SOURCE FEATURES AND SCALING OF BURIED AND SURFACE EXPERIMENTAL EXPLOSIONS IN ISRAEL

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ABSTRACT

During the second year of the project additional observations were collected to study empirical features of seismic energy generation for different explosion seismic sources, and how this energy is partitioned between P, S, and surface waves, in specific geological conditions and tectonic settings of the Middle East. The observations concern buried experimental explosions and surface military detonations, for which Ground Truth information (GT0) and blast design parameters were collected.

We analyzed source features and scaling for single-fired, surface explosions at Sayarim military range near Eilat, observed at near-source 3C portable short period (SP) seismometers and regional International Monitoring System (IMS) broadband (BB) stations. A dataset of combined observations of seismic and infrasound waves at collocated sensors was also collected, with S-wave manifestation at distances of up to 150 km. Ground-truth data for 19 explosions in a broad charge weight range (100-8500 kg), recorded at numerous portable and permanent SP and BB stations, facilitated the analysis of energetic characteristics of seismic signals depending on the yield. Source scaling parameters were determined for regional phases observed at BB station EIL (33-38 km). Obtained estimations and waveform features for the surface seismic sources were compared to nearby Sayarim buried (borehole) experimental explosions conducted by the Geophysical Institute of Israel (GII) in 2004, recorded also at EIL. After correction the data for the distance and type of explosives, the scaling power law parameter for P-waves (0.91) with maximal amplitudes was found similar to that for the buried explosions (0.93). The new jSTAR software developed at GII was applied to collected seismograms for the energy generation analysis.

Analysis of Bet-Alpha buried explosions, conducted by GII in 2005 at a basalt quarry and recorded at BB MMLI station, confirmed that amplitudes of regional phases and local magnitudes are well correlated with the scaled depth. Coda-derived moment-rate spectra techniques were applied to BB records for determination of stable regional magnitude for some large-scale calibration explosions conducted by GII: A series of three depth of burial (DOB) experimental explosions of near-spherical charges (five tons of Ammonium Nitrate Fuel Oil [ANFO]) at different depths (22, 43, and 63 m) at Rotem phosphate quarry is scheduled for July 2006. During preparations of the experiment, a number of test shots were conducted in marl rocks to elaborate optimal blast design parameters. Large cavities (up to 3 m) were created at significant depths (up to 63 m) using a special technique, and a number of fully coupled and partially decoupled test explosions were conducted and recorded by numerous portable seismic sensors and permanent stations.

OBJECTIVES

The main objectives of the project are 1) conduction of experimental single-fired explosions of special design; 2) elaboration and verification of empirical source scaling relationships, estimating dependence of seismic wave parameters on different source features; and 3) quantifying the coupling and specific seismic source features, including energy generation analysis and partitioning into various regional phases.

RESEARCH ACCOMPLISHED

During the second year we collected an extensive Ground Truth dataset of surface explosion seismic sources. The collected data were used for 1) analysis of energetic characteristics of seismic signals depending on the yield and estimation of source scaling parameters for regional phases; and 2) comparison of the scaling parameters, waveforms and spectral features to nearby buried explosions observed at the same BB station.

Data of Bet-Alpha explosion series (2005) were used to analyze peak amplitudes and local magnitudes versus charge weight, scaled depth and explosives type. Coda-derived moment-rate spectra technique was applied to BB records for determination of stable regional magnitude for some large-scale calibration explosions conducted by GII.

During preparations of experimental explosions of near-spherical charges at different depths (planned for July 2006), several small test shots were conducted to elaborate optimal blast design parameters and to create large size cavities. The test shots were recorded by portable near-source sensors and used for the energy generation analysis.

In the waveform analysis we used new jSTAR software developed at GII that provides joint processing of different data formats for SP and BB stations (Polozov and Pinsky, 2005).

Collection of Data and Ground-Truth Information for Sayarim Surface Military Detonations.

GT0 data and records for 13 explosions were collected in May-June 1998 during a joint experiment of Israel Defense Forces (IDF) and the US Army Corps of Engineers at the Sayarim military range (Gitterman et al., 2001). The point-like single charges in the range 215-2200 kg of different configurations and explosive composition (TNT, ANFO and Khanit) were detonated on the ground surface (Lat 29.9378ºN, Lon. 34.8185ºE). A similar explosion series of half-spherical charges at about the same site (Lat. 29.95429ºN, Lon. 34.82911ºE) was conducted in October 2003. We collected data for three shots (Figure 1, Table 1). A significant feature of all the shots was that the charges consisted of pure explosives of exactly known weight.

To extend the observation distance range for surface seismic sources, we used data of nearby large explosions (4.5-8.5 tons) intended to destroy outdated ammunition. We visited the explosion site (Lat. 29.99140ºN, Lon. 34.80469ºE) on December 6 and 7, 2005, observed and collected GT0 for three shots, which we placed on the land surface and exposed to the air (Figure 2). Equivalent TNT charge weight was estimated considering shell casing and different explosive types (Table 1).

We measured detonation time and recorded seismic and acoustic waves by near-source portable seismic stations. (A low-frequency infrasound sensor Chaparral 2 was installed in 2005 at the village of Zofar at 73 km; high-quality signals were observed that will be used in a future research).

All selected explosions were well recorded by IMS BB station EIL; some shots were observed also at SP ISN stations (up to 150 km), and close BB stations HRFI, KZIT (in 2003, 2005).

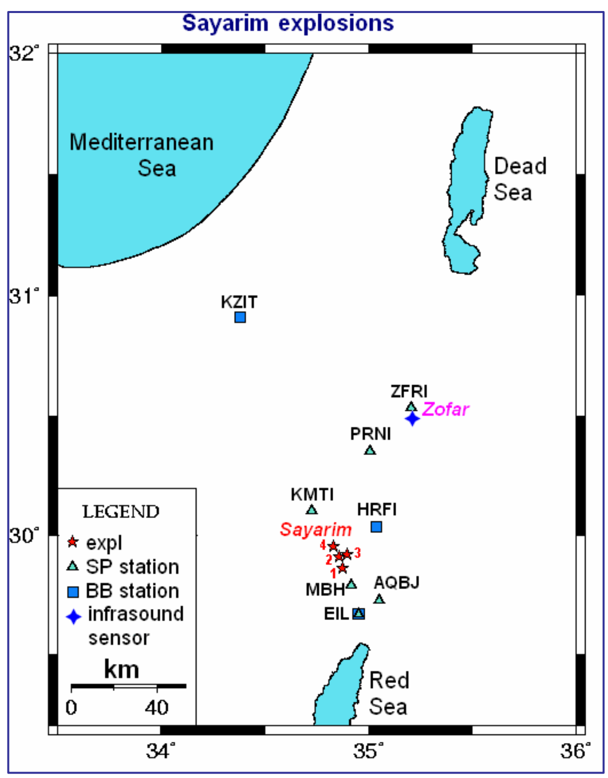

Figure 1. Controlled Sayarim explosions and recording stations: 1 - buried charge-weight series in 2004; 2 & 3 – surface experimental series in 1998 & 2003; 4 –detonations of old ammunition in 2005.

Table 1. Collected Ground Truth parameters (GT0) of surface experimental shots and detonations of old ammunition at Sayarim military range.

Ex. No	Date	O.T.	Charge W, kg	Design	TNT equiv.§	Distance to EIL, km
1	20.05.98	11:37:47.5*	830	TNT cylinder, d~1m, h~1.5m, detonation down	830	32.2
2	24.05.98	14:37:13.70	830	TNT half-spherical, detonation up	830	
3	26.05.98	14:44:02:69	1000	ANFO, detonation down	800	
4	28.05.98	12:25:29*	1000	ANFO	800	
5	02.06.98	09:18:46.67	480	TNT half-spherical, detonation up	480	
6	02.06.98	16:30:18*				
7	03.06.98	09:08:57*				
8	03.06.98	15:50:35.68				
9	03.06.98	16:31:06.16				
10	04.06.98	16:43:58.90	1000	ANFO	800	
11	07.06.98	15:16:56.8*	202	H6, warhead MK83	215	
12	08.06.98	09:49:07.9*	1025	830 TNT (cubic), 195 ANFO	986	
13	08.06.98	16:15:58.0*	2200	TNT+hanit	2200	
14	27.10.03	11:30:44.75	830	TNT half-spherical	830	33.5
15	30.10.03	10:59:29.60	830	TNT half-spherical	830	
16	06.11.03	09:00:31.00	100	TNT cylinder	100	
17	06.12.05	14:18:47.5*	8500	7.5 ton henamit (emulsion) 1 ton TNT (ammunition shells)	7375	38.3
18	07.12.05	13:24:38.6*	4680	4.23 ton henamit (emulsion) 0.45 ton compositeB (ammun. mines)	4086	38.6
19	07.12.05	13:30:15.8*	8570	7.57 ton henamit (emulsion) 1 ton TNT (ammunition shells)	7434	38.3

* O.T. is estimated from records of close SP and BB stations;
§ Explosive TNT equivalent: ANFO – 80%, henamit – 85%, compositeB – 109%.

Figure 2. Sayarim ammunition explosion on Dec. 6, 2005 (Ex.17). Industrial explosive (ANFO-like emulsion Henamit) was added to provide full demolition of the shells (left). The right photo is made from a distance ~3 km, with a large zoom (courtesy of Y. Hamashdyan of IDF).

The three explosions in 2003 were also recorded by portable stations of a special design. The acoustic sensors (low-frequency electret condenser microphone put in a resonance box) were grouped in triangles, each side 100 m long, forming a tripartite array (Figure 3). Each array included a vertical SP seismometer (L4C) collocated with one of the microphones. Acoustic sensors geometry is configured to provide better estimation of source location, which was a major goal of the observations (Pinsky et al., 2005).

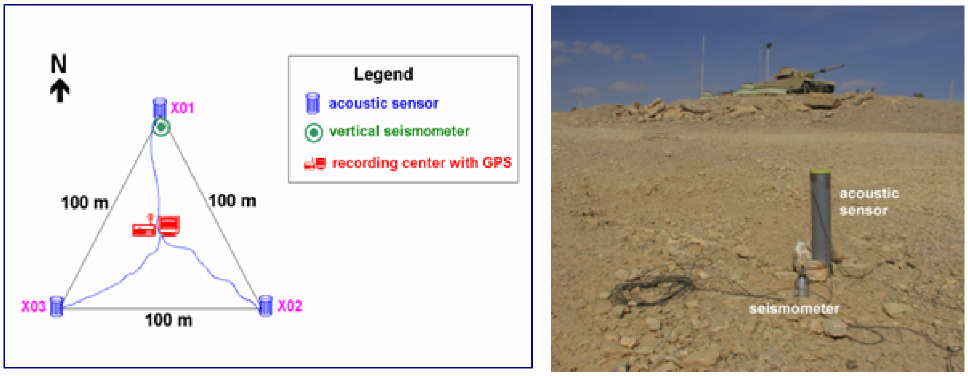

Figure 3. Observations in 1998: (a) Configuration of a hybrid seismic/acoustic portable tripartite array; (b) installed sensors in the Northern apex of the station triangle during one of the shots.

Energy Generation and Source Yield Scaling for Sayarim Surface Explosions.

Strong infrasound phases were observed at seismic channels of local SP and BB stations, which in some cases show much higher amplitudes than seismic waves (Figure 4). Figure 4 also demonstrates a striking example of antipodal manifestation of acoustic phases of the same explosion at two SP stations situated at the same epicentral distance but in opposite directions (Ex.14, Oct. 27, 2003), and the ratio was changed to the opposite on another day (Ex.16, Nov. 6, 2003). These observations correspond to the well known fact that acoustic amplitudes and phase propagation time depend strongly on atmospheric conditions along the infrasound propagation path, especially the altitude distribution of wind direction and velocity (Stump et al., 2002).

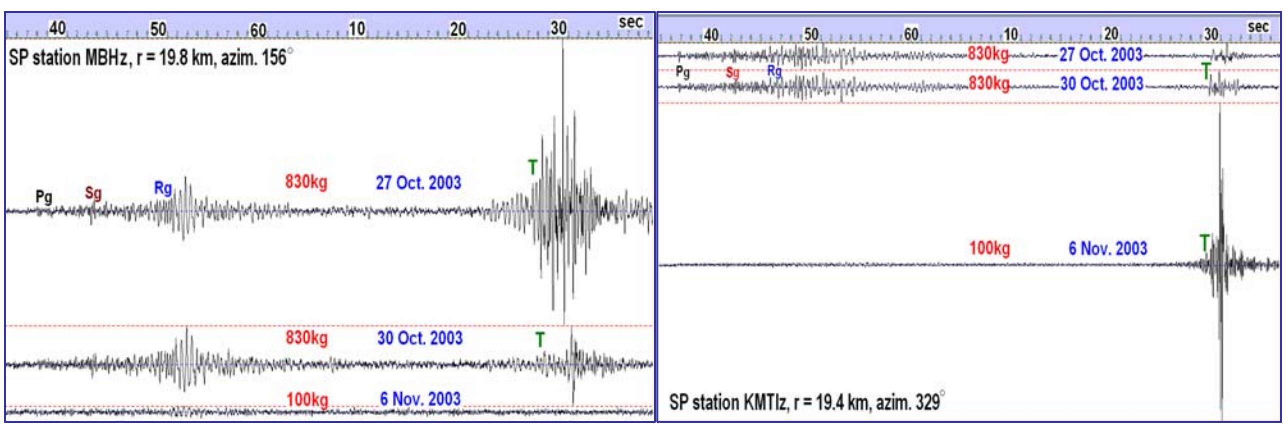

Figure 4. Observations of diverse acoustic phases (T) from surface shots in 2003 at two ISN seismic stations (plotted in absolute scale, filter 1-15 Hz is applied).

The extensive GT0 dataset of about 20 closely-spaced explosions in the broad range of charges 100-8500 kg, recorded at numerous SP and BB stations, facilitate the analysis of seismic energy generation depending on the yield. For a preliminary analysis of energetic characteristics we selected observations at IMS BB station EIL, located at 32-38 km from the explosions (Table 1). Spectra of pre-signal noise showed energy maximum at ~0.2-0.3 Hz, mostly up to ~1 Hz, then seismograms were filtered in the frequency band of 1-20 Hz for 80-Hz data and 1-10 Hz for 20-Hz data (Figure 5). Initially we measured maximal signal amplitudes which are closely correlated with the energy of radiated seismic waves. For Sayarim shots, observed at the EIL station, maximal amplitudes are presented in first arrivals of P phase (Pg), while S waves are not manifested clearly (Figure 5a). Amplitude spectral shapes of seismic phases are found coherent in general for the five times charge increase (Figure 6). For surface (Rg) waves the dominant frequency and simple spectral shape are about the same for the four shots, only the maximal spectral amplitude is raised ~4 times, whereas spectra of P (Pg) phase are more complicated and the dominant frequency is varied from 2.8 Hz for the largest explosion to 5-6 Hz for smaller shots.

a **b**

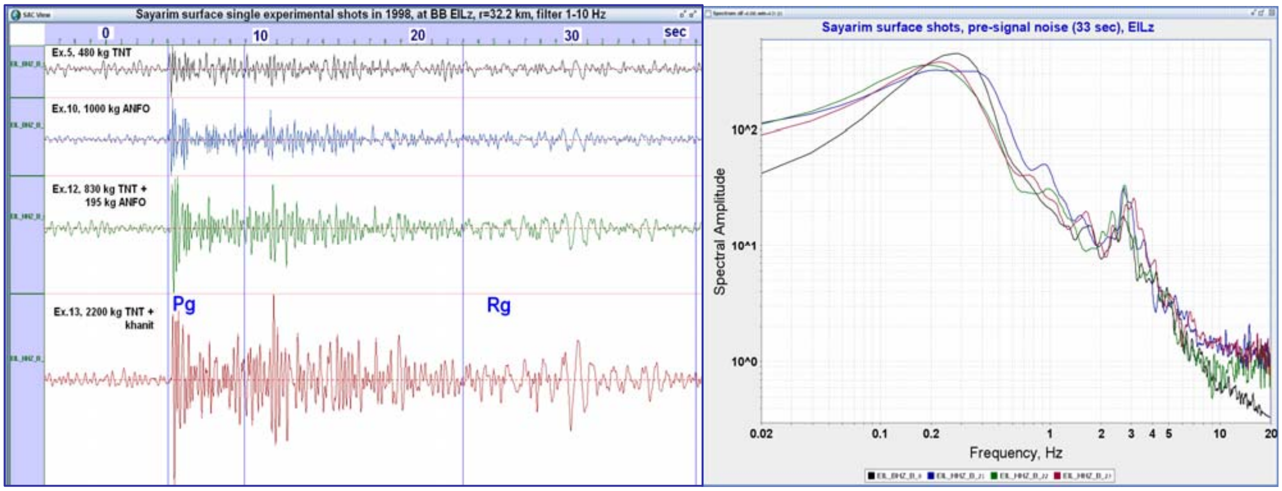

Figure 5. (a) Seismograms (in absolute scale) of 4 selected Sayarim surface explosions at BB station EIL (vertical), low-frequency noise (f<1 Hz) is filtered, vertical lines show windows for spectral analysis; (b) spectra of pre-signal noise (curve colors fit the appropriate seismograms).

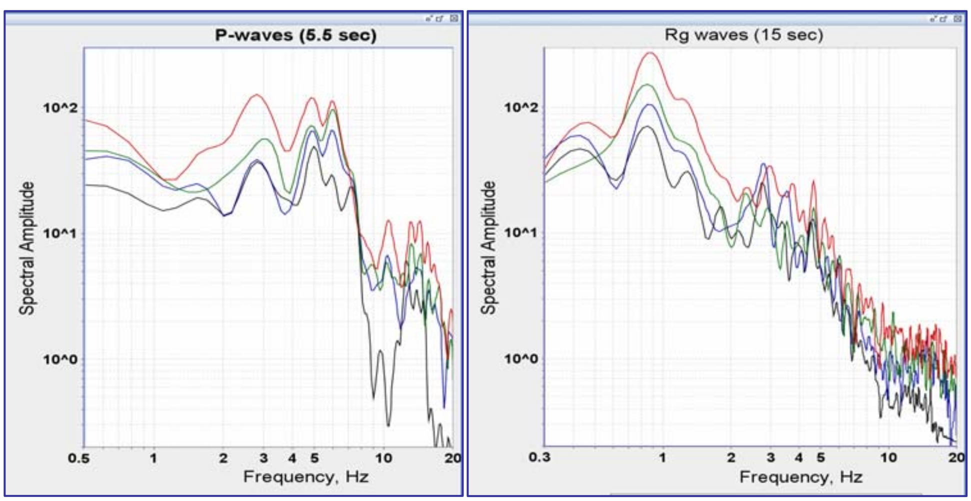

Figure 6. Spectra of P waves and surface waves (Rg) at EIL (vertical) for 4 explosions (the data were pre-filtered in the 0.5-20 Hz band). Curve colors fit the seismograms on Figure 5.

We evaluated a source scaling relationship of surface shots constrained by records at BB station EIL. Measured peak amplitudes (Pg phase) were corrected (Table 1) for distance r (VPA~ $r^{-1.7}$, r_0=35 km) and for various explosives (ANFO energy - ~80% of TNT) (Gitterman et al., 2001). The corrected Vertical Peak Amplitudes (VPA, micron/sec) are plotted against charge weight W (kg) for 19 shots (Figure 7). The data were fitted with the power law equation:

$$VPA_{(mic/sec)} = a * W_{(kg)}^{b} \quad (1)$$

The r.m.s. procedure produced estimates of a = 0.0002258 and b = 0.918 for Pg phase at EIL.

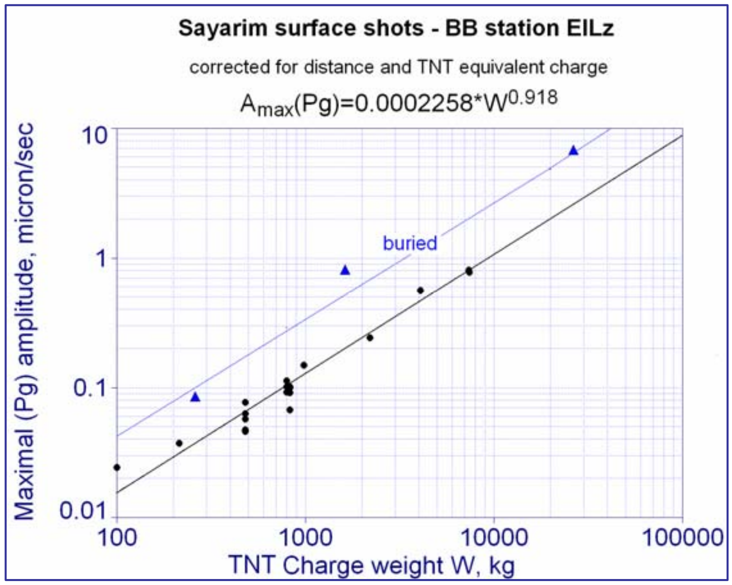

Figure 7. Yield scaling of surface seismic sources at BB station EIL. Data of 3 buried (borehole) Sayarim experimental explosions (2004) at EIL are also shown for comparison (▲).

Comparison of Surface and Buried Seismic Sources.

The very high scaling power law parameter for P-waves b=0.918 is similar to b=0.93 for the nearby buried explosions (in boreholes of large diameter ~0.6-0.7 m, depth 20 m) conducted by GII in 2004, observed at the same BB station EIL (Gitterman et al., 2005) (Figure 7). A lower *b*-value could be expected due to a small charge-rock contact surface for single surface charges resulting in a decrease of explosive energy share transferred to the ground for larger shots. Supposedly the 3 ammunition detonations with the largest multiple charges, placed on a large enough area ~25 m^2 (see Figure 2) (compared to a small area 1-3 m^2 for other single experimental shots in the dataset), produced enhanced Pg-amplitudes, resulting in the high *b*-value.

We compared waveforms and spectra for Sayarim surface and buried (2004) explosions. A comparison sample is presented on Figure 8 for a pair of sources with similar charge weight ~2 tons, observed at BB station EIL, with the same propagation path (North-South). (The buried explosion was in a single borehole, partially contained, with the scaled depth h=1.4 m/$kg^{1/3}$). Both explosions produce maximal amplitudes in P waves on vertical component and clear Rg wave at vertical and about-radial (NS) components, but S-wave manifestation is different: evident Sg arrival at about-transversal (EW) component is found for the buried shot, whereas it is not visible on the surface shot record.

a b c

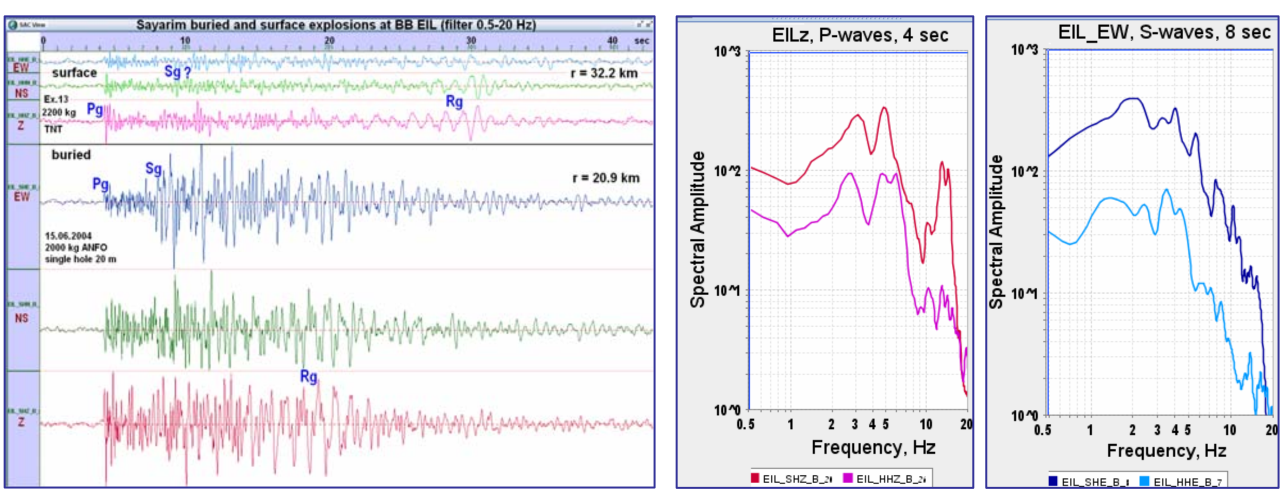

Figure 8. Seismograms in absolute scale (a) and spectra of Pg (b) and Sg (c) for surface and buried shots at EIL. Spectra colors fit appropriate seismograms.

Arrival of Rg, carrying most of the signal energy, cannot be found due to a small distance range, and the Rg group velocity is rather low: 1.0-1.3 km/sec (for close distances 21-32 km). No significant difference or shift to low frequency is found in spectral shapes of Pg and Sg waves for the surface shot comparing to the buried one (Figure 8,b,c) (see Stevens et al., 2003).

Energy Estimations for Bet-Alpha Explosion Series.

We estimated relative seismic energy generated by 4 Bet-Alpha explosions conducted by GII on a basalt quarry (Gitterman et al., 2005). All the shots were well recorded at CNF BB station MMLI located at r=13 km (Figure 9). Maximal vector amplitude and seismic energy for the whole signal (in time window 20 sec) were calculated from measured peak amplitudes for 3 components. Energy values (ratio) relative to the first explosion of 0.5-ton ANFO (Table 2, Figure 10a) were also estimated.

Table 2. Maximal amplitudes, local magnitudes, and energy from Bet-Alpha explosions at BB station MMLI.

Charge, ton	Mag. M_L	Peak Vector, counts	Amplit. Ratio	Energy, counts	Energy Ratio
0.5 (ANFO) single hole	1.5	4147	1	654947	1
0.5 (TNT) single hole	1.5	4330	1.04	689228	1.05
2 (ANFO) two holes	1.4	3277	0.79	429110	0.66
20 (ANFO) 20 holes	2.6	25248	6.1	19822576	30.3

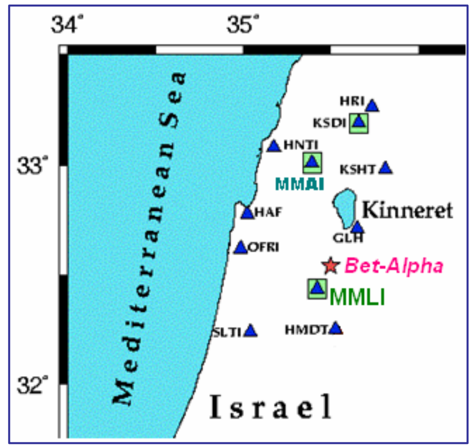

Figure 9. Bet-Alpha explosions and recording stations (symbols are the same as on Figure 1).

a b

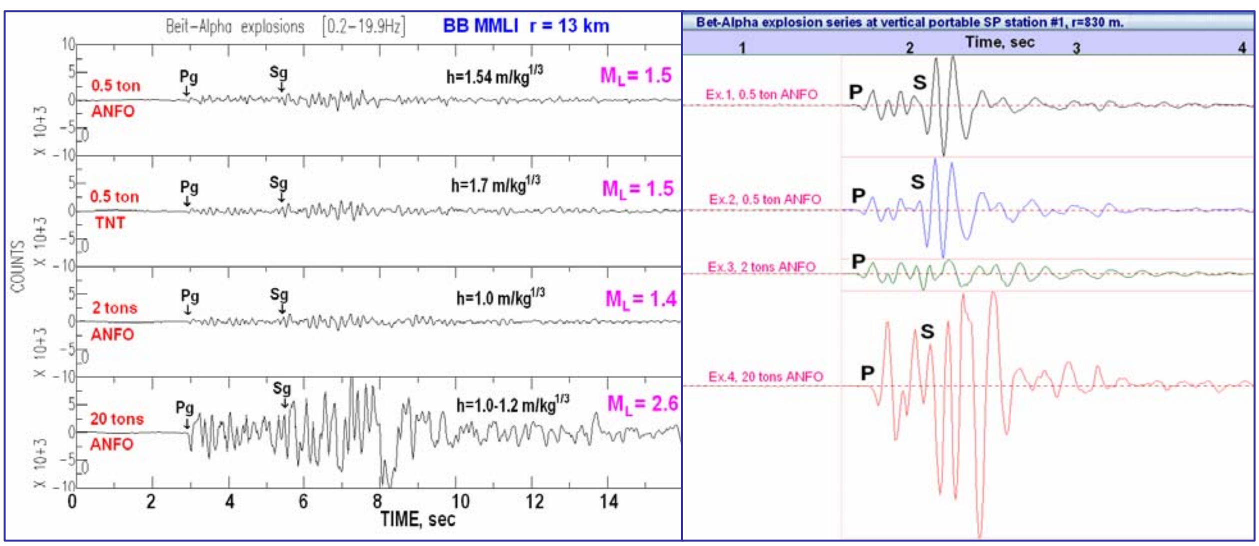

Figure 10. Seismograms (in absolute scale) of Bet-Alpha shots show reduced amplitudes and magnitudes under insufficient scaled charge depth *h* at close BB (a) and portable SP station at ~1 km (b).

For this local seismic observation, a relatively small increase 4-5% in amplitude/energy values is found for a 0.5-ton TNT shot compared with a 0.5-ton ANFO shot. Reduced amplitudes and an energy drop are found for the larger poorly-contained 2-ton shot (in two boreholes), resulting in a low local magnitude of M_L=1.4 compared with a fully-contained 0.5 ton shot with M_L=1.5 (Figure 10a). More significant energy decrease is observed at a near-source portable SP station (Figure 10b). For the largest calibration, a 20-ton shot with the estimated magnitude of M_L=2.6 is also relatively small according to empirical relationship for simultaneous blasts in boreholes (Gitterman, 1998); seismic energy is increased more than 30 times, relative to 0.5-ton shots, that is conformed to about one unit magnitude (M_L) raise.

Analysis of seismic source features and blast design parameters for Bet-Alpha experiment shows that the main reason of reduced seismic strength is smaller, insufficient scaled charge depth $h=H/W^{1/3}$, where H is depth from the surface to the charge center, m, and W is charge weight, kg. The scaled depth for the 0.5 ton shot h=1.54 m/kg$^{1/3}$ is found large enough to provide full containment of the explosion, whereas two larger shots of 2 tons (h=1.0 m/kg$^{1/3}$) and 20 tons (h=1.0-1.2 m/kg$^{1/3}$) produced rock outbreaks and energy losses into the air. These effects, clearly seen on explosion photos and video-records, provide an explanation of reduced magnitudes for the two explosions. The obtained data show the importance of scaled DOB charges as a crucial factor of seismic coupling.

Coda-Derived Moment-Rate Magnitude.

Coda-derived moment-rate spectra technique (Mayeda et al., 2003) was applied to BB records for determination of stable regional magnitude for some large-scale calibration explosions conducted by GII: Dead Sea underwater explosions 2-tons and 5-tons in November 1999 (Gitterman and Shapira, 2001) and Sayarim valley explosion 32.5 tons in June 2004 (Gitterman et al., 2004). For Dead Sea explosions we used recordings of BB IMS stations MRNI (at distance 164 km) and EIL (212 km), for the Sayarim explosion we used data of CNF BB station HRFI (27 km).

Obtained moment-magnitude values fit well to local (duration) magnitudes estimated from Israel network SP stations (Figure 11).

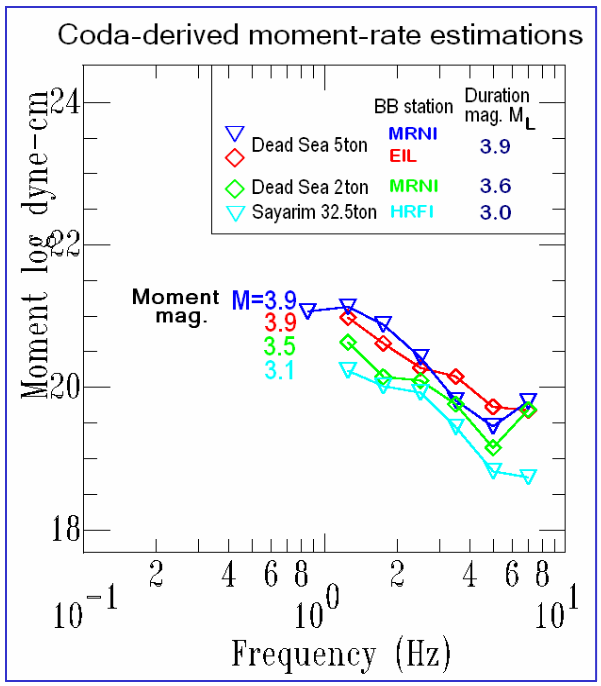

Figure 11. Coda-magnitude estimations for large-scale calibration explosions conducted by GII.

Preparation of a DOB Explosion Series.

During a long time we have been conducting direct preparations of the DOB experiment, that includes three explosions of the same charge at different depths: 22 m, 43 m, and 63 m. One of the main goals of the experiment is to observe regional phases at remote stations, especially at the IMS array AS49 (MMAI) at Mt. Meron, located at ~200 km from a planned explosion site. According to the recent revised magnitude-charge relationship (Gitterman at al., 2005) the charge ~5 tons should be used to provide explosion magnitudes M_L~2.4-2.5 necessary for such observation.

A special complicated design and technology are utilized, developed by Tamar Advanced Quarrying Ltd. (B. Hayoun) and Rotem Amfert Negev Ltd. (U. Yasur, Y. Levi): deployment of explosives in a cavity, created beforehand by a small charge, thus forming near-spherical sources (Figure 12). For the planned ANFO explosives (density ~0.8 gr/cm^3) the diameter of a cavity capable to accommodate this charge is ~2.3-2.5 m. The most important conditions for such an experiment are homogeneity of rock media for all the sources (i.e., for depths 15-65 m), and plasticity of the rocks allowing creation of large cavities (suitable for consolidated sediments of medium strength).

Figure 12. Snapshots of the GeoVISION borehole camera video-records show a borehole inner view before (left) and after (right) a small preparatory explosion. The measuring strip (~80 cm length) attached to the camera is exposed as almost straightened over the created cavity bottom.

Geophysical surveys (seismic refraction and reflection profiles, and microgravity) are also planned at the experiment site by the GII team, in order to estimate the homogeneity of the upper layer and obtain the sub-surface velocity model in the near-source zone. Another important goal will be the evaluation of radius and volume of non-linear source zones created after the explosions, which supposedly should have different size (Figure 13), for characterization of the signal strength and corner frequency and correlation with observed local magnitude and features of regional phases.

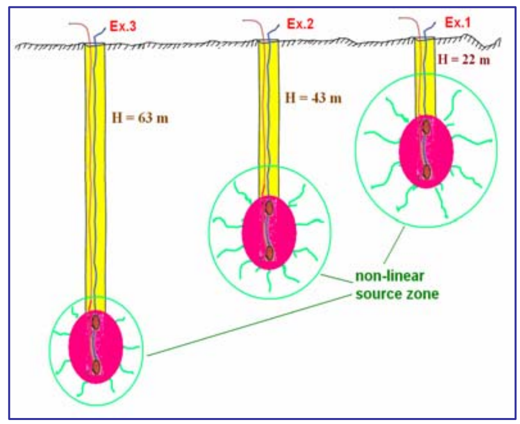

Figure 13. Schematic view of supposed diverse non-linear zones for explosions at different depths.

There is no known and ready technique to create the large size cavity (~2.5 m) at depths more than 60 m in soft consolidated sediments using a vertical borehole with the diameter 6.5", and prevent possible rock-falls in the cavity or borehole blockage. Therefore, a special trial explosion series was conducted (in marl rocks, on Rotem phosphate quarry area) in April-June 2006, before the main DOB experiment. The main goal of the trial series was to test an existing technique (that was used before to produce much smaller cavities) and estimate the optimal small charge or series of charges for creation of appropriate cavities (Figure 14). A number of cavities were created at depths 25-63 m, with maximal size up to 3 m. A part of the trial shots were recorded by several portable seismic instruments (SP 3C stations, accelerometers and engineer sensors) at distances 0.2-5 km, the data are being analyzed, and the results will be used for tuning the observation system during the DOB experiment.

It was revealed that these trial cavities cannot be used for the DOB experiment (with charges of 5 tons), due to a ground shaking hazard for a nearby (~500 m) quarry laboratory building. Nevertheless, we found that they present a good chance for conducting of a decoupling experiment (with smaller charges and decreased seismic strength, permitted for this site).

Due to the very complicated technical realization of the experiment, the preparation activities took several months, more time than planned. The experiment is scheduled for July 2006.

Figure 14. A trial shot (~300 kg ANFO) in a hole with depth 63 m. Ejection of gases and dust lasted ~30 sec, a cavity of ~3m size was created.

CONCLUSIONS AND RECOMMENDATIONS

1) The project event database was extended to study empirical features of seismic energy generation for different wave phases from GT0 surface military explosions in broad range of charge weight and design features.
2) These specific surface sources are different from buried (borehole) sources in generation of seismic energy and waveforms, especially due to radiation of strong acoustic waves, taking most of explosion energy and propagating in atmosphere to large distances. In some cases (depending on atmosphere conditions), strong acoustic phases are found at remote seismic SP and BB IMS stations. Combined interpretation of obtained seismic and infrasound signals may contribute to the analysis of energy generation, source characterization, and related identification task.
3) The extensive GT0 dataset of closely-spaced surface explosions in a broad range of charges, recorded at IMS BB station EIL, facilitated the analysis of seismic energy generation depending on the yield. The scaling power law parameter for P-waves (0.91) with maximal amplitudes was found similar to that for the buried explosions (0.93). Comparison with nearby Sayarim borehole experiment recorded also at EIL demonstrated similar spectral shapes and regional waveforms, except of Sg phase at the transversal component. In the following research this analysis should be conducted for other energetic parameters, in different frequency bands, and for other phases (Sg, Rg) observed at records of EIL and other SP and BB stations from surface and buried shots.
4) The results obtained for Bet-Alpha borehole experiment confirm the importance of scaled depth of buried charges as a crucial factor in seismic coupling well correlated with amplitudes of regional phases and local magnitudes. The experiment contributed to the study of explosion source features in specific geological settings (basalt quarry).
5) A specific blasting technique was used for creation of large (up to 3 m size) and deep (up to 63 m) near-spherical cavities in soft sediments, during preparation of a DOB experiment scheduled for July 2006. Preliminary analysis of obtained results shows that such cavities could be used for a cheap decoupling experiment.

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We thank the IDF personnel for the help in collecting GT0 data for Sayarim military detonations. We appreciate the great efforts of engineers and workers of Tamar Advanced Quarrying Ltd and Rotem Amfert Negev Ltd. involved in preparation of the planned complicated DOB experiment. We also wish to thank Mr. A. Polozov for his permanent support in data processing and analysis by his new software, jSTAR.

REFERENCES

Gitterman, Y. 1998. Magnitude yield correlation and amplitude attenuation of chemical explosions in the Middle East, in *Proceedings of the 20th Annual Seismic Research Symposium on Monitoring a CTBT*, pp. 302–311.

Gitterman, Y. and A. Shapira (2001). Dead Sea Seismic Calibration Experiment contributes to CTBT Monitoring, *Seism. Res. Lett.* 72: (2), March/April 2001, pp. 159–170.

Gitterman, Y., V. Pinsky, and A. Shapira (2001). Improvements in Monitoring the CTBT in the Middle East by the Israel Seismic Network, Contract DSWA01-97-C-0151, Final Report DTRA–TR-01-35, 196 pp.

Gitterman, Y., V. Pinsky, K. Solomi, R. Hofstetter, C. Gurbuz, and M. Ergin (2004). Using ground truth events for travel time calibration and studying seismic energy generation and partitioning into various regional phases, in *Proceedings of the 26th Seismic Research Review: Trends in Nuclear Explosion Monitoring*, LA-UR-04-5801, Vol. 1, pp. 61–72.

Gitterman, Y., V. Pinsky, A. Hofstetter (2005). Using ground truth explosions for studying seismic energy generation and partitioning into various regional phases, in *Proceedings of 27th Seismic Research Review Ground-Based Nuclear Explosion Monitoring Technologies*, LA-UR-05-6407, Vol. 1, pp. 550–560.

Mayeda, K., Hofstetter, A., O'Boyle, J. and Walter, W. (2003). Stable and transportable regional magnitudes based on coda-derived moment-rate spectra, *BSSA* 93: 224–239.

Pinsky, V., Y. Gitterman, A. Hofstetter, A. Shapira (2005). Robust location of surface explosions by a network of acoustic arrays, *Geophys. Res. Lett.* 33: L02317, doi:10.1029/2005GL024304.

Polozov, A., Pinsky V. (2005). New software jSTAR for seismic network and array data processing and joint seismological database. GII Rep. 546/185/05, 27 pp.

Stevens, J. L., Rimer, N., Xu, H., Baker, G. E., Murphy, J. R., Barker, B.W., Lindholm, C., Ringdal, F., Gibbons, S., Kværna, T., and Kitov, I. (2003). Analysis and simulation of cavity-decoupled chemical explosions, in *Proceedings of the 25th Seismic Research Review- Nuclear Explosion Monitoring: Building the Knowledge Base*, LA-UR-03-6029, Vol. 1, pp. 466–475.

Stump, B. W., S. M. McKenna, C. Hayward, and T.-S. Kim (2002). Seismic and infrasound data and models at near-regional distances, in *Proceedings of the 24 th Seismic Research Review-Nuclear Explosion Monitoring: Innovation and Integration*, LA-UR-02-5048, Vol. 2, pp. 572–581.