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NUMERICAL SIMULATION OF LANDMINE EXPLOSIONS: COMPARISON BETWEEN DIFFERENT MODELLING APPROACHES

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Abstract. Until decade ago the design of mechanical structures, having to resist to explosive events, was mainly performed using experimental tests with explosive materials. In the last years, numerical methods are assuming importance thanks to the following advantages: high cost reduction, flexibility in investigating different scenarios and the chance to study explosive phenomena without risks. An explosion is a complex and multidisciplinary subject. It involves a large number of physical parameters which influence the amount of energy transferred to the target above the detonation. The aim of this paper is to describe numerical models to simulate landmine explosion and blast loading on structures, using different approaches: an Arbitrary Lagrangian Eulerian (ALE) mesh and a pure Lagrangian mesh. For what concerns the ALE simulations, three different cases are analyzed. First of all, the numerical model of the landmine explosion is validated through the comparison with experimental data. The same model is then used to evaluate the effect of detonations against two structures, using a fluid-structure algorithm: a steel plate and a human leg. For this type of simulations, an Eulerian approach is needed, in order to reproduce the expansion of the mix of sand, air and gas against the target. When the gas encounters the target a fluid structure interaction algorithm (FSI) determines the pressure values, which are transferred from the Eulerian parts to the Lagrangian ones. The main disadvantage of an ALE approach is the large computational time, which is further aggravated by the need to use quite fine mesh resolution to adequately reproduce the air shock. For this reason it is interesting to use 2D modeling. The second approach is based on empirical airblast equations developed by Kingery and Bulmash, for the application of pressure loads due to explosives in conventional weapons, and was implemented in LS-DYNA by Randers-Pehrson and Bannister. This methodology is applied to simulate the detonation against the plate and the results are compared with the corresponding results obtained using an ALE approach.

1 INTRODUCTION

Recently, in the explosive phenomena field, the numerical simulations are assuming a relevant importance for structure design. The numerical approach brings significant advantages compared to experimental tests: no risks, high cost reduction and great opportunity to study different scenarios just changing the model parameters. Usually, the experimental repeatability is quite difficult to achieve, so it is complicated to carry out right and univocal considerations. Moreover, the explosion tests are very complex to perform and require high experience and high instrumentations cost. On the other hand, the numerical simulation allows performing a first stage of *Design of Experiment*, since it make possible the study of many different scenarios, changing the parameters involved. By the comparison and the analysis of the numerical results, it is possible to better understand the phenomena evolution, so it is possible to focus the attention on the critical situations, which in turn are useful to validate the numerical results. In any case, frequently, the experimental tests cannot be realized, because restrictive laws on explosive materials are in force, so the numerical simulation represents the unique tool available for the design.

In general, the numerical simulations of explosions are very complicated, because many factors have to be taken into account: the explosive material properties, the properties of the medium in which the shock-wave is transmitted and the target type. Besides, the numerical solution is further complicated by the simultaneous presence of fluids and solids. It is recommended to use a combination of pure Eulerian mesh, used for modeling fluids, and pure Lagrangian mesh, used for modeling solid structures. In order to allow the expansion and compression of neighboring fluids in the same region, it is necessary to define an appropriate algorithm for simulating the mixing of different fluids. The fluid-structure interaction is another feature to take into account, which is very expensive from a computational point of view. The fluid-structure interaction algorithm allows transferring the pressure values, generated in the fluid, to the target structure. Finally, the numerical model needs an equation of state to represent the detonation expansion of the gas produced by the detonation.

In this work, a benchmark numerical model has been realized in LS-DYNA [1] in order to reproduce a landmine explosion and the results have been validated through the comparison with experimental data obtained from Canadian Defense Department [2] with a 3D and 2D approaches. Following, the same landmine model has been used to study the effects of the explosion against two different structures: a steel square plate [3] and the human leg extracted from THUMS [4].

The results obtained for the plate are then compared with the results obtained for the same case using the airblast model, implemented in LS-DYNA, with a pure Lagrangian mesh. The empirical blast equations were developed by Kingery and Bulmash [5] for the application of pressure loads due to explosive in conventional weapons. Kingery and Bulmash performed a series of tests, varying the charge weights, and used curve fitting techniques to represent the data with polynomial equations. The equations were then implemented in the computer program CONWEP, which was introduced in LS-DYNA by Randers-Pehrson and Bannister [6]. In the present work, this model is applied to simulate the detonation against the square plate and the results are compared with the corresponding results obtained using the ALE approach.

2 EXPLOSIVE MATERIAL EQUATION OF STATE

In the numerical models of such events, the equation of state (EOS) of the explosive, which expresses the pressure as a function of density and energy, is a crucial aspect. In the past, different theoretical and empirical approaches have been developed to describe the explosions and the behavior of the gas produced during the detonation. The Jones-Wilkins-

Lee (JWL) equation of state, which is implemented in LS-DYNA, is the most commonly used thanks to its simplicity. Moreover, a relevant number of high explosive materials have a good representation using this equation, which defines the pressure as:

$$P = A\left(1 - \frac{\varpi}{R_1 v}\right)e^{-R_1 v} + B\left(1 - \frac{\varpi}{R_2 v}\right)e^{-R_2 v} + \frac{\varpi E}{v}$$

where v is the relative volume, E is the internal energy and A, B, ω, R_1 and R_2 the input constants.

3 MULTI-MATERIAL GROUP

During an explosion different materials are mixed together generating the expansion of some fluids inside other ones. Generally, two kinds of fluids take part in the explosion: the gas produced by the detonation and the fluids in which the explosion propagates (air, water, sand, etc.). For these reasons, the Eulerian mesh is recommended, since it is appropriated to describe the fluids behavior. Moreover, it is necessary to define a common space where the fluids can interact each others, which is represented by the Multi-Material Groups (MMG) and presents a common mesh for all the material belonging the same MMG. The definition of MMG is such that each element of the discretized volume can include, at the actual timestep a fluid different from that of the previous timestep, simulating the expansion of a fluid inside the another ones.

In LS-DYNA, when an Eulerian mesh is adopted, the solution is obtained in two steps. At the beginning, the problem is solved from a Lagrangian point of view, in which the mesh deforms following the material flow. In the second step, the nodes are considered to be in the initial position and the solution is mapped from the deformed mesh.

4 FLUID-STRUCTURE INTERACTION

The interaction between fluid materials, which are modeled with an *Arbitrary Lagrange-Euler* (ALE) mesh, and solids, for which the Lagrangian mesh is recommended, is a relevant factor in the simulation of explosive phenomena, in which high pressure can be generated in a very short time. To solve this problem a fluid-structure interaction algorithm (FSI) is necessary. The FSI is a multi-physic phenomenon where a fluid, acting against a structure, generates the shape structure modification due to pressure and shear loads.

Sometimes, the FSI could be stationary and this happens if the loads applied by the fluid are exactly balanced from the reaction force of the structure, so the fluid reaches strain equilibrium. In the explosion field, the FSI is a transient phenomenon and the structure deformation is dynamic and changes with time. Since the fluid-structure interaction algorithm is very time consuming, it is recommended to use it only in problems where high pressure impacts the target very quickly. When the FSI is more stationary, it is suggested to use simple contact algorithms.

The FSI algorithm is based on a soft coupling between Eulerian and Lagrangian solvers, which are dedicated, respectively, to obtain the fluid and structural solutions. The Lagrangian structure imposes the interface boundary location, the displacements and the velocity. This information represent the interface conditions used by the fluid solver to compute the pressure to apply to the structural interface as exterior forces, which, in turn, represent the input for the structural solver. This means that at each timestep, the fluid and structural response are separately solved and then coupled together before starting the calculation for the next timestep (see Fig. 1).

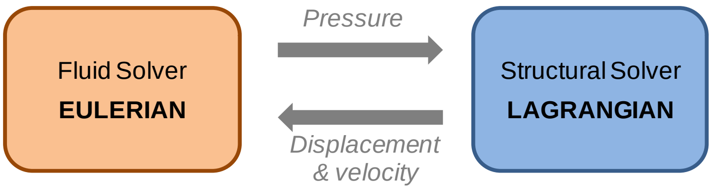

Figure 1: Scheme of the FSI algorithm.

The interaction between the pressure wave, generated by the explosion, and the structure, invested by it, produces the reflection of the pressure wave itself with the same sign. This makes the overpressure value to be increased with respect to the incident one. In the case of perfectly rigid structure the effective overpressure should be twice the incident one. If the structure intercepted by the pressure wave is deformable, this produces an immediate decreasing of the fluid pressure. As a matter of fact, the deformation produces the presence of some void zones close to the deformed surfaces, in which the fluid can expand reducing its pressure. This phenomenon becomes more relevant in case of rigid fluids, as e.g. for undersea explosions. The previous considerations make clear the advantages of using a FSI algorithm instead of simulating in a decoupled manner the fluid expansion and the structure deformation.

5 BENCHMARK MODEL: LANDMINE

In the technical-scientific literature, about explosion scenarios, the most part of the available experimental data regards landmine explosions tests. Therefore, a benchmark landmine model is realized in LS-DYNA and the numerical results are compared with the experimental ones, obtained by Bergon, Walker and Coffey in [2].

The test setup is shown in Fig. 2. A 100 g cylindrical charge, with a diameter of 64 mm and a height of 20 mm, of C-4 was used. A steel cylindrical container (inner diameter 889 mm, height 698 mm and thick 12.7 mm) is filled with dry sand (Silica 20), where the mine was buried. The sieve analysis of the sand showed that the diameter of the majority of the particles was between 160 and 630 microns, so the mean density is 1.8 kg/dm^3. The mine was buried at different depths of burial (DOB): 0 mm, 30 mm and 80 mm and for each case about six tests were performed. Pressure transducers were located above the soil surface at different heights (see Fig, 2) and at different depths in sand, with the aim of recording the trend of the pressure history vs. time and the time at which the pressure wave reaches the transducer. Other measurements regard the pit dimensions, the height and the diameter of the clouds of the produced gas and the height of the cloud of sand ejected in the atmosphere.

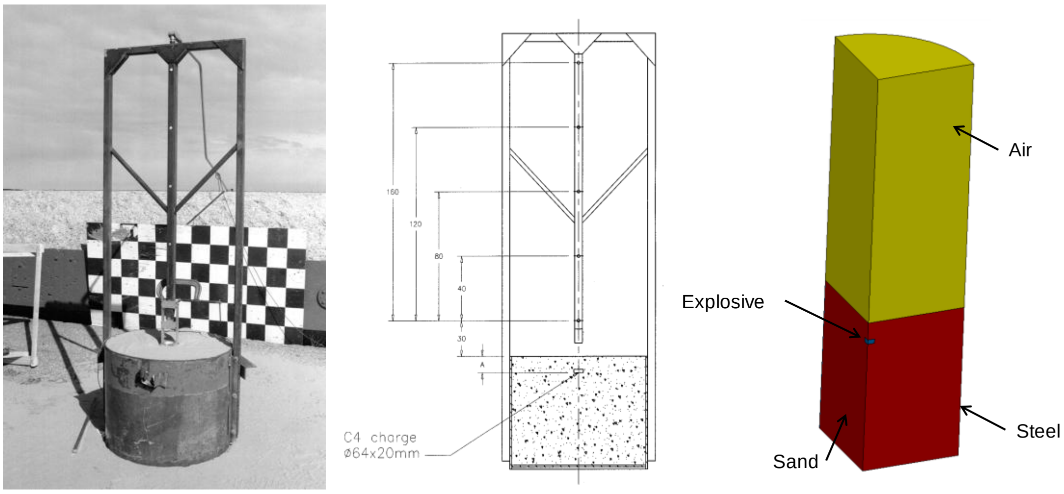

Figure 2: Experimental tests setup [2] and FE 3D model of the landmine at DOB 8 cm.

The numerical model (see Fig. 2) reproduces the geometry and the materials properties used for the material strength model and the equation of state are taken from [8]. The explosive is modeled combining the JWL equation of state with a model, which controls the detonation characteristics of the explosive. The steel pipe is modeled using an elastic-linear plastic strength model. The soil is modeled using an ad-hoc formulation, introduced in LS-DYNA for the description of soil and foam behavior, which allows defining the plastic yield function and the pressure vs. volumetric strain curve. Finally, the air is modeled from a pure hydrodynamic point of view using a polynomial equation of state, equivalent to the ideal gas law. Some of the models used are probably too simple, but the choice has been made on the basis of the available data in scientific literature.

As first attempt, the explosive, the air and the sand are modeled using 3D solid elements, while the steel pipe is modeled with 2D shell elements. The results show that, as expected, the explosion event is axisymmetric (at least as long as the pressure wave does not reach any boundaries). For this reason, the same case is also modeled using a 2D axysimmetric geometry (the ALE 2D axysimmetric option has recently been introduced in LS-DYNA). The aim is both reducing the computational time and having the possibility to increase the number of elements for studying the mesh influence on the solution. As a matter of fact, the main goal of this paper is to build reliable and stable numerical models of explosion events. The meaningfulness of the results is demonstrated through the comparison with experimental data. In any case, since a lot of data of the experimental tests are unknown, it is difficult to perfectly reproduce the same event. On the other hand, the perfect match between numerical and experimental results is not the main goal, since it would imply to optimize the materials parameters to obtain the best fit.

The comparison between numerical results and experimental data in terms of relative pressure vs. time curves are reported in Fig. 3 for the 3D case and the coarser 2D case. The comparison is made for the DOB 0 and DOB 8 in correspondence of the measuring point placed at 30 cm. The EOS introduced for the air is such that the air is at -1 bar at the initial condition, so in the diagram, the numerical pressure history starts when the pressure become positive.

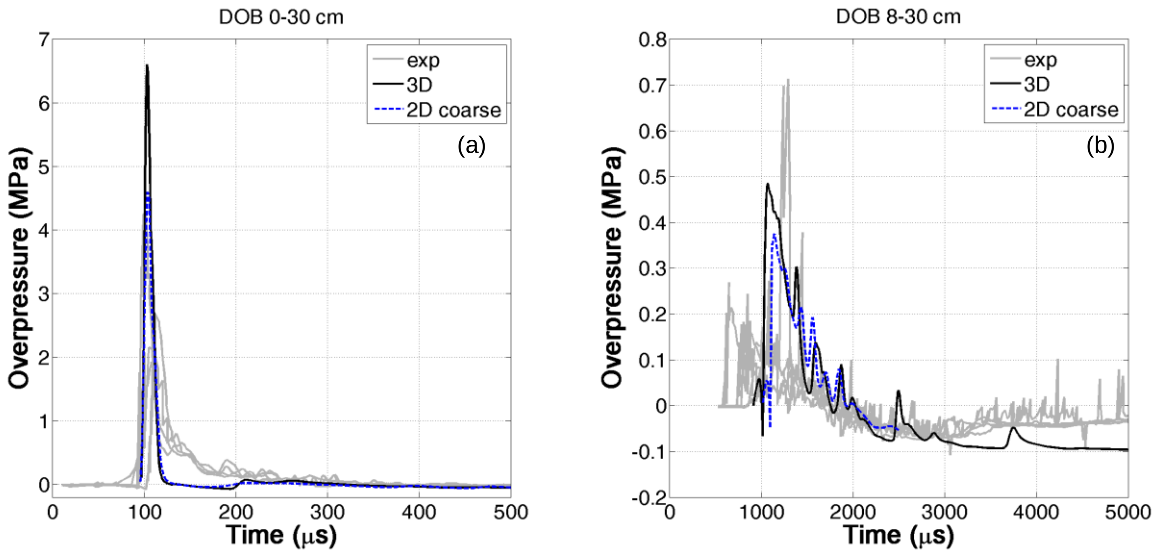

Figure 3: comparison between numerical results and experimental data [2] in terms of relative pressure vs. time curves, obtained at 30 cm above the soil surface: (a) DOB=0 cm; (b) DOB=8 cm.

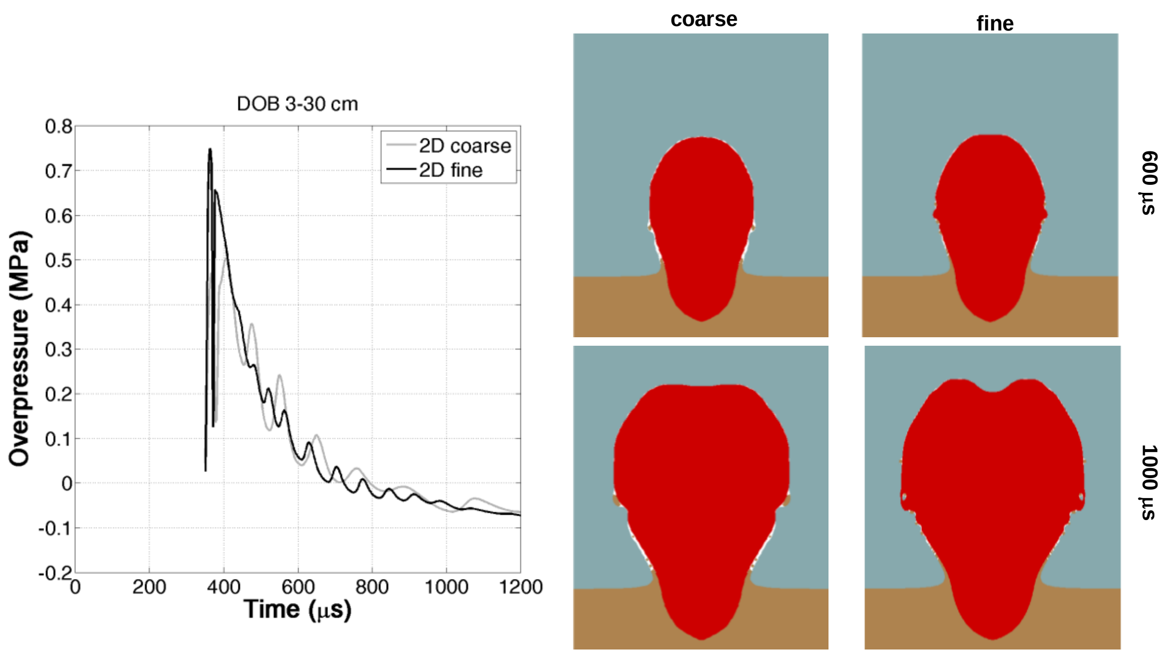

Figure 4: comparison between numerical results obtained for the 2D axysimmetric case varying the mesh dimension. The results are in terms of overpressure vs. time curves, obtained at 30 cm above the soil surface and in terms of spatial fluid distribution (at two different times).

Moreover, the numerical history is shifted in time in order to synchronize the time at which the peak of overpressure arrives. Looking at the results it is possible to conclude that the model is able to reproduce the same evolution obtained experimentally with a sufficient level of accuracy, especially for what concerns the case at DOB=0. Increasing the depth of burial the differences between numerical and experimental results become more significant. This could also be correlated to the fact that it is quite difficult to correctly model the soil, since it is a very heterogeneous material. In Fig. 4 the results obtained for the 2D axisymmetric case are reported for two different mesh dimensions (coarse: 10×10 mm; fine: 5×5 mm). The results are reported both in terms of pressure vs. time histories and in terms of fluids distribution for the case at 0 DOB at 30 cm. Looking at the results it is possible to notice that decreasing the mesh size both the shape of the fluids distribution and the speed of propagation changes with respect to the coarser case.

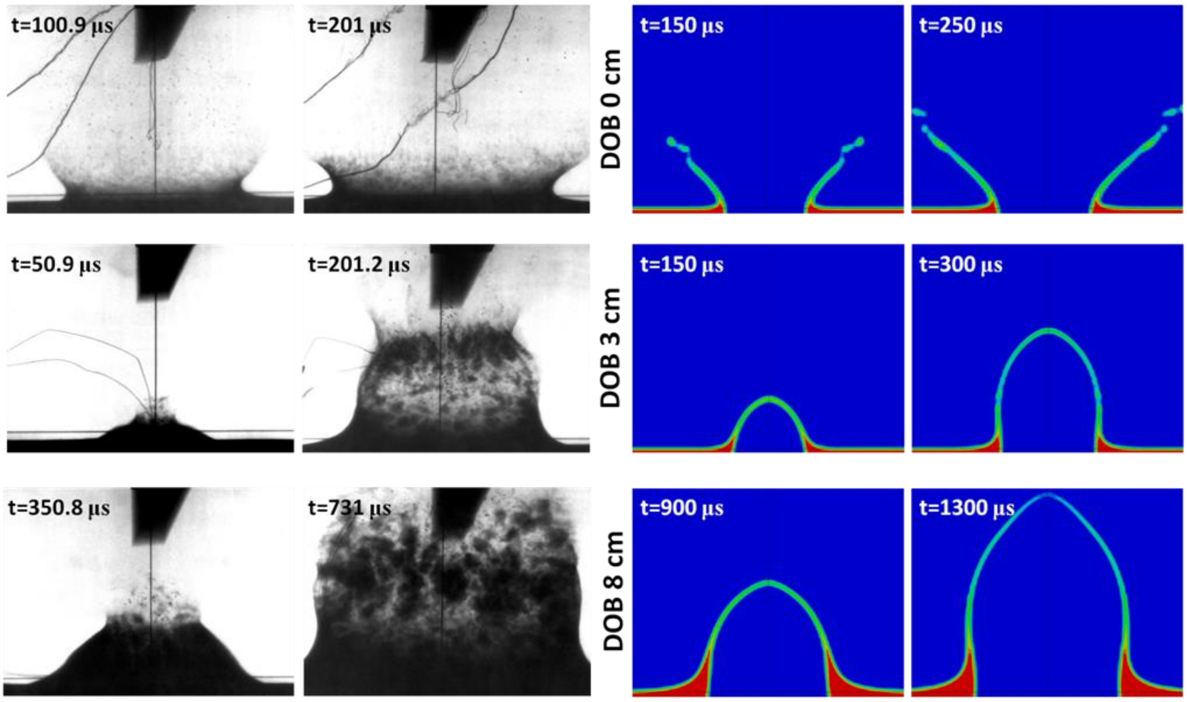

Figure 5: qualitative comparison between numerical (2D axysimmetric fine case) and experimental [2] results in terms of cloud of sand (two different time steps for the three DOB)

In Fig. 5 a qualitative comparison in terms of sand volume fraction is made between numerical results (case 2D axysimmetric - fine) and the images taken by the high speed camera for the three depths of burial at two times (for each experimental test two images are available). In each case, the synchronization is qualitatively performed on the first image and then the second one is taken after a time equal to the time interval between the experimental images. By the comparison, it is possible to conclude that the numerical models are, in general, able to reproduce the phenomenon evolution and the shock-wave propagation.

6 SQUARE STEEL PLATE

The numerical model of the landmine is then used in order to evaluate the effects induced by the detonation on a steel square plate, placed at a certain distance above the explosive charge. The results are compared with the experimental data obtained by the Australian Department of Defense [3]. The square plate used for the test was made is AS3678-250 steel and had 1200 mm of edge and 5 mm of thickness. The explosive charge used was a sphere of Pentolite with a mass of about 250. Four different tests were performed varying the distance between the charge and the plate between 200 and 500 (two tests at 500 mm, one test at 400 mm and one test at 250 mm). The experimental data were obtained by a LVDT displacement gage, accelerometers and pressure gages placed on the plate. The experimental setup is reported in Fig. 6, in which also the scheme of the numerical model is shown. As first approach the 3D model of a quarter of the system is built, in which the plate is modeled with shell elements. In order to achieve a good accuracy of the results it is needed to increase a lot the number of the elements. For this reason, also if the geometry is not axysimmetric, a 2D model is also analyzed, since it allows refining the mesh.

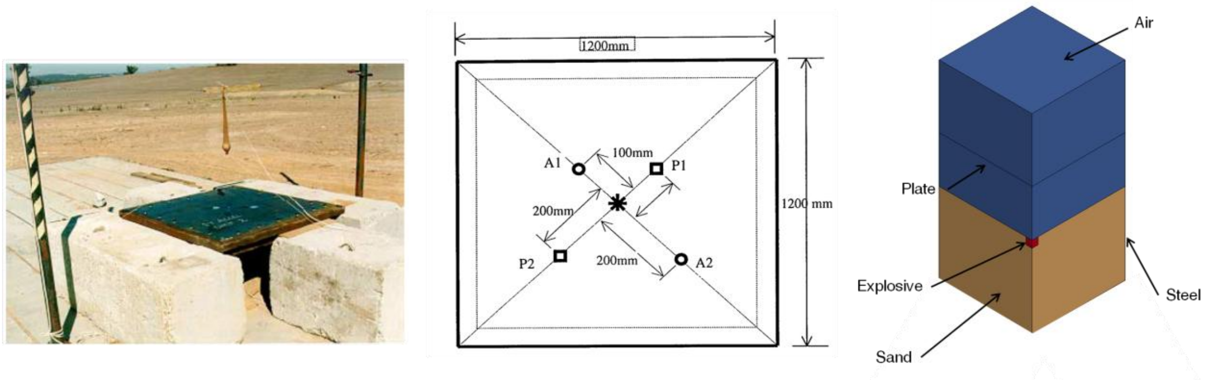

Figure 6: Scheme of the experimental test [3] and 3D numerical model (250 mm).

The models described in the previous paragraph for a DOB=0 cm are adapted to correctly reproduce the geometry of this type of tests. In [3] there is not any specification of the typology of the soil on which the charge is positioned. Anyway this could strongly influence the goodness of the results, since it affects the amount of energy transmitted to the target. As first approximation, the same properties of the previous analysis are used. The strength model and EOS parameters for Pentolite are taken from [8] and those of plate from [3].

In Fig. 7 the comparison between experimental and numerical data in term of pressure vs. time curves is reported for the measuring point indicated as P1 and P2 in Fig. 6. Similarly, also the history plot of the acceleration in correspondence of the measuring points A1 and A2 are reported. As mentioned before, since the explosion can be considered axysimmetric, both 3D and 2D case are analyzed, also if this implies an error in the geometry of the plate and the mine. Different 2D models are built varying the mesh dimension: the coarsest one presents a mesh dimension comparable with the 3D one. The results are shown for the 2D (coarse and fine) and 3D cases solved with the FSI algorithm and for the 3D case solved using the CONWEP algorithm [6]. The case study regards the plate placed at 250 mm above the soil.

As it is possible to notice, considering the same mesh dimension (2D coarsest and 3D, both with FSI and CONWEP), the results are comparable. Otherwise, decreasing the elements dimension, especially for the measuring point 1, greater values both for pressure and acceleration can be obtained. Maybe, in order to better appreciate the comparison with the experimental data it would be necessary to consider an average value obtained in correspondence to the area of the sensor. From the results, it is possible to asses that, also if the CONWEP model is very simple, it produces acceptable results, especially when the explosion is originated in air, which is the case used for the model calibration. The reliability of this model decreases when the landmine is buried in sand and, therefore, there is the interaction between sand and explosive. Comparing the experimental and numerical results, reported in Fig. 7, it seems that the frequency response of the sensors used during the tests (especially for the accelerometers) is too limited.

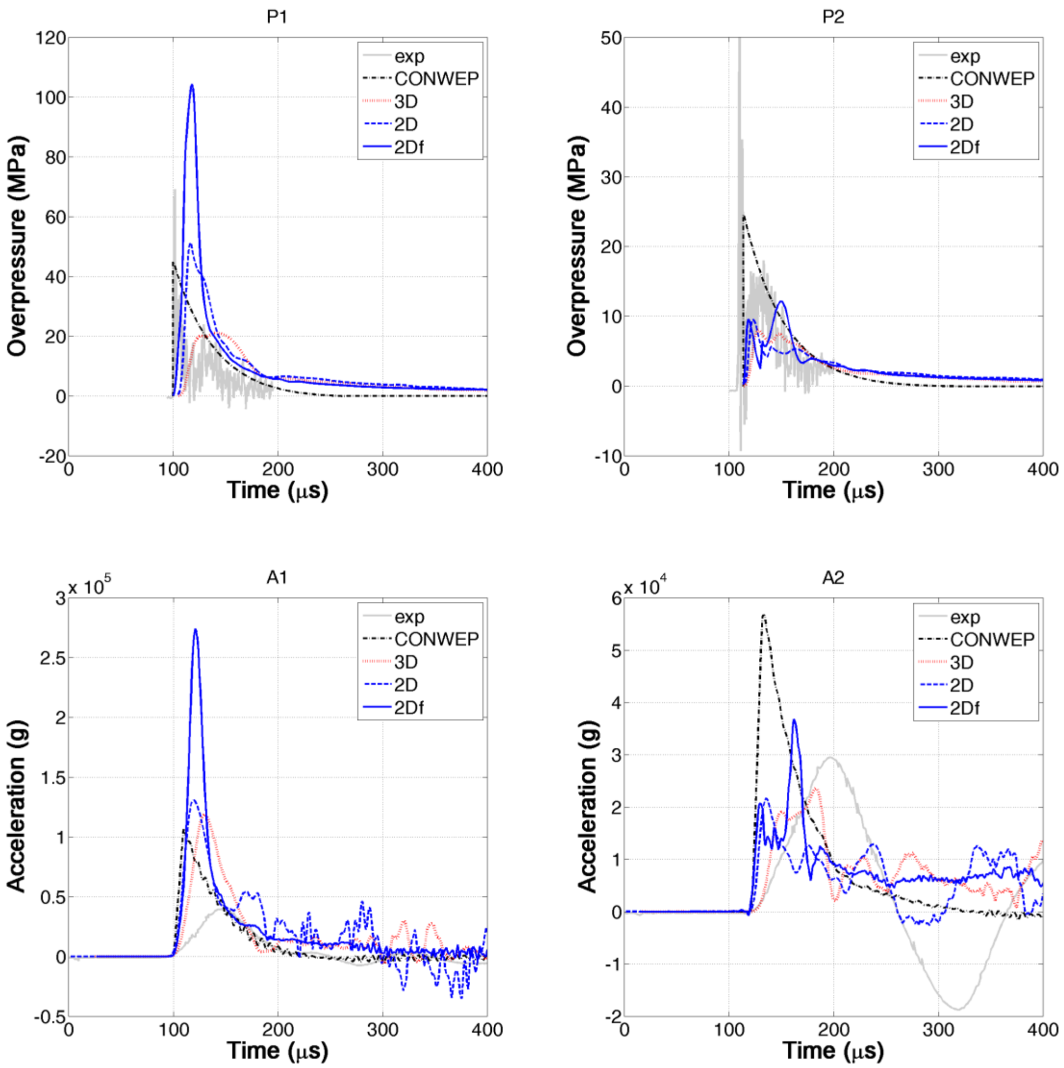

Figure 7: Comparison between experimental [3] and numerical (CONWEP in 3D, FSI in 2D and 3D) data in term of pressure (P1 and P2) and acceleration (A1 and A2) vs. time curves (plate at 250 mm).

In Fig. 8, the time evolution of the fluids distribution is reported for two 2D cases obtained varying the mesh dimension. As mentioned before, increasing the number of elements, both the shape of the clouds of fluids and the speed of propagation change. In fig. 9 there is the comparison in case of 2D models at DOB 0, as before, and DOB 10, in a fully saturated wet sand (2200 kg/m^3). The qualitative comparison regards the shape of the deformed plate in the two cases obtained at the same time (2 ms) after the detonation. The quantitative comparison is made in terms of internal and kinetic energies of the plate (per unit length, circumferentially): if the explosive is buried in a dense soil the impulse is longer and a greater amount of energy is transferred to the plate. The different level of danger between the air-bust and the explosion with debris projection is it well known from a phenomenological point of view and justifies the effort made for the developing of reliable methods for the fluids-structure interaction.

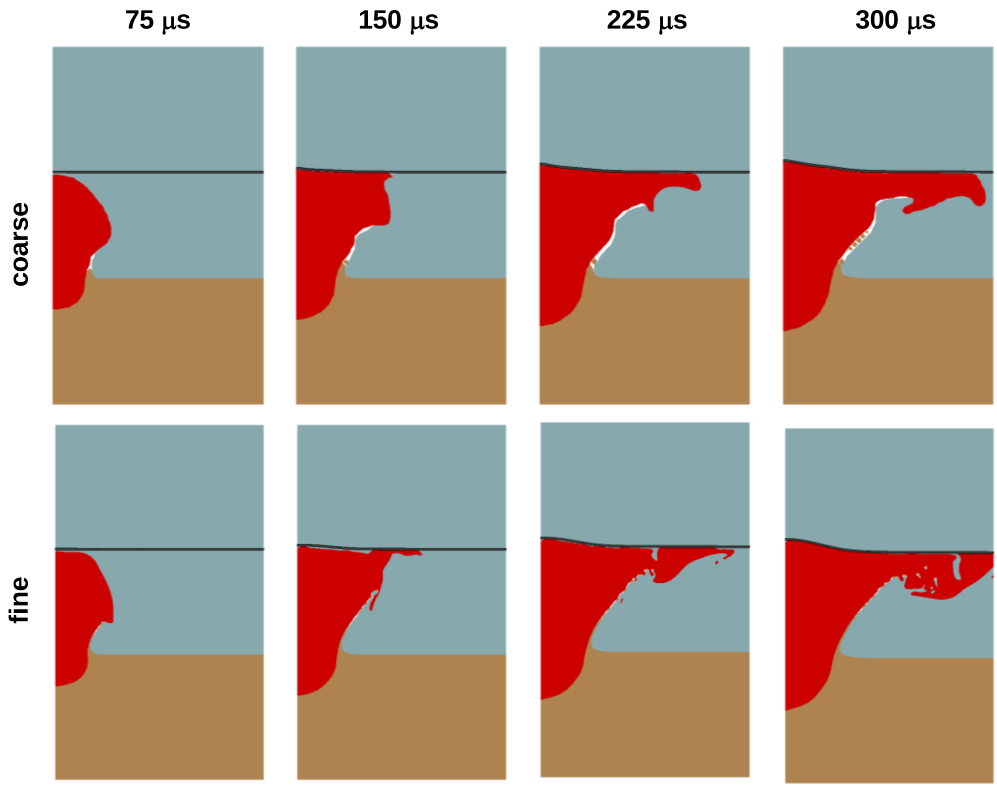

Figure 8: Time evolution of the fluids distribution is reported for two 2D cases obtained varying the mesh dimension (coarse: 10×10 mm and fine 2.5×2.5 mm, plate at 250 mm).

8 HUMAN LEG: THUMS MODEL

The objective of this paragraph is the description of the problem concerning the numerical simulation of the explosion against a complex structure, such as a human body. The USA Defence Department published a report on the number of incidents during the mine clearing operations, from which it appears evident the importance in the protection system for the lower limbs. The model represents a human leg extracted from THUMS (Total HUman Model for Safety). It is a sophisticated FE model developed by Toyota [4] for the prediction of the results in case of the numerical simulation of crush tests, so it is calibrated for the prediction in case of impact events. The complete model represents a sitting average-sized American men. For the evaluation of the consequences of the shock-wave propagation, it is sufficient to take into account only the leg, since the shock amplitude decays very quickly and no effects are produced in the remaining part of the body. The numerical model of the leg is assembled with the numerical model validated for the case of the landmine, adding the FSI algorithm with the fluids and the leg.

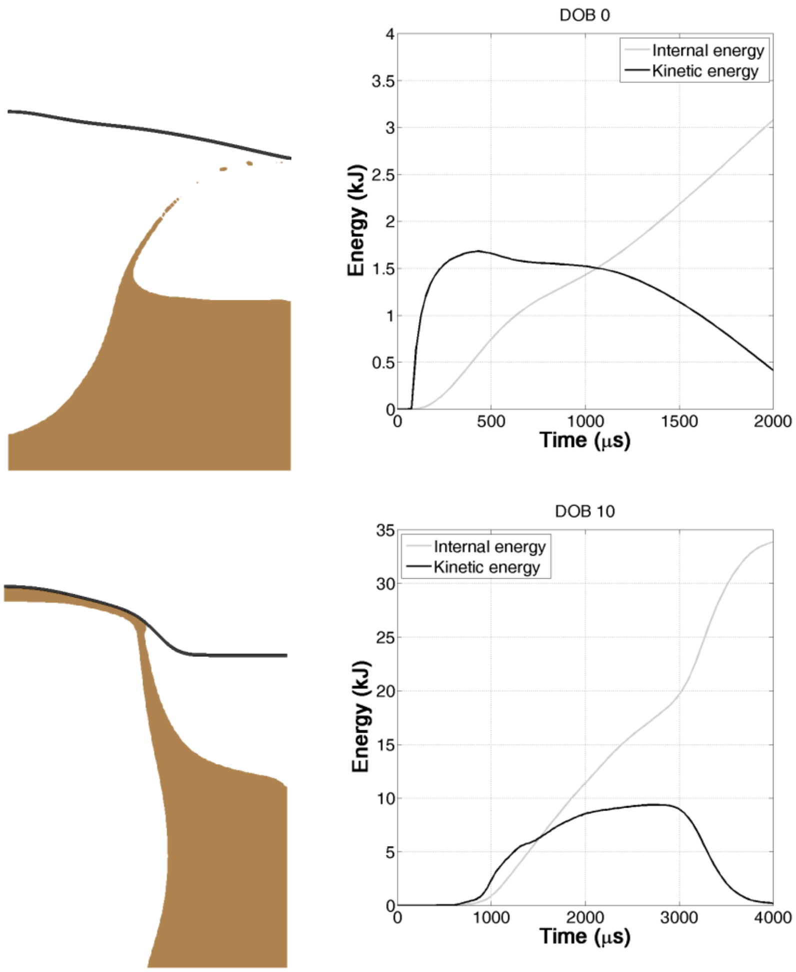

Figure 9: Comparison between DOB 0 and DOB 10 (plate at 250 mm): shape of the deformed plate at 2 ms and time history of internal and kinetic energies (per unit length, circumferentially).

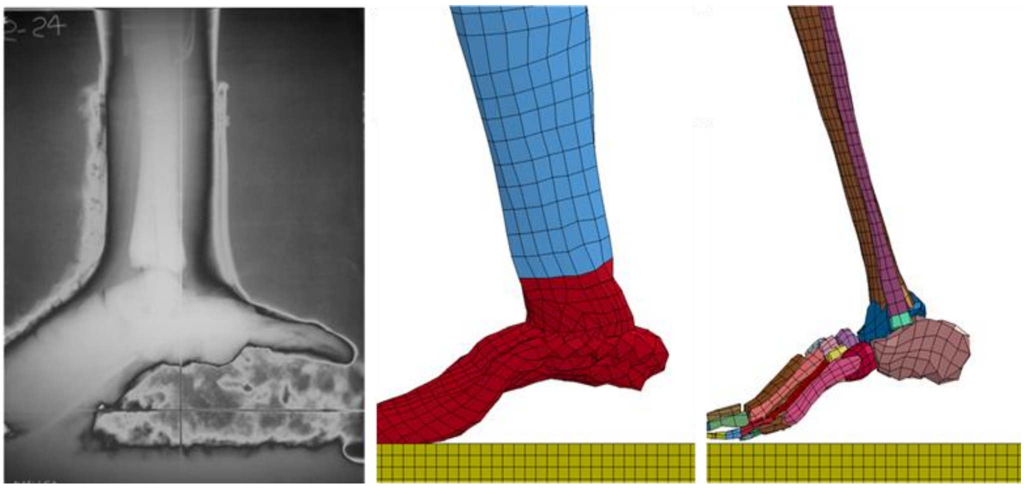

Figure 10: Comparison between numerical and experimental results in terms of damage on the foot.

The numerical results are qualitatively compared with the data obtained experimentally on an artificial leg (FSL, Frangible Surrogate Leg) by Bergeron, Coley and Fall in [9].

In Fig. 10, the image taken from an experimental test is compared with the LS-DYNA result, for evaluating the damage of the foot. The test was performed on a unprotected combat boot and the flash x-ray demonstrates that: the calcaneus is pulverized, a high compression acts on the heel, fracture and dislocation of foot phalanges and bones occur, the crack propagates up to the tibia and finally lacerations are provoked. Looking at the numerical results, it is possible to notice that the model is able to reproduce these effects, so it could be used in the military protection development.

9 CONCLUSIONS

This paper described numerical models to simulate landmine explosion and blast loading on structures, using different approaches: Arbitrary Lagrangian Eulerian (ALE) mesh and a pure Lagrangian mesh. For what concerns the ALE simulations, three different cases was analyzed: the numerical model of the landmine explosion varying the DOB and the detonations against two structures (a steel plate and a human leg), using a fluid-structure algorithm. For this type of simulations, an Eulerian approach was needed, in order to reproduce the expansion of the mix of sand, air and gas against the target. When the gas encounters the target a fluid structure interaction algorithm (FSI) determines the pressure values, which are transferred from the Eulerian parts to the Lagrangian ones. The results showed that the numerical model realized are able to reproduce with a good level of accuracy the detonation event and the consequences on different structures. The second approach is based on empirical airblast equations and was applied to simulate the detonation against the plate and the results were compared with the corresponding results obtained using an ALE approach.

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