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MODELLING BLAST EFFECTS FOR A MULTILAYER "REINFORCED-CONCRETE SLAB–SOIL MASS" SYSTEM

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Abstract. This paper presents a numerical study explosion loading on a multilayer protective system of the "reinforced-concrete slab–soil mass" type, aimed at enhancing the safety of shallow underground structures. The concept of multilayering is examined as a fundamental principle of blast protection, where a reinforced-concrete slab works together with underlying porous layers (sand, gravel, soil) to form an energy-absorbing system that attenuates stress transmission with depth.

The blast response is modelled in ANSYS Explicit Dynamics using a coupled Eulerian–Lagrangian formulation. The explosive charge (500 kg TNT equivalent) and surrounding air are represented by Eulerian domains with a JWL equation of state, while the reinforced-concrete slab and soil mass are modelled by Lagrangian meshes. For the soil, a pressure-dependent Drucker–Prager-type model with compaction and rate effects (SAND DP4) is employed, whereas the concrete behaviour is described using a standard ANSYS concrete model, including strength, shear, volumetric response and damage. Impedance boundary conditions are applied at the outer faces of the model to minimise artificial wave reflections.

Structural integrity is assessed primarily through the maximum principal stress σ_1, which governs crack initiation in brittle concrete and in the surrounding soil. Path-based post-processing (Path Plot) is used to obtain Max Principal Stress distributions along selected lines beneath slabs of varying thickness (0.2, 0.6, 1.0 and 1.5 m). The results demonstrate that increasing slab thickness significantly reduces tensile stress peaks in the soil and smooths their spatial distribution due to improved shielding and damping. The interference pattern of incident and reflected waves is clearly visible in the stress profiles, highlighting critical zones where tensile stresses and damage risks are greatest.

The proposed modelling approach and obtained results provide a methodologically robust basis for optimising the thickness of reinforced-concrete slabs and the properties of underlying porous layers, enabling more reliable design of blast-resistant multilayer systems for shallow underground facilities.

Keywords: blast loading, multilayer protective systems, reinforced-concrete slab–soil mass, ANSYS Explicit Dynamics, Eulerian–Lagrangian coupling, Drucker–Prager model, RHT concrete model, underground protective structures, porous energy-absorbing layers, maximum principal stress.

1. Introduction

Protective structures designed to withstand explosion loads are generally multilayered; the materials of the layers may differ significantly in their physico-mechanical properties. The complex interaction of shock waves often leads to spalling, delamination, and, consequently, failure of the protective structural element.

The use of porous materials of various structures–such as soils, powders, and materials with internal voids–is motivated by their high energy-absorption capacity.

Therefore, a conventional reinforced-concrete slab placed on draining layers of gravel and sand is a typical surface multilayer protective system capable of effectively safeguarding shallow, dual-use underground facilities. (Fig.1).

Research on porous materials is presented in a substantial body of publications. However, for practical calculations these works often prove insufficiently informative, as they typically lack the necessary experimental data on material properties, and the proposed solution approaches are overly general in nature.

In the work [1, 2], the deformation of various soil types under blast loading is simulated, and the obtained results are compared with real experimental studies, confirming the high reliability of the simulations. One of the methods for protecting shallow underground structures may be a multilayer system comprising a reinforced-concrete slab and a soil mass ("reinforced-concrete slab–soil mass"). The porous me-

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dium is represented by the soil layer located beneath the reinforced-concrete slab. The study proposes a numerical methodology for analyzing wave processes in structures with protective layers made of porous materials.

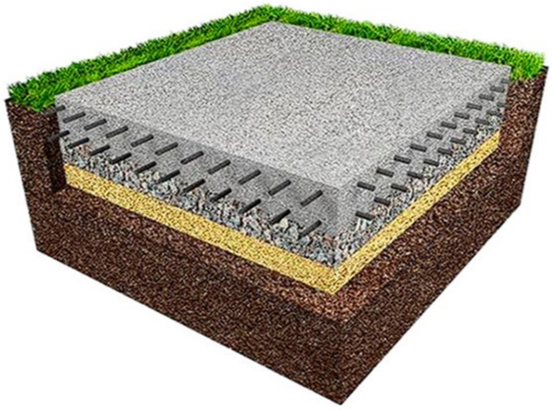


Figure 1 – Multilayer surface protective reinforced-concrete slab placed on draining layers of gravel and sand

The proposed multilayer protective system model and the numerical methodology for analyzing wave processes in structures with porous interlayers provide a basis for an engineering-sound assessment of the stability of underground facilities under impact–blast loading. The main objective of this study is to demonstrate that the use of pressure-dependent constitutive models for soils and damage models for concrete makes it possible to reproduce the key mechanisms of compaction, damage accumulation, and failure required for reliable prediction of structural response.

2. Methods

A multilayer system consisting of a reinforced-concrete slab and a soil mass requires the consistent use of several material models.

If we analyse the deformation mechanism of a porous medium under impulsive loading, then under explosive action a shock wave propagates in the soil mass, causing a successive change in the state of the porous medium: initial failure of the bridges between pores (cells) of the porous structure; subsequent densification of the material (compaction); closure of pores upon reaching the "skeleton" density of the material; compression of the skeleton with a further increase in pressure and shear strains in the matrix. According to the rheological behaviour of soils, at stress levels up to approximately 0.1–0.3 MPa, soils predominantly exhibit elastic properties. As the load increases, viscous, plastic and nonlinear effects become apparent. The nonlinearity is caused by micro-damage to the structure during compression, which is accompanied by the evolution of physical and mechanical characteristics: changes in density, deformation modulus, Poisson's ratio, etc. The problem of soil deformation is extensively covered in the literature, where a substantial experimental basis has been accumulated regarding the stress–strain state of soil media [3, 4].

To analyse the combined effect of an impact impulse and an explosion, it is advisable to use pressure-dependent models of the Mohr–Coulomb / Drucker–Prager type, which describe friction, cohesion and the dependence of strength on hydrostatic compression. If it is necessary to reproduce the compaction of a porous medium, equations of state that take porosity into account can be used, ensuring the transition from the failure of the pore structure to compression of the skeleton.

For the reinforced-concrete slab, which is a material with high compressive strength and low tensile strength, the RHT (Riedel–Hiermaier–Thoma) concrete model is well suited. This is a model for concrete and other brittle geomaterials (rock, ceramics, stone). It is applied under dynamic loading conditions: explosions, impacts, ballistic penetration, seismic effects. The model is implemented in ANSYS to reproduce the material response at high strain rates. The RHT model is suitable for scenarios such as blasting or impact; it makes it possible to describe the gradual accumulation of damage up to complete failure and to correctly reproduce wave propagation and crack formation in the concrete medium [5, 6].

The key features of the model are that RHT combines: (1) a strength surface, which defines elastic–plastic yielding depending on the stress state; (2) a damage model, which accounts for the accumulation of microcracks and the degradation of stiffness and strength; (3) a failure surface, which describes the complete loss of load-bearing capacity; and (4) a medium mechanics component, which distinguishes between behaviour in compression and in tension (concrete is strong in compression and weak in tension) [7, 8, 9].

The main equation for the strength surface is given by

$$\left(\frac{\sigma_{eq}}{f_c(p)}\right)^2+\left(\frac{\sigma_m}{f_t(p)}\right)^2=1, \tag{1}$$

where σ_{eq} – equivalent deviatoric stress, σ_m – mean (hydrostatic) pressure, $f_c(p)$ – is the compressive strength as a function of pressure p, $f_t(p)$ – is the tensile strength as a function of pressure p. All stresses and strengths (σ_{eq}, σ_m, $f_c(p)$, $f_t(p), p$) are expressed in megapascals (MPa).

Effect of strain rate (dynamic increase factor, DIF):

$$\sigma_{dyn}=\sigma_{stat}\cdot\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^k, \tag{2}$$

where σ_{dyn} – dynamic strength, σ_{stat} – static strength, $\dot{\varepsilon}$ – strain rate, $\dot{\varepsilon}_0$ – reference (baseline) strain rate, k – material constant (≈ 0.02–0.06 for concrete).

Damage evolution:

$$D=\frac{\Delta\varepsilon_p}{\varepsilon_f}, \tag{3}$$

where D – damage variable ($0 \le D \le 1$), $\Delta\varepsilon_p$ – increment of plastic strain, ε_f – critical failure strain. When D =1, the material is completely failed (fully damaged).

A distinctive feature of ANSYS Explicit Dynamics is its support for various computational solvers. One of the main unique capabilities of this software product is the solver coupling mechanism, which makes it possible to combine several solvers within a single model. The algorithm for coupling an Eulerian computational mesh with a Lagrangian one enables the solution of problems involving the interaction of gases and liquids with solid bodies [10, 11, 12].

Thus, ANSYS Explicit Dynamics is a universal and flexible tool for modelling complex dynamic phenomena, in particular explosive effects on materials and structures. Owing to the use of an explicit formulation, the finite element method, and a wide range of material models, Explicit Dynamics makes it possible to accurately reproduce the interaction of a blast wave with multicomponent media. The ability to combine Eulerian and Lagrangian solvers, as well as to apply strength, failure, and artificial erosion models, makes this software package an effective tool for engineering analyses where both the physical properties of materials and the complex geometry of objects must be taken into account. This, in turn, opens up opportunities for predicting the consequences of explosions in the context of the safety of underground structures, optimising their design, and increasing their resistance to dynamic loads.

3. Theoretical and experimental part

In the model, an explosion of a moving charge (Fig. 2) with a TNT equivalent of 500 kg is considered, with a detonation delay interval of 0.025 ms, acting on a soil mass covered by a reinforced-concrete slab of varying thickness: 0.2 m, 0.6 m, 1.0 m, and 1.5 m. Above the surface of the two-layer geological body there is an air layer 4 m thick (semi-transparent region in Fig. 2). The air domain is represented as a rectangular parallelepiped with a square base measuring 40×40 m and a height of 4 m, located above the surface of the geological body. As the material model for the explosive, the "TNT" model from the standard Ansys library is used, with the JWL (Jones–Wilkins–Lee) equation of state. The explosion occurs at depth, at a charge velocity of 800 m/s.

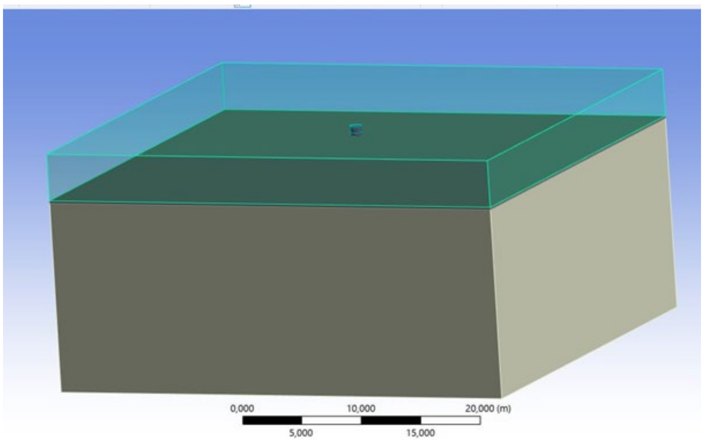
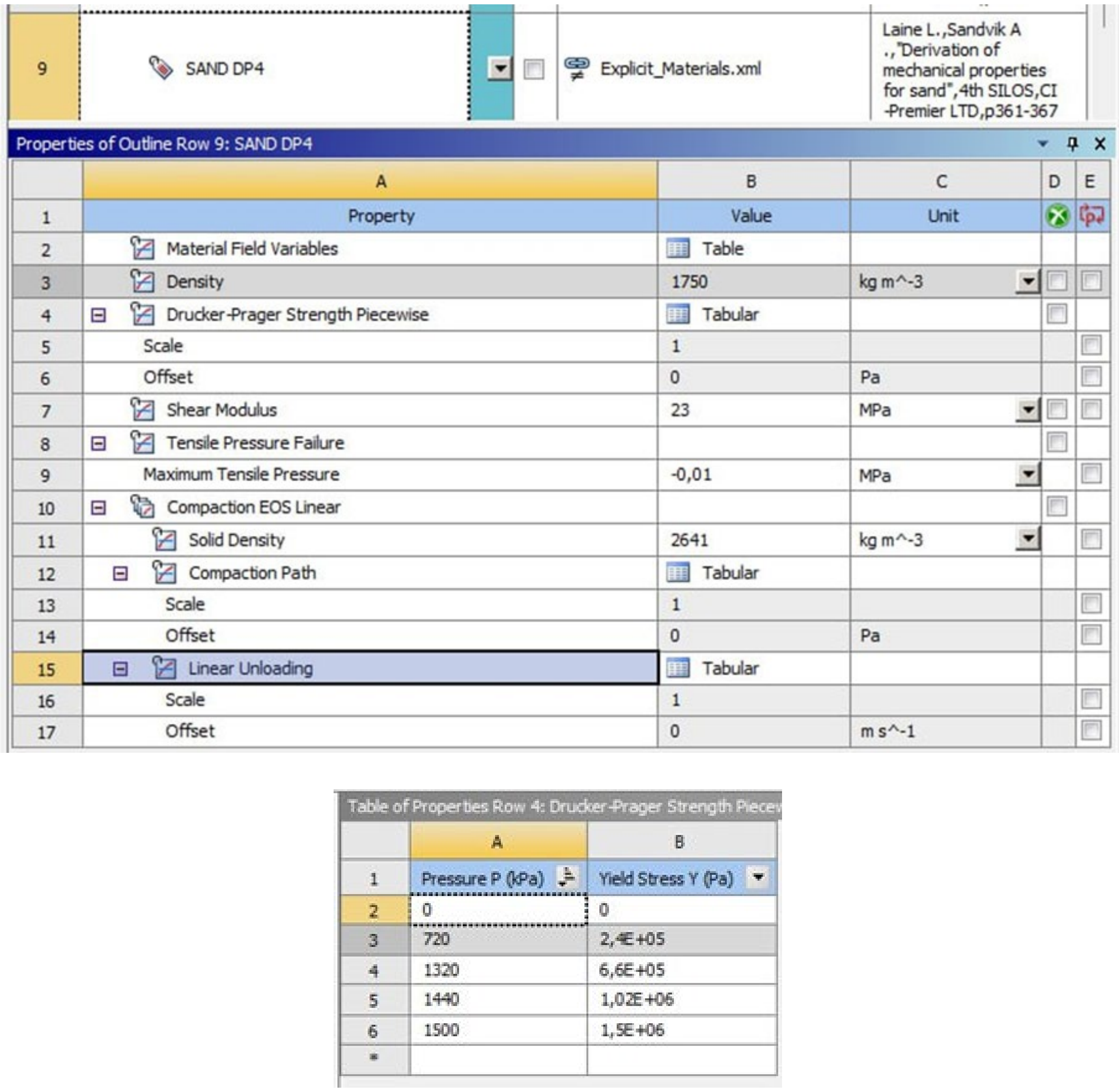


Figure 2 – Geometry of the model

As the material model to describe the behaviour of concrete under loading, the “CONC-35MPA” model from the standard ANSYS library was used. It incorporates a combination of strength models, shear modulus and bulk compression models, as well as equations of state. This makes it possible to accurately reproduce the dynamic behaviour of concrete under explosive loading.

To describe the behaviour of detonation products and their interaction with solid bodies, an Eulerian solver was selected for the explosive bodies. A Lagrangian solver was chosen for the concrete structure, and a Lagrangian solver was also selected for the soil mass [13].

For the soil mass, the “SAND DP4” model (Fig. 3) was created with the following characteristics:



9	SAND DP4	Explicit_Materials.xml	Laine L.,Sandvik A .,"Derivation of mechanical properties for sand",4th SILOS,CI -Premier LTD,p361-367

Properties of Outline Row 9: SAND DP4

	A	B	C	D	E
1	Property	Value	Unit		
2	Material Field Variables	Table			
3	Density	1750	kg m^-3		
4	Drucker-Prager Strength Piecewise	Tabular			
5	Scale	1			
6	Offset	0	Pa		
7	Shear Modulus	23	MPa		
8	Tensile Pressure Failure				
9	Maximum Tensile Pressure	-0,01	MPa		
10	Compaction EOS Linear				
11	Solid Density	2641	kg m^-3		
12	Compaction Path	Tabular			
13	Scale	1			
14	Offset	0	Pa		
15	Linear Unloading	Tabular			
16	Scale	1			
17	Offset	0	m s^-1		

Table of Properties Row 4: Drucker-Prager Strength Piece

	A	B
1	Pressure P (kPa)	Yield Stress Y (Pa)
2	0	0
3	720	2,4E+05
4	1320	6,6E+05
5	1440	1,02E+06
6	1500	1,5E+06
*		

Figure 3 – Geomechanical properties of the soil medium

This material model is adapted for describing granular media that undergo large deformations, compaction and partial failure under explosive loading. The model combines granular plasticity, compaction and tensile failure, which makes it possible to realistically simulate the behaviour of loose media. This model allows for accurate reproduction of compaction, loss of load-bearing capacity, wave propagation and deformations in sand that arise under the action of a blast wave. Its use is justified in problems involving explosive effects on soil masses, especially when it is important to account for non-uniform compaction.

As the material model to describe the behaviour of air under loading, the "Air (Atmospheric)" model from the standard ANSYS library was used. Thus, in each case of solving the problem, the model includes four bodies: an Eulerian explosive body; an Eulerian air body; a Lagrangian geological body; and a Lagrangian concrete body. The computational mesh of the model is a combination of Lagrangian and Eulerian meshes (Fig. 4).

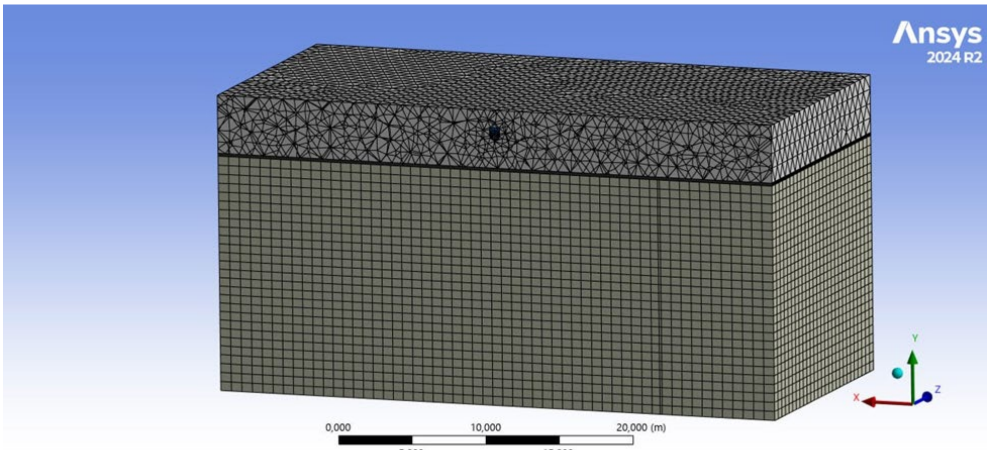


Figure 4 – The computational mesh of the model is a combination of Lagrangian and Eulerian meshes

The Lagrangian mesh is tied to the body and moves together with it in accordance with the displacements of its points. For modelling and optimisation purposes, the mesh size was set to 1 m for the soil, 0.15 m for the slab, and 0.3 m for the rocket. The mesh statistics are as follows: 354.685 nodes and 265.494 elements for the soil mass and a slab with a thickness of 0.2 m.

The Eulerian mesh is generated independently of the bodies and their position; it is fixed in space with respect to the coordinate axes, and the motion of the body is tracked by the flow of material from one element to another. For the purposes of modelling and optimisation of the computations, the Eulerian domain was defined as a rectangular parallelepiped shifted upward along the Z-axis, with dimensions equivalent to those of the geological body, in order to capture the effect of detonation products above its surface. The element size of the Eulerian mesh was chosen such that the edge length of an Eulerian element is half that of a Lagrangian element, which is dictated by software limitations and the developers' recommendations [14, 15, 16].

As boundary conditions, so-called impedance boundaries were chosen for the lateral and bottom faces of the model (Fig. 5), as well as for all faces of the Eulerian computational domain. They make it possible to reduce the influence of reflected waves that arise at the boundary of the computational region during the propagation of blast waves. Impedance boundaries approximate the condition of free wave passage, based on the acoustic impedance of the medium (the product of density and sound speed), and ensure the transmission of the normal component of velocity without significant reflection. In ANSYS, such a boundary is implemented by accounting for the variation of pressure and velocity along the characteristic emanating from the boundary, assuming zero reference values for an initially stationary medium. In this way, the effect of possible blast-wave reflections at the boundaries of the computational domain is minimised, taking into account the model dimensions and the nature of blast-wave propagation.

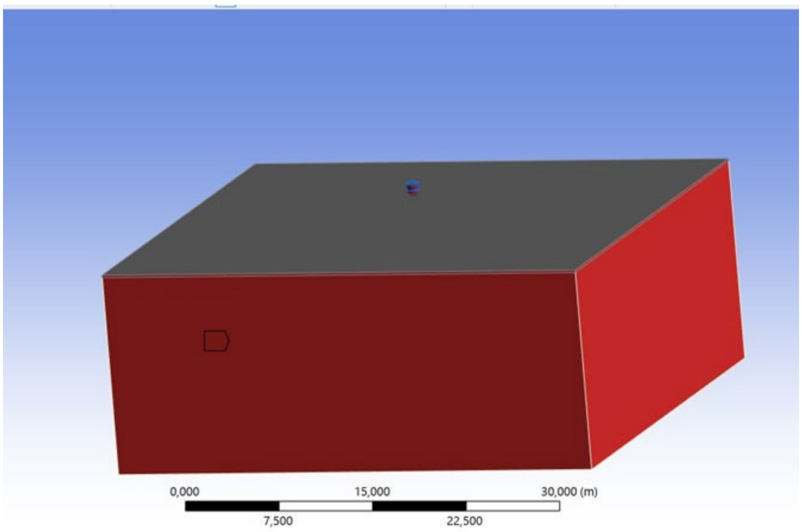
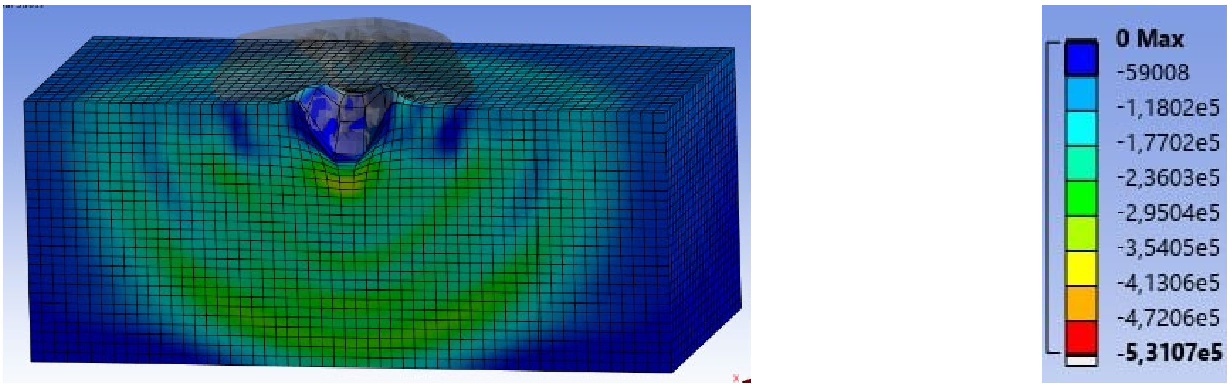


Figure 5 – Impedance boundaries of the model (red)

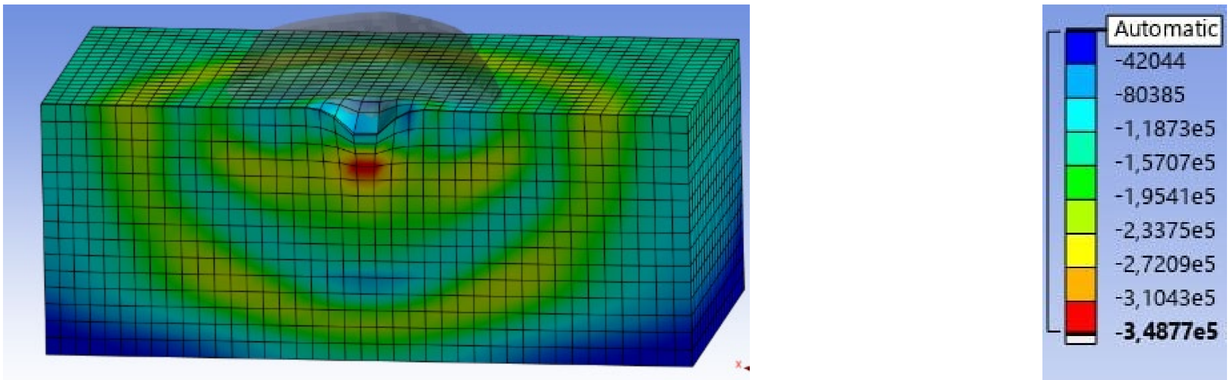
To assess the structural integrity of concrete under blast (impulsive) loading in ANSYS Explicit Dynamics, it is appropriate to use the principal stresses, first of all the maximum principal tensile stress σ_1 [17, 18]. This is due to the brittle nature of concrete and its pronounced strength asymmetry: it has high compressive strength f_c and low tensile strength f_t. Therefore, both for the Drucker–Prager (DP) model (soils) and for the RHT model (concrete structures), monitoring σ_1 remains a key indicator of the onset of crack formation. [19, 20].

When considering an underground concrete structure under blast loading, the Max Principal Stress σ_1 is directly correlated with the tensile strength f_t (with DIF), which defines the initiation of cracking. The von Mises criterion complements the picture for metallic elements (reinforcement), but does not replace the analysis of principal stresses for the concrete part.

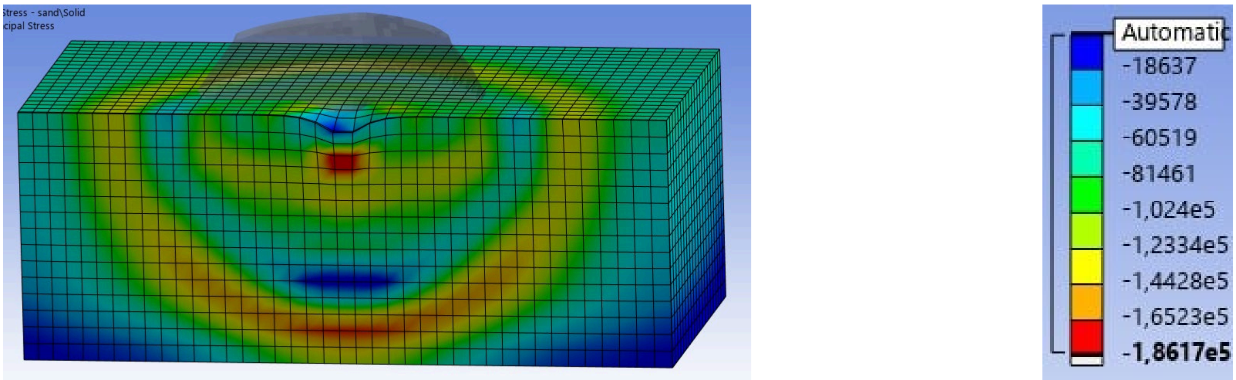
When evaluating the dynamic strength of concrete (in tension/compression/shear) under ballistic loading, it is usually higher than the static strength due to the visco-brittle nature of the material: at high strain rates $\dot{\varepsilon}$ (Eq. 2), cracks do not have time to grow, and therefore higher stresses are required to cause failure. Figure 6 shows the tensile loading (Maximum Principal Stress) at time 50 ms for the soil mass covered with reinforced-concrete slabs of different thicknesses. [21, 22].



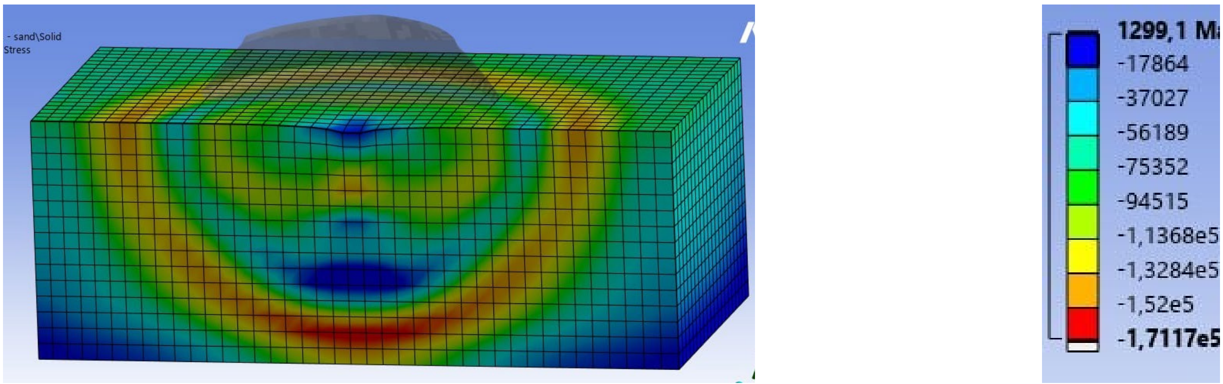
The thickness of the slab is 0.2 m.



The thickness of the slab is 0.6 m.



The thickness of the slab is 1.0 m.



The thickness of the slab is 1.5 m.

Figure 6 – Maximum Principal Stress in moment time 0.05 s for reinforced-concrete slabs of different thicknesses

In Figure 7, two points are selected, and the Path Plot function is used to generate XY-curves of the maximum principal stress distribution along the chosen path betwee them.

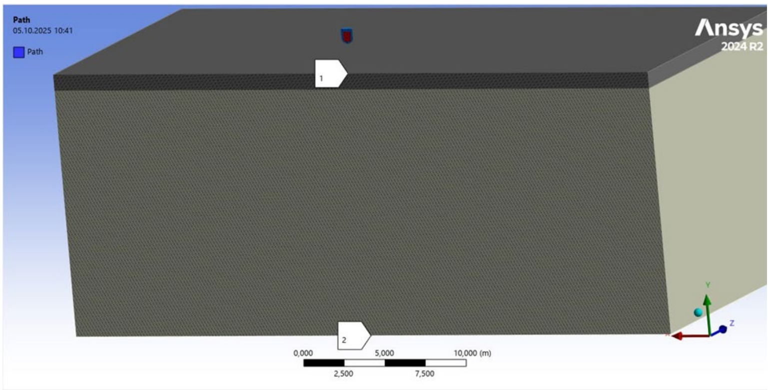
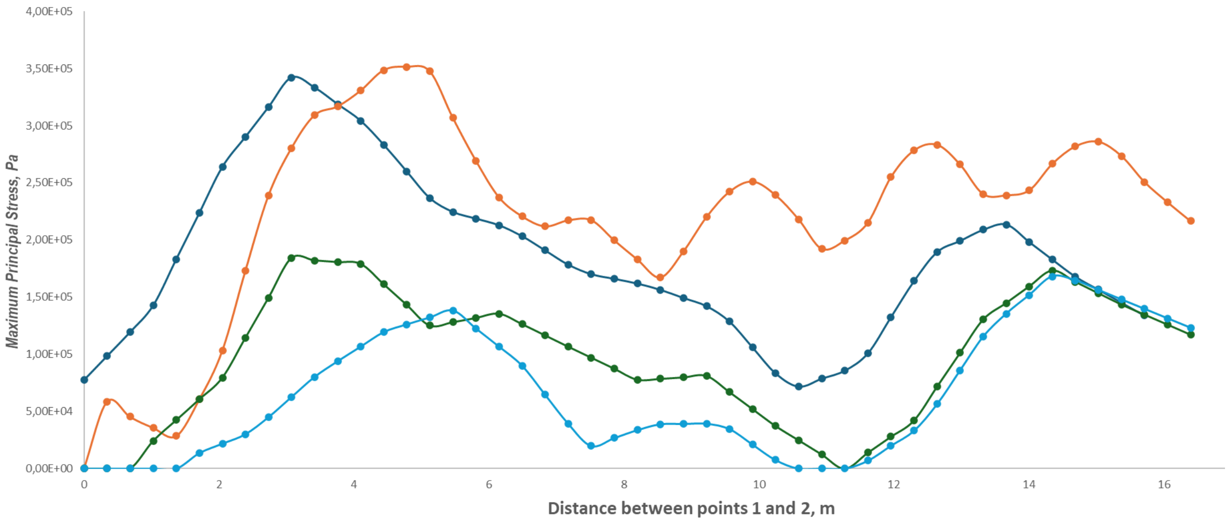


Figure 7 – Analysis area along path 1-2

The combined Max Principal Stress graphs along path 1→2 for different slab thicknesses are presented in Figure 8.



curve 1– 0.2 m; curve 2– 0.6 m; curve 3 – 1 m; curve 4 – 1.5 m

Figure 8 – Combined results of Maximum Principal Stress calculations along path 1→2 for different slab thicknesses

As a result of the calculations, it is clearly seen that the thinner the slab, the greater the transmission of tensile peaks into the soil. Curve 1 (slab thickness 0.2 m) has the largest amplitudes (up to ~$3.5–3.8\times10^5$ Pa ≈ 0.35–0.38 MPa). For curve 2 (slab thickness 0.6 m), the peaks are smaller (~$2.5–2.7\times10^5$ Pa), for curve 3 (slab thickness 1.0 m) they are lower still (~$1.8–2.1\times10^5$ Pa), and for curve 4 (slab thickness 1.5 m) they are the smallest (mostly $<1.3\times10^5$ Pa, locally up to ~1.8×10^5 Pa at the end). This is a classical example of shielding and damping due to the increase in stiffness and mass of the slab.

The shape of the curves, which consist of several maxima, is explained by wave interference. The repeated "crests" with a spacing of about 3–4 m indicate the interaction of incident and reflected waves. Thicker slabs shift the locations of the peaks and smooth them out. The most critical zones are in the regions of the first peaks (≈ 2–4 m from point 1) and further around 12–16 m: here, for the thin slab, the tensile stresses are the highest, and accordingly the risk of loosening/crack formation in the soil and spalling of the rear zone of the slab is greatest.

To reduce tensile stresses in the soil along path 1→2, it is reasonable to increase the slab thickness or to optimise the underlying soil layer by increasing its thickness in order to enhance energy absorption, thereby reducing the first peaks.

4. Conclusions

The article presents the concept of multilayering and substantiates it as a fundamental principle of blast protection. Porous intermediate layers (sand, gravel, soil) in combination with a reinforced-concrete slab form an effective energy-absorbing system that reduces loading with depth in the soil mass, thereby enabling the protection of shallow-buried underground structures.

A consistent numerical methodology is proposed for the "concrete slab–soil mass" system. The use of pressure-dependent strength models for soils (Drucker–Prager with allowance for compaction, dilatancy and rate effects) and damage models for concrete (RHT) is justified. The choice of solvers and the problem setup ensure correct reproduction of wave processes.

The use of ANSYS Explicit Dynamics with a combination of Eulerian (detonation products, air) and Lagrangian (concrete, soil) solvers linked through a coupling mechanism makes it possible to model the interaction of gas-dynamic fields with solid bodies. This provides a physically consistent transition from elastic response to plasticity and failure under impulsive loading.

The obtained modelling results make it possible to optimise the destructive loads transmitted into the soil mass at certain depths. As a result of the simulations under the selected initial conditions, it was established that increasing the slab thickness significantly reduces tensile peaks in the soil along path 1–2 and thus increases the protective effectiveness of the system.

Increasing the thickness and optimising the underlying porous layers (thickness/grain size distribution/moisture content) are key levers for reducing the transmitted impulse.

The article demonstrates a methodically validated numerical modelling scheme for blast loading of multilayer "reinforced-concrete slab–soil" systems in ANSYS Explicit Dynamics. The chosen combination of material models and solvers adequately reproduces the key mechanisms of compaction, damage and failure, which makes it possible to reliably assess the resistance of underground structures and to develop recommendations regarding the strengthening of structures and the configuration of energy-absorbing layers.

Conflict of interest

Authors state no conflict of interest.

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МОДЕЛЮВАННЯ ДІЇ ВИБУХУ ДЛЯ БАГАТОШАРОВОЇ СИСТЕМИ «ЗАЛІЗОБЕТОННА ПЛИТА — ҐРУНТОВИЙ МАСИВ»

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Анотація. У статті представлено чисельне дослідження вибухового навантаження на багатошарову захисну систему типу «залізобетонна плита – ґрунтовий масив», спрямоване на підвищення безпеки підземних споруд неглибокого закладання. Концепція багатошаровості розглядається як базовий принцип вибухозахисту, за якого залізобетонна плита спільно з підстильними пористими шарами (пісок, гравій, ґрунт) формує енергопоглинальну систему, що послаблює передачу напружень у глибину ґрунтового масиву.

Вибуховий відгук моделюється в ANSYS Explicit Dynamics із використанням поєднаної Ейлерівсько–Лагранжевої постановки. Вибуховий заряд (еквівалент 500 кг тротилу) та навколишнє повітря описуються Ейлерівськими областями з рівнянням стану типу JWL, тоді як залізобетонна плита та ґрунтовий масив моделюються за допомогою Лагранжевих сіток. Для ґрунту застосована тискозалежна модель типу Drucker–Prager з урахуванням компакції та швидкісних ефектів (SAND DP4), а поведінку бетону описано стандартною бетонною моделлю ANSYS, яка включає міцність, зсув, об'ємну деформацію та пошкодження. На зовнішніх гранях моделі задано імпедансні граничні умови для мінімізації штучних відбиттів хвиль.

Структурну цілісність оцінюють передусім за максимальним головним напруженням σ_1, яке визначає початок тріщиноутворення в крихкому бетоні та навколишньому ґрунті. Постобробка на основі шляхів (Path Plot) використовується для отримання розподілів Max Principal Stress уздовж обраних ліній під плитами різної товщини (0,2; 0,6; 1,0 та 1,5 м). Результати показують, що збільшення товщини плити суттєво зменшує піки розтягувальних напружень у ґрунті та згладжує їх просторовий розподіл завдяки кращому екрануванню та демпфуванню. Інтерференційний характер взаємодії падаючих і відбитих хвиль чітко проявляється в профілях напружень, що дозволяє виділити критичні зони з найбільшими розтягувальними напруженнями та ризиками пошкодження.

Запропонований підхід до моделювання та отримані результати створюють методично обґрунтовану основу для оптимізації товщини залізобетонних плит і властивостей підстильних пористих шарів, що, у свою чергу, забезпечує більш надійне проектування вибухостійких багатошарових систем для підземних споруд неглибокого закладання.

Ключові слова: вибухове навантаження, багатошарові захисні системи, система «залізобетонна плита – ґрунтовий масив», ANSYS Explicit Dynamics, Ейлерівсько–Лагранжева постановка, модель Drucker–Prager, модель бетону RHT, підземні захисні споруди, пористі енергопоглинальні шари, максимальне головне напруження.