Yield Estimation Model and Its Accuracy Analysis for Near-Surface Explosions of Soil-Rock-Mixture Site

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Abstract: Explosion yield estimation based on seismic data (ground motion in the near field) is one common approach to estimate near-surface explosion yield. The near-surface yield estimation models of different site media are usually established through chemical explosion experiments. However, the site media of current chemical explosion experiments are mainly soil and hard rock, lacking the experiment data and yield estimation model of soil-rock-mixture site. To solve the above problem, the seismic (ground motion) data of chemical explosion experiments at different depths in soil-rock-mixture site were gathered to establish the near-surface yield estimation model for soil-rock-mixture site. Besides, analysis was made regarding yield estimation accuracy and effects of rock-soil types on accuracy. The results show that the rock-soil type has great influence on the yield estimation accuracy of near-surface explosions, and the near-surface yield estimation model of soil-rock-mixture site has high accuracy in estimating explosion yield.

1. Introduction

Explosion yield estimation based on seismic data (ground motion in the near field) is one common approach to estimate near-surface explosion yield [1-6]. Its prediction accuracy has a close relation with geological characteristics [7-11], explosion source buried depth [3, 5, 10, 12-18]. Coupled seismic waves (ground motion) of near-surface explosions show significantly different energy under different geological characteristics and explosion source buried depths. Studies have shown that different types of rock and soil medium such as saturated soil [12], alluvium [3, 10], sandy clay [13], concrete [14, 15], limestone [16, 17] and granite [5] have different coupling coefficients. Relative to soft rock medium, hard rock medium coupling coefficient undergoes steeper changes with buried depth [19].

Within the range of local distance (<10 km [1-3]), seismic wave data of different buried depths under different geological characteristics are usually gathered through field experiments (ground motion in the near field), and the relationship between yield and waveform parameters, distance, buried depth is established by the scaling law. Explosion yield [1-3, 5, 10, 17] of similar sites is estimated using the peak value of the specific phase in the velocity or displacement waveform. Koper [1] established the empirical relationship between surface explosion yield and waveform parameters by using the law of scaling, and discussed the robustness of the waveform parameters such as the displacement peak of the first arrival P wave, the low-frequency asymptote of the displacement spectrum, and the corner frequency. Bonner et al. [2] further considered the effect of buried depth, using the coupling factors of...
different buried depth sources in the alluvium to equate the peak particle velocity value of the fully contained explosion source with the peak particle velocity value of the surface explosion source, so that SAY surface explosion yield can be predicted. Afterwards, based on the HRIII experiment, Bonner et al. [9] studied the relationship between surface wave peak particle velocity and explosion yield of surface and above-ground explosion sources in alluvium and limestone. An yield estimation model was established based on peak particle velocity, which can be used for predicting surface and above-ground explosion source yield. Ford et al. [3] modified the yield estimation model based on HRI and HRII series chemical explosion experiment data. Taking into account the impact of the explosion height (buried depth) of the near-surface explosion source, he established a quantitative model regarding the peak displacement variation of first arrival P wave with yield, distance and explosion height (buried depth). On the basis of Ford, Templeton et al. [10] conducted a more thorough discussion on the yield estimation model based on the HRI, HRII, HRIII and SAY chemical explosion experiment data, compared and analyzed the near-surface explosion yield estimation model under two geological components of alluvium and sedimentary rock. He discussed the influence of broadband seismometer and short-period seismometer on the measured data and the robustness of different P-wave characteristic quantities for yield estimation model, which has guiding significance for the modeling of near-surface chemical explosion yield estimation. Pasyanos et al. [5, 17] earned the relationship between peak displacement and yield, distance by analyzing a large number of chemical explosion experiment data at different buried depths in hard rock medium, thereby establishing a near-surface yield estimation model for hard rock medium.

At present, based on series of explosion experiments such as DM/DB [1], HRI-III [3,9,10] and SAY [2,10], the near-surface explosion yield estimation models in soil and hard rock mediums have been established. However, the medium types in the above chemical explosion experiment sites are mainly soil and hard rock. There are few chemical explosion experiments in soil-rock mixture medium, and there are insufficient relevant experiment data and near-surface yield estimation models. In response to the above problems, this paper analyzes the seismic wave (ground motion) data in chemical explosion experiments under different buried depths in the soil-rock-mixture site medium, establishes a near-surface yield estimation model for the soil-rock-mixture site, discusses the accuracy of yield estimation and the impact of rock-soil type on accuracy.

2. Theory

The basic yield estimation model for underground explosion is [20]

\[ A = KW^n r^{-m} \]  

where \( A \) is the seismic wave (ground motion) acceleration peak, velocity peak or displacement peak, \( K, n, \) and \( m \) are undetermined constant terms, \( W \) is the yield, and \( r \) is the distance from the explosion source.

For near-surface explosions, seismic wave characteristic parameters exhibit S-curve characteristics in its change with buried depth. Using the hyperbolic function \( \tanh \) to modify the basic yield estimation model, the near-surface yield estimation model can be obtained [3,10]

\[ A = KW^n r^{-m} 10^{(\tanh(k+j))} \]  

where, \( h \) is the explosion height, \( l, k \) and \( j \) are undetermined constants. Studies have shown that [1,3,10] the displacement peak of the first arrival P wave of the seismic wave is the most robust in the yield estimation model. By substituting the P wave displacement peak value into the above formula and adopting the scaling relationship, the near-surface yield estimation model of the P wave displacement peak value can be established [10],

\[ \log_{10}(d_s) = \beta_1 + \beta_2 \log_{10}(r_s) + \beta_3 \tanh(\beta_4 h_s + \beta_5) \]  

where \( d_s = d/W^{1/E}, v_s = v/W^{1/E}, r_s = r/W^{1/E}, h_s = h/W^{1/E}, E \) characterizes the energy scaling law. In square-root scaling law, \( E \) takes 2, in the cube-root scaling law, \( E \) takes 3. Studies have shown that [10,20,21], the displacement obeys the cube-root scaling law, and \( E \) takes 3.

When the explosion source is located at a high buried depth (\( h_s \rightarrow \infty \)), the third term on the right
side of the equation (3) is equal to $\beta_3$, and displacement relationship under high buried depth ratio is then obtained \[17\]

$$d_s' = 10^{\beta_3 \log_{10}(r_s)} \tag{4}$$

By substituting formula (4) into formula (3), the yield estimation model of the explosion source with relatively high buried depth is established \[17\]

$$d_s = d_s' \cdot 10^{[\tanh(\beta_3 h_s) + 1]} \tag{5}$$

When there is insufficient buried depth data, Templeton et al. \[10\] simplified the explosion height term of the above formula which excludes undetermined constants, so that a simplified yield estimation model is established

$$A = K W^n R^m 10^{[\tanh(H)]} \tag{6}$$

$$\log 10(d_s) = \beta_2 + \beta_3 \log 10(r_s) + \beta_3 [\tanh(h_s)] \tag{7}$$

$$d_s = d_s' \cdot 10^{[\tanh(h_s) + 1]} \tag{8}$$

3. Experimental data

The medium of the near-surface chemical explosion experiment site is a soil-rock mixture, mainly composed of sand and gravel, and the gravel content exceeds 50%. The site has flat terrain. There are 5 chemical explosion experiments (see Table 1) of different buried depths and 8 seismic (ground motion) measuring points (see Figure 1). The seismic (ground motion) measuring points are distributed linearly with respect to the explosion center.

| Number | Yield/kg | Buried depth/m | Description | |
|--------|----------|----------------|-------------|----|
| E01    | 30       | 30             | Fully contained explosion | |
| E02    | 30       | 20             | Fully contained explosion | |
| E03    | 10       | 15             | Scaled buried depth is closer to that of E02; fully contained explosion | |
| E04    | 30       | 0              | Half buried, half of the explosion source is placed in the ground medium | |
| E05    | 30       | -0.16          | Explosion source is placed on the ground | |

![Figure 1. Distribution of Measuring points.](image)

Each measuring point acquires data in both radial and vertical directions, and the effective frequency range of the data is 0.5-170 Hz. In this frequency range, the sensor's frequency response
curve is flat, and the signal-to-noise ratio of the measuring point data is high (see Figure 2). In addition, the main frequency of the measuring points is distributed between 9-75 Hz (see Figure 3) and is located in the 0.5-170 Hz frequency band, indicating that effective frequency range can reflect the main signal information.

Figure 2. Typical normalized spectrum for signal and noise (D08’s vertical data of E03).

Figure 3. Main frequency distribution interval of E01-5 explosion sources

Use 0.5-170 Hz to filter the velocity waveform of the measuring point, and the first velocity peak after filtering is shown in Figure 4. It can be seen from the figure that the data in both radial and vertical directions of the high buried depth explosion source (E01-03 explosion sources) has relatively high amplitude, while the radial amplitude is significantly larger than the vertical one for the surface explosion sources (E04-05 explosion sources). It indicates that the radial and vertical data need to be considered at the same time when processing signal amplitude of high buried-depth explosion source. In addition, because the energy of the high buried-depth explosion source coupled to the ground medium is greater than that of the surface explosion sources, the first peak velocity of the high buried-depth explosion source is greater than that of the surface explosion source. For the surface explosion sources, because E04 explosion source is half-buried explosion source whose energy is relatively better coupled to the ground medium than E05 explosion source which is emplaced on the ground, the first peak velocity produced by E04 explosion source is larger than that by E05 explosion source.
Ford et al. [1, 3, 10] pointed out that displacement is more robust than velocity in the yield estimation model. By integrating the first peak of the filtered velocity waveform, the first peak values of radial and vertical displacements are calculated. The root mean square of the first peak values of the radial and vertical displacement is taken as the first peak value of displacement at the measuring point. The results are shown in Figure 5 and Figure 6. It can be seen from the figure that in the log10 scale, the first peak value of displacement and scaled displacement of E01-05 explosion sources show good linear relationship with distance and scaled distance. Under the same explosion source yield and different buried depths, E01 and E02 explosion sources show basically the same relationships of displacement and scaled displacement with distance, indicating that buried depth has little effect on the first-peak value of the displacement of the measuring point in the case of high buried depth. Under the same scaled buried depth and different yields, E02 explosion source has significantly higher first-peak value of displacement than E03 explosion source, but the two show basically the same changing relationship of scaled displacement and distance, indicating that the relationship between displacement and buried depth, distance meets the scaling law. In addition, due to the better coupling between the high buried-depth explosion source and the ground medium compared with the surface explosion sources, high buried-depth explosion source has significantly higher first-peak value of scaled displacement than surface explosion sources. For the surface explosion sources, the half-buried explosion source has greater energy coupled to the ground medium than E05 explosion source, so E04 explosion source has larger first-peak value of displacement and scaled displacement than E05 explosion source.
4. Discussion

4.1. Influence of rock-soil type

By substituting the high-buried-depth scaled displacements obtained by fitting the data of E01-03 explosion sources into equation (9) and taking yield estimation model coefficients of alluvium and hard rock medium (see Table 2) respectively as the undetermined coefficients of explosion height term, the estimated values of E01-05 explosion source yield can be calculated (see Table 3). It can be seen from Table 3 that the yield estimated intervals of E04 and E05 explosion sources are 9.68–48.09 kgTNT and 7.06–36.22 kgTNT respectively and the true yield 30 kgTNT exists in the estimated interval, indicating that for explosion source near the ground surface, rock-soil type (characteristics) of the site greatly affects the yield estimation results. It is also indicated that the model coefficients of alluvium and hard rock media can be used to calculate the estimated interval of the surface yield for the soil-rock-mixture site, and the true value exists within this interval. For explosion sources with high buried depth, prediction results based on the model coefficients of different rock-soil media are consistent, and the relative error from the true value is between 4%–21%, and the average relative error is 12%. The high buried depth estimation results suggest that rock-soil type has little impact on the estimation accuracy of high buried-depth explosion source.
In sum, the rock-soil type has little effect on the prediction accuracy of high buried-depth explosion source yield, but it has a greater impact on the yield prediction accuracy of the surface explosions. The yield result is smaller than the true one when alluvium yield estimation model coefficient is used to predict soil-rock mixture, but the yield estimation result is higher when the hard rock medium yield estimation model coefficient is taken. By using the yield estimation model coefficients of alluvium and hard rock medium, the estimated interval of the surface explosion yield can be predicted for the soil-rock-mixture site.

| Parameter | Alluvium (Ford et al. [3]) | Alluvium (Templeton[10]) | Limestone (Pasyanos et al.[17]) |
|-----------|----------------------------|---------------------------|----------------------------------|
| $\beta_3$ | -0.22                     | -0.22                     | -0.55                            |
| $\beta_4$ | 4.84                      | 9.55                      | 4.84                             |
| $\beta_5$ | 1.23                      | 1.85                      | 1.23                             |

| Estimated yield value /kgTNT | true value | Alluvium (Ford et al.[3]) | Alluvium (Templeton[10]) | Limestone (Pasyanos et al.[17]) | Relative error |
|-----------------------------|------------|---------------------------|---------------------------|----------------------------------|----------------|
| No.1 Explosion Source       | 30         | 36.33                     | 36.33                     | 36.33                            | 0.21            |
| No.2 Explosion Source       | 30         | 26.39                     | 26.39                     | 26.39                            | 0.12            |
| No.3 Explosion Source       | 10         | 11.09                     | 11.09                     | 11.09                            | 0.04            |
| No.4 Explosion Source       | 30         | 9.68                      | 10.31                     | 48.09                            | –               |
| No.5 Explosion Source       | 30         | 7.06                      | 7.32                      | 36.22                            | –               |
| Maximum relative error      | 0.76       | 0.76                      | 0.60                      | –                                | –               |
| Average relative error      | 0.38       | 0.37                      | 0.25                      | –                                | –               |

### 4.2. Yield estimation models

Since E01-03 explosion sources are fully contained explosion sources with high buried depth, the energy produced by the explosion is mainly coupled to the ground medium and then seismic waves are formed by ground motion and propagated away, and there is quite small energy coupled to the air. Hence, the first peak value of scaled displacement of E01-03 explosion sources accords with high buried depth displacement, that is, equation (4). Due to the limited buried depth data, for the undetermined coefficients of the yield estimation model (Equation (5)), only $\beta_1$-$\beta_4$ are retained, and $\beta_5$ takes 0. Substitute the scaled displacement under high buried depth into equations (5) and (8) respectively, and fit the displacement data of E04-05 explosion sources to obtain model coefficients (see model 1 and model 2 in Table 4) and model curve (see Figure 7(a) and Figure 7(b)). In addition, in order to comprehensively analyze the performance of the yield estimation model, three other yield estimation models are also given. For model 3, the attenuation coefficient of scaled displacement under high buried depth is obtained by fitting the data of E01-05 explosion sources, and the attenuation source term is obtained by fitting the above attenuation coefficient to the data of E01 explosion source. Substitute the resulting scaled displacements of high-buried-depth explosions into equation (8), and fit the displacement data of E02-05 explosion sources to obtain the model coefficients (see Model 3 in Table 4) and the model curve (see Figure 7(c)). For model 4, the simplified model of yield estimation (formula (7)) is used to directly fit the data of E01–05 explosion sources to obtain model coefficients (see model 4 in Table 4) and model curve (see figure 7(d)). For model 5, substitute the fitting relationship of E01 explosion source into equation (8) as high buried depth scaled displacement, then model coefficients (see Model 5 in Table 4) and model curve are obtained by fitting E02-05 explosion sources (See Figure 7(e)).
It can be seen from Figure 7 that the above yield estimation models can reflect the change trend of the measured data, but compared with the models 2-5, model 1 has better performance of overlapping with the measured data. In addition, the yield estimation model curves of E01-03 explosion source data completely overlap, and the model curve does not change with the buried depth. This is because E01-03 explosion sources have deeper buried depth, and its scaled displacement meets the scaled law of displacement under high buried depth.

![Model 1](image1)
![Model 2](image2)
![Model 3](image3)
![Model 4](image4)
![Model 5](image5)

Figure 7. Fitted results of yield estimation models.

Table 4. Yield estimation model coefficients of soil-rock mixture.

| Parameter | Model 1 | Model 2 | Model 3 | Model 4 | Model 5 |
|-----------|---------|---------|---------|---------|---------|
| $\beta_1$ | 2.93    | 2.90    | 2.83    | 2.71    | 2.83    |
| $\beta_2$ | −1.62   | −1.62   | −1.58   | −1.49   | −1.57   |
| $\beta_3$ | −0.81   | −0.84   | −0.85   | −0.82   | −0.79   |
| $\beta_4$ | 2.71    | −       | −       | −       | −       |

4.3. Yield estimation

Based on the above yield estimation models, the yields of E01-05 explosion sources were inverted, with the inversion results shown in Table 5. It can be seen from the table that the maximum, average and standard deviation of the model 1’s yield estimation error are the smallest among the five models, and the maximum relative error and average relative error of model 1 are significantly smaller than the yield estimation errors of the alluvium and hard rock medium models (see Table 3). Besides, the maximum relative error of model 1 does not exceed 21%. The above results indicate that model 1 has the best yield estimation performance among the five models and has a high estimation accuracy.
5. Conclusion

In this paper, based on the seismic wave (ground motion) data of different buried-depth explosion experiments in the soil-rock-mixture site, a near-surface yield estimation model is established for the soil-rock-mixture site, and the yield estimation accuracy and the effect of rock-soil types on accuracy are analyzed. The results show that rock-soil type has little influence on the yield prediction accuracy of high buried-depth explosion source, but has a great impact on the prediction accuracy of near-surface yield. When alluvium model coefficients are used to predict the yield of soil-rock mixture, the value is relatively smaller than the true value, and the yield estimation result is larger when hard rock medium model coefficients are used for prediction. When yield estimation model coefficients of alluvium and hard rock mediums are used at the same time, it is possible to predict the estimated interval of the surface yield of the soil-rock-mixture site. Finally, it is proved that the near-surface yield estimation model of soil-rock-mixture site has a high accuracy in estimating explosion yield.

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References

[1] Koper, K.D., Wallace, T.C., Reinke, R.E., et al. (2002) Empirical scaling laws for truck bomb explosions based on seismic and acoustic data. Bulletin of the Seismological Society of America, 92(2): 527-542.
[2] Bonner, J., Waxler, R., Gitterman, Y., et al. (2013) Seismo-acoustic energy partitioning at near-source and local distances from the 2011 Sayarim explosions in the Negev Desert, Israel. Bulletin of the Seismological Society of America, 103(2A): 741-758.
[3] Ford, S.R., Rodgers, A.J., Xu, H., et al. (2014) Partitioning of seismoacoustic energy and estimation of yield and height-of-burst/depth-of-burial for near-surface explosions. Bulletin of the Seismological Society of America, 104(2): 608-623.
[4] Jiang W.B., Chen, Y., Peng, F. (2020) The yield estimation of the explosion at the Xiangshui, Jiangsu chemical plant in March 2019. Chinese J. Geophys. (in Chinese), 63(2): 541-550.
[5] Pasyanos, M.E., Kim, K. (2018) Seismoacoustic analysis of chemical explosions at the national security site. Journal of Geophysical Research: Solid Earth, 124: 908-924.
[6] Pasyanos, M.E., Myers, S.C. (2018) The coupled location depth yield problem for North Korea's declared nuclear tests. Seismological Research Letters, 89(6): 2059-2067.
[7] Lu, Q., Wang, Z.J., Zhang, J.S., et al. (2019) Tamped explosion in loess and rock-like sandy soil. Explosion and Shock Waves, 39(5): 52202-52207.
[8] Xiao, W.G., Wang, X.J., Zhu, H.F., et al. (2012) Experimental study on seismic coupling effects of underground explosions in different materials. Explosion and Shock Waves, 32(3): 267-272.

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[2] Bonner, J., Waxler, R., Gitterman, Y., et al. (2013) Seismo-acoustic energy partitioning at near-source and local distances from the 2011 Sayarim explosions in the Negev Desert, Israel. Bulletin of the Seismological Society of America, 103(2A): 741-758.
[3] Ford, S.R., Rodgers, A.J., Xu, H., et al. (2014) Partitioning of seismoacoustic energy and estimation of yield and height-of-burst/depth-of-burial for near-surface explosions. Bulletin of the Seismological Society of America, 104(2): 608-623.
[4] Jiang W.B., Chen, Y., Peng, F. (2020) The yield estimation of the explosion at the Xiangshui, Jiangsu chemical plant in March 2019. Chinese J. Geophys. (in Chinese), 63(2): 541-550.
[5] Pasyanos, M.E., Kim, K. (2018) Seismoacoustic analysis of chemical explosions at the national security site. Journal of Geophysical Research: Solid Earth, 124: 908-924.
[6] Pasyanos, M.E., Myers, S.C. (2018) The coupled location depth yield problem for North Korea's declared nuclear tests. Seismological Research Letters, 89(6): 2059-2067.
[7] Lu, Q., Wang, Z.J., Zhang, J.S., et al. (2019) Tamped explosion in loess and rock-like sandy soil. Explosion and Shock Waves, 39(5): 52202-52207.
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[2] Bonner, J., Waxler, R., Gitterman, Y., et al. (2013) Seismo-acoustic energy partitioning at near-source and local distances from the 2011 Sayarim explosions in the Negev Desert, Israel. Bulletin of the Seismological Society of America, 103(2A): 741-758.
[3] Ford, S.R., Rodgers, A.J., Xu, H., et al. (2014) Partitioning of seismoacoustic energy and estimation of yield and height-of-burst/depth-of-burial for near-surface explosions. Bulletin of the Seismological Society of America, 104(2): 608-623.
[4] Jiang W.B., Chen, Y., Peng, F. (2020) The yield estimation of the explosion at the Xiangshui, Jiangsu chemical plant in March 2019. Chinese J. Geophys. (in Chinese), 63(2): 541-550.
[5] Pasyanos, M.E., Kim, K. (2018) Seismoacoustic analysis of chemical explosions at the national security site. Journal of Geophysical Research: Solid Earth, 124: 908-924.
[6] Pasyanos, M.E., Myers, S.C. (2018) The coupled location depth yield problem for North Korea's declared nuclear tests. Seismological Research Letters, 89(6): 2059-2067.
[7] Lu, Q., Wang, Z.J., Zhang, J.S., et al. (2019) Tamped explosion in loess and rock-like sandy soil. Explosion and Shock Waves, 39(5): 52202-52207.
[8] Xiao, W.G., Wang, X.J., Zhu, H.F., et al. (2012) Experimental study on seismic coupling effects of underground explosions in different materials. Explosion and Shock Waves, 32(3): 267-272.
[9] Bonner, J.L., Russell, D.R., Reinke, R.E. (2013) Modelling surface waves from aboveground and underground explosions in alluvium and limestone. Bulletin of the Seismological Society of America, 103(6): 2953-2970.

[10] Templeton, D.C., Ford, S.R., Rodgers, A.J., et al. (2018) Seismic models for near-surface explosion yield estimation in alluvium and sedimentary rock. Bulletin of the Seismological Society of America, 108: 1384-1398.

[11] Perret, W.R., Bass, R.C. (1975) Free field ground motion induced by underground explosions. Sandia Laboratories, SAND74-0252.

[12] Mu, C.M., Ren, H.Q., Li, Y.C., et al. (2010) Experiment study of explosion energy coupling coefficient with different burial depths in saturated soils. Rock and Soil Mechanics, 31(5): 1574-1578.

[13] Ye, Y.Q., Ren H.Q., Li, Y.C., et al. (2011) Study of prediction of ground shock parameters in field at different depths of burst in sandy clay. Chinese Journal of Rock Mechanics and Engineering, 30(9): 1918-1923.

[14] Mu, C.M., Ren, H.Q., Shi, B.M. (2016) Investigation on the shock acceleration of concrete at different depths of burst. Journal of Vibration and Shock, 35(3): 1-6.

[15] Li, C.Q., Mu C.M., Shi, B.M. (2017) Investigate on shock stress propagation in concrete at different depths under blasting. Journal of Vibration and Shock, 36(6): 140-145.

[16] Zhao H.L., Hou, A.J., Tong, H.F., et al. (2011) Prediction method of the direct ground shock parameters of explosion at different buried depths in free field of limestone. Explosion and Shock Waves, 31(3): 290-294.

[17] Pasyanos, M.E., Ford, S.R. (2015) Determining the source characteristics of explosions near the Earth's surface. Geophysical Research Letters, 42: 3786-3792.

[18] Kitov, I.O., Murphy, J.R., Kusnetsov, O.P., et al. (1997) An analysis of seismic and acoustic signals measured from a series of atmospheric and near-surface explosions. Bulletin of the Seismological Society of America, 87(6): 1553-1562.

[19] Drake, J.L., Little C.D. (1983) Ground shock from penetrating conventional weapons. US Army Engineer Waterways Experiment Station, ADP001706.

[20] Murphy, J.R., Lahoud, J.A. (1969) Analysis of seismic peak amplitudes from underground nuclear explosions. Bulletin of Seismological Society of America, 59(6): 2325-2341.

[21] Adams, W.M., Preston, R.G. (1961) Summary report of strong-motion measurements, underground nuclear detonations. Journal of Geophysical Research, 66(3): 903-942.