Planetary and Space Science 107 (2015) 3–9

Contents lists available at ScienceDirect

Planetary and Space Science

journal homepage: www.elsevier.com/locate/pss

SPH calculations of asteroid disruptions: The role of pressure dependent failure models

Martin Jutzi

University of Bern, Center for Space and Habitability, Physics Institute, Sidlerstrasse 5, 3012 Bern, Switzerland

ARTICLE INFO

Article history:
Received 14 March 2014
Received in revised form
18 September 2014
Accepted 22 September 2014
Available online 5 October 2014

Keywords:
Asteroids
Collisions
Collisional physics

ABSTRACT

We present recent improvements of the modeling of the disruption of strength dominated bodies using the Smooth Particle Hydrodynamics (SPH) technique. The improvements include an updated strength model and a friction model, which are successfully tested by a comparison with laboratory experiments. In the modeling of catastrophic disruptions of asteroids, a comparison between old and new strength models shows no significant deviation in the case of targets which are initially non-porous, fully intact and have a homogeneous structure (such as the targets used in the study by Benz and Asphaug, 1999). However, for many cases (e.g. initially partly or fully damaged targets and rubble-pile structures) we find that it is crucial that friction is taken into account and the material has a pressure dependent shear strength. Our investigations of the catastrophic disruption threshold Q_D^* as a function of target properties and target sizes up to a few 100 km show that a fully damaged target modeled without friction has a Q_D^* which is significantly (5–10 times) smaller than in the case where friction is included. When the effect of the energy dissipation due to compaction (pore crushing) is taken into account as well, the targets become even stronger (Q_D^* is increased by a factor of 2–3). On the other hand, cohesion is found to have an negligible effect at large scales and is only important at scales $\lesssim$1 km.

Our results show the relative effects of strength, friction and porosity on the outcome of collisions among small ($\lesssim$1000 km) bodies. These results will be used in a future study to improve existing scaling laws for the outcome of collisions (e.g. Leinhardt and Stewart, 2012).

1. Introduction

Collisions play a fundamental role in the formation and evolution of the planets and the small body populations of the Solar System. Models of the evolution of such populations (e.g. the Asteroid Belt) compute the time dependent size and velocity distributions of the objects as a result of both collisional and dynamical processes. A scaling parameter often used in such numerical models is the critical specific impact energy Q_D^*, which results in the escape of half of the target's mass in a collision. The parameter Q_D^* is called the catastrophic impact energy threshold (also called the dispersion threshold). The specific impact energy is often defined as $Q = 0.5 m_p v_p^2 / M_T$, where m_p, v_p and M_T are the mass and the speed of the projectile and the mass of the target, respectively. The catastrophic disruption threshold Q_D^* is then given by the specific impact energy leading to a largest (reaccumulated) fragment M_{lr} containing 50% of the original target's mass. In recent studies (e.g. Stewart and Leinhardt, 2009; Leinhardt and Stewart, 2012), a more general definition of the specific impact energy was proposed which also takes the mass of the impactor into account:

$$Q_R = \frac{0.5 m_p v_p^2 + 0.5 M_T V_T^2}{M_{tot}} = \frac{0.5 \mu V_i^2}{M_{tot}} \tag{1}$$

where $M_{tot} = m_p + M_T$ and $\mu_i = m_p M_T / M_{tot}$ and V_i is the relative velocity. The corresponding radius R_{C1} is defined as the spherical radius of the combined projectile and target masses at a density of 1 g cm^{-3}. According to this new definition, the catastrophic disruption threshold is then called Q_{RD}^*.

Values of Q_D^* (or Q_{RD}^*) have been estimated using both laboratory and numerical hydrocode experiments (see e.g. Holsapple et al., 2002; Asphaug et al., 2002). For the small body populations, the first suite of numerical calculations aimed at characterizing the catastrophic disruption threshold in both the strength regime and the gravity regime was performed by Benz and Asphaug (1999), who used a smoothed particle hydrodynamics (SPH) code (Benz and Asphaug, 1994, 1995) to simulate the breakup of basalt and icy bodies from centimeters-scale to hundreds of kilometers in diameter. More recently, Leinhardt and Stewart (2009) computed Q_D^* curves using the hydrocode CTH (McGlaun, 1990) to compute the fragmentation phase and the N-body code *pkdgrav* (Richardson et al., 2000)

E-mail address: martin.jutzi@space.unibe.ch

http://dx.doi.org/10.1016/j.pss.2014.09.012
0032-0633/

to compute the subsequent gravitational evolution of the fragments. In this study, the dependency of Q_D^* on the strength of the target was investigated. In a recent study by Jutzi et al. (2010), the effect of target porosity on Q_D^* was investigated using an extended version of the SPH code (Jutzi et al., 2008). In this study, the size and velocity distribution of the fragments was computed as well, using the *pkdgrav* code. Benavidez et al. (2012) performed a study of a large number of collisions among $R_t = 50$ km rubble pile bodies using the original SPH code by Benz and Asphaug (1994, 1995).

A numerical tool which is very suitable and has been often used to study disruptive collisions among rocky bodies in general, and was used in many of the above-mentioned asteroid disruption studies, is based on the SPH method. Over the last decades, the basic method has been extended by implementing additional physics (e.g. Benz and Asphaug, 1994, 1995; Jutzi et al., 2008, 2009) with the goal to realistically model rocky bodies with various internal structures. In addition to improved constitutive models, models which mimic the complex macroscopic structure of rubble pile-like bodies have been used as well (e.g. Asphaug et al., 1998; Benavidez et al., 2012). Although the SPH models used in planetary sciences have been significantly improved over the last decades, they were still lacking aspects that can be important in some impact regimes. For example, previous SPH strength models used the so-called von Mises yield criterion, which does not describe well the behavior of rocky materials which are known to have a pressure dependent shear strength. Furthermore, fully damaged material was treated as a strengthless 'fluid' in previous models. Finally, while self-gravity is included in the versions of the SPH codes used to model giant collisions, it is often not implemented in the SPH code versions which also include the physics of solid bodies.

In this paper, we present improvements of the SPH technique concerning the modeling of the disruption of strength dominated bodies. These improvements include a pressure dependent Drucker–Prager-like yield criterion, and a friction model for the damaged material. A few test cases are presented. Using the improved models, we then systematically study the effects of various target properties (strength, porosity and friction) on the outcome of a disruptive collision (Q_D^*). In this study, we use targets with a homogeneous internal structure (i.e., it is assumed that the voids or inhomogeneities are sufficiently small that their distribution can be assumed to be uniform and isotropic over the relevant scales). In Section 2, we present our numerical tool and the recent improvements and show two test cases. In Section 3, the catastrophic disruption threshold Q_D^* is investigated as a function of material properties. In Section 4, the results are discussed and future work is indicated.

2. Modeling

2.1. Previous SPH models

Benz and Asphaug (1994, 1995) extended the standard gas dynamics SPH approach to include an elastic–perfectly plastic material description (see, e.g. Libersky and Petschek, 1991) and a model of brittle failure based on the one of Grady and Kipp (1980). In the fracture model, a state variable D (for damage) was introduced which expresses the reduction in strength under tensile loading and which varies between $D=0$ and $D=1$. Damage accumulates when the local tensile strain reached the activation threshold of a flaw. As stress limiter, the von Mises yield criterion was used. Finally the so-called Tillotson equation of state for basalt (Tillotson, 1962) was used to relate the pressure to the density and the internal energy. We refer the reader to the papers by Benz and Asphaug (1994, 1995) for a detailed description of this method. This code was then used for instance by Benz and Asphaug (1999) to make a first complete characterization of Q_D^* for basalt and ice targets at different impact speeds. The same version (in terms of material models) of the SPH code was used by Benavidez et al. (2012) to study collisions among rubble pile asteroids. Jutzi et al. (2008) extended the Benz and Asphaug (1994, 1995) method by implementing a sub-resolution porosity model based on the P-alpha model (Herrmann, 1969; Carroll and Holt, 1972). In this implementation, a distention parameter $\alpha = \rho_s/\rho$ is introduced where ρ is the bulk density of the porous material and ρ_s is the density of the corresponding solid (matrix) material. The distention α is defined as a function of pressure via the so-called crush-curve. It is used in the EOS to compute the pressure as a function of the matrix density. The porosity model was successfully tested by a comparison to laboratory experiments involving porous pumice (Jutzi et al., 2009). The SPH code used by Jutzi et al. (2008) and in the later studies is a parallelized version (Nyffeler, 2004) of the original code by Benz and Asphaug (1994, 1995).

2.2. Recent improvements

In the original implementation of the strength and fracture model by Benz and Asphaug (1994, 1995), the pressure independent von Mises yield criterion was used. However, it is known that the shear strength of rocks is pressure dependent (i.e., it increases with increasing confining pressure). A pressure dependent yield criterion often used to deal with rocky materials is the Drucker–Prager yield criterion:

$$\sqrt{J_2} + \alpha_\phi I_1 - k_c = 0 \tag{2}$$

where I_1 is the first invariant of the stress tensor, J_2 is the second invariant of the deviatoric stress tensor α_ϕ, and k_c are the Drucker Prager constants, which are related to Coulomb's material constants (coefficient of friction μ and cohesion Y_0) (see e.g. Bui et al., 2008). For the implementation in our SPH code, we use $\sqrt{J_2}$ as a measure of the stress state, and we define a pressure dependent yield strength Y_i for intact rock following Collins et al. (2004):

$$Y_i = Y_0 + \frac{\mu_i P}{1 + \mu_i P/(Y_M - Y_0)} \tag{3}$$

where Y_0 is the shear strength at $P=0$ and Y_M is the shear strength at $P=\infty$ and μ_i is the coefficient of internal friction. As in the previous model, Y_i is temperature dependent:

$$Y_i \to Y_i\left(1 - \frac{u}{u_{melt}}\right) \tag{4}$$

where u is the specific internal energy and u_{melt} is the specific melting energy.

In the original model by Benz and Asphaug (1994, 1995), fully damaged material was treated as strength-less (fluid). As we shall see in Section 2.3.1, this simplification leads to reasonably accurate results in the case of disruptive collisions between initially intact bodies. However, in many situations it is important to take into account the friction in the modeling of fully damaged (i.e, granular) material. This is certainly the case when we want to study collisions between rubble pile like, granular bodies, or to study the finally shape of a body after an impact, and it is also expected to be important in the cratering regime of impacts. To model fully damaged rock (damage $D=1$), which includes granular material in general, we use a yield strength:

$$Y_d = \mu_d P \tag{5}$$

where μ_d is the coefficient of friction of the damaged material (Collins et al., 2004). Note that Y_d is limited to $Y_d \le Y_i$. In case the modeling starts with an intact or partially damaged material, a smooth transition between the criterions (3) and (5) is used:

$$Y = (D-1)Y_i + DY_d \tag{6}$$

where Y is limited to $Y \le Y_i$.