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INVESTIGATION AND MODELLING OF LARGE SCALE CRATERING EVENTS – LESSONS LEARNT FROM EXPERIMENTAL ANALYSIS

Ms Alison Gibbings
PhD Researcher, Advanced Space Concepts Laboratory, University of Strathclyde, Glasgow, UK
alison.gibbings@strath.ac.uk

Ms Eirini Komninou
PhD Researcher, Advanced Space Concept Laboratory, University of Strathclyde, Glasgow, UK
eirini@komninou@strath.ac.uk

Dr Massimiliano Vasile
Reader, Advanced Space Concepts Laboratory, University of Strathclyde, Glasgow, UK
massimiliano.vasile@strath.ac.uk

ABSTRACT

Initiated as part of the 2010 Spin Your Thesis campaign, a new ESA Education programme, a group from the University of Glasgow Space Advanced Research Team successfully conducted a series of impact cratering experiments under a highly accelerated reference frame. This aimed to: reproduce and define the physical conditions of large-scale cratering events onto highly porous asteroids; provide cratering response data for the validation and advancement of numerical models; and support the generation of a reliable scaling theory for cratering events. Impact cratering is a fundamental process that has shaped and continues to shape the formation and evolution of our solar system and other planetary systems. Although much is known on the impact dynamics of rocky, brittle bodies, such as asteroids, little is known on the physical response of highly porous bodies. Consequently the physical response of porous bodies can not be compared to conventional models. Therefore throughout the experiment campaign, variation into the target material's porosity and projectile density was examined. All in-situ measurements were recorded relative to the crater's morphological profile and ejecta distribution. This occurred under increasing levels of acceleration, thereby validating that the experiment occurred within the crater dominated gravity regime. This paper details the programmatics issues of the initiative, experiences and lessons learnt from the student perspective. From its initial proof-of-concept the Spin Your Thesis campaign provided a solid foundation from the development of an experimental idea, enabling high scientific return and personal development.

I. ACRONYMS

ELGRA	European Low Gravity Research Association
ESA	European Space Agency
ESTEC	Engineering Space Research and Technology Centre
G	Gravity
LDC	Large Diameter Centrifuge
NEAR	Near Earth Asteroid Rendezvous
NEAs	Near Earth Asteroids
SEM	Scanning Electron Microscope

II. INTRODUCTION

Understanding the dynamics of impact cratering is not only critical to understanding the long-term evolution of our solar system, but in examining the effective methods of asteroid mitigation and deflection. While much is known about the physical response of consolidated, rocky, brittle bodies, comparatively little is known about the physical response of highly porous bodies. Consequently the physical response of porous bodies can not be compared to conventional models. There is now a need to update the existing models to account for the diversity within the asteroid population. Data gathered from the NEAR spacecraft, coupled with ground based radar and meteorite analysis strongly suggests that a large proportion of asteroids can be considered to be highly porous. Of the surveyed bodies 43 % have an estimated bulk density of less than 2.0 g/cm^3, and a further 22 % have a bulk density below 1.5 g/cm^3 [1].This implies that much of their structural interior is occupied by void space. This void space, characterised by porosity, can otherwise affect the asteroid's international structure, impact dynamics and cratering response. This will therefore ultimately influence several mission design and evolutionary parameters. This includes: the impact lifetime of the asteroid(s), the energy required for disruption & ejecta retention, and for the deflection and mitigation of Near Earth Asteroids (NEAs) [2]. The latter may also impose the inclusion of additional performance margins. It is therefore with this combined purpose – collision evolution and mitigation - that a series of impact experiments were conducted within the Large Diameter Centrifuge (LDC) facility of the European Space Agency (ESA) Engineering Space Research and Technology Centre (ESTEC). This experiment aimed to: reproduce and the define the physical conditions of large scale cratering events onto highly porous bodies; provide cratering response data for the validation and advancement of numerical models; and support the generation of a reliable scaling theory for cratering events. This was in a combined effort to understand the long-term impact evolution of asteroids and to support the mission capabilities of future mitigation and exploration based activities.

This paper details the application of the centrifuge in providing an experimental platform, and gives an introduction to the team and management structure. An overview of the experimental design and the observed results is also given. This is followed by an assessment of the experiment schedule, lessons learnt and concluding remarks.

THE CENTRIFUGE

From the late 1970s the centrifuge has been recognised as a valuable and cost-effective technique for studying a range of lithostatic loading conditions and dynamical responses [3]-[7]. 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. It also preserves the flexibility, repeatability and diversity of investigating the influence of various impact events. This includes the local environment, geometry, projectile(s) and target material(s).

Initial centrifuge experiments investigated the response of explosive cratering on dry sand and clay. The main emphasis was to determine the extent of which the depth-of-burial influenced the cratering response [5][6][8]. This was followed by hypervelocity impact events onto sand (dry and wet), followed by a composite mixture [9][10]. These experiments provided a good insight into the current understanding of the scaling relation of impact mechanics. This is applicable over several orders of magnitude in crater size. However, the influence of porosity is still not fully understood. Centrifuge experiments therefore provide a means to further derive and rigorously test the framework of scaling; thereby providing data for the continued development and validation of numerical simulations.

Throughout the experimental campaign variation into target material's porosity and projectile density was examined. This was relative to the crater formation, ejecta profile and material characteristics. Data recorded the crater shape (diameter, depth, volume) and ejecta distribution (shape, spread, composition). Each impact event was repeated under increasing levels of acceleration. This was initially performed to validate the cratering response and experimental conditions – similarly analysis - within the centrifuge. Following validation, impact cratering tests were performed under fixed levels of acceleration. A maximum operating level, in accordance to the LDC requirements of twenty times the force of gravity (20G) was used throughout [13].

THE TEAM

Support was provided by the University of Glasgow Aerospace Engineering department, and the team consisted primarily of two PhD students and two undergraduate Earth science students. Activities were led by Alison Gibbings; a PhD research student whose research is focused on the experimental and numerical modelling of asteroid deflection technique. The collected and subsequently analysed data from the 2010 Spin Your Thesis campaign formed the experimental bases of her PhD thesis. Ms Gibbings' main responsibilities before the experimental campaign included the initial proposal and design of the experiment, procurement, scheduling and testing of the hardware. It was a critical responsibility to ensure that the design of the experiment produced scientifically viable results. Eirini Komninou is also a PhD research student within the Space Advanced Research Team. Her research focuses on optimal multidisciplinary small-scale satellite design; developing tools and methodologies based on bio-inspired techniques. Such tools will lead to solving complex combinatorial problems such as optimal satellite design both on a subsystem and system level. She was pivotal to the success of the experimental campaign; offering her services during the integration & test phase, during the experiment campaign and for the initial analysis and image processing of the collected data. The two Earth science students assisted in the manufacturing and characterisation of the asteroid analogue target material.

The main endorsing professor from the University of Glasgow was Dr Massimiliano Vasile. He is a reader within the Advanced Concept Laboratory and the supervisor for both Ms Gibbings and Ms Komninou. Dr Vasile successfully sourced additional funds for the project, ensured that the project was on schedule and interfaced with the University. Support and advice was also given during the data analysis phases of the project. Additional resources from the University were given to support the project; assisting in its overall scientific return. This included initial characterisation of the target material through centrifugal, static, and compressive testing. These activities were performed within the Earth Science and Civil Engineering departments of the University.

The ESA assigned European Low Gravity Research Association (ELGRA) mentor was Dr Willy Benz, from the University of Bern, Switzerland. He provided invaluable advice in developing the experimental design, test schedule and numerical simulations of the impact cratering events. The latter was also supported by Dr Martin Jutzi, also from the University of Bern, Switzerland. Continued technical support was offered by Dr. Kevin Housen. This included a detailed insight into the initial scaling laws, the derived similarity requirement and target material selection.

The manufacture of the experiment was largely conducted by QD Plastics Ltd. This was in partnership with the University of Glasgow. QD Plastics Ltd built the experiment chamber and mounting interfaces for the cameras, target material and lighting. BlastTech Ltd provided the projectile release mechanism. Donations of expanded perlite – a composite part of the target material - were given by William Sinclair Holdings Plc.

MANAGEMENT DESIGN PROCESS

Throughout the project's development, leading to delivery and execution of the experimental campaign the flow and control of information became paramount. The development of the experiment was communicated to the ESA Education office and LDC staff members through the iterative updates of the 2010 Spin Your Thesis Experiment Report. This detailed the background to the project, experiment design, and proposed procedure. It was later updated to include the results, discussions, conclusions and area of the future work. Following submission specific feedback was given and areas of potential concern highlighted. This iterative process ultimately improved the development and overall robustness of the experiment design. It was critical that the proposed experiment's adhered to the LDC test environment and associated requirements.

Before manufacture, two internal University-based reviews occurred. This included a preliminary design review and a critical design review; the latter included external reviewers from QD Plastics Ltd. The designs were constantly compared to the original scientific objectivities, environmental constraints (size and mass restrictions), and budgetary issues.

THE EXPERIMENT

The experiment comprised of four main elements. This, as illustrated in Figure 1 included the test chamber, the target material, the projectile(s) and the projectile firing mechanism. Due to budgetary constraints, the design maximised the use of commercially available 'Off-The-Shelf' components.

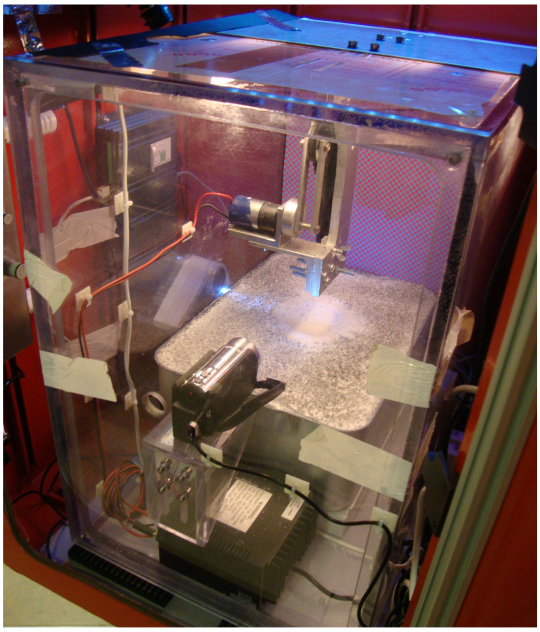

Figure 1: The Impact Cratering Experiment within the Centrifuge at ESA/ESTEC

The entire impact experiment occurred within a secure and controllable regular volume of the test chamber. This ensured that all impact events occurred within a pre-determined volume. All impact events occurred against a chessboard backdrop. This provided a visual reference frame for all observations. Perpendicular impacts into the target material – a composite mixture of expanded perlite and sand – were achieved through a dedicated release mechanism. This was provided by an adapted air pistol and provided impact velocities above the wavespeed of the target material. Velocities of 403 m/s for the polystyrene projectile and 347 m/s for the derline projectile were achieved. The release of each projectile was controlled remotely through a relay system; activation of a small step motor pulled the trigger back. The intended placement of each impact event was achieved through the precise alignment of the firing mechanism. Ideally the impact velocities should be as large as possible.

Two high speed, high resolution cameras (Panasonic HDC-SD60) recorded the impact response. A third camera was used as a timing aid to assist in the release of the projectiles. External lighting was reduced to adhere to the cameras' lighting requirements.

The target material was manufactured from a composite mixture of expanded perlite, quartz sand and water. It is similar, although not identical, to those used in previous impact experiments [10][11]. Varying the relative proportions of the composite parts enabled the porosity values -95 %, 82 % and 67 % - to be varied. This provided a homogeneously weak, dry, gradual material, with very little cohesion. Furthermore, within the accelerated reference frame the target material did not experience separation of its composite parts. This was initially tested within the University of Glasgow Earth and Geological department, and is shown in Figure 2.

Figure 2: Preliminary Testing of the Asteroid Analogue Target Material in the Sigma Centrifuge at the University of Glasgow

Minimal separation would only be accepted if it was less than the diameter of the projectiles. This otherwise defines a length-scale relationship against the impact duration, expected penetration depth of the crater and diameter of the impacting projectile(s). If the separation layer exceeds the penetration depth of the crater then the coupling parameters – momentum and energy – of the impact will be affected. Coupling should occur within a homogenous target material, not a separated medium. Thankfully none of the samples experienced any form of separation within a 20 G environment.

To manufacture each sample the relative mixtures were blended together and then placed within a target container. The samples were then allowed to cure overnight and then baked at 105 ºC. This is the standard temperature for the bake-out of gradual material; avoiding the loss of material and structure. Uniform heating enables the majority of the water content to be removed. During bake-out, the samples were periodically removed and its mass measured. Bake-out was continued until convergence occured and all the water has been removed. After bake-out each sample was cooled. A long cooling time is used to minimise the creation of any internal thermal stress within the target material.

The target contained consisted of a deep sided aluminium tray and resulted in an impact volume of 0.021 m^3. This corresponded with the maximum available floor space within the test chamber and gondola. Ideally the target container should be as large as possible. This is to prevent any adverse boundary and wave reflection affects from influencing the outcome of crater diameter and general morphological profile.

Also performed within the University of Glasgow Earth and Geological department, the target material's physical characteristics were examined. This was achieved by a Scanning Electron Microscope that assessed the composition and orientation of the grain particles within each sample. Conducted before and after the impact cratering event this enabled the assessment of the crushing and compaction of the pore space, and any evident distortion within the material matrix. Selected samples were additionally preserved by applying an epoxy resin to the impact site. Utmost care was taken to avoid the resin making any morphological changes to the impact site.

Before testing, each sample of target material was covered with a light colour lacquer. This was used to enhance the visual inspection of the cratering event. This followed a pre-existing procedure [5][10].

EXPERIMENT SCHEDULE

During the experimental campaign priority was given to the quality of the measurement(s). All measurements – crater shape and the ejecta distribution - were therefore compared, directly and in-situ, with the predicted modelled outcome. If a strong correlation was shown the experiment was not repeated. If not shown, the test was repeated to a maximum of three times. In this event, less important tests would not have been performed. Improved quality and the overriding creditability of the most significant measured test event were therefore considered critical. The experiment followed an incremental schedule.

Twenty four impact events across two days were planned. Prior to the testing campaign the team was unsure of the scheduling arrangement (including access to the ovens to bake-out the target material) at the LDC and how many impact cratering events could be physically conducted per day. Fortunately 83 % of the planned cratering events could be performed. This slight reduction was the result of four samples of the target material being lost. Two samples were lost during the bake-out processing. This was the result of an over-activated fan. Two more were lost due to the miss-firing of the projectile release mechanism. However, these initial losses were recovered by performing additional testing using the highest – 95 % - porosity samples. These samples consisted of an expanded perlite only mixture where no target material had to be manufactured. A key asset of the experimental campaign was to have an adaptable test schedule and the ongoing support of the ESA Education Office and LDC technical members.

The manufacture of the target material was inherently messy and labour intensive. Dust from the expanded perlite was hard to control. The team made a conscious effort to contain the mess and thoroughly cleaned the facilities of the LDC after use. This should be noted for future activities. Pre-made mixtures of the relative sample mixture should have been made beforehand, where water can be added within a contained unit before it is emplaced within the target container. The amount of expanded perlite was also over estimated. Throughout the preservation process needed for the later SEM analysis, only the 67 % and 82 % porosity samples could be preserved. The lightweight aggregates of the highest porosity samples – expanded perlite only – made it impossible to conserve the samples without imparting changes to its cratered response. Furthermore, because the 95 % porosity sample consisted of very fine particles, the characterisation of the ejecta velocity became increasingly difficult. The fine particles obscured the field of view of the camera that was further limited by one directional observation. Therefore the velocity of the individual fragments could not be measured; only the largest fragments were therefore characterised.

Nevertheless ten impact cratering events into the highest – 95 %– porosity target material were conducted. Eight impact events were performed for the high - 82 % - porosity samples and four impact events for the mid – 67 % - porosity target material. Throughout the testing campaign the experiment and data collection – crater depth, volume etc - had to run simultaneously. This was an expectantly busy and high stress environment. An extra day scheduled after the foreseen centrifuge activity would have provided redundancy in performing the data collection. Despite this the experiment set-up itself worked nominally and provided a wide range of statically viable data points for the validation of current models and scaling laws.

OBSERVED RESULTS

Each impact cratering event provided a geometrically symmetric and stable crater. No slumpage (due to possible vibrations of the centrifuge through (de)-acceleration operations) of the crater was observed. Neither did airflow (experiment occurred within ambient air) not the coriolis acceleration affect the formation of the crater.

For the mid – 67 % - and high – 82 % - porosity samples the impact cratering event resulted in a simple bowl shape crater. The two radii could be easily identified. The rate of ejecta decreased with increasing porosity. This corresponded to an increasing depth. Under the highest porosity conditions – 95 % - the crater displayed characteristics of complex cratering. This included the formation of a central peak, a relative low depth-to-diameter ratio and decreased ejecta from the crater rim. This is shown in Figure 3. Given in Figure 3 depth was inferred as a function of pixel illumination where nearest neighbour square sampling was used throughout.

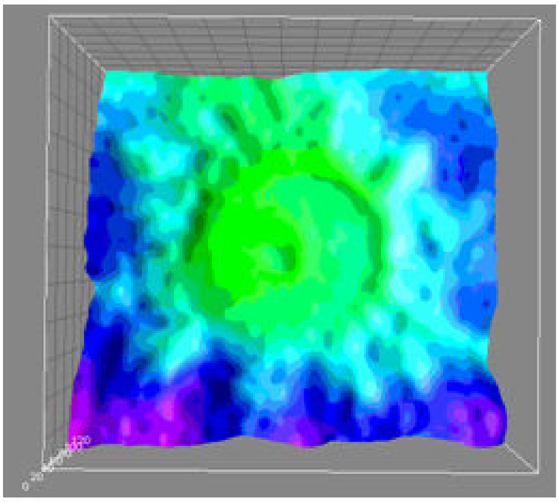

Figure 3: Impact Cratering Response of a Highly Porous Sample. Displays Complex Cratering Response.

Following analysis all data has been compared to the numerical scaling laws and used for validation in the modelling techniques. This assessment is given in [11][12]. This analysis also included assessment relative to the target material's physical characteristics. Compressive strength, cohesion, bulk density, porosity and bulk modulus have been examined in [12]. Variation in the projectile density had a negligible affect on the crater shape.

Similarity the formation of the ejecta blankets was also observed to be geometrically similar. The occurrence and range of the ejecta blankets decreased with increased porosity. The majority of the ejecta were re-deposited within, or in close proximity to the crater bowl. These depositions would have assisted in decreasing the apparent depth and volume of the crater. However, the volume of the ejected material is small. Compared to the rate of compression the ejecta did not refill the crater. Porosity is considered to attenuate the impact shock wave. This dampens the ejecta velocity profile and distribution. Ejecta can therefore not escape far beyond the crater rim and so is retained within or close to the initial crater.

This has a significant affect for the potential mitigation and deflection of asteroids. Additional momentum provided by the ejecta is critical to amplifying the impulse of any impactor(s). Little ejecta would infer that the overall contribution to the momentum ejecta enhancement coefficient would be low. This would decrease with increasing porosity.

PERCEIVED BENEFITS

The centrifuge experiment platform, provided by the 2010 Spin Your Thesis Campaign, provided a viable method of assessing the impact cratering events of highly porous bodies. This permitted the development of an initial idea into a fully capable working experiment that yielded a high scientific return. The processed data formed the basis of a PhD thesis and many other technical papers, journals and conference presentations. This provided a platform for the continued validation of the existing numerical models and analytical scaling theory.

Also all members of the team were greatly enriched by this experience. Designing, building, testing and eventually conducting the experiment varied greatly from how the team had imaged. The team were constantly learning how to effectively manage and delivery a project. Project management, experimental design, problem solving and effective scheduling were key in the development of the project. Post processing data analysis and critical thinking developed the collected data into meaningful science. Operating within a highly technical environment, the team remain deeply indebted for the ongoing support and tuition by the ESTEC staff and technicians at the LDC.

FUTURE WORK

Despite the success of this campaign, further study is required into the field of impact cratering on highly porous bodies. Many other interrelating factors apply. This includes impacts at highly oblique angles, the occurrence of multiple impact, the variations in surface curative and local topography and the affect of an inhomogeneous profile [14]. A greater variation in projectile density could also be considered. Furthermore following successful validation of the experiment's design parameters and similarity more detailed analysis could be performed. Future experiments could see the integration of 'ejecta collector bins' and the effective 'tagging' of the ejecta particles. Due to the restricted development, budgetary and scheduling constraints, these issues were not addressed within the 2010 experimental campaign. However, it is foreseen to be the subject of discussion in future experimental opportunities. The team remain eager and enthusiastic to apply the lessons learnt from the 2010 Spin Your Thesis opportunity to subsequent editions, other students and other future experimental arenas. This will only serve to increase the knowledge and applicability of impact cratering on highly porous bodies; thereby advancing the understanding of numerical scaling laws and validating analytical modelling techniques.

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REFERENCES

[1] Britt D.T, Yeomans, D. Housen, K et al 2002 *Asteroid Density, Porosity and Structure* In: Bottke, Jr, WF (Eds.), Asteroids III, University Of Arizona Press, Tucson, pg 485-500.

[2] Jutzi, M, Michek, P et al "Numerical Simulations of Impacts Involving Porous

Bodes II. Comparison with Laboratory Experiments", *Icarus,* Vol 201, pg 802-813, 2009

[3] Schmidt, R.M, Housen, K.R "Some Recent Advances in the Scaling of Impact and Explosion Cratering", *Internal Journal of Impact Engineering*, Vol 5, pg 543-560, 1987

[4] Schmidt R.M, Holsapple K.A, "Theory and Experiments on Centrifuge Cratering", *Journal of Geophysical Research*, Vol 85, No B1, 1980

[5] Schmidt, R.M., "Meteor Crater: Energy of formation—implications of centrifuge scaling", in: Proc. Lunar Planet. Sci. Conf. 11th, pp. 2099–2128, 1980

[6] Schmidt, R. M "A centrifuge cratering experiment: Development of a Gravity Scaled Yield Parameter", in Impact and Explosion Cratering, edited by D. J. Roddy, R. O. Pepin, and R. B. Merrill, pp. 1261-1278, Pergamon, New York, 1977

[7] Holsapple K, Schmidt R.M "Point Source Solutions and Coupling Parameters in Cratering Mechanics", *Journal of Geophysical Research,* Vol 92, No B7, page 6350-6376, 1987

[8] Johnson, S. W., J. A. Smith, E.G. Franklin, L. K. Moraski, and D. J. Teal *Gravity and atmospheric Pressure Effects on Crater formation in Sand*, J. GeoPhys Research 74(20), 4838-4850, 1969

[9] Melosh, H.T, Ryan E.V, Asphaug, E 1992 *Dynamic Fragmentation in Impact: Hydrocode Simulation of Laboratory Impacts*, Journal of Geophysical Research Vol 97, pg 14735-14759

[10] Housen K.R, Holsapple K 2002 *Impact Cratering On Porous Asteroids*. Academic Press, Icarus 163. Pg 102-119

[11] Gibbings, Vasile *Large Scale Impact Cratering onto Highly Porous Asteroids*, Final Experiment Report, ESA Education Office, Spin Your Thesis 2010, Number 1293

[12] Gibbings, Vasile et al Centrifugal Impact Cratering Experiment, In Press, Icras

[13] ESA 2009 *Experimenter Specification and Users Manual*, LDC-ESUM 21082009

[14] Gibbings , Vasile M 2010 *The Physical and Dynamical Invesitgation of Large Scale Impact Cratering Events on Highly Porous Asteroidal Bodies* Initial Spin Your Thesis Proposal, ESA Education Office