Penetration of Granular Projectiles into a Water Target

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The penetration of low-speed projectiles into a water target has been studied in the last several years to understand the physics behind the formation and collapse of cavities. In such studies, the projectiles employed were solid bodies or liquid drops. Here we report similar impact experiments using granular projectiles, with the aim to investigate how the morphology of the cavities is determined by the balance between the dynamic pressure exerted by the fluid and the cohesive strength of the impactors. From the results we present and discuss in this manuscript, we speculate on the dynamics of meteorite disintegration in the atmosphere of our planet.

Since the seminal work of Worthington and Cole more than one hundred years ago1, many scientists still aim to understand how the energy of a solid projectile, or the energy of a drop, is transferred into a liquid target2–9. Not only the cavities they form are enthralling, but also their pinch-off and collapse, the jets they produce and the instability of the rims. Altogether, low4, moderate7, or high1,5 Reynolds numbers have been considered in such studies.

This article reports on experimental results on the same subject, but with a distinctive feature: the projectiles we used in our experiments are not solids but granular. We would like to find out if such projectiles either endure the impacts or not. We observe that they do when the cohesive energy that holds them together is larger than the impact energy, and do not otherwise. Depending on the outcome, the morphology of the water cavities and the dynamics of penetration is different. Our study aims to understand not only the reasons for such results but to conceive a possible geophysical implication.

Results

Three different impact events are shown in Fig. 1. Figure 1a shows the evolution of the cavity produced by a projectile with the highest mass \( m = 42 \text{ g} \) and an impact speed of \( v_{\text{imp}} = 6.42 \text{ m/s} \), corresponding to a height \( h = 2.1 \text{ m} \). The cavity is very similar to the one produced by a solid object. Figure 1b depicts the cavity formed by the same projectile but this time for \( v_{\text{imp}} = 8.97 \text{ m/s} \) (\( h = 4.1 \text{ m} \)). Clearly, in this more energetic impact grains suffer detachments due to lateral friction with the fluid. Finally, Fig. 1c shows the impact of a granular projectile with \( m = 31.2 \text{ g} \) and \( v_{\text{imp}} = 10.94 \text{ m/s} \) (\( h = 6.1 \text{ m} \)), where a greater cavity, due to the full pulverization of the projectile, is obtained. A video illustrating the sequence can be found in the supplementary material.

In Figs. 2a–d we show a sequence of the final cavities formed by different projectiles and impact velocities at a distance of penetration of three and a half projectile diameters, \( z = 3.5 \text{ D} \). It is clear that the process of erosion and/or fragmentation changes the cavity morphologies. In Fig. 2e we depict the phase diagram of the cavity shapes in terms of the released height and packing fraction. We can clearly see that there are two regions: the dark and sky blue (triangles), corresponding to the case where the projectiles endure the impacts, and the yellow and red (dots and squares), where they fragment. This diagram prompt us to define a dimensionless number \( C_{c} \) as the ratio of two pressures: the comminution pressure \( P_{c} \) and the dynamic pressure \( P_{d} = (1/2) \rho_{w} v_{\text{imp}}^{2} \), where \( \rho_{w} \) is the density of water. It is beyond the scope of this work to theoretically estimate the pressure needed to comminute the projectiles as a function of their cohesion properties. However, to circumvent this tough problem, we do measure the force needed to crush the projectiles by means of a simple technique: we compress them onto the plate of a balance. From the forces thus obtained, we estimate the comminution pressures, see Method section. When \( C_{c} \approx 1 \) we obtain the black thick line in the phase diagram of Fig. 2e. Thus, when \( C_{c} > 1 \) the cohesive forces dominate over the dynamic pressure and the aggregates don’t fragment. Moreover, they produce cavities similar to those produced by solid projectiles (see Figs. 2a,b). When \( C_{c} < 1 \) fragmentation takes place: the ball deforms during the impact, grains disperse and larger cavities form (Figs. 2c,d).
The dynamic equation that describes the penetration into the water medium after the projectile impacts with an initial velocity \(v_{imp}\) is: \(mg - F_b - F_d = ma\), where \(m\) is the mass of the projectile, \(g\) gravity, \(F_b\) the buoyant force, \(F_d\) the drag force, and \(a\) the acceleration. The depth of the projectile is equal to the cavity depth until the instant \(t_c\), in which the cavity is closed. Therefore, for any instant \(t < t_c\), the depth of the projectile can be expressed as: \(z(t) = \frac{-a_0 t^2}{2} + v_0 t\), where \(a_0\) and \(v_0\) are the deceleration and the initial velocity of immersion.

In Fig. 2f we fit the experimental \(z/D\) vs \(t\) data obtained for solid and granular projectiles of the same diameter \(D\) impacting the water target with a velocity \(v_{imp} = 16.78 \text{ m/s}\). Clearly, there is no fragmentation at all for solid projectiles and the above equation describes the trajectory of these perfectly. In the case of granular projectiles released at low heights and high packing fractions, the fragmentation is small so they behave similarly as the solid ones (see the inset of Fig. 2f, where only the dynamics of the solid and the smallest packing fraction projectiles are shown). But when the impact force exceeds the cohesive forces of the granular projectiles (large heights and low packing fractions), fragmentation occurs, the balls deform, lose the coherence and the penetration dynamics is much slower. In this case, \(z(t)\) strongly differs from the theoretical prediction, see Fig. 2f.

Figure 3a shows the velocity of the cavity fronts (normalized with \(v_0\) which is the velocity of the projectiles at a depth of \(D/3\)) as a function of depth (normalized with the diameter of the balls). These data were obtained by taking the derivatives of \(z/D\) vs \(t\) of Fig. 2f. Clearly, the lower the value of \(\eta\) the larger the decrease of \(v/v_0\) during immersion. Furthermore, Fig. 3b shows the initial immersion velocity of the projectiles as a function of \(1 - \eta\) for different heights, see figure caption for details. When the height is small (squares), all the balls penetrate the fluid with the same \(v_0\) regardless the value of \(\eta\). Therefore, the drag force, which is proportional to \(v_0\) is the same for small heights. However, \(v_0\) decreases notably when they fragment (for small values of \(\eta\) and larger heights), and this is why \(a_0\) is smaller compared to the solid projectile, see inset of Fig. 3a. Note that for the largest height and \(\eta\), \(a_0\) is maximum. A plausible explanation is that after the impact, the fragmentation of the granular projectile is not fully attained so the fragmented body sinks as a unit with an increased cross section. Therefore, the drag is greater. For lower packing fractions, the drag is exerted on the individual grains. In both cases, we follow the front of the cavity.

The volumes of the cavities are the only source of information to provide a quantitative measure of the fragmentation of the projec-
tiles. Since what we see with our fast camera is that the cavities have a parabolic shape, is then rather simple to determine the volume of the displaced fluid. The relation between the area of a parabola and the corresponding paraboloid of revolution is: \( V = \frac{1}{2} \pi \lambda A \), where \( \lambda \) and \( A \) are the width and area of the parabola, respectively. In Fig. 4 we show \( V \) (normalized to the volume of the projectile \( V_{\text{imp}} \)) as a function of \( z \), for two projectiles with masses \( m = 31.2 \) and \( 42 \) g having impact velocities between \( v_{\text{imp}} = 6.42 \) and 16.78 m/s. We include the volume of the cavities produced by solid impactors for equal masses and velocities, as a reference. Surprisingly, regardless the release height, namely, the impact velocity, the solid balls produce cavities with very similar volumes (black symbols), not only during the penetration but even at a depth of 3.5 D (see inset of Fig. 4). For high packings (green) and low impact velocities (squares), the cavities are of similar size than cavities made by solid balls. By increasing the impact velocity, the fragmentation of the granular projectiles takes place and the size of the cavity increases notably. Indeed, for loose projectiles (pink) fragmentation always occurs for the entire range of impact velocities (symbols) and the volume of the cavities is maximum.

**Discussion**

Our results indicate that granular projectiles fully disintegrate when the dynamic force exerted by the fluid is larger than the cohesive force that holds them together. According to the phase diagram shown in Fig. 2e, \( 140 \) kPa is a sufficient pressure for this to occur. Such phenomenon resembles the impact of water drops onto an immiscible liquid target, where fragmentation into a collection of non-coalescing daughter drops has been recently observed 9. However, drops have surface tension and therefore non-coalescing daughter drops are rather few (it is required a very high impact energy to produce small drops in the millions 8). In contrast, a relative small energy suffices to comminute our granular spheres into countless grains, see Method section.

Non-consolidated granular bodies were recently used by us to perform impact cratering experiments on sand, hopefully to learn about geophysical phenomena where graininess is a relevant issue 12–14. Here, based on the results presented in the previous section, we aim to learn about the entrance of a meteor in the atmosphere of our planet considering the above disintegration results.

Since the high-energy entries of large granular meteors into Earth’s atmosphere are rare events, and therefore we cannot witness their endurance or destruction, we carried out low-energy impacts into another type of “atmosphere”: water. Such “atmosphere” is much denser than air. The idea is to compensate the low laboratory energies using, as a target, a medium whose density is six orders of magnitude higher than the density of air at high altitudes. In this way, the low value of \( v_{\text{imp}} \) (in the expression of the dynamic pressure) is compensated by the high value of \( \rho \) (with the result of reaching the same dynamic pressure existing in a geophysical impact). Moreover, the water tank is like a “bubble chamber” where we can spy the impact events.

Figure 4 | Volume of the cavities produced by impactors. (a) \( V/V_{\text{imp}} \) vs \( z/D \) for granular and solid projectiles, see text for details. Inset: Total volumes, normalized also with the volume of the impactors, as a function of impact velocity for various packing fractions.

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**Figure 3 | Dynamics of penetration.** (a) \( V/V_0 \) vs \( z/D \) for a release height of \( h = 14.35 \) m (dots) for different values of \( \eta \) (see color nomenclature in the figure caption of Fig. 2). Inset: \( \eta_i \) (normalized to \( 1-\eta \)). (b) \( V/V_0 \) vs \( 1-\eta \) for different release heights: 2.1 m (squares), 4.1 m (triangles), 6.1 m (rhombus), and 14.35 m (dots). \( V \) is the velocity of the solid balls measured at \( z = D/3 \). Clearly, a substantial loss of impact energy is observed as \( \eta \) decreases. The inset shows how \( \eta_i \) changes with the impact velocity.

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We display two important numbers: the Reynolds (Re) and the comminution number \( C_c \) we defined above. For the impact velocity of 16.78 m/s, \( \text{Re} = 612470 \) (bear in mind that the diameter of the spheres is 3.65 cm and the kinematic viscosity of water is \( 1 \times 10^{-6} \) m²/s) and \( C_c \) according to the phase diagram of Fig. 2, is approximately 0.13.

The same value of Re emerges if we consider a projectile ten times as large (30.74 cm of diameter), falling in the atmosphere of the Earth with a velocity of 17000 m/s at an altitude of 45 km (where the kinematic viscosity up there is \( 0.008533 \) m²/s). Furthermore, in our experiments, at the largest speed, \( P_d \) is 141 KPa. Enough, as we
120 litres of water were poured into a Plexiglas tank with dimensions 60 × 50 × 60 cm. An experiment starts when a granular projectile is released from a height h, measured from the water surface, into this tank. After the impact, the projectile produces a cavity that is filmed at 200 fps with a high speed camera (DRS Lightning RDT Plus). It is varied from 0.1 to 14.30 m, corresponding to impact velocities from 1.4 to 16.78 m/s. The granular projectiles produce well-defined cavities whose shape depends on the packing fraction. We observe either no fragmentation at all, minor erosion, coarse fragmentation, and full pulverization of the projectiles. 120 ml of polyvinyl aluminum and 20 g of an anionic polymer, that together promote flocculation, are used to ensure that the fluid clears out in less than five minutes when the projectiles disintegrate and disperse.

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