EXPERIMENTAL STUDIES OF EJECTA DYNAMICS: IMPLICATIONS FOR SCALING AND MODELS.

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Introduction

The formation of an impact crater is a continuum of processes that can be divided conceptually into three stages [1]: the *penetration or compression* stage, during which the projectile transfers its momentum and energy into the target material; the *excavation* stage, in which the target material moves in response to the impact-generated shock, with some material being ejected above the original target surface to be redeposited in the ejecta deposit that surrounds the final crater; and the *modification* stage, after which the transient crater is in its final, pre-erosional form.

In this contribution, I will discuss how the excavation stage of crater growth is studied through laboratory experiments. In particular, I will examine current methods for measuring ejecta dynamics which are well-suited for comparison with numerical models and scaling relationships.

Motivation

In many ways, the laboratory is the optimum setting in which to investigate the excavation stage of crater growth because the initial conditions of the event can be controlled and the excavation of the crater can be observed and recorded in real time as the crater grows. Both the momentum and energy deposition from projectile to target is recorded which is particularly relevant in the case of oblique impacts which are the norm on planetary surfaces [2,3]. An understanding of experimental impacts provides “ground-truth” for numerical models, and a baseline for interpreting the complex ejecta deposits observed in the field. Current scaling relationships are based on data from impact experiments and continue to be modified by new experimental discoveries.

The Evolution of Experimental Techniques

Initial studies of ejecta dynamics in the laboratory simply recorded the ejecta curtain as it moved across the target surface allowing for analysis of ejecta curtain angle, morphometry, and expansion speed for vertical and oblique impacts [e.g., 4]. While these data are vital to understanding ejecta deposition, more detailed measurements of individual ejecta particles in flight would be needed to characterize the subsurface flow-field, transfer of energy and momentum, and to constrain numerical models and scaling relationships.

A series of innovative experiments was performed in which the advancing ejecta curtain was physically dissected into discrete masses of ejecta that were filmed as they traveled along ballistic trajectories [5]. However, the effect of the apparatus used to dissect the curtain on the trajectories was unknown and could have been significant [6].

The first non-invasive technique for observing individual ejecta trajectories (during laboratory-scale explosion events) used a high-intensity light source to illuminate a vertical slice of the ejecta curtain perpendicular to a still camera equipped with a rotary shutter [7]. The resultant photographs showed individual ejecta trajectories as dashed lines.

Ejection-Velocity Measurement System (EVMS) – Two decades later, this photographic method was refined and automated for use at the Vertical Impact Facility at Johnson Space Center [8]. With the EVMS system, a laser sheet is projected vertically through the impact point, perpendicular to the target surface, and parallel to the camera plane. This sheet is strobed at a known rate and illuminates ejecta traveling along ballistic trajectories. By extrapolating the ejecta trajectories back to the target surface it became possible to quantify the ejection position, speed, and angle of a number of individual ejecta particles throughout the majority of crater growth (Figure 1).

Three-Dimensional Particle Image Velocimetry (3D PIV) – The 3D PIV technique commonly used to provide quantitative measurements of fluid flow in wind tunnels was modified for use in impact experiments at the NASA Ames Vertical Gun Range [9,10]. A horizontal laser plane is projected parallel to and a few centimeters above the target surface while two CCD cameras, providing left-eye and right-eye views, look down onto the target surface from above. Each camera takes two images in rapid succession at a preset time after impact and the four resultant images are processed in a way that yields three-dimensional velocity vectors for small groups of ejected particles in all directions around the impact point (Figure 2).

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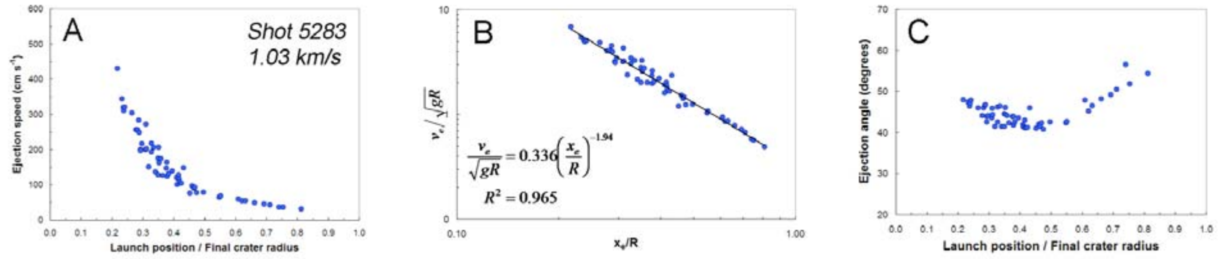

Figure 1: Ejection parameter data obtained using the EVMS system [8] during an impact of a 3.18 mm diameter glass sphere into 0.5-1.0 mm grain size sand at 1.03 km s^{-1} under vacuum conditions. These data are representative of measurements for a range of impact velocities and also for aluminum projectiles. (A) Ejection speed versus scaled crater radius. (B) Scaled ejection speed versus scaled crater radius. The equation represents the fit using standard ejection-speed scaling relationships [6]. (C) Ejection angle versus scaled crater radius. Note the increase in ejection angle during the second half of crater growth.

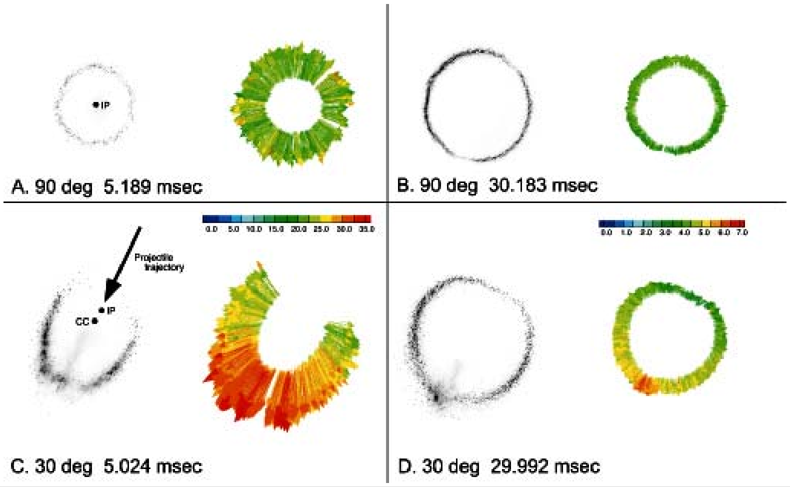

Figure 2: Examples of images and velocity measurements using the 3D PIV system [9,10] during impacts of 6.35 mm diameter aluminum spheres into 0.5 mm grain size sand at velocities near 1.0 km s^{-1} under vacuum conditions. For each pair, the raw image is given on the left and the processed image, showing current ejecta velocities within the laser plane (km s^{-1}), is on the right. (A) and (B) were taken at two different times during vertical impacts with (C) and (D) taken at similar times during 30° impacts. The vertical impacts are azimuthally symmetric while the 30° impacts retain their initial asymmetry as the crater grows.

Implications for Point-Source Scaling

These studies have already yielded intriguing results regarding the excavation stage of impacts. The standard assumption that, while an oblique impact may be asymmetric at early times, it rapidly becomes symmetric and can be approximated as a vertical impact is clearly not the case. Asymmetries in ejection speed and angle during oblique impacts exist up through the first half of crater growth when the majority of material has been excavated from the growing crater [10]. In addition, the subsurface flow-field inferred from the most widely used point-source model, Maxwell's Z Model [11], is not located at a single, stationary point beneath the target surface even for vertical impacts [12,13]. Examining the data using both ejecta-scaling and crater-scaling relationships [6] yields disparate values of the scaling parameter μ for the same series of impacts [14] which may be related to the point-source assumption or potential target material properties [15].

Implications for Numerical Modeling

With the quantitative measurement of ejecta dynamics in the laboratory, the line between experimental observations and numerical models is fading. Direct comparison is now possible between the results obtained from experimental impacts and numerical models performed at experimental scales. A few such studies have already begun [e.g., 16,17,18] but further work is needed. Ideally, numerical models would be able to replicate all of the various observations that are now possible during laboratory experiments. Collaborations could include not only the experiments discussed here, but also those dealing with final crater morphometry, shock-wave propagation [19], crater growth rates [20,21], atmospheric interactions [22], clustered impacts [23], and many more.

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