

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

ANALYSIS AND SIMULATION OF CAVITY-DECOUPLED CHEMICAL EXPLOSIONS

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ABSTRACT

The objective of this project is to improve our capability to quantitatively predict 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.

We have previously reported on the analysis of data from seven decoupled chemical explosions conducted from 1986-2002 in Älvdalen, Sweden. The last four explosions were conducted in a cavity approximately 4 meters high by 8 m wide by 30 m long (1,000 m³). The first three explosions were in two smaller chambers approximately 3 meters high by 4 meters wide with lengths of 17 meters (200 m³) and 25 meters (300 m³). Explosive yields ranged from 2,500 kg to 10,000 kg, with charges consisting of TNT, ANFO, and ammunition shells. The smallest explosion in the largest chamber appears to be fully decoupled, while the other explosions are partially coupled. Several 1,000 kg explosions were also conducted in the two smaller chambers, but we do not have times for these events, and they were not identified in seismic bulletins. We have applied a waveform correlation procedure to the NORSAR data for the approximate time period of the explosions using data from one of the larger events as a matched filter and have identified the data for some of the smaller explosions, allowing us to expand the data set further. For the more recent explosions, near field data were recorded on pressure gauges in the chamber and adjacent tunnel, and on velocity gauges in boreholes at several locations near the chamber. We have modeled these data using three-dimensional finite difference calculations. The calculations show enhanced signals in the direction along the small axis of the chamber and reduced signals near the long end of the tunnel. Although we do not have free field data from all directions, the data for the available locations are consistent with these calculations.

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

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

Swedish Decoupled Chemical Explosions

At a site within Älvdalen Skjutfält in central Sweden, a number of decoupled chemical explosions have been carried out within three underground chambers at a depth of approximately 100 meters (Gronsten and Krest, 2002; Gronsten, 2000). Figure 1 shows the location of the site together with the locations of the seismic arrays HFS (Hagfors, Sweden), NRS (NORES, Norway), and the wide aperture NORSAR array. Stevens et al. (2003) described preliminary data analysis using data from seven decoupled explosions at the Älvdalen site. This data set has now been expanded by searching the NORSAR archives for additional data from smaller (1000 kg) explosions that were not previously detected. Table 1 lists all events for which some seismic data has been identified.

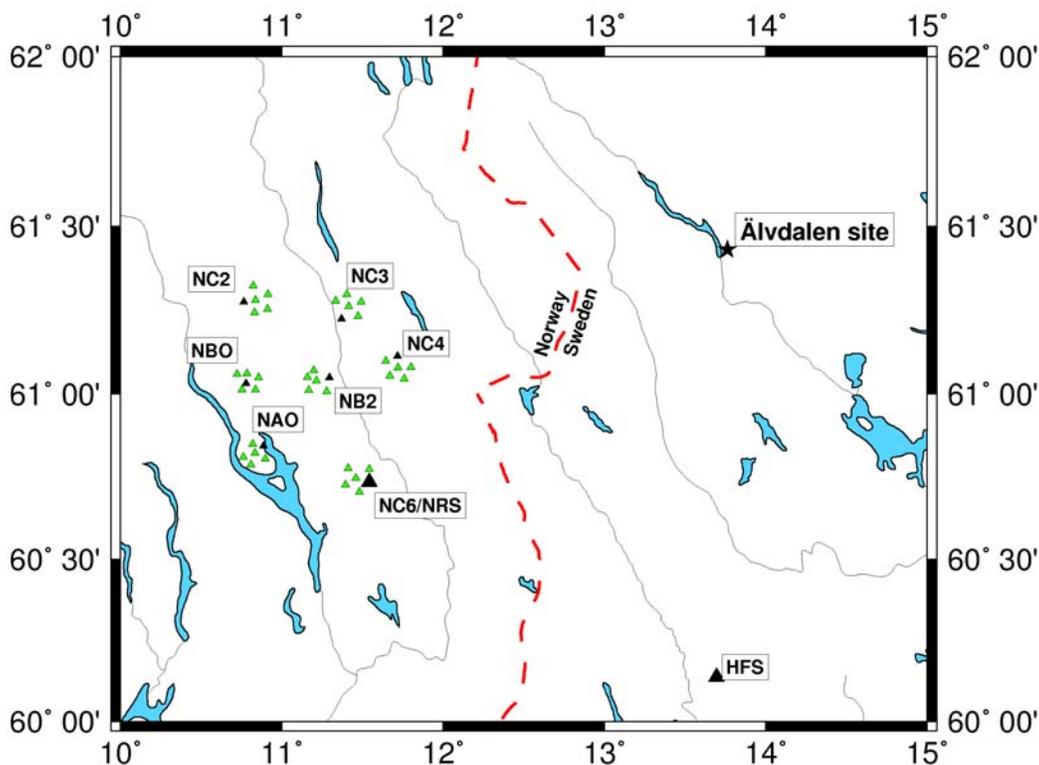


Figure 1. The location of the explosion site relative to the HFS and NRS arrays and the NORSAR (NOA) sub-arrays. The dashed line is the Norway/Sweden national boundary.

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

Table 1 Cavity decoupled chemical explosions at the Älvdalen site. Origin times of the 1986-89 events were derived from waveform cross-correlation measurements. Origin times of the 2000-2002 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)
1986C168	1986-168:10.06.15.9	1000	TNT	300	3.3
1986C177	1986-177:09.14.06.6	1000	TNT	200	5.0
1986C260	1986-260:11.34.17.4	1000	Ammunition Shells	300	3.3
1986C246	1986-246:11.50.45.1	1000	Ammunition Shells	200	5.0
1987C141	1987-141:10.16.08.3	1000	ANFO	300	3.3
1987C146	1987-146:10.47.38.2	5000	ANFO	300	16.7
1987C259	1987-259:10.36.13.0	5000	ANFO	200	25.0
1989C242	1989-242:10.12.21.0	1000	Ammunition Shells	300	3.3
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 1000 kg events did not appear in any seismic bulletin and a visual search of the records for the corresponding day (the time was not available) identified only one probable signal. We therefore developed a waveform correlation technique using the event with the largest signal (1987C259) as a master event. The data from this event was cross-correlated with the data for the known day of each event. Arrivals from all six of the 1000 kg events were identified using this technique. Figure 2 shows an example for event 1986C177.

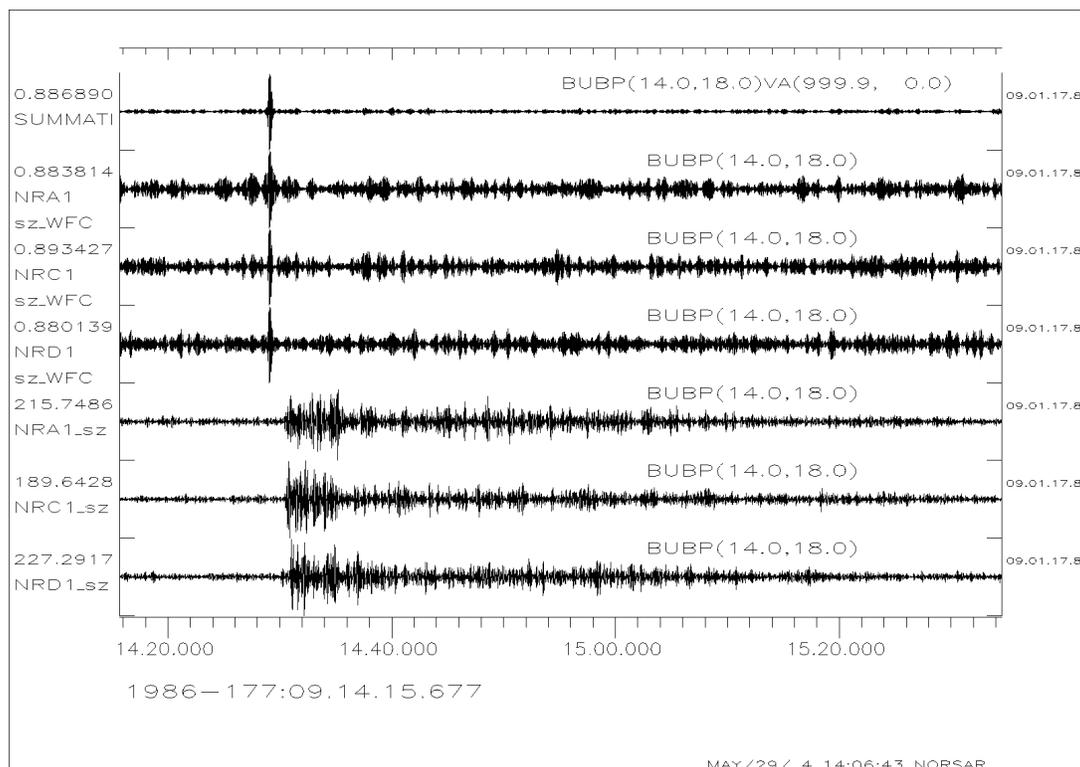


Figure 2. Results of waveform correlation between the filtered master event waveforms and NORES data, which includes the hypothesized Älvdalen event. The lowermost three traces indicate the filtered data, the traces labeled WFC, the corresponding correlation coefficient traces and the upper trace gives the summation of all NORES waveform correlation traces.

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

NORES P-wave spectra are shown in Figure 3 for all of the explosions, with the exception of 2002C164 which was conducted after NORES was destroyed by a lightning strike, and the 1986C246 event which occurred at a time the station was not operating. Each line is the arithmetic mean of a spectrum calculated by the Thomson Multitaper Method (Thomson, 1982) from each of the available NRS short period channels in an 8.0 second time window beginning at the first P-arrival. Spectra are corrected to Hagfors response for the sake of comparison with the figures in Stevens et al. (2003). The spectra clearly show the decoupling effectiveness of the cavities, as well as the relatively enhanced coupling of the larger explosions in the smaller chambers. The largest signals are from the 5000 kg explosions in the 200 and 300 m³ chambers, and these signals are approximately twice as large as the signals from the 10,000 kg explosions in the larger 1000 m³ chamber.

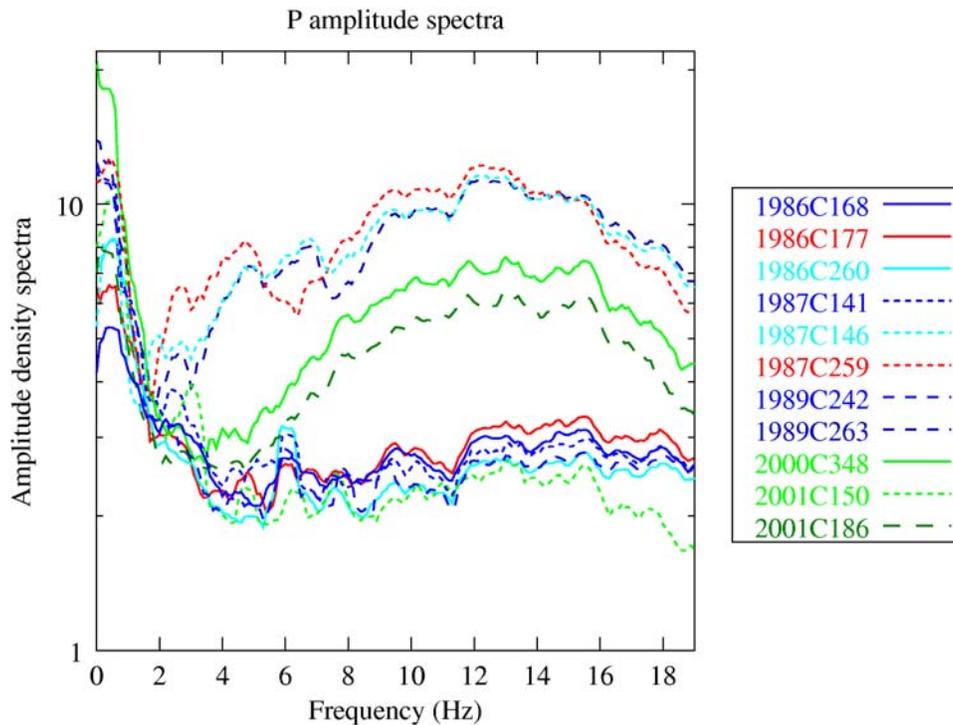


Figure 3. Amplitude spectra from the Älvdaalen explosions for which NORES data exists. Green lines are events which took place in the 1000m³ chamber, blue lines are events which took place in Chamber A (300m³), and red lines are events which took place in Chamber B (200m³).

The spectra of the five 1000 kg and the 2500 kg explosions are substantially lower than the spectra of any of the larger events. Somewhat surprising is that the spectrum of the 2500 kg explosion is lower than any of the 1000 kg explosions, suggesting that there was more nonlinear coupling from these 1000 kg events than from the 2500 kg explosion. This is possible since the 2500 kg explosion was in the larger 1000 m³ chamber, but is inconsistent with the predictions obtained from an equivalent volume spherical cavity.

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 (Herbst et al, 1961):

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

where k is between 0.5 (Latter) and 1.0 (Patterson), ρgh is the overburden pressure at depth h , 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 Swedish chamber explosions are all at approximately 100 meters depth in granite. Figure 4 shows the Latter criterion for full decoupling together with the actual parameters calculated from the known depth and volume for each of these explosions. All of the explosions exceed the Latter threshold, although the 2500 kg explosion as well as the 1000 kg explosions in the 300 m³ cavity are close to fully decoupled.

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

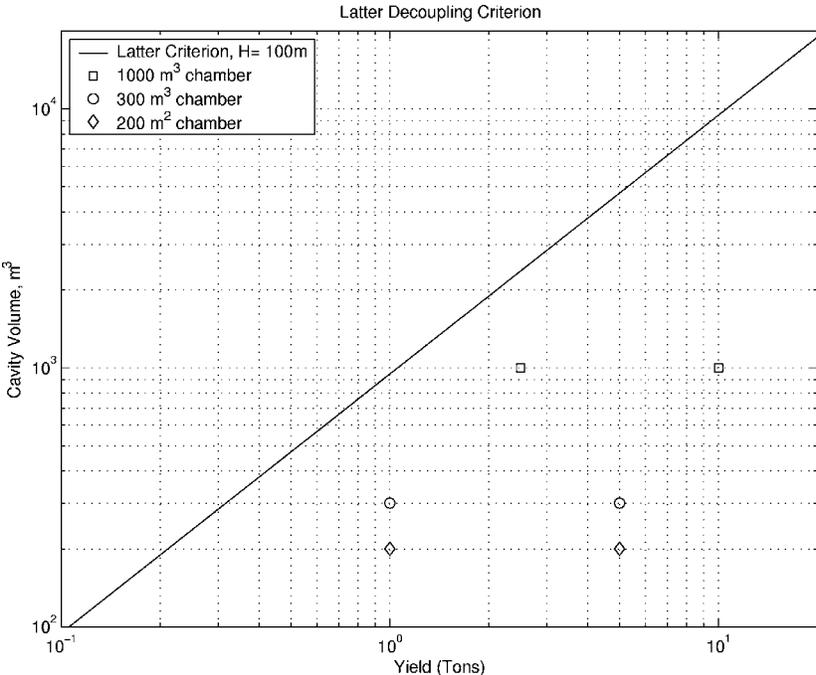


Figure 4. Latter decoupling criterion calculated for the conditions of the Swedish chamber explosions. The actual values for the Swedish chamber explosions are marked.

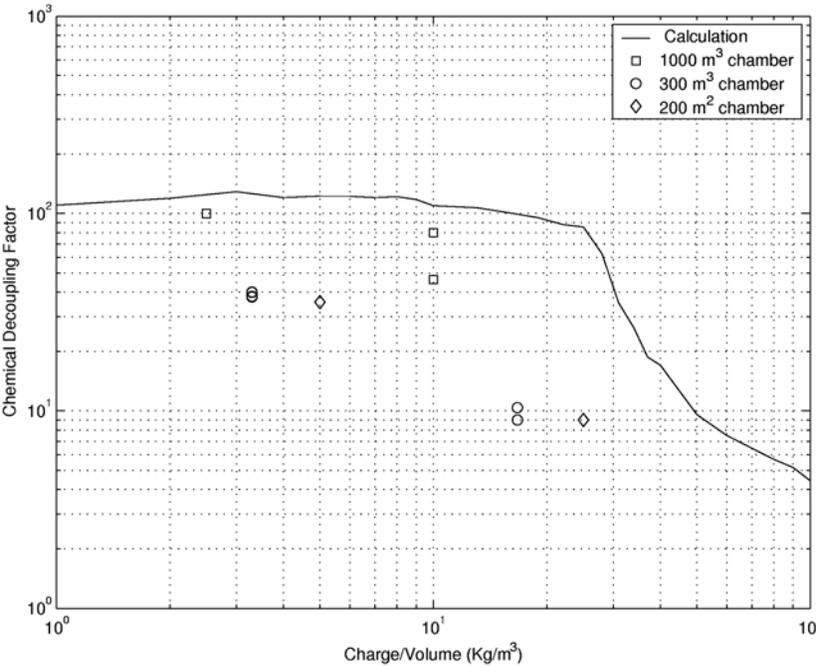


Figure 5. Observed and predicted decoupling factor for Swedish explosions. The Swedish explosions were in rectangular chambers in granite with volumes of 200 m³, 300 m³ and 1000 m³. The calculations were for a chemical explosion in a 6.3 meter spherical cavity in granite (1000 m³).

Figure 5 shows the observed and predicted decoupling factor for Swedish explosions. The 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 since we do not have data for a tamped explosion, so the smallest signal was arbitrarily scaled to have a decoupling factor of 100. The horizontal axis corresponds approximately to the overdrive factor above full decoupling. There are two things to notice from this figure. First, the calculations predict that decoupling

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

will be nearly complete up to more than a factor of 10 above the Latter threshold. This is because the chamber is in a material (granite) with considerable strength, while the Latter criterion assumes that it is only necessary for the explosion to overcome overburden pressure. Second, the decoupling factor is generally less than predicted. Although decoupling is nearly complete for events up to 10 times the Latter threshold, as mentioned above there is significantly more coupling observed for the 1000 kg events in the smaller chambers than for the 2500 kg event in the larger chamber. Also, the explosions with the largest signals show that coupling increases substantially at yields above $10 \times$ Latter at lower charge/volume than the calculations predict.

The differences between the observed and calculated decoupling factors shown in Figure 5 are likely due to the fact that the calculations were performed for a spherical cavity while the actual explosions were in a rectangular chamber. To improve our understanding of these geometrical effects, several three-dimensional finite difference calculations were performed using the “Stellar” code. Stellar is a second-order accurate Eulerian two- and three-dimensional stress wave propagation code with the same constitutive models that were used for the spherically symmetric calculations. The chamber was modeled as an air-filled chamber with dimensions 4.8m high, 30m long, and 7.2m wide. The near field results are sensitive to the layout of the explosive in the chamber, so several layouts were used in the simulations. Figure 6 shows the regions of nonlinear deformation (corresponding to non-zero plastic work) for the calculation of the 2500 kg explosion. Note that this is the most decoupled of any of the explosions. The calculations show that while the region of nonlinear deformation is limited to the part of the chamber near the explosion, there is a significant amount of nonlinear deformation and this will lead to enhanced coupling relative to a fully decoupled explosion.

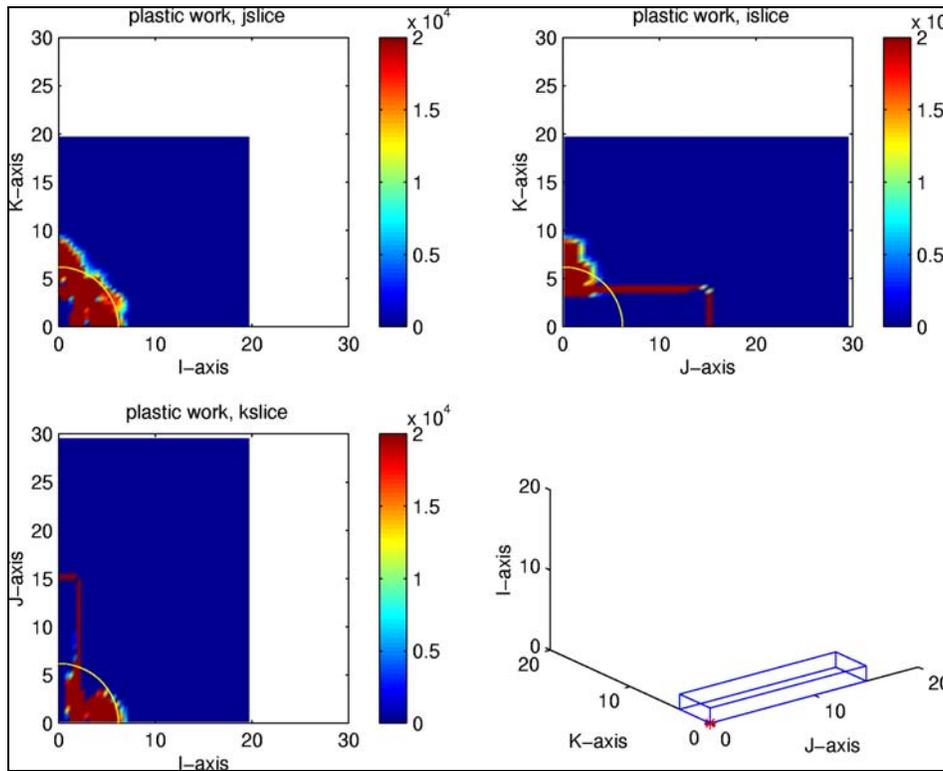


Figure 6. Regions of nonlinear deformation for 2500 kg chamber calculation. The three figures show the nonlinear deformation around each of the three axes. The yellow line shows the size of an equivalent volume sphere.

Figure 7 shows the calculated waveforms at the locations of recording stations V1 and V2 drillholes for one of the 10,000 kg calculations, together with the horizontal and vertical components of the recorded waveforms at the same locations. The chamber reverberations are stronger than the observations, however the peak amplitudes and general shape and duration of the waveforms are reproduced fairly well. The calculations predict a strong radiation pattern

26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

to the waveforms, with stronger amplitudes above and below the chamber and reduced amplitudes along the long axis of the chamber near the recording points V1 and V2.

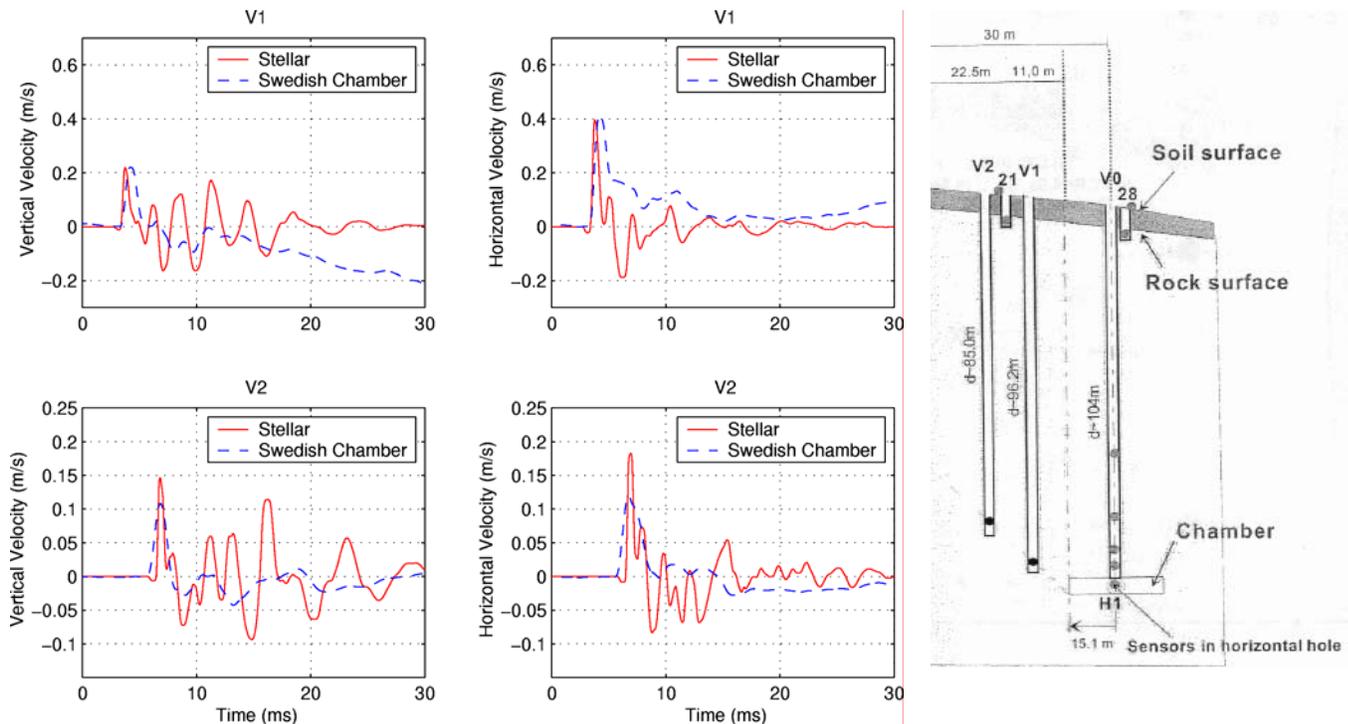


Figure 7. Data and calculated waveforms at stations V1 and V2. The station geometry relative to the chamber is shown on the right.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are derived from analysis of the Swedish chamber explosions:

- A fully decoupled chemical 2.5 ton explosion is detectable at NORSAR at a distance of 140 km. 1.0 ton decoupled explosions are also detected, however the signals from these events, which were in smaller chambers, are larger than that of the 2.5 ton explosion so they appear to be partially coupled.
- This data set covers a range of yields overdriven beyond full decoupling by factors of approximately 2-25.
- Decoupling remains approximately complete for yields less than 10 times the Latter decoupling criterion, and there is more variation in coupling than predicted by a spherical cavity model for explosions with small overdrive.
- At yields higher than 10 times the Latter criterion coupling increases rapidly, increasing by an order of magnitude for a factor of 2 increase in yield/volume.
- 3D nonlinear calculations of the chamber explosions show strong nonlinearity at the points closest to the explosion. This leads to enhanced coupling relative to the equivalent volume sphere.

ACKNOWLEDGEMENTS

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26th Seismic Research Review - Trends in Nuclear Explosion Monitoring

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