Coupling of Particle Blast Method (PBM) with Discrete Element Method for buried mine blast simulation

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Abstract

This paper presents two meshless methods: particles blast method (PBM) and discrete element method (DEM). Particle blast method (PBM) is intend to model the gaseous behavior of high velocity, high temperature detonation products. PBM is developed based on corpuscular method (CPM), which has been successfully applied to airbag deployment simulation where the gas flow is slow. For blast simulation where gas flow is extremely high, the equilibrium assumption in CPM is no long valid. By reformulating the particle interaction algorithm, we proposed the PBM that is capable of modelling thermally non-equilibrium system and applied this method for the simulation of blast loading. DEM focus on the modeling of granular media, which might exhibit complex behavior under different condition. Finally, the paper present the coupling of PBM with DEM for buried mine blast simulation.

Introduction to Particle Blast Method

The development of PBM is inspired by the development of numerical method for airbag deployment simulation. One of the earliest and widely used method is control volume (CV), or uniform pressure method. When gas is inflated into airbag, the associated energy is transferred to pressure and uniformly distributed to bag surface simultaneously. The underline physical assumption in CV is the wave speed in infinite, which clearly is not right. It is not surprising that for certain condition as out-of-position, the CV has been recognized as less effective in duplicating the airbag interaction with fidelity. To remedy this circumstance, LSTC put a lot of effects on investigating different numerical method, including Conservation Element and Solution Element (CESE), Arbitrary Lagrangian Eulerian (ALE). However, an Eulerian approach to the modeling of fluid structure interaction is subjected to several difficulties. One major disadvantage is greater advection error relative to Lagrangian simulations, when advection is used, both momentum and kinetic energy is not conserved at the same time. Also, greater computational effort is needed over Lagrangian simulations due to the advection. Another disadvantage is that there are geometrical complexities are hard to handle with continuum-based Eulerian approaches. Complex geometries need to be considered in the type of simulation and it is known to be very expensive with the continuum-based Eulerian approaches.

To circumvent those difficulties, a corpuscular particle method (CPM) [1] has been proposed for airbag deployment application. The CPM consider the effect of transient gas dynamics and thermodynamics by using a particle to represent a group of gas molecules. Each particle carries translational energy as well as spin energy. There is a balance between translational energy and spin energy for each particle. The translational energy transfer to and from spin modes of the gas species during particles collision is determined from the heat capacities. The pressure is built up by the moment transfer as particles collide and rebound from structure surface.

CPM has been applied to different type of airbag deployment simulation and achieved great success. Compared to Eulerian approach, this method is simple and numerical stable, has a similar accuracy but requires significantly less CPU resource, easily cope with the complex geometries during fluid structure interaction.

It is therefore naturally to ask, can this approach be utilized to other field, such as to describe blast loading? However, the initial investigate show是 CPM is not able to correctly capture the propagation speed of an explosive blast wave, the calculated pressure is severely underestimated.

The reason is the particle collision algorithm in CPM assumes that the system is always in thermal equilibrium state. This might be a reasonable assumption for airbag simulation with moderate temperature and low pressure, however, for blast simulation where gas flow is extremely high, the assumption of thermal equilibrium is invalid.

By modifying the particle collision algorithm, especially the energy transfer between translational modes and spin modes, we proposed a Particle Blast Method (PBM) [2] for the simulation of thermally non-equilibrium system. In PBM, the balance between translational energy and spin energy for each particle collision pair is no long valid, however, the balance between translational energy and spin energy is statistically satisfied when the system reach equilibrium state. Furthermore, to better represent gas behavior at extreme pressure and temperature, co-volume effects have been considered.

Figure 1 shows a process that spherical shaped TNT explosion within a rigid sphere. This process is simulated by CPM and PBM respectively. The corresponding energy vs time curves for CPM and PBM are also plotted in *Figure 1*. For both CPM and PBM, the total energy (internal energy= translational energy + spin energy) is conserved, the two total energy curves are almost identical. However, the translational energy curves are quite different. For CPM, since the method assume an equilibrium state system, the total translational energy is conserved and the curve remain constant. For PBM, at the time right after detonation, the system is in extreme condition, partial of the spin energy is transferred to translational energy such that PBM predict a higher averaged particle velocity compared to CPM. When time is greater than 0.02ms, as particles rebound back from rigid surface and the system reach equilibrium state, partial of the translational energy is transferred back to spin energy and PBM predict a similar curve as CPM. Furthermore, the equilibrium state in PBM is statistically satisfied.

Figure 2 consists in ALE 2D, CPM, and PMB simulation of a 15kg of TNT detonation. On the screenshots, the grid represents squares of 10cmx10cm each. *Figure 2* shows the results at time 0.4ms. For CPM, it can be seen on the screenshots that, the wave travelled a distance of 8 grid meshes (80cm) at time 0.4ms, instead of the 113cm expected from ALE simulation. With the modified particle collision algorithm, the PBM results are in perfect accordance with ALE simulation.

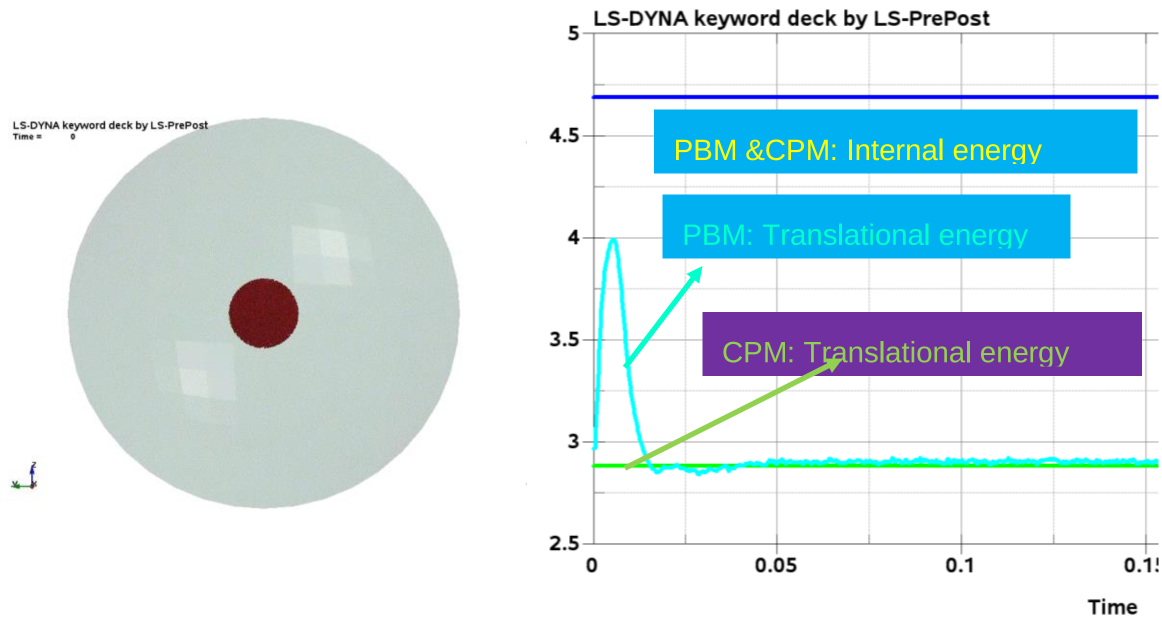
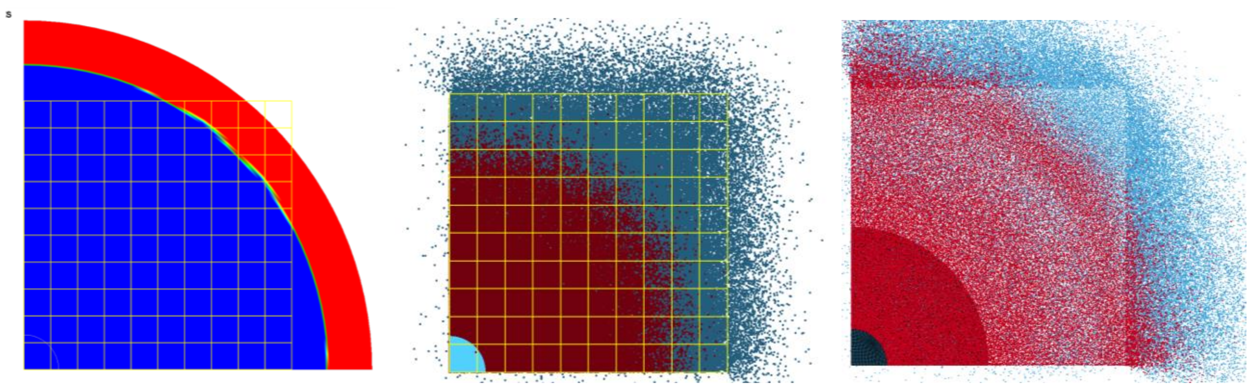


Figure 1 Energy curve for a blast in closed volume



ALE CPM PBM

Figure 2 Comparison of ALE with CPM and PBM at t=0.4ms

Air Blast Simulation

The experimental example is taken from [3], where clamped square 3.4 mm thick AL-6XN plates are exposed to the blast loading from a spherical charge consisting of 150 g C-4. The charge was placed 150mm, 200mm, and 250mm from the plate. The test apparatus allowed 613 mm square test plates to be fully edge-clamped using a cover plate and series of bolts. The region exposed to sand impulse was 406 mm x 406 mm. The region below the plate was hollow and shielded from the blast, enabling the target unrestricted deflection. (*Figure 3*).

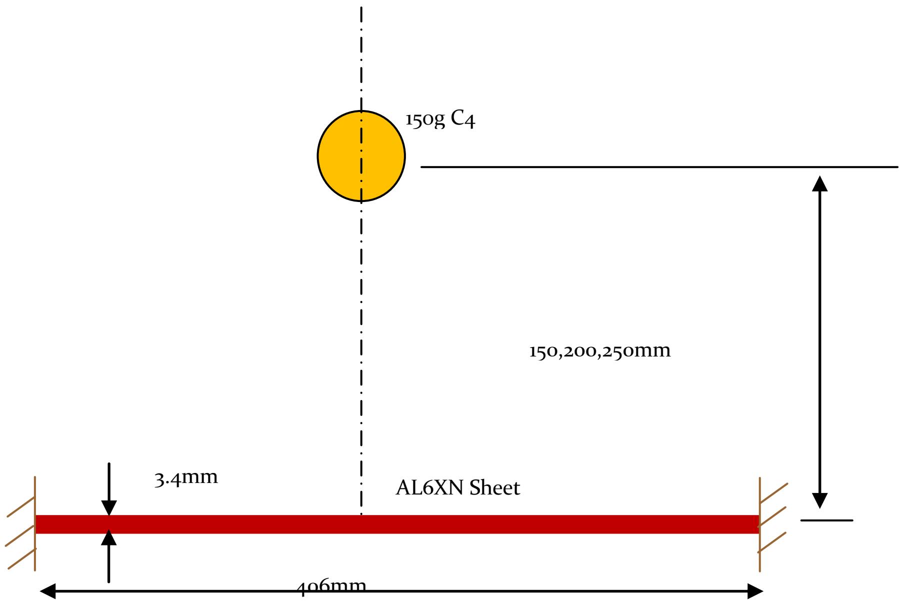


Figure 3 Sketch of the experimental set-up

The AL-6XN steel is a relatively new stainless steel with high strength, very good, and excellent corrosion resistance in chloride environments. The AL-6XN stainless steel material was modeled using a modified Johnson-Cook constitutive equation *MAT_MODIFIED_JOHNSON_COOK. The material parameters used in the simulation are adopted from [3] and listed in *Table 1*.

ρ (kg/m^3)	E(Gpa)	ν	χ	C_p (J/kgK)	α(K^{-1})	$\dot{\varepsilon}_0$(S^{-1})
8060	195	0.3	0.9	500	1.5E-5	1.E-3
A(MPa)	B(MPa)	n	C	m	Tr(K)	Tm(K)
410	1902	0.82	0.024	1.03	296	1700

Table 1 Material properties of the AL-6XN stainless steel

As comparison, an Arbitrary Lagrangian Eulerian (ALE) simulation of the test set-up were conducted in [3]. In the ALE model, the air and high explosive domain were modeled with 8-node reduced Elurian hexahedrons. The JWL equation of state was used to model high explosive. The JWL equation of state defines the pressure as

$$p = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (2)$$

Where A, B, R_1, R_2, and ω are JWL parameters. See *Table 2*. The air was modeled as ideal gas with initial energy density 0.253 MJ/m^3 and $\gamma = 1.4$.

D(m/s)	A	B	R_1	R_1	ω	ρ(kg/m^3)	E(J/m^3)
8190	597.4	13.9	4.5	1.5	0.32	1601	8.7E9

Table 2 JWL parameters of high explosive

The parameters used in the particle blast method of high explosive are shown *Table 3*. The detonation velocity, internal energy, and density were taken from the JWL equation of state parameters. The heat capacity ratio γ was also derived from JWL equation of state parameter ω as $\gamma = 1 + \omega$. Only co-volume coefficient *b* is used as adjustable parameter

D(m/s)	γ	ρ(kg/m^3)	E(J/m^3)	b
8190	1.32	1601	8.7E9	0.6

Table 3 Particle parameters of high explosive

Numerical Results

A cross-section of the bare charge simulation model at different time is shown in *Figure 4*. The volume of air used in the model was 1.0m^3. Free boundary conditions were used such that no reflections from the boundaries are present. A convergence study was used to determine the optimum number of particles for the C-4 charge, $N_{he,}$ and the surrounding air, N_{air}, for a converged solution. The number of air particles is set such that air particle mass equal to C-4 particle mass. Simulations were conducted using (N_{he}; N_{air}) = (25,000; 212,000), (50,000; 425,000), (1,000,000; 850,000) and (2,000,000; 1,700,000). *Figure 5* shows the central node displacement vs time plot for different stand-off distance for (N_{he}; N_{air}) = (1,000,000; 850,000). The simulations with particles were terminated after 10ms. Damping was then added to the plate and the permanent deformation was computed. The predicted permanent central deflections of the plate are given in Table 4, and compared to the experimental results. From this study it was concluded that convergence was reached when (N_{he}; N_{air}) = (50,000; 425,000). The accumulated impulse versus time that are being transferred to the target plate are shown in *Figure 6*

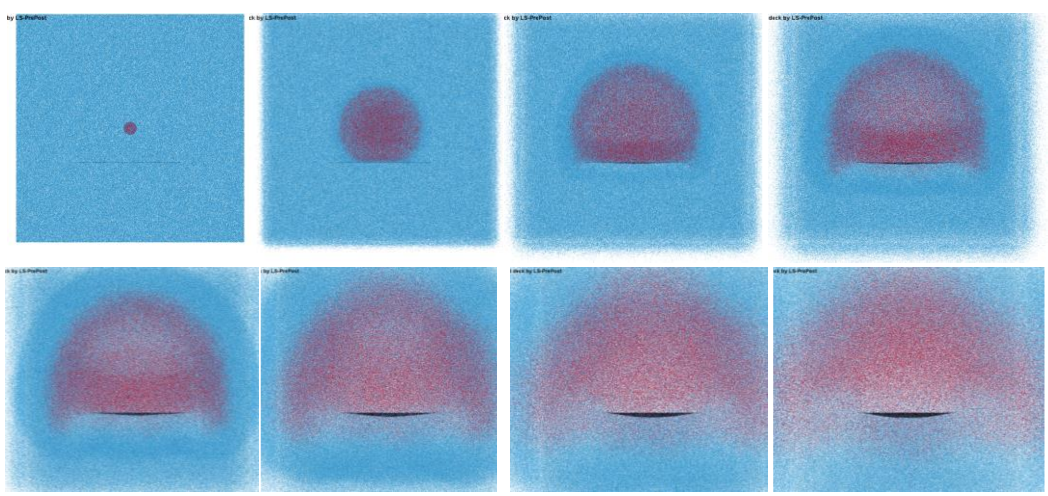


Figure 4 PBM simulation with (200000:1700000) after detonation

The numerical results for a bare C-4 charge at stand-off distance of 150mm using the PBM were also validated against Arbitrary Lagrangian–Eulerian simulations [3]. In the ALE models quarter symmetry conditions were applied. The air and high explosive domain were modeled with 1,134,000 8-node reduced integrated Eulerian hexahedrons. The JWL-EOS parameters for the C-4 charge used in the ALE simulations are given in *Table 2*. The air was modeled as an ideal gas with initial internal energy 0.25MJ/m^3 and γ 1.4. As seen from Table 4, the result from the ALE simulation over-predict the measured permanent deflection by about 15%. The result from PBM simulation are in good agreement with experimental test. The maximum error come from 200mm model with PBM over predict experimental result with 7.5%. The relative error for 150mm and 250mm model are 2.6% and 3.0% respectively.

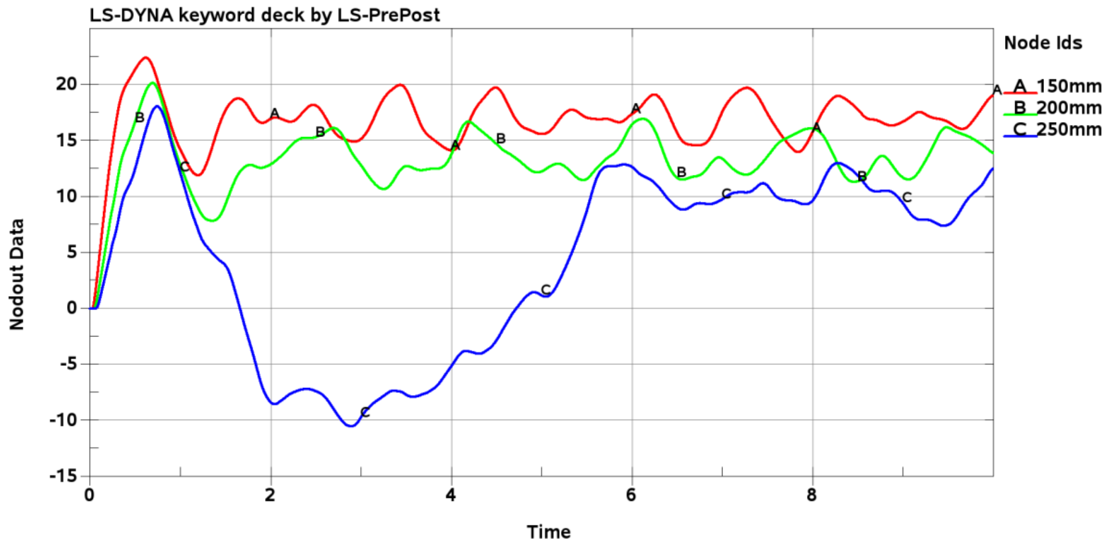


Figure 5 Central node displacement versus time for 150mm, 200mm and 250mm stand-off distance.

R(mm)	Test	N_{he} =25k N_{air} =212k	N_{he} =50k N_{air} =425k	N_{he} =100k N_{air} =850k	N_{he} =200k N_{air} =1.7M	ALE
150	17.0	17.48	17.03	16.92	17.13	19.8
200	12.7	13.65	14.36	14.69	14.61	
250	11.3	11.39	11.04	11.13	11.08	

Table 4 Center displacement as function of stand-off distance

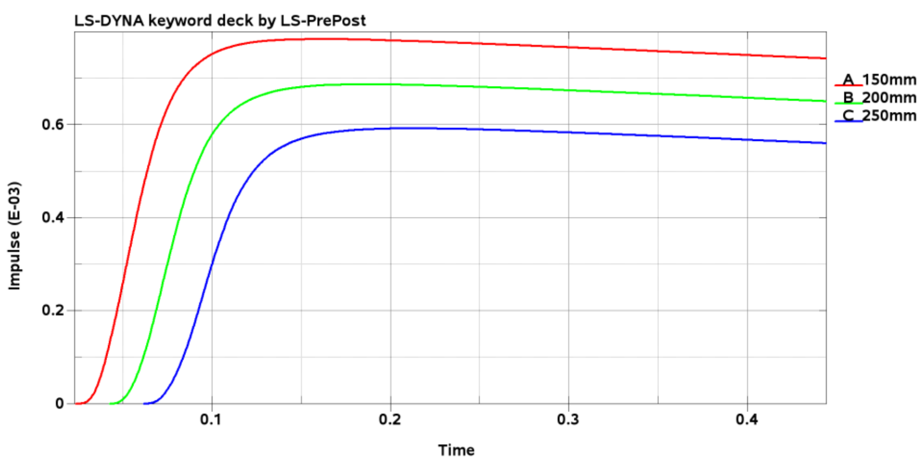


Figure 6 Reflected impulse for 150mm, 200mm and 250mm stand-off distance

Coupling of PBM with DEM for buried mine blast simulation

Blast loads from soil-buried landmines and improvised explosive (IED) are the major endangering and challenging threats to the civilian and military personnel during recent warfare. Detonation of the soil-buried landmines and the subsequent interactions of the resulting shock waves, detonation products, air, and the soil ejecta with the surrounding media and structures involve numerous highly non-linear phenomena of a transient nature. Arbitrary Lagrangian–Eulerian methods (ALE) are often employed to gain deeper insight into the mechanics of phenomena that involve the interactions between explosives, soils, and structures that are excited by such complex multicomponent systems. A major limitation of ALE approach is the lack of soil constitutive relations that adequately capture various regimes of soil behavior that evolve during the course of the detonation event. Classical soil mechanics models (such as Drucker–Prager) are often employed in ALE methods, however, the application of classic soil model are restricted to a soil packing density so high that the real particle–particle contacts are semi-permanent and consolidation is dominated by particle deformation and inter-particle friction (solid like behavior). When the particle assembly is widely dispersed, their ability to describe soil ejecta is questionable. Furthermore, most of the currently available materials model for soil/sand contain a large number of parameters whose estimation via numerical analysis and /or experimental measurements is very difficult and cumbersome.

Granular materials, such as sand, soil, are simply very large ensembles of discrete particles. Although granular materials are very simple to describe they exhibit a tremendous amount of complex behavior to applied loads and deformations. They can behavior solid-like (able to support static shear loads), fluid like (can flow in a dense state), or gas-like (grains can separate and collide), even at the same time (*Figure 7*). Therefore, when using FEM to model the granular material as a continuum, complex constitutive models or/and a priori assumptions regarding the location and type of failure are required to capture the features of soil response that emerge as a consequence of its discrete nature. However, granular flow often involves modeling large motion of discrete particles and significant geometry changes of soil masses, continuum based approach does not explicitly consider the particle-scale interactions underlying the macro-scale response observed in the laboratory and field.

Figure 7 2001 El Salvador Landslide Located Near San Salvador (photo:usgs)

With increasing computational speeds, discrete element method (DEM) is becoming a popular tool for the study of large displacements of granular materials. Despite their inherent simplifications, discrete element methods can accurately capture the macro-scale response of granular materials. Simulations of conventional laboratory tests using the discrete element method can provide useful insight into soil response at the particulate level. Parameters that are difficult to measure in conventional laboratory testing can easily be monitored in these simulations. In addition, carefully controlled sensitivity analyses can be carried out to better understand the sensitivity of the response of granular materials to specific parameters. Once validated, DEM can provide useful information to explain the complex response exhibited by granular materials in conventional laboratory tests.

The discrete element method (DEM) permits study of the kinetics of microscopic particles through use of contact mechanics, and has been used by numerous researchers to investigate kinematically admissible deformation fields observed in laboratory tests of granular masses. In LS-DYNA®, the DEM is realized using rigid spherical particles in accordance to Cundall & Strack [5]. The DEM computes the motion of each spherical particle using Newton’s law of motion and thus, each particle may have three displacements and three rotations as degrees of freedom. As usual for the DEM, a penalty-based contact is used to capture the particle-particle (and particle-wall) interaction of dry and wet particles [4]. cf. Figure 8.

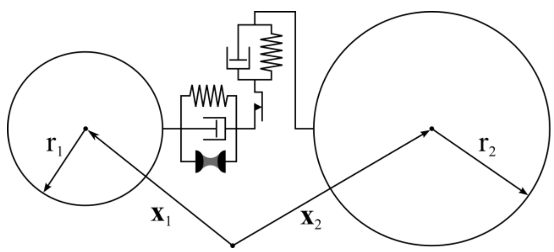


Figure 8 *Penalty-based particle-particle interaction in LS-DYNA.*

Davidson [6] numerical modeled the triaxial compression test procedure, where plastic pearls were utilized in triaxial tests, and across a range of confining pressures (25 kPa, 50 kPa, and 100 kPa). Figure 9 (from [6]) shows the comparison with experimental measurements from [7] and the deviatoric shear stress versus axial strain that agree well with the corresponding experimental measurements. It can be seen that discrete element methods can accurately capture the complex behavior of granular materials. The nature of these interactions is determined by particle size, material density, friction angle, cohesion, and other soil properties.

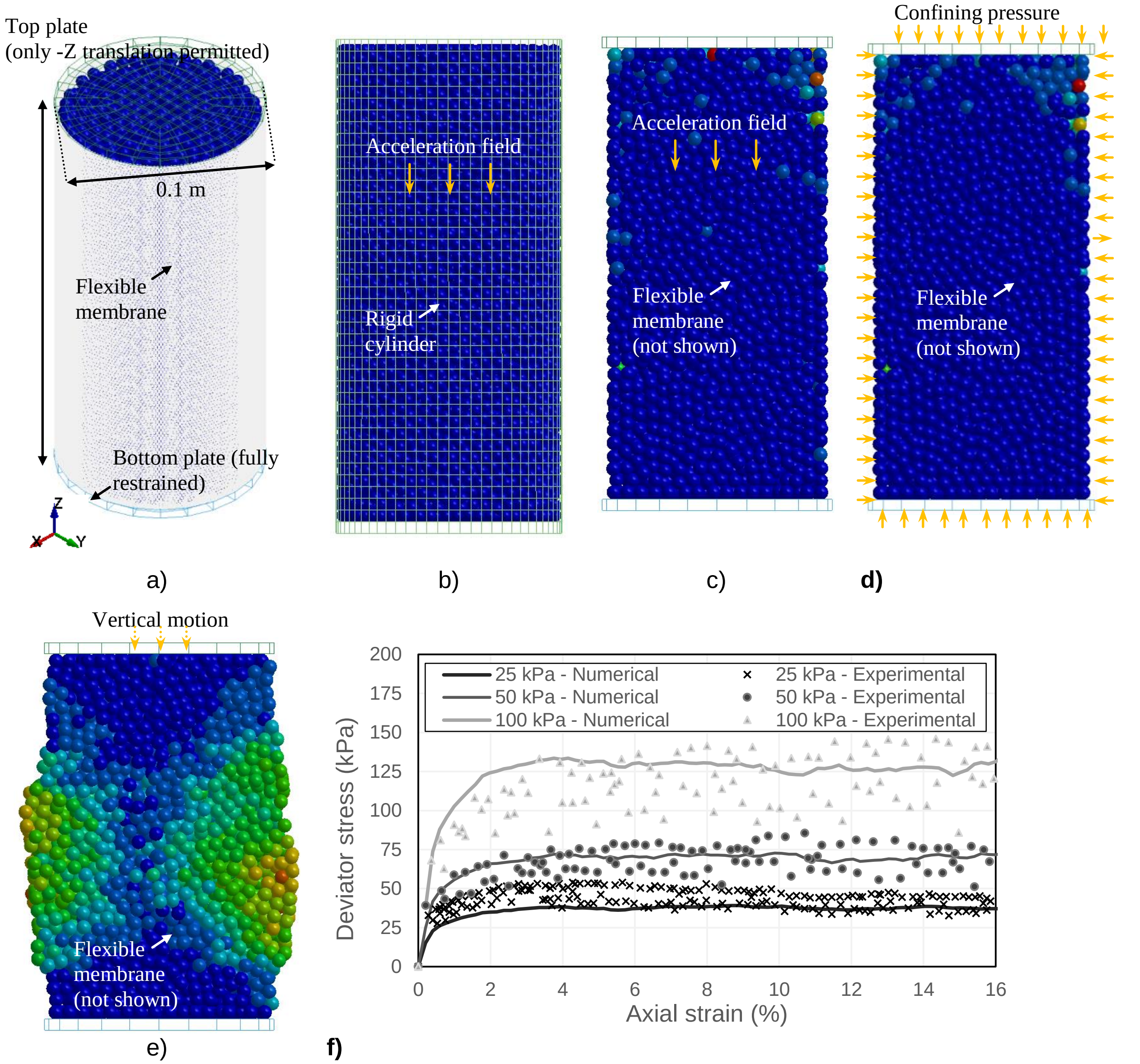


Figure 9 Triaxial compression test model: a) Isometric view of packed sample; b) Sample packing; c) Sustained application of the acceleration field; d) Application of confining pressure; e) Depression of the top plate (displacement field shown); f) Validation against [7]

In this study, DEM is coupled with PBM to investigate the blast load from soil-buried cylindered shaped charge. The experimental example is taken from [8], where blast trials with the explosives placed in soil at three different burial depths were performed. The experimental set up is shown in Figure 10, where a ground blast rig with the sides 3 × 2 m and total height 2.7 m includes a hanging test module. The test module consists of a square target plate of steel quality Weldox 700E with dimension 600 × 600 × 8 mm, held in place at the corners with a plate holder. The inner diagonal length of the plate holder is 627 mm.

The square sand boxes were made of wood with the side 950mm while the height varied between 500 and 600 mm. The grain density for the sand is about 2700kg/m3. The charge was 0.75kg Swedish military plastic explosive m/46 with a density of 1500kg/m^3. The charge was formed to a cylindrical shape resulting a diameter to height ratio of 3. The three different DOB (depth of buries) were 0, 50, and 150mm, measured from the soil top surface to the mine top surface. The stand-off to the target plate was 250mm and measured from the target plate to the surface of the sand. For detailed experimental setup information, please refer to [8].

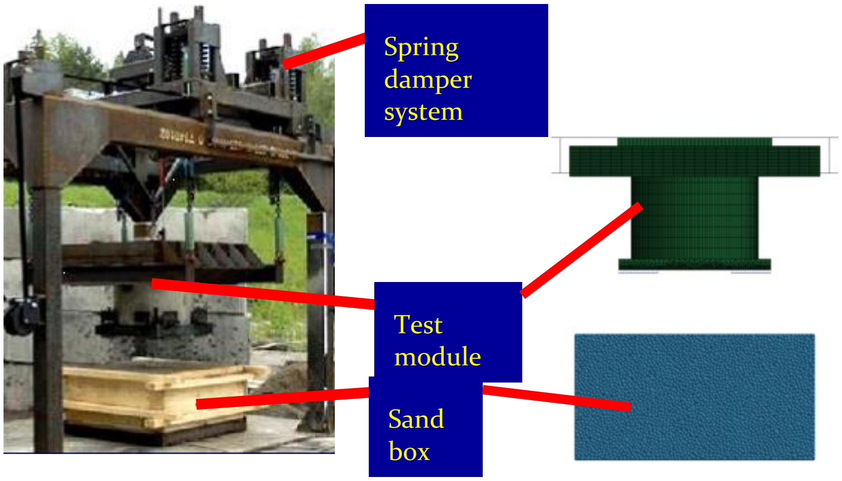


Figure 10 Experimental set up and numerical model of explosions in soil

The numerical models to simulate the field blast trials are shown in Figure 10. The model setup for coupling of PBM and DEM is straightforward and a simple instruction can be found at [9]. The loading by air was assumed to be negligible. Hence, only the m/46 were modeled by PBM using 100,000 HE particles. The PBM parameters for m/46 are transferred from JWL parameters [8] and listed in Table 5. The surrounding sand were modeled by 465,000 DEM. The density of DEM is adjusted such that total mass of DEM equal to the total mass of soil. The sensitivity upon the simulations of the particle contact parameters (contact stiffness, damping parameter and friction coefficient) for the sand were investigated, it was found that the results are not sensitivity to contact stiffness. Furthermore, if frictional coefficient or damping parameter is greater than 0.3, results are not sensitivity to both parameters. The simulations with saturated wet sand adopted the same procedure as for the dry sand, but with reduced frictional coefficient enlarged density to account the water mass.

D(m/s)	γ	$\rho(kg/m^3)$	$E(J/m^3)$	b
7680	1.29	1500	7.05E9	0.6

Table 5 Particle parameters of high explosive

A cross-section of the explosion behavior for 50mm DOB is shown in *Figure 11*. The numerical results have been compared with corresponding experiments and the results from all the simulation cases are shown in Table 6. Most of the numerical results over predict the experimental results. Regarding the max plate deformation, Case1 over predict the experimental result with 6.7%, while Case3 and Case4 under predict the experiment result with 2.8% and 2.3%. The most accurate results is obtained for Case2, with only 0.5% difference. Regarding the residual plate deformation and impulse transfer, all the numerical results over predict the experimental results. The plate deformation increased from flush-buried explosive to the intermediate depth of burial, then decreased. Numerical simulation show a similar trend with increased burial depth. The measured trends show an increased impulse transfer with increased burial depth, which is also captured by numerical simulation.

DOB(mm)		δ_{max}	δ_{res}	Impulse
0 (wet)	Test	92.2	84.6	1990
	Numerical	98.4	96.5	2202
50 (wet)	Test	102.5	91.8	2623
	Numerical	102.0	100.5	2954
50 (dry)	Test	92.2	82.2	2205
	Numerical	94.8	93.0	2888
150 (wet)	Test	72.3	59.4	2883
	Numerical	74.0	68.5	3386

Table 6 Comparison of test and numerical results

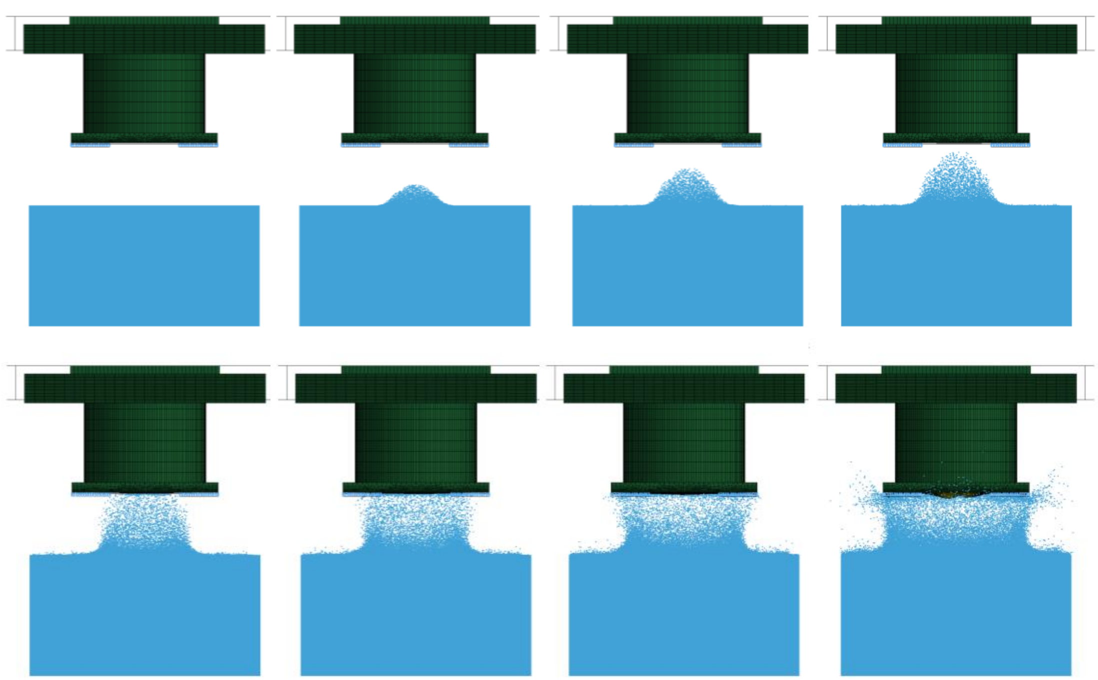


Figure 11 Explosion behavior for 50mm DOB

Summary

A particle blast method for the simulation of blast loading has been developed. This method is based on Lagrangian description of motion, thus avoid the advection errors and severe contact problems in coupled Lagrangian-Eulerian approach. Furthermore, the absence of field equations makes the method numerically simple, robust and very efficient. The results from the particle blast method are in good agreement with corresponding ALE simulation results and available experimental data. Compared to ALE method, the particle blast method is more straightforward to use and less CPU demanding. When coupled with DEM, this method is suitable for land mine and Improvised Explosive Devices (IEDs) simulation.

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