R 878

TECHNICAL REPORT

CIVIL ENGINEERING LABORATORY

Naval Construction Battalion Center, Port Hueneme, California 93043

DESIGN CRITERIA FOR SOIL COVER OVER BOX-SHAPED AMMUNITION MAGAZINES

By

W. A. Keenan (CEL) and L. C. Nichols (WPNSTA Concord)

May 1980

Sponsored by

NAVAL FACILITIES ENGINEERING COMMAND

Approved for public release; distribution unlimited.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
TR-878

2. GOVT ACCESSION NO.
DN987048

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
DESIGN CRITERIA FOR SOIL COVER OVER BOX-SHAPED AMMUNITION MAGAZINES

5. TYPE OF REPORT & PERIOD COVERED
Final; Sep 1979 – Mar 1980

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
W. A. Keenan, CEL
L. C. Nichols, WPNSTA Concord

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
CIVIL ENGINEERING LABORATORY
Naval Construction Battalion Center
Port Hueneme, California 93043

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
63725N;
Y0995-01-003

11. CONTROLLING OFFICE NAME AND ADDRESS
Weapons Quality Engineering Center
Naval Weapons Station, Code 30
Concord, California 94518

12. REPORT DATE
May 1980

13. NUMBER OF PAGES
96

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)

15. SECURITY CLASS. (of this report)
Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Explosives safety, ammunition magazine, explosives storage, ammunition depots, explosion effects, dynamic structural response.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Theory is formulated for effects of an internal explosion on the dynamic response and behavior of the earth-bermed roof of box-shaped ammunition storage magazines. The theory considers the ratio of charge weight to magazine volume, scaled vent area of the magazine, depth and density of soil cover, characteristics of the roof slab, and the net explosive weight of storage. Predictions from theory are correlated with experimental data derived from field tests in which HE charges were detonated inside small-scale, box-shaped

(continued)

20. Continued

ammunition magazines. Test variables were depth of soil cover, soil density, and net explosive weight. Excellent agreement was found between the measured and predicted response of the roof over the entire history of response. Theory is translated into design criteria for the minimum depth of soil cover required over the roof of a box magazine in order to mitigate the debris hazard and/or contain explosion effects from an inadvertent explosion. Problem solutions are presented to illustrate applications of the theory and design criteria. Results have positive implications in the future design and siting of ready service and special weapons magazines and missile test cells which typically have a small ratio of net explosive weight to magazine volume. Further, results offer a rational basis for designing physical security and survivability attributes into construction standards which deviate from established standards without degrading the level of explosives safety.

Library Card

Civil Engineering Laboratory
DESIGN CRITERIA FOR SOIL COVER OVER BOX-SHAPED AMMUNITION MAGAZINES (Final), by W. A. Keenan and L. C. Nichols
TR-878 96 pp illus May 1980 Unclassified

1. Munitions storage 2. Explosives storage I. Y0995-01-003

Theory is formulated for effects of an internal explosion on the dynamic response and behavior of the earth-bermed roof of box-shaped ammunition storage magazines. The theory considers the ratio of charge weight to magazine volume, scaled vent area of the magazine, depth and density of soil cover, characteristics of the roof slab, and the net explosive weight of storage. Predictions from theory are correlated with experimental data derived from field tests in which HE charges were detonated inside small-scale, box-shaped ammunition magazines. Test variables were depth of soil cover, soil density, and net explosive weight. Excellent agreement was found between the measured and predicted response of the roof over the entire history of response. Theory is translated into design criteria for the minimum depth of soil cover required over the roof of a box magazine in order to mitigate the debris hazard and/or contain explosion effects from an inadvertent explosion. Problem solutions are presented to illustrate applications of the theory and design criteria. Results have positive implications in the future design and siting of ready service and special weapons magazines and missile test cells which typically have a small ratio of net explosive weight to magazine volume. Further, results offer a rational basis for designing physical security and survivability attributes into construction standards which deviate from established standards without degrading the level of explosives safety.

CONTENTS

BACKGROUND

The Weapons Quality Engineering Center (WQEC) at the Naval Weapons Station, Concord, Calif., performs surveillance and quality evaluation testing of various types of Naval ordnance material. Tests are routinely conducted on major caliber gun ammunition components, such as primers, base detonating fuzes, mechanical time fuzes, point detonating fuzes, VT fuzes, and various other explosive devices. In 1947, two fuze and primer magazines (1XT 1 and 1XT 2) were constructed to support explosive test operations at the WQEC. In 1952, four more such magazines were constructed because of increased testing requirements. The specific locations of the 1XT magazines in the WQEC complex are shown in Figure 1.

The design of a 1XT magazine is shown in Figure 2. All magazines are eight feet square by seven feet high for a total volume of 448 cu ft. The magazines are reinforced concrete construction, barricaded, and covered with 2 feet of earth. The magazines were built to specifications contained in PWO Concord Drawing Nos. 500484 and 500424 of 6 Jan 1947 and Y&D Drawing No. 516978 of 29 May 1952, and met all safety requirements of that time. However, through a number of evolutions of NAVSEA OP-5, "Ammunition and Explosives Ashore," the fuze and primer magazines now require waivers (Ref 1). In accordance with DOD's current policy concerning operational waivers, the WPNSTA Concord Master Plan includes MILCON Project P-252 which provides for construction of six new fuze and primer magazines at an area more remote to the WQEC. Obviously, this solution will be costly, requiring new access roads, the use of trucks to transport explosives to and from the test area, and will increase the potential for an explosive accident/incident by virtue of the extra handling and transportation involved.

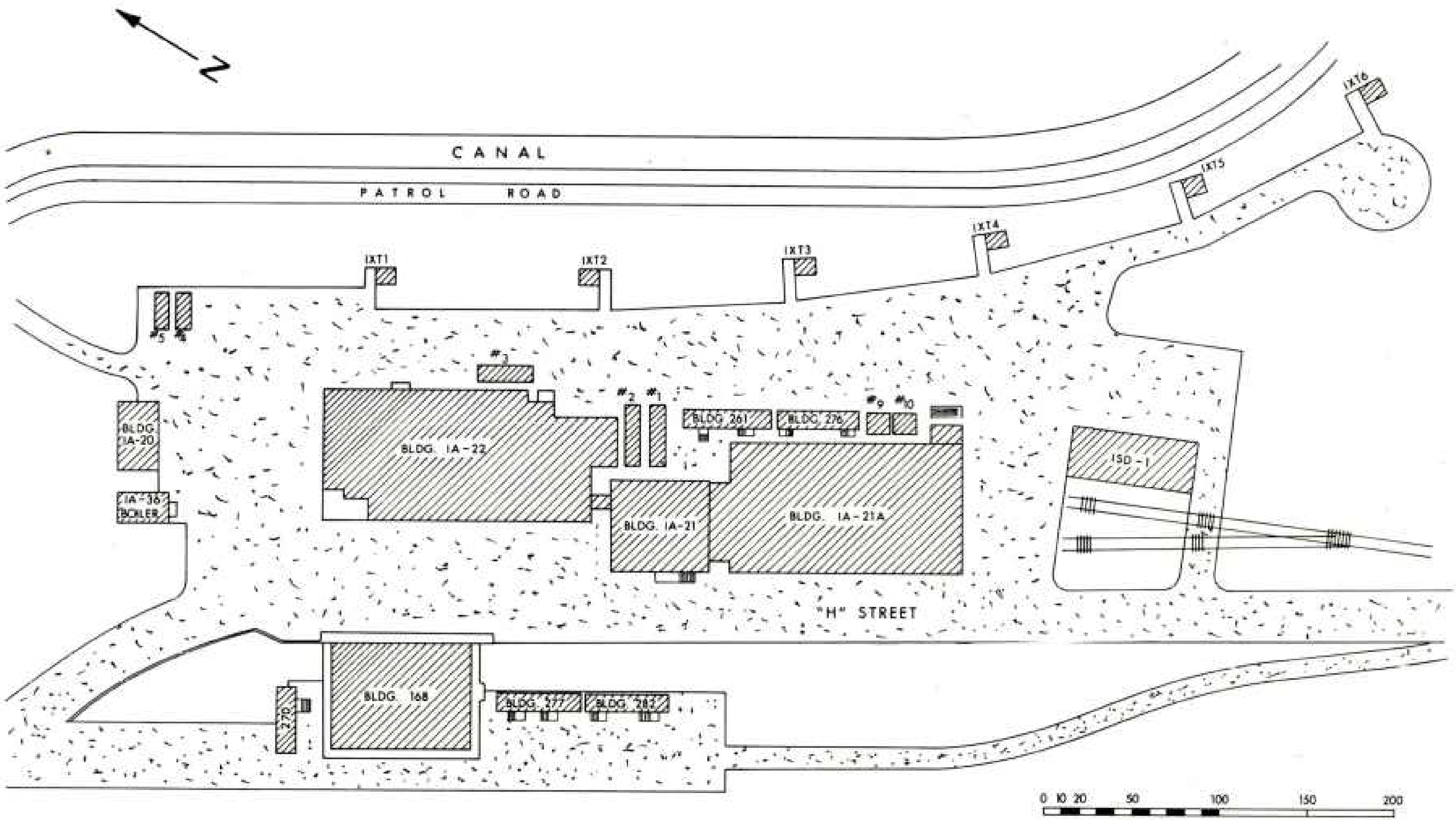


Figure 1. Site plan for IXT magazines, WPNSTA Concord.

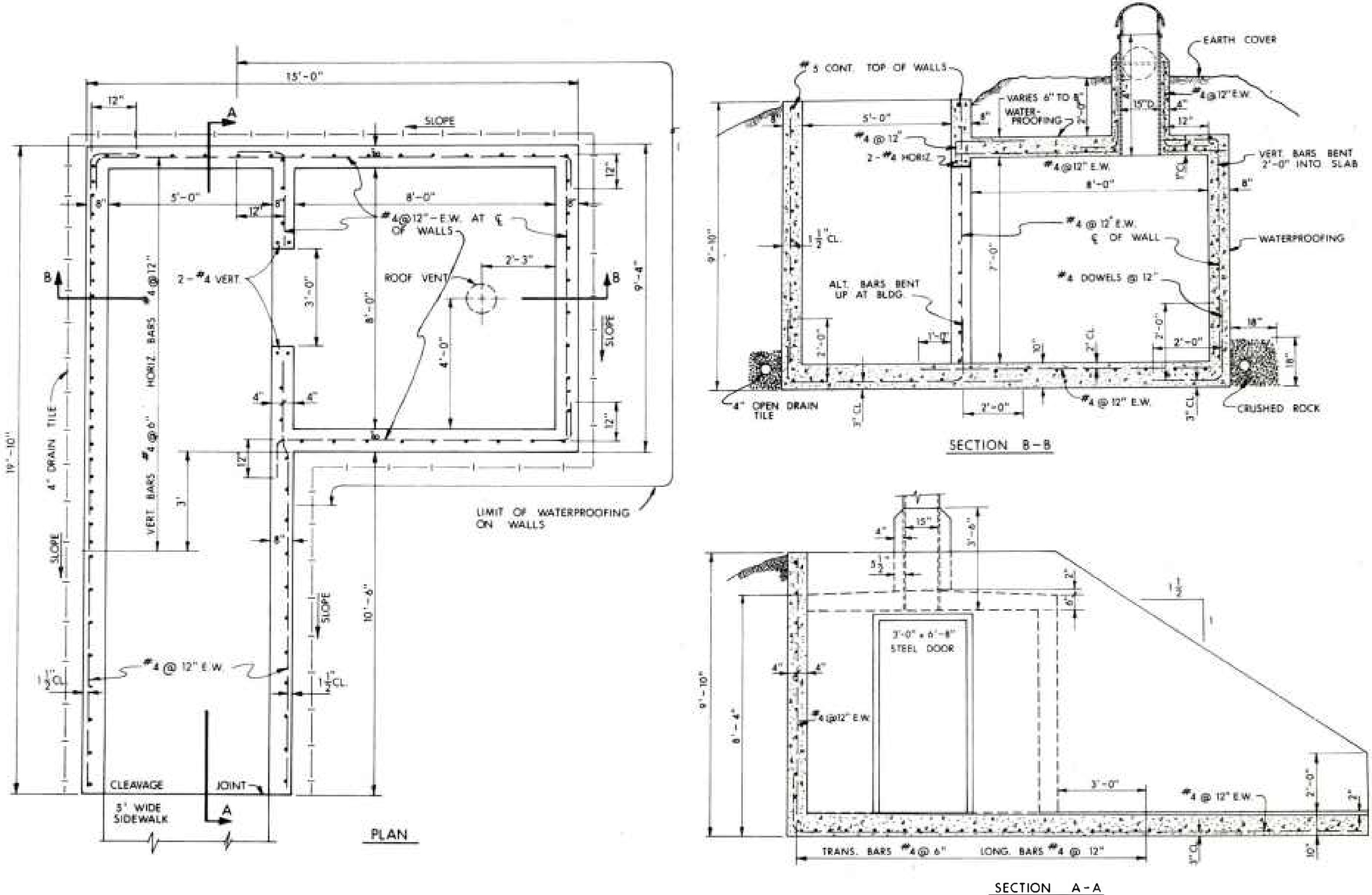


Figure 2. Design Details of IXT Magazines at WPNSTA Concord.

The magazines store a total net explosives weight (NEW), W, equal to 8.0 pounds maximum of Class 1, Divisions 1 and 2, Category (04) material. The magazines violate NAVSEA OP-5 safety standards, which require a 400-foot minimum separation distance from the magazines to inhabitated areas. The standard is intended to mitigate the debris hazard to people and property from an inadvertent explosion inside a magazine.

The minimum separation distance could be reduced to 80 feet (inhabited building distance) if it can be demonstrated that the debris hazard from an explosion involving 8.0 pounds NEW will not exceed this range. This reduced separation distance would eliminate the existing safety waiver.

One possible scheme for mitigating the debris hazard is to cover each magazine with soil to a depth sufficient to contain fragments and debris but permit blast and gas pressures to vent through the barricaded door opening. According to NAVSEA OP-5, the minimum depth of soil cover, d_s, required to contain fragments and debris is

$$d_s = 3.5W^{1/3} \quad (1)$$

For the 1XT magazines, W = 8 pounds, and from Equation 1, d_s = 7.0 feet. A structural analysis of the 1XT magazine showed that the dead load corresponding to 7 feet of soil cover exceeds the safe load capacity of the roof. The analysis also showed that the roof slab offers no structural resistance, i.e., no strain energy absorbing capacity, against the forces from an internal explosion. The upward motion of the roof slab must be resisted entirely by the mass effects of the soil cover and concrete roof slab. WPNSTA Concord requested the Civil Engineering Laboratory (CEL) to assist them in a study to determine the minimum depth of soil cover required to mitigate the debris hazard from an explosion in a 1XT magazine.

This report covers the results of the study. It presents results of a theoretical study conducted by CEL and a series of small scale explosives tests conducted by WPNSTA Concord. The study was sponsored by WPNSTA Concord.

OBJECTIVE

The objective of the study is to establish design criteria for the minimum depth of soil required over the roof of a box-shaped ammunition storage magazine in order to mitigate the debris hazard from an inadvertent explosion.

THEORY

A typical box-shaped, earth-covered magazine is shown in Figure 3. The box is constructed of reinforced concrete. The roof slab is designed to safely support the dead load of the soil above the slab. The roof slab is not reinforced to resist the blast pressures from an internal explosion. The roof slab has essentially no capacity to resist uplift forces by absorbing internal strain energy.

Blast Environment

Consider an explosion inside the box-shaped magazine shown in Figure 3. The explosion produces both blast and gas pressures. The total impulse, i, acting on the roof of the box is a function of the scaled vent area, $A/W^{2/3}$, and charge density, W/V. According to Reference 2, the scaled total impulse is

$$\frac{i}{W^{1/3}} = 569\left(\frac{A}{W^{2/3}}\right)^{-0.78}\left(\frac{W}{V}\right)^{-0.38} \tag{2}$$

and the scaled duration of the gas pressure is

$$\frac{T}{W^{1/3}} = 2.26\left(\frac{AW^{1/3}}{V}\right)^{-0.86} \tag{3}$$

Equations 2 and 3 are empirical relationships derived from test data. The total impulse, i, includes effects of both blast and gas pressures.

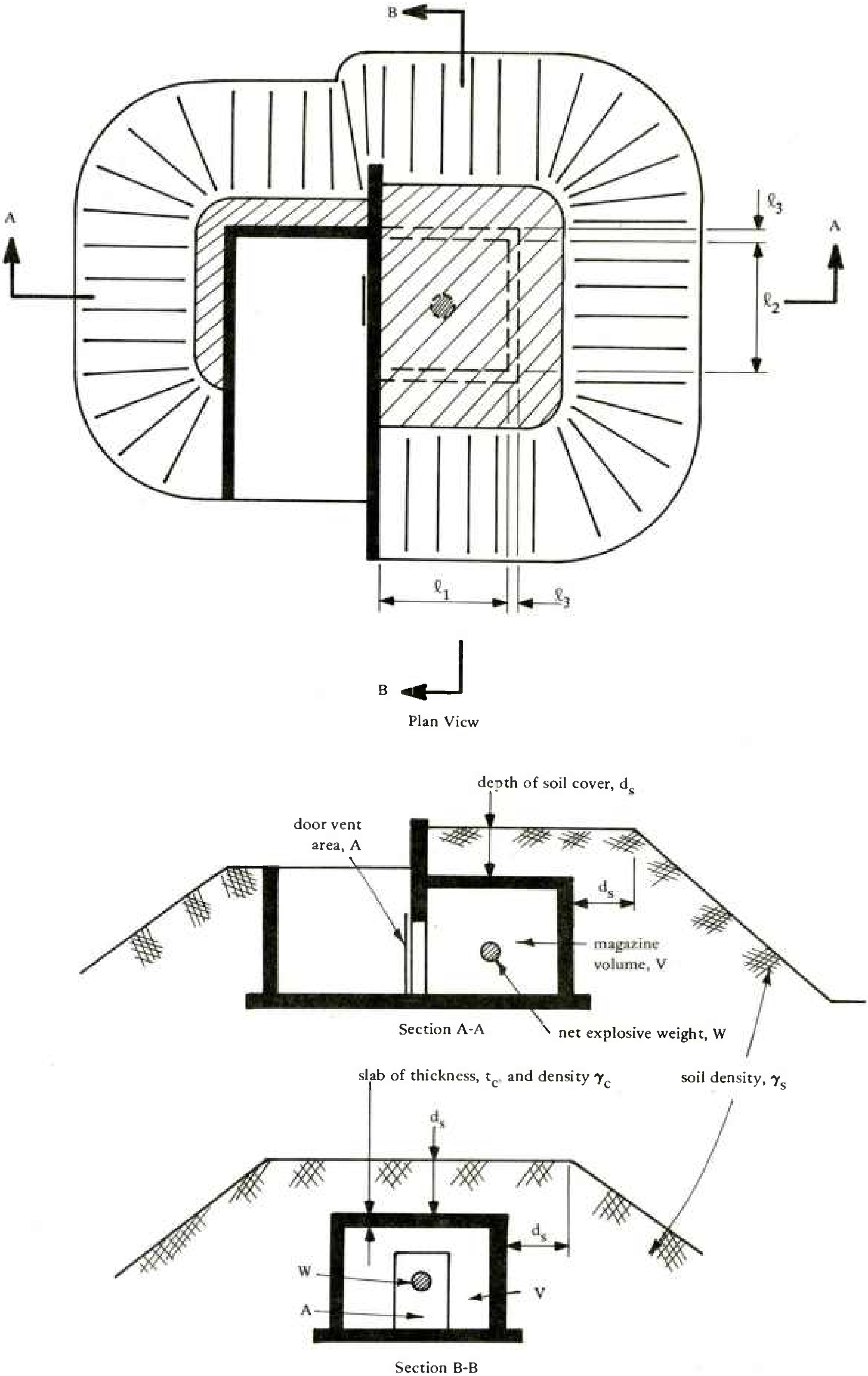


Figure 3. Typical earth-covered, box-shaped, ammo storage magazine.

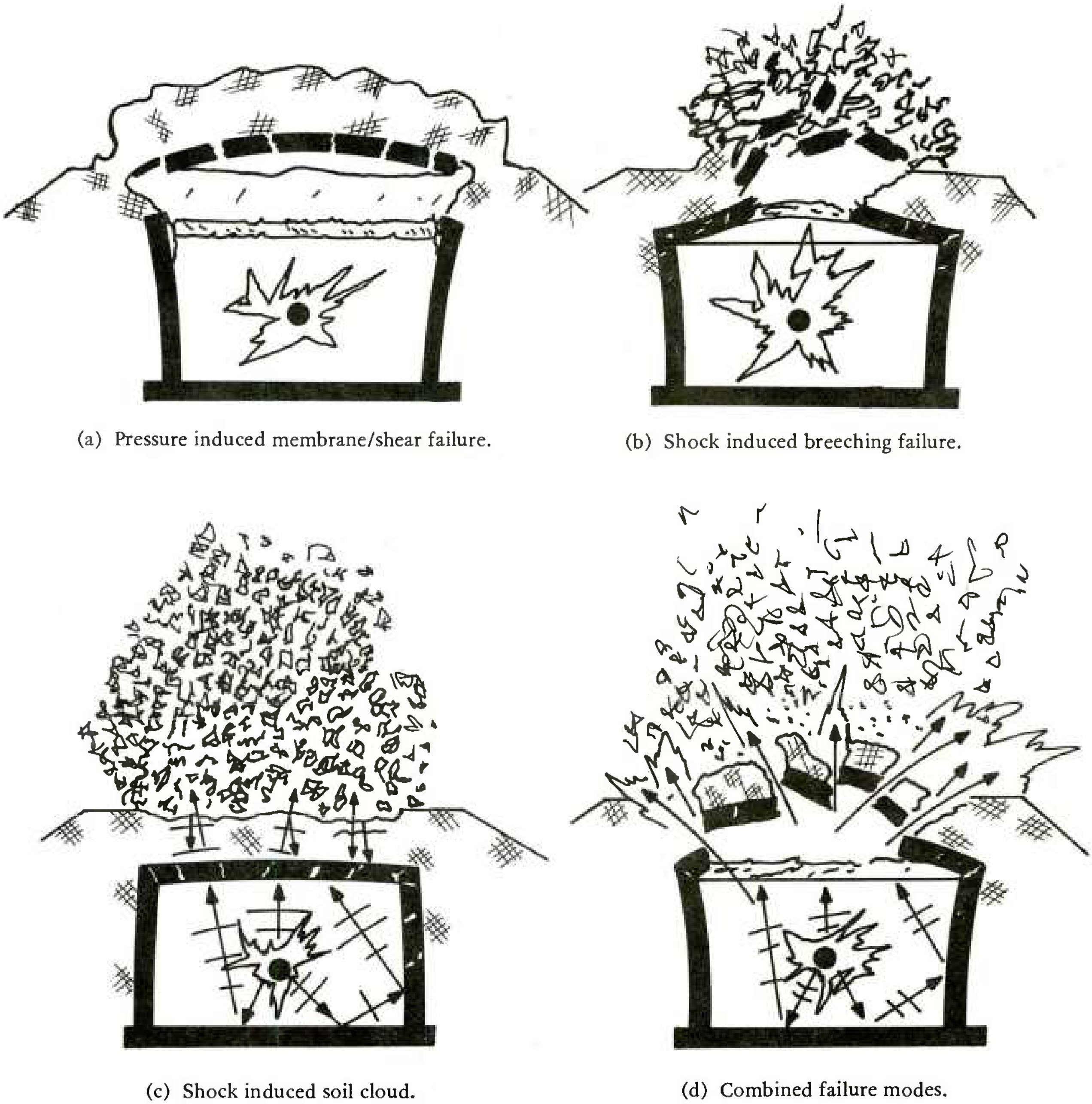
Roof Response

Possible modes of behavior for the soil-bermed roof of a box magazine are illustrated in Figure 4. The explosion generates pressures which deflect the slab upward. The response will eventually cause the slab to fail. Failure will occur either by tearing the slab free from its supports (Figure 4a) or by local breeching (break-up) of the slab (Figure 4b).

Consider the support failure illustrated in Figure 4a. A support failure results from shear and/or tension forces which develop near the perimeter of the slab. Due to the characteristics of the loading associated with an internal explosion, the roof slab is most likely to fail in shear (Ref 3). The shear failure will occur almost simultaneously with the time of the explosion. This behavior will prevent the slab from absorbing any significant amount of internal strain energy. Should a shear failure not occur, the slab will deflect until the tensile membrane stresses associated with large deflections (deflections equivalent to about one-tenth the span) eventually cause rupture in tension of reinforcing bars near the supports. In most cases, the strain energy absorbed in a membrane failure is insignificant compared to the total energy imparted by the explosion, especially if the roof slab is not reinforced to resist internal pressures.

The time histories of the pressure generated inside the box and the resulting response of the roof are shown in Figure 5. If the time to maximum response of the roof, t_m, is much greater than the load duration, T, i.e., $t_m > 3T$, then t_m can be calculated, without introducing significant error, by considering only the total impulse, i, and neglecting the time variation in the pressure pulse. The impulse imparts an initial psuedovelocity to the roof equal to i/M where M is the total effective mass of the soil cover plus concrete slab per unit area of the roof. Neglecting the strain energy absorbed during failure of the slab, the upward displacement of the roof, x, at any time, t, is

$$x = \frac{144i}{M} t - \frac{1}{2}gt^2 \qquad (4a)$$



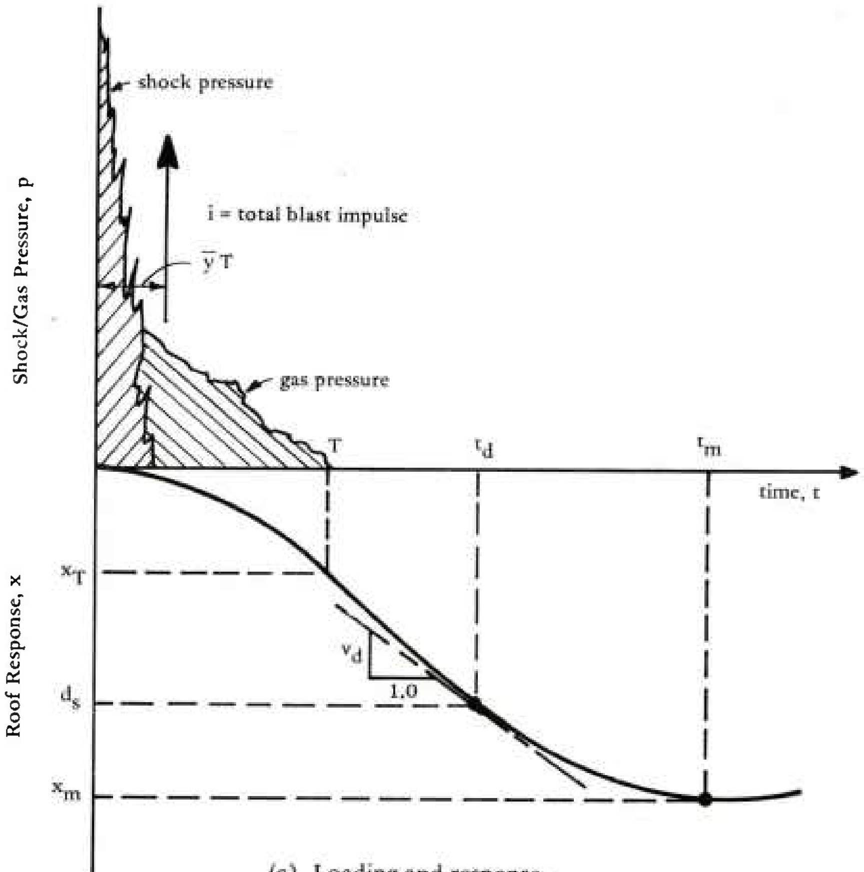
(a) Pressure induced membrane/shear failure.

(b) Shock induced breeching failure.

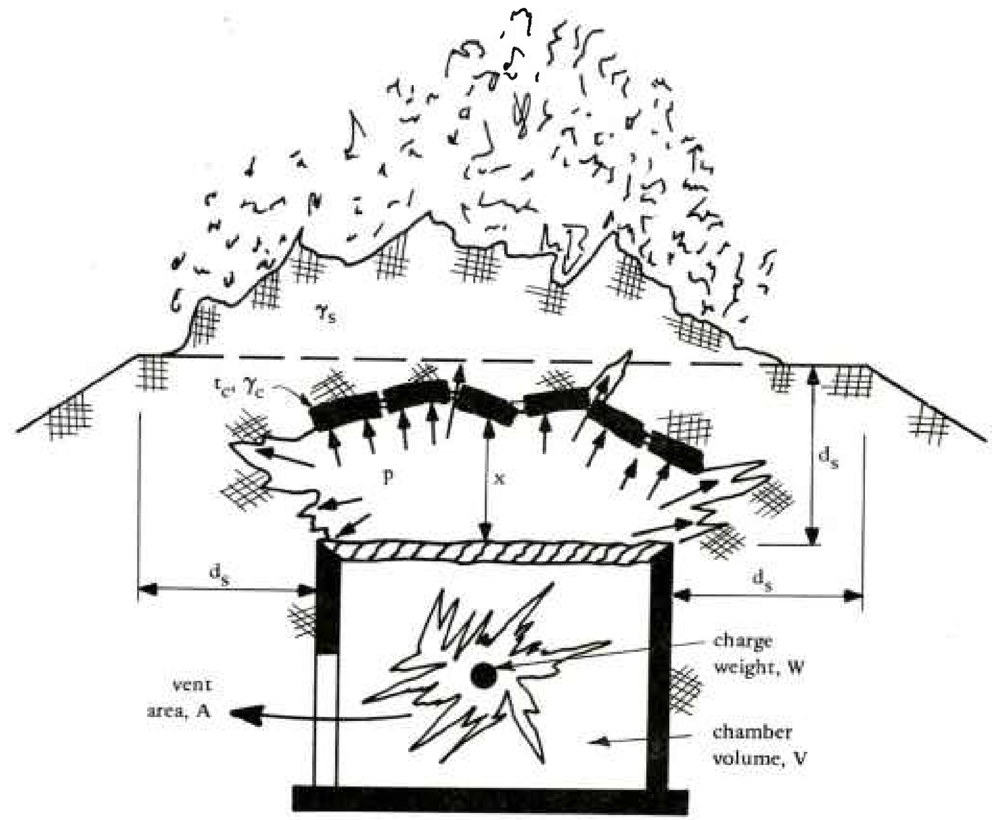
(c) Shock induced soil cloud.

(d) Combined failure modes.

Figure 4. Failure modes of soil berm and roof slab.



(a) Loading and response.



(b) Explosion effects.

Figure 5. Time history of internal pressure and roof response for box magazine.

At time $t = t_m$, $v = 0$. Therefore,

$$t_m = \frac{144i}{gM} \tag{4b}$$

Combining equations 4a and 4b at $t = t_m$,

$$x_m = \frac{(144i)^2}{2gM^2} \tag{4c}$$

An idealized description of the soil mass mobilized by the roof slab is shown in Figure 6. The soil fails by shear along a plane rising from the edge of the failed roof slab at an angle α with the horizontal. The angle α is a function of the angle of internal friction, ϕ, which depends on the type of soil in the berm. The total mass, $\bar{M}$, of the soil wedge plus concrete roof slab is

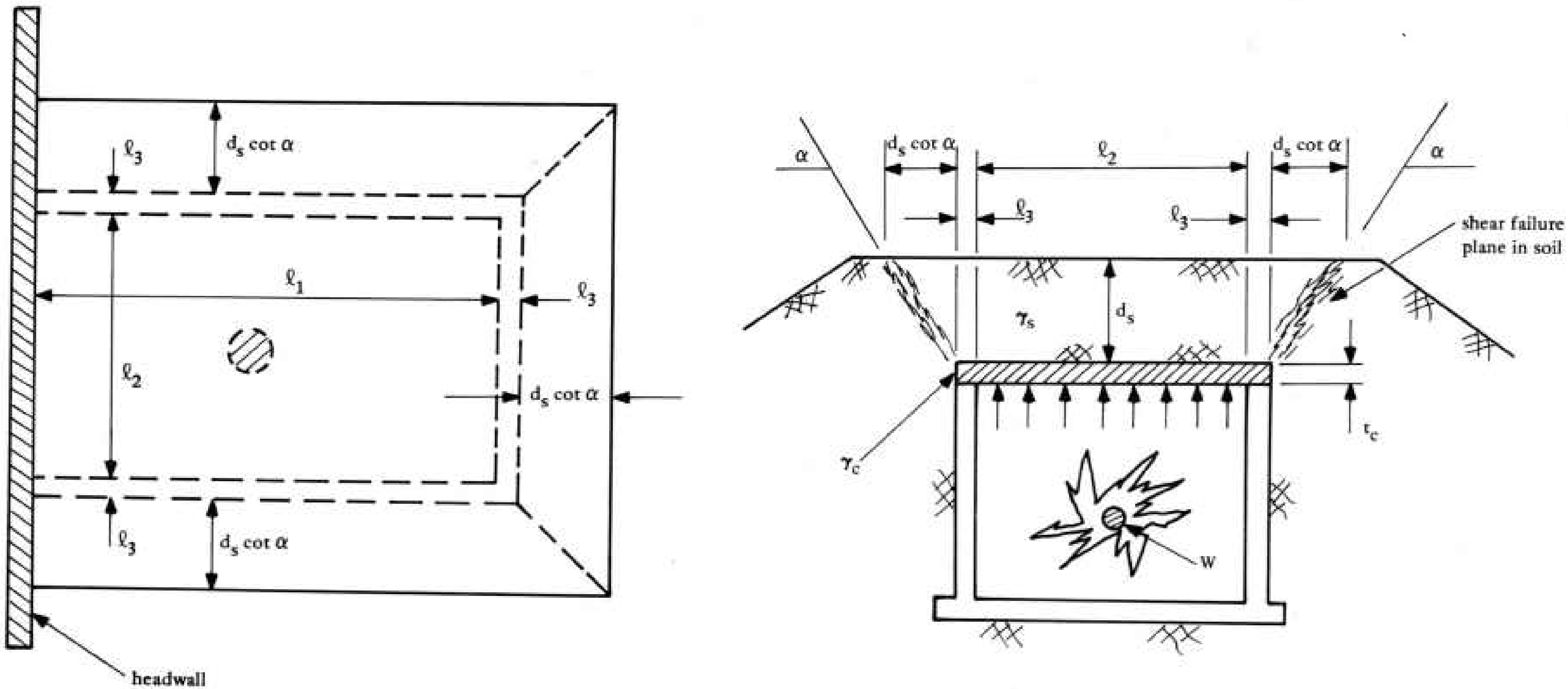
$$g\bar{M} = (\ell_1 + \ell_3)(\ell_2 + 2\ell_3) \left\{ t_c\gamma_c + \frac{d_s\gamma_s}{2} \left[1 + \left(\frac{\ell_1 + \ell_3 + d_s \cot \alpha}{\ell_1 + \ell_3} \right) \left(\frac{\ell_2 + 2\ell_3 + 2d_s \cot \alpha}{\ell_2 + 2\ell_3} \right) \right] \right\} \tag{4d}$$

The equivalent average mass, M, per unit area of the loaded roof is

$$gM = \frac{g\bar{M}}{\ell_1 \ell_2} \tag{4e}$$

Combining Equations 4d and 4e and rearranging terms,

$$gM = d_s \gamma_s k \tag{4f}$$



(a) Plan view of soil wedge.

(b) Section of soil wedge.

Figure 6. Idealization of effective soil mass mobilized by roof slab.

where

$$k = \left(1 + \frac{\ell_3}{\ell_1}\right)\left(1 + \frac{2\ell_3}{\ell_2}\right)\left\{\frac{t_c\gamma_c}{d_s\gamma_s} + \frac{1}{2}\left[1 + \left(1 + \frac{d_s \cot\alpha}{\ell_1 + \ell_3}\right)\left(1 + \frac{2d_s \cot\alpha}{\ell_2 + 2\ell_3}\right)\right]\right\} \tag{4}$$

Combining Equations 2, 4b, and 4f, the scaled time when the slab reaches its maximum displacement is

$$\frac{t_m}{W^{1/3}} = \frac{569 \times 144}{\gamma_s k d_s}\left(\frac{A}{W^{2/3}}\right)^{-0.78}\left(\frac{W}{V}\right)^{-0.38}$$

or

$$\frac{t_m}{W^{1/3}} = \frac{81936}{\gamma_s k d_s}\left(\frac{A}{W^{2/3}}\right)^{-0.78}\left(\frac{W}{V}\right)^{-0.38} \tag{5}$$

Combining Equations 1 and 5, the time to maximum response relative to the load duration is

$$\frac{t_m}{T} = \frac{36255}{\gamma_s k d_s}\left(\frac{A}{W^{2/3}}\right)^{0.08}\left(\frac{W}{V}\right)^{0.48} \tag{6}$$

Combining Equations 2, 4c, and 4f, the maximum response of the roof is given by

$$\frac{d_s^3\,(x_m/d_s)}{W^{2/3}} = \frac{(569)^2(144)^2(32.2 \times 10^{-6})}{2k^2\gamma_s^2}\left(\frac{A}{W^{2/3}}\right)^{-1.56}\left(\frac{W}{V}\right)^{-0.76}$$

or

$$\frac{d_s^3\gamma_s^2k^2(x_m/d_s)}{W^{2/3}} = 108087\left(\frac{A}{W^{2/3}}\right)^{-1.56}\left(\frac{W}{V}\right)^{-0.76} \tag{7}$$

The error in Equation 7 is negligible provided that t_m/T, given by Equation 6, is greater than about 3.0. If $t_m/T < 3.0$, the maximum roof response is sensitive to the loading history which complicates the response equation.

The depth of soil cover required to limit the roof response of a box-shaped magazine is determined from Equations 4, 6, and 7. Given the design parameters of a box-shaped magazine (namely, ℓ_1, ℓ_2, ℓ_3, α, A, V, W, t_c, γ_c, and γ_s), the factor k is calculated from Equation 4 and the minimum depth of soil cover, d_s, required to satisfy a prescribed failure criterion, x_m/d_s, from Equation 7. The computed value of d_s must be checked for accuracy using Equation 6 to determine if $t_m/T \geqq 3.0$. The computation of d_s is direct for $\alpha = 90$ degrees.

The computation of d_s requires an interation process if $\alpha < 90$ degrees. For this case, the factor k is a function of d_s and the computational process is as follows:

1. Estimate the value of d_s.
2. Compute k from Equation 4.
3. Compute d_s from Equation 7.
4. Use the computed value of d_s as the new estimate of d_s in step 1.
5. Repeat steps 1 through 4 until the assumed and computed values of d_s are equal.
6. Compute t_m/T from Equation 6. If $t_m/T \geqq 3$ then the computed value of d_s is correct; if $t_m/T < 3$ the value of d_s is overly conservative.

Equations 7 and 6 are plotted in Figures 7 and 8, respectively, to facilitate the computational process.

Given d_s, the computational process is direct. The value of k is found from Equation 4 and the maximum permissible charge weight, W, (required to satisfy a prescribed failure criteria, x_m/d_s) or the maximum roof response, x_m, (given the value of W) is computed from Equation 7. In either case, the value of d_s, x_m, or W from Equation 7 is correct provided t_m/T given by Equation 6 is greater than 3.0.

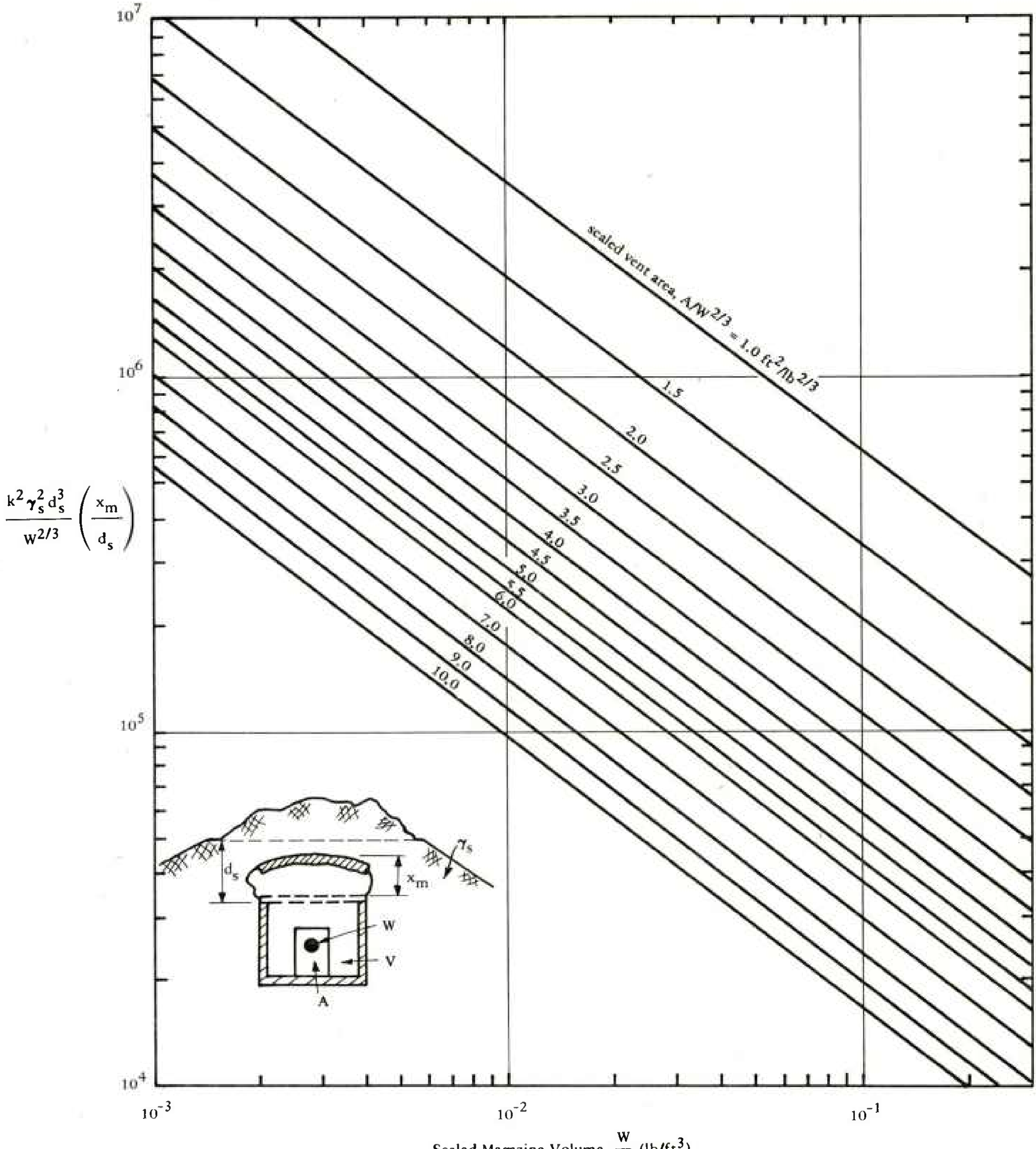


Figure 7. Design chart for response of an earth-covered roof.

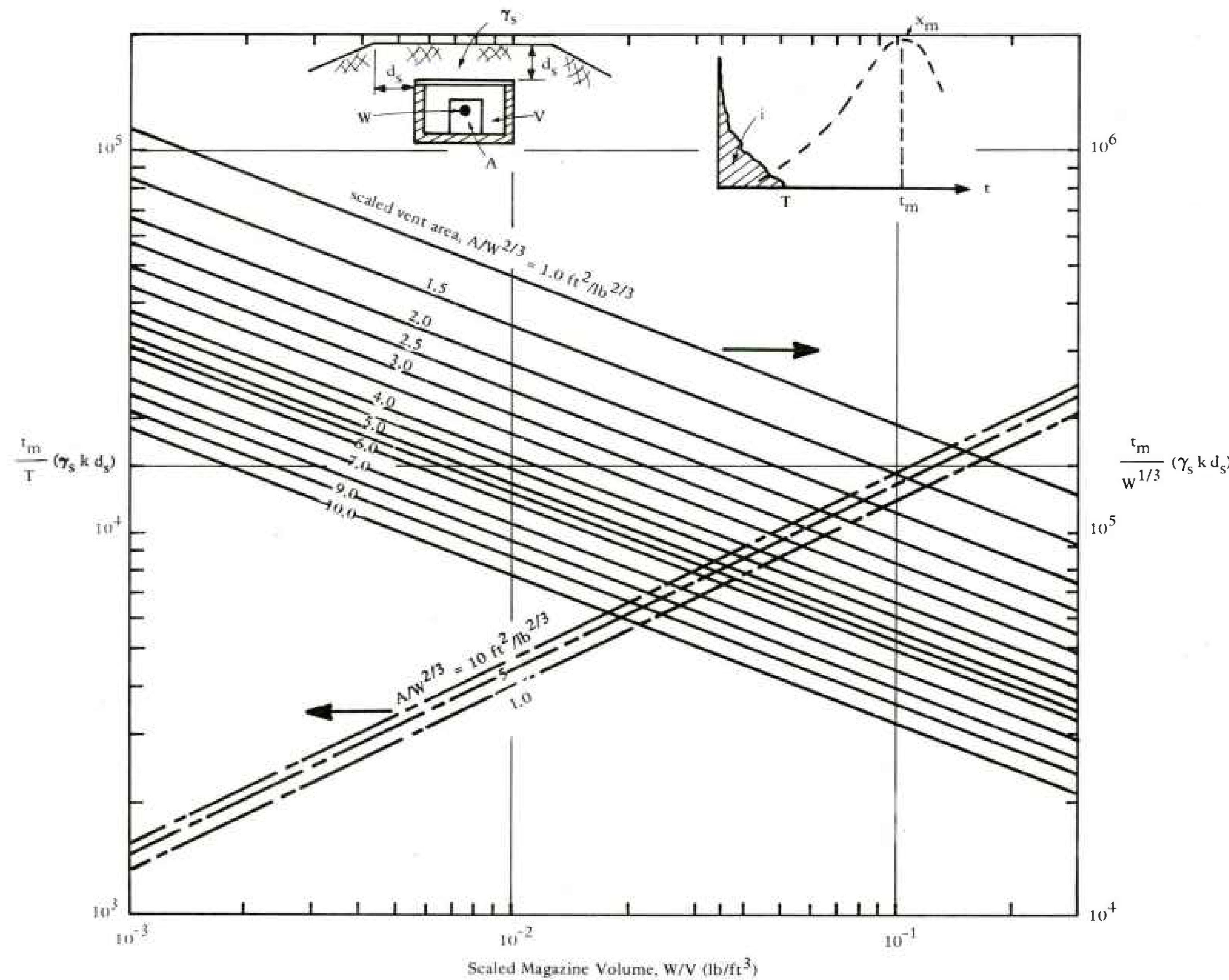


Figure 8. Time to maximum response for an earth-covered roof.

Roof Debris

The previous formulation describing roof response assumed that the concrete roof slab fractures along its perimeter and the entire area of the slab remains intact as it moves upward under the force of the explosion. But the explosion may cause local breeching (break-up) of the roof slab, as illustrated in Figure 4b. Should breeching occur, concrete debris missiles of various sizes will be propelled upward by the force of the explosion. These debris missiles are a potential hazard to inhabited areas outside the magazine.

The risk to people and property from debris missiles depends upon their number, mass, and striking velocity. According to NAVSEA OP-5, the safe range from an explosion producing debris missiles is the range beyond where no more than one debris missile per 600 sq ft of land area strikes with an energy content exceeding 58 ft-lb (Ref 1).

A more conservative safety criterion is to define the safe range, R_s, as the range beyond where no debris missiles will strike the ground surface. If v_d is the launch velocity of any concrete debris missile resulting from failure/break-up of the roof slab, then this safety criterion is satisfied provided

$$v_d \leqq \sqrt{R_s g} \qquad (8)$$

Equation 8 is conservative. It neglects the energy dissipated from tumbling and air drag during missile flight. Further, it assumes that the debris missile is launched from the magazine at the critical launch angle producing the maximum throw range.

The minimum depth of soil cover necessary to satisfy Equation 8 is derived as follows. If the intensity of compression and tension waves traveling upward through the roof slab are sufficient to breech (break-up) the roof slab, breeching will occur almost immediately after the explosion. The slab will break-up into concrete debris missiles of various sizes. Neglecting the time variation in the pressure pulse and the energy required to breech the slab, the psuedovelocity imparted to a concrete debris missile is i/M where M is the total effective mass of the soil cover plus concrete debris missile per unit area of the missile. Given this psuedovelocity, the upward displacement of the missile, x, at any time, t, is

$$x = \frac{144i}{M} t - \frac{g}{2} t^2 \tag{4a}$$

and the corresponding velocity of the missile is

$$v = \frac{144i}{M} - gt \tag{9a}$$

Combining Equations 4a, 4f, and 9a,

$$x = \left(\frac{144i}{kd_s\gamma_s} - \frac{v}{g}\right)\left(\frac{144ig}{kd_s\gamma_s}\right) - \frac{g}{2}\left(\frac{144i}{kd_s\gamma_s} - \frac{v}{g}\right)^2 \tag{9b}$$

When the missile has moved upward a distance equal to the original depth of soil cover, $x = d_s$. Letting $v = v_d$ when $x = d_s$, then from Equation 9b,

$$d_s = \left(\frac{144i}{kd_s\gamma_s} - \frac{v_d}{g}\right)\frac{144ig}{kd_s\gamma_s} - \frac{g}{2}\left(\frac{144i}{kd_s\gamma_s} - \frac{v_d}{g}\right)^2 \tag{9c}$$

Combining Equations 2, 8, and 9c, a conservative estimate for the maximum safe charge weight so that the strike range of concrete debris missiles will not exceed some prescribed R_s is

$$W = \left[4.63 \times 10^{-6}\, k^2 d_s^2 \gamma_s^2 (2d_s + R_s)\left(\frac{A}{V^{0.487}}\right)^{1.56}\right]^{1.0564} \tag{9}$$

Rearranging terms, the safe range beyond which no concrete debris missiles will strike the ground surface is

$$R_s = \left[\frac{216{,}000\ W^{0.9466}}{k^2 d_s^2 \gamma_s^2 \left(A/V^{0.487}\right)^{1.56}} \right] - 2d_s \qquad (10)$$

The minimum depth of soil cover, d_s, required to limit debris missiles to a range R_s from an explosion of magnitude W is also found from Equation 10. The computation of d_s requires an iteration process because the value of k depends on d_s. The iteration process is that proposed for solving Equation 7.

It is important to emphasize that Equations 9 and 10 are based on the following assumptions: (1) no energy is lost in breaking the missile free from the slab, (2) the concrete debris missile enters free flight when $x = d_s$, (3) at $x = d_s$ the missile enters free flight at the launch angle which produces the maximum throw range, and (4) during free flight the missile experiences no loss of energy from effects of air drag and tumbling. The above assumptions are conservative; the safe charge weight is greater, and the safe range and the safe depth of soil cover are less than the values given by Equations 9 and 10, respectively.

The relationship for k in Equations 9 and 10 depends on the failure mode of the roof slab and the characteristics of the earth-bermed roof. Equation 4 yields the proper value for k if the roof slab fractures along its perimeter and remains intact as it moves upward under the force of the explosion. If the explosion breeches the roof slab, concrete debris missiles of various sizes will be propelled upward. For a rectangular shaped concrete debris missile of area $s_1 s_2$ and thickness t_c the proper relationship for k is

$$k = \frac{t_c \gamma_c}{d_s \gamma_s} + \frac{1}{2} \left[1 + \left(1 + \frac{2d_s}{s_1} \cot \alpha \right) \left(1 + \frac{2d_s}{s_2} \cot \alpha \right) \right] \qquad (11)$$

For a reinforced concrete roof slab, the most likely values for s_1 and s_2 are the spacing of the reinforcing bars in each span of the slab (Ref 4). For the special case where $\alpha = 90$ degrees, the value of k from Equation 11 is independent of s_1 and s_2, i.e., the size of the missile.

All preceding theory assumes that the blast energy delivered to the bermed roof of a box magazine is that defined by Equation 2. Further, it assumes that this energy transfer is completed in time T given by Equation 3. This condition is not always the case. For certain ranges and combinations of the parameters, gas pressures are still present inside the magazine after the bermed roof has reached a stage of failure which provides a path for gas pressures to vent through the roof. For such cases, some of the blast energy defined by Equation 2 bleeds or jets through the soil berm and vents to the atmosphere; i.e., all the blast energy is not converted to kinetic energy of the soil and roof slab. If pressures in the jet are large, they may spew soil at high velocity into the air. This phenomenon will occur if the duration of the gas pressure inside the magazine (Equation 3) exceeds the time when venting through the soil-bermed roof first begins. If t_d is the time when venting through the roof first begins, then all theory developed thus far is applicable for cases where $t_d/T \geqq 1.0$. For $t_d/T < 1.0$, Equation 7 overestimates x_m, Equation 9 underestimates the safe charge weight, and Equation 10 overestimates, by a wide margin for large charge weights, the maximum possible strike range of concrete debris missiles, and the minimum depth of soil cover. Thus, definition of the time ratio t_d/T is very important and derived as follows.

Referring to Figure 5, the roof response, x, at any time $t > T$ is precisely expressed by

$$x = \left(\frac{144i}{M}\right)(t - \bar{y}T) - \frac{1}{2}gt^2, \qquad t \geqq T \tag{12a}$$

The factor $\bar{y}$ is related to the centroid of the pressure-time pulse and therefore depends on the rate of decay of pressure inside the magazine. If venting through the bermed roof begins at time $t = t_d$ when $x = d_s$, then from Equation 12a,

$$d_s = \left(\frac{144i}{M}\right)(t_d - \bar{y}T) - \frac{1}{2}gt_d^2, \qquad t_d \geqq T \tag{12b}$$

Rearranging terms,

$$\left(\frac{t_d}{T}\right)^2 - \frac{288i}{gMT}\left(\frac{t_d}{T}\right) + \frac{288i\bar{y}T}{M} + d_s = 0 \qquad (12c)$$

Solving for t_d/T,

$$\frac{t_d}{T} = \frac{144i}{k\gamma_s d_s T} \pm \sqrt[2]{\left(\frac{144i}{k\gamma_s d_s T}\right)^2 - \frac{288i\bar{y}}{k\gamma_s d_s T} - \frac{2d_s}{gT^2}} \qquad (12d)$$

Combining Equations 2, 3, and 12d,

$$\frac{t_d}{T} = \gamma - \sqrt[2]{\gamma^2 - 2\gamma\bar{y} - \frac{12161d_s}{W^{2/3}}\left(\frac{A}{W^{2/3}}\right)^{1.72}\left(\frac{W}{V}\right)^{1.72}} \qquad (12)$$

provided $\frac{t_d}{T} \geqq 1.0$

where $\gamma = \frac{36255}{k\gamma_s d_s}\left(\frac{A}{W^{2/3}}\right)^{0.08}\left(\frac{W}{V}\right)^{0.48}$

Equations 4a through 11 are the correct solution provided t_d/T given by Equation 12 is greater than 1.0. If t_d/T is less than 1.0, then values given by Equations 4a through 11 are overly conservative.

Soil Cloud

The explosion generates shock waves. The shock waves travel outward and strike the roof, walls, and floor. The waves reflect and bounce back and forth between these surfaces. Waves striking the roof slab result in a train of compression waves which travel upward through the concrete slab and soil berm at a velocity near the speed of sound. The compression waves compress the soil and lose energy as they travel upward. When each wave passes through the concrete-soil interface of the roof and the soil-air interface of the berm, a reflected wave forms and travels in the opposite direction. The reflected wave is a tension wave. The net stress in the soil berm at any time is equal to the difference between the magnitude of stress in the compression and tension waves.

If the net stress is tension, it peels off successive layers from the outer skin of the soil berm. The peeling process continues, as the wave advances, until the energy in the wave is eventually dissipated by the nonlinear properties of the soil. The peeling process is most likely to occur within a relatively shallow outer layer of the soil berm. The peeling process may be repeated by trailing waves in the wave train. However, the trailing waves are less effective due to their lower energy content and interference with reflected waves. The peeling process, should it occur, throws soil particles into the air to form a soil cloud, as illustrated in Figure 4c.

The height of the soil cloud, h, at any time, t, is difficult to express mathematically due to the almost random nature of the wave train and the nonlinear properties of the soil. However, one can speculate from a deductive analysis of the phenomenon that the maximum height of the soil cloud, h_m, depends on the soil properties and the characteristics of the pressure pulse inside the magazine. In other words, h_m is probably a function of d_s, γ_s, W/V, W, and $A/W^{2/3}$. In other terms, a major parameter is probably the length (feet) of the wave relative to the depth of soil cover, d_s. Given sufficient test data, one could derive an empirical relationship between h_m and these parameters.

The total mass of soil pushed into the soil cloud by the tensile waves is of interest. This soil mass represents mass which is not available to suppress the upward motion of the roof, at least in the early stages of roof response. Theory for predicting the mass of soil pushed into the soil cloud is not available.

EXPERIMENT

Design details of the 1XT magazines at WPNSTA Concord are shown in Figure 2. The design was analyzed to evaluate effects of an inadvertent explosion involving the operating storage capacity of a 1XT magazine (8.0 pounds TNT). The structural analysis showed that the roof slab will safely support the dead weight of the soil berm but the blast loading will surely tear/shear the slab free from adjoining walls. Further, the force of an explosion may possibly breech the roof slab because of the low percentage and large spacing of reinforcing bars.

Definition of the response and behavior of the roof slab and soil berm following failure of the roof slab was considered critical to judging the safety of the 1XT magazines. But theory used to predict this stage of behavior was suspect; no experimental data were available to validate the theory. Consequently, an experiment was designed to validate the theory used to predict the dynamic response and behavior of the roof slab and soil berm of a box magazine. The experiment was designed by CEL and conducted by the WQEC Laboratory at WPNSTA Concord in the tidal area adjacent to buildings A-11 and A-19 on Fields Road.

Design of Experiment

The experiment involved detonating composition C-4 charges inside small-scale box magazines and recording the response and behavior of the roof slab and soil berm. Design details of the test magazine are shown in Figure 9.

The test magazine was not a true model of the 1XT magazine. A true model must scale mass and magazine dimensions since these parameters strongly influence response and behavior, especially after the roof slab fails. Since it was not possible to scale gravity, the technical approach was to vary the depth of soil cover, d_s, soil density, γ_s, and charge weight, W, in a small-scale magazine which produced approximately the same blast environment as in the 1XT magazine. If theory predicted results measured in these tests then it was reasonable to expect that the same theory would predict the response and behavior of the roof slab and soil berm in the 1XT magazine.

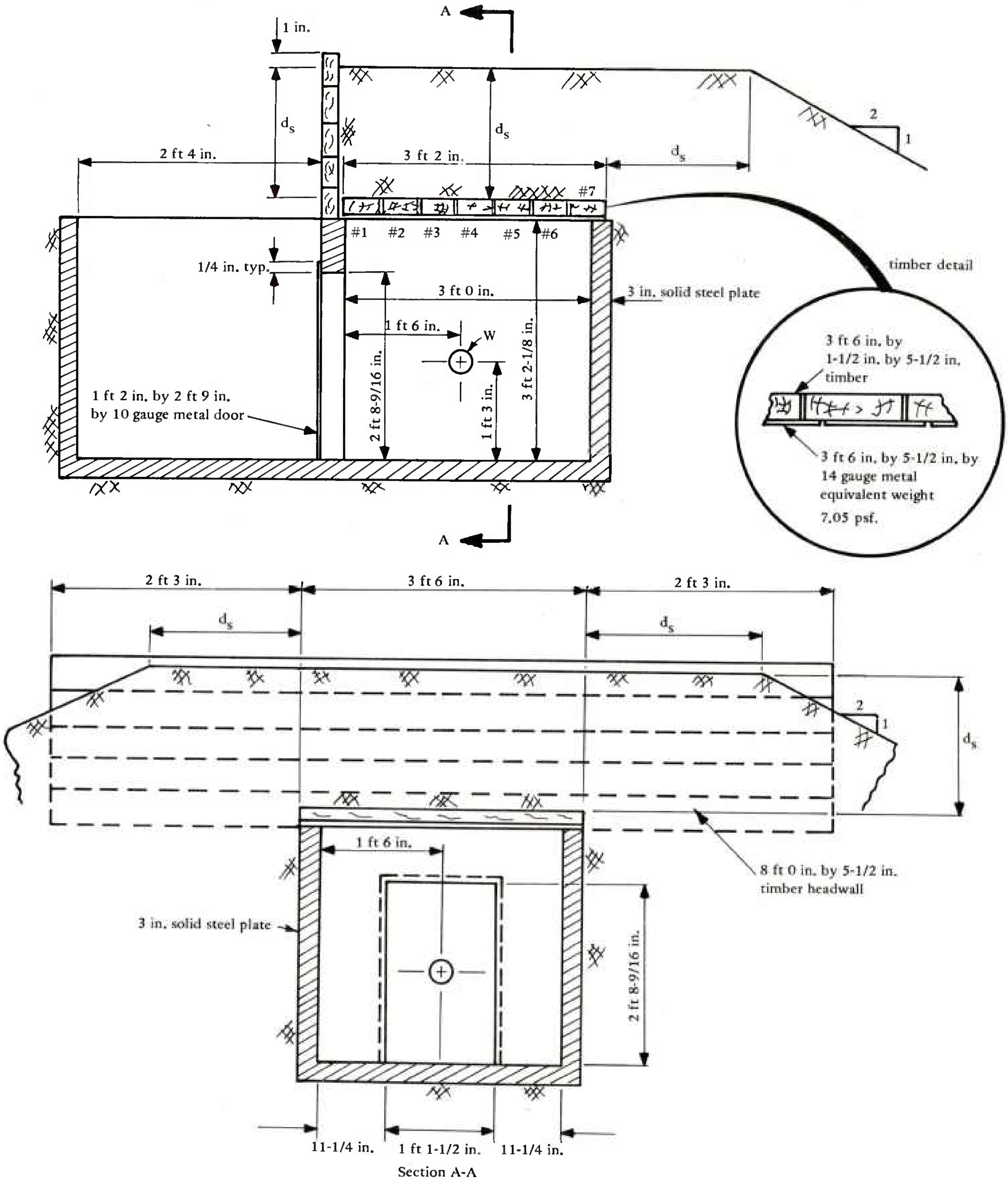


Figure 9. Design details of small-scale test magazine with timber/metal roof.

The test magazine was approximately a 0.40 geometric scale model of the 1XT magazine. This scale factor provided a design such that 0.51 pound TNT equivalent detonated in the small-scale magazine simulated the shock and gas pressure environment from 8.0 pounds TNT detonated in the 1XT magazine.

Test Chamber. The floor, walls, entryway, and barricade of the test magazine were constructed from 3-in.-thick steel plate, joined together with full penetration welds. Final construction of the chamber is shown in Figure 10. The chamber utilized an existing steel box which was not a perfect geometric scale model of the prototype chamber. However, the critical parameters, W/V and $A/W^{2/3}$, which control the scaled blast environment inside a magazine, were nearly identical in the small-scale and prototype magazines. In the prototype 1XT magazine, V = 448 cu ft and A = 20.01 sq ft which for W = 8.0 pounds TNT (operating storage capacity) corresponds to W/V = 0.0179 lb/cu ft and $A/W^{2/3}$ = 5.000 ft/$lb^{1/3}$. In the chamber of the test magazine, V = 28.57 cu ft and A = 3.07 sq ft which for W = 0.51 pound TNT corresponds to W/V = 0.0179 lb/cu ft and $A/W^{2/3}$ = 4.809 sq ft/$lb^{2/3}$. In other words, the charge densities of the prototype and test magazines were identical and the degree of venting was in error by 4% on the conservative side, for a test charge weight of 0.51 pound TNT equivalent. Thus, the test magazine was a $(0.51/8.0)^{1/3}$ = 0.40 scale model of the blast environment in the 1XT magazine.

The test chamber was buried in the ground at the test site as shown in Figure 11. The lip of the chamber was approximately 1 inch above ground level.

The configuration of the entryway in the test magazine (Figure 10) was different from that in the prototype (Figure 3). However, the difference was not considered to be significant because the vent area of the entryway was so much larger than the door opening in both the test and prototype magazines.

Figure 10. Steel test chamber for small scale test magazine.

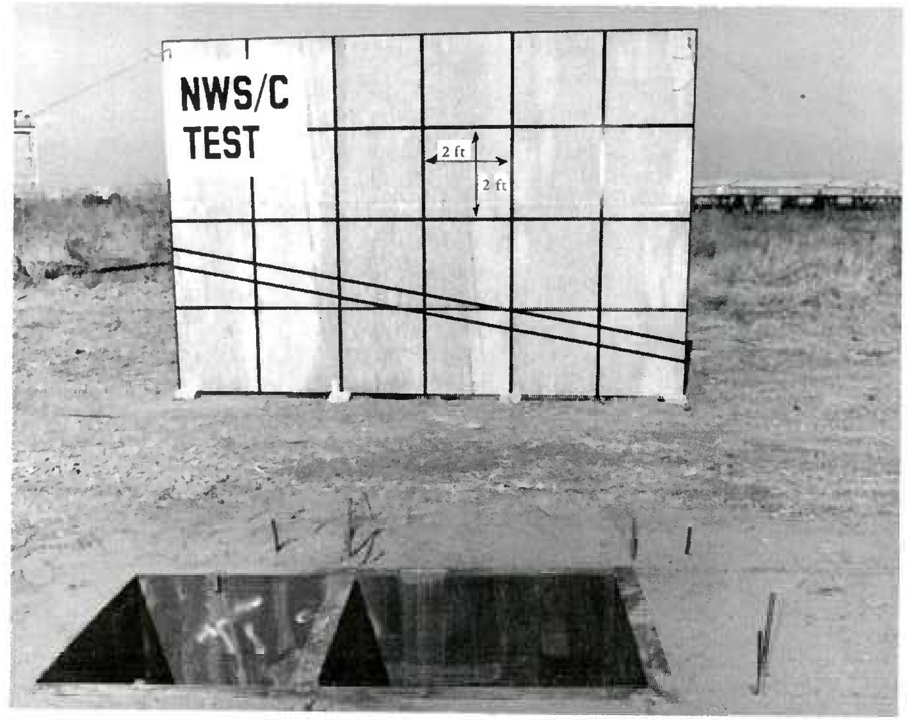


Figure 11. Test chamber buried flush with ground surface.

Door. The door on the 1XT magazine is a single leaf, hinged door constructed from 3/8-inch steel plate. The door on the test magazine was 10 gauge steel sheet (0.14 inch) which is slightly less than the thickness required to properly scale mass (i.e., 0.40 x 3/8 = 0.15 inch). The door was held in place at mid-height by two shear pins which simulated the shear strength of hinges on the 1XT magazine. The door was replaced after each test.

Test Charge. The test charge was Composition C-4 explosive shaped into a right cylinder with a length-diameter ratio equal to 1.0. The charge was held in position by Mastik fiberglass tape with the cylindrical axis oriented in a horizontal position. The charge was suspended from the timber roof by a wire hanger. The charge was positioned midway between the walls and 15 inches above the chamber floor. This position simulated a prototype charge resting on a table, 15/0.40 = 37.50 inches above the floor of the 1XT magazine; this is the severest storage condition for focusing direct and reflected shock waves toward the roof.

Headwall and Roof. The headwall and roof of the test magazine were constructed from 2- by 6-inch timbers (Douglas fir) as shown in Figure 9. The headwall timbers were bolted to four 3-inch steel angles which were fixed to the chamber walls.

The roof timbers were 42 inches in length. Strips of 14 gauge steel plate, 5-1/2 inches wide and 42 inches long, were nailed to the bottom face of the roof timbers. The steel strips overlapped adjoining timbers 3/4 inch to seal the roof from blast pressures and shield it from the products of combustion. Adjacent timbers (with metal strip attached) were not mechanically joined in any way; each timber was free to move upward independent of the others, except for the restraint provided by the overlapping metal strip.

The roof slab of the 1XT magazine is reinforced concrete, 0.58 feet thick (average). Based on a concrete density of 145 lb/cu ft, the dead mass of the roof in the test magazine should be 0.40(145 x 0.58) = 33.8 lb/sq ft. The dead mass of the timber/metal roof on the test magazine was 7.05 lb/sq ft which corresponds to an equivalent timber roof 2.64 inches thick based on a timber density of 32 lb/cu ft.

The timber roof rested on the top of the chamber walls as shown in Figures 12 and 13. The roof timbers were not fastened to the chamber walls. This detail closely simulated the design of the 1XT magazine roof slab which, according to a structural analysis, offered essentially no resistance to uplift forces. Further, this detail yielded a slightly conservative measure of the response and behavior for a bermed roof on an IXT magazine.

Soil Berm. The density of the soil cover on the 1XT magazines was measured to be 124 lb/cu ft. The soil is of very low clay content, relatively sandy, with rocks not exceeding 1 inch throughout. It was determined that standard road base aggregate, when wet, has approximately the same density; therefore, the roof timbers were covered with this road base aggregate in a berm-like fashion. The maximum size of aggregate was 1/4 to 3/8 inch. The maximum weight of an aggregate was approximately 10 grams.

The density of the soil, γ_s, was controlled by the addition of water from a fire hose. Samples were taken from the soil pile prior to placing on the test cell, and the density measured by the displacement technique. When the desired density was achieved, the soil was placed over the roof slab with a front end loader. The berm configuration shown by Figure 14 was achieved by lightly compacting and scraping the berm with the front end loader.

The berm was configured in such a manner that the soil depth, d_s, was extended for a distance d_s beyond the vertical extension of the chamber walls, except at the headwall. The area outside a projection of the roof slab onto the surface of the berm was spray painted white to improve photographic contrast. This scheme proved very effective in recording the failure mechanism of an earth bermed roof. Beyond a distance d_s from the chamber walls a slope of 1:2 was maintained to ground level. Figure 14 illustrates the configuration of the test magazine and the painted area of the berm prior to testing.

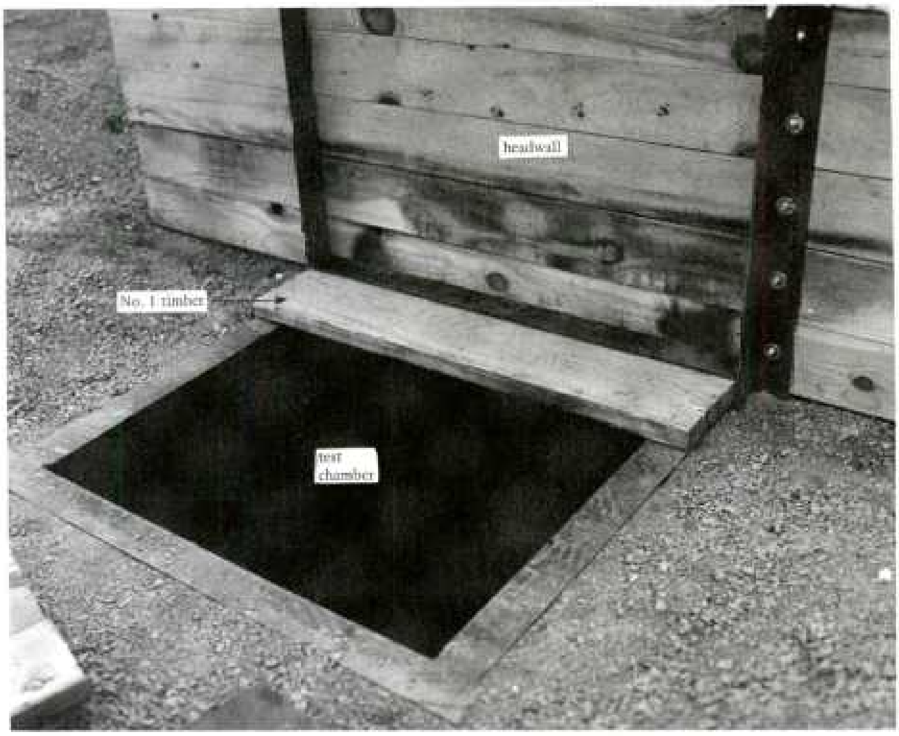


Figure 12. Test chamber with headwall and number one timber in-place.

Figure 13. Timber headwall and roof without soil berm.

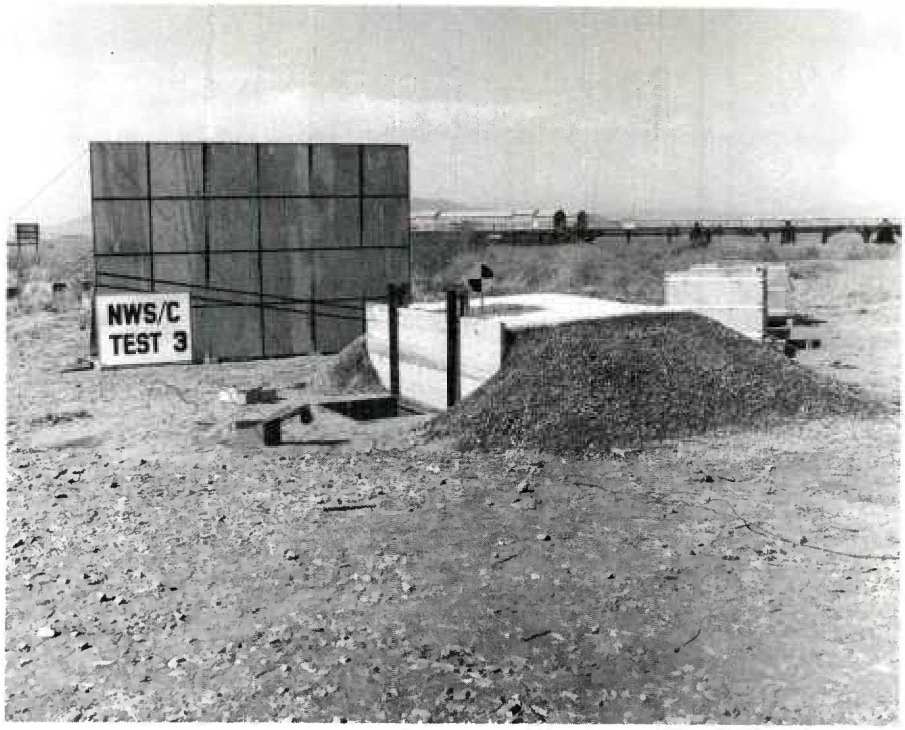


Figure 14. Test magazine with top of berm painted prior to test.

Instrumentation

Target/Backdrop. A target, 30 inches high, marked in 6-inch segments, was bolted directly to the midspan of the timber located over the center of the roof (timber no. 4 in Figure 9). The target plus stand weighed 9 pounds, which was approximately 10% of the total mass of the roof slab. Details of the target are shown in Figure 13.

A 12-ft-wide by 8-ft-high backdrop with a 2-foot grid was placed 15 feet behind and parallel to the centerline of the chamber. The backdrop served to eliminate all background interference and enhance the contrast to better define the behavior and response of the bermed roof. Figure 11 shows the backdrop in relation to the test chamber.

Camera. The behavior of the test magazine was recorded with a Fastex Model WF-15 high speed motion picture camera and a Nikon F with 85 to 210 mm zoom lens set at approximately 180 mm. For test 3 the cameras were at a distance of 45 feet from the center of the test chamber; for tests 4, 5, 6, and 8 the distance was 72 feet; for test number 7 the distance was 100 feet

Test Results

The test results are summarized in Table 1. The vertical growth of the soil cloud and upward displacement of the timber roof as a function of time are plotted in Appendix A. Photographs of the earth-bermed roof at various stages of dynamic response and behavior are shown in Appendix B. High speed camera coverage of each test is stored at the Civil Engineering Laboratory (Code L51), Port Hueneme, Calif. 93043 and at the Weapons Quality Engineering Center (Code 30), WPNSTA, Concord, Calif. 94520. A discussion of results and anomalies in each test follows.

Tests 1 and 2. Tests 1 and 2 (unreported in Table 1) were pilot tests in which a mass of soil was contained within a three foot square box, constructed from timber in accordance with WQEC drawing number 3307, Explosive Test Chamber Soil Containers. The platform of the box was constructed from 2 x 6-inch timbers, 42 inches in length and constrained laterally within an angle iron frame. The walls were constructed from 3/4-inch plywood held in place with banding straps. The walls of the box were not mechanically connected to the platform of the box; the walls served as a sleeve to contain a given depth of soil cover on the platform. The box platform was not fastened to the test chamber; the platform simulated a zero strength roof structure. The bottom face of the timber platform was protected against the products of combustion by 14 gauge mild steel strips which overlapped adjoining timbers 3/4 inch. Lead wool was placed around the lip of the test chamber before placing the soil box "roof berm" assembly in place to seal off the test chamber.

In test no. 1, the weight of road base aggregate (plus timber box) was 3,353 pounds or 373 lb/sq ft of roof area and the charge weight was 0.51 pound TNT equivalent of Composition C-4 explosive. The results of the explosion were totally unexpected. The entire roof structure and soil container assembly were lifted from the test chamber, and venting gas pressures expelled five timbers out from underneath the box. The box was elevated a total of 29-1/4 inches. Three of the 14 gauge steel skins were torn loose and one was thrown a distance of

43 feet. The platform timbers were thrown a maximum distance of 16 feet. The results clearly demonstrated that given failure of an earth-bermed roof with gas pressures still present inside the magazine chamber, the jetting of these pressures to the atmosphere can be destructive and a major cause of debris hazard. Based on this behavior, a second test was performed using a similar soil box "roof berm" design but a smaller charge weight.

In test no. 2, the weight of road base aggregate (plus timber box) was 3,353 pounds or 373 lb/sq ft of roof area and the test charge was 0.21 pound TNT equivalent. The test results were similar to test no. 1. The soil box lifted a total height of 7.3 inches. Number 1 timber was ejected and no. 2, 3, and 4 timbers were spread apart so that about half of the soil was spilled into the chamber.

Close examination of the high speed film showed that the soil appeared not to be rising but that the timber box was rising, similar to a sleeve, around the soil column. It was concluded that the failure mode associated with both tests 1 and 2 was due to shock waves which traveled up through the steel walls of the test chamber, through the roof planks, and into the walls of the timber box. Reflection of these compression waves, as tension waves, caused the walls of the box to rise faster than the soil mass within the box. This phenomenon is the well known billiard ball effect: i.e., the last element in a chain which is impacted is accelerated as a function of the energy contained in the initial impact. As the box walls lifted off their timber platform, soil spilled out and was blown helter-skelter by the jetting blast pressures. The relative displacement between the box walls and box platform also allowed the venting pressures to tear apart the timber platform and throw timbers into the air. A 14 gauge steel strip sailed 45 feet and another 14 feet from the test magazine. Two by six-inch timbers were found at distances of 16, 9, 5, and 0.5 feet from the test magazine.

The results of tests 1 and 2 served as a basis for refining the test setup to that described in the section entitled "Design of Experiment": the construction of a timber headwall and roof slab and covering of the roof timbers with road base aggregate in a bermlike fashion. This test setup applies to all the follow-on tests.

Table 1. Test Results[a]

NWSC Test No.	Test Parameters[b]									Measured Results						Remarks
	Charge Weight		Soil Berm		Roof Slab		Scaled Parameters			Soil Cloud		Roof Slab Response				
	C-4 (gm)	W	γ_s	d_s (in.)	γ_c	t_c (in.)	$A/W^{2/3}$	W/V	$d_s/W^{1/3}$	h_m (in.)	t_m	x_m (in.)	t_m	v_d	x_m/d_s	
3	169	0.51	124	27.2	32	2.64	4.81	0.0179	2.84	39.5	340	c	c	c	c	Headwall failed; door not in place
4	169	0.51	125	27.2	32	2.64	4.81	0.0179	2.84	33	350	12	220	d	0.44	#1 timber restrained
5	169	0.51	108	22.8	32	2.64	4.81	0.0179	2.38	51	430	20.5	320	d	0.90	Good test
6	398	1.20	108	30.0	32	2.64	2.72	0.0420	2.35	66	575	23.5	350	d	0.78	Good test
7	169	0.51	127	17.5	32	2.64	4.81	0.0179	1.83	65	550	22.5	340	5.4	1.29	Good test. Smoke vents at 590 msec
8	169	0.51	113	20.6	32	2.64	4.81	0.0179	2.15	77	560	24.0	320	4.8	1.17	Good test

[a]Unless otherwise noted, units are as indicated in List of Symbols.

[b]For all tests: $A = 3.07\ ft^2$, $V = 28.57\ ft^3$, $\ell_1 = \ell_2 = 3.00$ ft, $\ell_3 = 0.25$ ft.

[c]Target obscured - no record.

[d]$x_m < d_s$.

Test 3. W = 0.51 pound TNT equivalent, d_s = 27.2 inches, γ_s = 124 lb/cu ft, and $d_s/W^{1/3}$ = 2.84 ft/lb$^{1/3}$. The soil cover contained the blast environment; the cover was sufficient to prevent the blast pressures inside the test magazine from bleeding/jetting through the soil cover to the atmosphere. The maximum upward displacement of the roof slab could not be determined; the soil cloud obscured the target. There was some fluffing of the soil berm; a soil cloud formed in the area immediately above the chamber and approximately 12 inches beyond, indicating fluffing of a soil wedge of approximately 23 degrees beyond the vertical extension of the roof structure. This area was well within the horizontal surface (45 degrees) of the soil berm. The soil cloud reached a maximum height of 39.5 inches in 340 msec (Figure A-1) in the shape of a pyramid above the roof slab. The no. 1 roof timber (Figure 9) was rotated about 15 to 20 degrees. This rotation was about the line where the timber abuts the headwall. The rotation/lifting action fractured the bottom two headwall timbers, allowing the soil to spill into the test chamber and entryway. This failure is judged to be unique to the headwall design for the test magazine and not representative of the headwall behavior in a full-scale magazine. This failure mode was prevented in the follow-on tests by strengthening the headwall. No problems with the test setup or procedure were encountered in the remainder of the test series.

Test 4. W = 0.51 pound TNT equivalent, d_s = 27.2 inches, γ_s = 125 lb/cu ft, and $d_s/W^{1/3}$ = 2.84 ft/lb$^{1/3}$. The soil cover completely contained the blast environment inside the test magazine and forced it to vent through the door/entryway. The maximum roof deflection was 12 inches at 220 msec (Figure A-2), well below the 27.2 inches of soil cover. The maximum height of soil cloud was 33 inches at 350 msec. Figure B-2 shows the condition of the soil berm at approximately 210 msec which is near the time of maximum roof response (220 msec). The high speed camera clearly shows that there was a compression of the soil of approximately 2-3/4 inches in the first 14 msec before the soil began heaving upwards. This phenomenon is attributed to the shock-induced compression wave as it raced upward through the soil, and before the net stress at the berm surface was tension. Figure B-3 shows the condition of the berm after the test.

Test 5. W = 0.51 pound TNT equivalent, d_s = 22.8 inches, γ_s = 108 lb/cu ft, and $d_s/W^{1/3}$ = 2.38 ft/lb$^{1/3}$. The soil cover completely contained the blast environment inside the test magazine. The maximum roof deflection was 20.5 inches at 320 msec, well below the 22.8 inches of soil cover, as shown in Figure A-3. Figure B-5 shows the condition of the soil berm at approximately 9.1 inches (70 msec, according to Figure A-3) which is shortly after the explosion and long before the roof slab reached its maximum displacement. Note the "pregnant" form of the berm and the extent of the berm area beyond the vertical projection of the roof slab, which is disturbed by the explosion effects. In this photo, the contour of the berm is believed not to be the contour of the roof slab below it. The berm contour is the shape of outer layers of soil, which have been thrown into the air by the shock induced reflected tensile waves. At some depth below the berm surface (Figure B-5) there is probably a "pocket" of air separating the soil cloud from soil mass which never experienced net tension stress. Soil particles near the berm surface are at this stage in "free" flight with a velocity which results in the soil cloud pattern shown in Figure B-6 at approximately 310 msec.

The high speed photo coverage of test 5 again showed a compression of the soil berm very early in the response history. In the first 10 msec the soil compressed approximately 4 inches before it began to heave upwards.

Observations after this test revealed an unusual displacement of roof timbers. Figure B-7 shows that the soil fell into the test chamber at the front and back of the chamber, but not in the middle. The remainder of the soil was removed, revealing that the timbers evidently responded to the pressure profile: i.e., the center timber (no. 3) was lifted first, then the adjoining timbers (no. 2 and 4) lifted vertically and towards the center of the test chamber, etc. This phenomenon resulted in a stacking pattern of the timbers, shown in Figure B-8.

Test 6. W = 1.20 pounds TNT equivalent, d_s = 30.0 inches, γ_s = 108 lb/cu ft, and $d_s/W^{1/3}$ = 2.35 ft/lb$^{1/3}$. There was total containment. The maximum displacement of the roof slab was greater than 22 inches (at 280 msec, the soil cloud obscured the target). According to the measured deflection-time plot in Figure A-4, the maximum roof response was probably 23.5 inches at 350 msec, well below the 30 inches of soil cover. Note that the scaled depth of soil cover in tests 5 and 6 are nearly identical but W and d_s differ. Yet, the larger charge (test 6) produced less deflection relative to the soil depth, d_s, even though the scaled depth of soil was nearly identical in both test 5 and 6. This is consistent with theory, as discussed later. Figure B-10 shows the condition of the soil berm near the time of maximum roof response.

Figure B-11 shows the condition of the soil berm near the time of maximum height of the soil cloud. The soil cloud reached a height of 66 inches at 575 msec. Note the horizontal ejection of soil at the headwall and the nonsymmetry caused by the presence of the headwall. Even though there was a substantial soil cloud, none of the aggregate was ejected beyond the area covered by the berm. The surface of the soil berm compressed approximately 4 inches in the first 15 msec, before the soil began to heave upwards. The force of this explosion was great enough to break the welds holding the entryway wall opposite from the headwall. Note that the maximum heights of the soil cloud in tests 5 and 6 were nearly the same, even though the charge weight in test 6 was much larger. This suggests that the gas pressure pulse, in addition to the shock pressure pulse, plays an important role in forming the soil cloud, i.e., the maximum soil cloud height may be driven by W/V (which determines the peak gas pressure) in addition to $W^{1/3}$ (which scales peak shock pressure).

Test 7. W = 0.51 pound TNT equivalent, d_s = 17.5 inches, γ_s = 127 lb/cu ft, and $d_s/W^{1/3}$ = 1.83 ft/lb$^{1/3}$. The maximum roof deflection was 22.5 inches at 340 msec, greater than the original depth of soil cover. Later, at 575 msec the soil cloud reached its maximum height of 65 inches. Figure A-5 shows the deflection-time plot for the roof slab and soil cloud. This test demonstrated that air passages through the soil berm can occur when the maximum roof response exceeds the original depth of soil cover, i.e., $x_m/d_s > 1.0$. This conclusion is drawn from the following observation and logic. At 589 msec, a full 60 msec after the soil cloud had reached its maximum height, smoke was seen to bleed from the test chamber through the soil cloud, as shown in Figure B-15. Theoretical predictions of the gas pressure duration showed that it was impossible, by a wide margin, for this smoke to be associated with "gas" pressure. Specifically, theory indicated a gas pressure duration of 14.9 msec (Table 2) compared to 589 msec when the smoke first appeared on the film. Surely, theory could not be in error by a factor of 4,000%! It is hypothesized that the following phenomena occurred. Long before the roof reached its maximum deflection, the gas pressures had completely vented through the door opening but the roof continued to move upward under inertia forces. This created a negative pressure inside the test chamber which prevented the smoke in the magazine (from the products of the combustion) from bleeding through the door opening. But when the roof had begun to fall, a slight positive pressure built up inside the test magazine. This pressure forced the smoke through air passages in the soil berm. Since no smoke was seen in the earlier tests where $x_m/d_s < 1.0$, it is believed that for $x_m/d_s > 1.0$, blast/gas pressures, if still present in a magazine, will vent through the soil berm. If these pressures are of sufficient magnitude, they will "jet" through the soil berm and scatter additional soil helter-skelter into the air.

Even though the roof timbers were raised above the original height of the soil berm by 4-1/2 inches, and even though air paths to the atmosphere occurred, no soil was ejected beyond the area covered by the berm, much less beyond a 30-foot radius. Further, no parts of the timber roof slab were ejected through the soil berm.

<u>Test 8</u>. $W = 0.51$ pound TNT equivalent, $d_s = 20.6$ inches, $\gamma_s = 113$ lb/cu ft, and $d_s/W^{1/3} = 2.15$ ft/lb$^{1/3}$. The maximum response of the roof slab, 24.0 inches at 560 msec, exceeded the original depth of soil cover, as shown by the plot in Figure A-6. The soil cloud reached a height of 77 inches at 560 msec. Even though the roof was lifted 2-1/4 inches above the original depth of soil cover, no material

was ejected beyond the area covered by the berm as shown in Figure B-20. As in test 7, smoke was seen to bleed through the soil cloud after the roof began to fall, as shown in Figure B-19. The explanation for the smoke is that described for test 7.

THEORY VERSUS EXPERIMENT

The measured and predicted results for each test are compared in Table 2. The measured and predicted upward displacements of the timber roof slab as a function of time are plotted in Appendix A for comparison.

Roof Response

The entire history of the measured roof response is captured within the theoretical response curves derived from Equations 2, 4a, 4f, and 4 for α = 85 and 90 degrees, as shown in Appendix A. In three of the tests (tests 4, 5, and 8) the theory for α = 90 degrees provides the best correlation with the measured roof response. In the other two tests (tests 6 and 7), theory for α = 85 degrees provides the best correlation. This strongly suggests that Equations 2, 3, and 4a and all other equations derived therefrom (in the report) are reasonably accurate, at least within the range of parameters tested. There is no obvious difference in the test setup or test procedure to explain the difference in α between tests 4, 5, and 8, and tests 6 and 7. Note that the correlation is excellent even in tests 7 and 8 where the roof slab was driven upward well in excess of the original depth of soil cover (i.e., $x_m/d_s > 1.0$). Most important, the excellent correlation implies that theory in the report adequately describes the internal blast loading, and the acceleration, velocity, and displacement of an unrestrained roof slab at any instant of time. It is concluded that the theory will yield slightly conservative estimates of the roof response and launch velocity of roof debris by assuming α = 90 degrees, at least for the road base aggregate used for the test magazines.

Table 2. Theory Versus Experiment

Test No.	Test Parameters: W TNT (lbs)	Test Parameters: d_s (in.)	Test Parameters: γ_s (lb/ft^3)	Blast Load (Theory): $i/W^{1/3}$ ($\frac{\text{psi-msec}}{\text{lb}^{1/3}}$)	Blast Load (Theory): T (msec)	Blast Load (Theory): $T/W^{1/3}$ ($\frac{\text{msec}}{\text{lb}^{1/3}}$)	Effective Soil Mass Factor, k, Theory @ α= 90°	k 85°	k 80°	Soil Cloud Height h_m (in.) Exper	h_m Theory	Soil Cloud Velocity v_o (ft/sec) Exper[a]	v_o Theory	Roof Slab Velocity @ $X = d_s$, v_d (ft/sec) Exper	v_d Theory @ α = 90°	v_d 85°	v_d 80°	Maximum Displacement x_m (inch) Exper	x_m Theory @ α = 90°	x_m 85°	x_m 80°	Time to Maximum t_m (msec) Exper	t_m Theory @ α = 90°	t_m 85°	t_m 80°	Time Ratio t_m/T Theory @ α = 90°	t_m/T 85°	t_m/T 80°
3	0.51	27.2	124	771	14.9	18.6	1.30	1.41	1.54	39.5		14.6		b	b	b	b	c	11.5	9.7	8.2	c	244	224	206	16.4	15.0	13.8
4	0.51	27.2	125	771	14.9	18.6	1.30	1.41	1.54	33		13.3		b	b	b	b	12.0	11.3	9.5	8.1	220	242	222	204	16.2	14.9	13.7
5	0.51	22.8	108	771	14.9	18.6	1.31	1.40	1.51	51		16.5		b	b	b	b	20.5	21.2	18.4	16.0	320	331	308	287	22.2	20.7	19.3
6	1.20	30.0	108	870	14.6	15.5	1.30	1.42	1.56	66		18.8		b	b	b	b	23.5	27.9	23.2	19.2	350	380	346	315	24.5	22.3	20.3
7	0.51	17.5	127	771	14.9	18.6	1.31	1.38	1.46	65		18.7		5.4	6.7	5.5	4.2	22.5	25.8	23.2	20.8	340	365	346	328	24.5	23.2	22.0
8	0.51	20.6	113	771	14.9	18.6	1.31	1.40	1.49	77		20.3		4.8	4.1	1.0	b	24.0	23.6	20.8	18.3	320	349	329	308	23.4	22.0	20.7

[a] $v_o = \sqrt{2gh_m}$

[b] $x_m < d_s$

[c] Target obscured -- no record.

Soil Cloud

No theory is available to describe the formation of the soil cloud, but it is worth noting the predicted maximum initial velocity of soil particles driven into the air. If a mass rises to some maximum height, h_m, then its initial velocity, v_o, must be $\sqrt{2gh_m}$ if air drag is neglected. According to Table 2, the predicted value of v_o ranged from 13.3 ft/sec in test 4 to 20.3 ft/sec in test 8. Note that v_o appears to increase roughly with decreasing $d_s/W^{1/3}$. If the maximum mass of soil particles was 1.0 pound (the average maximum mass of aggregate in the soil berm of test magazines was only 0.022 pound), then the kinetic energy of the particle, if v_o = 20.3 ft/sec (test 8), would be $0.5\ m\ v_o^2 = 0.5(1.0/32.2)(20.3)^2 = 6.4$ ft-lb. This is much less than 58 ft-lb, the energy content of a critical fragment, according to NAVSEA OP-5. In other words, the maximum velocity of soil particles in the tests was far from being considered "critical." However, the energy in soil particles leaving the soil berm of a full-scale test magazine involving a large explosion would certainly be much greater. Theory describing the formation of the soil cloud needs to be developed.

DESIGN CRITERIA

The development of construction standards for ammunition magazines is empirical. The magazine is dimensioned to meet functional requirements such as the number and size of doors, bulk storage capacity, floor area, and ceiling height. The box structure is usually designed to safely support a prescribed live load plus the dead weight of 2 feet of soil cover. The design is then field tested to observe its behavior and safety performance. To avoid anamolies and uncertainty from scaling effects, the test structure is usually a full or large-scale model. If the observed behavior and safety performance are acceptable, the design is then issued as a definitive standard for ammunition storage. Any requests for deviations from this standard are suspect and discouraged because of the empirical nature of the design process and the uncertainty in effects of any deviations on safety.

A deterministic design procedure that accounts for all parameters eliminates many of the problems resulting from the empirical design process. A deterministic procedure offers design flexibility to incorporate changes in functional, survivability, physical security, and safety requirements into construction standards without sacrificing the level of explosives safety.

The following design criteria offer a basis for establishing a deterministic procedure for designing and site planning box-shaped ammunition storage magazines. Caution should be exercised in applying the criteria to very large charge weights; the criteria are based on limited test data derived from small-scale tests. Additional theoretical studies and test data from large-scale magazines are needed to validate the criteria. Specific research requirements are addressed in the section FUTURE RESEARCH. Further, the criteria are no panacea for all ammunition storage problems. It appears that the economic benefits derived from the criteria are probably inversely proportional to the ratio of the net explosives weight of storage to the total volume of the magazine. The criteria offer a technique for eliminating certain safety waivers and introducing flexibility and economy into the design process and construction standards for ready service magazines, special weapons magazines, and missile test cells. In certain cases, the criteria may offer a means of increasing the survivability of parked aircraft without degrading safety.

Full Containment

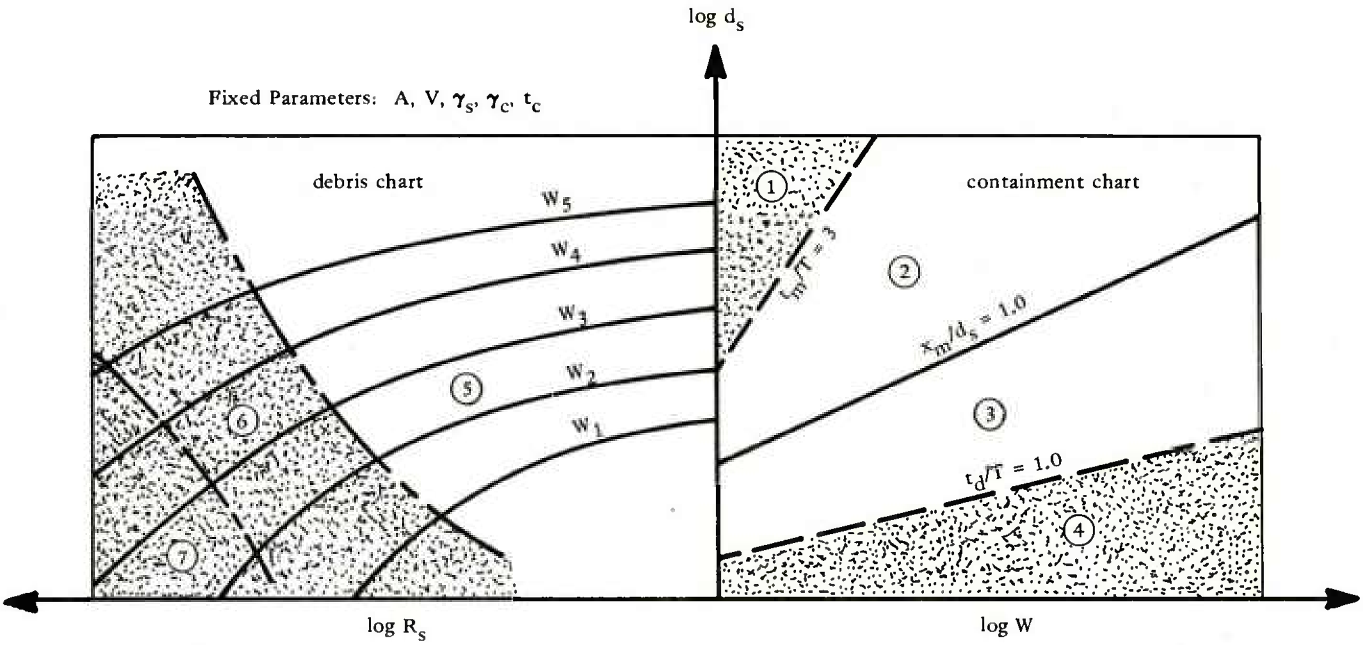
Full containment is defined as the condition where the earth-bermed roof provides an air-tight seal during the entire history of internal loading and berm response. Full containment prevents products of combustion (i.e., chemical gases, fire, and blast pressures) from bleeding through the soil berm and into the atmosphere; all products of combustion are forced to vent through the doors/headwall.

Full containment requires $x_m/d_s \leqq 1.0$. For design purposes let $x_m/d_s = 1.0$ and use Equation 7 to determine either the minimum depth of soil cover, d_s, maximum design charge weight, W, minimum magazine volume, V, or minimum vent area, A, required to achieve full containment. Use Equation 11 to determine k and assume $\alpha = 90$ degrees. Having satisfied the requirement that $x_m/d_s \leqq 1.0$, check the accuracy of the solution by computing t_m/T using Equation 6. If $t_m/T \geqq 3$ then the solution is a conservative but reasonable estimate. If $t_m/T < 3$, then the solution is overly conservative and the degree of conservatism increases with decreasing t_m/T. The ranges of parameters for full containment relative to other modes of behavior are illustrated in Figure 15.

Partial Containment

Partial containment is defined as the condition where the earth-bermed roof provides an air-tight seal during the entire history of internal loading but not during the entire history of berm response. Partial containment prevents blast pressures from bleeding or jetting through the soil berm; all blast pressures are forced to vent through the doors and headwall. Following escape of all blast pressures, the air-tight seal of the soil-bermed roof slab is broken, allowing products of combustion (i.e., chemical gases, fire, and concrete debris missiles) to escape through the bermed roof.

Partial containment requires $t_d/T \geqq 1.0$. For design purposes let $t_d/T = 1.0$ and use Equation 12 to determine either the minimum depth of soil cover, d_s, maximum design charge weight, W, minimum magazine volume, V, or minimum vent area, A, required to achieve partial containment. Use Equation 11 to determine k and assume $\alpha = 90$ degrees. There is no need to check the accuracy of the solution for partial containment. For the practical range of parameters, the requirements that $t_m/T > 3$ and $t_d/T \geqq 1$ are satisfied so the solution is a good estimate. The ranges of parameters for partial containment relative to other modes of behavior are illustrated in Figure 15.



PERFORMANCE	REGION	COMMENT
Full containment	1,2	Air tight roof seal during entire history of blast loading and roof response. No concrete debris missiles.
	1	Prediction overly conservative.
	2	Prediction good but conservative.
Partial Containment	3	Air tight roof seal during entire history of blast loading.
Debris Hazard	3,4	Debris hazard outside magazine.
	4	Launch velocity of concrete debris missiles overly conservative. Some blast pressures jet/bleed through soil cover.
	5	Debris prediction good but conservative.
	6,7	Debris prediction overly conservative.
Blast Hazard	5,6	Leakage blast pressures exceed 1.2 psi.
	7	Leakage blast pressures less than 1.2 psi.

Figure 15. Debris and containment charts.

Surface Motion

Surface motion refers to the vertical displacement of the ground surface or berm surface directly above a deeply buried ammunition storage chamber. In certain cases, operational considerations may require a design that limits the ground surface motions due to an explosion in the chamber. Given the stress-strain properties of the soil cover, it appears possible to derive a design criterion for x_m/d_s (the average compressive strain in a column of soil above the chamber) such that the energy produced by the explosion in the chamber is absorbed by the strain energy capacity of the lower layers of the soil mass with no perceptible motions at the ground surface. If d_s given by Equation 1 indeed prevents ground surface motions, then according to the containment graphs discussed in the section PROBLEM SOLUTIONS, x_m/d_s equal to about 0.05 to 0.10 will probably prevent ground surface motions.

Theory and test data are needed to establish design criterion for x_m/d_s that prevents ground surface motions. Given this criterion, Equation 7 could be used to determine either the minimum depth of soil cover, d_s, maximum design charge weight, W, minimum vent area, A, or minimum chamber volume, V, required to control ground surface motions for various types of soil. Further, the period of any ground surface motion, x_m, could be approximated to be 4 t_m where t_m is given by Equation 5.

Debris Hazard

Debris refers to concrete debris from the roof of the structural shell. The safe range from concrete debris is defined as the range beyond which no concrete debris missiles will strike the ground surface.

For design purposes, use Equations 9 and 10 to predict and control the debris hazard. Use Equation 9 to determine the maximum design charge weight, W, such that concrete debris missiles will not strike the ground surface beyond some prescribed range, R_s. Use

Equation 10 to determine either the safe range, R_s, beyond where no concrete debris missiles will strike the ground surface, or the minimum depth of soil cover, d_s, required to limit concrete debris missiles to some safe range, R_s. In both Equations 9 and 10, use Equation 11 to determine k and assume α = 90 degrees. Check the accuracy of the solution by computing t_d/T using Equation 6. If $t_d/T > 1$ then the solution is a conservative but reasonable estimate. If $t_d/T < 1$ then the solution is overly conservative and the degree of conservatism increases with decreasing t_d/T. Note that the debris range is zero if the magazine provides full containment ($x_m/d_s \leqq 1$). The relationship between parameters affecting the debris hazard is shown in Figure 15.

Blast Hazard

A box magazine covered with soil to a depth sufficient to provide either full or partial containment is equivalent to a hardened three-wall box with a hardened roof. For such designs, the graphs in Figures 38 and 39 of Reference 2 are applicable for predicting approximately the external blast environment at any distance to the front, sides, and rear of the magazine. The predicted blast environment is approximate because the graphs in Reference 2 do not consider effects from the magazine headwall. According to these graphs, either full or partial containment will dramatically reduce the close-in blast environment (e.g., at NAVSEA OP-5 intramagazine and intraline distances) to the sides and rear. The benefits at NAVSEA OP-5 inhabited building distance are insignificant. For large box magazines, the reduction to the rear and sides should significantly reduce the vulnerability of adjacent magazines and slightly reduce the "safe" distance to direct-support facilities (facilities allowed at NAVSEA OP-5 intraline distance, $R/W^{1/3}$ = 18 or approximately the 3.5-psi overpressure level).

The blast environment to the front will be greater than that from an ammunition magazine with say 2 feet of soil cover, but not by much according to Reference 2. If the increase is significant, this disadvantage might be overcome by orienting magazines in a herringbone pattern, as illustrated in the section PROBLEM SOLUTIONS.

For designs with $t_d/T \leqq 1$, the external blast environment is somewhere between the blast environment from an unconfined surface burst and the environment predicted from Figures 38 and 39 of Reference 2. The exact environment depends upon effects of time-dependent venting on the external blast environment. This effect of time-dependent venting should be addressed in future research.

Limitations

The design criteria are based on very limited test data derived from small-scale tests and a narrow range of design parameters. Additional test data from small-scale tests, large-scale validation tests, and theory for large W/V and W are needed before the design criteria are adopted for general application. In the interim, the following factors should be understood and considered before applying the design criteria.

1. Degree of Venting. According to Reference 2, the accuracy of Equations 2 and 3 depends on the degree of venting, $A/V^{2/3}$. The uncertainty in the internal blast environment predicted from Equations 2 and 3 increases with $A/V^{2/3}$. For $A/V^{2/3} < 0.2$, the gas pressure impulse overwhelms the total impulse (i.e., the shock impulse is a small part of the total impulse), and predictions should be reasonably accurate for any magazine geometry, such as a cube-, rectangular-, or arch-shaped magazine. But predictions from Equation 2 are questionable for $0.2 \leqq A/V^{2/3} < 0.6$, as illustrated in Figure 11 of Reference 2. For this range of $A/V^{2/3}$, the magazine geometry is an important factor, but predictions should be accurate for a cube-shaped magazine since both the shock and gas pressure impulses are theoretically proportional to $A/V^{2/3}$ for a perfect cube, as explained in Reference 2. For $0.2 < A/V^{2/3} < 0.6$, the design criteria should not be applied to magazine shapes that depart widely from a cube. Under no circumstances should the design criteria be applied to cases where $A/V^{2/3} > 0.60$, regardless of magazine shape, charge weight, etc. For this range of $A/V^{2/3}$, the errors in Equations 2 and 3 are probably very large, according to Figure 11 of Reference 2.

2. Headwall. The theory neglects effects of headwall breakup from the force of the explosion. Should the headwall fail, the area of the failed headwall provides an additional source of venting. However, neglecting breakup of the headwall is a conservative assumption in applying the design criteria to control the response and behavior of the roof and the safe range of concrete debris. Further, neglecting headwall response is often not a major source of error in the design criteria because most Navy ammunition magazines, especially those constructed in recent years, have very large doors that are a large percentage of the headwall area (i.e., the area of the doors is nearly equal to the area of the headwall). Alternatively, if the door area is a small part of the headwall area and the headwall indeed breaks up under the force of the explosion, the design criteria should be overly conservative.

3. Charge Weight. The roof slab will breech if the scaled distance from the charge to the roof is less than some critical value. For many magazines, this is the case and the shock impulse is a large portion of the total impulse. Under these conditions, the entire area of the roof slab may breech and the accuracy of the design criteria are unknown. For rectangular- and arch-shaped magazines with a large aspect ratio, the charge tends to be some shape other than a right cylinder having a length equal to the diameter. Effects of charge shape are unknown. Further, large charges will produce craters; the effects of craters on the accuracy of the design criteria are unknown.

4. Soil Properties. The theory correlates well with results obtained using road base aggregate for the berm. The effects of other soil types (e.g., soil with high clay content) are unknown. However, it is reasonable to speculate that if one assumes α = 90 degrees, the design criteria should at least be conservative, regardless of the soil type.

5. Footing Design. Imagine a box-shaped magazine with the roof slab securely tied to its walls but with a weak structural connection to the footings and floor slab. It is conceivable that in this case the effects of an internal explosion could lift the roof slab and walls upward

as an integral unit. Should this mode of behavior indeed occur, the added mass of the walls will tend to reduce the upward motion of the magazine, but the walls will tend to delay venting until some time after the roof slab reaches the original depth of soil. The likelihood of occurrence and effects of this failure mode are unknown.

6. Arch Magazines. Even though Equations 2 and 3 are applicable for arch magazines having $A/V^{2/3} < 0.2$, the failure mode of an arch probably precludes application of the design criteria in their present form to arch magazines. The bending stiffness of an arch is so low that the arch will probably tend to fold inward as it rises under the force of an explosion. If this arch behavior indeed occurs, it is likely that the entire mass of soil above the arch will not be mobilized to suppress upward motions. Alternatively, if the arch splits open near the crown line, the interaction of the soil cover and arch is different from that assumed in the theory and the design criteria are not applicable. Test data from small-scale arch magazines are needed to develop similar design criteria for the soil cover required over arch magazines.

PROBLEM SOLUTIONS

The following explosives safety problems and their solutions address the safe siting and design of box-shaped ammunition storage magazines. The problems demonstrate application of the theory and design criteria presented in this report. The first problem, concerning an operational safety waiver on 1XT magazines at WPNSTA Concord, is real. The solution given is the proposed solution for eliminating the safety waiver. All other problems are purely hypothetical. Further, the specified operational and performance requirements are not necessarily typical but were chosen to demonstrate several facets of the theory.

1XT Magazine

Six fuze and primer magazines are located at the WQEC complex, WPNSTA Concord. The site plan is shown in Figure 1. Design details for the 1XT magazines are shown in Figure 2. The magazines store a total net explosive weight, W, equal to 8.0 pounds maximum of Class 1, Divisions 1 and 2, Category (04) material. The critical parameters for the 1XT magazines are listed in Figure 16. According to a structural analysis of the 1XT magazines, the concrete roof slab offers essentially no resistance against uplift forces produced by an explosion inside the magazine. The minimum separation distance from an 1XT magazine to an inhabited building is 80 feet, as shown in Figure 1.

Problem Definition. The 1XT magazines violate NAVSEA OP5 safety standards which require a 400-foot minimum separation distance from any 1XT magazine to the inhabited buildings. This separation distance is intended to mitigate the debris hazard to the inhabited buildings.

During an AMHAZ Review Board visit to WPNSTA Concord, the waivers currently in effect for the 1XT magazines were discussed in depth. The AMHAZ Review Board suggested that the requirement for waivers could be removed if, given an inadvertent explosion involving 8 pounds TNT, it could be clearly demonstrated that explosion effects would be completely contained within the magazine or explosion effects would present no debris hazard to the inhabited buildings located 80 feet away.

Apply the theory in the report to answer the following aspects of the problem and determine the safety of the 1XT magazines.

(a) Will the soil-bermed roof of an existing 1XT magazine completely contain W = 8 pounds TNT?

(b) What is the maximum possible strike range of any concrete debris missile from the roof slab of the existing 1XT magazine?

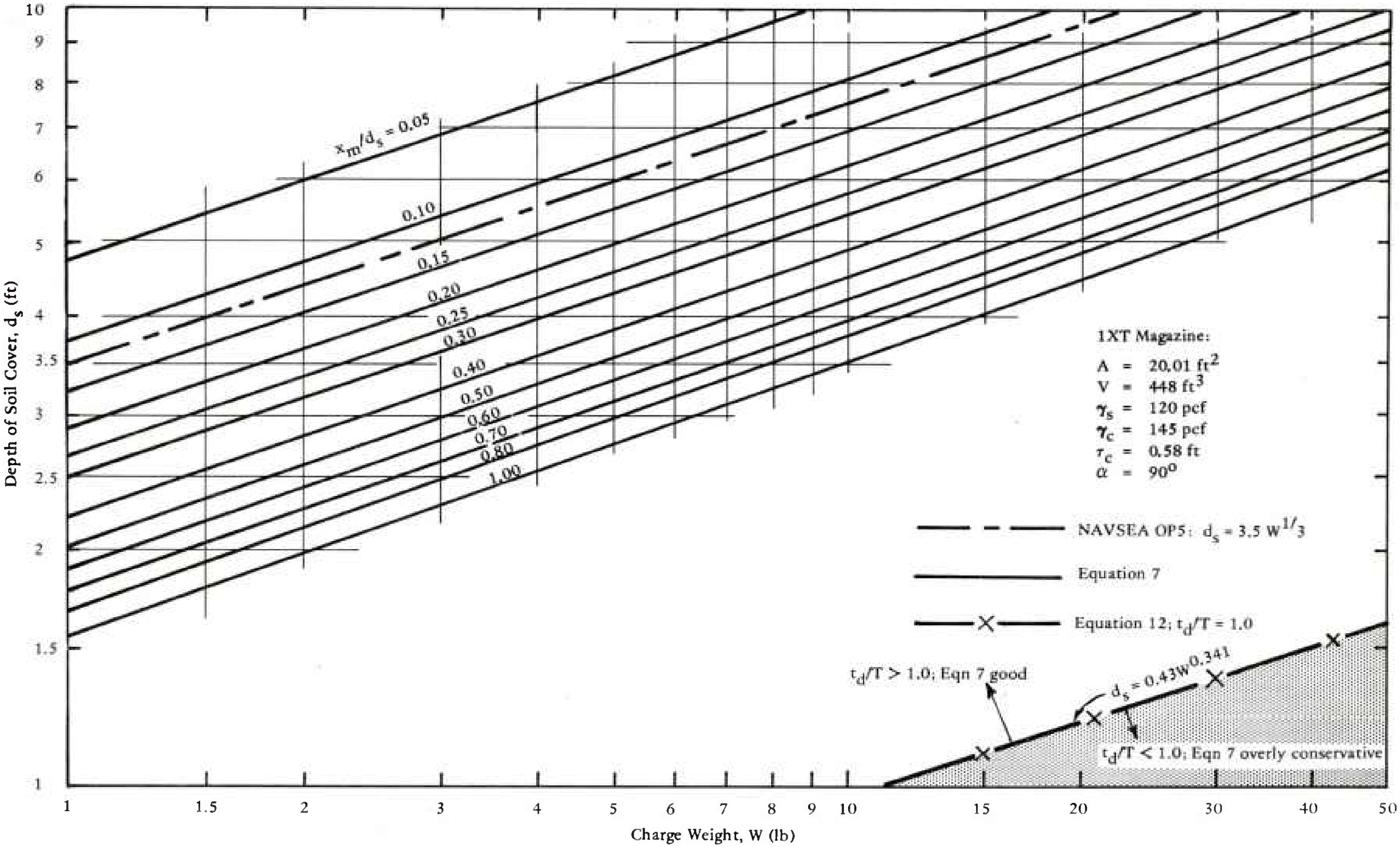


Figure 16. Containment of IXT magazine, WPNSTA Concord.

(c) What soil cover depth is required to completely contain an explosion involving 8.0 pounds TNT?

(d) What is the maximum safe storage capacity of an existing 1XT magazine?

(e) What soil cover depth is required to prevent the roof slab from rising more than 6 inches?

(f) Neglecting blast hazard, what is the safe storage capacity to control the debris hazard if the soil cover over the roof is increased from the present 2 feet to 3 feet?

(g) For W = 8.0 and 100 pounds TNT and a soil cover depth equal to 2 feet, will blast pressures bleed or jet through the soil cover? Or will all blast pressures instead escape through the door opening?

(h) For W = 50 pounds TNT, what is the critical depth of soil cover where any additional soil cover will not change the blast environment outside a 1XT magazine?

(i) Based on the above analysis, recommend a solution to the safety waiver problem.

Problem Solution. The values of critical parameters for the 1XT magazine are given in Figure 16. For these values, Equations 1, 7, and 12 (for $t_d/T = 1.0$) are plotted in Figure 16 where x_m/d_s is shown for any combination of W and d_s. Equations 7 and 12 (for $t_d/T = 1.0$) are plotted in Figure 17 where W is shown for any combination of d_s and R_s. The following solutions are derived from these figures.

(a) Entering Figure 16 with $d_s = 2$ feet and W = 8 pounds for the 1XT magazines, find $x_m/d_s > 1.0$. Since full containment, as defined in this report, requires $x_m/d_s < 1.0$, the 1XT magazines will not fully contain the explosion. By extrapolation, $x_m/d_s = 3.56$ (or alternatively, from Equation 11, k = 1.350 and from Equation 7, $x_m/d_s = 3.56$). Therefore, $x_m = 3.56 \times 2.0 = 7.12$ feet. Thus, the 1XT magazine soil berm will not contain the explosion and the roof slab will rise 7.12 feet.

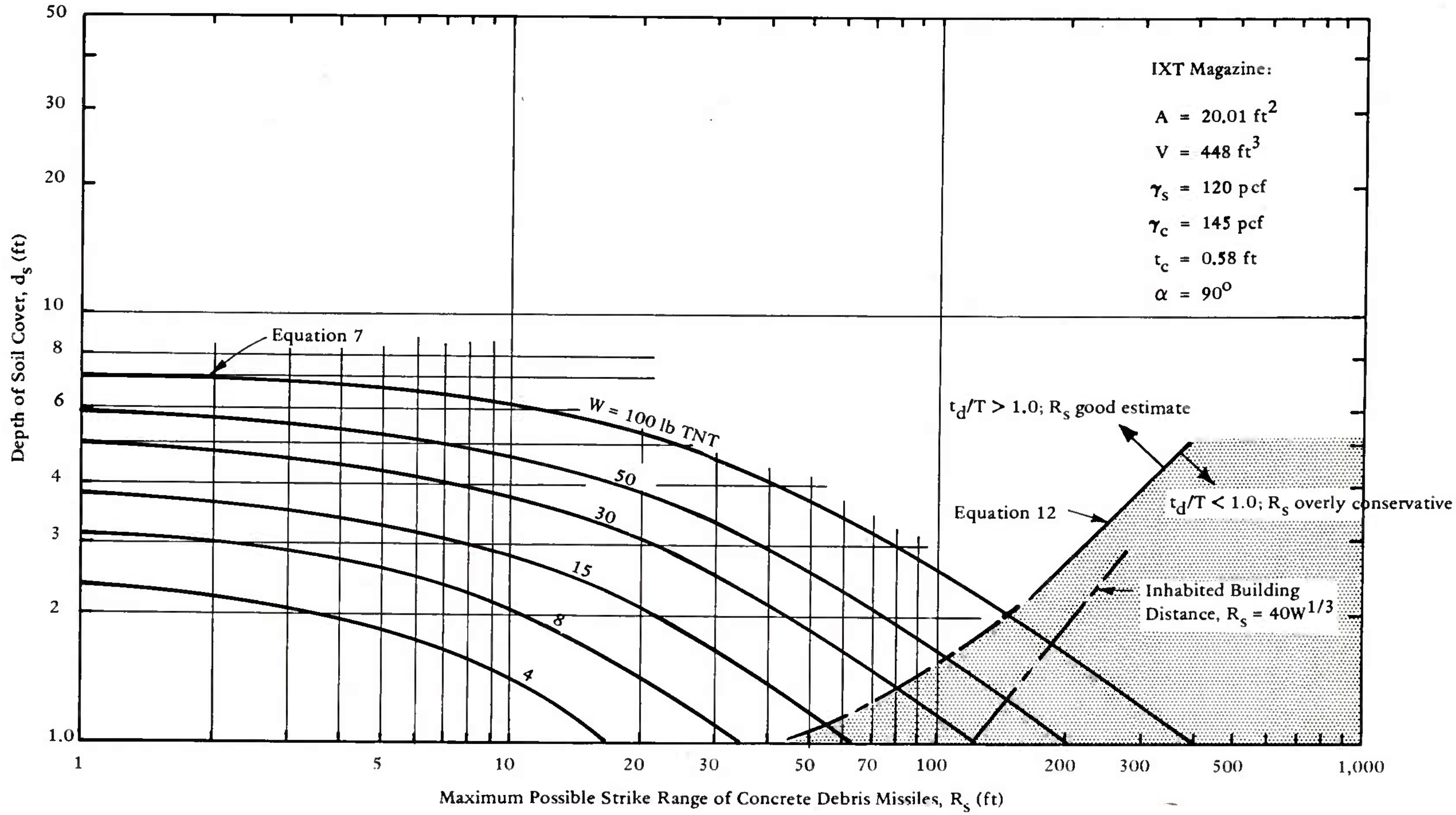


Figure 17. Debris hazard from breeching the roof slab of IXT magazine, WPNSTA Concord.

(b) Entering Figure 17 with d_s = 2.0 feet and W = 8 pounds for the 1XT magazine, find R_s = 10 feet. Thus, the maximum possible strike range of concrete debris missiles is 10 feet.

(c) Full containment is defined as the condition where x_m/d_s < 1.0. Entering Figure 16 with x_m/d_s = 1.0 and W = 8.0 pounds, find d_s = 3.2 feet. Thus, 3.2 feet of soil cover over the 1XT magazine is required to fully contain the explosion effects of 8 pounds TNT.

(d) The minimum distance from a 1XT magazine to an inhabited building is 80 feet. Thus, R_s = 80 feet. Entering Figure 17 with d_s = 2 feet and R_s = 80 feet, find W = 52.3 pounds TNT. Thus, the maximum safe storage capacity of a 1XT magazine is 52.3 pounds in order to limit concrete debris missiles to a range less than 80 feet. But to limit the blast pressures at the nearest inhabited building, current NAVSEA safety standards require $R_s \geqq 40\ W^{1/3}$, inhabited building distance, or $W \leqq (R_s/40)^3 = (80/40)^3 = 8$ pounds TNT. Thus, blast pressures, not debris, limit the safe storage capacity of a 1XT magazine to 8 pounds TNT.

(e) The solution requires trial and error. Enter Figure 16, with W = 8 pounds and say d_s = 7 feet, x_m/d_s = 0.12 or x_m = 0.12 x 7 = 0.81 foot which exceeds 6 inches. Repeating the process with W = 8 pounds and say d_s = 9 feet, x_m/d_s = 0.06 or x_m = 0.06 x 9 = 0.54 foot which is close to 6 inches. Thus, the soil cover over a 1XT magazine must be 9.1 feet in order to limit upward motion of the roof slab to 6 inches.

(f) Entering Figure 17 with d_s = 3.0 feet and R_s = 80 feet, find W = 100 pounds. Thus, neglecting blast hazard (which we found in problem (d) happens to control the safe charge weight) adding an additional foot of soil on top of the existing 2 feet of soil cover over the 1XT magazines increases the safe charge weight for debris hazard from 52 pounds to 100 pounds TNT.

(g) Entering Figure 17 with W = 8.0 pounds and d_s = 2.0 feet, find the "point" lies in the unshaded area of the graph, i.e., $t_d/T > 1.0$. Thus, for W = 8.0 pounds TNT, the roof slab rises to the original depth of soil cover at a time (t_d) greater than the duration of gas pressures inside the magazine, i.e., all blast and gas pressures will have escaped through the 1XT magazine door opening before they could bleed or jet through the soil berm.

Entering Figure 17 with W = 100 pounds TNT and d_s = 2 feet, find the "point" lies precisely on the line corresponding to $t_d/T = 1.0$. Thus, for W = 100 pounds TNT, the blast and gas pressures will have vented through the door opening at the instant when the roof slab has risen a sufficient distance ($x_m/d_s = 1.0$) to destroy the roof seal and allow pressures to begin jetting or bleeding through the soil berm; all blast and gas pressures will escape through the door opening.

(h) Entering Figure 16 with W = 50 pounds, $t_d/T = 1.0$ at $d_s = 0.43\ W^{0.341} = 0.43(50)^{0.341} = 1.63$ feet. Thus, adding soil to the roof slab will reduce the external blast environment (because $t_d/T < 1.0$) until d_s = 1.63 feet. For any $d_s > 1.63$ feet, blast and gas pressure will have escaped through the door opening before the roof slab has risen a sufficient distance ($x = d_s$) to allow them to vent through the soil berm; the blast environment outside the magazine will be identical for all $d_s > 1.63$ feet.

(i) According to the theory presented in this report, the safe charge weight for a 1XT magazine is 8 pounds TNT and is limited by blast pressure requirements. At 8 pounds TNT, the maximum possible strike range of concrete debris missiles from the roof slab is 10 feet, much less than the range (80 feet) to the nearest inhabited building. The safety waivers on the 1XT magazine should be lifted and MCON Project P-252 (estimated cost $492,000) should be canceled, subject to interpretation of the hazard presented by the soil cloud which has not been addressed in this report.

Large Box Magazine

WPNSTA Atlantis Master Plan includes MCON Project P-51 which provides for construction of 40 large box-shaped ammunition magazines to store special weapons. Design details of the magazines are shown in Figure 18. The design charge weight, W, for each magazine is 8,000 pounds TNT equivalent. Critical design parameters are listed in Figure 18. Faced with encroachment from the private community and a shrinking supply of buildable land area at WPNSTA Atlantis, the master planners must minimize the total land area encumbered by the storage depot.

Survivability, environmental control, and physical security are important factors in the design of the depot. The Special Projects Office requires a minimum soil cover of 8 feet over each magazine to defeat an assigned weapon threat. The base commander desires to have the minimum soil cover necessary to prevent nuclear material from being blown upward through the bermed roof into the atmosphere, should an HE explosion occur inside a magazine. The security office concurs; additional soil cover will increase the denial time of forced intrusion into a magazine. The safety office requests that the final construction standards for the depot be submitted for safety review, accompanied by documentation which clearly demonstrates that any deviations from established standards (e.g., a soil cover depth greater or less than 2 feet) will not degrade the level of explosives safety.

The master planners wish to examine the benefits of satisfying these requirements by arranging the magazines in a herringbone pattern, as illustrated in Figure 19. The design approach will be to provide at least 8 feet of soil cover but not less than the depth required to direct or vent all shock and gas pressures and debris through the headwall. This approach will reduce the blast and debris hazards to the sides and rear of any donor magazine but amplify and focus blast and debris effects to the front of the donor magazine. The herringbone pattern will suppress this effect by preventing the headwall and doors of any acceptor magazine from "seeing" the full face-on reflected pressures from any donor magazine.

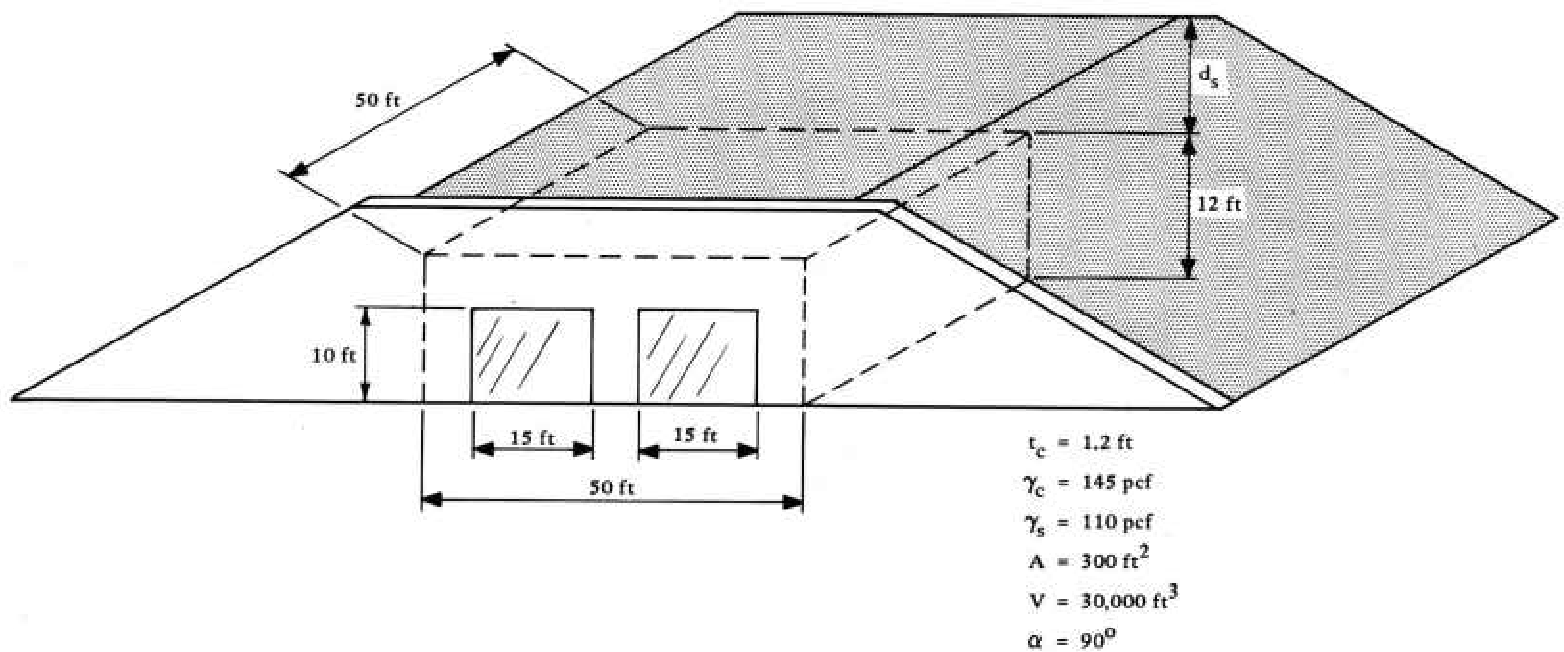


Figure 18. Details of large box-shaped ammo magazine.

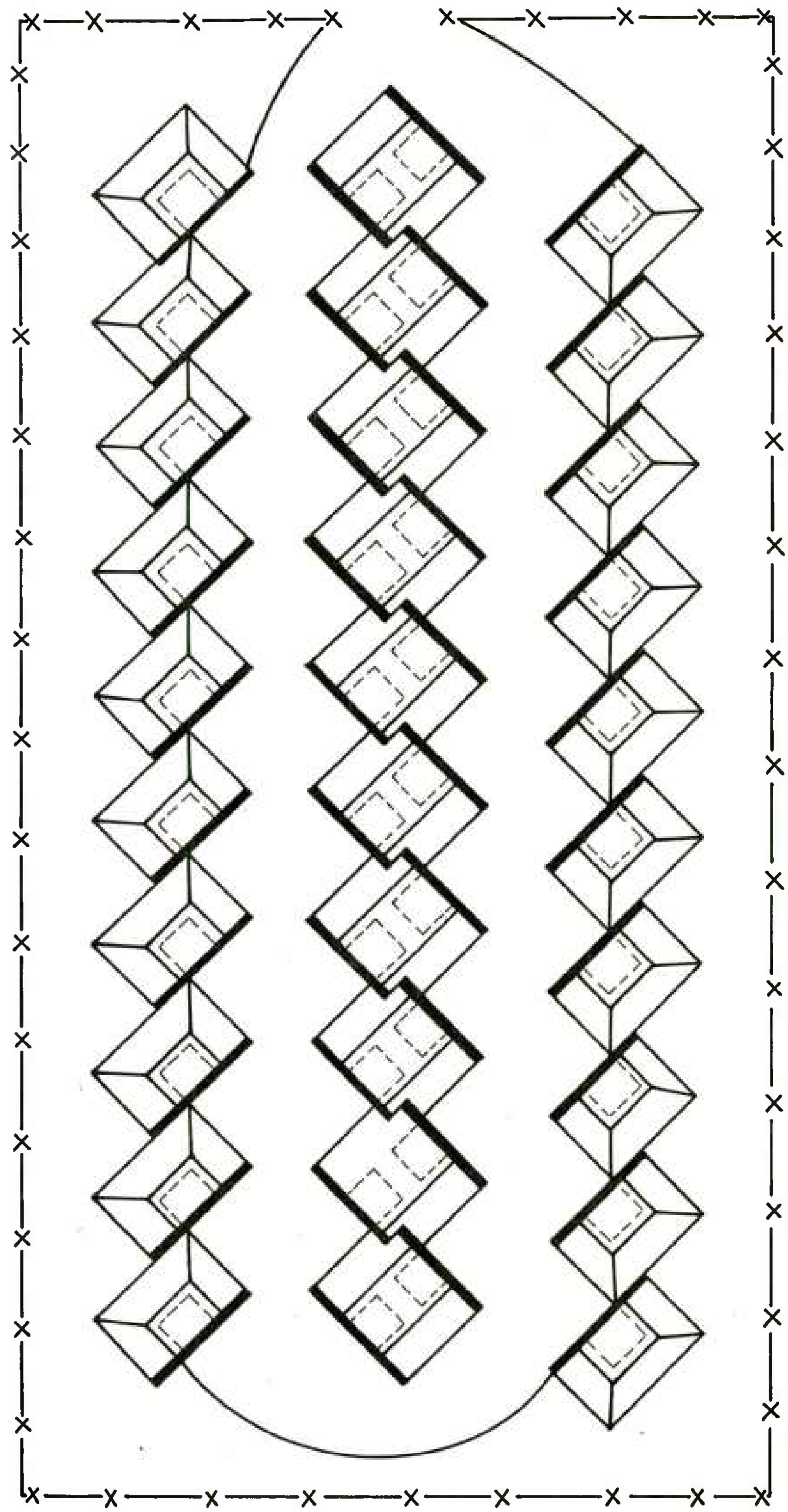


Figure 19. Herringbone-pattern for magazine depot, WPNSTA Atlantis.

Problem Definition. Apply the theory in the report to answer the following aspects of the proposed design concept for the ammunition depot.

(a) What soil cover depth is required to completely contain an inadvertent explosion involving 8,000 pounds TNT equivalent? How high will the roof slab rise?

(b) What soil cover depth is required to provide an air-tight seal and prevent shock and gas pressures from jetting or bleeding through the soil cover and instead force the pressure to escape through the headwall? How high will the roof slab rise?

(c) What is the maximum possible strike range of concrete debris missiles for the depth of soil cover found in (a) and (b)?

(d) What is the maximum possible strike range of concrete debris missiles for 8 feet of soil cover? Is the strike range a good estimate?

(e) What minimum depth of soil cover is required so that the blast hazard instead of the debris hazard controls the safe distance from the ammunition depot to an unrelated inhabited area outside the depot?

(f) List the minimum depth of soil cover required to satisfy each performance requirement.

(g) What construction details should be incorporated into the design of the roof slab in order to achieve the most desirable failure mode?

(h) How does the total encumbered land area of the depot for $d_s \geqq 4.5$ feet compare with the land area for a traditional depot layout (parallel magazine rows and columns) and safety criteria ($R_s = 1{,}250$ feet for $W \leqq 30{,}000$ pounds TNT)?

Problem Solution. Design parameters for the large box magazine are given in Figure 18. For these values, Equations 1, 6 (for $t_m/T = 3$), 7, and 12 (for $t_d/T = 1$) are plotted in Figure 20 where

x_m/d_s is shown for any combination of W and d_s. Equations 7 and 12 (for $t_d/T = 1$) are plotted in Figure 21 where W is shown for any combination of d_s and R_s. The solutions to the problem are derived from these figures.

(a) Full containment, an air tight berm seal at all times, is defined as the condition where $x_m/d_s \leqq 1.0$. Entering Figure 20 with $x_m/d_s = 1.0$ and W = 8,000 pounds (or alternatively, solving Equation 7 for d_s by trial and error), find $d_s = 23.8$ feet. And $x_m = 1.0$ $d_s = 1.0 \times 23.8 = 23.8$ feet. Thus, 23.8 feet of soil cover over the magazine is required to fully contain the explosion effects of 8,000 pounds TNT. The roof slab will rise 23.8 feet.

(b) To maintain an air tight roof seal until all shock and gas pressures have escaped through the door openings requires $t_d/T \geqq 1$. Entering Figure 20 with W = 8,000 and $t_d/T = 1$, find $d_s = 10.04$ feet. Alternatively, find in Figure 20 that $t_d/T = 1$ corresponds to $d_s = 0.636W^{0.307} = 0.636(8{,}000)^{0.307} = 10.04$ feet. Alternatively, from Equation 11, k = 1.1576, and from Equation 12 for $t_d/T = 1$, find by trial and error $d_s = 10.04$ feet. Thus, 10 feet of soil cover will provide an air tight roof seal until all shock and gas pressures have escaped through the door openings.

Entering Figure 20 with W = 8,000 and $d_s = 10.0$, find by interpolation $x_m/d_s = 11.25$ or $x_m = 11.25 \times 10.04 = 113$ feet. Alternatively, solving Equation 7 with $d_s = 10.04$, find $x_m = 113$ feet. Thus, with 10 feet of soil cover, an explosion involving 8,000 pounds TNT will drive concrete debris missiles 113 feet vertically into the air.

(c) Entering Figure 21 with W = 8,000 and $d_s = 23.8$, find $R_s = 0$ feet. Alternatively, from Equation 11 find k = 1.066, and from Equation 10 find $R_s = 0$ feet. Thus, 23.8 feet of soil cover will prevent any concrete debris missiles from escaping through the soil berm.

Entering Figure 21 with W = 8,000 and $d_s = 10$, find $R_s = 205$ feet. Alternatively, from Equation 11 find k = 1.1576, and from Equation 10 find $R_s = 205$ feet. Thus, 10 feet of soil cover will force all shock and gas pressures through the door openings and limit concrete debris missiles to strike ranges less than 205 feet.

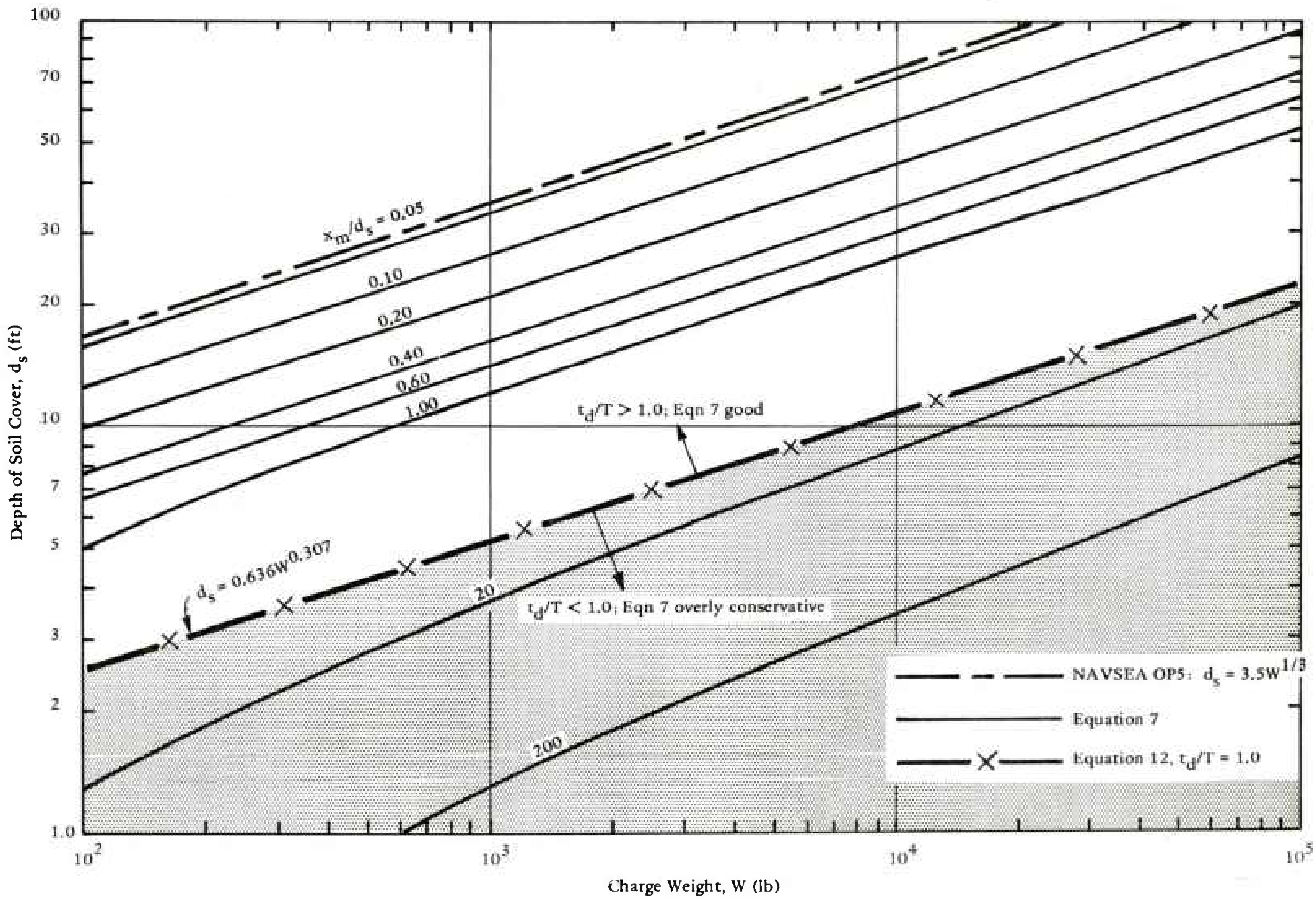


Figure 20. Containment of large box-shaped ammo magazine.

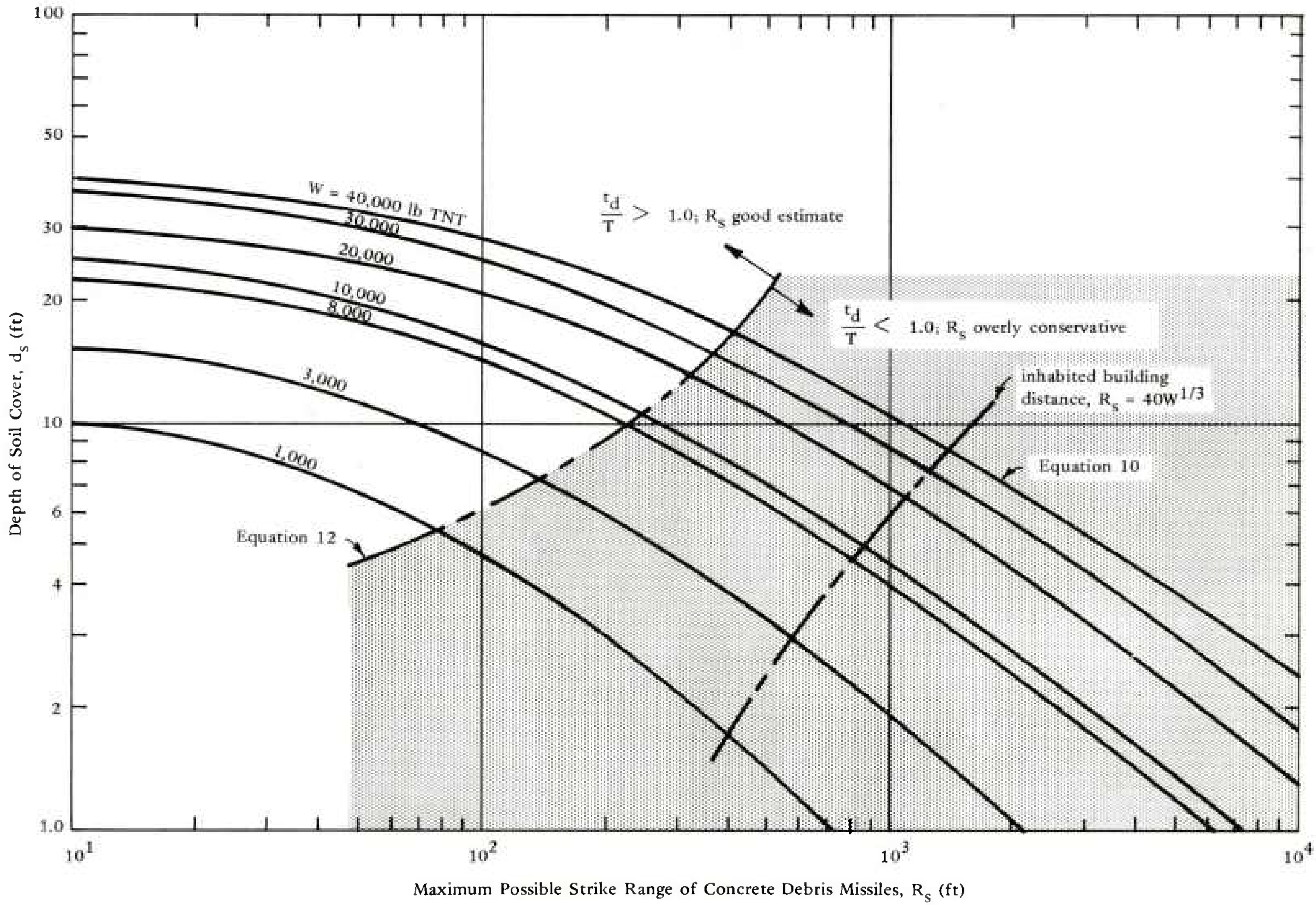


Figure 21. Debris hazard from breeching the roof slab of large box-shaped ammo magazine.

(d) Entering Figure 21 with W = 8,000 and d_s = 8, find R_s = 316. Alternatively, from Equation 11 find k = 1.1977, and from Equation 10 find R_s = 316 feet. Thus, with 8 feet of soil cover, the maximum possible strike range of concrete debris missiles is 316 feet.

In Figure 21, the point corresponding to W = 8,000 and d_s = 8 feet lies barely in the shaded area. Thus, the predicted maximum possible strike range (316 feet) is conservative but not by a wide margin.

(e) To mitigate the risk to people and property from blast pressures, NAVSEA OP5 requires a minimum separation distance from explosives stores to unrelated inhabited areas equivalent to $R_s = 40W^{1/3} = 40(8{,}000)^{1/3}$ = 800 feet from the nearest large box magazine. Entering Figure 21 with W = 8,000 and R_s = 800, find d_s = 4.55. Alternatively, solving Equation 10 with R_s = 800 find by trial and error d_s = 4.55 feet. Thus, the "safe" separation distances from the rear and sides of a large box magazine to unrelated inhabited areas are identical for blast and debris if the soil cover is 4.55 feet. In other words, adding more than 4.55 feet of soil cover will not reduce the encumbered land area outside the perimeter of the ammunition storage depot.

(f) The following table summarizes the impact of constraints imposed by the decision makers on the design of the depot.

Attribute	Depth of Soil Cover (ft)	Safe Range (ft)	
		Debris	Blast
Explosives Safety	2.0	1,250	800
Encumbered Land (Min)	4.55	800	800
Survivability	8.0	316	800
Environmental Control	10.0	205	800
Full Containment	23.8	0	800
Physical Security	More the better	-	800

(g) Provide no compression steel near supports of the roof slab. Provide no bent-up rebars. Use small rebars, closely spaced, vice large rebars, widely spaced, in all areas of the roof slab. Provide no shear steel at slab supports; adjust the slab thickness so that the concrete resists the maximum applied shear stresses at supports from dead plus live loads. Provide a minimum separation distance between ordnance stores and the roof slab to reduce the chance of locally breeching the roof slab. The above factors need to be test validated but should improve the chance of achieving the most desirable failure mode, that illustrated in Figure 4a.

(h) Increasing the soil cover from 2 feet to $d_s \geqq 4.5$ feet reduces the band "width" of encumbered land outside the footprint of the magazine depot from 1,250 to 800 feet or 36%. The reduction is limited by safety requirements for blast pressures. Note that a depth of soil cover sufficient to force all blast pressures out the front of a magazine ($d_s \geqq 10.0$ feet) will not reduce significantly the blast pressures at inhabited building distance ($40W^{1/3}$) to the rear or sides of a donor magazine, although the reductions on acceptor magazines "closer-in" to the rear and sides of the donor are dramatic.

Deep Underground Magazine

The master planners wish to consider the economy of an alternative concept to satisfy operational, safety, and security requirements of MCON Project P-51, WPNSTA Atlantis, described in the previous problem. The design concept is to store the special weapons in a deep underground facility consisting of eight storage chambers. Each chamber will store a net explosives weight, W, equal to (40 aboveground magazines x 8,000 pounds TNT ÷ 8 storage chambers) 40,000 pounds TNT per chamber. Design details of the underground facility are shown in Figure 22. The volume of each chamber and area of the access tunnel to each chamber are identical to the large box magazine design shown in Figure 18.

Problem Definition. Apply the theory in the report to answer the following aspects of the proposed design concept for the ammunition depot.

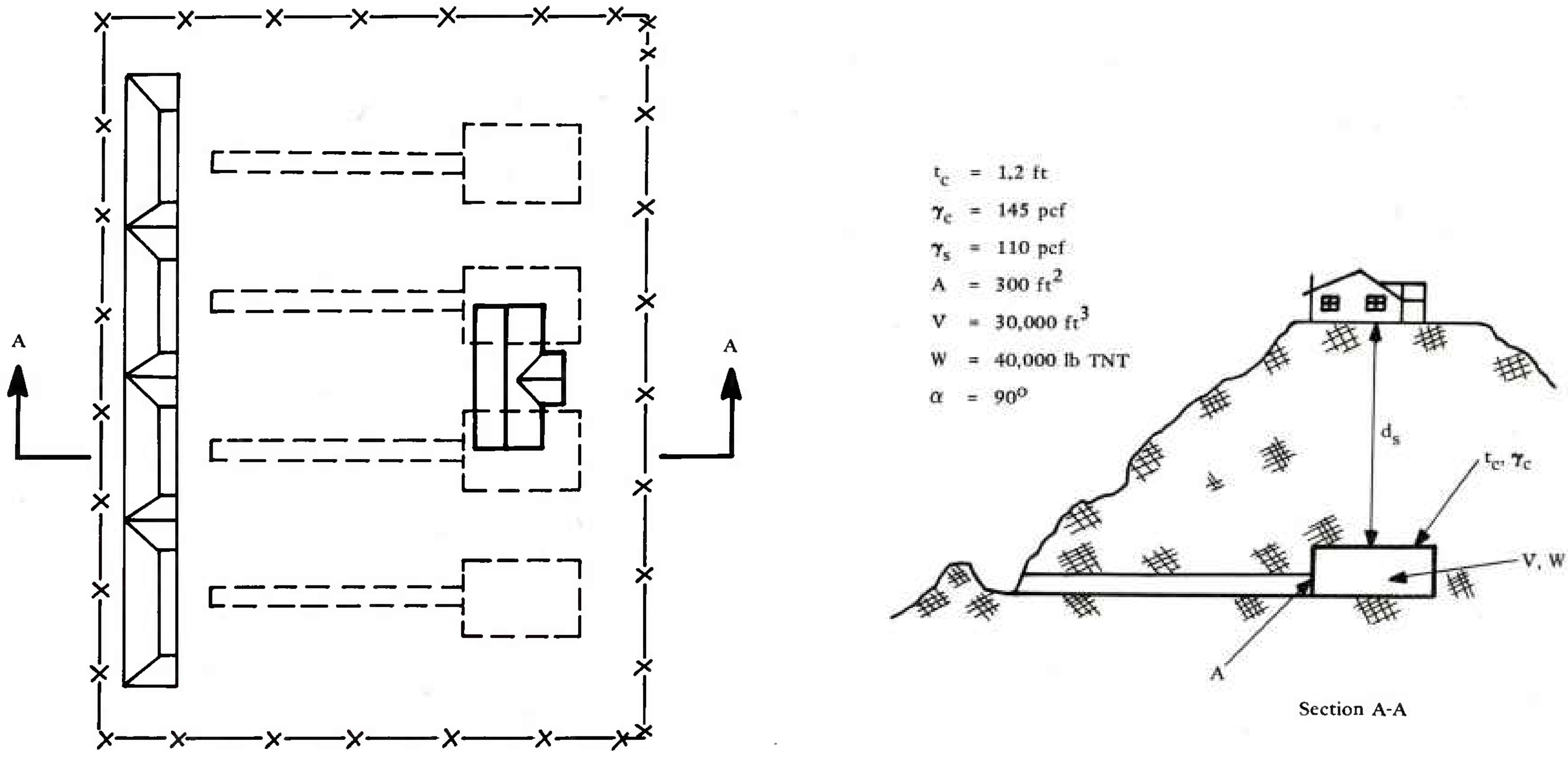


Figure 22. Deep underground storage depot, WPNSTA Atlantis.

(a) What depth of burial, d_s, will prevent ground surface motions from damaging the guard house (Figure 22) if the strain capacity of the soil in compression is 10%?

(b) Estimate the period (sec) of ground surface motions in (a) should they indeed occur.

(c) What are the advantages and disadvantages of constructing the caverns in a rock formation instead of soil?

Problem Solution. Design parameters for the deep underground caverns are given in Figure 22. The geometric parameters are identical to the large box magazine (Figure 18), so Figure 20 is the containment chart for the caverns. The solutions to the problem are derived from this figure.

(a) If the compressive strain in the soil immediately above the cavern is 10% and must be 0% at the ground surface, then the average strain is 5% if the soil strain decreases linearly with distance from the cavern roof. In other words, assume that if the design provides $x_m/d_s = 0.05$ at the cavern roof, then the energy of the explosion will be absorbed by strain energy in soil layers below the ground surface (i.e., the ground surface motions will be negligible if $x_m/d_s \leqq 0.05$).

Entering Figure 20 with W = 40,000 and $x_m/d_s = 0.05$, find d_s = 111 feet. Alternatively, from Equations 7 and 11 for the design parameters given in Figure 22,

$$d_s = \frac{1.697 \times 10^{10}}{(174 + 110\ d_s)^2}$$

Solving by trial and error, find d_s = 111 feet. Thus, the cavern must be located 111 feet below the ground surface to prevent ground surface motions. The validity of the assumptions made in arriving at this solution is unknown. Further, the solution neglects effects of the compression shock wave generated by the explosion; the solution assumes that the compression wave is dissipated by the soil cover before it reaches the ground surface. It is interesting to note that according to Equation 1 the required depth of burial is $d_s = 3.5\ W^{1/3} = 3.5(40,000)^{1/3} = 120$ feet vice 111 feet based on Equation 7.

(b) From Equation 11 for $d_s = 111$ feet, find $k = 1.01$, and from Equation 5, the time to maximum roof response is

$$t_m = \frac{81,936(40,000)^{1/3}}{(110 \times 1.01 \times 111)} \left[\frac{300}{(40,000)^{2/3}}\right]^{-0.78} \left(\frac{40,000}{30,000}\right)^{-0.38}$$

$$= 589 \text{ msec}$$

Therefore, the period is approximately $4t_m = 4 \times 589/1,000 = 2.4$ seconds. Thus, the ground surface motions, should they occur, will have a period of about 2.4 seconds. Again, this solution neglects the compression shock wave, and the validity of assumptions is unknown.

(c) The tensile strength of rock will reduce α and, in effect, mobilize a larger mass which will in turn reduce the required d_s. However, the cost of tunneling into rock may not offset the benefit of a reduced d_s; the cavern located in soil is probably a more cost-effective solution that provides equivalent performance and safety.

Missile Test Cell

WPNSTA Atlantis Master Plan includes MCON Project P-18 which provides for construction of missile test cells to support check-out of the CANOPUS Missile. The cells are adjacent to the weapons assembly area in Building 42. The net explosive weight (NEW) of the warhead plus 25% of the booster propellant is 300 pounds TNT equivalent. In accordance with NAVFAC P-397, the design charge weight, W, is 1.2 (300) = 360 pounds TNT (Ref 5).

The design concept for the missile test cells is shown in Figure 23. Operational requirements call for a minimum ceiling height of 12 feet to accommodate a minimum hook height of 10 feet for an overhead crane and a floor area 15 feet wide and 30 feet long to accommodate the missile test stand plus test support equipment. The cells are sited remote from the support building (50 feet) to mitigate risks to people and property from blast effects. The plan is to mitigate the debris hazard by placing soil in a berm-like fashion over the roof of the test cell. The cell will be a conventional reinforced concrete design sufficient only to support the dead weight of the soil cover and a design live load, i.e., the concrete box structure is not blast hardened, except for the backwall. The backwall is designed to support the cell door from the explosion effects of W = 360 pounds TNT in the test cell. The pathway from each test cell to the weapons assembly area is covered with a frangible metal structure for weather protection.

Problem Definition. Apply the theory in the report to answer the following aspects of the design concerning the soil cover.

(a) What depth of soil cover, d_s, over the test cell will completely contain W = 360 pounds TNT?

(b) What depth of soil cover, d_s, over the test cell will force all blast pressures to vent through the frangible wall and not to jet or bleed through the soil berm?

(c) What depth of soil cover, d_s, over the test cell will prevent any concrete debris missiles from reaching the inhabited operating building located 50 feet away ($R_s \geqq 50$ feet)? Is the computed value of d_s a good estimate or instead overly conservative?

(d) Will the depth of soil cover found in (c) prevent blast pressures from jetting or bleeding through the soil berm and in the process push soil and/or concrete debris missiles helter-skelter into the air at velocities possibly exceeding those assumed in the theory? What is the blast pressure inside the test cell when this process begins?

(e) What is the peak incident blast pressure at Building 42 from an explosion involving W = 360 pounds TNT in the test cell for the value of d_s found in (a), (b), and (c)?

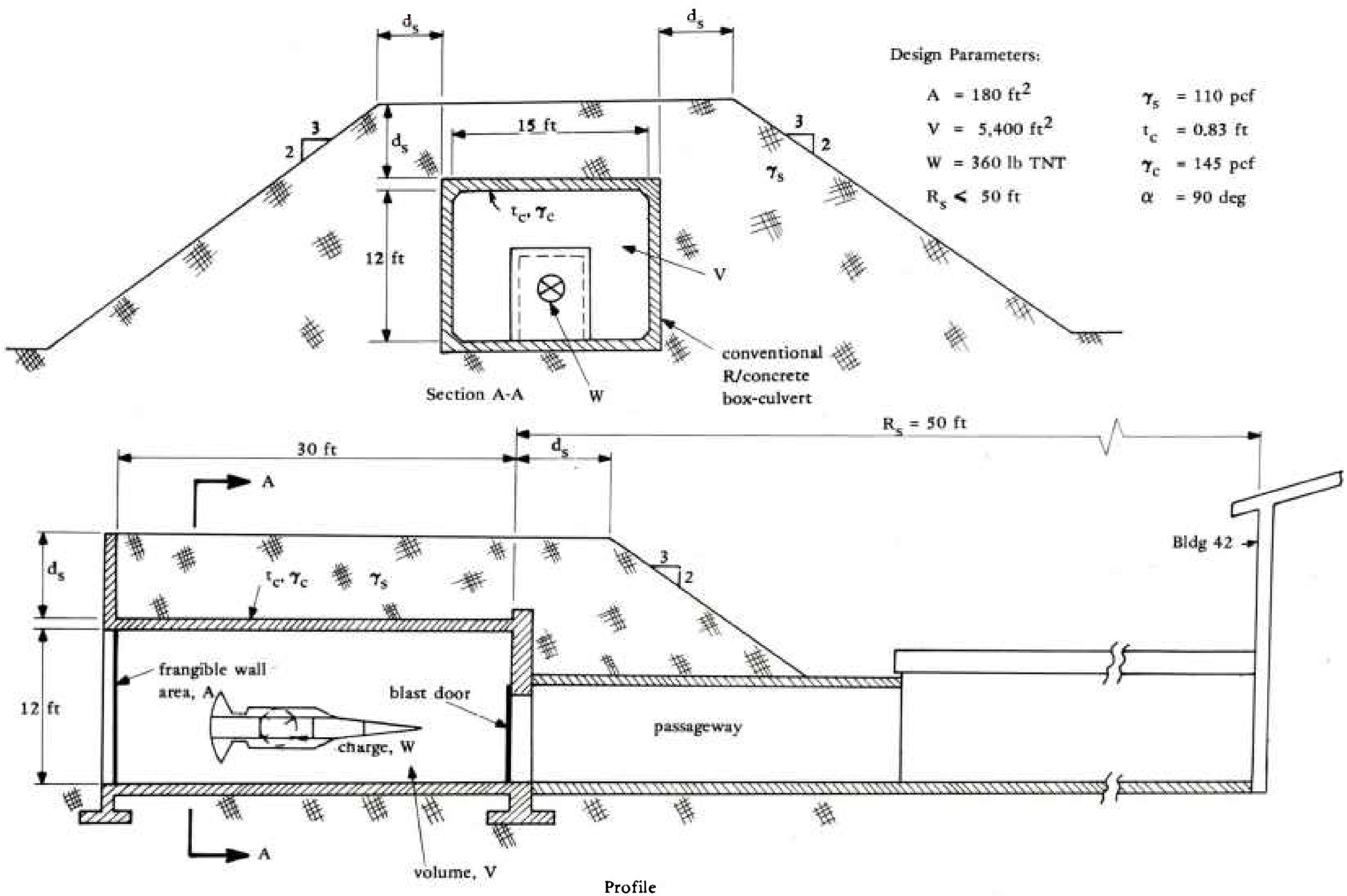


Figure 23. Design concept of test cell for CANOPUS Missile, WPNSTA Atlantis.

(f) What is the launch velocity of soil particles pushed up into the soil cloud by the shock pressures? What is the maximum size of the soil cloud? Could these soil particles possibly reach Building 42 if launched at the angle resulting in the maximum possible strike range? If yes, what will be their energy content (ft-lb) when they strike the building if the maximum size aggregate is 3/4 inch?

(g) What depth of soil cover is recommended? What is the maximum possible range of concrete debris missiles?

(h) What are the possible benefits of this design concept compared to the traditional blast resistant design using laced reinforced concrete?

Problem Solution. The values of critical design parameters for the CANOPUS Missile test cell are given in Figure 23. The solutions to this design problem will be derived from the equations in the report.

(a) Failure criteria for full containment, i.e., air tight soil berm, requires $x_m/d_s \leqq 1.0$. For the design parameters given in Figure 23, $A/W^{2/3} = 180/(360)^{2/3} = 3.5569\ ft^2/lb^{2/3}$ and $W/V = 360/5{,}400 = 0.0667\ lb/ft^3$. From Equation 7,

$$\frac{d_s^3 \gamma_s^2 k^2 (x_m/d_s)}{W^{2/3}} = 108087(3.5569)^{-1.56}(0.0667)^{-0.76} = 1.1689 \times 10^5$$

Substituting known values and rearranging terms,

$$d_s = \frac{1.1689 \times 10^5 (360)^{2/3}}{(145 \times 0.83 + 110 d_s)^2} = \frac{5.9153 \times 10^6}{(120 + 110 d_s)^2}$$

By trial and error, find $d_s = 7.22$ feet. Thus, 7.2 feet of soil cover is required over the missile test cell for the cover to fully contain the explosion effects from 360 pounds TNT.

(b) To prevent jetting or bleeding of blast pressures through the soil berm requires $t_d/T \geqq 1.0$. From Equation 12 for $t_d/T = 1.0$,

$$1.0 = \gamma - \sqrt{\gamma^2 - 2(0.3)\,\gamma - \frac{12161 \times d_s}{(360)^{2/3}} (3.5569)^{1.72}(0.0667)^{1.72}}$$

and

$$\gamma = \frac{36255(3.559)^{0.08}(0.0667)^{0.48}}{(110d_s + 145 \times 0.83)} = \frac{1.094 \times 10^4}{110d_s + 120}$$

Therefore,

$$1.0 = \frac{1.094 \times 10^4}{110d_s + 120} - \sqrt{\left(\frac{1.094 \times 10^4}{110d_s + 120}\right)^2 - \frac{0.6564}{110d_s + 120} - 20.235d_s}$$

By trial and error, find $d_s = 2.1$ feet. Thus, a soil cover depth equal to 2.1 feet or greater will force <u>all</u> blast pressures to escape through the frangible wall and not to jet or bleed through the soil berm.

(c) From Equation 10 for $R_s = 50$ feet,

$$R_s = 50 = \left\{ \frac{216000\ (360)^{0.9466}}{k^2 d_s^2 \gamma_s^2 \left[\frac{180}{(5400)^{0.487}}\right]^{1.56}} \right\} - 2d_s$$

$$50 = \frac{11.7923 \times 10^6}{(120 + 110d_s)^2} - 2d_s$$

By trial and error, find $d_s = 3.05$ feet. Thus, 3.05 feet of soil cover over the missile test cell is required to prevent concrete debris missiles from possibly reaching the inhabited building located 50 feet away.

In (b) above we found $d_s \geqq 2.1$ feet is required for $t_d/T \geqq 1.0$. Since $d_s = 3.05$ feet > 2.1 feet, the value $d_s = 2.1$ feet is a good estimate (but conservative for reasons listed in Debris Hazard) of the soil cover required to limit the maximum possible strike range of debris missiles to less than 50 feet.

(d) Since $d_s = 3.05$ feet exceeds $d_s = 2.1$ feet which corresponds to $t_d/T = 1.0$, no shock or gas pressures will jet or bleed through the soil berm; all blast pressures will escape through the frangible wall.

(e) Found the soil cover in (a), (b), and (c) above is a depth such that $t_d/T \geqq 1.0$. Therefore, in each case the missile test cell is equivalent to a three-wall cell with a hardened roof and Figure 38 of Reference 2 applies. The scaled distance from the frangible wall to Building 42 is $(50 + 30)/(360)^{1/3} = 11.25$ ft/lb$^{1/3}$. Entering Figure 38 of Reference 2 with this scaled distance, find the peak incident blast pressure at Building 42 is 7 psi. But entering Figure 39 of Reference 2 with W/V = 360/5,400 = 0.07 lb/ft^3, find the maximum possible peak incident pressure at any scaled range behind the cell is 6.5 psi. Thus, the peak incident blast pressure at Building 42 is 6.5 psi for (a), (b), and (c).

(f) Theory is not available at this time to answer the questions posed in Problem Definition, (f).

(g) Use 3.05 feet of soil cover over the test cell to limit concrete debris missiles to strike ranges less than 50 feet where Building 42 is located.

(h) Possible benefits are lower design and construction costs compared to the current safety standard which requires a laced reinforced concrete cell designed to resist the blast loading from 360 pounds TNT. The designer instead is instructed simply to design a conventionally reinforced concrete box culvert, 30 feet long, 15 feet wide, and 12 feet high. The culvert must safely support 3.05 feet of soil cover (plus any design live load requirements) which will extend at least 3 feet beyond the exterior face of each wall where the berm then slopes at 3:2 to the ground surface. The backwall must be blast hardened to support the blast hardened door to seal out blast pressures from escaping into the tunnel passageway.

The design concept also offers greater flexibility in meeting future operational requirements; more soil cover can be added to the soil berm if future operations require a larger rated charge capacity for the missile test cell.

SUMMARY

1. Theory developed in the report predicted the entire measured response history of unrestrained timber roof slabs of small-scale, earth-covered, box-shaped ammunition magazines when the shear failure plane of the soil was assumed to be 85 to 90 degrees with the horizontal.

2. The excellent correlation between theory and experiment is the basis for design criteria which offer, for the first time, a deterministic procedure for designing the earth cover over box-shaped ammunition storage magazines to control their structural performance and the debris hazard to prescribed levels.

3. The design criteria offer a technique for eliminating certain types of safety waivers and introducing flexibility and economy into the design process and construction standards for ammunition facilities without sacrificing the level of explosives safety. The criteria are especially applicable to facilities storing a small net explosives weight relative to the structure volume, such as ready service magazines, special weapons magazines, and missile test cells.

FUTURE RESEARCH

The following tasks should be addressed in future research.

1. Theory for predicting the growth of the soil cloud

2. Theory that accommodates time-dependent venting for conditions where $t_d/T < 1.0$

3. More accurate definition of the ratio x/d_s where the soil berm loses its air-tight seal

4. A sensitivity analysis of magazine parameters

5. Theory, similar to that presented in this report, for the dynamic response and debris hazard of earth-covered, arch-shaped ammunition magazines

6. Additional test data from small-scale magazines for extreme variations of design parameters, especially for small values of $d_s/W^{1/3}$, larger charge weights, large values of $d_s/W^{1/3}$, and reinforced concrete roof slabs unrestrained at supports

7. Large-scale tests of box-shaped magazines for 50 pounds $< W <$ 30,000 pounds TNT

8. Theory that accounts for the dynamic response of a magazine headwall

9. Theory that accounts for charge shape (pancake), scaled distance from charge to roof slab, and the crater formed by an explosion

10. Survey the current and projected mix of Navy weapons and define the door size, floor area, aspect ratio, ceiling height, and explosives and bulk storage capacity of a box-shaped ammunition magazine which best satisfies operational requirements for Navy ammunition storage

11. Test data that demonstrate effects of soil type on the shear angle, α, of the soil failure plane in the berm

12. Application of the NSWC hydrocode to validate Equations 2 and 3 for variations of $A/V^{2/3}$

13. Theory for the safe debris range that accounts for jetting of blast pressures through the soil berm, probability distribution for the launch angle of roof debris, and the energy losses of debris during free flight

14. Determine the economic benefits of adding soil cover over ammunition magazines to control their dynamic response and behavior and to mitigate the hazard of debris

15. Theory for effects of explosions inside earth-covered aircraft shelters on their response, behavior, and debris hazard

ACKNOWLEDGMENTS

Sincere appreciation is extended to the field personnel and staff at WPNSTA Concord for care in handling of the explosives. The quality of test data demonstrates a level of proficiency unsurpassed by any research organization.

Mr. Jerome Hopkins of CEL reviewed and computerized the theory. His thoroughness and timely response are appreciated.

REFERENCES

1. Naval Sea Systems Command. NAVSEA OP-5: Ammunition and explosives ashore, vol 1, rev 5. Washington, D.C., Oct 1976.

2. Civil Engineering Laboratory. Technical Report R-828: Blast environment from fully and partially vented explosives in cubicles, by W. A. Keenan and J. E. Tancreto. Port Hueneme, Calif., Nov 1975.

3. __________. Technical Memorandum M-51-77-10: Shear stress in one-way slabs subjected to blast load, by W. A. Keenan. Port Hueneme, Calif., Aug 1977.

4. Naval Civil Engineering Laboratory. Technical Report R-621: Strength and behavior of restrained reinforced concrete slabs under static and dynamic loadings, by W. A. Keenan. Port Hueneme, Calif., Apr 1969.

5. Naval Facilities Engineering Command. NAVFAC P-397, Army TM-5-1300, and Air Force AFM 88-22: Structures to resist the effects of accidental explosions. Washington, D.C., Jun 1969.

LIST OF SYMBOLS

A Vent area of magazine, ft^2

d_s Depth of soil cover over roof of magazine, ft

g Gravity, 32.2×10^{-6} $ft/msec^2$

h Vertical height of soil cloud, ft

h_m Maximum height of soil cloud, ft

i Total impulse of shock plus gas pressures, psi-msec

k Factor related to shear strength of soil berm and properties of roof slab

m Mass, $lb\text{-}msec^2/ft$

M Average unit mass of soil wedge plus roof slab, $psf\text{-}msec^2/ft$

$\bar{M}$ Total mass of soil wedge plus roof slab, $lb\text{-}msec^2/ft$

R Horizontal distance from magazine, ft

R_s Horizontal distance beyond which no debris missiles strike ground, ft

s_1 Length of concrete debris missile, ft

s_2 Width of concrete debris missile, ft

t Elapsed time from instant of explosion, msec

t_c Thickness of roof slab, ft

t_d Time when $x = d_s$, msec

t_m Time to maximum response of roof slab and soil cloud, msec

T Time duration of shock/gas pressure inside magazine, msec

v Velocity, ft/sec

v_d Velocity of roof slab when $x = d_s$, ft/sec

v_o Velocity at time $t = 0$, ft/sec

V Volume of magazine chamber, ft^3

W Net explosive weight, lb TNT

x Vertical displacement of roof slab, ft

x_d Vertical displacement of roof slab at $x = d_s$, ft

x_m Maximum vertical displacement of roof slab, ft

x_T Vertical displacement of roof at time $t = T$, ft

$\bar{y}$ Time constant related to centroid of pressure-time pulse

α Angle of shear plane failure for soil relative to horizontal, deg

ℓ_1 Length of magazine chamber, ft

ℓ_2 Width of magazine chamber, ft

ℓ_3 Thickness of magazine walls, ft

γ_c Density of roof slab, lb/ft^3

γ_s Density of soil berm, lb/ft^3

ϕ Angle of internal friction for soil

Appendix A

PREDICTED AND MEASURED RESPONSES OF EARTH-BERMED ROOF AS A FUNCTION OF TIME

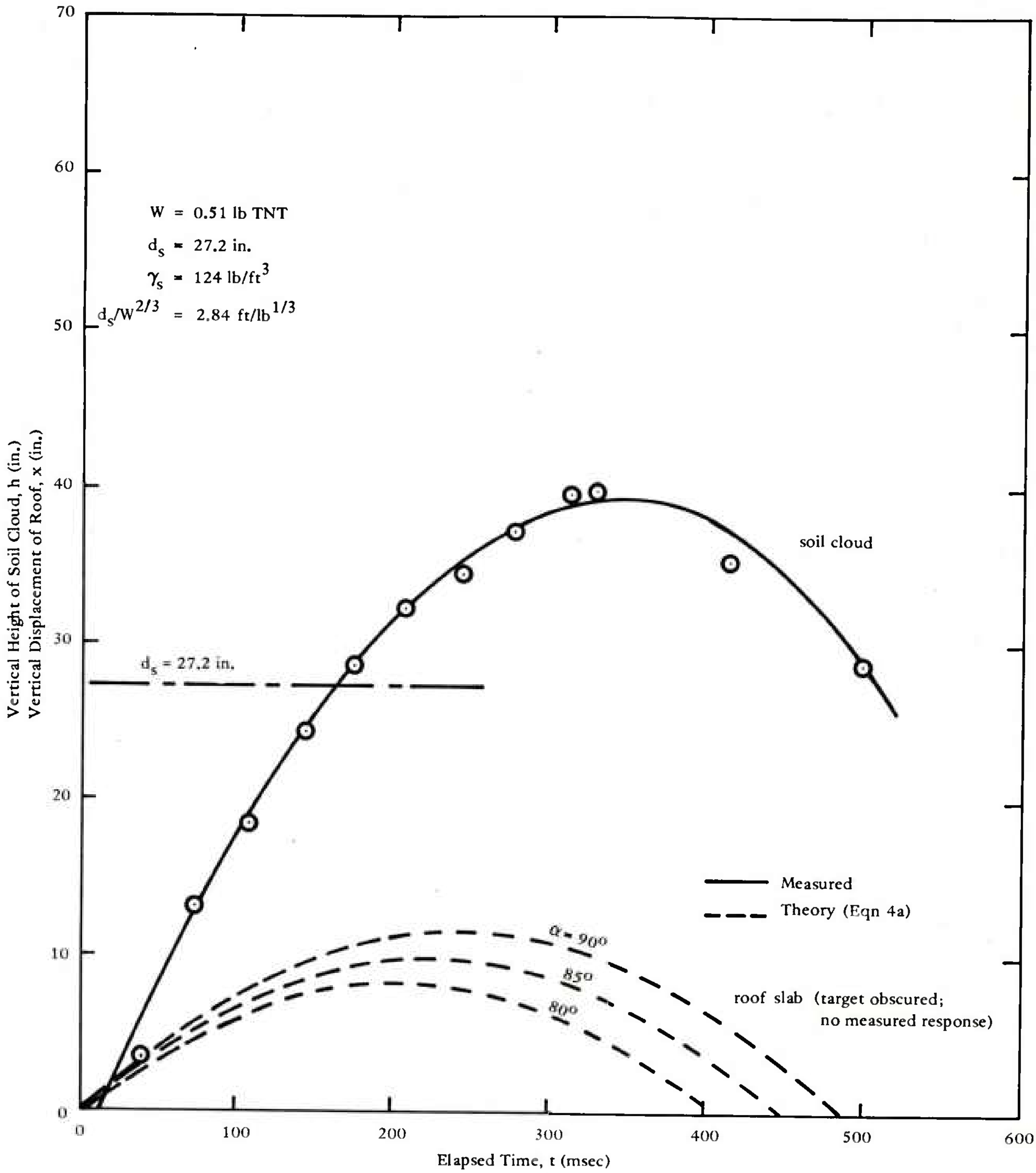


Figure A-1. Growth of soil cloud and response of roof — Test 3.

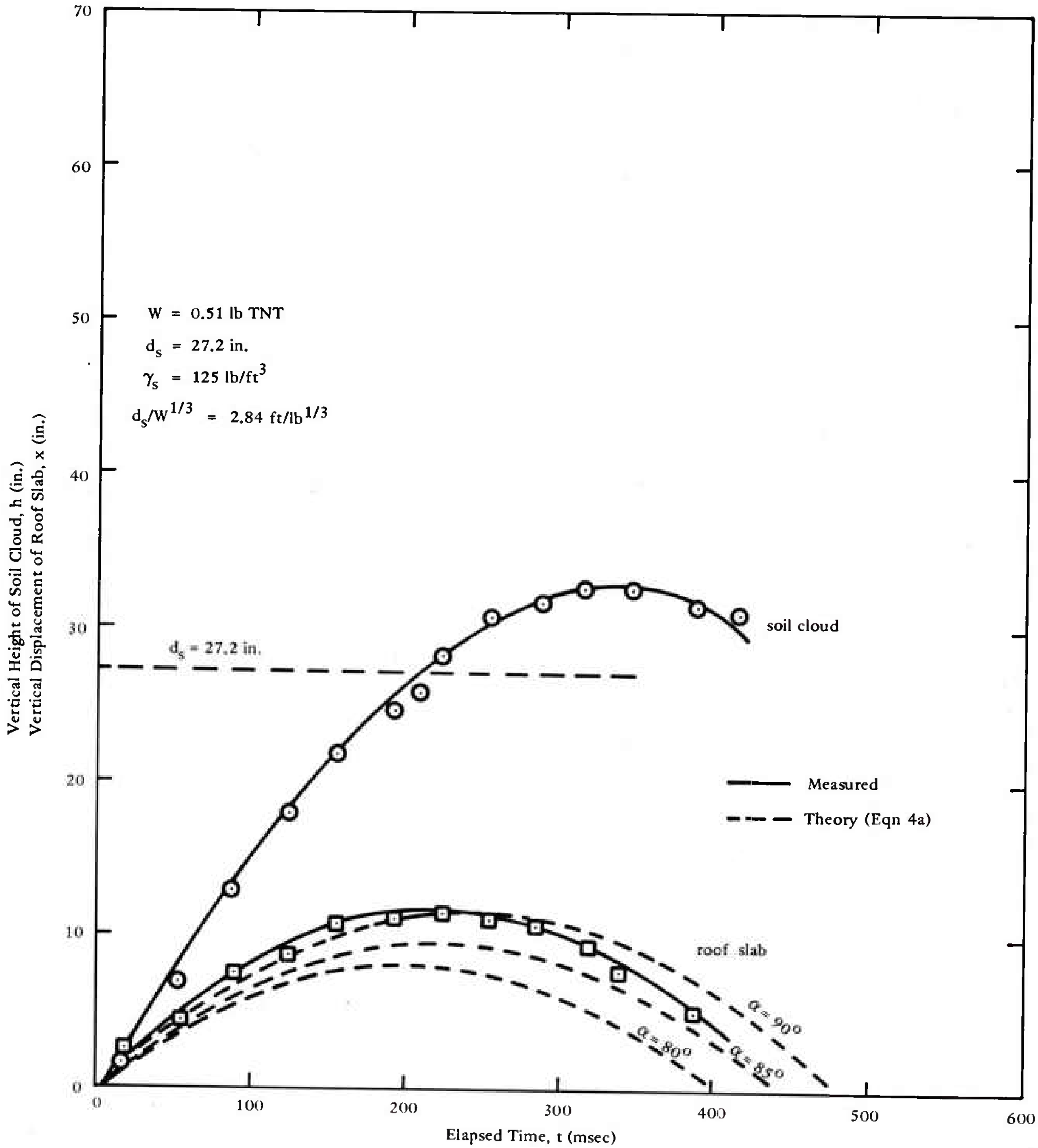


Figure A-2. Growth of soil cloud and response of roof — Test 4.

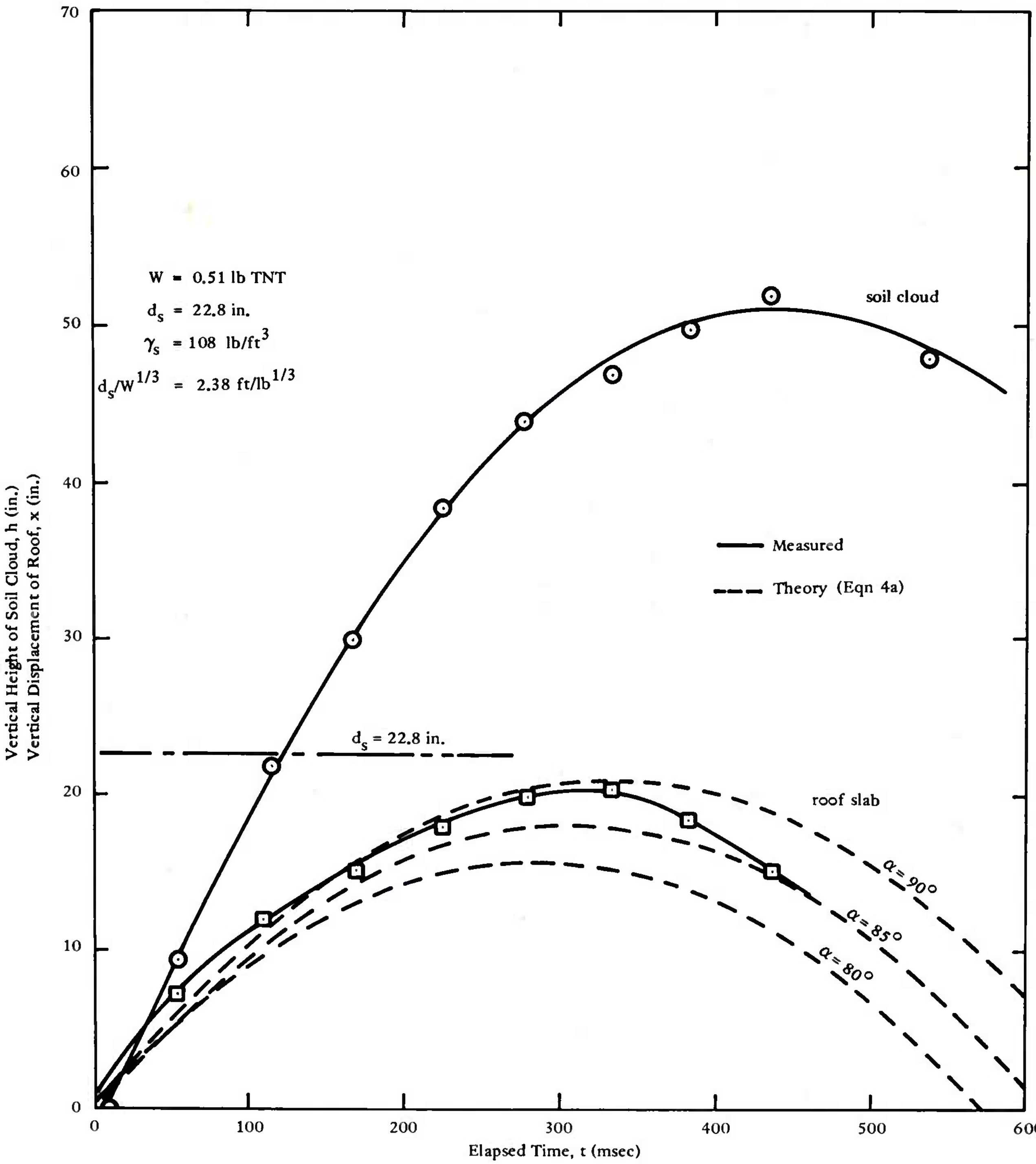


Figure A-3. Growth of soil cloud and response of roof — Test 5.

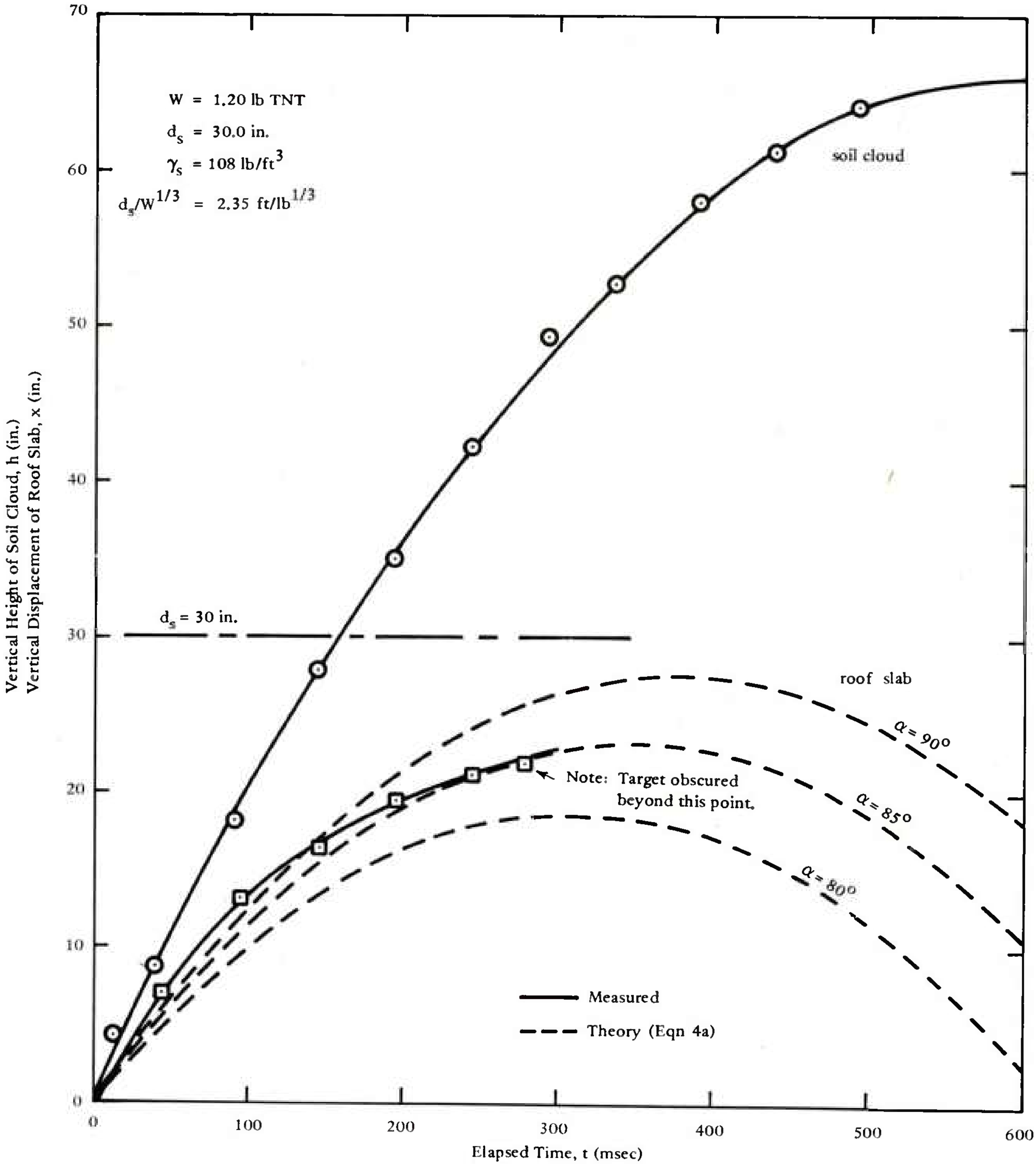


Figure A-4. Growth of soil cloud and response of roof – Test 6.

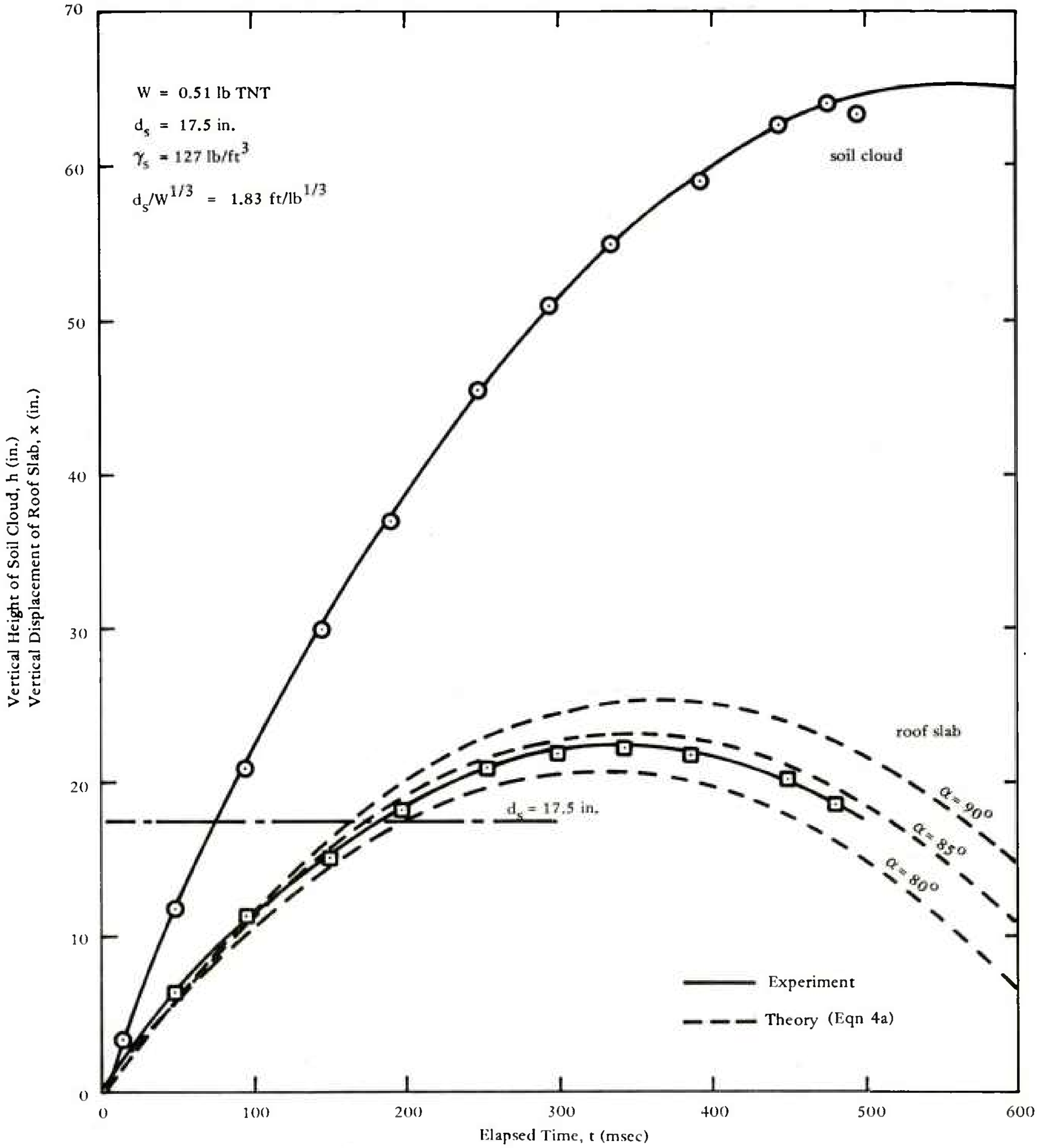


Figure A-5. Growth of soil cloud and response of roof — Test 7.

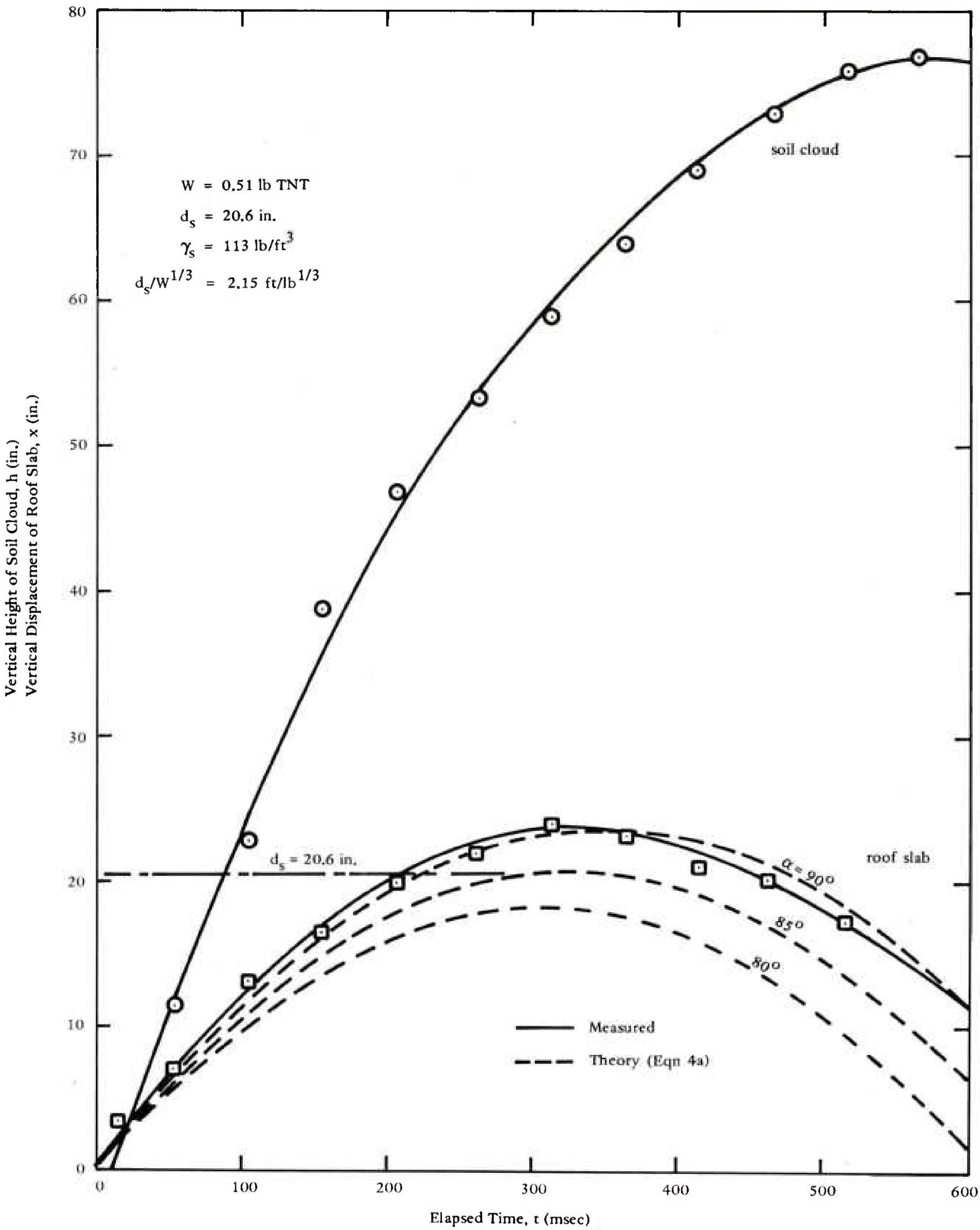


Figure A-6. Growth of soil cloud and response of roof — Test 8.

Appendix B

PHOTOGRAPHS OF EARTH-BERMED ROOF OF TEST MAGAZINES AT VARIOUS STAGES OF RESPONSE

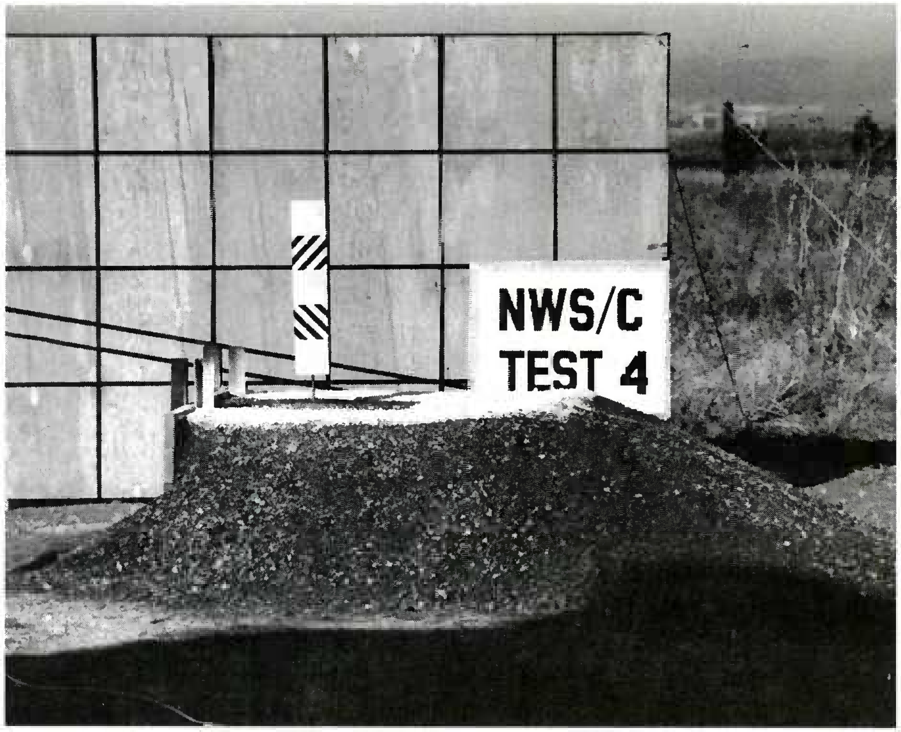


Figure B-1. Pre-shot view of test magazine -- Test 4.

Figure B-2. View of test magazine near time of maximum roof response – Test 4.

Figure B-3. Post-shot view of test magazine -- Test 4.

Figure B-4. Pre-shot view of test magazine -- Test 5.

Figure B-5. View of test magazine shortly after time of detonation – Test 5.

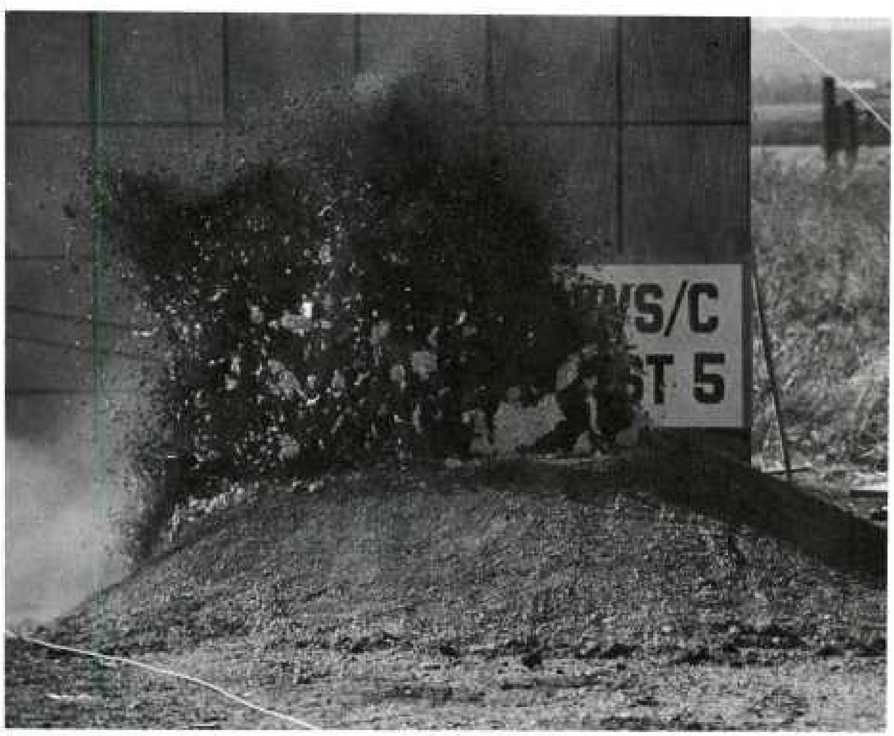


Figure B-6. View of test magazine near time of maximum roof response -- Test 5.

Figure B-7. Post-shot view of earth berm – Test 5.

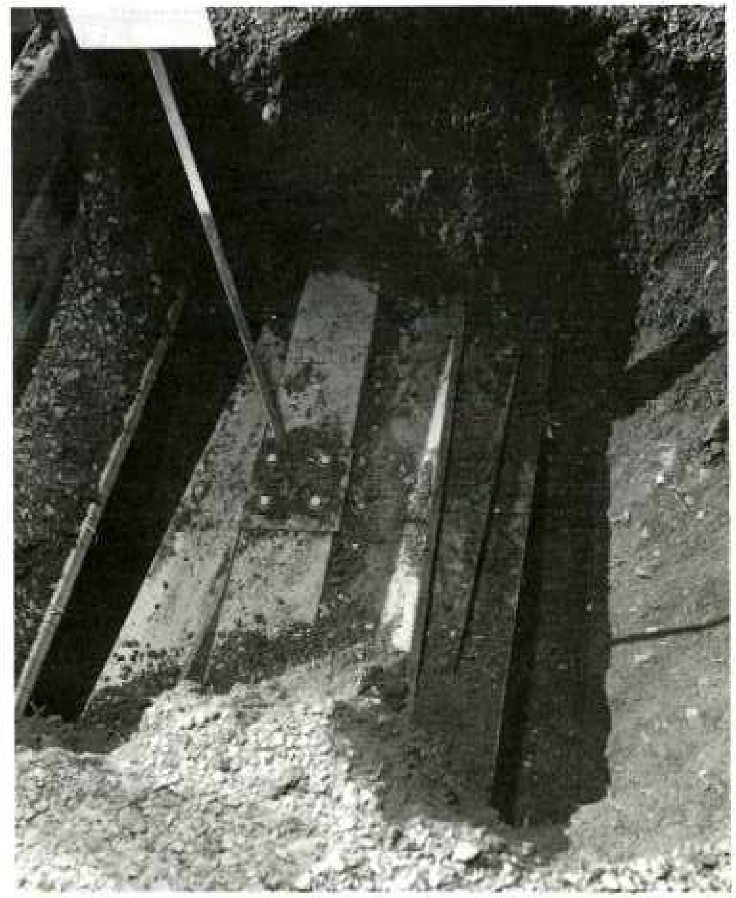


Figure B-8. Post-shot view of roof timbers -- Test 5.

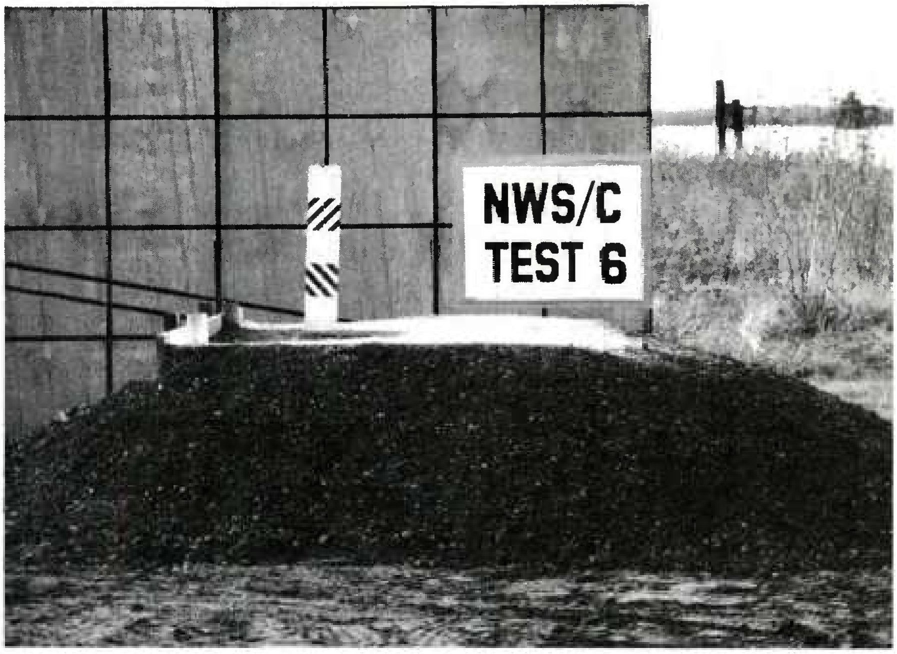


Figure B-9. Pre-shot view of test magazine -- Test 5.

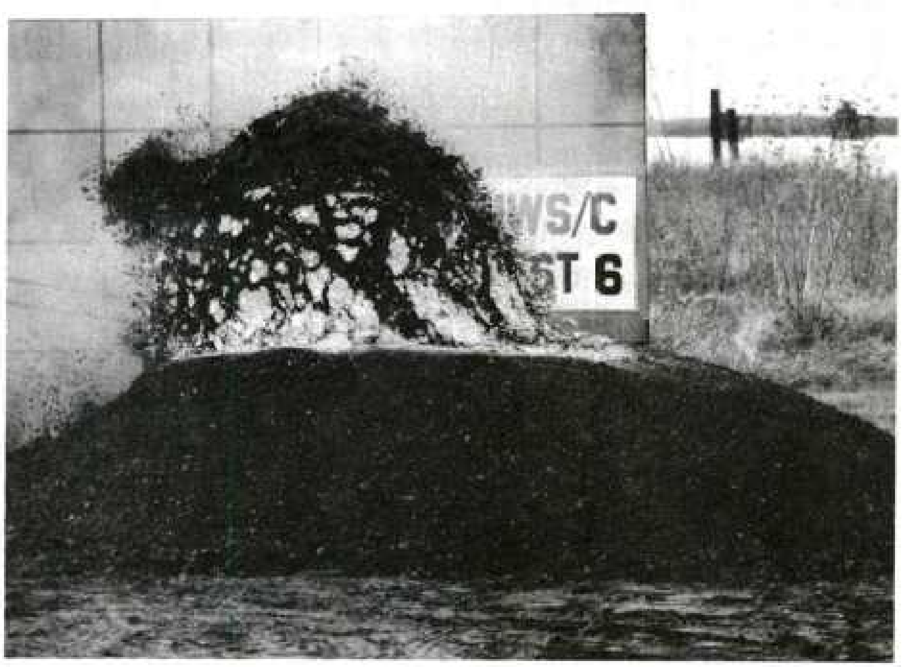


Figure B-10. View of test magazine near time of maximum roof response -- Test 6.

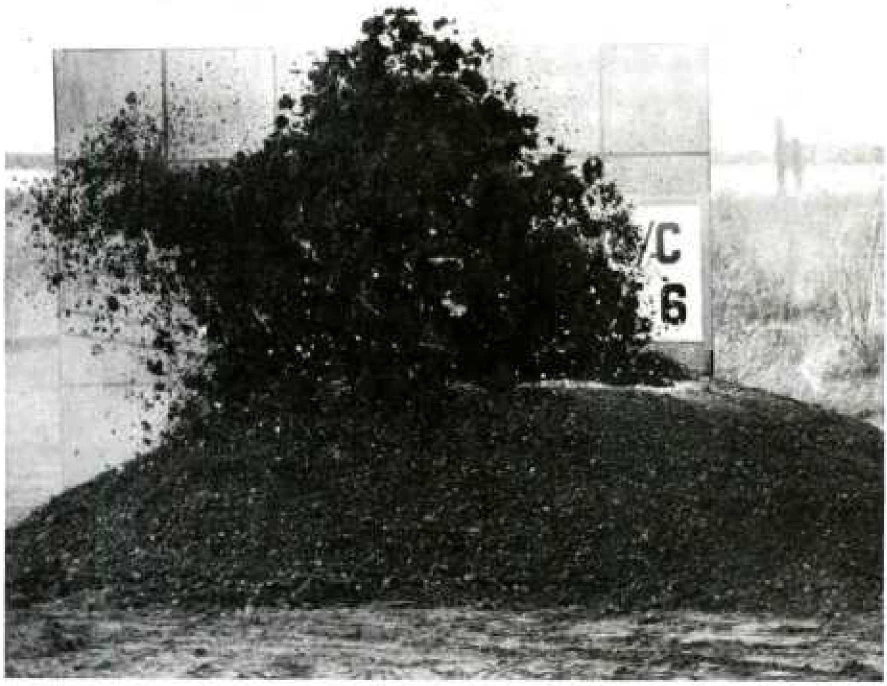


Figure B-11. View of test magazine near time of maximum height of soil cloud -- Test 6.

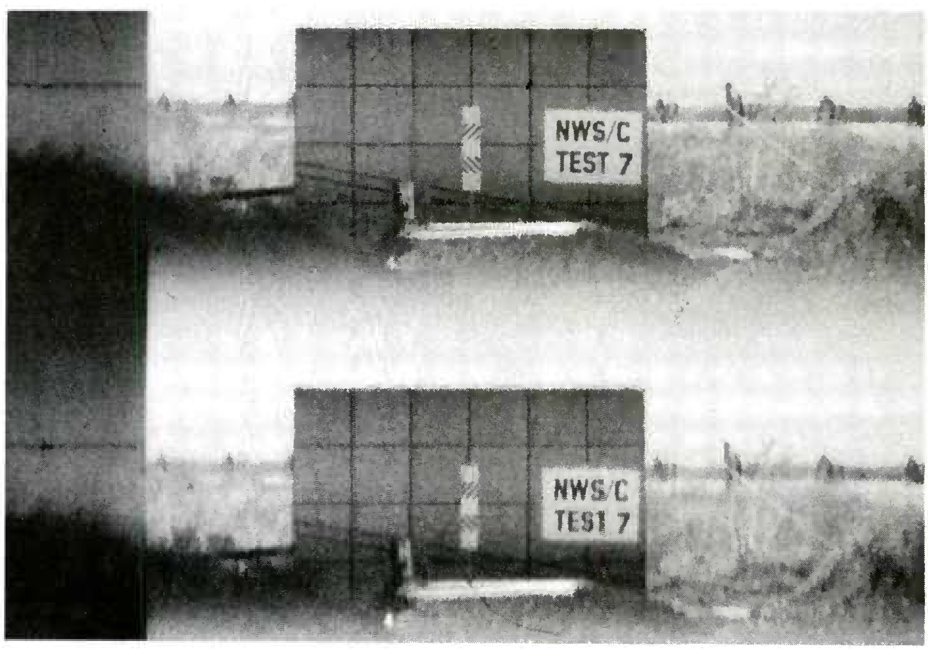


Figure B-12. Pre-shot view of test magazine -- Test 7.

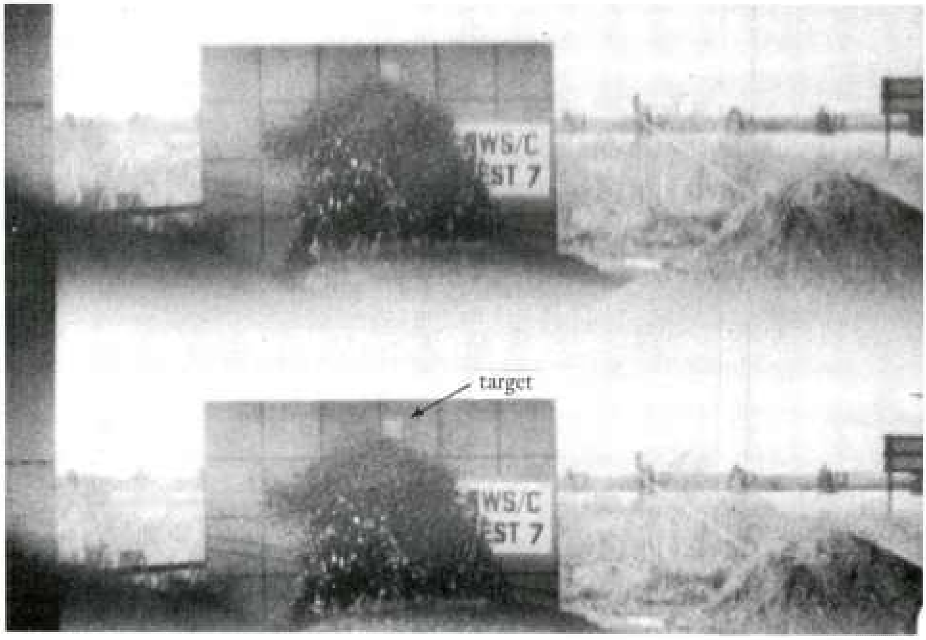


Figure B-13. View of test magazine near time of maximum roof response -- Test 7.

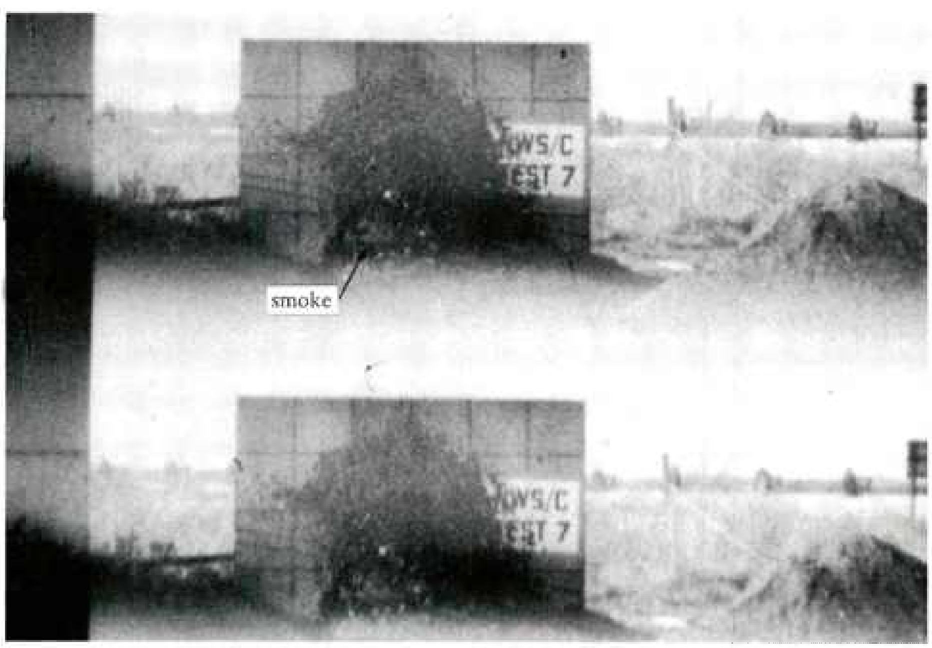


Figure B-14. View of test magazine near time of maximum height of soil cloud -- Test 7.

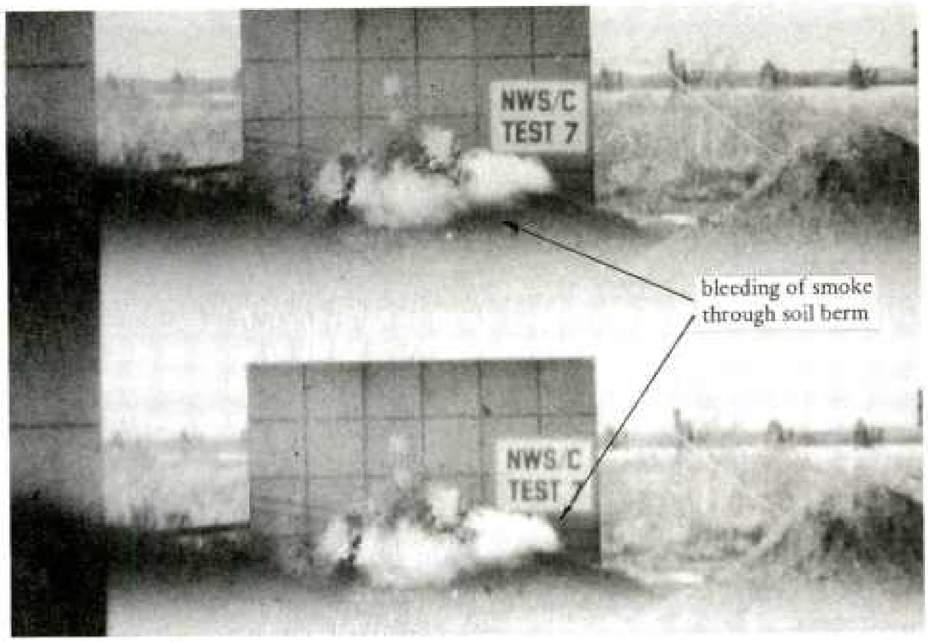


Figure E-15. View of test magazine showing escape of gases through soil berm -- Test 7.

Figure B-16. Pre-shot of test magazine – Test 8.

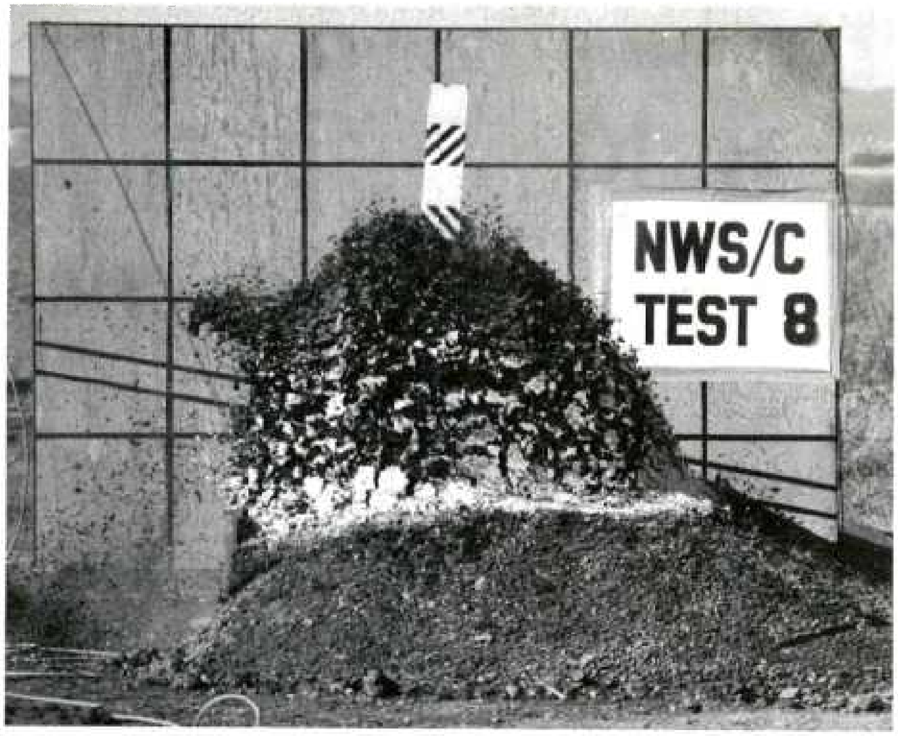


Figure B-17. View of test magazine near time of maximum roof response -- Test 8.

Figure B-18. View of test magazine near time of maximum height of soil cloud -- Test 8.

Figure B-19. View of test magazine showing escape of gases through soil berm – Test 8.

Figure B-20. Post-shot view of test magazine -- Test 8.

DISTRIBUTION LIST

AFB AF Tech Office (Mgt & Ops), Tyndall, FL; CESCH, Wright-Patterson; HQAFESC/DEMM, Tyndall AFB, FL; MAC/DET (Col. P. Thompson) Scott, IL; Stinfo Library, Offutt NE; WPNS Safety Div, Norton, CA
AMMO HAZARDS REVIEW BD Chairman, NAS, Norfolk, VA
ARMY ARRCOM, Rock Island, IL; BMDSC-RE (H. McClellan) Huntsville AL; DARCOM; Savanna Army Depot (Bynd), IL; Savanna Army Depot (Ernst), IL
ARMY AMMUNITION PLANT SARHW-FEM Hawthorne, NV
ARMY COE Philadelphia Dist. (LIBRARY) Philadelphia, PA
ARMY CORPS OF ENGINEERS MRD-Eng. Div., Omaha NE; Seattle Dist. Library, Seattle WA
ARMY ENG DIV Huntsville, AL
ARMY ENG WATERWAYS EXP STA (S Kiger) Vicksburg, MS
ARMY MTMC Trans Engr Agency MTT-CE, Newport News, VA
ASST SECRETARY OF THE NAVY Spec. Assist Energy (Leonard), Washington, DC
CINCLANT Civil Engr. Supp. Plans. Ofr Norfolk, VA
CNO Code NOP-964, Washington DC; OP-411F, Wash DC
COMOCEANSYSPAC SCE, Pearl Harbor HI
DOD Explos Safety Board, Wash DC; Explosives Safety Board (Library), Washington DC
DOT Office of Hazardous Matl Ops, Wash DC
DTIC Defense Technical Info Ctr/Alexandria, VA
MARINE CORPS BASE M & R Division, Camp Lejeune NC; PWO Camp Lejeune NC; PWO, Camp S. D. Butler, Kawasaki Japan
MARINE CORPS HQS Code LFF-2, Washington DC
MCAS Facil. Engr. Div. Cherry Point NC; Code PWE, Kaneohe Bay HI; Code S4, Quantico VA; PWO Kaneohe Bay HI
NAF PWO, Atsugi Japan
NALF OINC, San Diego, CA
NARF Code 640, Pensacola FL
NAS CO, Guantanamo Bay Cuba; Code 18700, Brunswick ME; Dir. Util. Div., Bermuda; ENS Buchholz, Pensacola, FL; PWD Maint. Div., New Orleans, Belle Chasse LA; PWO Belle Chasse, LA; PWO Key West FL; PWO, Dallas TX; PWO, Glenview IL; SCE Lant Fleet Norfolk, VA; SCE Norfolk, VA; Security Offr, Alameda CA
NATL RESEARCH COUNCIL Naval Studies Board, Washington DC
NAVACT PWO, London UK
NAVAEROSPREGMEDCEN SCE, Pensacola FL
NAVAIRSTA Code 500, San Diego, CA
NAVAIRSYSCOM PMA 258 Washington, DC
NAVCOASTSYSTCTR Library Panama City, FL
NAVEDTRAPRODEVCEN Tech. Library
NAVEDUTRACEN Engr Dept (Code 42) Newport, RI
NAVFACENGCOM Code 043 Alexandria, VA; Code 044 Alexandria, VA; Code 0451 Alexandria, VA; Code 0454B Alexandria, Va; Code 04B5 Alexandria, VA; Code 1113 (T. Stevens) Alexandria, VA
NAVFACENGCOM - CHES DIV. Code 101 Wash, DC
NAVFACENGCOM - LANT DIV. Eur. BR Deputy Dir, Naples Italy; RDT&ELO 102, Norfolk VA
NAVFACENGCOM - NORTH DIV. Code 1028, RDT&ELO, Philadelphia PA
NAVFACENGCOM - PAC DIV. (Kyi) Code 101, Pearl Harbor, HI; Code 402, RDT&E, Pearl Harbor HI; Commander, Pearl Harbor, HI
NAVFACENGCOM - SOUTH DIV. Code 09 (Watts) Charleston, SC; Code 90, RDT&ELO, Charleston SC
NAVFACENGCOM - WEST DIV. Code 04B San Bruno, CA; Code 402 San Bruno, CA; RDT&ELO Code 2011 San Bruno, CA
NAVFACENGCOM CONTRACT AROICC, Point Mugu CA; Eng Div dir, Southwest Pac, Manila, PI; OICC, Southwest Pac, Manila, PI; OICC/ROICC, Balboa Canal Zone; ROICC LANT DIV., Norfolk VA; ROICC, Keflavik, Iceland
NAVPHIBASE CO, ACB 2 Norfolk, VA
NAVSEASYSCOM Code 05M13 (Newhouse) Wash DC; Code 62T2, Wash DC; SEA-04H, Wash DC
NAVSECGRUACT PWO, Adak AK
NAVSHIPYD Tech Library, Vallejo, CA

NAVSTA CO Roosevelt Roads P.R. Puerto Rico; Maint. Div. Dir/Code 531, Rodman Canal Zone; PWO, Keflavik Iceland; PWO, Mayport FL; SCE, San Diego CA; SCE, Subic Bay, R.P.
NAVSUPPACT LTJG McGarrah, SEC, Vallejo, CA
NAVSURFWPNCEN PWO, White Oak, Silver Spring, MD
NAVTECHTRACEN SCE, Pensacola FL
NAVWPNCEN Code 2636 (W. Bonner), China Lake CA; Code 3276 China Lake, CA
NAVWPNSTA Code 09, Concord, CA; Naval Weapons Handling Center, Earle, NJ
NAVWPNSTA PW Office (Code 09C1) Yorktown, VA
NAVWPNSTA Safety Br, Concord, CA
NAVWPNSUPPCEN Code 09 Crane IN
NCBC Code 156, Port Hueneme, CA
NMCB 5, Operations Dept.
NORDA Code 440 (Ocean Rsch Off) Bay St. Louis MS
NSD SCE, Subic Bay, R.P.
NTSB Chairman, Wash DC
NUSC Code 131 New London, CT; Code EA123 (R.S. Munn), New London CT
ONR Code 700F Arlington VA
PHIBCB 1 P&E, Coronado, CA
PMTC Pat. Counsel, Point Mugu CA
PWC CO Norfolk, VA; CO, (Code 10), Oakland, CA; CO, Great Lakes IL; Code 10, Great Lakes, IL; Code 120, Oakland CA; Code 120C, (Library) San Diego, CA; Code 128, Guam; Code 154, Great Lakes, IL; Code 220 Oakland, CA; Code 220.1, Norfolk VA; Code 30C, San Diego, CA; Code 400, Great Lakes, IL; Code 400, Oakland, CA; Code 400, Pearl Harbor, HI; Code 400, San Diego, CA; Code 420, Great Lakes, IL; Code 610, San Diego Ca; LTJG J.L. McClaine, Yokosuka, Japan; Utilities Officer, Guam; XO (Code 20) Oakland, CA
U.S. MERCHANT MARINE ACADEMY Kings Point, NY (Reprint Custodian)
USCG G-EOE-4/61 (T. Dowd), Washington DC
LEHIGH UNIVERSITY Bethlehem PA (Linderman Lib. No.30, Flecksteiner)
LIBRARY OF CONGRESS WASHINGTON, DC (SCIENCES & TECH DIV)
MIT Cambridge MA; Cambridge MA (Rm 10-500, Tech. Reports, Engr. Lib.)
PURDUE UNIVERSITY Lafayette, IN (CE Engr. Lib)
UNIVERSITY OF ILLINOIS URBANA, IL (LIBRARY)
UNIVERSITY OF MASSACHUSETTS (Heronemus), Amherst MA CE Dept
AMMAN & WHITNEY CONSULT ENGRS N Dobbs New York, NY
ASSOC AMER RR Bureau of Explosive, Chicago, IL
AUSTRALIA Dept of Const, Canberra; Dept of Hsng & Const, Sydney
BROWN & CALDWELL E M Saunders Walnut Creek, CA
CANADA Trans-Mnt Oil Pipe Lone Corp. Vancouver, BC Canada
HERCULES INC. D Richardson, Magna, UT
GLIDDEN CO. STRONGSVILLE, OH (RSCH LIB)
KAMAN SCIENCES CORP T Cook Colorado Springs, CO
MCDONNEL AIRCRAFT CO. Navy Tech Rep St Louis, MO; R Carson, St. Louis, MO
RAYMOND INTERNATIONAL INC. E Colle Soil Tech Dept, Pennsauken, NJ
SWITZERLAND T Schneider, Zurich
THE NETHERLANDS Director Tech Rsch Prins Maurits Lab, Rijswijk
UNITED KINGDOM Atomic Energy Auth (F R Farmer) London
R.F. BESIER Old Saybrook CT