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ESTIMATE OF EARTH MEDIA SHEAR STRENGTH AT THE NEVADA TEST SITE

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MASTER

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ESTIMATE OF EARTH MEDIA SHEAR STRENGTHS AT THE NEVADA TEST SITE

ABSTRACT

We present a method of estimating the effective shear strength of the fractured rock that surrounds a nuclear detonation. To do this, we measure the cavity radii from previous detonations. We also use numerical computer codes to model the explosion phenomenology and develop the functional relationship between the normalized cavity displacement and the normalized shear strength of the rock. In this sense, the computer codes serve as replica models that are dimensionally analyzed to interpret the field experience. We separate the effects

of gravity and overburden pressure from the effects of the material properties and give scaling laws for each. We have analyzed approximately 300 nuclear detonations at the Nevada Test Site (NTS) and have found that the most frequent shear strengths are between 0.020 and 0.060 kbars. They are also essentially independent of the depth-of-burial ranges considered. We obtained good agreement between predicted shear strengths and those measured from core samples for different areas at the Nevada Test Site.

INTRODUCTION

There have been more than 300 nuclear test detonations at the Nevada Test Site during the past 20 years. The energy yield of the explosion and the final cavity radius (measured below the center of the detonation) have consistently been recorded for the majority of the tests. Thus, there are extensive data that have never been fully utilized. One reason for this is the difficulty of separating the effects

of the material properties from the effects of the in situ stress, the gravitational field, and yield scaling laws on the cavity radii. Except for those tests conducted within the last seven years, there are relatively little material properties data available.

An earlier report¹ clearly shows that shear strength is the primary material property that determines the velocity field around the expanding

cavity, and thus determines cavity size. It also shows that the velocity field around the expanding cavity is insensitive to large variations in compressibility or air-filled porosity. Later studies²⁻⁶ yield similar results.

Butkovich⁷ uses expansion adiabats for rock gases to determine cavity pressure at full expansion (measured cavity radius). His results show a linear relationship between cavity pressure P_c and the overburden pressure P_o . The ratio P_c/P_o is 2.25 for a shot in salt, 2.0 for granite, and 1.4 for shots in saturated tuffs. However, the effects of gravity are not considered in the analysis, leading to the conclusion that the shear strength is an increasing function of the overburden.

A subsequent study⁸ examined the effect of the overburden pressure on cavity radii and the fracture system in the rock surrounding the cavity. A scaling law was given for cavity radii as a function of yield, depth of burial (overburden pressure), and a characteristic shear strength. This law is very similar to the scaling laws developed earlier by the French based on their Hoggar granite experiments.^{9,10} If these same scaling laws are applied to detonations in rocks with very low strengths, they reduce to scaling laws similar

to those proposed by Butkovich and Higgins (1967),¹¹ and Boardman (1963).¹² None of the above formulas for cavity radii sufficiently separate the effects of gravity from those of strengths and overburden pressure. Therefore, those formulas do not provide meaningful information about the shear strength from measured cavity radii.

To understand how the above affects the response of rock near a nuclear detonation, we propose a method of normalizing the extensive database acquired from past experience. The method employs the concepts of similarity and modeling.¹³ For two years we have been conducting a series of TENSOR¹⁴ calculations and a comprehensive parameter study¹⁵ using the LLL explosion code, SOC.¹⁶ The results of these calculations will be used extensively in the following analysis. SOC (one-dimensional) and TENSOR (two-dimensional) are numerical finite-difference Lagrangian computer codes. They model stress-wave propagation by integrating the conservation equations of continuum mechanics in both time and space. The codes also model the elastic response, plastic-flow, and brittle failure of earth media under dynamic stress loads.

The parameter study is specifically designed as a model from which functional relationships can be obtained

between the dimensionless response terms and the dimensionless variables of the study. We use the term "model" in the same sense as Baker et al.¹³ and Murphy,¹⁷ who wrote, "A model is

a device which is so related to a physical system, that observation on the model may be used to predict accurately the performance of a physical system in the desired respect."¹⁷

PARAMETER STUDY

Because the results of the parameter study are important in the present analysis, we will briefly review some of the initial conditions and variables of that study.

The parameter study was conducted on the SOC code in spherical geometry. The source region was defined by the radius of rock vaporization with the assumption that 70 t of rock per kt of nuclear yield are vaporized by the detonation.⁷ One kt was used for the source energy and resulted in an initial cavity pressure of 1.1 Mbar. The source region was zoned and the rock gas allowed to expand along the adiabat that passed through the $P_0 = 1.1$ mb point of the gas tables for $\text{SiO}_2 + 20\%$ water.⁷ The body forces in the equation of motion were set to zero for all calculations (i.e., no gravity terms).

The equation of state representing the rock was modeled as a saturated tuff with an initial bulk modulus of 49.5 kbars, a soundspeed of 2.0 km/s, a constant Poisson's ratio of 0.3, and a density of 2.0 Mg/m^3 . Figure 1

shows the compressibility curve to 40 kbars.

The only material property that was varied in the parameter study was shear strength. A simple Von Mises yield surface was used in which the shear strength was constant with confining pressure and equal to the unconfined compressive strength. The

Fig. 1. Pressure vs compressibility (μ) response for parameter study.

rock was assumed to have zero tensile strength. Figure 2 shows the five yield surfaces used in the study.

The only other variable in the study was overburden pressure. A constant hydrostatic stress was set in each zone outside the source region to represent the lithostatic overburden stress; each SOC problem was run in a horizontal direction from the detonation point. We performed calculations for each shear strength at overburden pressures of

0, 24, 40, 60, 120, and 240 bars.

The equation-of-state model and initial conditions were kept as simple as possible to apply established scaling methods and to ensure that both variables in the study could be represented by a single value number. Although it has been shown that the complexity of the equation-of-state model does not affect scaling,¹⁸ the simpler models contain all the relevant physics and are easier to analyze.

Fig. 2. Shear strength envelopes for parameter study.

DIMENSIONLESS VARIABLES

The following seven variables can be used as a base set to normalize all the dimensional variables involved in explosion phenomenology. The dimensions of each variable are expressed in terms of length (L), time (T) and force (F):

$r(L)$ Distance from the explosion center; normalizes all other variables with units of length.

$t(T)$ Time from initiation of cavity gas expansion; normalizes all time intervals and frequencies.

$c(LT^{-1})$ Sound velocity; normalizes all variables with units of velocity.

$W(FL)$ Energy yield of source.

$P(FL^{-2})$ Overburden pressure; normalizes all variables with units of stress or energy density.

$\rho(FL^{-4}T^2)$ Mass density.

$K(FL^{-3})$ Equals density times gravitational constant and represents inertial effects of gravity; normalizes all stress gradients.

Application of Buckingham π Theorem on the above variables yields the following dimensionless π terms:

$$\pi_1 = \frac{ct}{r} \quad (1)$$

$$\pi_2 = \frac{\rho c^2}{P} \quad (2)$$

$$\pi_3 = \frac{Pr^3}{W} \quad (3)$$

$$\pi_4 = \frac{Kr}{P} \quad (4)$$

$$\pi_5 = (\pi_3)^{1/3} = \frac{P^{1/3}}{W^{1/3}} r \quad (5)$$

The Hopkinson cube-root scaling law is π_5 . Other π terms can be formed with combinations of the above five, such as

$$\pi_6 = (\pi_3 \pi_4)^{1/4} = \frac{K^{1/4}}{W^{1/4}} r,$$

which gives fourth root scaling for gravity, and

$$\pi_7 = (\pi_5 \pi_5)^{1/2} = \frac{K^{1/8} P^{1/6}}{W^{7/24}} r,$$

which gives Westine's scaling for crater dimensions.¹⁹ Based on TENSOR calculations, we will show that Westine's scaling seems to be the

appropriate scaling law for cavity displacements.

Two other π terms required for this analysis are developed by normalizing the cavity displacement and shear strength using the parameters from the base set, with the same dimensions. These are:

$$\pi_8 = \frac{R_c - R_v}{r}$$

and

$$\pi_9 = \frac{P_o}{\tau},$$

where R_c is the final cavity radius and R_v is the radius of rock vaporization which is also the initial source radius of our parameter study. The shear strength of the parameter study is τ . Multiplying π_5 by π_8 gives the dimensionless response term for analysis of the parameter study:

$$\pi_{10} = \pi_5 \pi_8 = \frac{P_o^{1/3} (R_c - R_v)}{W^{1/3}}.$$

METHOD OF ANALYSIS

The final cavity radius determined from the parameter study is shown in Fig. 3 as a function of the overburden pressure for the five shear strengths. All the calculations came to a static equilibrium condition with the exception of those with overburden pressures P_o equal to zero and also those with shear strengths τ of 10 bars. The equilibrium position for the $\tau = 10$ bars curve was estimated.

The following points in Fig. 3 should be noted:

- The stronger the rock, the less sensitive the cavity radius is to overburden pressure.
- The cavity radius is much more sensitive to the shear strength than the overburden pressure.

- The cavity radii from the parameter study are much less sensitive to the overburden than the cavity radii from the CEP (Containment Evaluation Panel) formula* using the average K constant of 70.2.

A comparison of the CEP formula for cavity radius with the formulas calculated by the parameter study indicates that one should expect an increase in shear strength with depth of burial. The following analysis will show this is not the case.

Figure 4 shows the same information as Fig. 3, using the dimensionless π

* $R_c = \frac{KW^{1/3}}{[\rho h]^{1/4}}$, where W is the yield in kt, ρ is the average overburden density in Mg/m^3 , and h is the depth or burial in metres.

Fig. 3. Cavity radius vs overburden pressure for five shear strengths.

terms π_9 and π_{10} ; it demonstrates the power of dimensionless analysis in reducing the entire parameter study to a single functional relationship. Figure 4 indicates that within the ranges of the shear strength and overburden pressures considered in the parameter study, the important factor in determining cavity displacement is ratio of π_{10}/π_9 , and not either one individually.

The overburden stress P_0 in the normalized displacement (π_{10}) could be replaced by the shear strength τ

to yield a different functional relationship to the ratio of P_0/τ . However, the same shear strength yields the identical cavity radius in both cases. Note that when dimensional analysis is applied to the results of the parameter study, the effects of the primary material property τ and in situ stress P_0 (both of which control cavity growth) are separated from the forces of gravity and stress gradients.

The main effect of including gravity is to alter the exponent on

Fig. 4. Normalized cavity displacement vs normalized shear strength.

the yield (W) that normalizes the cavity displacement. The results of the parameter study can be expressed in the following form:

$$P_o^{1/3} (R_c - R_v) = W^\alpha f(P_o/\tau)$$

where $\alpha = 1/3$ in the absence of gravitational forces, but will have a different value with gravity included. The results of five TENSOR calculations were used to evaluate the above equation to determine α with gravitational forces included. TENSOR, being two-dimensional, correctly

models gravitational effects.

If we rewrite the above equation as

$$\frac{P_o^{1/3} (R_c - R_v)}{f(P_o/\tau)} = W^\alpha,$$

it provides the proper format to determine α .

Yields were varied from 2.2 to 180 kt in nine TENSOR calculations. Strength varied from 30 to 106 bars; overburden pressures varied from 35 to 100 bars. Air-filled porosity varied from zero to 16%. The only

consistent features among all the TENSOR calculations were the numerical scheme used to process the equation-of-state information and the modeling of gravity.

The left hand side of the above equation was evaluated for each TENSOR calculation where P_0 was defined as the overburden pressure at the shot horizon; $f(P_0/\tau)$ was taken from Fig. 4 based on the ratio of P_0/τ from each TENSOR calculation. Figure 5 shows the left hand side plotted against W , the yield of each TENSOR calculation on a $\ln-\ln$ scale. The slope of the line gives an α of 0.295. This is very close to the experimentally determined scaling factor of $1/3.4$ from explosive cratering measurements and also to Westine's scaling exponent of $1/24 = 0.292$ developed from dimensional analysis.

A recent empirical fit to measured cavity radii in Area 3 at NTS by Weaver,²⁰ resulted in a yield exponent of 0.293. Thus, there is very close agreement on the value of α between our calculational approach, a theoretical approach, and two empirical approaches. At this point, everything required to estimate the characteristic shear strength based on measured cavity radii has been provided.

The functional relationship between the primary parameters that control cavity growth has been isolated from any gravitational effects. At the same time, the effect of gravity on the yield exponent has been verified using the functional relationship from the numerical calculations.

Fig. 5. Westine scaling applied to cavity radii from TENSOR calculations.

ESTIMATED SHEAR STRENGTHS FOR PAST EVENTS

As background data for our analysis, we requested the following information for approximately 300 past nuclear events from the LLL data bank:²¹

- Hole designation.
- Event name.
- Energy yield W .
- Depth of burial h .
- Measured cavity radii R_c .
- Overburden density ρ_o .
- Density in the working point region ρ_{WP} .

The overburden and working point densities were only available for about 100 events. For the remaining events, a density of 2.0 gm/cm^3 was assumed, within 20% of most measured values.

To find the characteristic shear strength for each event, the value of $f(P_o/\tau)$ is determined by

$$f(P_o/\tau) = \frac{P_o^{1/3} (R_c - R_v)}{W^{7/24} \rho_{WP}}$$

where

$$P_o = \rho_o g h,$$

$$R_v = 2.557 \left(\frac{W}{\rho_{WP}} \right)^{1/3} \text{ m.}$$

The energy yield W , depth of burial h , and densities ρ_o and ρ_{WP} are taken from the data bank. The

equation for R_v (the radius of vaporization) uses the assumption that 70 t of silicate rock are vaporized per kt of nuclear energy.⁷

The ratio $[P_o/\tau]$ is then determined from Fig. 4, using the value of $f(P_o/\tau)$. The shear strength then, is simply

$$\tau = P_o / [P_o/\tau]$$

where P_o has already been determined.

As previously stated, the CEP formula (Fig. 3) implies that shear strength increases with depth. Using measured cavity radii from the LLL data bank, the shear strengths have been calculated for a large number of events and are shown as a function of depths for Areas 2, 3, 7, 8 and 9, 10, 11 and 12, in Figs. 6, 7, 8, 9, 10, and 11, respectively. Those events with yields less than 1.0 kt have been omitted in the present study. These figures clearly illustrate that shear strength is independent of depth of burial at least for the range of burial depths examined. This conclusion is considered an important result of this paper, but in reality is more of a byproduct rather than a goal of the present study.

A more instructive representation of the calculated shear strengths

Fig. 6. Estimated shear strength vs DOB, Area 2.

Fig. 7. Estimated shear strength vs DOB, Area 3.

based on the cavity radii is given in Figs. 12 and 13. These figures present a histogram of the events with shear strengths in 10-bar intervals between 0 and 150 bars. All strengths greater than 150 bars are shown at the end. Most of the shear strengths are between 30 and 60 bars. Area 3 has the largest percentage of events with shear strengths in excess of 100 bars.

Fig. 8. Estimated shear strength vs DOB, Area 4.

Fig. 9. Estimated shear strength vs DOB, Areas 8 and 9.

The histogram in Fig. 14 shows the sum total of events vs shear strength for Areas 2, 3, 7, 9 and 10. It clearly shows the most common shear strengths are those between 20 and 60 bars. If we assume the shear strength results of Fig. 14 are representative of the full range for Yucca Valley, then the average shear strength is

Fig. 10. Estimated shear strength vs DOB, Area 10.

Fig. 11. Estimates shear strength vs DOB, Areas 11 and 12.

Fig. 12. Histogram of number of events vs shear strength, Yucca Valley.

63.2 bars. The value 63.2 bars is a factor of approximately 4 to 5 lower than that cited previously.⁴

Fig. 13. Histogram of number of events vs shear strength, Area 12.

Fig. 14. Histogram showing total number of events vs shear strength, Yucca Valley.

COMPARISON WITH MEASURED STRENGTH DATA

The geology at NIS is very complex and varies considerably, not only between the different zoned areas, but also within each area. The entire test site is highly faulted resulting in rising paleozoic scarps, variations in the depth of the water table, and the presence or absence of various lithologic layers. Compared to the number of rock types at the test site as well as the number of tests conducted, there is relatively little in the way of measured strength data. However, we have applied the measurements to all test events conducted in the same or similar geologic media.

For those events with documented shear strength measurements, there is good agreement with the calculated shear strengths based on the cavity radii method presented in this paper. We do not feel that this fact validates the cavity radii method. One can still question whether laboratory tests on small core samples are truly representative of the in situ material behavior on the much larger nuclear test scale. However, the agreement obtained does establish confidence in the use of small core-sample measurements in numerical calculations as well as in the method based on cavity radii.

If past events were detonated in a nice homogeneous media without nearby impedance layers, and if all cavity radii were measured accurately, then the method presented here would be preferable to any small sample test. It would then provide a measure of the average strength of the shocked and fractured rock surrounding the cavity. The strength of the rock within two to four cavity radii controls cavity growth. This strength would also represent the strength associated with the residual stress field that develops around explosive spherical charges and which is important in determining the containment prospects of proposed nuclear detonations. Figures 15 and 16 show radial and tangential stress, respectively, as functions of distance from the center of the detonation during the growth of the cavity. These figures (from the parameter study¹⁵) show that a stress field exists around the cavity all during the time of its growth. That field initially increases with distance from the cavity, opposes the outward motion of the cavity, and is directly proportional to the shear strength of media. Thus the strength as determined by cavity radii provides the average strength for a large mass of

Fig. 15. Radial stress vs range at various times during cavity growth.

rock in the crushed and compacted state and at the relevant confining pressure required for analysis of any post shock phenomenology.

Cavity radii are measured with postshot drill holes that tag the position of radioactive melt at the bottom of the cavity. Errors in measurement can occur when the down-hole position of postshot drill holes is surveyed. In addition, the radioactivity log is often difficult to analyze and uncertainties exist in determining the cavity radius. These uncertainties can affect cavity radii

for low-yield events, especially less than 1 kt. In some cases, the emplacement hole is over-drilled and is either left open below the explosive device or loosely stemmed so that radioactivity is found far below the expected cavity surface.

Additional problems occur in relating cavity radii to strength when the device is detonated near the paleozoic surface. Depending on the distance to the paleozoic surface and the shape of that surface, the measured cavity radii can be affected more by the reflective compressive

Fig. 16. Tangential stress vs range at various times during cavity growth.

wave and flow of the tuff along the paleozoic surface than by the strength of the work point rock.

To eliminate some of these obvious sources of errors, we have eliminated events with yields less than 1 kt, those with depths of burial less than three cavity radii of the paleozoic surface, and those with reported open holes below the device.

Measurements of shear strength from small core samples are also not without problems. Relevancy is one such problem. Explosion phenomenology most sensitive to rock strength occurs after the initial shock wave passes,

leaving the rock crushed and fractured. Most strength data is reported from tests on unfractured rock. The measured strength is also very sensitive to water content (i.e., degree of saturation of the sample). In some cases this is not known. Sometimes only dry or fully saturated samples are measured; water content for partially saturated rock then has to be estimated. Strength measurements on samples from the same piece of core may vary by a factor of three or more. This leads to the problem of using these data to determine the representative strength to

characterize the large mass of rock surrounding the explosion center.

Because strength measurements at the test site are relatively scarce, we will present all the data we could obtain to compare with events in the same or similar media. The following discussion will show the shear stress at failure as a function of the mean stress in the sample at failure for different areas of the test site. Using the stress profiles in Figs. 15 and 16, we have plotted the shear strength from cavity radii at the overburden pressure of the working point plus 100 bars.

ALLUVIUM - Area 2

Shear strength data exist for small samples of reconstituted alluvium from U3ct.²² Reconstituted samples were used because intact samples were essentially impossible to obtain or prepare for testing. The water content varied from 7 to 12% by weight, corresponding to a 40 to 60% saturation. Eight data points are shown in Fig. 17 at confining pressures that range from 0.08 to 2.0 kbars. Five tests yielded strengths in excess of 0.1 kbars through which a line representing the upper limit on the strength has been

Fig. 17. Shear strength vs pressure for partially saturated alluvium, Area 2.

drawn. Three tests gave strengths less than 0.06 kbars through which a line representing a lower limit of shear strength has been drawn.

The estimated shear strength based on cavity radii from events in Area 2 is also shown in Fig. 17. Events used were restricted to yields greater than 1 kt and depths of burial between 150 and 400 m. The alluvium in Area 2 between these depths has an average density of 1.9 Mg/m^3 and an average saturation of 72.1%.²³ Most of the estimated strengths based on cavity radii are grouped closer to the lower measured limit and may indicate a higher degree of saturation in Area 2 than in the test samples.

ALLUVIUM -- Area 3

Figure 18 shows the same laboratory test data as Fig. 17. The estimated strengths from cavity radii measurements are from those events in Area 3 that occurred between 150 and 400 m with yields of more than 1 kt. The alluvium above the water table has an average density of 1.71 Mg/m^3 and an average degree of saturation of 50.5%.²³ The samples were tested at the average degree of saturation consistent with the area. The spread in the estimated strengths coincides with the spread in the measured triaxial laboratory tests; many are near the 0.1-kbar range. The event

Fig. 18. Shear strength vs pressure for partially saturated alluvium, Area 3.

in U3ct, from which the samples were taken, resulted in a cavity radius that yielded an estimated shear strength of 0.088 kbars (indicated in Fig. 18 by an asterisk). This is very near the average of the maximum and minimum laboratory test strengths.

SATURATED TUFF — YUCCA VALLEY

Samples from U2en at a depth of 685 m (about 100 m below the water table) were soaked in water for two to four days before testing to insure full saturation. The shear strength measurements²⁴ provided a relatively

large spread in strength as indicated by the dashed lines in Fig. 19. Seven samples were tested at zero confining pressure where the shear strength varied between 0.022 and 0.117 kbars. Three samples had a shear strength of 0.030 kbars. Three samples were tested at a confining pressure of 0.2 kbars, with one strength at 0.052 kbars and two at 0.076 kbars. Three more samples were tested at 0.5 kbars of confining pressure with one shear strength of 0.155 kbars and two at 0.112 kbars. The solid line in Fig. 19 is drawn through those points that gave

Fig. 19. Shear strength vs pressure for saturated tuff at depths near 600 m, Yucca Valley.

reproducible results in the tests. All samples tested with a confining pressure yielded in a ductile manner.

Figure 19 gives the results for nine events. For all nine, the cavities were fully contained in the same formation as the samples, located well below the water table but at least three cavity radii above the paleozoic surface. One event was excluded because of an open hole below the detonation point. Only two events are outside the spread of experimental results from the laboratory tests and seven are grouped about the solid line that represents the best estimate of the average

strength. The strengths based on cavity radii are shown plotted at the overburden pressure of the detonation point plus 0.1 kbar as mentioned earlier.

SATURATED TUFF (50% clay) - Area 8

Triaxial shear strength data from samples taken from Ue8f²⁵ and Ue8i²⁶ at a depth of 339 m and 308 m, respectively, are shown in Fig. 20. The samples consisted of altered tuff with 50% or more montmorillonite clay content. The swelling clay absorbed enough water to saturate. The measurements were taken for a post-shot analysis of the Baneberry event.

Fig. 20. Shear strength vs pressure for saturated tuff (50% clay), Area 8.

There were three events, including Baneberry, within the immediate vicinity of the exploratory holes from which the samples were taken. Baneberry and the other event closest to the exploratory hole gave cavity radii consistent with a shear strength of 0.030 kbars. The only other event in the area indicated a shear strength of 0.144 kbars. The geology at the Baneberry site is now well known because of the intensive post-shot drilling program; the geology of the other two events is unknown. TENSOR calculations of the Baneberry event,²⁷ using the measured strength from Ue8f and the known geologic structure, gave the same final cavity radius measured postshot.

SATURATED TUFF — Area 12

The nuclear tests in Area 12 have primarily been conducted in horizontal tunnels. The accessibility of the tunnels has allowed extensive observation of the geologic layering and permitted careful selection of samples from the various tuff units in the region. More laboratory tests have been performed on Area 12 tuffs than for any other area or rock type at the test site. Figure 21 shows the maximum and minimum shear strength as a function of mean pressure from U12e.14.²⁸ Numerous tri-axial tests were performed and identical tests gave results that

varied by a factor of three or more.²⁸

In Fig. 21 we show the estimated shear strengths for all those events in Area 12 with a cavity radius reported in the LLL data bank. Most of these strengths are grouped within the limits of variation from the tri-axial tests. Three events gave estimated strengths slightly higher than the maximum curve and two events resulted in very high strengths. The two high-strength values are suspect and may be caused by an incorrect cavity radius measurement, proximity of the detonation point to the paleozoic surface, or the possible experimental configuration of the event. Figure 22 compares the same event data with strength measurements on samples from other tunnels in Area 12.²⁹⁻³¹

WET GRANITE — Area 15

The granite in Area 15 is highly fractured and jointed but in its normal state is relatively dry. However, in drilling the holes for the two events in this area, a large amount of water was used such that the pre-detonation conditions were modified to those of a wet granite. Laboratory tests of dry and wet samples showed a remarkable difference in strength. Calculations by Cherry³² and Wagner³³ showed that the wet fractured strength gave the best overall results when compared to the

Fig. 21. Shear strength vs pressure for saturated tuff at depths near 400 m, Area 12.

Fig. 22. Additional shear strength vs pressure measurements for Area 12.

experimental measurements. Wagner³³ concluded that, "in the region into which the cavity expands the effective yield strength is on the order of 200 bars." As can be seen in Fig. 23, the two events in the granite gave estimated shear strength based on cavity radii of 0.221 and 0.191 kbars. This also compares well with the measured fractured wet strength curve.³⁴

PARTIALLY SATURATED TUFF - Area 16

Eight samples from U16a.05 were

tested for strength: four with zero confining pressure and four at 0.5 kbars confining pressure.³⁵ The reported water content varied from 15.8 to 17.5% by weight; the degree of saturation is unknown. None of the tests gave reproducible results and two curves have been drawn to represent the maximum and minimum of the measured data in Fig. 24. Of the four events with measured cavity radii in Area 16, three gave estimated strengths within the scatter of the laboratory test data.

Fig. 23. Shear strength vs pressure for wet granite, Area 15.

Fig. 24. Shear strength vs pressure for partially saturated tuff, Area 16.

CAVITY RADII FORMULA

The results presented in this paper can be simplified into a more easily used form for cavity radii:

$$R_c = \frac{6 W^{7/24}}{P_o^{1/12} \tau^{1/4}}$$

where

W = yield, kt

P_o = overburden pressure, bars

τ = shear strength, bars

R_c = cavity radius, m.

Comparison of the above equation with SOC and TENSOR calculations resulted in maximum error of ± 8% for a range of [P_o/τ] between 0.1 and 5.0. A rough estimate of the shear strength from past events with measured cavity radii is obtained as follows:

$$\tau = \frac{(63)^4 W^{7/6}}{P_o^{1/3} R_c^4}$$

where shear strength is in bars.
This equation provides an estimate of the shear strength within $\pm 20\%$ of

the values determined previously in this report.

A complete listing of all events with a measured cavity radii and corresponding strengths based on that cavity radii is available to those with a proper security clearance.

CONCLUSION

Since the late 1950's, researchers have used numerical computer models to simulate explosions in earth media with varying degrees of success. Calculations have been made to attempt to match experimental velocity and stress measurements and explain observed phenomenology. Much of the inconsistency in matching field data stems from inadequate material behavior models, resulting in the common point of view that calculations are valid only when compared relatively to other calculations, i.e., parameter studies.

Parameter studies have greatly helped to understand the phenomenology of explosions in earth media and to pinpoint the role and sensitivity of various material properties on the response of the rock to the detonation. Concepts in dimensional analysis and similarity methods have also been applied to explosions for many years with various degrees of success. While the scaling laws for the explosive energy source size

and gravitational effects have been solved, the scaling laws for the material properties have not.

Accepting the theory that the shear strength is the dominant material property that affects cavity growth, we conducted a computer parameter study as a model for similarity analysis. Results of that study showed that a functional relationship exists between the normalized cavity displacement and the normalized shear strength in the absence of any gravitational effects.

We applied this functional relationship to TENSOR calculations that also included the effects of gravity. We obtained essentially the same exponent on the explosion yield as other investigators using an empirical analysis. Thus the effects of gravity have been separated from the effects of the material properties and the scaling laws for both have been identified.

The analytical expression derived in this study were applied to

approximately 300 nuclear tests at NTS to estimate the effective shear strength based on cavity radii measurements. The results of this analysis show that the most frequent strengths are between 0.020 and 0.060 kbars and are relatively independent of depth. Comparison with measured shear strength data from laboratory triaxial tests is remarkably consistent and in excellent agreement, thereby supporting both methods as a means of

measuring rock strength.

The parameter study shows that the cavity displacement is not the only measurable response function dominated by the strength; the wave length of the outgoing stress wave is also controlled by shear strength. In addition, particle velocity histories measured some distance from the detonation point can be also used to estimate the effective shear strength of the rock.

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