IMPACT AND PENETRATION OF STEEL PROJECTILES ON BRITTLE TARGETS

V. Mehra, S. Chaturvedi
Computational Analysis Division,Bhabha Atomic Research Centre, Visakhapatnam, INDIA-530012
E-mail of corresponding author: vmehra10@yahoo.com

ABSTRACT

We have carried out a study of impact and penetration of a hard-steel ogive-nosed projectile on a thick brittle target. The projectile has a length-to-diameter ratio of 10 and a radius of 7.1 mm. The strike velocities range between 400 m/s and 1000 m/s. The target is a semi-infinite block of limestone, which is illustrative of brittle geological materials. The limestone EOS is of Mie-Gruniesen form with parameters derived from fitting the empirical Hugoniot generated from SESAME data. The limestone has a von Mises criterion for plasticity with a pressure-dependent yield surface. A damage model for limestone is included. The computationally-obtained depth of penetration yields, via, the cavity-expansion technique of Forrestal et al, an estimate for the penetration resistance (R) of the target. Once R is determined, the projectile deceleration versus time can be predicted. Though the estimation of deceleration history is not an issue for simulations, it helps validate the simulation results. The target resistance has been found to inversely depend upon the projectile size in the experiments on penetration into limestone performed by Frew. The initial inter-particle spacing of the SPH particles sets the spatial resolution of the simulation. We perform the simulation at various resolutions at each strike velocity to understand the effect of resolution on the numerical depth of penetration and the agreement with the experiment. We find that runs at higher strike velocities require progressively finer resolution in order to have good agreement with experimental penetrations. The target resistance, calculated from simulation data, is velocity-dependent and increases with the strike velocity.

INTRODUCTION

It is necessary to evaluate the structural integrity of reactors under accident scenarios. One such scenario involves the impact of high-velocity projectiles on the containment structure. Computer simulations of such phenomena allow a parametric study involving different projectile and containment materials, different velocities and angles of impact,and so on. The simulations may be done through conventional mesh-based Lagrangian or Eulerian hydrocodes. Under conditions of large deformation, mesh-based techniques suffer from severe disadvantages. Lagrangian meshes tend to self-entangle, thereby causing the simulation to halt. The Eulerian mesh does not self-entangle but has problems with material diffusion. Smooth particle hydrodynamics (SPH) is a meshless computational method meant for continuum dynamics simulations. SPH is particularly applicable to problems involving large material deformation such as high-speed impact of solid bodies, chemical explosions, explosive forming, etc. In SPH, the continuum fields such as velocities, pressure, local density, temperature and stresses are carried by a set of moving, interacting (pseudo) particles. The inter-particle interactions are derived from the continuum equations through interpolation and discretization.

The material for the reactor would normally be concrete which is an example of brittle material. An interesting and relevant class of brittle materials in this context is the class of geological materials. The geological materials include various types of soils and rocks such as sandstone, limestone and granite. Studies on the geological materials are hampered by their peculiar characteristics such as sample inhomogeneity and sample dependence of the material properties. In particular, the construction of material models and equations of state for geological materials is thus rendered difficult. Hence, progress in the characterization of geological materials and the development of appropriate material models has been slow relative to other material classes such as metals, ceramics and plastics. Many models of varying complexity have been proposed for geological materials [1-4]. Another approach that has been tried is of using semi-empirical interaction between the projectile and the geological target in terms of a target resistance [5,6]. The empirical concept of sliding friction between the projectile and the target [7] has also been used along with a partial material model for the geological target.

In this work, we explore the validity of a relatively simple geological material model. We consider the impact of ogive-nose steel projectiles on limestone targets (t*he Frew experiments* [5]) that have been used as benchmarks by various investigators [2,6,8]. In these experiments, slabs of limestone were impacted by specified ogive-nose projectiles. The projectiles were of 3 CRH (caliber-radius-head) and length-to-diameter ratio of 10. Three sets of experiments were performed with the projectile diameter and masses being 7.1 mm, 20 g; 12.7 mm, 117 g; and 25.4 mm, 931 g,respectively. The strike velocity varied between 400 m/s to 1500 m/s. We restrict our simulations to the strike velocity range from 450 m/s to ~1 km/s and to the impacts made with the smallest projectile that Frew *et al* used.

SMOOTH PARTICLE HYDRODYNAMICS

Smooth particle hydrodynamics (SPH) is a meshless technique especially suited to the projectile impact and penetration since it does not suffer from mesh self-entanglement problem and the need for consequent complex rezoning procedures. It also handles material erosion without any special logic. In SPH, the fields such as velocity, pressure, density, temperature, stresses and strains are carried by a set of moving, interacting pseudo-particles. The particle interactions are derived from the continuum equations through interpolation and discretization. Further details about SPH may be had from [9].

MATERIAL MODELS

Hard Steel Projectile

The projectile is modeled as a high-strength steel with a Mie-Gruneisen EOS [10]. The yield strength is taken as 1.5 GPa [6].

Limestone Target

Limestone is modeled with an EOS of Mie-Gruneisen form [11]:

$$p=\frac{\rho_0 c_s^2 \zeta\left(1+\zeta\left(1-\Gamma/2\right)\right)}{1-\left(S-1\right)\zeta}+\Gamma E$$

where ρ_0=2.44 g/cm^3 is the initial density of limestone; c_s^2 =3.63 km/s is the sound velocity in the limestone and $\zeta=(\rho/\rho_0)-1$. The EOS parameters, Γ and S are derived from fitting the empirical Hugoniot generated from SESAME data. The generated Hugoniot is valid up to 40 GPa corresponding to the particle velocity of approx. 5 km/s; thus we may safely employ the EOS with these parameters. We use Γ =0.62 and S=1.46.

The limestone is modeled as a von Mises elastic-plastic material with a pressure-dependent yield surface:

$$Y=Y_m-\left(Y_m-Y_0\right)\exp\left[-\alpha P/\left(Y_m-Y_0\right)\right]$$

where Y is the dynamic yield strength, Y_0 and Y_m are zero-pressure and high-pressure yield strengths respectively, and α is a material-specific parameter. For limestone, Y_0=2.0 MPa, Y_m=1000 MPa and α=0.5. A damage model for limestone is also incorporated. The limestone particles are damaged and rendered unable to take stress, although retain inertia, if the pressure exceeds +60 MPa..

The Littlefield model does not take into account certain features of the geologic materials such as porosity and dilatancy upon failure. However, it captures the dominant features of the cratering such as crater dimensions [11,12].

SIMULATIONS

SPH simulations for the impact of ogive-nosed steel projectiles on thick limestone targets are performed for impact velocities between ~450 m/s and ~1000 m/s. The projectile has length-to-diameter ratio of 10 and the radius is 7.1 mm. The targets are thick limestone blocks of lateral dimension 51 cm by 51 cm for smaller velocities and 101 cm by 101 cm for larger velocities. The initial inter-particle spacing of the SPH particles sets the spatial resolution of the simulation. Simulation are repeated at various resolutions at each strike velocity. Various combinations of inter-particle spacing in projectile (d_P) and the target (d_T) have been tried out. The values of the final depth of penetration (P_{SPH}) as obtained from the SPH runs are given out in Table.1 for various (d_T ,d_P/d_T)

An initial configuration showing the particle placement can be seen in Fig.1.

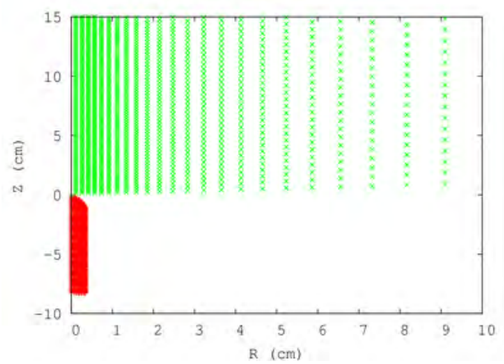
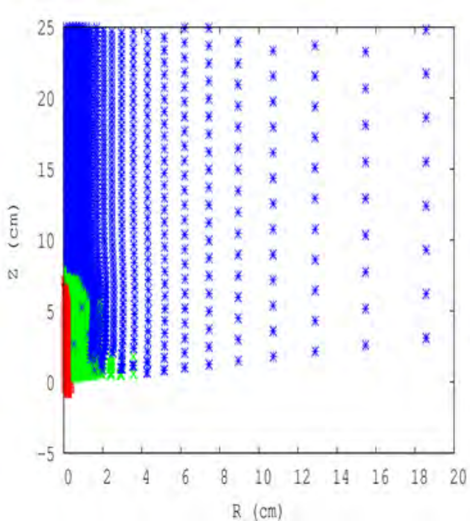


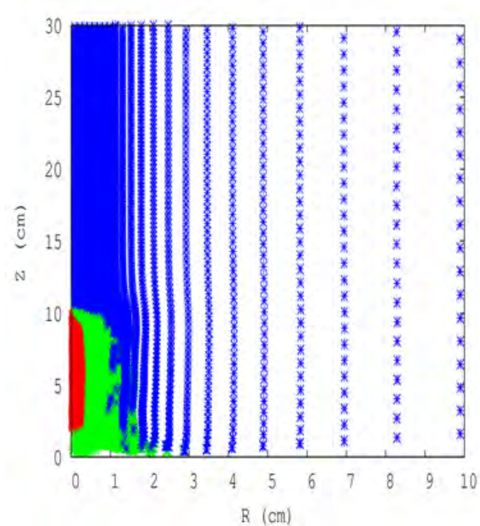
Figure.1 Geometry and the initial particle placement for the impact on the limestone target. The impact is along the Z-axis. The target particles are more spaced as we move away from the axis of impact. Shown is the configuration in R-Z coordinates. Red indicates projectile particles while target particles. are green.

V_s (m/s)	P_{EXP} (cm)	d_T (cm)	d_P/d_T	P_{SPH} (cm)
497	6.7	0.33	1.5	5.1
		0.33	2.5	5.7
		0.33	4.5	6.8
		0.22	1.5	6.1
		0.22	2.5	6.1
		0.15	1.5	6.9
		0.15	2.5	7.6
597	10.5	0.33	1.5	6.5
		0.33	2.5	6.8
		0.33	4.5	8.2
		0.22	1.5	7.4
		0.22	2.5	7.5

		0.15	1.5	8.6
		0.15	2.5	9.1
		0.12	1.5	9.7
		0.12	2.5	10.3
787	16.5	0.33	1.5	8.1
		0.33	2.5	8.1
		0.33	4.5	10.1
		0.22	1.5	10.8
		0.22	2.5	9.1
		0.15	1.5	13.2
		0.15	2.5	12.1
		0.12	1.5	14.1
		0.12	2.5	15.6
		0.1	1.5	16.1
		0.1	2.5	16.6
1037	27.1	0.33	1.5	9.5
		0.33	2.5	10.8
		0.33	4.5	12.9
		0.22	1.5	16.3
		0.22	2.5	15.5
		0.15	1.5	21.4
		0.15	2.5	21.2
		0.1	1.5	23.5
		0.1	2.5	24.8

Table 1: The depth of penetration in the SPH simulations with the indicated parameters: δ_t, δ_p being the particle sizes in the target and projectile materials respectively. The impact velocity and the corresponding experimental value of depth of penetration is also given.





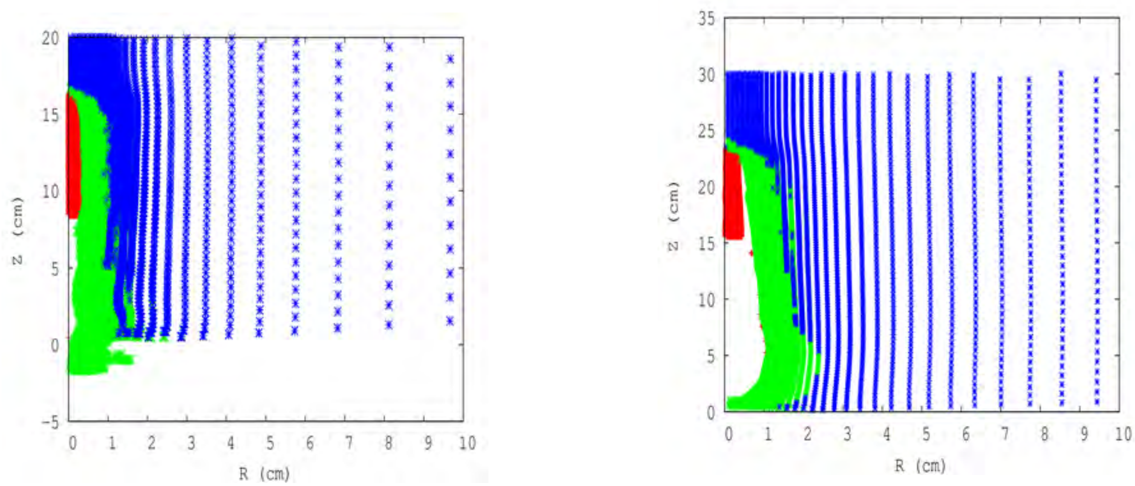


Figure2: The final configurations of the the projectile impacts on limestone target. Left top: impact at 497 m/s; right top: impact at 597 m/s; left bottom: impact at 787 m/s; right bottom: impact at 1037 m/s. The configuration of the projectile + target is shown once the projectile has come to a rest. Red indicates SPH particles belonging to the projectile. Blue indicates undamaged limestone particles and green shows damaged limestone particles

The following observations are gleaned from Table 1.

1. The numerical depth of penetration P_{SPH} is less than experimental depth of penetration P_{EXP} for all impact velocities at lower resolutions.
2. P_{SPH} increases and hence the match P_{EXP} with gets better as the resolution increases.
3. At a constant target resolution d_T, the match of P_{SPH} with P_{EXP} is closer for higher values of ,d_P/d_T , That is, the goodness of the match is better with greater projectile resolution.
4. The resolution required to achieve good match increases with the impact velocity.
5. Close match of P_{SPH} and P_{EXP} is obtained for all strike velocities. This shows that SPH along with the Mie-Gruniesen EOS and geological strength model for the limestone rock represents the projectile impact process into limestone rocks at 400-1000 m/s as well as other competitive models while being simpler in formulation.

Target resistance, calculated using the prescription given in [5], turns out to increase with the strike velocity. At 497 m/s, it is 64 MPa, increasing to 92 MPa at 597 m/s, 160 MPa at 787 m/s and 279 MPa at 1037 m/s impacts. The target resistance given out in [6] can not be directly compared with our values since there it is given only as the average over the velocity range 400 m/s-1500 m/s.

CONCLUSIONS

The experiments of Frew et al [5] on the impact of ogive-nosed hard steel projectiles on thick limestone slabs are modeled with SPH technique using a relatively simple EOS and strength model introduced by Littlefield et al [11]. The SPH reproduces the experimental depth of penetration but higher velocities require progressively higher resolution to achieve a good match. The resulting computational demands are partly mitigated by our finding that all the particles in a given SPH simulation need not have same mass *i.e.* the resolution can be varied locally to a significant extent without loss in accuracy. Thus the required number of SPH particles can be greatly reduced. The target resistance is velocity-dependent and increases with the strike velocity. Thus this relatively simple material model is qualitatively and qualitatively able to reproduce the experimental results.

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