

ANALYSIS AND SIMULATION OF CAVITY-DECOUPLED CHEMICAL EXPLOSIONS

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ABSTRACT

The objective of this project is to improve our capability to predict quantitatively the decoupling effectiveness of underground cavities in a variety of realistic configurations. This is being accomplished by expanding the existing decoupling data set with data that have recently become available from Russian and Swedish decoupled chemical explosions, and by performing data analysis and numerical modeling of this data set. This is a joint project of Science Application International Corporation (SAIC), the Russian Institute for the Dynamics of the Geospheres (IDG), and NORSAR.

NORSAR has obtained data from seven decoupled chemical explosions in Sweden. The explosions were conducted from 1987-2002 in Älvdalen, Sweden. The explosions were well recorded by the NORES, HAGFORS, and NORSAR arrays, except for the last explosion, which occurred shortly after NORES was damaged by lightning. NORSAR participated in the explosions during the summer of 2001 and 2002. They deployed a number of temporary instruments including one surface instrument for each event on site near the explosion. The last four explosions were conducted in a cavity 5 meters high by 10 m wide by 25 m long. The first three explosions were in smaller chambers. Explosive yields ranged from 2500 kg to 10,000 kg, with charges consisting of TNT, ANFO and ammunition shells. The rock overburden for each explosion was approximately 100 m. Spectral shape of decoupled explosion data is distinctly different from surface explosions in the same area. Variations in coupling depending on the size of the chamber are clearly observable. The smallest explosion in the largest chamber appears to be fully decoupled, while the other explosions are partially coupled. Near field data was recorded on pressure gauges in the chamber and adjacent tunnel, and on velocity gauges in boreholes at several locations near the chamber. We have completed some data analysis of waveforms and spectra at the arrays, and numerical modeling of some of the near field and regional data.

IDG has digitized a set of surface seismic data recorded from a series of Soviet high-explosive cavity decoupling tests conducted in a mine in Kirghizia in the summer of 1960. These decoupled tests were carried out in a variety of mined cavities in limestone with the objectives of assessing the dependence of cavity decoupling effectiveness on cavity volume, cavity shape, and charge emplacement geometry. In a previous study, Murphy et al (1997) conducted extensive analyses of free-field data recorded from these tests in the mine at distances on the order of 10-200 m. However, only limited waveform data were available from this regime, which made it difficult to determine the frequency dependence of the decoupling factors with a high degree of confidence. In the present study, seismic data recorded from a number of these tests on the surface at distances of 5 and 10 km from the source region have been recovered and digitized. We have analyzed the digitized 3-component seismic data that was recorded at surface stations located 5 and 10 km away, and compared these results with those obtained earlier from close-in data. High quality recordings are available from the 1 ton tamped and decoupled tests at the 5 km station, and the 6 ton tamped and decoupled tests at the 5 and 10 km stations. Results of detailed analyses of these data have proven to be generally quite consistent with those obtained from the previous analysis of the corresponding free-field data. In particular, all the decoupled tests conducted in the center of the cavities show low frequency chemical decoupling factors in the range 20-30, while that conducted 1 m from the wall of the 4.92 m radius cavity is about a factor of two smaller, indicating increased seismic coupling associated with nonlinear response of the cavity wall. The seismic signals observed from the 1 ton explosions conducted at the centers of the 2.88 m and 4.92 m radius cavities were found to be nearly identical, confirming that both of these tests were fully decoupled. These experimental results are currently being integrated with the results of theoretical simulation studies in an attempt to define scaling laws appropriate for decoupled explosions conducted in limestone cavities.

OBJECTIVE

The objective of this project is to improve our capability to predict quantitatively the decoupling effectiveness of underground cavities in a variety of realistic configurations. This will be accomplished by 1) expanding the existing decoupling data set using data that have recently become available from Russian and Swedish decoupled chemical explosions; 2) performing numerical simulations of these data and other decoupled data and then using the results to refine the material models used in the simulations; 3) performing numerical modeling of decoupled chemical explosions in nonspherical cavities for a variety of realistic material models and cavity geometries. This is a joint project between SAIC, the Russian Institute for the Dynamics of the Geospheres, and NORSAR.

RESEARCH ACCOMPLISHED

Although cavity decoupling has been the subject of extensive study over a period of nearly 40 years, there is still considerable quantitative uncertainty in the decoupling factor – the ratio of coupled to decoupled seismic signal that can be achieved under different conditions. This uncertainty comes from three sources – first, there is only a limited amount of decoupled data available; second, there is considerable uncertainty in the low pressure equation of state used in numerical modeling of decoupled explosions; and third, there has been only a limited investigation of the effectiveness of decoupling by nonspherical cavities. In this research project, we address all three of these issues. First, we expand on the existing data set using data that have recently become available from Russian and Swedish decoupled chemical explosions. Second, we perform numerical simulations of these data and then use the results to refine the material models used in the simulations. Third, we perform numerical modeling of decoupled chemical explosions in nonspherical cavities for a variety of realistic material models and cavity geometries.

NORSAR has been a participant in a series of recent Swedish decoupled chemical explosions, and has fielded a variety of instruments to record this data set. NORSAR is also gathering data from surface explosions and earthquakes for comparison with the decoupled explosion data. IDG has been reviewing and digitizing data from a series of Soviet high-explosive cavity decoupling tests conducted in a mine in Kirghizia in the summer of 1960. SAIC is performing numerical simulations of some of these explosions.

This paper is organized into three parts:

1. A description of the Swedish decoupling experiments
2. A description of the Kirghizia data and analysis
3. A brief review of cavity decoupling theory and description of numerical simulations.

Swedish Decoupled Explosions

At a site within Älvdalen Skjutfält in central Sweden, a number of decoupled chemical explosions have been carried out within underground cavities at a depth of approximately 100 meters. At Mossibränden, a site less than 20 kilometers from this chamber, outdated ammunition is routinely detonated at ground level by the Swedish Armed Forces. The seismic signals from both categories of explosions have been collected into a database and analyzed. The geographical location of the explosion sites is ideal for the purpose of comparison. The sites are in very close proximity to each other and are approximately equidistant from the seismic arrays HFS (Hagfors, Sweden), NRS (NORES, Norway), and the wide aperture NORSAR array (Figure 1). Figure 2 shows the location of the underground chamber relative to the surface and local instrumentation.

Table 1 Cavity decoupled explosions at the Älvdalen site. Origin times of the 1987-89 events were estimated from arrival times at NORES. Origin times of the 2000-2001 events were determined from a station at the explosion site.

Origin ID	Explosion origin time	Explosion charge (kg)	Explosive	Chamber Volume (m ³)	Charge/Volume (kg/m ³)
1987C146	1987-146:10.47.38.2	5000	ANFO	300	16.7
1987C259	1987-259:10.36.13.0	5000	ANFO	200	25.0
1989C263	1989-263:10.06.03.5	5000	ANFO	300	16.7
2000C348	2000-348:10.03.02.0	10000	TNT	1000	10
2001C150	2001-150:10.03.56.2	2500	TNT	1000	2.5
2001C186	2001-186:10.41.23.5	10000	Ammunition Shells	1000	10
2002C164	2002-164:08.59.25.1	10000	TNT/powder	1000	10

The seismic signals resulting from the three Älvdalen events from 1987 and 1989 have far higher amplitudes than the later events which probably reflects the differences in charge/cavity volume as displayed in Table 1. Despite the larger amounts of explosives used, the larger chamber size results in far weaker signals.

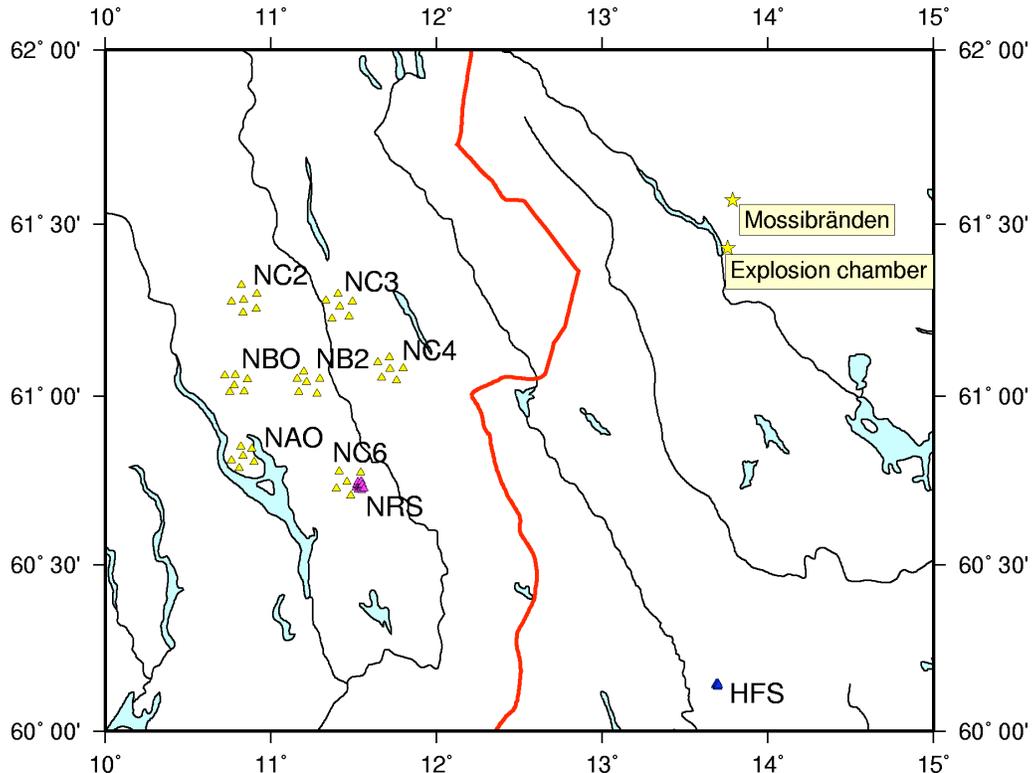


Figure 1. The location of the explosion sites relative to the HFS and NRS arrays and the NORSAR (NOA) sub-arrays. The solid red line is the Norway/Sweden national boundary.

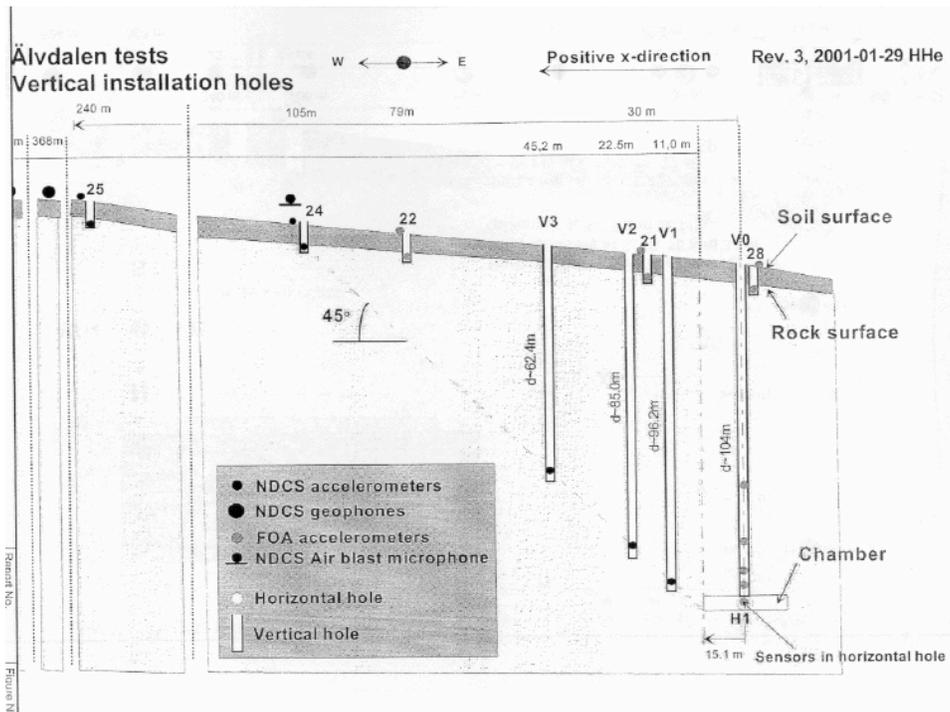


Figure 2. Location of chamber relative to the surface and local instrumentation.

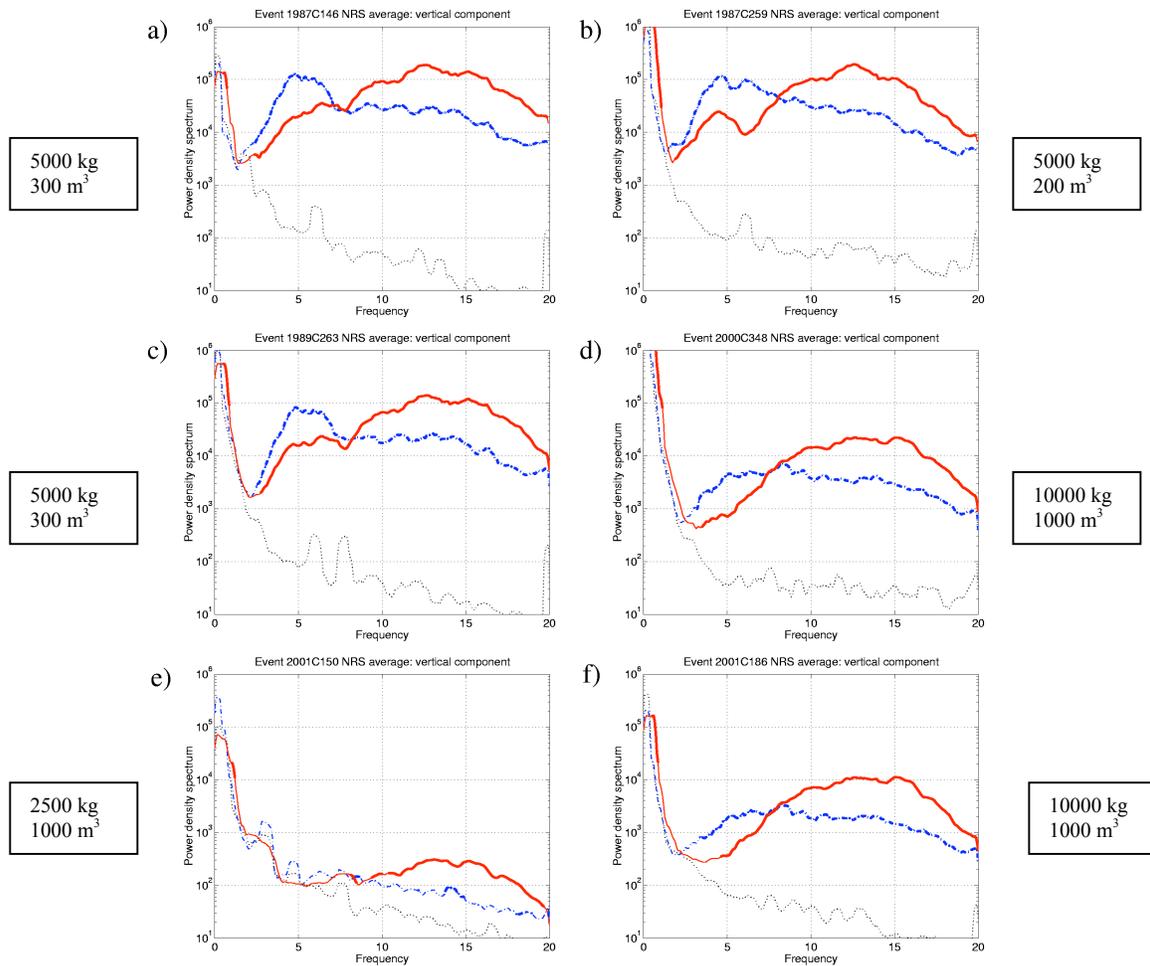


Figure 3. Average power density spectra (PDS) from NORES vertical component data for six decoupled explosions as indicated; all spectra are converted to HFS response. The solid red line indicates PDS for the P window, the dashed blue line indicates PDS for the S window and the dotted black line indicates PDS for the noise window. At frequencies where the PDS for the P or S window is less than 4.0 times that for the noise window, the signal spectrum is shown as a thin line.

In order to quantify the differences between these decoupled events, we examine the power density spectra. For each component, three time windows were defined corresponding to the P arrival, S arrival, and pre-event noise. A 5 second window of waveform data was extracted immediately after the P onset, and a 10 second window immediately after the S onset. A 10 second window ending 2 seconds before the P onset was defined in order to quantify the level of noise which is expected in the signal. A power density spectrum was calculated for each time window. In order to provide a common basis for comparison, we have converted all spectra to the characteristics of the HFS response. Unlike the NORES response, the HFS response is flat to velocity over the passband. Converted power density spectra, averaged over the vertical components of the NORES array, are shown in Figure 3 for the 6 explosions listed in Table 1 which were recorded by NORES, for frequencies up to the Nyquist frequency of 20 Hz. The results displayed in Figure 3 clearly show that the reduction in seismic energy is greater for the explosions in the larger chamber than those in the smaller chamber. This indicates that a greater decoupling is associated with the larger chamber.

NORSAR has also collected a large number of recordings from surface explosions for comparison with the decoupled data. A detailed analysis of this data is given in Stevens et al (2002). A characteristic difference between the two sets of events is that the surface explosions have more long period energy than the decoupled explosions (Figure 4). This difference is predictable because of the longer time duration of the surface source relative to the decoupled explosion.

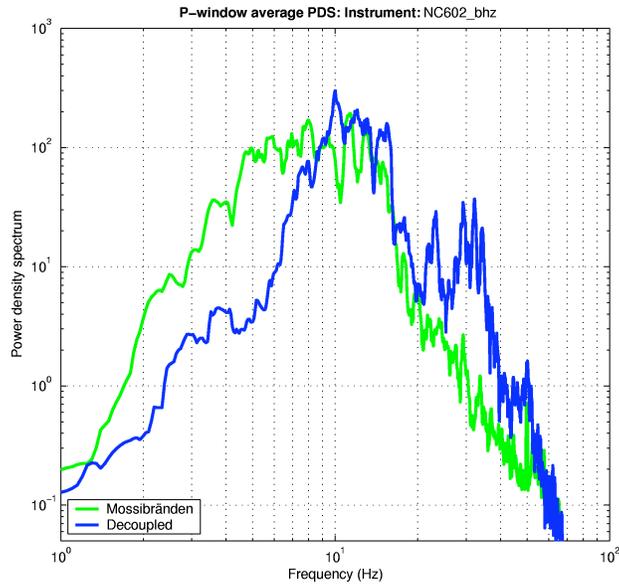


Figure 4. Power density spectra for the P arrival time window recorded on a high frequency GeoSys instrument with a 200 Hz sampling rate located at NORSTAR. The blue line (first) corresponds to the 2001C186 decoupled explosion and the green line (second) is the average of 5 surface explosions.

Kirghizia Decoupled Explosions

During the summer of 1960, Soviet scientists carried out a series of high explosive (HE) cavity decoupling tests in a mine in the Tywya Mountains of Kirghizia. These included tests designed to evaluate the effects of cavity shape and charge geometry on decoupling effectiveness, in addition to conventional spherical cavity tests similar to those employed in the corresponding U.S. COWBOY test series. The Kirghizia test series was composed of 10 tamped and 12 decoupled explosions with yields of 0.1, 1.0 and 6.0 tons. For the cavity tests the explosives were suspended in the chambers and included cases in which the explosives were positioned off center, near the cavity walls. The configurations of the various cavity tests are graphically summarized in Figure 5 for each of the five test chambers.

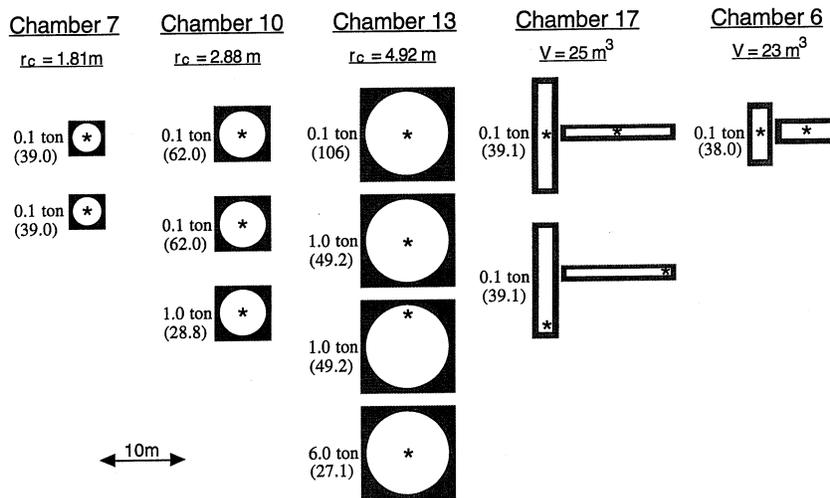


Figure 5. Graphical summary of the Kirghizia HE decoupling tests conducted in each of the excavated explosion chambers. The asterisk denotes the emplacement location of the charge within the chamber for each test. For the nonspherical cases, both horizontal (left) and vertical (right) sections through the chambers are displayed. The numerical values shown in parentheses below the yield values are the scaled radii in $m/kt^{1/3}$, with equivalent volume spherical cavity values listed for the nonspherical cases.

In our previous analysis of these tests (Murphy et al, 1997), we focused on free-field data recorded in the mine at distances on the order of 10 – 200 m. Unfortunately, only limited waveform data were available from this regime and, consequently, the analyses focused primarily on comparisons of peak amplitude values. While such comparisons provided a reasonable basis for comparing the relative decoupling effectiveness of different cavity configurations, they did not provide an adequate data set for confidently determining the frequency dependence of the absolute level of the decoupling factor. Consequently, under the current effort, we have recovered and digitized seismic data from these tests recorded at surface stations located at distances of 5 and 10 km. High quality recordings are available from the 1 ton tamped and decoupled tests at the 5 km station, and the 6 ton tamped and decoupled tests at the 10 km station. Results of detailed analyses of these data have proven to be generally quite consistent with those obtained from the previous analysis of the corresponding free-field data. Examples of these data are shown in Figure 6 which provides a comparison of vertical component recordings at the 5 km station from 1 ton tamped and decoupled explosions. In this case, the decoupled tests were conducted at the center of spherical cavities with radii of 4.92 and 2.88 m, and 1 m from the wall of the 4.92 radius cavity. It can be seen that the signal levels for the tests in the centers of the two different sized cavities are very comparable, indicating peak motion decoupling factors of about 20 and suggesting that both of these tests in different size cavities were fully decoupled. The signal level for the test near the cavity wall is about a factor of 2 larger, suggesting some significantly enhanced coupling associated with local nonlinear wall response.

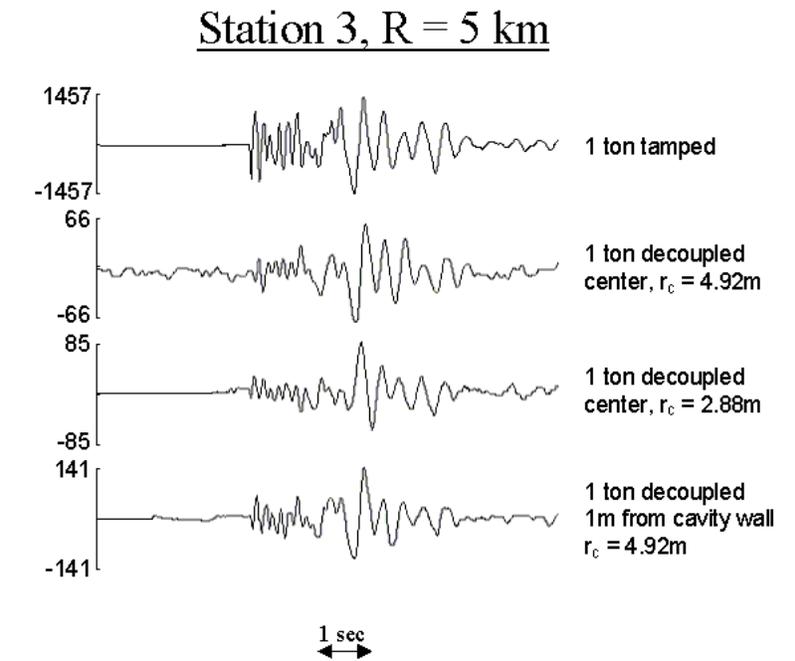


Figure 6. Vertical component recordings at the 5 km surface station from 1 ton tamped and decoupled explosions.

Recordings from the 6 ton tamped and decoupled explosions at the 10 km station are shown in Figure 7. In this case the decoupled explosion was detonated at the center of the 4.92 m radius spherical cavity. Again, the peak signal levels from the two tests shows a decoupling factor of a little more than 20, consistent with the results from the 5 km station and suggesting that this larger test was also fully decoupled. We have computed frequency-dependent decoupling factors between 1 and 4 Hz from these 5 and 10 km station recordings and the results are shown in Figure 8, where it can be seen that the decoupling factors for the two 1 ton tests in the centers of the different sized cavities over this frequency band are essentially identical and consistent with a low frequency decoupling factor in the range 20 - 30. This confirms that these explosions must have been essentially fully decoupled. The frequency dependent decoupling factor for the 1 ton test near the cavity wall is quite similar to the other two in shape, but lower by about a factor of 2, independent of frequency over this range. The results from the 6 ton test are in good agreement with those of the fully decoupled 1 ton tests, suggesting that it also was essentially fully decoupled. The decoupling factor for all of these fully decoupled tests over this frequency band is somewhere in the range of about 20 to 30. Also shown on this figure are the corresponding results at higher frequency (i.e. 10 – 200 Hz) obtained previously by Murphy et al (1997) using the limited free-field waveform data. It can be seen that the results from the

two distance regimes are generally quite consistent, confirming a low frequency decoupling factor in the range of 20 – 30 for these fully decoupled tests in limestone.

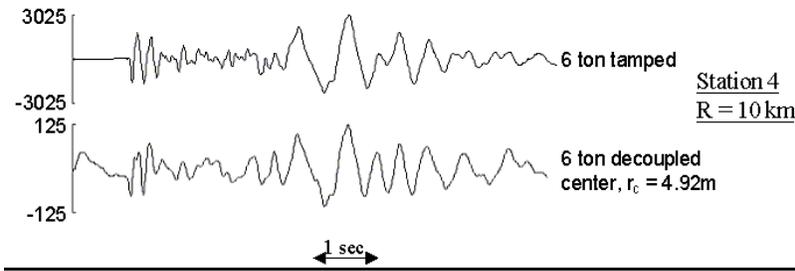


Figure 7. Vertical component recordings from the 6 ton tamped and decoupled tests at the 10 km station.

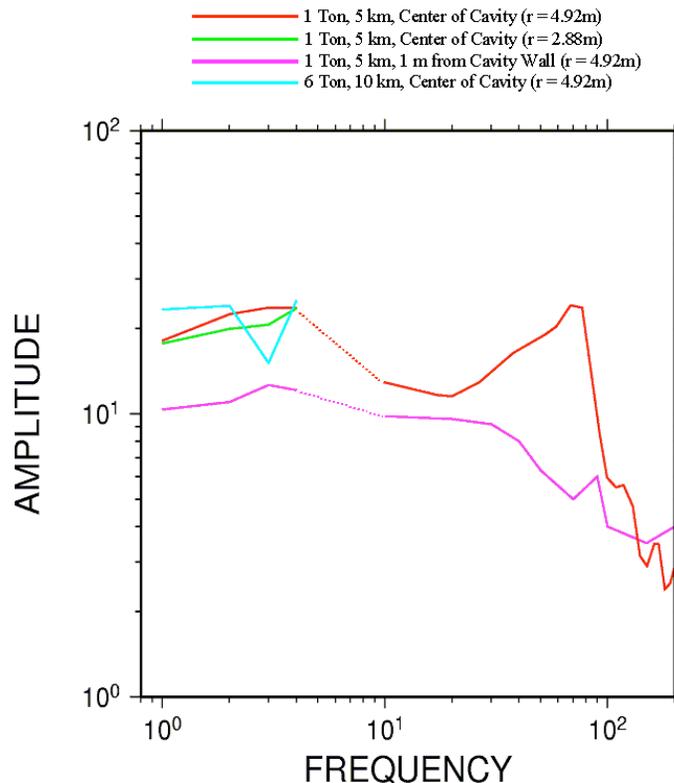


Figure 8. Frequency dependent decoupling factors for the 1 and 6 ton tests at the 5 and 10 km stations. Also shown are the corresponding results at higher frequency (i.e. 10 – 200 Hz) obtained previously by Murphy et al (1997) from the corresponding free-field data.

Cavity Decoupling Theory and Numerical Simulations

The source function for a fully decoupled explosion can be described as a pressure pulse applied to the wall of a cavity in an elastic medium. The actual physics is more complicated than this – there are reverberations in the cavity that cause high frequency spectral peaks, for example. However the simple model is useful for illustration and has most of the characteristics of a decoupled explosion.

The reduced velocity potential (RVP) for a pressure pulse $P(t)$ with derivative $\dot{P}(t)$ and corresponding Fourier transforms $P(\omega)$ and $\dot{P}(\omega)$ applied to the wall of a spherical cavity is (Stevens et al, 1991):

$$\dot{P}(\omega) = \dot{P}(\omega) \frac{R^3 \omega_0^2}{4\omega \omega_0^2 + i\omega \omega_0 \omega (\omega + 2\omega_0) / 4\omega \omega_0^2} e^{i\omega/\omega_0} \quad (1)$$

where $\omega_0 = \omega / R$, where R is the cavity radius, ω is the compressional velocity of the external medium and λ and μ are the Lamé constants of the external medium. For a step in pressure of magnitude P_0 applied at time $t = 0$,

$\dot{P}(\omega) = P_0$, and for this or any pressure pulse with static value P_0 , in the low frequency limit, we have

$$\omega = P_0 R^3 / 4\omega \quad (2)$$

For an explosion in an air-filled cavity, the static value of the pressure is related to the yield W by

$$P_0 = \frac{(\gamma - 1)W}{V} \quad (3)$$

where γ is the adiabatic expansion constant, which is approximately 1.2 for air and 1.3 for chemical explosion products, and V is the cavity volume.

The “decoupling factor” D is defined as the ratio of the fully coupled to decoupled source:

$$D = \omega_{tamped} / \omega_{decoupled} \quad (4)$$

The theoretical decoupling decreases with frequency. Figure 9 shows the coupled and decoupled source function and the frequency dependent decoupling factor obtained by taking the ratio of coupled to decoupled source. The decoupling factor decreases by an order of magnitude at high frequencies beginning at about 10 Hz, which is consistent with the observed differences between low and high frequencies in the Swedish explosions, as well as the observed frequency dependence in decoupling observed in the Kirghizia explosions (Figure 8).

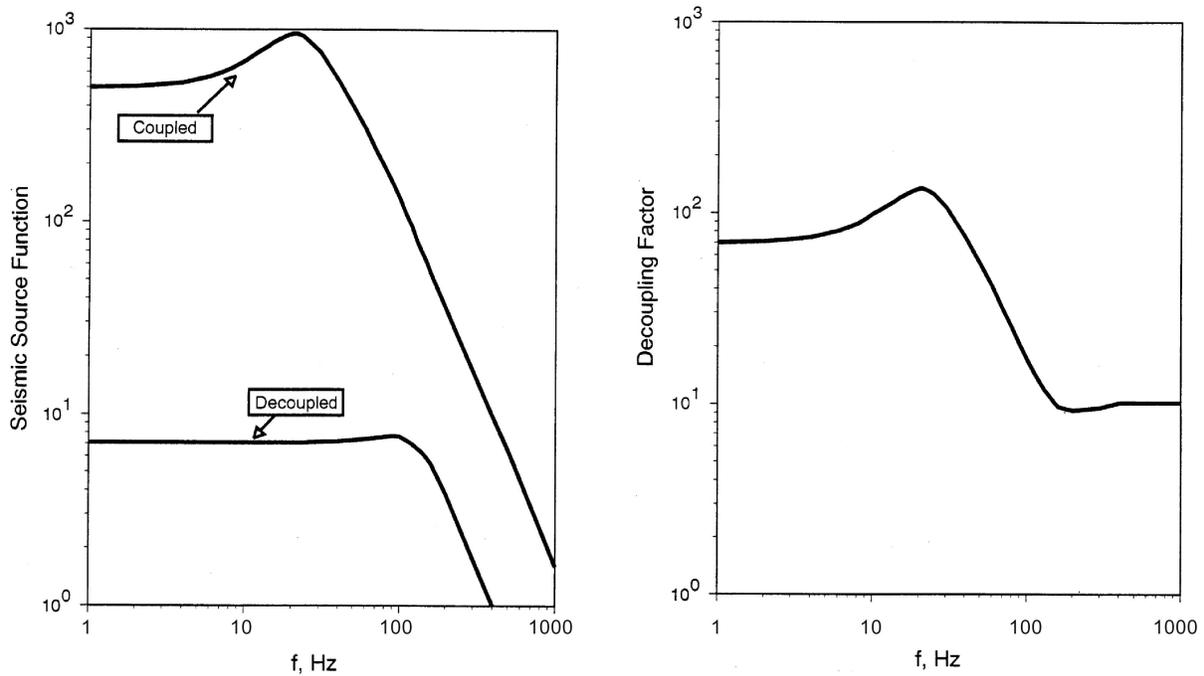


Figure 9. Source functions for fully coupled and fully decoupled 10-ton chemical explosions for a step pressure source in the cavity (left) and frequency dependent decoupling factor (right).

The criterion for full decoupling is usually expressed in terms of a requirement that the late-time, equilibrium pressure in the cavity be less than or equal to some constant, k , times the overburden pressure:

$$\frac{(\gamma - 1)W}{V} \leq k \rho g h \quad (5)$$

where k is between 0.5 and 1.0, and $\rho g h$ is the overburden pressure at depth h .

For the conditions of the Swedish chamber explosions which are at a depth of 100 meters depth in granite, the criteria for full decoupling is in the range of $1 \text{ kg/m}^3 - 2 \text{ kg/m}^3$. Since these criteria were developed for spherical cavities, and nonspherical cavities bring the walls closer to the explosion where they experience a stronger shock, we expect some nonlinear behavior at lower yields. So referring to Table 1, the Swedish explosions cover a range from almost fully decoupled (2500 kg in 1000 m^3 chamber) to being overdriven beyond full decoupling by about a factor of 20. When the explosion yield is increased above the yield required for full decoupling, the coupling increases slowly at first, then changes rapidly and eventually reaches tamped coupling. However, there have been relatively few observations of partial decoupling, and the observations have been quite variable. The Swedish explosions therefore add some valuable new data points to help constrain this effect.

Figure 10 shows a comparison between the “observed” decoupling factors for the Swedish explosions and decoupling factors for a series of calculations of chemical explosions in a cavity in granite. “Observed” is in quotes because we do not have data from a tamped explosion for comparison. Instead, we scaled the decoupling factor of the most decoupled explosion to 100 to agree with the calculation for a fully decoupled explosion. The figure shows that the explosions remain almost fully decoupled until the charge/volume is approximately equal to 10, after which increases in yield cause a rapid decrease in decoupling. The calculation also shows this effect of nearly constant decoupling followed by a rapid decline. In the calculation the decline occurs at a higher charge/volume, most likely because the material used in the calculation was a stronger granite model, and because the Swedish cavities are not spherical, which increases coupling. Further calculations are now being done for more appropriate granite models, as well as calculations in two and three dimensional geometries.

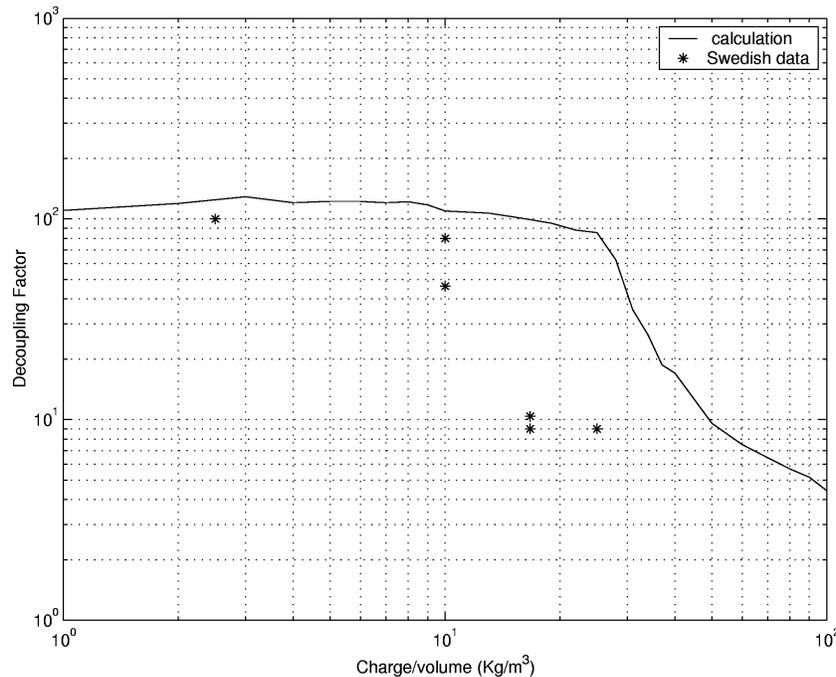


Figure 10. Observed and predicted decoupling factor for Swedish explosions. Calculations were for a chemical explosion in a 6.3 meter spherical cavity in hard (non-weakening) granite. The decoupling factor contains an unknown scale factor. The horizontal axis corresponds approximately to the overdrive factor above full decoupling.

CONCLUSIONS AND RECOMMENDATIONS

We are in the second year of a project to evaluate the decoupling effectiveness of underground cavities in a variety of configurations. New datasets have been provided by NORSAR and IDG that help to constrain the problem, particularly for the important partially coupled regime. Over the next year, the data set will continue to increase, and we will continue analysis of the data using empirical data analysis and numerical modeling of the chemical explosion data.

Following is a summary of some of the results achieved to date on this project.

Kirghizia Mine explosions provided by IDG:

- New data recorded on the surface at distances of 5 and 10 km have been analyzed and the results have been found to be generally consistent with previous results obtained from more limited free-field data, confirming low frequency decoupling factors in the range of 20-30 for fully decoupled HE tests in limestone.
- An explosion close to a cavity wall increases coupling by about a factor of 2.
- Decoupling in this data set is insensitive to cavity shape.

Swedish decoupled explosions provided by NORSAR:

- This new data set covers a range of yields overdriven beyond full decoupling by factors of approximately 2-20.
- The explosions in the smaller chambers produced far stronger signals despite significantly lower yields, consistent with expectations for partially coupled explosions.
- The resulting seismic signals from the Älvdalen cavity explosions display a low ratio of low frequency (2-6 Hz) energy to high frequency (8-16 Hz) energy. This ratio was lower for 10000 kg explosions in a 1000 m³ chamber than for 5000 kg explosions in chambers of 200 m³ and 300 m³.

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