

Interaction underground structures with soil media under blast load

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ABSTRACT: The analysis of protective structures embedded in soil subjected to impulsive loading caused by an explosion or impact is a complex problem that requires knowledge of modern physical and mathematical tools for describing high-rate deformation processes in materials with varying strength and stiffness. To solve such problems, numerical simulation is most commonly used today. The accuracy of the results depends on the correctness of the computational model, the method used to construct and manage the finite element mesh, the selection of material behavior models and their parameters for soil, concrete, and steel reinforcement. These models must accurately represent the behavior of the structure and the soil medium under high-rate and large deformations, and also account for changes in material properties under impulsive (short-term) loading compared to static (long-term) loads. This paper presents the results of an evaluation of the effects of explosion and impact on a protective structure embedded in soil, performed using the Ansys/LS-DYNA software suite.

KEYWORDS: Numerical modeling, Ansys/LS-Dyna, buried structure, soil medium, explosion, impact.

1 INTRODUCTION

During the design of protective structures of both underground and above-ground types, numerous issues arise related to their analysis and the application of an appropriate impulsive loading regime caused by explosions or impacts. These processes are highly transient, with a typical duration of about 0.1–0.2 seconds, and are accompanied by significant deformations in both the structure itself and the surrounding soil with which the structure interacts. Currently, numerical modeling – particularly the finite element method (FEM) – is most commonly used for analyzing such structures and assessing the effects of explosions and impacts. Similarly, simplified pseudo-dynamic approaches such as spectral analysis fail to account for the interaction between embedded structures and the surrounding soil medium. As a result, the most appropriate approach for such problems is direct time integration, with a typical time step on the order of 0.001 seconds.

When using the finite element method, a separate issue is the selection of the mesh generation method and its resolution. The primary approaches include:

1. Lagrangian.
2. Eulerian.
3. Arbitrary Lagrangian-Eulerian (ALE).
4. Smooth Particle Hydrodynamics (SPH).

Each method has its own advantages and limitations. The Lagrangian mesh makes it easy to track material interfaces before and after deformation and is computationally efficient. However, it becomes impractical in cases involving large deformations and rapid changes over time.

The Eulerian and Arbitrary Lagrangian-Eulerian methods are more suitable for problems involving extreme distortions, such as underground or underwater explosions. Their main drawback lies in the size of the computational domain and the complexity of model setup.

Smooth Particle Hydrodynamics is a meshless Lagrangian method. It also handles large deformations well, but is computationally expensive and time-consuming. All of these modeling approaches are available in the Ansys/LS-DYNA software package.

In solving such problems, it is often more appropriate to model the soil using Eulerian or SPH meshes, as the soil behaves unstably and undergoes large deformations under explosive shock loading. However, if the region of interest is sufficiently far from the explosion epicenter, it is possible to combine Lagrangian with Eulerian or SPH meshes. Explosion modeling can also be carried out in several ways: either by using a specific command that defines the time-dependent

explosive loading function, or by physically modeling the explosive material, including its mass and volumetric expansion during detonation.

An important issue in these analyses is the choice of material models and their parameters, since all processes involved occur rapidly and are highly dynamic. Models that accurately describe the behavior of materials under high strain rates must be selected. A separate challenge is the selection of an appropriate failure criterion, as material behavior under dynamic loading can differ significantly from that under static loading.

To improve the accuracy and deepen the understanding of the processes involved in explosions or mechanical impacts, physical experiments are essential. These experiments provide the basis for validating numerical simulation results and for developing computational models that closely replicate real-world behavior observed during testing.

Approaches for modeling soil under large deformations are discussed in Bojanowski & Kulak (2010). Comparisons of various explosion modeling techniques can be found in Tabatabaei & Volz (2012); Barsotti et al. (2016); Schwer (2010); and Slavik (2010). The behavior of sandy soil under dynamic loading is described in Nazhat (2013). The effects of explosive loads on embedded structures are examined in Jayasinghe et al. (2013) and Koneshwaran (2014), while impact load modeling is covered by Van Dorsselaer et al. (2012) and Sangi & May (2009).

2 MAIN INVESTIGATION

2.1 Finite element model

To investigate the effects of explosion and impact, an embedded protective structure was considered, with overall dimensions of $4.9 \times 2.45 \times 2.795$ meters.

The surrounding soil medium is sandy soil with the following properties: density – 1750 kg/m³, shear modulus – 60 MPa, and bulk unloading modulus – 130 MPa. Additionally, a pressure-dependent volumetric strain relationship was applied for the soil, as defined in the study by Nazhat (2013).

Three different embedment scenarios of the structure in the soil were analyzed: 1) covered with a 0.5 m thick soil layer; 2) Embedded at a depth of 1.0 m; 3) Embedded at a depth of 1.5 m.

The amount of explosive used in the study corresponds to 50 kg of TNT equivalent. The explosion was initiated directly at the soil surface.

The simulations were carried out using the ANSYS/LS-DYNA software package. To optimize computation time, a

symmetric portion of the structure and the surrounding soil mass was modeled. Symmetry boundary conditions were applied on the symmetry plane (ZOX), restricting displacement in the direction perpendicular to the plane. Special *non-reflecting boundary conditions* were applied to the bottom and lateral faces of the soil domain. These boundary conditions prevent the reflection of blast-induced waves back into the model domain (LS-DYNA, 2025).

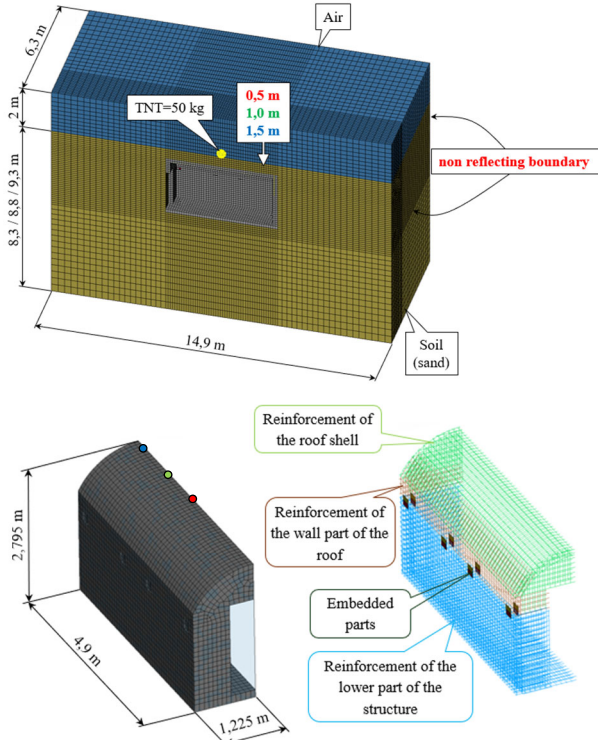


Figure 1. Finite element model.

The computational model was developed using the Multi-Material Arbitrary Lagrangian-Eulerian (MM-ALE) approach. Air, soil, the explosive charge, and the space surrounding the protective structure were modeled using an Eulerian mesh, while the protective structure itself was modeled using a Lagrangian mesh. Discrete reinforcement within the protective structure was modeled using beam elements, and embedded steel fixtures were represented with shell elements in Figure 1.

2.2 Material models

Soil was modeled using the *Soil and Foam* material model (LS-DYNA, 2025). For concrete, the *CSC Concrete* material model (LS-DYNA, 2025) was used, which allows for realistic behavior simulation based on a limited set of input data. The following parameters were applied in the analysis: density – 2500 kg/m³, compressive strength – 35 MPa, and aggregate size – 1.5 cm. The failure criterion for this model is based on both the element damage level and the maximum principal strain. For steel, the *Plastic Kinematic* material model (LS-DYNA, 2025) was used. The *Null* material model combined with the *Linear Polynomial* equation of state (LS-DYNA, 2025) was used to represent the surrounding air, while the *Vacuum* material was used to model the space around the structure. The explosive was modeled using the *High Explosive Burn* model and the *JWL* equation of state (LS-DYNA, 2025).

3 RESULTS

In Figure 1 shows the elements in the upper part of the protective structure where the explosion-induced pressure was measured. The colors of the marked elements correspond to the colors of the curves on the graphs in Figure 2.

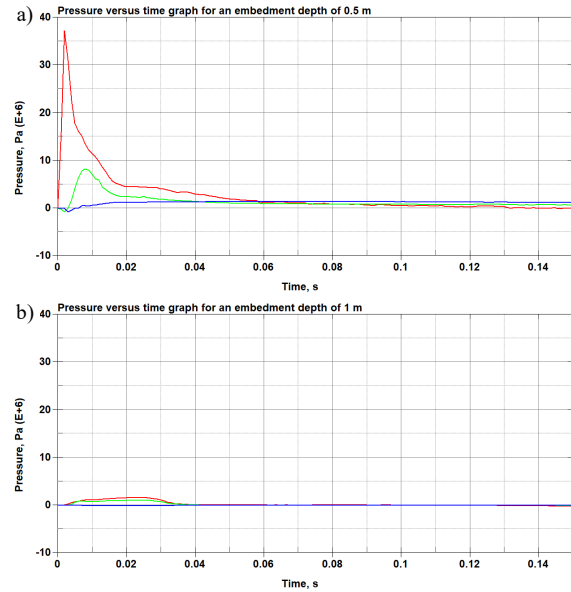


Figure 2. Graphs of pressure versus time on the structure's surface: a) 0,5 m; b) 1 m.

According to the obtained graphs in Figure 3, it was established that increasing the embedment depth from 0.5 m (with a pressure of 37.3 MPa) to 1 m (with a pressure of 1.6 MPa) reduces the blast pressure on the surface of the structure by a factor of 23. Further embedment into the soil did not result in a significant effect.

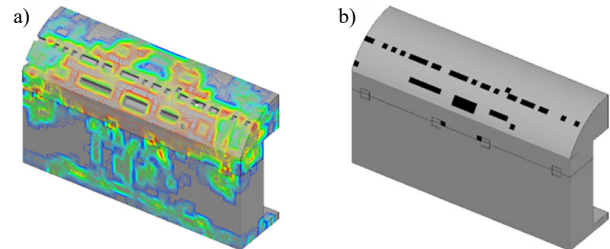


Figure 3. Distribution at a depth of 0.5 m: a) plastic deformations; b) damage zones in the shelter structure.

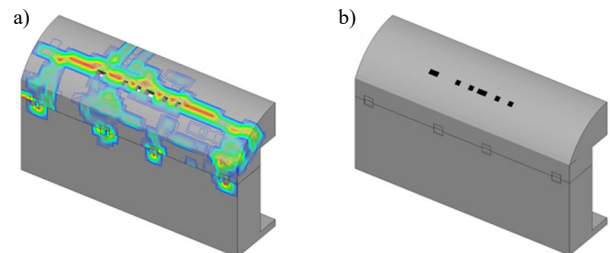


Figure 4. Distribution at a depth of 1 m: a) plastic deformations; b) damage zones in the shelter structure.

Zones of plastic deformation cover almost the entire surface of the structure at a depth of 0.5 m, whereas at 1 m depth they are present only in the upper part. The number of elements removed from the calculation decreased by 53%, with 236 elements removed at 0.5 m depth and 110 elements at 1 m depth.

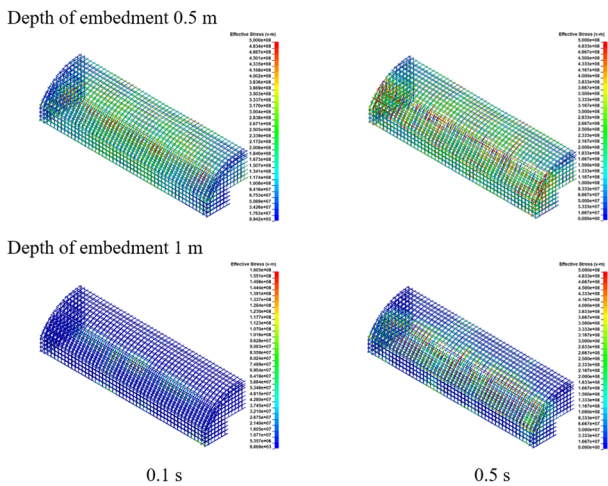


Figure 5. Stress contour maps in the reinforcement of the upper part of the shelter.

Figure 5 shows that at a depth of 0.5 m, the stresses in the reinforcement reach their maximum value of 500 MPa within 0.1 seconds of loading, whereas at a depth of 1 m, they decrease by 68% over the same time interval and amount to 160.5 MPa.

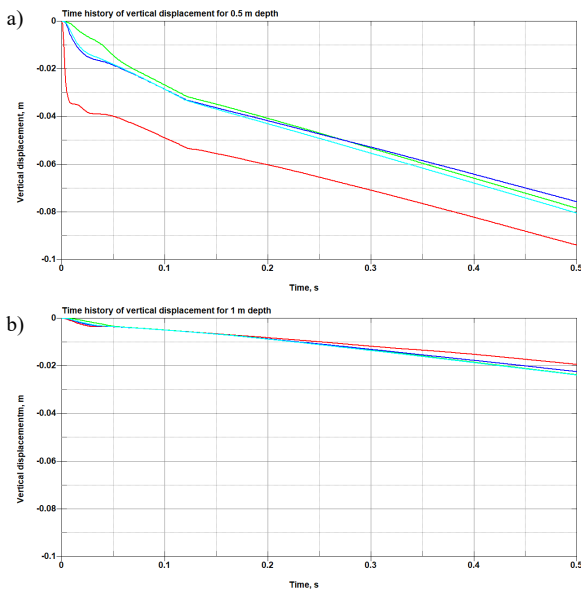


Figure 6. Displacement graph of the structure: a) 0,5 m; b) 1 m.

According to the graphs in Figure 6, the vertical displacements of the structure decrease fourfold with an increase in embedment depth by 0.5 m. At an embedment depth of 0.5 m, the maximum displacement is - 9.4 cm, while at 1 m it is 2.4 cm.

4 INFLUENCE OF STRIKE

The impact on the embedded structure was also analyzed, simulating the strike of a 200 kg projectile traveling at a velocity of 50 m/s at an angle of 60° to the ground surface. Structures embedded at depths of 0.1 m and 0.5 m were considered.

The model and material parameters were taken to be the same as those used in the previously discussed cases.

The projectile was modeled as a rigid body.

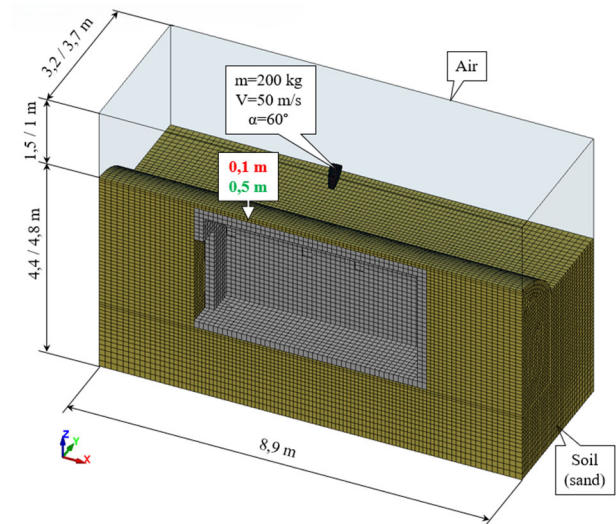


Figure 7. Finite element model for analyzing the impact of a projectile strike.

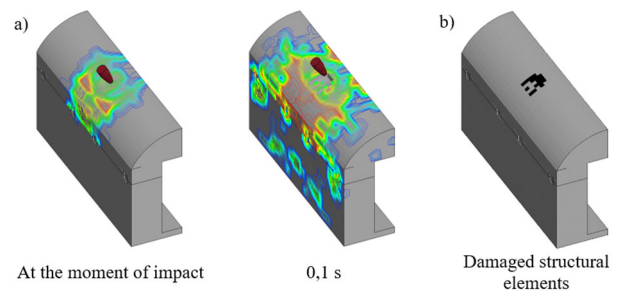


Figure 8. Distribution at a depth of 0,1 m: a) plastic deformations in the shelter elements as a result of the impact; b) zones with damaged components.

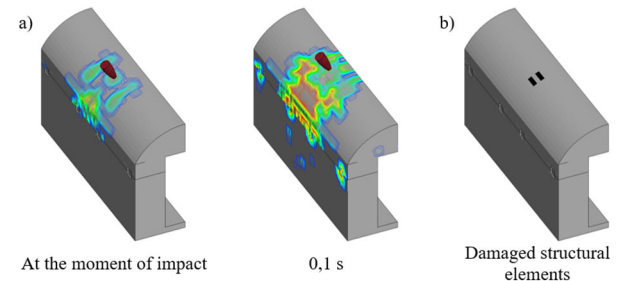


Figure 9. Distribution at a depth of 0,5 m: a) plastic deformations in the shelter elements as a result of the impact; b) zones with damaged components.

Based on the results shown in Figure 8 and Figure 9, it can be concluded that under impact loading, even a slight increase in embedment depth – from 0.1 m to 0.5 m – can significantly reduce the damage zones in the structure caused by the projectile impact. The zones of plastic deformation become smaller, as does the damage to the structure itself. The number of damage zones predicted by the simulation decreased by 79%, amounting to 29 for the 0.1 m case and 6 for the 0.5 m case.

The influence of varying the embedment depth of the structure in the soil on the projectile velocity at the moment of impact with the structure was investigated separately. Calculations were performed for depths of 0.5 m and 1 m. The results are presented in Figure 10.

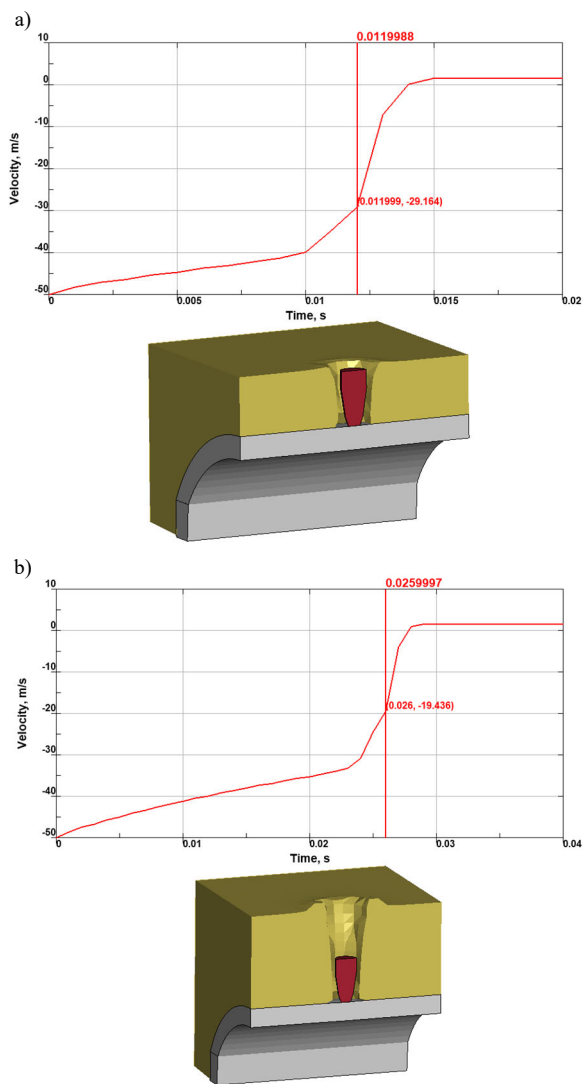


Figure 10. Projectile velocity at the moment of impact for embedment depths: a) 0.5 m; b) 1.0 m.

It was established that increasing the embedment depth by 0.5 m reduces the projectile velocity at impact by 33%. At a depth of 0.5 m, the velocity is 30 m/s, while at 1.0 m it decreases to 20 m/s.

5 CONCLUSIONS

It has been shown that for modeling the soil medium under explosion or impact loading, an Eulerian mesh should be used, as it allows the reproduction of large deformations caused by such effects. The protective structure and its elements are best modeled using a Lagrangian mesh, as the deformations in the structure are significantly smaller compared to those occurring in the soil mass.

It was demonstrated that the *soil and foam* material model from the ANSYS/LS-DYNA library can be applied to describe soil behavior under dynamic loading. The *cscm concrete* material model from the ANSYS/LS-DYNA database allows for a satisfactory reproduction of the stress-strain state of concrete under explosive and impact loading with a minimal amount of input data, while the *plastic kinematic* model enables the simulation of plastic and kinematic hardening of steel.

It was established that increasing the burial depth of the structure in the soil from 0.5 m to 1 m under the action of an explosive charge with a TNT equivalent of 50 kg placed on the ground surface has a significant positive effect: the pressure on

the surface of the structure caused by the explosion decreases by a factor of 23, structural displacements are reduced by a factor of 4, and the stresses in the reinforcement decrease by 68%. At a depth of 0.5 m, zones of plastic deformation in the reinforced concrete structure cover almost the entire surface, while at a depth of 1 m, they appear only in the upper part of the structure, with the area of damaged zones reduced by 53%. Further increases in burial depth did not result in significant changes.

The effect of the impact from a 200 kg projectile traveling at a speed of 50 m/s at an angle of 60° to the ground surface was also studied. It was found that increasing the burial depth of the structure from 0.1 m to 0.5 m significantly affects the level of structural damage due to the impact, with the number of damaged zones on the surface of the structure decreasing by 79%.

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