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Modeling of soil density zones in the vicinity of an explosive charge

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Abstract

Modeling the change in the parameters of the soil exposed to the performance of the explosion, considering the heterogeneity of the soil, the dependence on the water content and the different calibration experimental parameters, is a challenge. The models, incorporated in the computer program Ansys 2020 R1 Autodyn 2D hydrocode, were used to model the performance of the explosive charge in the soil and can be used with certain accuracy to estimate the change in soil density in the environment of the explosive charge in an infinite environment. The processes of performance of three types of explosives on the density of the soil in the vicinity of the explosive charge and the influence of the mass of the ANFO explosive charge on the radius of the resulting expansion were modeled. The modeling results for cavity diameter are compared with the experimental data and presented in the article.

Keywords*: soil, density zone, explosive charge, Autodyn 2D hydrocode*

1. Introduction

The energy of the explosion is used for various purposes in the military and civilian fields. Blasting is a technique of using explosives primarily for crushing solid rocks, in mining and construction applications. Blasting in the soil can be classified as special methods that include excavation, drainage, soil improvement and the creation of expansion for the placement of anchors. Modeling the change in the parameters of the soil exposed to the performance of the explosion, considering the heterogeneity of the soil, the dependence on the water content and the different calibration experimental parameters, is a challenge. The models, incorporated in the computer program Ansys 2020 R1 Autodyn 2D hydrocode, were used to model the performance of the explosive charge in the soil and can be used with certain accuracy to estimate the change in soil density in the environment of the explosive charge in an infinite environment. The processes of performance of three types of explosives on the density of the soil in the vicinity of the explosive charge and the influence of the mass of the ANFO explosive charge on the radius of the resulting expansion were modeled. Modeled expansion dimensions were compared with experimental data.

The soil is a three-phase system (solid particles, water and air) and it is difficult to predict soil deformation under impact load such as one that is produced by an explosion. Difficulty is in the main fact that effective stress principle and soil dynamics principles are invalid under blast loading. The solid particles deform under loading, and water and air are trapped in the voids because of the very short load duration, thus providing additional load resistance [1]. The common practice in modeling soil behavior under a blast load is primarily based on empirical formulas from field tests [1]. According to the complexity of the problem, soil behavior under blast loading has been studied by many researchers: Wang and Lu 2003; Tong and Tuan 2007; Grujicic et al. 2008 and the others [2]. An additional difference appears if the soil is cohesive or non-cohesive. In cohesive soils, two deformation mechanisms exist. The first deformation mechanism, at low pressure, the soil skeleton deformation is determined by the elastic deformation of bonds on the contact surfaces of grains; the first mechanism at high pressure is determined by a failure in bonding and the displacement of grains (plastic deformation). The second deformation mechanism is the deformation of all the soil phases. When soil is being compressed, both mechanisms act simultaneously, but at certain phases of the loading, one of the mechanisms predominates [3]. Commercial explosives used for blasting are characterized by non-ideal detonation (lower energy, pressure and velocity of detonation and longer time of heat release [4, 5, 6].

ANFO explosives, AN powder explosives and water gels are commercial explosives. They show the non-ideality of detonation to a certain extent, in the sense of deviation from the classic, hydrodynamic detonation model. At the same time, the pressure and velocity of the detonation are significantly dependent on the conditions in which the process takes place, that is, the confinement of the system boundaries and the stiffness of the boundaries (for example, in the case of detonation in air, water, rock or a steel pipe); the diameter and size of the charge and the energy and speed of the initial impulse. Related to the above, when modeling the process of expansion in clay and densification of clay in the vicinity of the explosive charge, it is necessary to rationally choose the parameters that describe, in the case of the application of Autodyne hydrocode, JWL (Jones Wilkins Lee) the adiabatic of the detonation product gases in accordance with the shape and mass of the explosive charge and the conditions in which the process takes place. Since the models or codes for the calculation of detonation parameters (detonation velocity, detonation pressure, explosion energy, volume of gases produced by detonation) are found on several calculation approaches based on the chemical composition of the explosive and the ideal detonation process, it is necessary to make corrections based on the measured detonation velocities. Thus, when modeling with Ansys 2020 R1 Autodyn 2D hydrocode, correction of JWL parameters obtained by computer code Explo 5 with values of detonation velocities measured on the same sample size in simulated conditions of clay soil was made for the explosive input data. The specified explosives (ANFO, ammonium nitrate powder and water gels) used in the research differ in their performance, which can be expressed by the parameters given in table 1. The performance of explosives is expressed in relative values obtained by dedicated testing methods and reflects the ability of the explosive to function in certain conditions or media. The working performance is determined mostly by the detonation velocity and detonation pressure of the explosive used. The results of recent research have shown that the primary role in the performance of explosives in the soil [7] is played by the amount of energy applied, i.e. the mass of the explosive, and only secondarily by the type of explosive, i.e. the velocity and pressure of detonation. During the detonation process of the explosive, by rapid oxidation, it turns into highly compressed gaseous products (pressures are from several tens to several hundreds of kBar). During adiabatic, almost instantaneous expansion, the gases have an impact effect on the surrounding soil and, after the soil shifts in the immediate vicinity of the blasthole, they generate an area of soil with higher densities. The highest densities occur at the boundary of the expansion and decrease with distance from the blasthole. Such a distribution is a consequence of the consumption of impact energy, i.e. the loss of gas pressure. According to previous results, the volume of the resulting expansion depends mostly on the mass of the explosive, while the values of soil densities can be related to the type of explosive, i.e. the magnitude of individual detonation pressures. The paper analyzes the behavior of soil during shock wave propagation, through density changes in cohesive soil. Laboratory and field tests were conducted as part of previous research. Laboratory tests included determining the physical and mechanical parameters of the soil, while field tests included measuring the geometric parameters of the expansion caused by blasting with ANFO explosives. Using numerical simulation Ansys 2020 R1 Autodyn 2D hydrocode for different ANFO charge masses, the expansion dimensions and soil densities in the vicinity of the expansion were determined. After validating the model solution with experimental values, simulations were conducted for two more types of commercial explosives, namely AN powder and water-gel explosives. In this part of the research, an analysis of density changes in the surrounding soil after blasting was conducted and the soil response zones to the passage of a shock wave caused by the detonation of an equal mass of 1 kg of different commercial explosives were defined.

2. Materials and Methods

2.1. Soil characteristics

Detailed laboratory analyzes of the soil in which the blasting was carried out showed that it is highly plastic clay (content: 3.5% gravel, 3.1% sand, 55.6% silt and 37.8% clay) [7]. Laboratory analysis of soil compressibility in an oedometer were carried out and the results are shown in Figure 1 in the form of a Hugoniot diagram.

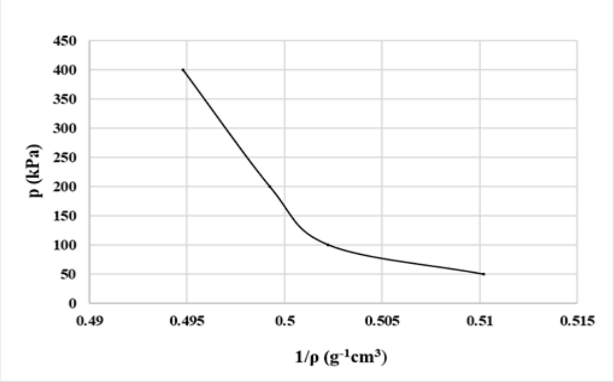

Fig. 1. Hugoniot curve for tested soil

The initial soil density was determined, as 1.96 g/cm^3, and the density of solid particles as 2.71 g/cm^3.

2.2. Explosive characteristics

Commercial explosives used in the research differ in composition and type of mixture and thus in detonation characteristics. The basic, relevant parameters of the explosives used are shown in Table 1.

Table 1. Explosive parameters

Type of explosive	Chemical composition	Density (g/cm^3)	Velocity of Detonation (Measured) (m/s)	Pressure [GPa]	Theoretical Heat of Detonation (Literature and Producer Declaration) (KJ/kg)
ANFO	NH_4NO_3 and mineral oil	0.90	2000	0.86	3597
Ammonium nitrate powder explosive	ammonium nitrate, trinitrotoluene, dinitrotoulene, paraffin wax, and moisture	1.05	4000	3.24	4276
Watergel	NH_4NO_3, MMAN, water, $NaNO_3$, and aluminum	1.25	4576	5.83	4591

The velocities of detonation (VOD) of the concerned explosive properties were derived from experimental results, measured by the electro-optical method, with the same properties and confinement at the test field in charges as in simulations. The measured values deviate from the declared, theoretical values of the detonation velocity, especially with ANFO explosive due to the pronounced non-ideality, especially in the form of the applied charge.

2.3. Numerical simulation

Numerical simulation was performed using Autodyne software via Compaction EOS Linear model where the elastic bulk stiffness of the material is defined as a piecewise linear curve of sound speed (c) versus density (ρo). The bulk stiffness of the material is given by equitation:

$$K = \rho_0 c^2 \qquad (1)$$

The level of compaction in the material is given by equitation:

$$\alpha = \frac{\rho_s}{\rho_0} \qquad (2)$$

Initially, ρ_o will be equal to the value defined in the density property of the material. Material property ρ_s is the solid zero pressure density of the material and corresponds to the fully compacted material density. For a porous material the initial density will be less than the solid density hence the value of α will be greater than 1.0. As compaction takes place, α will reduce to a value of 1.0 for the fully compacted state [8].

The explosive detonation and expansion were modeled by using Jones-Wilkins-Lee (JWL) equation of state (EOS) given by the following equitation:

$$P = C_1\left(1-\frac{\omega}{R_1V}\right)e^{-R_1V} + C_2\left(1-\frac{\omega}{R_2V}\right)e^{-R_1V} + \frac{\omega E}{V} \qquad (3)$$

where, P is the hydrostatic pressure, C_1, C_2, R_1, R_2 and ω empirically derived constants which provides different values for different explosives; V is the specific volume of detonation product over the specific volume of undetonated explosive and E is specific internal energy [8]. JWL constants for used explosives are determined using termocode EXPLO 5 and they are given in table 2.

Table 2. JWL coefficients [4].

Type of explosive	**A (Mbar)**	**B (Mbar)**	**R_1 (-)**	**R_2 (-)**	**ω (-)**	**D (cm/µs)**	**P (Mbar)**	**E_0 (Gerg/mm^3)**
ANFO	0.062805	0.001513	2.193732	0.464714	0.177879	0.304939	0.01933323	0.029706
Amonnium nitrate powder	0.79023	0.01257	4.6797	0.9529	0.1933	0.4022	0.0379	0.0318
Watergel	2.38931	0.022655	5.203369	1.054384	0.158459	0.4587	0.05828	0.0412

3. Results and discussion

The effect of an explosive charge during detonation in the soil can be visualized through zones that change the surrounding environment through a change in density and a change in particle size and particle bonding. In the blasting of solid rocks, classical models describe a zone of intense crushing in the immediate vicinity of the borehole or charge. In the soil, there is no fracturing, fragmentation and crushing, but rather soil compression and an increase in density, which is determined by the nature of the soil. The outer zone of the explosive performance is a seismic zone in which the density does not change, there is no movement of material and no plastic deformation, but the particles vibrate elastically and dissipate the remaining energy. The sizes of the zones, or their widths seen from the blasthole, depend on the physical and mechanical properties of the soil, the detonation properties of the explosive and the mass of the explosive charge.

By releasing the energy of the explosive through the detonation process, ideal or non-ideal, the detonation gases, which are heated to several thousand degrees and compressed to pressures from several tens of kBar to several hundred kBar in the volume of the initial explosive, suddenly expand. In this case, they act on the environment via a shock wave that initially fractures and/or pushes the material of the environment (depending on the properties and type of the environment). Secondarily, immediately after the impact, the products of the expansion push the material of the environment and either crush it or increase its density in the case of soil. At the end of the process, around the expansion in the soil caused by the performance of the explosive charge, an area of increased soil density is formed with a maximum, crystalline density in a very thin zone directly next to the contact of the expansion and with a distribution of densities to the undisturbed soil density. The simulated processes formed zones of different densities, where the widths of the zones, or the volumes of the substance with a change in density, depend on the mass and type of explosive charge described by the detonation parameters of the explosive used.

The results for all three types of explosives showed that the surrounding soil behaved uniformly with the use of the same mass of explosive. The first zone is a zone of sudden increase in soil density and it extends from the edge of the expansion to 450 mm viewed from the center of the detonation zone. The second zone, or the zone of gradual decrease in density, extends from 450 mm to 600 mm. The third zone extends from 600 mm to 1350 mm, in this zone the density drops to approximately the initial value, while in the fourth zone (zone around 1500 mm) the soil remains undisturbed.

The results of changes in soil density under the performance of explosives of different detonation properties are shown in Table 3 and in Figures 2, 3 and 4, while the zones are shown in Figure 5.

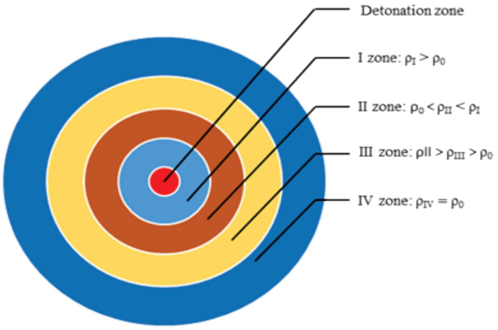

Fig. 2. Density change zones display

Table 3. Results of soil density by zones (1 kg of explosive)

Type of explosive	Zone I Density (g/cm^3)	Zone II Density (g/cm^3)	Zone III Density (g/cm^3)	Zone IV Density (g/cm^3)
ANFO	2.46	2.09	2.04 – 2.01	1.96
Amonnium nitrate Powder	2.16	2.03	2.02 – 1.96	1.96
Watergel	-	2.40	2.07 – 2.01	1.96

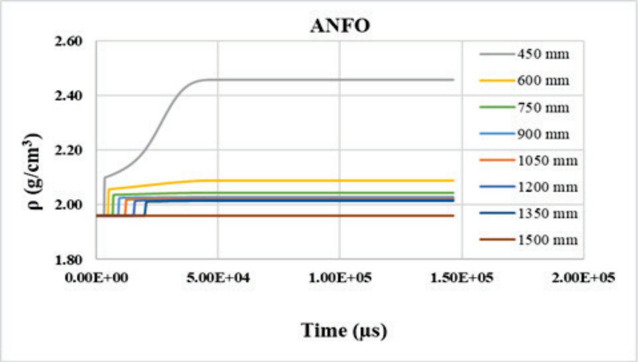

Fig. 3. Density profile of surrounding soil when using ANFO explosive.

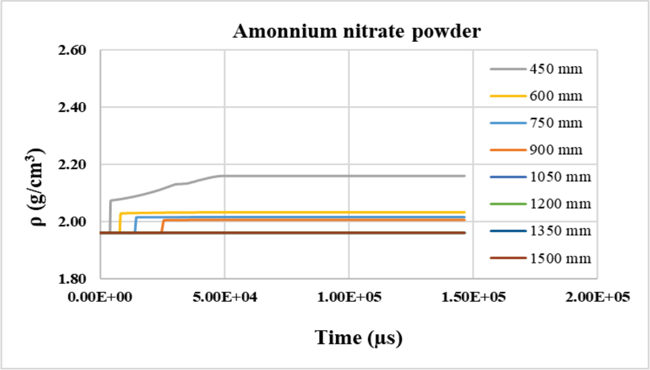

Fig. 4. Density profile of surrounding soil when using ANFO explosive.

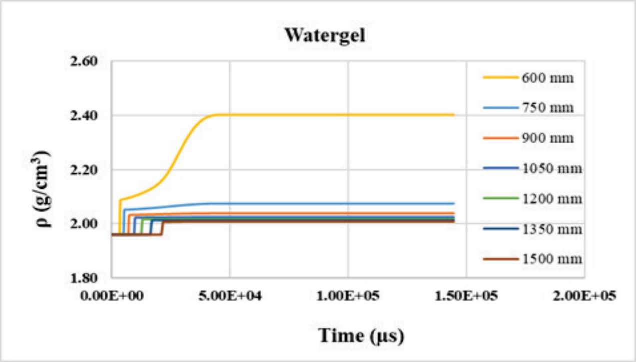

Fig. 5. Density profile of surrounding soil when using Watergel explosive.

The analysis of the results was carried out from the aspect of the size or radius of the resulting expansion and from the aspect of the change in density in the vicinity of the expansion. It can be concluded that 1 kg of commercial explosive of any type (ANFO, Ammonium nitrate powder or Watergel) produces expansions of almost equal dimensions. The simulation results match well with the results of the experiments conducted for ammonium nitrate powder explosive and ANFO explosive. From the experimental data it can be concluded that the sizes of the expansion radii are somewhat larger for ammonium nitrate powder explosive. With a closer comparison and review of the data, such a deviation of approximately ten percent can be attributed to the error in measuring the expansion dimensions during the in situ experiment. The model results were experimentally confirmed for ANFO, while there are no experimental results for ammonium nitrate powder explosives or water gel. Such results can be linked to the fact that the detonation pressures of the product gases, which can be considered the main acting mechanism in the formation of expansion, have values many times higher than the compressive strengths of the soil. In this case, when acting on the entire volume of soil, due to the significantly higher pressure in relation to the strength, small differences in the pressures of individual explosives do not have a significant impact on the total expansion volume. Analysis of the parameter of the product of the theoretical detonation energy and the volume of the gases produced (QxV), which is called the explosion power, and which can be used to assess the working capacity, results in differences of 15 percent for the observed explosives. It can be concluded that the amount of explosion power is relevant to the size of the expansion in the soil. For the observed explosives, the explosion powers range from 2000 to 2200, i.e. they differ within 15%. The results of the modeled and measured explosion power expansion radii for the explosives used are given in Table 4.

The results are shown in table 5 and in figures 6, 7, 8 and 9.

Table 5. Explosive parameter

Total mass of ANFO explosive	Zone I Density (g/cm^3)	Zone II Density (g/cm^3)	Zone III Density (g/cm^3)	Zone IV Density (g/cm^3)
0.23 kg	2.08	2.03	2.02 – 1.96	1.96
0.4 kg	2.39	2.06	2.03 – 1.96	1.96
1 kg	2.46	2.09	2.04 – 2.01	1.96
1.5 kg	-	-	2.15 – 2.02	1.96

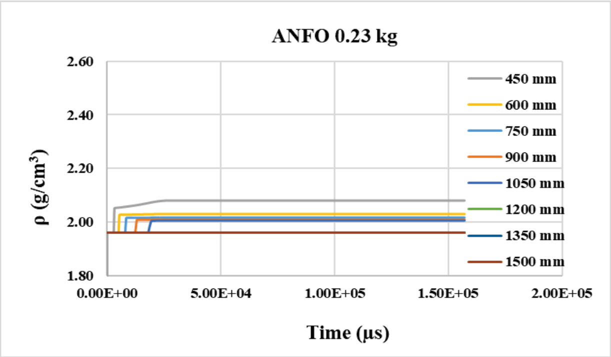

Fig. 6. Density profile of surrounding soil (0.23 kg of ANFO).

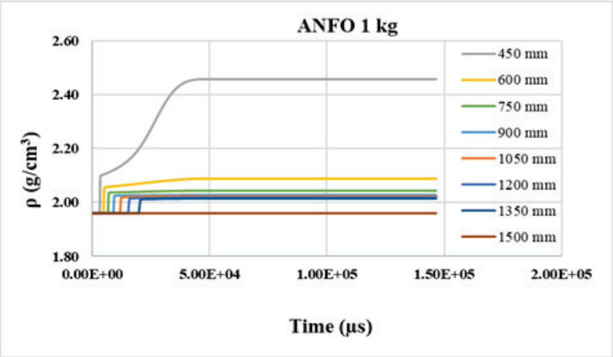

Fig. 8. Density profile of surrounding soil (1 kg of ANFO).

By analyzing the data, it was observed that for different charge masses of the same explosive, the zones remain the same with minimal density deviations, except for the mass of 1.5 kg. The dependence of the density of the soil after detonation on the mass of the explosive charge is shown in the graph in Figure 10.

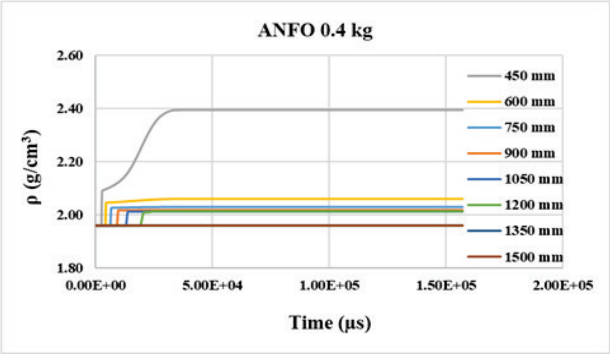

Fig. 7. Density profile of surrounding soil (0.4 kg of ANFO).

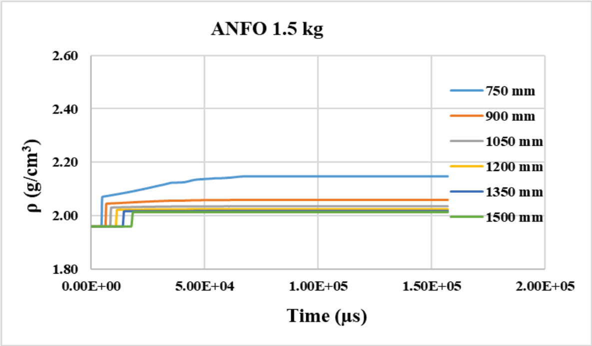

Fig. 9. Density profile of surrounding soil (1.5 kg of ANFO).

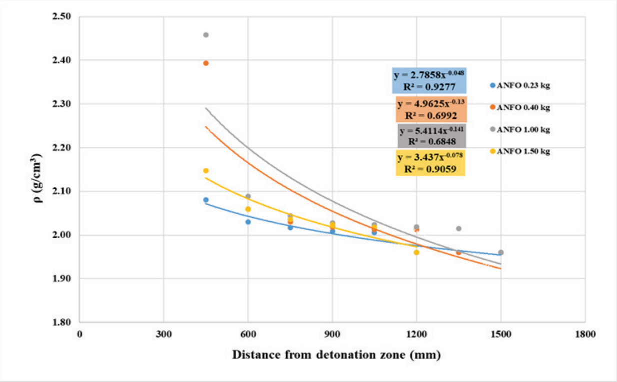

Fig. 10. The dependence of the density of the soil after detonation on the mass of the explosive charge.

The graphs show relatively strong correlations and the patterns are applicable for estimating the soil density in the vicinity of the resulting expansion.

At a mass of 1.5 kg, a change in zones occurs, i.e. at this mass of explosive, a larger expansion radius occurs and thus zones I and II disappear. Given the observations, an analysis of the dependence of the explosive mass on the expansion radius was conducted. The analysis is graphically presented in Figure 11.

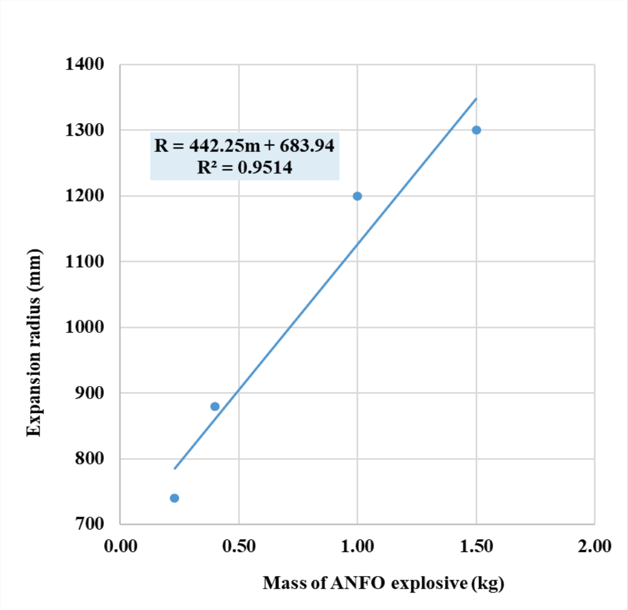

Fig. 11. Dependence of the radius of expansion in relation to the applied mass of explosives.

By analyzing the dependence of the radius of expansion in relation to the applied mass of explosives, a strong relationship was observed, and it can be assumed that by applying the expression:

$$R = 442.25m + 683.94 \tag{4}$$

It can estimate the radius of expansion of coherent soil when ANFO explosive is applied.

4. Conclusion

According to the conducted modeling and analysis and comparison with experimental data, it can be concluded that the radius of expansion does not depend significantly on the type of commercial explosive, that is, the product of the theoretical detonation energy with the volume of the resulting gaseous products is relevant.
From this fact, a connection can be drawn to the overall effect of the detonation effect, which is not necessarily only the effect of the shock wave on the detonation front, but is the sum of the effects of the subsequent expansion of gases.
Using the applied model, the geometric characteristics of the resulting expansion can be estimated with sufficient accuracy for engineering purposes for the soil conditions and the explosive used. In doing so, special attention should be paid to the parameters of the non-ideal detonation explosive with which the simulation is entered, as well as to the input parameters related to the characteristics of the soil for which the modeling is carried out.

5. References

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