Optimization of seismo-acoustic land mine detection using dynamic mechanical impedances of mines and soil

Dimitri Donskoy, Nikolay Sedunov, Alexander Ekimov, Mikhail Tsionskiy
Stevens Institute of Technology, Castle Point on Hudson, Hoboken, NJ 07030
Phone: (201) 216-5316, Fax: (201) 216-8214, E-mail: ddonskoy@stevens-tech.edu

ABSTRACT

Seismo-acoustic detection has demonstrated a high potential for the detection of land mines with a low probability of false alarms. A key element in the implementation and optimization of this new detection approach is the physical model of the mine-soil system. The validated model of the mine-soil system employs a mass-spring approach, which characterizes the dynamic response of the system using very few (three to six) parameters derived from the dynamic mechanical impedances of the soil and the mines. This presentation describes the model and the results of the impedance measurements of live antitank and antipersonnel mines. The paper also deals with the optimization of the detection algorithm and its performance based on mine type, burial depth, and soil condition.

Keywords: landmine detection, seismo-acoustics, dynamic impedance, engineering model, optimization

1. INTRODUCTION

A key element in implementing this new technical concept is the development of a physical model of the system under test: the mine/soil system. The appropriate model leads to an optimum detection algorithm and helps to demonstrate the mine detection capabilities of the technique applied to mine type, burial depth, and soil condition.

Any physical model of a dynamic system starts with a comparison of the wavelength and characteristic geometric size of the system. If the wavelength is shorter than the size of the target, the wave approach should be use. If the wavelength is longer than the target, the lump-element approach is more appropriate. In the case of a mechanical system such as a mine/soil system, the use of the lump-element (mass-spring-dashpot) approach is justified as long as low frequency waves are used. These low frequency waves are much longer than the size of a mine and its burial depth. In fact, this approach is valid for the tens to hundreds of Hz frequency range. The range where the most successful practical results were obtained.

The first such lump-element model was introduced in 1999, [1]. According to this earlier version of the model, the soil on top of the mine has mass (inertia) and stiffness, determined by the compressibility of the soil, and is supported by a compliant mine's top. For simplicity, the dynamic mass of the mine's top diaphragm was neglected, so the resulting dynamic mechanical model of the mine/soil system consists of soil mass, M_s, and its stiffness, K_s, mine stiffness, K_m, and damping coefficients, R_s and R_m, for the soil and the mine respectively. The resulting spring-mass system suggested the presence of the resonance response of the mine/soil system which was observed in numerous laboratory and field tests [1-3]. In order to quantify this model we conducted measurements of the dynamic mechanical impedances of the live mines and determined each mine's characteristic parameters, such as their dynamic masses, stiffnesses, and damping coefficients. The results of these measurements are presented in the next chapter. One of the important findings is that most of the test mines exhibited a clearly defined mechanical resonance of their casing. This indicates that the dynamic mass of the mine's casing may have significant impact on the overall dynamic response of the mine/soil system and must be included in the model.

2. MEASUREMENTS OF MINE IMPEDANCES

Dynamic mechanical parameters of the mines (stiffness, K_m, dynamic mass, M_m, and damping coefficient, R_m) can be determined using measurements of their dynamic impedances. The impedance, Z_m, of the mechanical system is defined as the ratio of the applied force to the resulting vibration velocity. For a one-degree mechanical system it is equal to

$$Z_m = -jK_m/\omega + R_m + j\,\omega M_m, \tag{1}$$

where ω is the angular frequency.

The impedance measurements were performed in August, 2000. Live mines (with explosive charge but without fuses) were placed on 2x2x2 cu. ft. concrete foundation flush with the ground level. External force (airborne acoustic pressure) was applied in the range 30 – 800 Hz and measured with a microphone. Vibration velocity, V, of the mine's top diaphragm was measured with a non-contact laser-doppler vibrometer. The resulting magnitudes of the dynamic impedances (per unit area) of mines, z_m = P/V, were calculated and recorded as a function of frequency.

The measurements were taken for two representative mines of the same kind and demonstrated good data repeatability. Figure 1 shows the typical impedance of an AT mine. Remarkably, most of the antitank mines exhibited clearly defined mechanical resonances of their casing (shown as minimum on the Fig.1). Most of the resonances were found between 100 Hz and 400 Hz. Some AP mines have resonances as well. Regardless of the resonances, most of the measured live mines (we measured nearly 50 AP and AT mines) had a higher compliance (lower stiffness) than the surrounding soil.

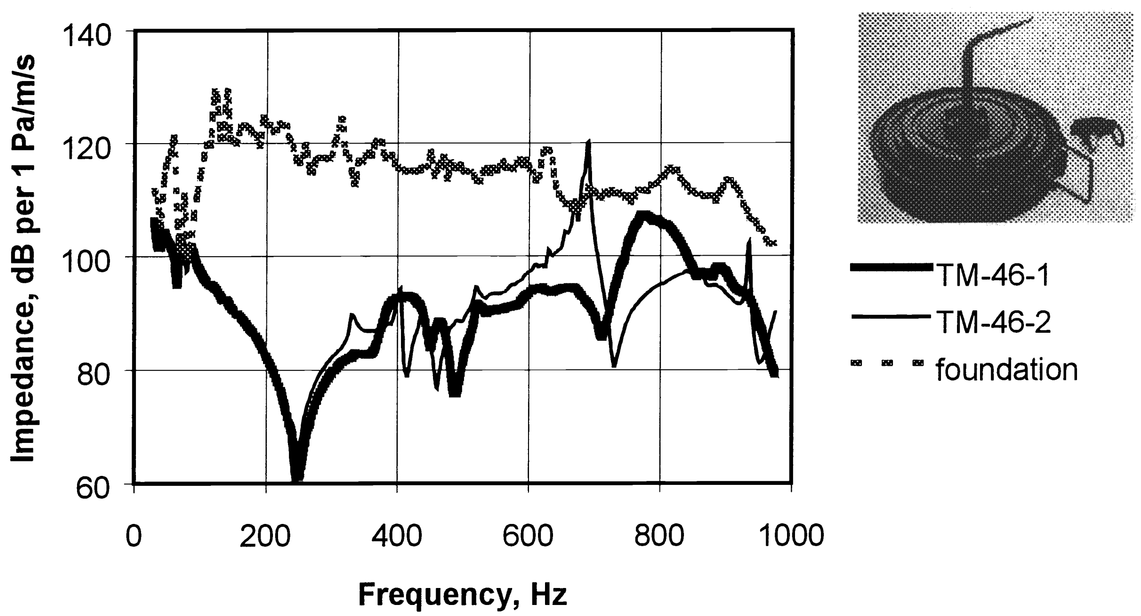


Fig.1. Impedances of two samples of an AT metal mine TM-46 and a foundation

Table 1 shows dynamic parameters of some mines determined from their measured impedances. All parameters are normalized to area and denoted by lower case letters. Soil stiffness, k_s, (per unit area) measured at the test location was near 10^9 Pa/m and the stiffness of the concrete foundation and rigid targets such as piece of metal were well above 10^9 Pa/m.

This comparison confirms that in the specified frequency range, the stiffness of most of the mines is less than the stiffness of the soil and much less than the stiffness of the rigid targets, which explains the detection and discrimination capabilities of the linear and nonlinear seismo-acoustic technique as was outlined in earlier papers [1, 4].

These measurements also revealed that many mines have their own mechanical resonances,. Therefore, the dynamic mass of the mines could have an appreciable impact on the resulting dynamic response of the mine/soil system, and this mass must be taken into account.

Table 1. Dynamic parameters of live mines

Mine type	Resonance frequency f_0 (Hz)	Dynamic stiffness k_m*10^7 (Pa/m)	Dynamic mass m_m (kg/m^2)	Damping coefficient r_m (kg/s·m^2)	Description
TS-50	520	10	9	4000	AP Plastic
VS-50	330	6	13	3300	AP Plastic
PONZ-2	380	50	85	26000	AP Plastic
VS-1.6	220	2.5	12	1700	AT Plastic
TMA-5	190	0.2	1.4	300	AT Plastic
SH-55	280	2.5	8	3000	AT Plastic
VS-HCT-2	465	2.8	3.3	500	AT Plastic
TM-46	250	4	16	1200	AT Metal
TMA-4	250	17	65	20000	AT Metal

Another interesting observation from these impedance measurements is that impedance of the empty mine casings could be significantly different from the impedances of live mines, Fig.2. We believe that this is primarily due to the alteration of the mechanical integrity of mine casing during its disassembly and reassembly.

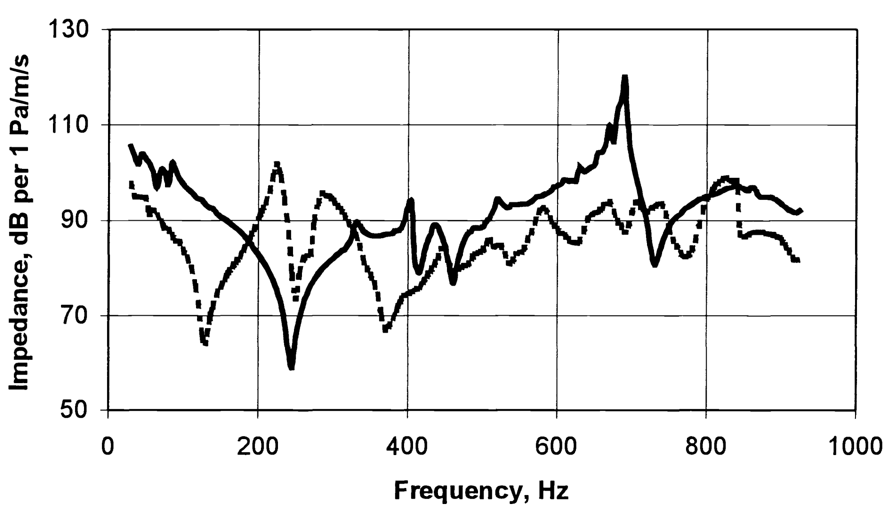


Fig. 2. Impedances of live TM-46 (solid curve) and TM-46 casing only (dashed curve).

3. ENGINEERING MODEL OF MINE/SOIL SYSTEM

We use the term "engineering model" to emphasize the practical focus of this developed model. Another reason to use this term is the introduction of new soil parameters, which are directly related to the seismo-acoustic detection technique. Some of these parameters were easily evaluated, some could be measured on site.

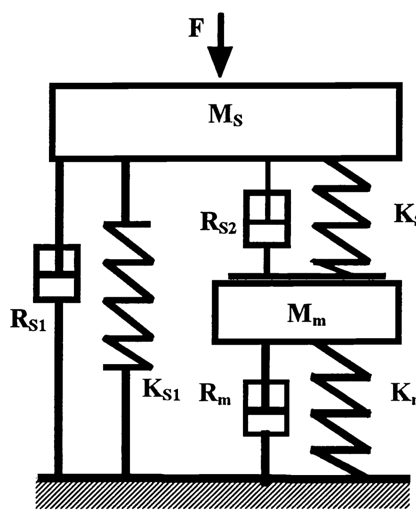
Before proceeding to the modeling of the mine/soil system, one question should be answered. What is the nature of the mine resonances? With a few exceptions, this is due to the bending resonance of a casing's upper diaphragm. If we simplify the diaphragm as a circular plate, hinge-supported along its perimeter; the bending resonance of such a plate can be evaluated using the following formula:

$$f_0 \cong 0.92\frac{h}{a^2}\sqrt{\frac{E}{12(1-\upsilon^2)\rho}} \quad , \tag{2}$$

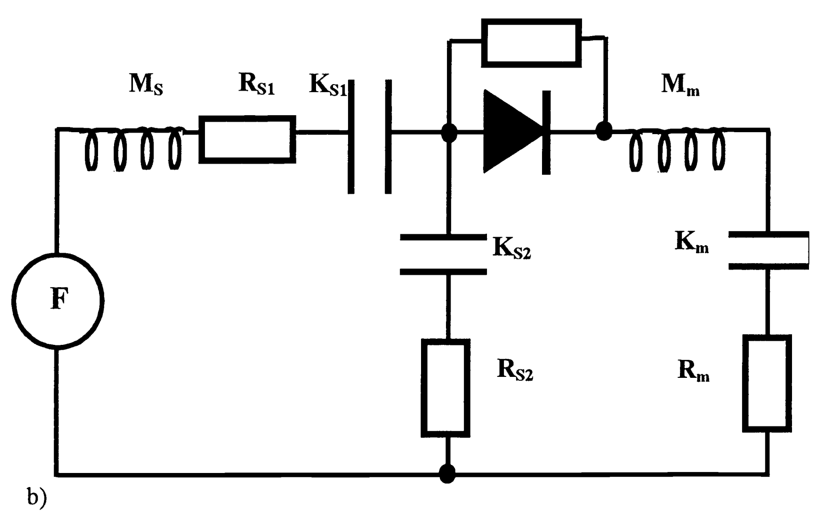
where h and a are the thickness and radius of the plate, E, ν, ρ are the material properties of the plate (Young's modulus, Poisson's ratio, and density respectively). This formula gives quite an accurate estimate of the resonance frequency. Thus, for the steel plate 0.001 m thick and 0.1 m radius, the resonance frequency is 290 Hz, which is in the range of the measured resonance frequencies.

Buried in soil, mines and soil create a unified mine/soil system whose dynamic behavior could be described using the diagram on Fig.3a. In this diagram M_S is the mass of the soil on top of vibrating mine; K_{S1} and K_{S2} are the shear and the compression stiffnesses of soil; R_{S1} and R_{S2} are the soil damping coefficients due to shear and compression of the soil respectively. All these soil parameters are depth dependent. Mine parameters were introduced earlier.

Analysis of this system is easy to perform using an equivalent electrical diagram in which external force, F, equivalent to voltage generator, masses, stiffnesses, and damping parameters are represented by inductances, capacitors, and resistances respectively, as shown in the Fig.3b. In this diagram, an additional nonlinear element (a diode with a shunt resistor) is introduced to account for the nonlinear behavior of the system due to separation effect at the soil-mine interface [1, 4]. This completes the linear and nonlinear model of the mine/soil system in a low frequency range.



a)



b)

Fig.3. Equivalent mechanical, (a), and electrical, (b) diagrams of the mine/soil system in low frequency range.

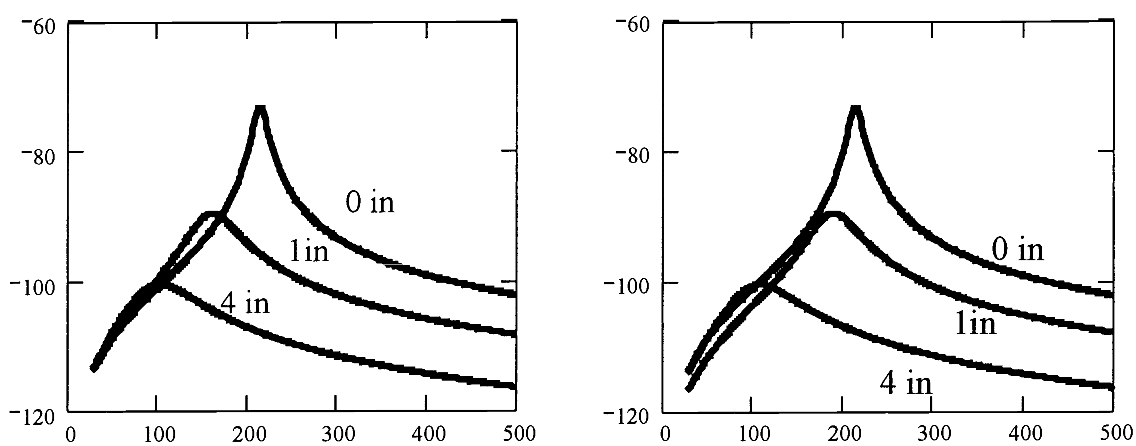
There is no doubt that the behavior of the real soil and its interaction with the mine can be more complicated than the model suggests. Thus, the soil could exhibit a certain degree of nonlinearity, especially loose or unconsolidated soil. The proposed model by no means claims to be a comprehensive description of the complicated system under consideration. However, as any engineering model, it helps to understand the physical mechanisms involved, and provides qualitative, as well as quantitative evaluation of the dynamic behavior of a mine/soil system. This is essential for the development and optimization of the detection technique.

4. OPTIMIZATION OF SEISMO-ACOUSTIC DETECTION

As the model suggests, the optimum detection (maximum contrast of soil surface vibration on and off the buried mine – on/off contrast) will take place in the vicinity of the soil/mine resonance. This is supported by numerous laboratory and field tests results [1-4]. Besides resonance, the maximum contrast is also directly proportional to stiffness contrast between the soil and the mine; that is, the more compliant the mine relative to soil compliance, the greater the on/off contrast.

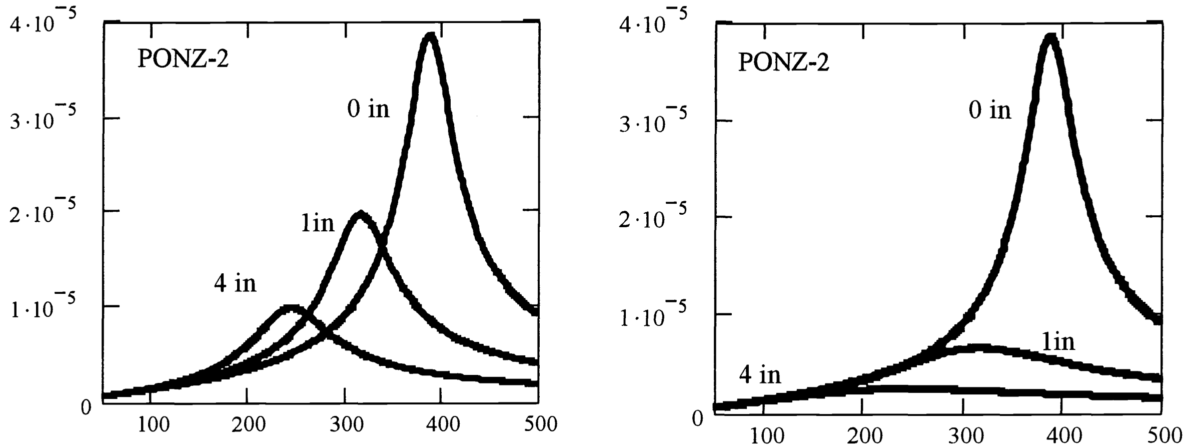
Analysis of the developed model also indicates that the soil damping coefficient, R_{s1}, and stiffness, K_{s1}, associated with shear deformations, have a very strong impact on optimum detection; in fact, much stronger than the parameters R_{s2}, and K_{s2}, associated with compression-tension of soil. Figures 4 and 5 illustrate the effect of parameters M_s, K_{s1} and R_{s1} on the surface vibration velocity above the buried mine. The soil mass increases with the burial depth, so, as a result, the resonance frequency shifts to the lower range. In addition, the velocity magnitude also reduces with the depth due to the damping coefficient R_{s1} increase. The coefficient R_{s2} has little effect on the surface velocity, if the mine stiffness is less than the soil stiffness; $K_m < K_{s2}$.

The soil shear stiffness parameter K_{s1}, may have a significant effect on the resonance frequency shift as illustrated in Fig. 4b vs. Fig.4a. The damping coefficient R_{s1} has a very strong effect on the surface velocity (its magnitude) as shown in Fig.5. The higher the R_{s1} the less the on/off contrast.



a) b)

Fig.4. Surface vibration velocity (dB scale) vs. frequency (Hz) for burial depths 1 and 4 inches. The shift in resonance frequencies in Fig. 4b is due to 10 fold K_{s1} increase.

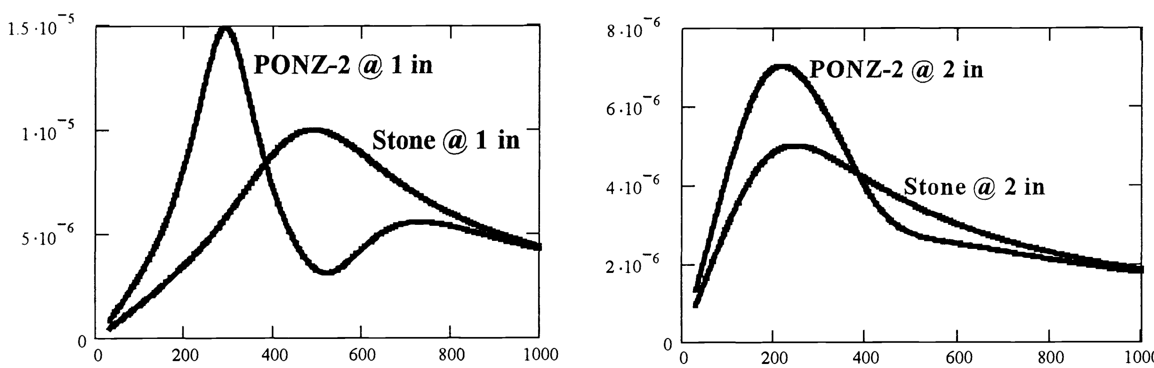


a) b)

Fig.5. Dependances of surface velocity (linear scale) vs. frequency (Hz) for mine PONZ-2 buried at 1 and 4 inches. The reduction of velocity magnitude in Fig. 5b is due to 5fold R_{s1} increase.

5. FALSE ALARMS AND NONLINEAR DISCRIMINATION

Fig. 6. Illustrates a possible false alarm situation, where a stone buried 2 inches below the surface exhibits the same resonance frequency as a relatively rigid mine PONZ-2 buried at the same depth, Fig. 6b. In a situation like this, the nonlinear effect due to the separation at the soil/mine interface could provide the needed discrimination capabilities.



a) b)

Fig.6. Surface velocity (linear scale) vs. frequency (Hz) for mine PONZ-2 and a stone buried at 1 inch, (a), and 2 inches, (b)

The acoustic manifestations of the nonlinearity of a dynamic system may be variable. The classical nonlinear effect is the nonlinear distortion of the probe sinusoidal (frequency ω_0) signal: generation of harmonics with the frequencies $2\omega_0$, $3\omega_0$, etc. Another effect is the generation of the signals with combination frequencies. For example, with a bi-harmonic probe signal having frequencies ω_1 and ω_2, the nonlinearity leads to the generation of signals with the frequencies $\omega_1 \pm \omega_2$. The combination frequency effect is more practical for mine detection purposes because it is generated primarily on the nonlinear mine/soil interface, while harmonic frequencies can be generated directly by a source.

Fig. 7 demonstrates the nonlinear on/off contrast of surface velocity at difference frequencies. These measurements were conducted at the U.S. Army testing ground in August, 2000. Two primary frequencies were broadcast: one was 350 Hz fixed, while the other one was swept between 550 – 590 Hz. The signals with the respective difference frequencies 200 – 240 Hz on and off target (AT mine at 3 in depth) were measured and demonstrated very high contrast, as shown on Fig. 7. Earlier measurements, [1, 4], also demonstrated discrimination capabilities of nonlinear detection.

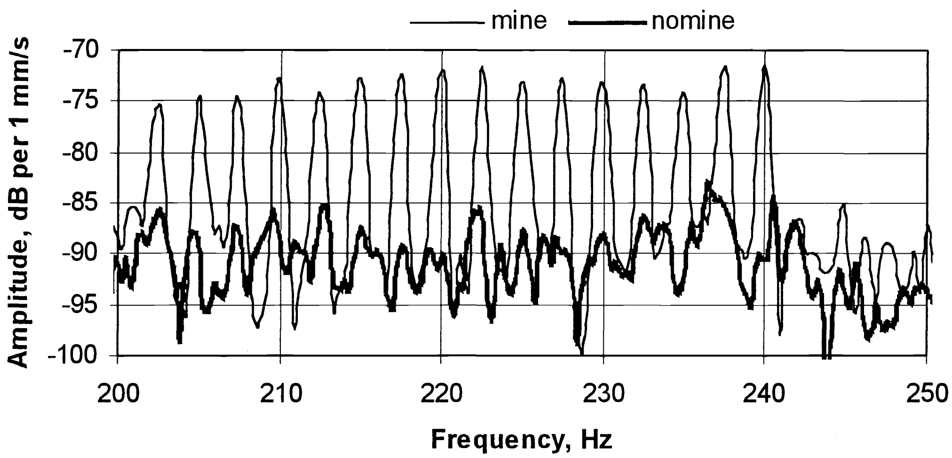


Fig.7. Nonlinear detection of AT mine at 3 in depth

CONCLUSION

The developed engineering model, supported by numerous laboratory and field tests, shows that the observed dynamic behavior of a mine/soil system creates a foundation for an innovative mine detection and discrimination technique. This technique is capable of detecting metallic and non-metallic mines with a low false alarm rate. The detection technique utilizes the effects of the soil/mine resonance and the nonlinear transformation of a probing bi-harmonic seismo-acoustic signal at the soil-mine interface.

For the first time, the unique identification of the dynamic parameters (dynamic mass, stiffness, and damping) of live mines were determined using mine impedance measurements. This data, along with the developed model and on-site soil calibration measurements, allows for the optimization of the technique and the evaluation of the detection capabilities of the developed nonlinear seismo-acoustic scheme with various mine types and burial depths.

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