COMPARISON OF FULL SCALE AND SCALED-MODEL KLOTZ TUNNEL EXPLOSION TEST RESULTS

Presented at:

Twenty-Seventh DoD Explosives Safety Seminar
Department of Defense Explosives Safety Board
Las Vegas, Nevada

August 20 - 22, 1996

By:

Dr. Khosrow Bakhtar, ARSM
Bakhtar Associates
2429 West Coast Highway, Suite 201
Newport Beach, California 92663
Telephone: (714) 642 - 3255
Fax: (714) 642 - 1655
e-mail: kbakhtar@aol.com

and

Mr. Joseph Jenus, Jr.
Chief, Explosion Hazards Reduction Program (EHR)
Eglin Air Force Base, Florida 32542

Report Documentation Page

Form Approved
OMB No. 0704-0188

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1. REPORT DATE **AUG 1996**	2. REPORT TYPE	3. DATES COVERED **00-00-1996 to 00-00-1996**
4. TITLE AND SUBTITLE **Comparison of Full Scale and Scaled-Model Klotz Tunnel Explosion Test Results**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Bakhtar Associates, ,2429 West Coast Highway, Suite 201,Newport Beach,CA,92663**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES **See also ADM000767. Proceedings of the Twenty-Seventh DoD Explosives Safety Seminar Held in Las Vegas, NV on 22-26 August 1996.**		
14. ABSTRACT **see report**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**16**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

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By:

Dr. Khosrow Bakhtar, ARSM
Bakhtar Associates
2429 West Coast Highway, Suite 201
Newport Beach, California 92663
Telephone: (714) 642 - 3255
Fax: (714) 642 - 1655
e-mail: kbakhtar@aol.com

Mr. Joseph Jenus, Jr.
Chief, Explosion Hazards Reduction Program (EHR)
Eglin Air Force Base, Florida 32542
Telephone: (904) 882 4685 Ext. 328
Fax: (904) 882 - 9381

ABSTRACT

Under high loading density, explosion effects in underground storage structures are associated with 1) blast pressure, 2) primary and secondary fragments, 3) chemical hazards, 4) thermal hazards, and 5) ground shocks. Extensive studies have been performed in the past on the hazardous effects of blast pressure, induced thermal and chemical environments, and ground shocks. However, the degree and extent of fragment-induced hazards associated with accidental detonation of explosives stored in rock/soil structures (underground magazines) are still not fully verified. The empirical relationships used are too general and do not account for the site specific characteristics of geologic and engineered systems. The KLOTZ Tunnel explosion test which was conducted in 1988 at China Lake, California, demonstrated how rupturing of the storage magazine cover can create a serious debris hazardous environment. The site specific characteristic data on the geologic and engineered systems for the full scale KLOTZ Tunnel provided a unique opportunity to design a series of scaled model tests and determine the applicability of physical modeling technique (at 1-g) to explosion hazards reduction research. The model test experiments were designed at a prototype-to-model scale of 20:1. This paper provides details of the five scaled model tests conducted, data obtained, and analytical methods developed for analysis of the scaled model tests. The scaled model tunnel explosion test results are compared with those obtained from the full scale test. Emphasis is placed on comparing the maximum hazardous fragment and the quantity-distance (Q-D) ranges, launch angles, and velocities for the prototype and model tests. In conclusion, formulation of the Bakhtar Explosives Safety Criteria, for siting; design; construction; performance assessment; risk analysis; loading density optimization; accident investigation, for underground munitions storage facilities are elaborated upon.

1. INTRODUCTION

Studies relative to the explosive safety quantity-distance (Q-D) effects from detonations of shallow underground magazines in hard rocks have been underway since early 1970 (Jenssen, 1988). The overall objective of the test program is to determine the hazardous effects of debris, airblast, and ground motion produced by accidental detonation of explosives magazines which rupture the overhead cover of the underground chamber. Based on data from near surface bursts, many empirical relationships have been developed to determine the free-field airblast pressure and induced ground motion. However, estimates of the debris thrown and the associated kinetic energy are much harder to make in the absence of detailed information on site specific characteristics of geologic system.

In order to study the explosive safety quantity-distance, a shallow underground tunnel/chamber explosion test was performed at the Naval Air Warfare Center, NAWC, (formerly called Naval Weapons Center) in China Lake California, on August 24, 1988. The test program was funded on an equal share basis by three organizations: the United States Department of Defense Explosives Safety Board (DDESB), the British Ministry of Defense Safety Services Organization, and the Norwegian Defense Construction Service. Additional funds were made available by the governments of France, Switzerland, and Sweden for add-on instrumentation. The test consisted of a 20,000 kg (44,000 lbs.) net explosive weight detonation inside a half-scale tunnel/chamber system constructed in highly weathered granitic rock mass. Prior to shotcreting and emplacement of explosives, complete rock mass characterization was performed in the tunnel and associated explosives chamber and relevant geologic and geo-engineering information were documented (Bakhtar, 1988).

Based on the pre-blast rock mass characterization, five major joint sets and a single shear zone were identified within the site. The major joint sets were blocky with well defined dip/strike. The block sizes were generally 0.43-m (17 inches) to 0.56-m (22 in.) in length. The "Q" system developed by Barton, et.al., (1977) was employed for rock mass characterization. Values of 0.65 and 1.30 were obtained for the tunnel and chamber respectively, which categorized the rocks from "very poor" to "poor" on the basis of the Q system. Index tests performed in situ indicated that unconfined compressive strength of the rocks was much less than expected because of extensive weathering.

Post-blast analysis of rock mass, reported by Bakhtar (1989), based on visual observation of the site revealed the following:

- Larger ejecta were from the jointed-blocky rocks.
- The intact rocks with minor random joints were broken into smaller pieces in comparison with those from major joint sets.
- Observation around the test site indicated the majority of pieces (ejecta) with at least one smooth-weathered face (from major joints sets) were less than 0.43-m x 0.43-m x 0.30-m (17 in. x 17 in. x 12 in.) in size.
- The majority of pieces (ejecta) originating from intact rock were less than 0.25-m x 0.25-m x 0.38-m (10 in. x 10 in. x 15 in) in size.

- Broken rocks (ejecta) originating from intact and jointed rocks were observed beyond 300-m (982 ft) from the original location of the portal.

- Large pieces of concrete (debris) 0.97-m x 0.79-m x 0.38-m (38 in. x 31 in. x 15 in.) were thrown more than 61-m (200 ft) from the original portal location.

- The sizes of ejecta thrown from the jointed rocks were larger than those from the intact rocks.

- Higher kinetic energy was associated with the ejecta from joint sets than ejecta from intact rocks.

The results of the above observations indicate the importance of site characterization, identification of major geologic features, and an understanding of the basic mechanical and physical properties of the rock mass hosting the explosive repository.

Data obtained from the tunnel explosion test in China Lake, California, provided a unique opportunity to physically construct a series of scale model experiments, based on physical modeling technique at 1-g, to validate more precise "Scaling Laws" for the current Q-D standards for underground storage of munitions.

This paper provides details of physical model experiments at 1-g, {(prototype): (model)=20:1}, and comparison of "dynamics" of blast-induced fragments for model-prototype test results. The dynamics of the blast-induced fragments, for given characteristics of the geologic and engineered systems, are defined by (Bakhtar, 1996):

1. Initial fragment projection angle.
2. Initial fragment velocity
3. Maximum fragment throw distance.
4. Fragment density per 56 m^2.
5. Fragment impact energy.

2. PROTOTYPE KLOTZ TUNNEL

The overall characteristics of the engineered and geologic systems, for the prototype KLOTZ tunnel tested in China Lake, California are shown in Tables 1 and 2, respectively. They constitute the pertinent prototype data which were used to construct the Air Force scaled model tunnel tests.

3. AIR FORCE MODEL TUNNELS

The overall dimensions of the model engineered system are shown in Table 1. To facilitate the ease of model construction, the range and average values for the overall characteristics of the prototype geologic system, shown in Table 2, were used to arrive at the respective model values.

4. PHYSICAL MODELING

4.1 MATERIAL MODEL

The difficulties and high expenditure associated with testing full scale (prototype) structures warrant the need for scale models in which the linear dimension, or geometry, of the prototype structure is reduced by a

Table 1. Prototype-Model Dimensions at 20:1 Scale.

PROTOTYPE DIMENSIONS (DESIGNED)	MODEL DIMENSIONS (CALCULATED)
CHAMBER*	CHAMBER
5 m wide x 4 m high x 18 m long (16.4 ft x 13.1 ft x 59.1 ft)	0.25 m wide x 0.2 m high x 0.9 m long (10 in x 8 in x 35 in)
TUNNEL	TUNNEL
2.4 m wide x 2.4 m high x 25 m long (8 ft x 8 ft x 82 ft)	0.12 m wide x 0.12 m high x 1.2 m (5 in x 5 in x 50 in long)

* - Actual volume = 332 m^3 (11,725 ft^3)

Table 2. Overall Characteristics of Geologic System.

CHARACTERISTICS	RANGE OF NUMERICAL VALUES	AVERAGE
Joint Roughness Coefficient JRC	2 - 6	4
Block Length (L_n)	17 in (0.43 m) - 22 in (0.56 m)	20 in (0.51 m)
Laboratory Sample Size (L_o)*	3.94 in (0.10 m)	3.94 in (0.1 m)
Joint Wall Compr. Strength JCS_o	2310 psi (15.9 MPa) - 9000 psi (62.0 MPa)	4695 psi (32.4 MPa)
Joint Effective Normal Str. σ'_n	0.29 psi (0.002 MPa) - 32 psi (0.22 MPa)	12.90 psi (0.089 MPa)
Smooth Hydraulic Aperture (e_o)	0.011 in (0.279 mm) - 0.017 in (0.432 mm)	0.014 in (0.355 mm)
Residual Friction Angle (ϕ_r)	19° - 25°	21.6°
Basic Friction Angle (ϕ_b)	30°	30°
Unconfined Compressive Strength of Intact Rock (Schmidt Hammer) σ_c	5715 psi (39.41 MPa) - 16,132 psi (111.25 MPa)	10310 psi (71.11 MPa)
Joint Strikes	N38°E - N60°E	N52°E
Joint Dips	48° - 90°	67°
Q-Values	0.65 - 1.30	≈1.0

* Corresponds to the length of the profile gage.

certain definite scale. Because the geometry is scaled down, the strength-related parameters also need to be scaled down in order to maintain dimensional homogeneity between the model and prototype structures. The

design of synthetic geologic materials, herein called "rock-simulants," for scaled model testing needs to be done in such a way that similarity in material behavior (i.e., prototype/model behavior) is conserved and the important dimensionless strength related ratios remain unchanged for the model and prototype materials.

For geologic materials, scaling plays an important role and affects the material behavior, particularly, the overall strength. Other features of geologic materials that may affect the behavior of full scale structures are discontinuities and unconformities. These need to be accounted for in physical modeling. In general, the choice of the model depends on:

- nature of the investigation
- limitations of the testing facility
- economic constraints.

In order to realistically model a particular geology with associated discontinuities at the reduced scale, the proper ingredients need to be mixed in appropriate proportions to produce low strength "rock-like" materials. Because no standard low-strength rock-simulants exist, the method developed by Bakhtar (1987) and described in detail by Bakhtar (1986, 1987) can be employed to identify and formulate low-strength synthetic geologic materials which have dimensionless strength properties similar to those of rock. It is important to note that the feasibility of model testing based on the material scaling developed Bakhtar (1987) for underground structures has been proven through a decade of research sponsored by the Defense Nuclear Agency (DNA). Also, candidate material models should exhibit rock like behavior at reduced scale, not only under uniaxial loading but triaxial and hydrostatic loading conditions. It should be emphasized that for realistic simulation, the dimensionless quantities such as angle of internal friction (ϕ) and Poisson's ratio (ν) should match for model and respective prototype materials. An updated discussion on material model testing and characterization are provided in a recent report (Bakhtar, 1993). The complete simulitude would require the following conditions to be satisfied:

$$\{(\sigma_C)/(E)\}_{PROTOTYPE} = \{(\sigma_C)/(E)\}_{MODEL}$$
$$\nu_{PROTOTYPE} = \nu_{MODEL}$$
$$\phi_{PROTOTYPE} = \phi_{MODEL}$$

where:
σ_C = Unconfined Compressive Strength
E = Elastic (Young's) Modulus
ν = Poisson's ratio
ϕ = Internal Friction Angle

4.2 MODEL TESTING CONCEPT

The most important initial step in planning a physical modeling experiment is the identification of the pertinent parameters. In many cases, economic constraints, limitation of testing facility, and the nature of the investigation control the choice of the model. However, results of almost two decades of research (Bakhtar, 1993) indicate that physical modeling in geomechanics and structural engineering may be performed under 1-g by choosing two different approaches, as outlined below:

(1). **Material Scaling** - in which the geometry and strength related properties of the model materials are scaled. In such cases, the load required to cause deformation in the model must be reduced in order to maintain the similitude conditions with its prototype.

(2). Replica Scaling - in which the

geometry is scaled, however, the strength related properties of the model material are matched with those of its respective prototype. In such cases, the load causing deformation in the model must be increased to maintain the similitude conditions with its prototype.

The emphasis in this paper is directed toward adherence to the theory and application of the scale-model testing under normal gravity (1-g) using the material scaling approach. Based on the author's more than 20 years of experience, replica scaling is more costly. In many cases, its application becomes distorted in geomechanics and structural engineering during the construction phase of models.

Also, centrifuge testing has limited applications in modeling geologic systems in which structural features, (joints, discontinuities, etc.) as well as the characteristics of the engineered system are important parameters for modeling. However, the centrifuge technique may be used for component testing of a discrete part of a prototype structure.

4.3 SIMILITUDE CONDITIONS

The derivation of the general theory of similarity between a rock model and its prototype can best be discussed in terms of a purely mechanical system. Complete mechanical similarity requires that conditions of geometric and dynamic similarities be satisfied between a model and its prototype within the range of loading of interest in a particular investigation. **Geometric similarity** means that the model is true to scale in length, area, and volume. **Dynamic similarity** means that the ratios of all types of forces are equal. These forces result from inertia, gravity, viscosity, elasticity (fluid compressibility), plasticity, surface tension and pressure. Magnetic forces are not considered for investigations of interest to blast loading. It can be argued that complete mechanical similarity also requires kinematic and thermal similarity, which is not discussed in the present paper. However, it is the author's opinion that within the scope of most experimental investigations, dynamic similarity coupled with geometric similarity provide the necessary provisions for solving problems related to the load response of geologic and engineered systems.

Pertinent variables for modeling an elastic-brittle rock to failure initiation are length, stress, unit weight, angle of internal friction, modulus of elasticity, Poisson's ratio, and time. By modeling all or a selected number of these parameters, the researcher will have the necessary tools for studies related to performance and load response (static or dynamic) of structures designed in a rock mass.

For static problems, only two fundamental dimensions are involved: force "F" and linear dimension "ℓ". The similitude requirements that govern the dynamic relationships between the model and its prototype structure depend on the geometric and material properties of the structure and on the type of loading. In general, the dynamics of any structure are governed by an equilibrium balance of time-dependent forces on the structure. These are the inertia forces that are the product of the local mass and acceleration, the resistance forces that are a function of stiffness of the structure in the particular direction in which motion is occurring, and the energy dissipation of the damping forces, whether material or construction related.

For modeling structures in a rockmass, the

following basic conditions of similarity must be satisfied:

- **Geometric Similarity** - requires the ratio of the distance between any two points in the prototype to the corresponding distance in its model to be constant.

- **Kinematic Similarity** - requires that the movement of particles in the model follow those of its prototype with respect to time and space.

Geometrically and kinematically similar structures are dynamically similar if the ratios of various similar mechanical forces that act on any two corresponding particles in the prototype and its model are constant. These parameters are those of elastic, plastic, viscous, gravity, inertia, and friction related forces. Assuming F^* is the force scale factor, the above conditions can be mathematically represented by:

$$\frac{(F_g)_m}{(F_g)_p} = \frac{(F_i)_m}{(F_i)_p} = \frac{(F_v)_m}{(F_v)_p} = \frac{(F_e)_m}{(F_e)_p} = \frac{(F_f)_m}{(F_f)_p} = F^* \qquad (1)$$

where:

F_g = Gravity Force
F_i = Inertia Force
F_v = Viscous Force
F_e = Elastic Force
F_f = Friction Force

It should be pointed out that in this section, the general theory of similarity between a model and its prototype for a purely mechanical system is discussed. Thermal properties are important parts of similarity modeling in geomechanics. However, the emphasis in our discussion is on application of physical modeling for scale-model testing of structures in rock, not dynamic treatment of tectonic evolution. For the later, an excellent treatise by Ramberg (1967) and Hubbert (1937) are available as possible references. Therefore, the similitude conditions are discussed by using the KLOTZ Tunnel tested in China Lake (Halsey, et al. 1989) as the prototype and constructing its 1:20th model - US Air Force Scaled-Model Experiments (Bakhtar, 1993). Furthermore, results of model tests, which form the basis for the Bakhtar Explosives Safety Criteria, are compared with those from the prototype to show the applicability of the modeling approach and the predictive capabilities of the formulated empirical expression.

The derivation of similarity conditions between a prototype and its model can be shown, based on the "stress equation of motion" and the "conservation of angular momentum" (Bakhtar, 1993). The mechanical properties of the model can be completely specified, if the properties of its prototype are known, in terms of the fundamental scale factors mass (m^*), length (ℓ^*), and time (t^*). Several scale factors of interest for model testing, relating mechanical properties of the model to those of its prototype, are shown in Table 3. The remaining scale factors can be derived using the fundamentals of mechanics as discussed by Bakhtar (1993).

The experimental procedure followed for physical modeling of the tunnel explosion scenario are outlined in the following sections. The technical approach is particularly unique because the prototype scenario was modeled at a smaller scale at a fraction of the prototype cost. By preserving the similitude conditions, the results from the scale model tests can be used to predict

prototype behavior. Furthermore, the geologic and engineering systems were physically modeled and tested under pre-determined controlled conditions which facilitated the ease of instrumentation and retrieval of maximum information.

5. TEST BED PREPARATION

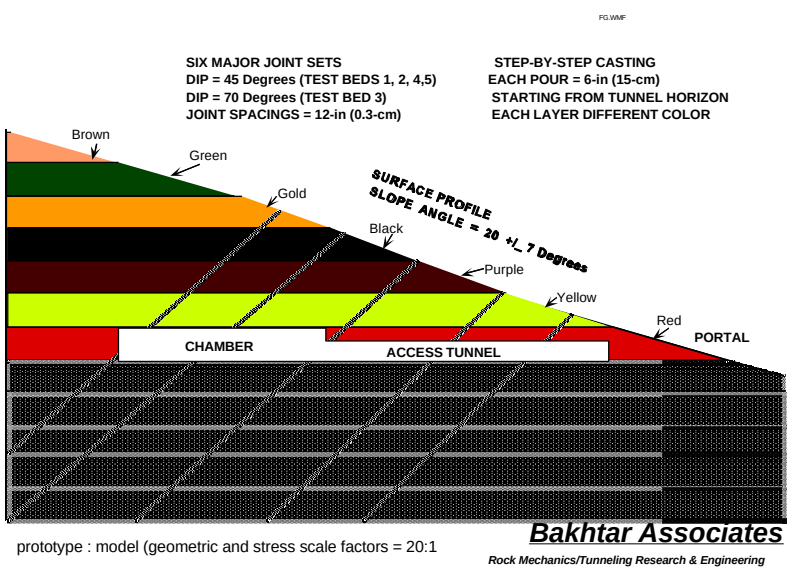

Figure 1. Schematic of A Typical Test Bed.

Cement based compounds were used to formulate the required material model at 20:1 stress and geometric scale factors. (Bakhtar, 1987). The overall properties of the material model, including those of seismic, were used to select a test site with similar seismic impedance.

At marked positions five square trenches with surface area 3.35-m x 3.35-m (11-ft x 11-ft) and depth of approximately 1.83-m (6-ft) in the back and 0.61-m (2-ft) at portal area were excavated to construct the test beds. The volume of earth materials excavated at each location was approximately 14-m^3 (18-yd^3). Total earth material excavated was about 60-m^3 (90 yd^3). The cut materials were hauled outside the test range and stored, to facilitate their ease of emplacement as fill during the site restoration phase of the program.

A step-by-step casting procedure was employed for simulating the geologic features during construction phase of the test beds.

At appropriate depth, model structures (tunnels) were embedded within the test beds to simulate the engineered system. The model structures were fabricated using wire-mesh and gypsum- based cement. Figure 1.Shows a cross-sectional view of a typical test bed with associated discontinuities and geologic features.

Table 3 - Scale Factors for Mechanical Quantities*.

Quantity	Dimensional Form	Scale Factor⊕
Linear Dimension	L	ℓ^*
Area	L^2	ℓ^{*2}
Volume	L^3	ℓ^{*3}
Density	ML^{-3}	$m^*\ell^{*-3}$
Time	T	$\ell^{*1/2}$
Stress	$ML^{-1}T^{-2}$	$m^*\ell^{*-2} = m^*\ell^{*-1}t^{*-2}$
Force	MLT^{-2}	$m^*\ell^*t^{*-2} = m^*$
Velocity	LT^{-1}	$\ell^{*1/2}$
Acceleration	LT^{-2}	$\ell^*t^{*-2} = 1$
Angular Velocity	T^{-1}	t^{*-1}
Mass	M	$m^* = \rho^*\ell^{*3}$
Energy+	ML^2T^{-2}	$m^*\ell^{*2}t^{*-2}$
Impulse	MLT^{-1}	$m^*\ell^*t^{*-1}$
Strain	LL^{-1}	1
Friction Angle	L^O	1
Poisson's Ratio	$\Delta l_1/L_1/\Delta l_2/L_2$	1
Frequency	T^{-1}	t^{*-1}
Curvature	L^{-1}	ℓ^{*-1}

* - For Material Scaling at 1-g.
\+ - Same Scaling Relationship Applied to Impact Energy of Fragments
⊕ - Scale Factor = $\{\text{Characteristic}\}_{\text{prototype}}/\{\text{Characteristic}\}_{\text{model}}$

6. EXPLOSIVES MODELING

Composition-B explosives were used to simulate the equivalent detonation charge in the prototype test. The weight of explosives was based on the scaling relationship developed by the author (Bakhtar, 1996). Parameters used to model the explosives weight included, loading density, density and porosity of explosives (unit weight).

7. EXPLOSION TESTS

Figure 2 shows the general arrangement considered for charge detonation. Exploding

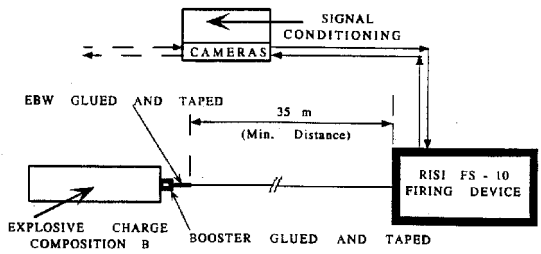

Figure 2. Explosives Charge Assembly.

bridge wires (EBW) are glued and taped to the boosters and subsequently to the comp-B for each case. A RISI Model FS-10 was used as the firing device. The firing device as synchronized with the camera triggering mechanism to facilitate photography and prevent excessive loss of films. The loading procedure for charge emplacement consisted of the following steps:

- EBW was glued and taped to the booster ;
- booster with attached EBW was glued and taped to one end of cylindrical shaped comp-B explosive;
- entire assembly was lowered into the model chamber with the aid of a long and narrow retractable wooden stick;
- required safety procedures for explosives handling and testing were followed;
- explosion tests were conducted once the ideal ambient conditions in terms of the light intensity and wind were confirmed (one to two days were allowed for fragment recovery);
- fragment recovery commenced immediately following the safety inspection post blast.

8. COMPARISON OF MODEL AND PROTOTYPE TEST RESULTS

The loading density for the five explosion tests conducted are shown in Table 4. The first three tests were conducted under identical conditions and were used to compare with the prototype results by applying the respective scale factors.

The maximum range for the prototype fragment recovery is dictated by the minimum debris mass and terminal velocity that induces a kinetic energy of 79 joules upon impact. This requirements led to calculation of a fragment average size of 1.3-mm as the cut-off distance (range) for the model tests debris recovery.

The impact energy of a fragment is scaled using the following relationship (Bakhtar 1993).
Using the above equation, the minimum kinetic

$$\frac{(ENERGY)_{PROTOTYPE}}{(ENERGY)_{MODEL}} = m^{*}\iota^{*2}t^{*-2} \qquad (2)$$

energy associated with a lethal ejecta missile fragment originating from the model tests can be determined as follows:

$$(\text{KINETIC ENERGY})_{\text{MODEL}} = (\text{KINETIC ENERGY})_{\text{PROTOTYPE}}\,(m^{*}\iota^{*2}t^{*-2})^{-1} \qquad (3)$$

or

$$(\text{KINETIC ENERGY})_{\text{MODEL}} = 79\,\{(\rho^{*}\iota^{*3})\,\iota^{*2}(\iota^{*1/2})^{-2}\}^{-1} \qquad (4)$$

But, ρ^{*}, the density scale factor, is unity and the geometric scale factor, ι^{*}, is 20; therefore, expression represented by Equation (3) becomes:

$(\text{KINETIC ENERGY})_{\text{MODEL}}$ =0.0005 joules, which means that for the scaled-model tests, fragments having kinetic energy upon impact of 0.0005 joules and above are lethal or hazardous based on the US Ammunition and

Explosives Safety Standards.

Volumes and weights of fragments recovered from Tests 1 to 5, at cut-off ranges, were calculated from Equation (5) in which d_f and U_f refer to average and true volume of fragments respectively.

$$d_f = (2.2\ U_f)^{1/3} = 1.3(U_f)^{1/3} \quad \ldots\ldots\ldots \quad (5)$$

The maximum distances, from respective portals, were calculated by accounting for the geometric scale factor as shown in Table 5. Also, included in this table are corresponding values for the volume and weight of the respective prototype fragments scaled up using appropriate scale factors.

As mentioned previously, the US DOD Ammunition and Explosives Safety Standards defines a hazardous fragment as one having a kinetic energy upon impact greater than 79 joules. The kinetic energies of impacting materials is given by the Equation (6)

$$\text{Kinetic Energy} = ½\{(m)\ (v^2)\} \qquad (6)$$

With a fragment mass of 27.28 g, the impact velocity at the maximum fragment range is 76 m/sec.

Measurements of launch angle and initial velocities were made using high speed films and introducing a "range-pole" into the picture to be used later as the scale for the photo analysis. In general, the accuracy by which these measurements are made is very much controlled by the ability to initiate the measurement as close as possible to the test bed floor. In many instances such measurements are impossible to make because of the dust cloud formed on the

surface following the detonation. For the five scale model tunnel explosion tests conducted, a series of fast frame cameras located 30.5 m (100 ft) away perpendicular to the chamber-portal axis were used to capture the events. Two range-poles were installed along the extended axis of tunnel- chamber on each test bed to provide the necessary scale and facilitate the ease of fragment velocity determination. An analytical projector was used for the analysis of the fast frame films. Table 6 shows the results.

By tracking a discrete fragment in time space, the author obtained the best estimate of initial velocity and launch angle. These values are shown in Table 4. Many hundreds of fragments radiating from the explosion site can be chosen for such calculations. However, experience and judgment should be used to select a suite of appropriate ejecta for such analyses.

The technique proposed by Jacobs (1994) was used for analysis and interpretation of the hazardous fragment density (more than 1 hazardous debris per 56 m^2).

The US DOD Explosives Safety Standards for fragment hazard range is the distance to a fragment or debris density of one hazardous particle per 56 m^2. All the fragments recovered within the ±20° sectors, was considered to be lethal and hazardous at the 20:1. The model values for the Q-D and maximum fragment range are scaled up by the geometric scale factor of 20 to get the prototype response as shown in Table 6. The maximum fragment range and the Q-D values for Tests 1 and 2 compared very closely with values reported by the Halsey, et al., (1989) and Joachim (1990) for the prototype test conducted in

Table 4. Loading Densities for Bakhtar 1:20th Scaled Model Tunnel Explosion Tests.

Test No	Chamber Volume m^3	Tunnel Volume m^3	Total Volume m^3	Weight of TNT kg	Weight Com-B Explos. kg	Loading Density kg/m^3	
						CHAMBER	TOTAL
1	0.045	0.017	0.062	2.988	2.213	66.40	48.20
2	0.045	0.017	0.062	2.988	2.213	66.40	48.20
3*	0.045	0.017	0.062	2.988	2.213	66.40	48.20
4	0.045	0.017	0.062	0.747	0.553	16.60	12.05
5	0.045	0.017	0.062	0.187	0.139	4.15	3.01

* - Joint orientation is changed to 70 degrees for the geologic system.
Loading density = [TNT equivalent explosive weight]/[Volume of chamber]
Total loading density=[TNT equivalent explosive weight]/[Total volume (chamber/tunnel)]

Table 5. Volume and Weight of Fragments at Maximum Range.

	Model Fragment Range (m)	Model Fragment Volume (cm^3)	Model* Fragment Weight (gm)	Prototype Fragment Range (m)	Prototype Fragment Volume (cm^3)	Prototype Fragment Weight* (gm)
Test-1	100.3	0.0022	0.0034	2005	17.6	27.28
Test-2	113	0.0022	0.0034	2261	17.6	27.28
Test-3	101.8	0.0022	0.0034	2036	17.6	27.28
Test-4	47.8	0.0022	0.0034	957	17.6	27.28
Test-5	18.9	0.0022	0.0034	378	17.6	27.28

Table 6. Estimation of Fragment Initial Velocities and Launch Angle from 20:1 Scaled Model Tunnel Explosion Tests

Test No.	Average Fragment Dimension (d_f)* (cm)	Model Initial Velocity (m/sec)	Model Fragment Launch Angle (Degrees)	Predicted Prototype Launch Angle (Degrees)	Predicted Prototype Initial Velocity (m/sec) **
1	0.86	24	43	43	107
	0.79	28	45	45	125
2	3.56	20	55	55	89
	0.86	17	46	46	76
	4.27	21	49	49	94
3	0.86	27	48	48	121
	0.69	21	55	55	94
4	0.61	26	55	55	116
5	----------	----------	----------	----------	----------

* - Refer to Equations (5) to calculate the volume.
** - prototype velocity = (model velocity) x (geometric scale factor)$^{1/2}$

California. These two tests (1 and 2) were conducted under identical conditions to check the reproducibility of the data by simulating the prototype tunnel explosion test under normal gravity at 20:1 scale.

Halsey, et al. (1989) reported post blast fragment recovery over distances in excess of 2-km or 2012-m (6601 ft) from the portal. Similarly, Joachim's analysis of Q-D within the ±20° revealed a single value of 656 m (2152 ft) for the quantity-distance based on the "one strike per 56 square meter standard".

The results of physical model tests predicted the fragment maximum range and the Q-D values within 8% and 6% of those reported by Halsey, et al. (1989) and Joachim (1990), respectively.

The ejecta initial velocity and launch angle reported for prototype test (Joachim 1990) were at the order of 100 m/sec (329 ft) and 45 degrees, respectively. These values matched very closely with those reported from the scale model tests (1, 2, and 3) as can be seen in Table 7.

9. CONCLUSIONS

The test results presented in Table 7 are unique in terms of the size, model materials, and mix proportions used to construct the test beds. They clearly reaffirm the importance and applicability of physical modelling based on material scaling; for prediction of the response of a structure subjected to explosives loading. They also confirm the importance of obtaining site specific data on geologic and engineered systems by conducting site characterization. This data directly influence the choice of the model size, properties of the model materials, and ultimately, test conditions.

10. ACKNOWLEDGEMENT

The scaled model tests and analytical approach reported in this paper were conducted under an Air Force SBIR Phase II.

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Table 7. Results of Fragment Analysis.

	Model Observed Maximum Fragment Range (m)	Model Q-D Range (m)	Prototype Observed Maximum Fragment Range (m)	Prototype Q-D Range (m)
Test-1	100.5	35.1	2005	702
Test-2	113.6	35.5	2261	709.7
Test-3	1018	26.4	2036	527.3
Test-4	47.8	23.8	957	476.4
Test-5	18.9	17.5	378	350.5

Note: All horizontal distances not slopes.

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