

IMPACT CRATERING EXPERIMENTS ONTO HIGHLY POROUS BODIES

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ABSTRACT

Asteroids represent both an opportunity and a risk. Their pristine environment captures the early collision evolution of the solar system; while their inherent ground impact potential could result in the mass extinction of life. Amongst the many possibilities of asteroid deflection, kinematic impactors have been theoretically proven to be a promising technique. However, this is primarily based on modelling rocky, brittle bodies. Little experimental consideration has been made for highly porous bodies. Therefore to advance current mitigation scenarios a series of experiments have been conducted. Under an accelerated reference frame this aimed to assess the impact cratering response of highly porous asteroids. All events were examined relative to the increasing levels of porosity and the impact's resultant morphological profile. This included crater shape and depth, and the ejecta profile. The latter was considered critical in assessing the overall contribution to the momentum enhancement exchange of any kinematic impact event.

INTRODUCTION

Asteroids, the leftover debris from planetary accretion are prime examples of bodies whose structure has been subjected to numerous impacts events; each occurring over extended and varying periods of geologic time. Understanding each collision event(s) is therefore not only fundamental to the long-term development of the solar system, but is vital to potential methods of hazard mitigation and deflection of Near Earth Asteroids. Therefore the modeling of kinematic impacts has been considered by many authors. However, this has mainly addressed the impact response of rocky and brittle bodies ^{[2][3]}. Little experimental data details the surface impact events into highly porous asteroidal bodies ^[10]. Understanding the physical processes of impact excavation and deposition of highly porous bodies remains an important mechanical property. This affects the precise response during any cratering and/or kinematic event ^[1].

Data gathered from the NEAR spacecraft, coupled with ground based radar and meteorite analysis strongly suggests that a large proportion of asteroids are considered to be highly porous. 253 Mathilde, located in the main asteroid belt is the most widely accepted example. Mathilde, shown in Fig 1, has been classified as a C-type asteroid with a mass estimate of 10^{20} kg, and an observed bulk density of 1.35 g/cm^3 ^[1]. The surprisingly low bulk density is associated with an implied internal porosity - compared with the typical densities of carbonaceous chondrite meteorites - to be in the order of 50 % ^[2]. However this value has the potential to reach as high as 75 % with the clustering of objects in the range of 25 to 55 % ^[3]. For comparison asteroid 16 Psyche and 22 Kalliope have an estimated porosity of 70 % ^[3]

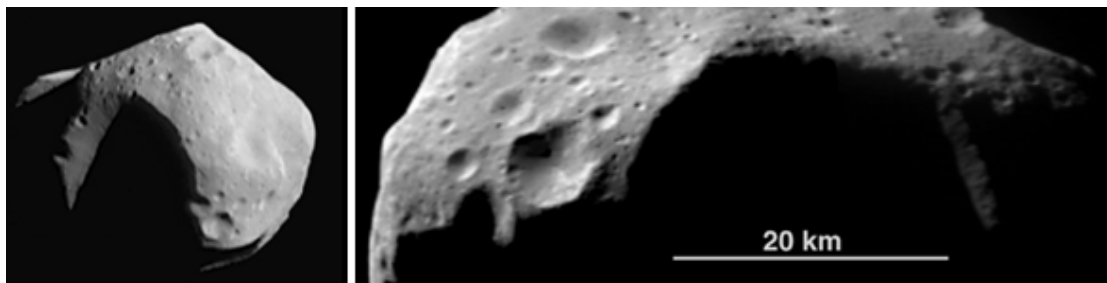


Fig 1: Asteroid 253 Mathilde ^[4]

Therefore gained through the ESA Education initiative - 2010 Spin Your Thesis Campaign - a series of impact cratering experiments were performed that intended to: reproduce, investigate and define the physical conditions of large-scale cratering events onto highly porous asteroids; support the generation of a reliable scaling theory for cratering events; and to provide cratering response data for the validation and advancement of numerical models. Each impact cratering event was assessed as a function of target material composition (i.e. porosity) and projectile density. The response was measured relative to the crater's morphological profile, inherent material characteristics and ejecta distribution. This occurred at increasing and fixed levels of gravitational acceleration. The increasing gravitational acceleration represented an increased length-scale of the simulated asteroid. This is therefore considered to be an analogue of large-scale impact events.

The precise conditions of any impact event(s) will ultimately influence several mission design and evolutionary parameters. This includes: the impact lifetime of the asteroid(s), the energy required for disruption & ejecta retention, the means of resource exploitation and, most importantly, for the deflection and mitigation of Near Earth Asteroids^[18]. Significant advances are therefore required to improve our current understanding of large-scale, highly porous impact events. This also includes the corresponding modeling techniques.

Within this paper the experimental design, conditions of similarly and results are presented. All data has been validated to impacts that occur within the gravity-dominated cratering regime. Data was then compared to the expected effect derived from the numerical scaling laws.

JUSTIFICATION OF A CENTRIFUGE

From the late 1970s the centrifuge has been recognized as a valuable and cost-effective technique for studying a range of lithostatic loading conditions and dynamic responses^{[5] [6] [7] [8] [9]}. The premise is based upon similarity analysis, where an accelerated reference frame is required to connect a sub-scale event to a much larger in-situ event^{[10] [11]}.

Given that a projectile (radius a , density δ , and velocity U) strikes a target material (mass density ρ , strength measure Y , porosity n , etc) under the influence of gravity, g , then the crater's volume can be expressed by the following functional relationship:

$$V = f[\{a, U, \delta\} \{ \rho, Y, n, \} g \dots] \quad (1)$$

Using standard tools of dimensional analysis, this expression can be reduced to^[9]:

$$\frac{\rho V}{m} = f \left[\frac{ga}{U^2}, \frac{Y}{\rho U^2}, \frac{\rho}{\delta}, n, \pi_M \right] \quad (2)$$

Using this function a scaling relationship between a set of non-similar events can be achieved. Variation in the impactor size, gravity, material selection and/or impact velocity can be obtained. This extends the capability of small scale laboratory experiments to model much larger in-situ impact events.

Further reductions in the dimensional analysis can be achieved by considering the material properties of the subscale laboratory experiment to be similar to the in-situ event. All non-dimensional ratios that involve the material properties – n , π - can therefore be ignored. π_M is further constrained by considering the target material's composition to be rate independent. Consequently, under this condition, each impact event is governed by, at most, three non-dimensional parameters^[9]. They have no dependence on position, scale or time, and are given by:

$$\frac{\rho V}{m} = \left[\frac{ga}{U^2}, \frac{Y}{\rho U^2}, \frac{\rho}{\delta}, \right] \quad (3)$$

The entire expression can then be quantified in terms of the crater efficiency, π_v , gravitational affects, π_2 , and surface strength, π_3 . This is given as:

$$\pi_v = \left[\pi_2, \pi_3, \frac{\rho}{\delta}, \right] \quad (4)$$

Impact events are then typically divided into two categories; the strength, π_3 , and the gravity dominated, π_2 , regimes [10][11]. Large-scale gravity dominated events occur when the material strength of the target material can be ignored. Assumptions of zero viscosity can also be defined. Under a gravity dominated event the only length-scale variable is either the projectile's radius and/or the gravity. Either can become sufficiently large. It is this factor, ga that dominates the cratering event, and is therefore very useful for large-size or large-scale gravity problems. Under this condition a small centimeter size scale event can be compared to a naturally occurring in-situ event, where the crater shapes are orders of magnitude larger.

Consequently the impactor radius, a (size scale), density, δ , and velocity, U , (a/U is a time scale) will not affect the crater separately, but must be related by a specific power law combination. This defines a target material with zero strength and viscosity and occurs over various magnitudes of impact size, velocities and gravity. A gradual, strengthless target material, with little or no cohesion is therefore required. Under this condition the impactor is considered to behave as an instantaneous point mass where the effect of the cratering event is considered to be much larger than the impactor. As a result the impact event will again be independent of time and length (size) measurement. The expanding shock wave will therefore originate from a single point source. This is a single measure of both the projectile's kinetic energy and momentum into the target material. All other parameters remain fixed. This is commonly known as the coupling parameter, C and defines the impulsive behavior of the impactor(s). This assumption must there be applied to all aspects of the cratering event and is defined as:

$$C = C[a, U, \delta] \Rightarrow C = aU^\mu \delta^v \quad (5)$$

The exponents μ and v are constants for the given target material. μ depends explicitly on the porosity of the target material. The exact value corresponds to the momentum and energy scaling limits. μ must therefore occur between 1/3 (momentum limit) $\leq \mu \leq 2/3$ (energy limit) and the maximum momentum scaling limit of v is equal to 1/3. These values are based on previous experimental and analytical analysis [9][10][17][5]. For each target material the exact value of μ and v can be determined numerically and/or graphically [10][12]. Therefore, within a centrifuge, relatively small projectiles with a comparatively low impact velocity can simulate a large projectile impacting the in-situ asteroid at various impact velocities. This provides the simulation of large-scale impact events.

Furthermore, under the conditions of similarity, current scaling laws exist that predict the crater's depth, radius and volume. Scaling laws provide a means of extending and extrapolating laboratory scale experiments to much larger events of interest. If the characteristics of the projectile(s), target material and local gravity are known, then the crater's shape and size at any scale can be predicted. Considering point-source approximation within the gravity regime the following relations can be summarized [10].

Crater measure of volume (V):

$$\frac{\rho V}{m} = (n) \left(\frac{ga}{U^2} \right)^{2+\mu} \left(\frac{\rho}{\delta} \right)^{\frac{2+\mu-6v}{2+\mu}} \quad (6)$$

Crater measure of radius (R):

$$R \left(\frac{\rho}{m} \right)^{\frac{1}{3}} = (n) \left(\frac{ga}{U^2} \right)^{\frac{-\mu}{2+\mu}} \left(\frac{\rho}{\delta} \right)^{\frac{2+\mu-6v}{3(2+\mu)}} \quad (7)$$

Crater measure of depth (h)

$$h \left(\frac{\rho}{m} \right)^{\frac{1}{3}} = (n) \left(\frac{ga}{U^2} \right)^{\frac{-\mu}{2+\mu}} \left(\frac{\rho}{\delta} \right)^{\frac{2+\mu-6v}{3(2+\mu)}} \quad (8)$$

These scaling laws enable the geometry and size of a cratering event to be modeled. This depends on the impact size, velocity, local gravity and the material properties (including porosity).

Equally the ejecta profile of each cratering event can also be the subject of numerical scaling laws and the conditions of similarity. The fate of ejecta will always be dependent on the product of acceleration, g , and crater radius, R , (range of

ejecta is a product of gR). Ejecta is therefore comparable to events that result in large craters at low levels of acceleration, and much smaller craters at higher levels of acceleration ^[10]. Consequently an induced acceleration is therefore required to assess the relative ballistic motion of ejecta.

The velocity of the ejected material as it passes through the original target surface at a distance, x , from the impact point can be measured as:

$$v = v[\{a, U, \delta\}\{\rho, Y, g, \}x, n..] \quad (9)$$

Using standard tools of dimensional analysis and the concept of coupling as given in the aforementioned text, the ejecta velocity can be expressed by three non dimensional ratios ^[19]. This defines:

$$\frac{v}{\sqrt{gR}} = F\left(\frac{x}{R}\right), \left(\frac{Y}{\rho g R}\right) \quad (10)$$

For impacts occurring within the gravity regime, this expression can be reduced to:

$$\frac{v}{\sqrt{gR}} = K_1 \left(\frac{x}{R}\right)^{-e_x} \quad (11)$$

K_1 is a constant and e_x is a material dependent exponent of the velocity decay. e_x can be summarized by:

$$e_x = \frac{3 - \alpha}{2\alpha} \quad (12)$$

The theoretical limit of e_x , based on point source approximation is 3 ^[19]. Therefore, through varying the centrifugal acceleration, cratering velocities and/or the physical properties of the impactor(s) & target material, the ultimate affect of large scale impact events can be investigated. This offers an opportunity to conduct comparatively low velocity, large-scale impact cratering events into highly porous asteroid analogue material(s).

EXPERIMENTAL DESIGN

The entire impact experiment was designed to occur within a secure and controllable rectangular cuboid. This formed the test chamber, and ensured that all the impact events were located within a pre-determined volume. To coincide with the gondola's door clearance and available free working space the test chamber's maximum external dimensions were 0.40(W)x0.60(H)x0.60(D) m. This provided a working volume of 0.144 m³. All impacts occurred against a chessboard style backdrop. This provided a visual reference plane for all recorded observations. The experiment set-up is shown in Fig 2:

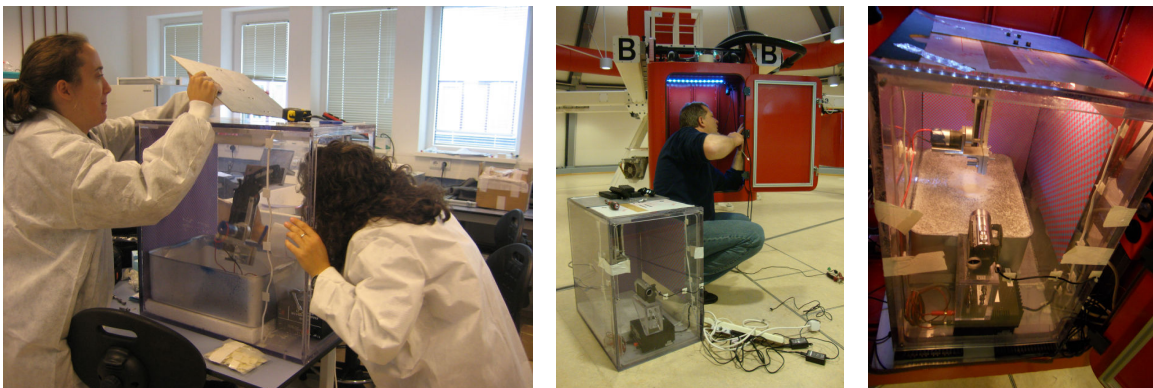


Fig 2: Experiment Set-Up of the Experiment within the Centrifuge

Within the test chamber the projectile release mechanism and the target material were mounted opposite each other, separated by 0.25 m. This permitted perpendicular-only impacts to occur. The release mechanism consisted of an adapted air pistol. This was controlled remotely through a relay system; activation of a small step motor pulled the trigger back. Two low density spherical projectiles were used; either polystyrene (1.07 g/cm³) or derlin (1.42 g/cm³). Each had a diameter of 4.5 mm. This was to simulate impact cratering events within the main asteroid belt. Impact velocities of 403 m/s and 347 m/s for the polystyrene and derlin projectiles respectively were achieved. This was above the bulk wavespeed, c , of the gradual target material.

The target material was housed in a high-sided target container. This provided an impact volume 0.021 m³ and had to correspond with the maximum available floor space within the test chamber. To prevent any adverse boundary and wave reflection affects from influencing the outcome of the impact event the target container should be as large as possible. The asteroid analogue target material was similar, although not identical, to that used in previous impact experiments^{[10][11]}. It consisted of a mixture of quartz sand and expanded perlite. This provides a homogeneously weak, dry, gradual material, with very little cohesion. Under these conditions gravity (i.e. ga/U^2) would be the dominating factor within the cratering event(s).

Three different levels of porosity were tested. Porosity was a product of the target material's manufacturing process; alternating the relative proportions of expanded perlite and quartz sand^{[10][11]}. This variation, in addition to the bulk density and porosity values is given in Table 1. Between the repeated samples a small amount of scatter (less than 5 %) was experienced. This was due to unavoidable variations in the emplacement of the target material into the target container^[10]. Given in Table 1, the measurement of porosity does not specify the form and size distribution of the voids. It therefore assumes that all of the voids are microscopic. The pores are consequently considered to be significantly smaller than the thickness of the projectile's shock front and numerical resolution. Furthermore the pore-spaces are considered to be homogenous, uniform and isotropic throughout the target material.

Table 1: Asteroid Analogue Target Material Mixture

	Mixture (Percentage by Mass)			Dry Density (g/cm ³)	Porosity (%)
	Expanded Perlite	Quartz Sand	Water		
Very High	100	-	-	0.060	97
High	21	27	52	0.389	78
Mid	11	59	30	0.607	68

The values given in Table 1 are considered to be a reasonable simulant for modeling low density, highly porous asteroids such as Mathilde^[10]. Compaction cratering in silicates can only occur if the bulk density is below ~ 2 g/cm³^[11]. Before testing, each target material was dusted with a light spray of black lacquer. This was used to enhance the visual inspection of the cratering event. Care was taken to avoid any cementation during the lacquering application. This followed a pre-existing procedure^{[7][10]}.

Two high speed, high definition digital camcorders (Panasonic HDC-SD60) were mounted inside the test chamber; one in the horizontal plane (perpendicular to the projectile's release) and one in the vertical plane. This provided the in-situ monitoring system over a large field-of-view. A third camcorder was used as a timing aid for the projectile release mechanism. This also enabled monitoring of the target material, assessing any degree of structural degradation (due to vibrations, changes in (de)-acceleration etc) or slumpage. None were observed. Neither the airflow (experiment occurred in ambient air) nor the Coriolis acceleration affected the formation of the crater shape. After each impact the crater's morphological profile was recorded. This included the apparent depth, diameter and volume. The ejecta distribution was also assessed. External illumination was achieved through two 30 W indoor strip lighting fixtures.

RESULTS

The impact data was successfully validated for impacts that occurred within a gravity dominated cratering regime, above the wavespeed of the target material. The conditions of similarity were therefore maintained. For all three samples of target material – mid, high and very high levels of porosity – the material dependent exponents were defined. All were classified with a low μ value. This corresponded to 0.38, 0.36 and 0.34 respectively. μ decreases with increasing porosity. This further defines a highly dissipative material and corresponds to impacts that occur under the conditions of momentum scaling. This also resulted in each crater being geometrically symmetric and stable. Furthermore the final crater shape was not affected by the slumpage, vibrations and/or the (de)-acceleration of the centrifuge. Nor were any grain or rate affects observed. The variation in projectile density had a negligible affect on the

crater shape. However this study was limited to relatively small variations in the projectile density. Future work is required to investigate this parameter.

Mid and high levels of porosity displayed a strong correlation against the numerical scaling relation. Simple bowl shape craters occurred. This permitted the clear identification of the crater's radii and a uniform cavity. At low levels of acceleration (i.e. smaller scale impacts) jets of ejecta were observed. An example is illustrated in Fig 3 (left). The rate of ejected material depends on the mass of the particles, the magnitude of the ejecta velocity and the size of the crater. However, only a small amount of material was contained within these jets. This originated from particles near, or at the centre of the impact. The occurrence of ejecta jets significantly reduced with increasing acceleration (therefore increasing size of the impact event) and porosity. This corresponded to a reduction of ejecta escaping the crater rim.

Under a fixed length-scale (i.e. local acceleration) a small and relatively insignificant amount of ejecta escaped the crater rim. An exemplar is given in Fig 3 (right). This formed a very thin layer on the surface. Interfered by video analysis, the majority of the ejecta were either re-deposited within, or at close proximity to the crater bowl. This corresponded to a decreasing depth of the impact crater. Penetration depth decreased with increasing porosity.



Fig 3: The Generations of Ejecta Jets (left); Reduced Rates of Ejecta Escaping the Crater Rim (Right)

High porous impacts are therefore considered to be dominated by the compaction, as opposed to the large-scale evacuation of ejecta^{[11][14]}. Compaction deforms and compresses much of the target material. The impact site undergoes plastic deformation. Under this condition the target materials' yield strength is exceeded and the outgoing pressure wave permanently compacts, crushes and collapses the pore space. The outgoing pressure wave is therefore larger than the crush pressure of the target material. Plastic deformation consumes much of the impact's initial kinetic energy, reducing its potential to transmit the imposing stress wave and associated ejecta deposits beyond the crater rim^{[15][16]}. Significant work is therefore required to compact the pores of the porous material. This dampens the ejecta velocity profile and distribution. Consequently little remaining energy is available for particle ejection. Each impact becomes more plastic as the local acceleration and porosity increases. Ejecta can not escape far beyond the crater rim, and so is retained within or close to the initial crater. This dominates the impact event, where the reduced density has little influence to otherwise increase the ejecta velocity. The reduction in ejecta velocity corresponds to a reduction in relative range. Only particles that are imparted with a significant impulse will be able to escape the crater rim. Therefore ejecta velocities will always determine the geometrical shape of the ejecta deposits.

However at very high levels of porosity the scaling relation become more uncertain. The diameter of the crater increased with increasing gravity (length-scale). This is in conflict with the numerical scaling laws, which predicts a decreasing crater diameter with increasing length-scale. Other oddities include the formation of a peak within the centre of the crater, a relatively low depth-to-diameter ratio and a decreasing rate of ejecta beyond the crater rim. Illustrated in Fig 4 these are clear characteristics of complex cratering. This is an additional cratering phenomenon, to which the current models of scaling can not be applied. Fig 4 (right) shows the relative height of the impact crater. This was a product of the illumination of each pixel. Nearest neighbor square sampling was used.

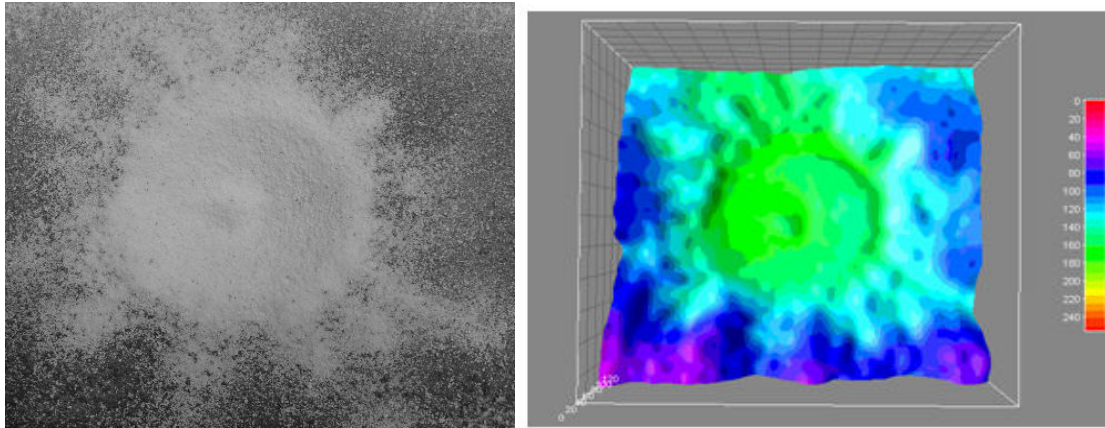


Fig 4: Formation of Complex Cratering

Governed by gravity, the formation of a complex crater is the result of large-scale, extensive failure – inwards slumping and collapse of the crater walls and structural uplift of material – of the transient crater. Before collapse the transient crater is gravitationally unstable. This instability results in late-state modification of the crater’s morphological profile. This results in a wide, shallow floor crater. The latter is due to the infilling of the lower regions. The creation of a complex crater can either be described by Bingham fluid motion or acoustic fluidization^[17]. More study on both theories is warranted. However, it can be summarized that complex cratering is sensitive to the compounded interactions between the affects of shock-waves, material strength, structure – including both density and porosity - and the local gravity.

CONCLUSIONS & FUTURE WORK

The centrifuge provided a viable method of assessing impact cratering events that are scaled analogues of much larger in-situ events. Determining crater formation and how much material is ejected, and at what angle and velocity is critical in the understanding of whether or not kinematic impactors are a plausible technique for the mitigation and deflection of Near Earth Asteroids. It is also vital in understanding the long-term evolution of our solar system. The ultimate outcome, or success, of any impact event depends on many external factors. A highly porous material will react significantly different to a denser, more consolidated material. Compaction and the crushing of the pore space, coupled with the rapid decay of shock dominates the impact mechanism. More work is applied to the compaction and crushing of the material’s pore space, than to the large scale evacuation of material from the impact site. Much more energy is therefore inherently absorbed and quickly dissipated. Comparatively less energy is available to eject material beyond the crater rim; the cratering event becomes more plastic as the porosity increases.

Highly porous bodies that can endure large-scale impact events may therefore not be an ideal candidate for kinematic deflection. Little ejecta would infer that the overall contribution to the momentum enhancement exchange would be low. The contribution decreases with increasing porosity. This additional momentum is critical to amplifying the impulse of any impactor(s); providing enough thrust to deviate the asteroid. The affect of porosity is not only to change the bulk density, but critically the compaction and crushing of pore spaces represents a significant sink of energy. Assessing the degree of porosity for potentially hazardous objects will therefore play a key role in determining the size of the impact required to achieve the necessary orbital change. Porosity has an overwhelming influence on the dynamics of each impact cratering event, and the associated transfer of momentum. This will undoubtedly affect the final impact cratering and/or mitigation results. For example, the use of multiple impactors in quick succession could be used to reduce the bulk volume of the porous body. This could be used to decrease the local porosity of the asteroid. Compaction of the pore space(s) would increase the local density, making the neighboring volume non-porous. A second set of impacts could then be used to induce the required change of momentum. If each impact were co-located occurring at the exact location, separated by a given time period, it is expected that more ejecta would be created by the second (or third etc) impact. Therefore more net momentum would be generated through the ejecta momentum enhancement coefficient. This would make the target body far more amenable to an energetic impact response.

However the impact response is also dependent on the rotational state, efficiency and local geometry of the impact event(s). When two or more bodies collide there is an immense spectrum of possible outcomes. This ranges from the re-adjustment of shape, size, external surfaces and rotational states. Therefore more study is required to address the affect

of porosity relative to impacts at highly oblique angles, variations in surface curvature, local topography and an inhomogeneous profile^[13]. The independent variation in projectile density also requires additional investigation.

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