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APPLIED NUMERICAL MODELING OF BALLISTIC MISSILE–SOIL INTERACTION USING ANSYS EXPLICIT DYNAMICS

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Abstract. The aim of this study is to enhance the geomechanical approach to analyzing the effects of dynamic loads on soil masses by improving a numerical model of the interaction between a ballistic missile and the soil medium. This model takes into account delayed detonation effects and is developed using the simulation environment ANSYS Explicit Dynamics. This advanced software tool is specifically designed to analyze high-speed dynamic phenomena, including shock wave propagation, large material deformations, and structural failure—all of which are typical for scenarios involving explosive loading, such as missile strikes.

The study focuses on evaluating the destructive effects of modern short-range ballistic missiles, particularly the Russian "Iskander" and the North Korean KN-23, on near-surface soil layers and critical underground infrastructure. A key objective is to examine crater formation, the depth and radius of soil displacement, and the degree of structural damage caused by both surface and subsurface explosions. Particular emphasis is placed on scenarios involving missile penetration into the soil followed by delayed detonation.

Model validation was carried out by comparing the numerical simulation results with real-world data collected from missile impacts in the Kyiv region, especially in Bucha, where a crater exceeding 10 meters in diameter and 8 meters in depth was documented after a missile strike. Such empirical data serve as a reference for verifying the adequacy of the model.

A hybrid Eulerian–Lagrangian computational mesh was employed to achieve more accurate simulation results: the soil body was represented using the Lagrangian formulation, while the missile body and explosive detonation products were treated within the Eulerian framework. The numerical model simulates the missile's penetration into the soil followed by a delayed detonation after 10^{-5} seconds. The missile parameters were set as follows: initial velocity of 800 m/s, total mass of 1500 kg, and an explosive payload equivalent to 500 kg of TNT.

To avoid artificial reflections of shock waves at the model boundaries, impedance-based boundary conditions were applied. This method ensures appropriate wave absorption and simulates the behavior of an infinite medium surrounding the modeled domain. The output of the simulations includes detailed data on crater morphology, material fragmentation and ejection, stress wave propagation, and pressure distribution in the soil mass.

The practical significance of the research lies in its contribution to assessing the resilience of underground civil and military facilities under realistic missile threat scenarios. The developed modeling approach offers valuable insight for designing protective structures, evaluating existing infrastructure vulnerabilities, and developing emergency response strategies for critical facilities exposed to extreme dynamic loads caused by modern ballistic weaponry.

Keywords: explosive, soils, detonation, dynamic loading.

1. Introduction

Since the early days of Russia's full-scale invasion of Ukraine, Kyiv and other major cities have been under constant attacks by ballistic missiles.

The severe shortage of shelters and the extremely short flight time of these missiles have forced civilians to use metro stations and other underground structures as bomb shelters. However, the structural resistance of these facilities has not been properly assessed in relation to the destructive capabilities of modern ballistic missiles [1, 2].

This makes it especially urgent to conduct such assessments, monitor locations with large concentrations of people, and forecast the reliability of shelters under potential missile strikes (fig. 1).

Explosive loading differs significantly from static or dynamic loading with alternating cycles.

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Figure 2 illustrates the nature of explosive loading in comparison to static and cyclic dynamic loading [3].

Figure 1 – Implementation of computer vision for practical use in a mine environment

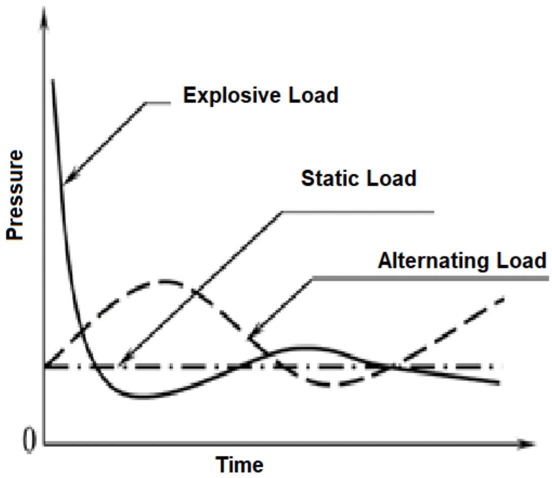

Figure 2 – Time vs pressure dependency for static, cyclic dynamic and explosive loading

As a result of such a specific type of loading, soils and structural materials behave differently compared to static loading.

Therefore, effective and reliable modeling can only be conducted using software that incorporates a mathematical framework capable of capturing the dynamic effects of explosions. Engineering software commonly used for static or cyclic dynamic load analysis is not suitable for this purpose [4, 5].

One of the most advanced software tools that includes the necessary algorithms for simulating explosion dynamics is ANSYS Explicit Dynamics, which enables more accurate predictions of the destructive impact of modern military weapons.

This study examines a real explosion that occurred during a missile attack in the Kyiv region, where a North Korean ballistic missile KN-23 was likely intercepted. The mayor of Bucha (fig. 3), Anatolii Fedoruk, shared images on his Telegram channel showing a massive crater created by the missile, over 10 meters wide and approximately 8 meters deep. All trees within a radius of about 40 meters were completely scorched.

Figure 3 – Crater formed by the impact of a KN-23 ballistic missile

The director of the information and consulting company Defense Express noted that the most frequently used ballistic missiles are the Russian Iskander and the North Korean KN-23 (24), which are very similar in technical characteristics and have a warhead weight of approximately 500 kg.

For Figure 4, data from Conflict Armament Research (CAR) and the Hague Code of Conduct against Ballistic Missile Proliferation (HCoC) were used.

Figure 4 – Specifications of KN-23 and KN-24 missiles

Modern missiles utilize either chemical or nuclear energy. In missiles such as the «Iskander», chemical energy is used, which is released during the decomposition of an explosive substance. As a result of an exothermic chemical reaction occurring within microseconds, the explosive material rapidly transforms into highly heated gaseous and vapor products with extremely high pressure, forming a high-pressure zone [6, 7].

This zone expands, compresses, and displaces the surrounding medium, transferring part of the explosive energy to it and initiating a shock wave that propagates through the medium at supersonic speed.

An explosion in a solid medium is accompanied by its destruction, fragmentation, and ejection. As the blast wave encounters various objects, it interacts with them by means of loading, damaging, and displacing. Additionally, the explosion products, missile fragments, and pieces of destroyed structures gain significant kinetic energy and act as secondary damaging factors.

From the initiation point, the explosive material transitions into explosion products layer by layer. The speed of this process is measured in kilometers per second and is always higher than the speed of sound in the original explosive substance.

If the charge is large enough, the speed of propagation stabilizes—this stage is known as detonation. Therefore, detonation velocity is one of the most critical characteristics of an explosive substance. For most common explosives, it ranges between 4000 and 8000 m/s. It depends on the chemical nature of the explosive, the charge's structural composition, and its density (ρ).

Another important parameter is the specific energy of the explosive transformation (*E*), which characterizes the explosive's capacity for exothermic reaction. It represents the amount of thermal energy released during the explosion of 1 kilogram of a specific explosive substance [8, 9, 10].

The aim of this study is to develop a numerical model of the interaction between a ballistic missile and the soil medium, taking into account delayed detonation, and to assess the impact of explosive loading on soil using ANSYS Explicit Dynamics (student license).

To achieve this goal, the task was set to develop a new methodology for evaluating and predicting the size of craters formed in soil masses as a result of ballistic missile impacts, using software and hardware tools for forecasting the extent of destruction and potential man-made disasters.

2. Methods

The missile detonates at the interface between two media—soil and air—at a short distance from the free surface.

As a result, the explosion affects not only loading, destruction, and displacement with compaction, but also causes significant soil ejection toward the free surface, forming a distinct ejecta crater.

A key modeling decision involves defining the type of explosion—whether as a contact charge or a buried (internal) charge. Internal charges are considered more effective.

That is why missiles such as the «Iskander» are equipped with concrete-penetrating warheads designed for delayed detonation (typically 10–50 ms). This enables the missile to penetrate into the medium—soil, in this case—and explode as a buried charge. Therefore, a delayed explosion was used in the simulation.

This study focuses solely on the explosive loads generated by detonation products and shock waves acting on targets, excluding the effect of fragmentation flows.

Initial and boundary conditions. The numerical modeling of missile impact followed by warhead detonation was carried out using ANSYS Explicit Dynamics.

For the bottom and lateral boundaries of the soil domain, an Impedance Boundary Condition was applied. This condition governs the reflection and transmission of shock waves at the model boundaries, which is particularly critical when simulating explosions and high-speed impacts [11].

When a shock wave reaches the edge of the computational domain, it is essential to properly define its behavior at the boundary. In this case, it is assumed that the wave does not reflect like from a rigid wall but is absorbed beyond the boundary, simulating a conditionally "infinite" medium.

3. Theoretical and experimental part

Several approaches are known in the literature for describing the motion of a deformable continuum medium. These include the Lagrangian, Eulerian, and Arbitrary Lagrangian-Eulerian (ALE) formulations [12, 13].

The use of the Lagrangian approach with a fixed mesh (Lagrangian formulation) has limited applicability for problems involving significant shape changes. Severe mesh distortion, especially in the contact zone, can lead to solutions with non-physical effects. For relatively low-velocity impacts, the problem can be solved using the Lagrangian formulation, which ensures high accuracy in describing the deformation of solid bodies during their interaction [14, 15].

In the Eulerian approach, the material flows through a spatially fixed mesh. In the ALE approach, the material flows through a mesh that itself moves in space. When modeling systems in which one part behaves like a fluid and the other like a solid, it is advisable to use the Lagrangian formulation for the solid body and the Eulerian formulation for the fluid. This method ensures the conservation of energy. For problems involving a wide range of velocities, the ALE formulation is recommended [16, 17, 18].

The computational mesh of the model is a combination of Lagrangian and Eulerian meshes. A Lagrangian mesh, which is attached to the body and moves with it according to the displacement of its points, is used for the soil mass and is set to 1 meter. The Eulerian mesh is used to capture the effects of detonation products above the surface of the soil mass and for the missile. The mesh element size is defined so that the edge length of an Eulerian element is half the size of a Lagrangian element edge. This is due to software limitations and developer recommendations. In our case, it was set to 0.4 meters.

Two scenarios were considered. In the first scenario, the explosive material was initially at rest and in a stress-free state (a case of a surface or attached charge). The detonation was initiated at the center of a cylindrical charge. In the second scenario, the key factor in the problem setup is the complex dynamics involving the missile impact, its penetration into the ground, and detonation after a certain time delay.

The initial velocity of the missile was defined as 800 m/s in the vertical downward direction. This configuration enables the modeling of the kinetic energy associated with the free-fall phase of the munition prior to its interaction with the target medium. The missile was assumed to have a total mass of 1500 kg, composed of aerospace-grade aluminum and containing 500 kg of TNT.

The detonation point was positioned within the TNT charge, with an activation delay of 10×10^{-5} s, allowing for a delayed initiation of the explosive event following the missile's impact with the ground.

To model the detonation process of the explosive material (TNT) located inside the missile, the present study employed the Jones–Wilkins–Lee (JWL) equation of state. This equation is a widely recognized approach for simulating explosive behavior under conditions of high pressure and velocity [19]. The JWL equation is expressed as:

$$P = A \cdot exp(-R1 \cdot V) + B \cdot exp(-R2 \cdot V) + \omega \cdot E / V,$$

where P denotes pressure (Pa), V is the relative volume (i.e., the specific volume normalized to the initial volume), and E is the specific internal energy of the explosive (J/kg). The parameters *A, B, R1, R2*, and ω are material-specific constants deter-mined experimentally for each explosive type. Specifically, A and B are empirical coefficients representing the exponential pressure components, *R1* and *R2* govern the pressure distribution, and ω is a gamma-like coefficient that accounts for the residual pressure [20].

For TNT, the JWL parameters used in this study – sourced from ANSYS reference data – are as follows: $A=3.712\cdot10^{11}$ Pa, $B = 3.231\cdot10^{9}$ Pa, $R1 = 4.15$, $R2 = 0.95$, $\omega = 0.3$, $E = 7.0\cdot10^{6}$ J/kg.

The JWL equation of state effectively describes the high-velocity detonation of explosives, making its application appropriate in the context of high-speed detonation and the transmission of pressure waves from the explosion to the missile casing and the surrounding environment. This enables the modeling of phenomena such as the structural failure of the missile casing due to internal pressure, the formation of shock waves in the soil, and the dynamic interaction between explosive products and solid materials.

For the simulation, TNT is selected as the explosive material, with its properties presented in Figure 5.

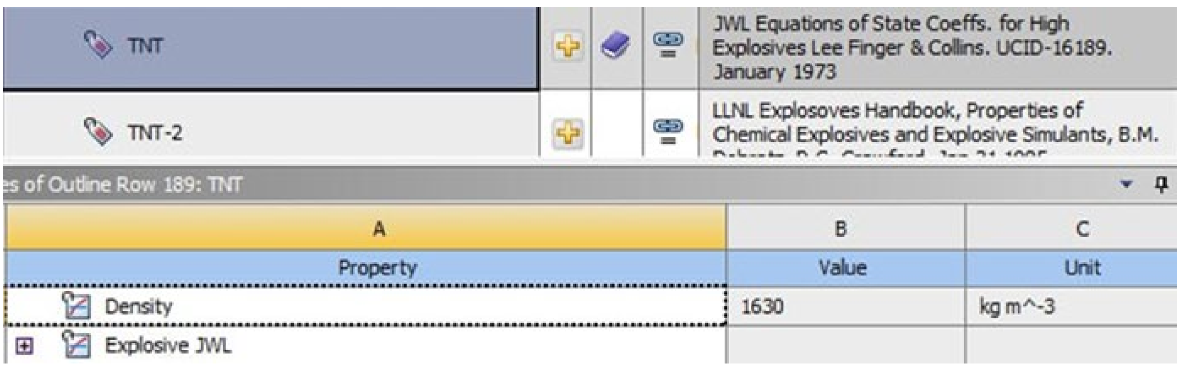

Figure 5 – Property of TNT in material model

To describe the mechanical behavior of soil under dynamic loading, the Drucker-Prager Strength Piecewise model was used (Fig.6). This extended model enables a nonlinear representation of strength dependence on pressure by introducing experimentally obtained values in the form of a tabulated pressure-strength relationship. This provides high accuracy when modeling theologically complex materials such as compacted soil or cemented sediments.

The Drucker-Prager Strength Piecewise model is defined through a table with the following parameters: Pressure *P* (Pa) – The pressure at which the corresponding strength is defined. Entered in Pascals (Pa). This value represents the level of ambient hydrostatic pressure. Yield Stress *Y* (Pa) – The shear strength (yield stress) at the corresponding pressure. Also entered in Pascals (Pa).

This defines the yield limit of the material at each specific pressure value [21], as shown in Fig. 6, 7.

Property	Value	Unit
Material Field Variables	Table	
Density	1750	kg m^-3
⊟ Drucker-Prager Strength Piecewise	Tabular	
Scale	1	
Offset	0	MPa
Shear Modulus	90	MPa
⊟ Tensile Pressure Failure		
Maximum Tensile Pressure	-34000	Pa
⊞ Compaction EOS Linear		

Figure 6 – Material model for loess sandy-loams with natural state of saturation

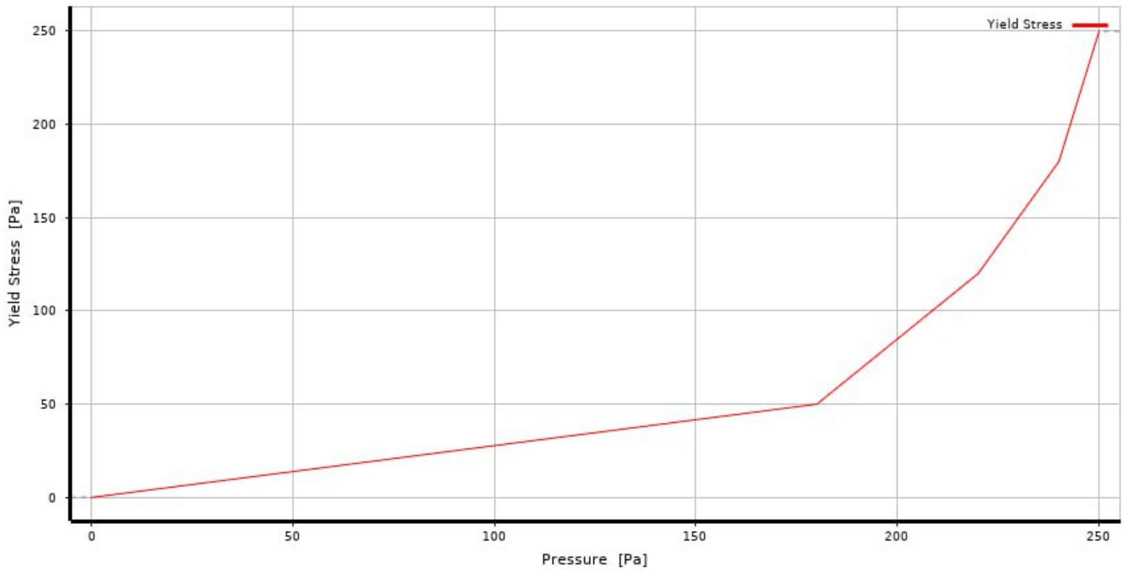

Figure 7 – Yield stress vs. pressure relation for yield-pressure ratio for loess sandy-loams with natural state of saturation

Figures 8 and 9 present the results of the simulation, namely the crater cross-section and the elastically deformed state of the soil after the surface detonation of the contact charge of the explosive, as well as the crater cross-section and the deformed state of the soil resulting from the deep explosion after the missile impact and penetration into the ground. The adequacy of the simulation results is assessed by qualitatively comparing the crater shapes obtained using mathematical simulation with photographic records of real craters formed during hostilities.

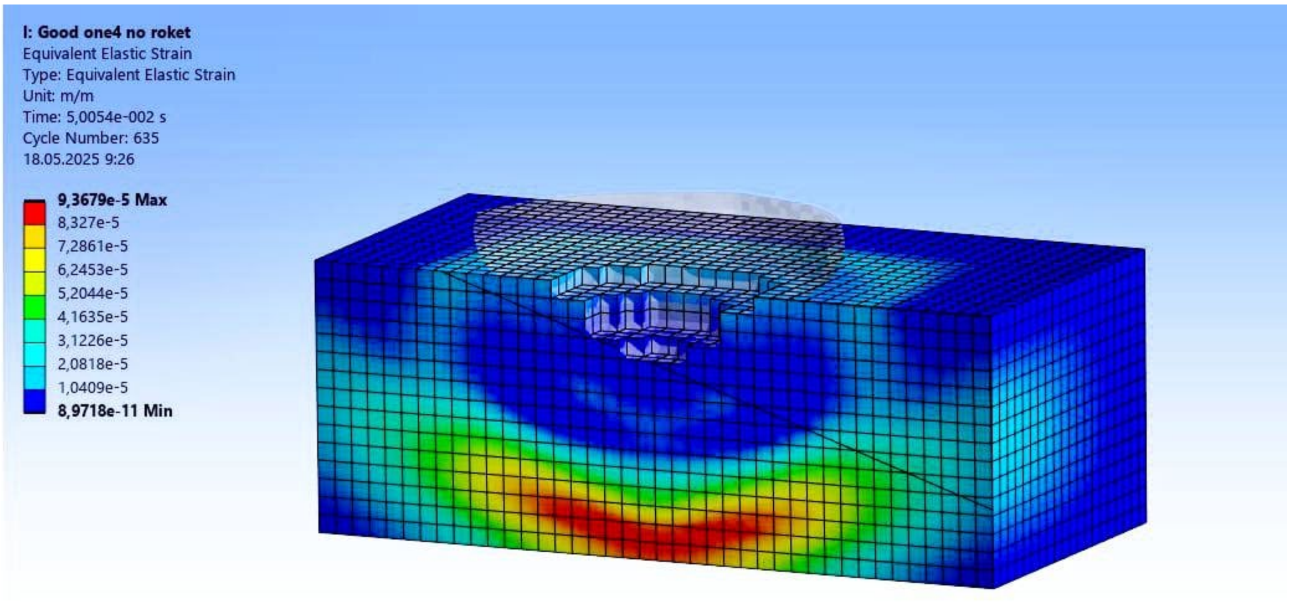

Figure 8 – Cross-sectional view of the crater and the elastic strain state of the soil following the surface detonation of a contact explosive charge

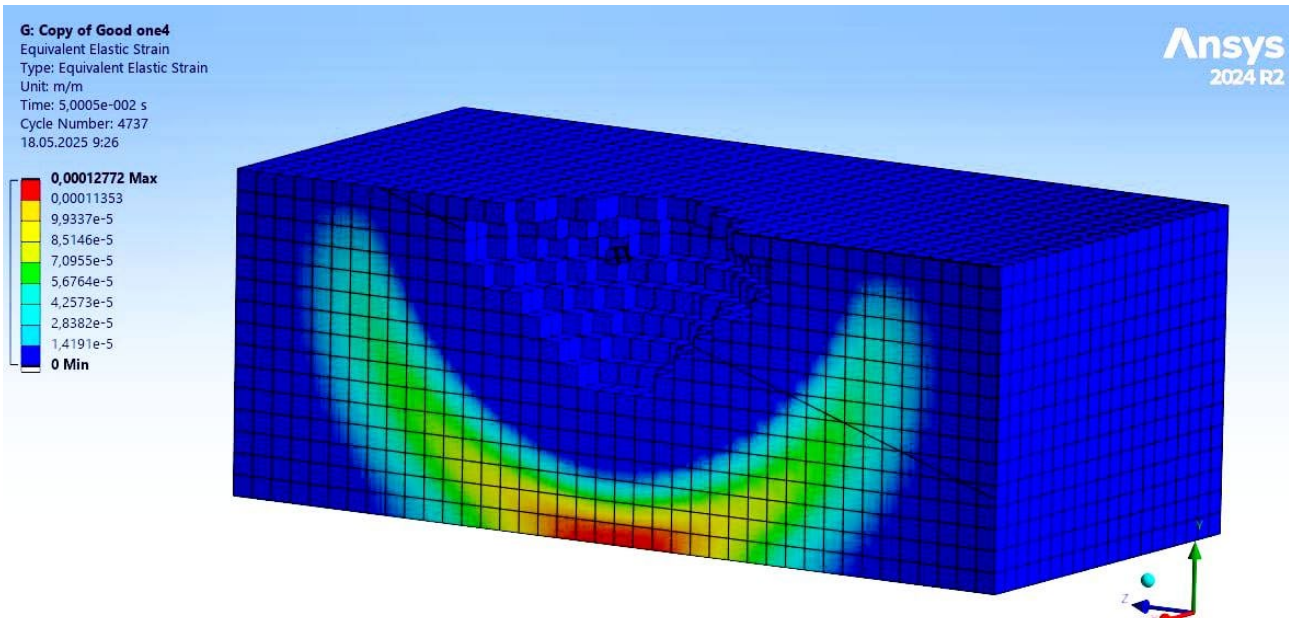

Figure 9 – Cross-sectional view of the crater and the strain state of the soil resulting from a buried explosion after missile impact and penetration into the ground

Comparison of the experimentally observed crater shapes with the results of numerical modeling allows the following conclusions to be drawn (fig.10, 11).

Modeling the process as a surface (attached) charge without accounting for the missile's penetration to a certain depth leads to an underestimation of the extent of soil destruction. The second modeling scenario provides a more realistic representation of certain patterns of the destruction process—for example, the formation of a multi-tiered (stepped) crater.

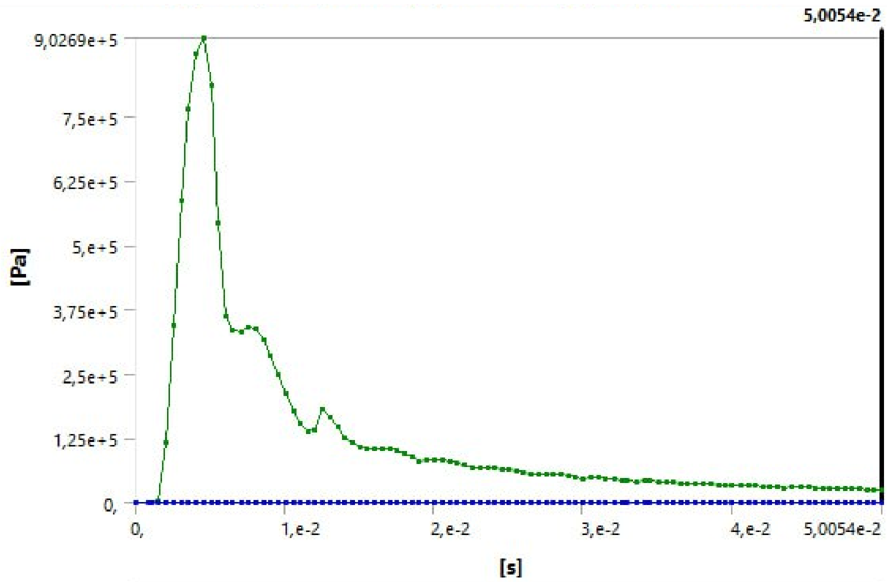

Figure 10 – Time history of von Mises equivalent stress in the soil for the surface charge detonation scenario

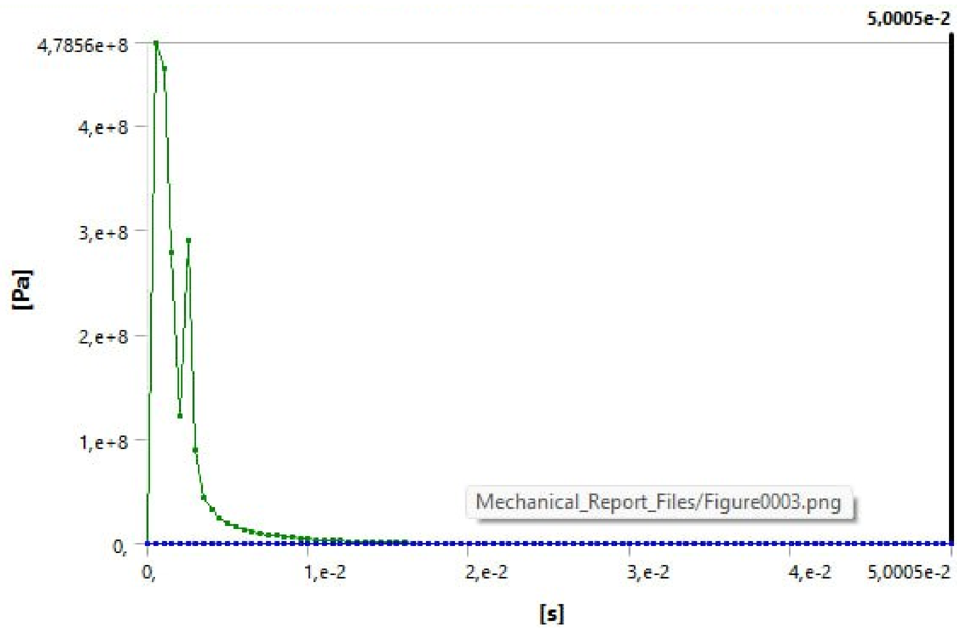

Figure 11 – Time history of von Mises equivalent stress in the soil for the buried explosion scenario involving missile impact and penetration

The maximum equivalent stress in the soil during a surface explosion is $9.03 \cdot 10^8$ Pa, while during a penetration explosion, the equivalent stress is three orders of magnitude higher, reaching $4.8 \cdot 10^5$ Pa. The detonation wave from the surface explosion exhibits three peaks with relatively low amplitudes of 1.9% and 5.7% of the maximum, whereas the penetration-type explosion has a single peak with an amplitude of 37% of the maximum. The damping time for the surface explosion is 0.05 seconds, while for the underground explosion it is 0.0125 seconds, indicating different dynamic mechanisms of the process and different soil responses to the explosion. This highlights the significantly greater destructive potential of penetration-type explosions.

4.Conclusions

This study presents a numerical simulation of the impact of explosive loading from modern ballistic missiles such as Iskander/KN-23 on underground structures, using the ANSYS Explicit Dynamics software environment and the JWL equation of state. The simulation results confirm that the explosion characteristics, detonation point, charge type, and properties of the soil medium critically influence the degree of structural damage.

Special attention was paid to conditions closely resembling real combat scenarios, including delayed detonation after missile penetration into the ground, missile impact velocity, and the dynamic interaction between explosive products and the surrounding medium. The obtained data enable more accurate predictions of explosive effects on engineering structures, which is particularly relevant for the protection of civilian populations during wartime.

It has been established that traditional approaches to the design and assessment of protective structures are insufficient in the context of modern high-precision weaponry. Therefore, there is a need to update regulatory frameworks by incorporating advanced numerical modeling techniques, as well as to improve structural design solutions based on the results of such studies.

Conflict of interest

Authors state no conflict of interest.

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ПРИКЛАДНЕ ЧИСЛОВЕ МОДЕЛЮВАННЯ ВЗАЄМОДІЇ БАЛІСТИЧНОЇ РАКЕТИ З ҐРУНТОМ З ВИКОРИСТАННЯМ ЯВНОЇ ДИНАМІКИ ANSYS

Зуєвська Н., Сахно І., Дармостук Д., Берездецький В., Зуєвський Ю.

Анотація. Метою цього дослідження є удосконалення геомеханічного підходу до аналізу впливу динамічних навантажень на ґрунтову масу шляхом розробки покращеної чисельної моделі взаємодії балістичної ракети із ґрунтовим середовищем з урахуванням затримки підриву. Модель реалізована в середовищі ANSYS Explicit Dynamics — сучасному програмному інструменті, що дозволяє моделювати високошвидкісні динамічні процеси, зокрема поширення ударної хвилі, великі деформації та руйнування матеріалів, характерні для вибухових навантажень.

Дослідження зосереджене на оцінці руйнівного впливу сучасних балістичних ракет малої дальності, таких як російський "Іскандер" та північнокорейський KN-23, на поверхневі шари ґрунту та критичну підземну інфраструктуру. Основну увагу приділено формуванню воронок, переміщенню ґрунту та масштабам руйнувань при поверхневих і заглиблених вибухах, зокрема у випадках проникнення ракети в ґрунт із затриманим підривом.

Верифікація моделі здійснювалася шляхом порівняння результатів чисельного моделювання з реальними даними, отриманими під час ракетних ударів по Київській області, зокрема в місті Буча, де було зафіксовано утворення вирви понад 10 метрів у діаметрі та 8 метрів у глибину. Такі емпіричні дані використовувалися як орієнтир для оцінки достовірності моделі.

Для досягнення більшої точності було використано комбіновану обчислювальну сітку Ейлера–Лагранжа: ґрунт моделювався у лагранжевому описі, тоді як корпус ракети та продукти вибуху — в ейлеровому. У моделі реалізовано сценарій проникнення ракети в ґрунт із затримкою підриву 10^{-5} секунд. Початкова швидкість ракети становила 800 м/с, загальна маса — 1500 кг, маса бойової частини — еквівалент 500 кг тротилу.

Для виключення штучного відбиття ударних хвиль на межах моделі були задані граничні умови на основі методу імпедансу. Це дозволило забезпечити реалістичну передачу та поглинання хвиль, що імітує поведінку "нескінченного" середовища навколо об’єкта моделювання. Результати симуляцій містять детальні дані про динаміку утворення вирв, викид матеріалу, поширення напружень та тиску в масиві ґрунту.

Практична цінність цього дослідження полягає у можливості застосування запропонованого підходу для оцінки стійкості підземних об’єктів цивільного та військового призначення в умовах ракетної загрози. Розроблена методика може бути використана у майбутніх дослідженнях з проектування захисних споруд, оцінки вразливості критичної інфраструктури та розробки планів реагування на надзвичайні ситуації, пов’язані з екстремальними вибуховими навантаженнями.

Ключові слова: вибухова речовина, ґрунти, детонація, динамічне навантаження.