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**FINAL REPORT
ON
DIRECT MEASUREMENT OF SOURCE RDP'S AND YIELDS
FROM NEAR-FIELD SOVIET SEISMIC DATA**

**PREPARED BY
SUBCONTRACTOR
WOODWARD-CLYDE CONSULTANTS
566 EL DORADO STREET
PASADENA, CA 91101**

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PROJECT MANAGER

**Chandan K. Saikia
Woodward-Clyde Consultants
Senior Project Scientist**

MASTER

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ABSTRACT

The objective of this study was to investigate the source characteristics represented in the form of a reduced displacement potential (RDP) of Soviet nuclear explosions and was based on the availability of in-country near-field data. At the start of the project, it was thought that data would be readily accessible to us with the start of the open exchange of seismic data between the US and the Soviet Union. In fact, we did receive near-field waveforms of two Soviet nuclear explosions from Azghir test site near the Caspian Sea following which the transfer of data stopped till the end of the project. Consequently, the research effort was descoped. Only recently, some additional data have become available at CSS (Center for Seismic Studies).

We have undertaken a thorough investigation of the limited data available from a large coupled shot (64 kT) in Azghir followed five years later by a decoupled shot (8 kT). We have successfully modeled the near-field data from these events to determine their source RDP's and establish a decoupling factor of 15 using a time-domain waveform modeling technique. The results of this study are presented in the enclosed manuscript: "Analysis of near-field data from a Soviet decoupling experiment".

ANALYSIS OF NEAR-FIELD DATA FROM A SOVIET DECOUPLING EXPERIMENT

By

Chandan K. Saikia¹, James P. McLaren¹ and Donald V Helmberger²

¹Woodward-Clyde Consultants, 566 El Dorado Street, Pasadena, CA 91101

²Seismological Laboratory, California Institute of Technology, Pasadena, CA 91125

ABSTRACT

Recently Adushkin *et al.* (1992a) presented some results on a decoupling experiment performed in a salt dome in Azghir near the Caspian Sea. A large coupled shot (64 kT) was followed five years later by a decoupled shot (8 kT) fired in the cavity formed by the earlier event. Both events were recorded locally and this data has been provided by the Soviet scientists in a cooperative effort to better understand the seismic coupling problem. This data, in conjunction with WWSSN observations, is analyzed in an effort to determine the RDP's and an estimate of t^* . Our preliminary results suggest that the RDP appropriate for the large event is quite similar to that of LONGSHOT (80 kT event). Their teleseismic observations are difficult to distinguish in waveshape. The M_s for LONGSHOT is 3.9 while that for the coupled Russian event is 3.3. The m_b for LONGSHOT (5.8) is slightly smaller than for the Russian event ($m_b=6.0$, ISC). This comparison of $m_b:M_s$ appears to be common to most Azghir events as compared to the US experience. The t^* appropriate for Amchitka ($t^*=0.9$) was established by near-field and teleseismic modeling of waveform data similar to those used in this study where we obtain a $t^*=0.5$ to 0.6. The RDP for the small event is less well resolved but appears to be only partially decoupled. Prior estimates of decoupling factors range from 30 (based on this data by Adushkin) to 70 (for the Sterling/Salmon experiment). Our analysis produces a decoupling factor of about 15 using near-field data which is similar to the teleseismic modeling result.

INTRODUCTION

The open exchange of seismic data between the US and the Soviet Union marks the beginning of a new era in the field of nuclear seismology and monitoring (Adushkin, 1992). In the past, all empirical studies of nuclear seismic data were restricted to the US and French test sites. Although the comparative studies of US and Soviet sites were limited to analysis of teleseismic data, some of the most revealing studies have been based on near field and regional data. In many ways, the less that the seismic energy propagates through the laterally varying earth, the more can be determined about the initial source. For example, Figure 1 displays a set of synthetic waveforms for a spherical and aspherical cavity explosion (labeled explosion, prolate and oblate) with the data at near-in distances for the MILROW event. The prolate and oblate cavity synthetics were produced with quadrupole correction for asphericity, both fixed at 40%

contributions (Stead and Helmberger, 1988). The modeling of these waveforms can be used in conjunction with teleseismic P-waves and long-period body waves and surface waves to establish appropriate RDP's and the effective attenuation operator t^* (Figures 2 and 3). Figure 2 shows a set of short-period WWSSN records for the Amchitka event LONGSHOT (Lay *et al.*, 1984a).

In Figure 3, we present four representative types of short-period MILROW waveforms in the four columns. At the bottom are shown the synthetic seismograms computed using varying t^* and a near-field source model ($K=9$, $B=1$, Helmberger and Hadley, 1981) given by

$$\psi(t) = \psi_{\infty} \{ 1 - e^{-Kt} [1 + Kt + (Kt)^2/2 - B(Kt)^3] \}$$

where the corner frequency parameter, K , scales as predicted by the Mueller-Murphy model (1971), B is a parameter related to the amount of overshoot in the reduced displacement potential, and ψ_{∞} is the measure of the long-period estimate. As the value of t^* increases, the interference of the second upswing, which is pP, becomes less apparent and the dominant period of the signal increases. Figure 4 shows the scaling of parameter B with yield. For increasing yield (ψ_{∞} for LONGSHOT is $0.137 \times 10^{11} \text{ cm}^3$, for MILROW is $1.4 \times 10^{11} \text{ cm}^3$, and for CANNIKIN is $5.69 \times 10^{11} \text{ cm}^3$) and depth of burial, the broadband estimate of B would decrease (Lay *et al.*, 1984b).

Our long term objective is to repeat this type of analysis at some of the former Soviet (i.e., CIS) test sites. The initial data set comes from a decoupling experiment performed in a salt dome in Azghir just north of the Caspian Sea (Adushkin *et al.*, 1992). Figure 5 shows the locations of many CIS peaceful nuclear explosions (PNE) as well as the Azghir test site. The yield of the coupled event (Dec 22, 1972) is 64 kT and the depth was 1 km. Figure 6 shows the cross-section and physical properties of the borehole where the testing of this event was carried out. A decoupled shot of 8 kt (March 29, 1976) was fired in the same cavity which was roughly 38 m in radius. This decoupled event was mislocated to the North by about 350 km and identified as an earthquake by the ISC.

DATA

Our study is based both on the analysis of waveforms recorded at near-field stations from the above two explosions and teleseismic data recorded on WWSSN stations. However, additional near-field data are expected to be available from eight other CIS explosions (Dr. Jerry Carter, Center for Seismic Studies, CSS, personnel communication). The data that have been analyzed so far were obtained from Adushkin via CSS and were digitized by the Soviets using the recently developed scanner technology at the California Institute of Technology. Both vertical and radial component data of these two events are shown in Figures 7 and were recorded on the standard recording channel consisting of a short-period pendulum seismometer with an

electromagnetically damped coil transducer (VBPP-seismometer of strong motion, USF, SM-3, S5S) with a natural period in the range of 1 to 4 seconds and galvanometer with natural period in the range 5-20 Hz. This produces a flat instrument response in the range 0.5-20 Hz. Following personal communication with Dr. Ivan Kitov from the Institute for Dynamics of the Geospheres, Moscow (IDG), the peak amplitude of the original data was multiplied by a factor of 4/3 to account for an inconsistency between the resolution of the scanner and the amplitude measurements of the digitizing program.

There were 17 portable seismic stations recording the decoupled explosions in the distance range of 1 to 154 km. The locations of these stations represented two profiles, one oriented to the north-east from 1 to about 84 km and other to the north-north west from 26 to 154 km.

The information on the in-country geology and technical conditions were made available to us by Dr. Ivan Kitov (personal communication). The depth of the sediment above the shot location is approximately 275 m with 210 m of shale and sand ($V_p=1800$ to 2000 m/sec) and 75m of gypsum and anhydrite with standard properties. The salt layer is approximately 2-3 km thick (average $V_p=4400$ m/sec). Beneath this salt layer, there is a limestone layer of about 15 to 20 km thickness with a V_p of 5 km/sec. The total thickness of the crust is approximately 40 km and the apparent velocity of P_g is 6.2 km/sec. This estimate of P_g velocity was obtained from the seismic measurements obtained during the explosions inside the salt dome.

MODELING OF SOURCE RDP FROM NEAR-FIELD DATA

The objective of this section is to model the RDP for the two events by keeping the data complexity, possibly caused by the variation in the crustal structure, at a minimum. The data appears to have some limitations as described below. For example, by inter-correlating the source of the coupled event with the records of stations 8 and 9 from the decoupled event and by inter-correlating the source of the decoupled event with records of station 8 and 9 from the coupled event, we produce two similar appearing seismograms at station 8 but two different-looking seismograms at station 9 (Figure 8). If the paths are the same, the resulting waveforms should look similar. This suggests that the seismograph at Station 9 may not have been replaced at exactly the same site when recording the decoupled event.

To minimize the path effect and to calibrate source RDP's, we have initially used the waveforms recorded at station 1 and 6 for both coupled and decoupled events. We modeled the waveforms from the coupled event recorded at station 6, even though the station is 4.6 km away from the source and not the closest station, because the decoupled event is sufficiently large for the initial P signal to have long periods, and close enough not to be affected strongly by the structure. To demonstrate the consistency of the derived source model, we have then modeled the data recorded at stations 2, 3 and 5 for the decoupled event.

We used the frequency-wavenumber algorithm (Saikia, 1993) to compute the medium

response which was convolved with the Helmberger-Hadley source as discussed above to synthesize the near-field seismograms. Two crustal models (IVAN.0 and IVAN.5, Figure 9) were used in this investigation. The model IVAN.0 was developed based on the geophysical parameters provided by Ivan Kitov. The IVAN.5 model is a slight modification of the IVAN.0 model, especially in the top layer. These two models produce synthetic seismograms which are similar in both shape and amplitude. However, we feel that IVAN.5 produces a better fit in the frequency content, although the improvement may be only marginal. The strategy to model the source RDP was to construct a set of synthetic seismograms for a suite of source models by varying the parameters K and B .

Figure 10 shows a suite of synthetic seismograms from the above two models at several distances. Clearly, the surface waves are poorly developed. The largest discrepancy appears to be the strong surface waves at stations 8 and 9 (18 km) relative to the direct P arrivals at the near-in station 1 and 8. This effect is apparently caused by 2D structure where the sediments thicken away from the dome and trap energy (Stead and Helmberger, 1988). Ivan Kitov is presently working on some possible 2D structures appropriate for these more distant stations. Figure 11 shows the preliminary agreement between the data and synthetic seismograms computed for the two events along with the map view diagram of the stations relative to the shot location. The source RDP's are also listed. At this stage, we have used $B=1$ and the Amchitka scaling law to derive ψ_{∞} . The coupled event is similar to the LONGSHOT explosion (80 kT; $B=1$, $K=16.7$ and $\psi_{\infty}=0.137 \times 10^{11} \text{ cm}^3$, Lay *et al.*, 1984) at Amchitka and so the source RDP's of the two events appear consistent. The synthetic for the IVAN.0 and the preferred models are displayed. While the agreement at station 6 is reasonable, there is a clear mismatch at station 1 for both the events in the duration of the signal following the initial P wave. This station is located at a distance of 1.03 km from the shot point and it is possible that the station is within the inelastic limit.

Figure 12 shows the comparison between data and synthetics for the decoupled event at the other three stations using the same source RDP. The amplitude and waveshape at these additional three stations have also been modeled.

To estimate the RDP of the coupled event we held the value of B at 1.0 simplify our assumptions. By modeling the waveform shapes of the coupled event we established that the optimal fit in near-field waveform for that event was obtained with a K of 26.43 and a ψ_{∞} of $0.66 \times 10^{11} \text{ cm}^3$. This RDP was used as described in the next section to establish the t^* for the source region.

MODELING OF TELESEISMIC WAVEFORMS

While the short-period P waves for the coupled event could be observed at several teleseismic WWSSN stations, the decoupled event was too weak to be recorded at these stations.

Although we did not have an exhaustive collection of WWSSN waveforms available for the coupled event, we were able to retrieve and digitize data from 12 stations, namely BAG, BUL, ESK, KTG, MAL, MAT, OXF, PRE, PTO, SDP, SHK and WIN. These WWSSN waveforms in conjunction with the derived source model given in the previous section for the decoupled event were analyzed in an effort to estimate the appropriate value of t^* for the Azghir area. With the source parameters of the coupled event established by near-field modeling, we were able to vary the t^* until we produced a suite of synthetics whose m_b was identical to that measured by the ISC.

Several seconds of short-period P waves were digitized and were modeled using the generalized ray theory (Langston and Helmberger, 1975). The m_b of this event is 6.0 (ISC bulletin) and to match this m_b , we needed a t^* of 0.53 seconds to map the source RDP of the coupled event. Figure 13 shows a comparison between data at several WWSSN stations and synthetics computed at the teleseismic station WIN located at 75.5° away from the shot. This t^* estimate is significantly lower than the t^* estimate obtained of 0.9 seconds obtained by Burdick *et al.* (1984) for the Amchitka site. The m_b for LONGSHOT(5.8) is slightly smaller than that of the coupled event. On the other hand, LONGSHOT has a large M_s of 3.9 as compared to 3.3 for the CIS event.

DECOUPLING FACTOR

The event of March 29, 1976 was detonated in the cavity formed by the explosion of the December 21, 1971. It is expected that the seismic waves from the 1976 event is affected by the air-filled cavity, the decoupling being directly dependent on the cavity radius and the media properties (Latter *et al.*, 1961). For example, Latter *et al.*, have estimated a decoupling factor as large as 200 or 300 in very hard rock and 150 in salt. Similarly, for the Sterling event, a decoupling factor of about 70 ± 20 was estimated by Springer *et al.*, (1968). In a recent study, Adushkin *et al.* (1992b) estimated a decoupling factor of 30 for the decoupled event based on the energy calculation consistent with a decoupling factor of 20 based on the amplitude measurements. The energy decoupling factor was calculated as the ratio of actual yield of the decoupled explosion to that of the effective yield estimated on the basis of statistical relationships established for the tamped explosions.

In this study, we have used two independent time-domain analyses for both near-field and teleseismic data separately to estimate the decoupling factor. To determine the decoupling factor from the near-field data, the announced yield (64 kT) of the coupled event is scaled to account for any amplitude differences, possibly caused by the inadequacies in the chosen one-dimensional velocity model IVAN.5. This is done by adjusting the yield by the ratios of the vector sum of initial P displacements in the vertical and radial seismograms of the data to the synthetic waveforms. We determined this ratio using station at 1.03 and 4.6 km. The values of $(Z^2 + R^2)^{1/2}$

for the initial displacements recorded at these two stations are 3.33 cm and 1.10 cm, respectively, and their corresponding synthetic values from IVAN.5 at the two stations are 9.67 cm and 1.48 cm, respectively. The mean of the two ratios, which is 0.547, is used to rescale the announced yield when computing the synthetics, thus reducing 64 kT to 35 kT. To determine the apparent yield of the decoupled event, we use the near-field surface waves recorded at station 8 and 9. The ratios of the surface wave amplitude of the decoupled event to the coupled event at station 8 are 0.007244 and 0.01903 and at station 9 are 0.01787 and 0.01912 for the vertical and radial components, respectively. If the yield is directly proportional to the amplitude, then the effective yield 35 kT multiplied by the mean value of the surface-wave amplitude ratios at each station would measure the apparent yield for the decoupled event, which is 0.46 kT estimated at station 8 and 0.646 kT estimated at station 9. Since the announced yield for the decoupled event is 8 kT, the average decoupling factor from this analysis is about 15.

For the teleseismic analysis, we made an adjustment to the Amchitka scaling law to account for the difference in t^* , i.e., 0.9 for the Amchitka event and 0.53 for the Azghir event, the same as the t^* estimated for the Shagan River test site by Murphy *et al.*, (1992). The regional m_b for the decoupled blast is 4.0 (Sykes and Lyubomirskiy, 1992), which consequently results in an estimate of 0.55 kT as the apparent yield for the decoupled event when the modified scaling law is used. This is equivalent to a decoupling factor of 15.

CONCLUSIONS

One of the important conclusions of this study is that the decoupling factors obtained in this study based on both teleseismic and near-field data are smaller than the value estimated by the Russians (Adushkin *et al.*, 1992b). Thus, the coupling is quite strong compared to the coupling estimated for the United States experiments. The near-field seismograms show variation of the waveform and a complex crustal structure is needed to model the waveforms. Nonetheless, we could use the waveforms recorded very close to the shot point to minimize the propagation effect and determine the source RDP of the two events.

The t^* measurement which we determined from modeling 12 stations is 0.53 seconds, which is significantly lower than the t^* previously established at Amchitka. The t^* measurement is based on a limited set of observations and more teleseismic observations from other events need to be analyzed to reduce uncertainty in this estimate.

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Figure 1. Comparison of synthetics for a spherical and aspherical cavity explosions (labeled Explosion, Prolate and Oblate) to data from CANNIKIN. The prolate and oblate cavity synthetics are computed with a quadruple correction for asphericity, both fixed at a 40% contribution. Peak amplitudes are in cm/s as displayed above each trace. The synthetics have been filtered with a $t^* = 0.05$ operator and detrended to remove an exponential with time artifact of the higher order terms of the asymptotic source expansion (Stead, 1989). The crustal model is 2D constructed from local geologic maps. The source parameters are based on 1D model (Lay *et al.* 1984).

Figure 2. Short-period WWSSN records from the Amchitka event LONGSHOT. These records plus similar records from MILROW & CANNIKIN were used to determine ($\bar{t}^* = 0.9$) which yields the proper (m_b) given the prospective source descriptions from the near-field data.

Figure 3. Example set of MILROW observations and synthetics showing the effects of t^* on waveshape but only the m_b measurements were used in estimating t^* , after Burdick, *et al.* (1984).

Figure 4. Reduced displacement potentials corresponding to source models of LONGSHOT, MILROW and CANNIKIN derived from both high-frequency and broadband data.

Figure 5. Map showing the location of Azghir north of the Caspian Sea. Also shown are the locations of other PNE (Peaceful Nuclear Explosions) from the former Soviet Union.

Figure 6. Cross section of borehole for the coupled explosion with yield of 64 kT. The air-filled cavity was created by this explosion and was used for the decoupled event.

12/22/71 - Y= 64kT M=6.0 (ISC)

03/29/76 - Y= 8kT M=4.4 (ISC)

Figure 7. Display of near-field vertical and radial component seismograms recorded at selected stations from the December 22, 1971 coupled (64 kT) and from the March 29, 1976 decoupled explosion (8 kt)

INTERCORRELATION OF 71/12/22 SOURCE WITH 76/03/29 RECORDS

INTERCORRELATION OF 76/03/29 SOURCE WITH 71/12/22 RECORDS

Figure 8. Results of an intercorrelation experiment where the assumed RDP's from the near-field seismogram at station 1 is convolved with the observations at $\Delta=17.8$ km (sta08) and 18.2 km (sta09). Note the mismatch in timing and amplitude.

Figure 9. Crustal models of the source region. Model IVAN.0 is based on the in-country geology provided by Ivan Kitov and IVAN.5 is modified version of IVAN.0 where the near-surface low-velocity material is removed.

RDP : $\Psi_{\infty}=0.66$ B=1.00 K=26.43
Depth=1.0km Component Z
Scaling Law - Amchitka

MODEL: IVAN.0

MODEL: IVAN.5

Figure 10. Example sets of synthetic seismograms computed using Helmberger and Hadley source type from the Amchitka scaling law using the crustal models IVAN.0 and IVAN.5. Although the models are only slightly different, the resulting synthetics differ significantly.

Figure 11. Comparison between data and synthetic seismograms at station 1 and 6 for both the events along with the map view. The source RDP of the two events are determined based on the agreement in the amplitude and the frequency content.

Azghir Decoupling Experiment

Decoupled Event 76/03/29 - Nearfield Data

$\Psi_{\infty}=0.02$ $B=1.00$ $K=90.60$

Figure 12. Using the source RDP of the decoupled event, the synthetic seismograms at other stations are compared with the data. The agreement between the data and the synthetics is reasonable.

TELESEISMIC SHORT-PERIOD DATA & REPRESENTATIVE SYNTHETIC COUPLED EVENT

DATA

SYNTHETIC

win del=75.501 az=209.62 k=26.43 B=1.00 Psi(inf)=6600 $t^*=0.53$

Figure 13. Comparison of an example set of teleseismic short-period waveforms for the Dec. 22, 1972 event and synthetics that match that ISC ($m_b=6$). A $t^*=0.5$ is required to map the RDP from Figure 10 into this m_b .

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