EXPLOSIVE SOURCE TO SIMULATE EARTHQUAKE-LIKE MOTION, AND A LOW-DENSITY EXPLOSIVE FOR SAFE REMOVAL AND EXCAVATION OF GEOLOGIC MATERIALS

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(Earthquake simulation, soil-structure interaction, explosion, low-density explosives)

1. INTRODUCTION

SRI International (formerly Stanford Research Institute) is a non-profit research organization that was founded in 1946 in cooperation with the trustees of Stanford University to provide a center where diversified scientific research could be performed. SRI performs contract research for industry, government, and foundations in the United States and abroad. Research is conducted in physical and life sciences, economics, management systems, electronics and radio sciences, information science, urban and social systems, and engineering systems. SRI does not engage in production or sales.

Poulter Laboratory has been engaged in studying the dynamic response of materials and structures to impact and impulsive loading for more than 50 years. Broad areas of expertise include structural dynamics, stress wave propagation, explosives and explosions, penetration mechanics, and fracture and fragmentation. The laboratory research work involves the world of dynamic phenomena where the events of interest occur in thousandths and millionths of seconds. Theoretical and experimental work are closely coordinated, theory providing the basis for experiment design and the results of experiments guiding development of theory. High-speed computers are used to facilitate theoretical investigations, and extensive state-of-the-art computer codes are maintained in the areas of impact dynamics, explosion research, structural response, wave propagation, thermodynamic equilibrium, and Lagrange analysis. Poulter Laboratory's main experimental facilities are located in Menlo Park, California. In addition, we have an explosive test facility located in the mountains between Livermore and Tracy, about 80 km from the headquarters in Menlo Park.

Two examples of recent research activities are discussed below. The first example involves the development and demonstration of a unique earthquake simulation technique that includes the soil-structure interaction. The second example describes a novel low-density explosive that can be used for controlled fragmentation and removal of geologic materials and can be used to displace large rock masses without shattering them into small debris.

2. EARTHQUAKE SIMULATION TECHNIQUE

SRI has pioneered an earthquake simulation technique, referred to as repeatable earthshaking by controlled underground explosion (RESCUE), that duplicates not only the seismic response spectra of strong earthquakes but also includes the relative motion between the structure and surrounding soil (soil-structure interaction). The RESCUE technique is being demonstrated in a nuclear-free area of the Nevada Test Site (NTS) by a non-profit organization called NeTI (Nevada Testing Institute), which is a partnership between SRI International, Massachusetts Institute of Technology (MIT), and Bechtel Nevada Corporation.

RESCUE consists of specially designed buried sources that expand and contract to produce oscillations in the soil that result in realistic seismic response spectra. RESCUE will be set up as a full- or large-scale testing facility by NeTI at NTS. The structures of interest will be constructed on a permanent soil test bed with the dynamic loads applied to structures through the surrounding soil. This earthquake simulation facility would therefore resemble a large shaking table but with the inclusion of soil. Because the sources do minimal damage to the surrounding soil (applied pressure is less than 1 MPa), sequential pulses of ground motion can be applied, and follow-on tests can be conducted at the same location and on the same structure.

To generate earthquake-like response spectra, the RESCUE loads are applied against a soil cantilever, which is formed by digging trenches around the soil test bed. The NeTI soil cantilever test bed for NTS would be approximately 46 meters square and will be surrounded by a 23-meter deep trench, as shown in Figure 1. The RESCUE source design shown in Figure 2 consists of a neoprene-rubber bladder around a rectangular mandrel. The steel canisters contain propellant that produces high pressure gas when ignited. This gas is vented into the source module in a controlled manner, causing expansion of the rubber bladder against the soil cantilever. When the bladder expands, it moves the soil. The source is surrounded by a steel frame that confines the bladder expansion to the direction of the soil cantilever motion. Individual sources are lined up side-by-side to apply a planar load to the test bed side. Each source can contain from 10 to 20 canisters to produce up to 20 pulses of ground motion. Also, the RESCUE technique is ideal for simulating near field earthquake loads, which consist of several high intensity short duration pulses.

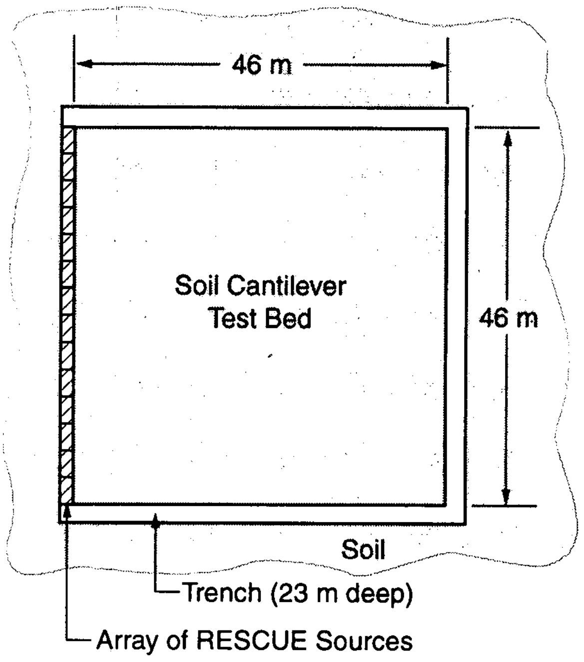

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Figure 1. NeTI soil cantilever test bed.

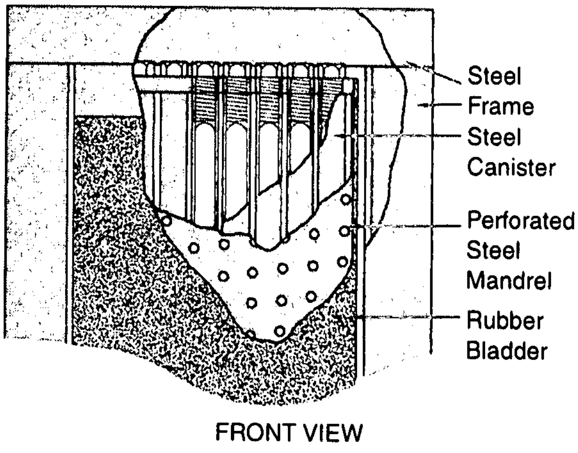

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Figure 2. SRI's RESCUE source design.

The RESCUE technique allows the characteristics of the generated pressure pulse to be easily controlled. The peak pressure depends on the initial pressure within the steel canister, which is a function of the propellant quantity. The rise time of the pulse depends on how quickly the gas from the canisters is vented into the rubber bladder, and the pulse duration depends on the timing of the release of pressure from the rubber bladder to the atmosphere. Therefore, it is possible to match the seismic spectra of virtually all earthquake motions of interest by adjusting the operational parameters of the RESCUE source.

To illustrate the anticipated capabilities of the RESCUE test facility, Lawrence Livermore National Laboratory performed numerical plane strain finite-element calculations using DYNA3D. Figure 3 shows a cross section of the numerical model and the multiple pressure pulses applied to the side of the test bed.

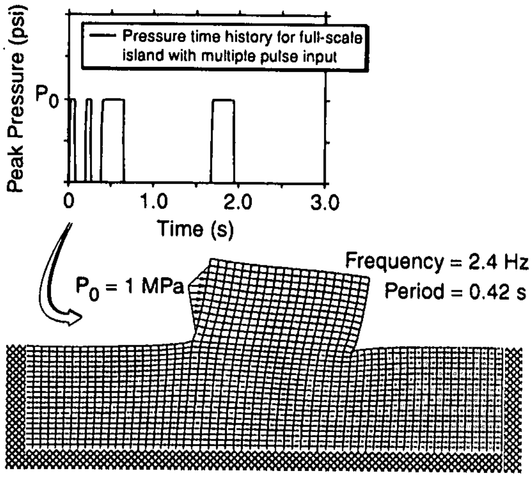

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Figure 3. DYNA3D model of NeTI soil cantilever test bed.

The calculations were performed using an elasto-plastic material model for soil. The following test bed soil properties, which are considered to be representative of the NTS alluvium, were adopted for use in the DYNA3D model:

- Density = 2000 kg/m^3
- Shear Modulus = 335 Mpa
- Shear Wave Velocity = 400 to 500 m/s
- Mohr-Coulomb Friction Angle = 40 degrees
- Poisson Ratio = 0.35

The calculation indicates that the soil cantilever model has a natural frequency of 2.4 Hz. Figure 4 shows the calculated response spectra for 1.0 MPa peak pressure applied to the side of the test bed cantilever. Also shown for comparison is the Japanese Electric Association (JEA) 3XS2 earthquake response spectra design guideline. As shown, the NeTI test facility approaches this guideline and, if required, can be optimized to match this guideline more closely.

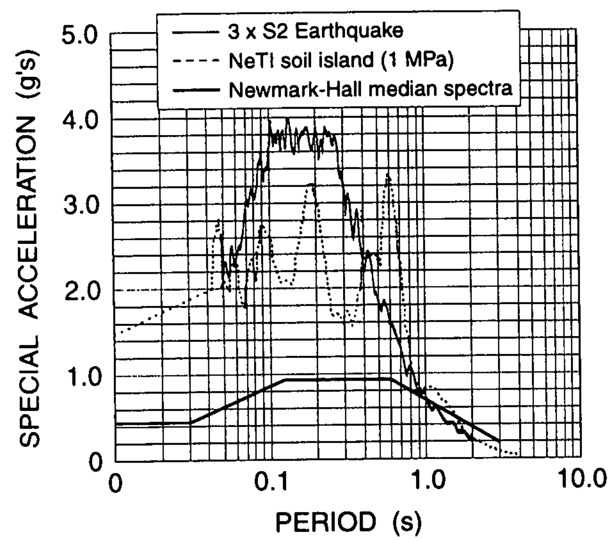

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Figure 4. NeTI soil cantilever test bed response spectra.

At present, the performance of the hardware required for the NeTI RESCUE facility is being evaluated through extensive testing of 1/5-scale prototype source modules called SRISM (SRI source module). SRISM is a 3-m-long source that has the capability of producing two pulses with peak pressures of about 1.0 MPa. The pressure within the source is vented using two specially designed fast responding vents. A series of preliminary tests already performed at SRI's remote test site have indicated the validity of the SRISM design source. These tests will be followed by field experiments at NTS using a complete SRISM source to be installed (at NTS) in June 1998.

3. CONTROLLED EXCAVATION USING A LOW-DENSITY EXPLOSIVE

Explosive fragmentation of concrete and rock is a topic of practical and strategic interest in a wide range of civilian (e.g., mining operations involving explosive fragmentation of rock) and military applications (e.g., surf zone obstacle clearance, weapons effects studies). Of particular interest are unique applications with specific fragmentation requirements that cannot be met using conventional explosives. An example of this type of application is the safe and timely removal of a rock slide from the vicinity of a roadway tunnel without compromising the structural integrity of the structure or the safety of individuals who may be trapped inside the tunnel.

In this study, we attempted to determine the effect of the applied explosive pulse shape on fragmentation. SRI International's dilute explosive tile (DET) [1] was used as a means of controlling the loading pulse and the fragmentation pattern. DET is a castable explosive consisting of PETN in a polystyrene matrix, that offers unique advantages over conventional explosives [e.g., Reference 1]. The primary advantages of the DET are that its detonation pressure can be varied over a wide range (3 to 50 kbar), and its impulse can be controlled independently by adjusting its thickness and configuration.

Five experiments were performed using 1-m-cube concrete specimens [Reference 2]. A 50-cm-deep borehole was drilled in the center of each of the specimens (Figure 5). Depending on the explosive used, the diameter of the borehole was varied such that the TNT-equivalent amount of explosive was kept constant at 312 grams. Three different explosives provided varying peak pressures and pulse durations, thus allowing us to investigate the effects of pulse shape on fragmentation (Table 1).

Two types of DET charges with different PETN concentrations were used in the present testing program: 15% DET which has a PETN concentration of 0.15 g/cm^3, and 30% DET, which has a PETN concentration of 0.30 g/cm^3. The density, detonation velocity, and Chapman-Jouget (C-J) pressure of these two types of DET, as well as those of Composition B, are provided in Table 1. The Composition B properties

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[1] DET is an SRI-owned product patented in the United States (Patent No. 4,722,280). A second patent for sprayable dilute explosive tile (Patent No. 5,417,161) was granted in 1993.

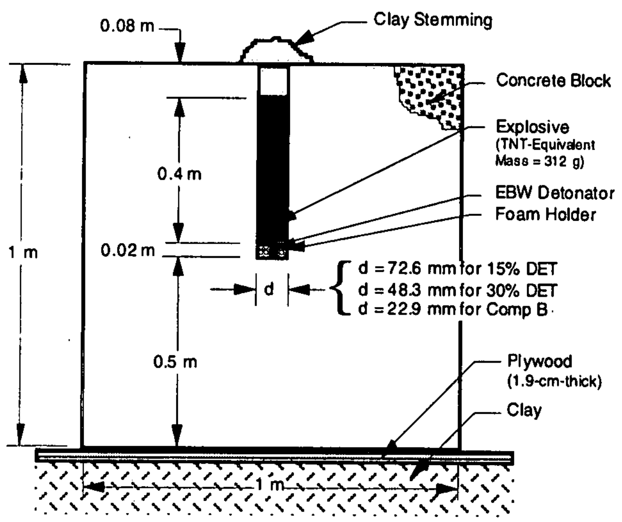


Figure 5. Configuration for the fragmentation experiments in concrete using 15% DET, 30% DET and Composition B.

Table 1. Density, detonation velocity and detonation pressure of the explosives used in the fragmentation experiments.

Explosive	Density (g/cm^3)	Detonation Velocity (km/s)	C-J Pressure (GPa)
15% DET	0.404	1.9±0.1	~0.4*
30% DET	0.60	2.3±0.1	~1.5*
Comp B	1.69	7.98	29.5

*The C-J pressures reported for DET in this table are rough approximations based on indirect measurements.

reported in Table 1 are handbook values [Reference 3]. On the other hand, the properties of 15% and 30% DET are based on experimental measurements.

The concrete used in fabricating the five specimens consisted of cement, aggregate, and water in the proportions shown in Table 2. A water reducing agent was also added to the mix to improve workability. The coarse aggregates consisted of crushed rock with a maximum aggregate size of 1.9 cm, and the fine aggregates consisted of sand with a maximum aggregate size of 4.75 mm.

Table 2. Mix proportions and compressive strength characteristics of the concrete used in fabricating the test specimens.

Material	Solid Volume (ft^3/yd^3)	Weight (lb/yd^3)
Cement (Type II)	3.59	705
Coarse Aggregate	9.41	1650
Fine Aggregate	8.52	1420
Air	0.67	0
Water	4.81	300
Total	27.00	4075

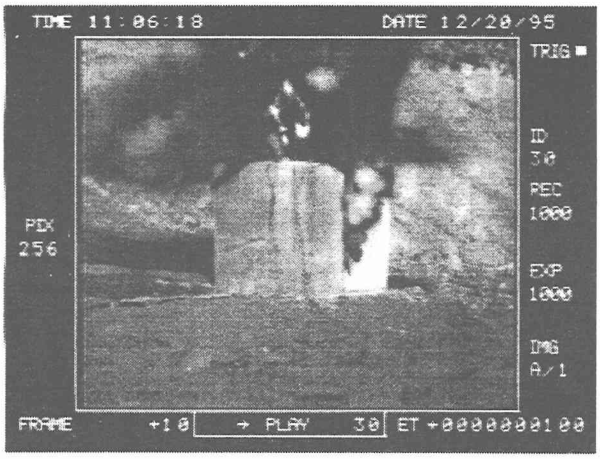
Compressive Strength	5450 psi (37.6 MPa)
Standard Deviation	348.3 psi (2.4 MPa)

The blocks were cast in-place near the Area 1 bunker at SRI International's Corral Hollow Experiment Site where they were later tested (see Gran et al. [Reference 4] for a description of the test site). The concrete was delivered to the test site by a local supplier. All the specimen blocks, as well as several 10.2-cm-diameter by 20.4-cm-long cylindrical specimens, were poured from a single batch. A mechanical vibrator and standard compaction procedures were used to ensure maximum compaction of the concrete.

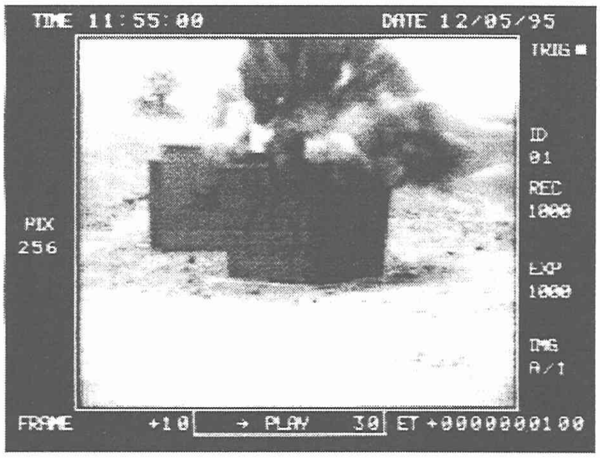
The cylindrical specimens were cured under the same environmental conditions as the 1-m-cube blocks so that the uniaxial compressive strength determined by testing these cylinders would be indicative of the strength of the blocks. All the explosive experiments were performed between 35 and 50 days after casting. Three uniaxial compression tests were performed at an age of 42 days. The results of the uniaxial compression tests are reported in Table 2.

A series of five explosive experiments (Experiments CF-01 through CF-05) were performed using Comp B and two different DET explosives, 15% DET and 30% DET. Experiments CF-01 and CF-04 were performed using 30% DET, Experiments CF-02 and CF-05 were performed using Comp B, and only one experiment, Experiment CF-03 was performed using 15% DET. Each of the five experiments was monitored using a digital high speed video camera that was operated at a framing rate of 1000 frames/s, a Locam high speed camera that was operated at a framing rate of 500 frames/s, and a standard video camera. The data from the high speed film shows significant differences in the fragmentation patterns produced by the three different explosives used. 15% DET produced the fewest fragments followed by 30% DET, and Comp B produced the largest number of fragments. 15% DET also produced the biggest fragments, followed by 30% DET, and then Comp B.

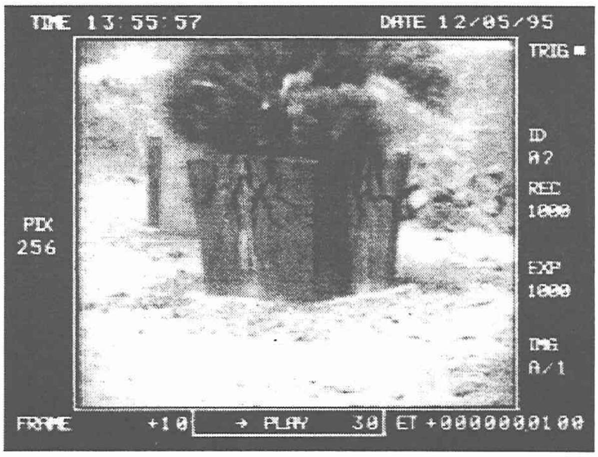
Figures 6 and 7 show photographs reproduced from the high speed videos taken during Experiments CF-01 through CF-03. These figures depict progressive stages of the evolution of the fragmentation process in these experiments. Each figure shows three time-correlated photographs, one from each experiment. The photographs in Fig. 6 depict the fragmentation



(a) Experiment with 15% DET.

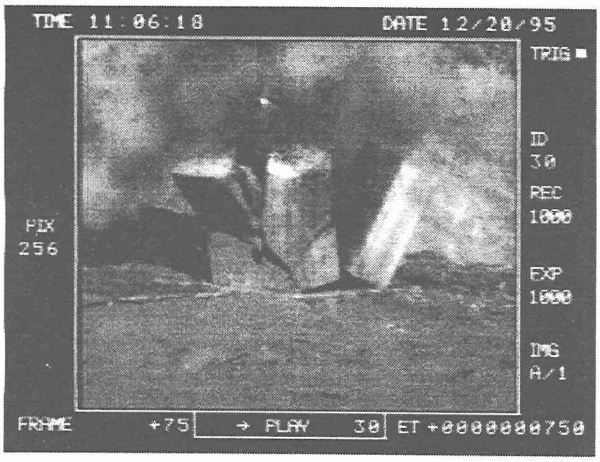


(b) Experiment with 30% DET.

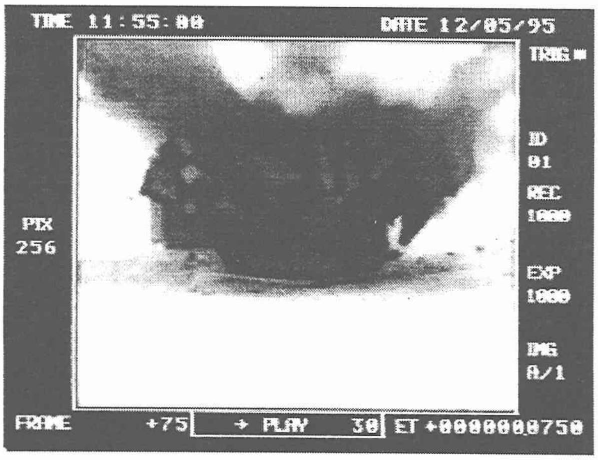


(c) Experiment with Comp B.

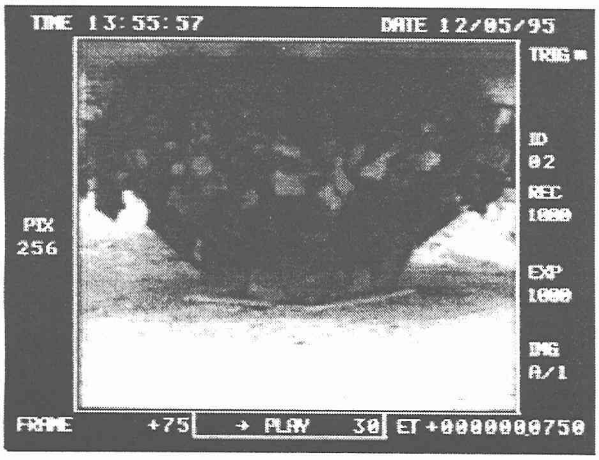
Figure 6. Fragmentation patterns 10 ms after detonation.



(a) Experiment with 15% DET.



(b) Experiment with 30% DET.



(c) Experiment with Comp B.

Figure 7. Fragmentation patterns 75 ms after detonation.

patterns in the concrete blocks 10 ms after detonation, and Fig. 7 depicts those same patterns at 75 ms after detonation. The first photograph in each figure corresponds to the experiment with 15% DET (Experiment CF-03), the second corresponds to the experiment with 30% DET (Experiment CF-01), and the third corresponds to the experiment with Comp B (Experiment CF-02).

A comparison of the results shown in Figs. 6 and 7 clearly indicates that the degree of fragmentation is a function of the pulse shape produced by the explosive charge. Comp B, having the highest detonation pressure and the shortest duration of the three explosives used in this study, is shown to cause more fragmentation than the other two explosives. On the other end of the spectrum, 15% DET, having the lowest detonation pressure and the longest duration of the three explosives used, is shown to cause less fragmentation than the other two explosives.

These observations are qualitative, largely based on post-test observations and high speed photography. To further quantify these observations, we performed two fragment recovery experiments — Experiments CF-04 and CF-05 — wherein the fragments generated during the experiment were softly recovered, weighed, and counted. The fragments generated during Experiment CF-03 were also recovered and characterized so that a quantitative comparison between the fragmentation patterns produced by the three different explosives can be performed.

Two measures by which fragment size distributions can be compared are the median fragment size which is defined as the size that divides the distribution such that 50% of the fragments by weight are larger and 50% are smaller than the median size, and the effective fragment size which is defined as the size that divides the distribution such that 90% of the fragments by weight are larger and 10% are smaller than the effective size. The median and effective fragment sizes for the experiments with the three different explosives are summarized in Table 3. Both the median and effective fragment sizes vary dramatically depending on the explosive, indicating that pulse shape has a significant effect on the observed fragmentation patterns.

Table 3. Measured properties of the effective and median fragments obtained from the experiments with different explosives.

Explosive Type	Effective Size		Median Size	
	Dia. (cm)	Mass (kg)	Dia. (cm)	Mass (kg)
15% DET	59.0	249.8	69.0	399.6
30% DET	14.4	3.64	49.0	143.1
Comp B	3.7	0.06	19.5	9.1

4. CONTACT INFORMATION

Poulter Laboratory is directed by Dr. James D. Colton with Dr. Mohsen Sanai (presenter of this paper), Associate Director, serving as the main point of contact for research activities in Japan. Dr. Sanai can be reached directly by e-mail at ms@unix.sri.com or through the SRI web site, http://www.sri.com/sri.html. Dr. Takao Kobayashi, the other presenter of this paper, can be reached directly at kobayash@unix.sri.com.

Mr. Paul R. Gefken, Dr. Donald R. Curran, and Dr. Jeffrey W. Simons of SRI and Mr. Peter Mote of NeTI are the main researchers involved with earthquake simulation activities. Dr. Tarabay Antoun of SRI is involved with the low-density explosive and controlled fragmentation research activities.

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