that some additional earth would be used to absorb metal fragments from an actual exploding projectile. The two roof sections were designed to support 20 in. and 27 in. of earth, respectively. The unsupported span length of the stringers was 7 ft, and the unit weight of the soil was 104.3 pcf.
Materials available for construction were assumed to be limited to nominal 2 x 12 planks. Spacing of the roof stringers was determined by considering the properties of the soil and the properties of the materials to be used in construction. The actual dimensions of the members were 1-1/2 in. by 11-1/2 in. Using the section modulus of the member and the allowable flexural and horizontal shear stresses for the grade and species of lumber, it was determined that four stringers would be needed for Bunker 1 and five stringers would be required for Bunker 2.

One of the problems which originally led to this investigation was encountered in the design of these roof sections. When the construction materials were purchased, the grade and species of lumber was described as Number 2, Southern Pine having an allowable flexural stress, $f$, of 1200 psi and an allowable horizontal shear stress, $H$, of 105 psi. However, when the materials arrived at the construction site, it was observed that the planks selected for stringers were Number 1, Dense, KD, Southern Pine, with an allowable $f$ of 1700 psi and an allowable $H$ of 120 psi. Both bunkers were quickly redesigned, based on the dead load of soil, and it was determined that the number of stringers in each section could be reduced by one. Three stringers, spaced 45 in. center-to-center, were used for Bunker 1 and four stringers, spaced 32 in. center-to-center, were used for Bunker 2 (Figs. 24, 25).

A 4-pound charge of TNT was detonated on each roof without failure of any of the structural members (Figs. 26, 27, 28 and 29). A failure was not anticipated in the roof section covered with 27 in. of earth, since small-scale tests had
Figure 24. Full-Scale Bunker 1.

Figure 25. Full-Scale Bunker 2.
Figure 26. Bunker 1--Before Firing.

Figure 27. Bunker 1--After Firing.
Figure 28. Bunker 2--Before Firing.

Figure 29. Bunker 2--After Firing.
indicated that no failure would occur when the actual depth of cover exceeded the measured R, in this case 21 in. A failure was expected in the roof section covered with only 20 in. of earth due to the fact that even with a 15 percent increase in R, calculated using Equation 3, the depth of cover was less than the measured R of 21 in.

It was originally intended to conduct additional tests using a minimum depth of earth cover on the structures. The intended cover for the respective roof sections was to be 17 in. and 23.5 in., the R calculated using Equations 3 and 6. Since Bunker 1, the roof section with three stringers, covered with only 20 in. of earth was not damaged, it seemed reasonable to assume that Bunker 2, the roof section with four stringers, covered with 23.5 in. of earth would not be damaged. Therefore, further testing was limited to Bunker 1.

A test on Bunker 1 with 17 in. of cover was conducted. Weather conditions on the day of this test, while typical of what must be anticipated in an actual situation, caused considerable difficulty. The soil cover was almost saturated and this increased the dead load on the structure by as much as 25-35 percent. A failure was anticipated, since the depth of cover was 4 in. less than the observed true crater radius and the dead load on the structure was greater due to the increased moisture content of the soil. In general, the actual failure was confined to the area directly under the explosive charge. The two pieces of decking directly under the charge were severely damaged with both flexural and shear failures being noted. None of the stringers were damaged; however, the
structure displaced sideways and the stringers rotated until their 11-1/2 in. dimension was in a horizontal orientation. This very localized failure could have been prevented by providing a greater depth of earth for cover over the structure. In the case of this particular roof section, an addition of only 3 in. of earth should have provided sufficient depth to prevent failure.
V. CONCLUSIONS

Although sufficient data was not obtained to provide statistical analysis, the basic concept appears valid. Since testing, using actual impacting and exploding projectiles, must be performed to completely confirm the concept, further tests with static detonations of TNT were not conducted. Based on the data and results obtained within the limits of the investigation the following conclusions are drawn:

1. The basic concept of providing a minimum depth of earth cover for a given explosive charge is valid.

2. The very short duration of a surface detonated explosion pulse and the energy absorbing characteristics of loose soil work to the designer's advantage. Protective structures, subject to attack by the type and size projectiles assumed in this investigation may be designed by considering the dead load of the soil and the mechanical and physical properties of the timbers used for the structure. Appropriate adjustments in allowable stresses and factors of safety applied to the dead load provide an even greater degree of protection.

3. Loose dry soil, contained by sandbag retainer walls, has better energy absorbing characteristics and reduces construction time, as compared to overhead cover composed entirely of partially filled sandbags. The added
confinement of the soil, due to the individual sandbags, may appreciably increase the load transmitted to the structural members. In addition, nearly saturated earth has very poor energy absorbing characteristics.

4. Graphs showing required depth of cover versus explosive charge and the measured unit weight of the soil to be used for the overhead cover provide a quick and easily understood method of determining the design load for the structure and greatly simplify design, or changes in design, of protective structures.

5. The revised Breaching Formula gives conservative values for the radius of destruction, \( R \). Use of this equation could lead to over-designed protective structures and excessive use of materials.

6. The measured radius of destruction, as determined by the crater analysis, provides a good check on the calculated value of \( R \); as the general terms for material factor, included in Equations 3 and 6, may not apply to the particular soil used for the overhead cover. The depth of cover used on the protective structure should not be less than the measured radius of destruction.

7. Values of \( R \) obtained from the equation for radius of destruction of a bomb may be inadequate if used without a factor of safety. Although tests conducted during this investigation were generally successful, the assumptions
made in the use of this equation may not apply to different soils or an actual exploding projectile. The assumption, that only the portion of the charge below the ground surface contributes to cratering, used in the derivation of this expression is not valid. Some cratering must be anticipated, even in the case of surface detonated explosive charges. However, this equation does consider penetration of the projectile, weight of explosive charge, a tamping coefficient, and a coefficient for the medium in which detonation takes place. As such it could be used to begin an investigation which deals with fuse-delay projectiles.
VI. RECOMMENDATIONS FOR FURTHER STUDY

As in many cases, during the course of this research several questions or problems arose which, although pertinent, were beyond the scope of this investigation. Although the data and results substantiate the concept for rapid field design, the limitations of time and facilities precluded tests or study of related problems.

The following are recommendations for further study and continued research in conjunction with the design of protective structures:

1. The basic concept should be field tested, using actual explosive projectiles. The short duration of the surface detonated explosion pulse causes practically negligible deflections in the structural members; however, the kinetic energy of the impacting round may be sufficiently large to cause flexural failures within the few milliseconds between impact and actual detonation of the explosive contained in the projectile.

2. The explosive effects of rockets appear to be no more severe than any other explosive projectile of comparable size. The propellant tube of the rocket is not fragmented upon detonation of the explosive warhead and continues to travel until stopped by the earth cover on the protective structure. A study of the most efficient materials for use as a barrier against this propellant tube and the location of this barrier, i.e., near the top or bottom of the overhead
cover, would be beneficial.

3. Equations 3 and 6 both contain terms which consider a tamped, or confined, explosion pulse. The increased radius of destruction of a fuse-delay projectile may be obtained by using different tamping coefficients in these equations. However, this is the relatively simple part of a design problem dealing with fuse-delay projectiles. The period of time between initiation and actual detonation may range from several milliseconds to several minutes. The amount of penetration will depend on the impact velocity, the composition of the overhead cover and the properties of the materials used in the cover. In order to prepare a graph of Minimum Depth of Cover versus Explosive Charge applicable to fuse-delay projectiles, the radius of destruction of a confined explosion pulse must be increased by the amount of penetration prior to detonation. This could provide areas for at least two additional investigations, i.e., penetration in cohesionless soils and penetration in cohesive soils.

4. The impact kinetic energy of the projectile, prior to detonation of a fuse-delay shell, is transmitted to the structural members, but just how much this energy might be attenuated by the loose soil in the overhead cover provides an additional area for further study.
VII. APPENDICES
APPENDIX A

Dynamic Load Factor for Explosion Pulse
In order to determine the deflection of a member subjected to a dynamic load one must know the natural period, $T_N$, of the structure, the duration and maximum amplitude of the dynamic load and the shape of the pulse. Determination of the natural period of the structure is not difficult, but for structures similar to those being investigated a rough estimate of one to ten seconds for the natural period would probably provide sufficiently acceptable results upon which to choose or determine a Dynamic Load Factor. An explosion is ideally assumed to cause a triangular pulse and the duration of this pulse may be determined using the expression given by Baum (3) as:

$$t = \frac{2\ell}{D}$$  \hspace{1cm} (1)

where

$t = \text{the duration of the pulse, in seconds.}$  
$
\ell = \text{the length of the explosive charge, in feet.}$  
$D = \text{the detonating velocity of the explosive, in feet per second.}$

The Dynamic Load Factor may be determined analytically by solving the differential equation of motion for a structure subjected to a triangular pulse, or it may be taken from a graph similar to that presented by Biggs (7). For a triangular pulse, this graph gives the Dynamic Load Factor for various ratios of time of pulse to natural period, $t/T_N$. After selecting a Dynamic Load Factor, the deflection due to a static load equal in magnitude to the maximum amplitude of the dynamic load may be determined using the usual equations for deflection. The product of the deflection, so determined, and the Dynamic Load Factor is the deflection caused by the dynamic load.
In the particular case of explosion loading, difficulty is encountered in choosing a Dynamic Load Factor. For example, if the explosive charge is one foot long and has a detonating velocity of 20,000 fps, Equation 1 gives a time of pulse, \( t \), of:

\[
t = \frac{2l}{D} = \frac{2 \times 1.0 \text{ ft}}{20,000 \text{ fps}} = 10^{-4} \text{ seconds}
\]

The assumption of 20,000 fps for the detonating velocity is conservative. Most of the high explosives used in the military have a detonating velocity of from 23,000 to 26,000 fps. Assuming an approximate natural period for the structure of one second, the ratio of time of pulse to natural period, \( t/T_N \), is \( 10^{-4} \).

The U.S. Army Corps of Engineers' graph, as presented by Biggs and shown in Fig. 30, shows a Dynamic Load Factor of about 0.16 for a value of \( t/T_N \) equal to 0.05. It seems reasonable to assume a much smaller value of Dynamic Load Factor for values of \( t/T_N \) in the range of \( 10^{-4} \) to \( 10^{-5} \). If the graph is extrapolated for smaller ratios of time of pulse to natural period, the Dynamic Load Factor approaches very small values for ratios between \( 10^{-3} \) and \( 10^{-4} \) (Fig. 31). Selection of a reliable Dynamic Load Factor, based on this extrapolation, is difficult. An expression which gives an approximation of the Dynamic Load Factor for values of \( t/T_N \) in this very small range is:

\[
D. L. F. = \pi (t/T_N)
\]
Figure 30. Dynamic Load Factor versus $t/T_N$, for Triangular Pulse.
Figure 31. Extrapolated Values of Dynamic Load Factor for Very Small Values of $t/T_N$. 

**Diagram:**
- **Y-axis:** Dynamic Load Factor (Maximum)
- **X-axis:** Ratio of Time of Pulse to Natural Period, $t/T_N$. 

Range:
- Y-axis: 0.0 to 0.9
- X-axis: 0.001 to 0.2
For a $t/T_N$ of $10^{-4}$ the Dynamic Load Factor is 0.000314.

As an example, consider a timber beam, 10 ft long, subjected to a dynamic load caused by the explosive charge discussed above. Considering the density and detonating velocity, the maximum explosion pressure is approximately $1.5 \times 10^6$ psi. Assuming an area of influence on the structure of 30 sq. in., the maximum amplitude of the explosion pulse is $45 \times 10^6$ lb. Assuming a value of $E$ for timber of $1.5 \times 10^6$ psi, a moment of inertia of the beam of $10^3$ in. $^4$ and considering the load as being concentrated at mid-span, the static deflection is computed as follows:

$$X_{\text{static}} = \frac{PL^3}{48EI}$$

$$= \frac{45 \times 10^6 \text{ lb.} \times 1728 \times 10^3 \text{ in.}^3}{48 \times 1.5 \times 10^6 \text{ psi} \times 10^3 \text{ in.}^4}$$

$$= 108 \text{ inches.}$$

Multiplying $X_{\text{static}}$ by the Dynamic Load Factor of 0.000314, the deflection due to the dynamic load is determined to be 0.034 in., which is certainly within the elastic range of the member.

By proper spacing of members, the designer can insure that the dynamic deflection and deflection caused by the earth cover does not exceed the maximum allowable deflection for each structural member.
APPENDIX B

Questionnaire
Commanding Officer,

Dear Sir:

The purpose of this letter is to ask your assistance in gathering field data for possible use in preparing my thesis toward a Master of Science Degree in Civil Engineering. I am presently enrolled at the University of Missouri - Rolla, under the Army's Graduate School Program. Having returned from Vietnam last November, I am fully aware that your time is extremely valuable. Although my letter is lengthy, the information I am requesting is fairly concise.

During my tour with the 8th Engineer Battalion, 1st Air Cavalry Division, I served as Commanding Officer of Company A, and later as Assistant S-3 of the Battalion. We had access to Standard Designs, complete with bill of materials, for structures which could be used as Tactical Operations Centers or anything else the tactical commander desired. These, we assumed, had been designed with all factors considered, including suspected or probable enemy incoming mortar and/or artillery rounds.

Only once, during my tour, was the responsible supply officer able to fill the required BOM as presented in the Standard Designs. Rather, the materials received were normally of reduced dimensions and in smaller quantities than originally requisitioned. The economics of having a standard design and sticking to it are not in question; however, my experience was that even though the required materials were not on hand the tactical commander needed his TOC as soon as possible. This, then, forced the engineer, in conjunction with the tactical commander, to redesign the final structure based on his experience and the available materials. When the job was completed, that ego deflating question, "Will it take a direct hit from a _____ round?", caused some embarrassment to many of us. To the best of my knowledge, none of our structures failed during enemy mortar, rocket or artillery attacks, but I'm still concerned that we engineers were not able to positively answer the question on the spot.

This is the subject I propose to investigate for my thesis. As you are aware, FM 5-34 does not contain a complete discussion of the variables involved in this type of structural dynamics problem. My plans are to try to identify these governing variables, e.g., weight of incoming round, weight and type of explosive contained therein, thickness and composition of overhead cover, span length of
structural members, etc., and provide some type of analytical guidelines for future use by combat engineer leaders. Hopefully this can be reduced even to terms and expressions which can be interpreted and used by all engineer leaders, not just the structural engineers.

As previously stated, my letter is long; however, I have presented to you the background concerning my topic of investigation. Your cooperation in completing the short questionnaire will be greatly appreciated. This data will aid in verifying or rejecting predictions based on textbook analysis.

Perhaps, unknowingly, I have asked for some classified data. I hope this is not the case, but if some of the questions do deal with classified information, thus preventing you from completely answering the question, I will understand. My student status at UMR can be verified by contacting the Professor of Military Science, University of Missouri - Rolla, Rolla, Missouri. Thank you for any assistant you may be able to provide.

Sincerely,

JOHN R. CHILDRESS
Major, Corps of Engineers
The purpose of this questionnaire is to obtain field data concerning structures (primarily timber structures) built by combat engineer units in support of tactical operations. The information will be used, in conjunction with research, to attempt to formulate guidelines and analytical techniques for use in the rapid field design of protective structures, built in the Theater of Operations.

1. Number of protective structures, built by your unit, which sustained a direct hit from an enemy round. Please give a brief description of the extent of damage, if any.

2. Size of the round and approximate range from which fired, e.g. 82mm mortar, 1500 meters.

3. Brief sketch, showing thickness and composition of overhead cover, size and span length of structural member, approximate location of impact, etc.

4. Other information which, in your opinion, will aid in this research.

A self-addressed, stamped, envelope is included for your use in returning this questionnaire. Your cooperation will be greatly appreciated and could materially affect the outcome of this research.
VIII. BIBLIOGRAPHY


Personal communication, February, 1970.


IX. VITA

John Ross Childress was born on December 18, 1939, at Cairo, Illinois. He received his primary and secondary education in the Public School System in Sikeston, Missouri.

In January, 1962, he received a Bachelor of Science Degree in Physics from the Missouri School of Mines and Metallurgy at Rolla, Missouri, and was commissioned in the Corps of Engineers, United States Army. He was selected to attend the University of Missouri - Rolla under the Army's Graduate Degree Program and began graduate study in February, 1969.

Major Childress is married to the former Miss Margaret Jean McClintic of Springdale, West Virginia.