OBLIQUE IMPACT EJECTA FLOW FIELDS: AN APPLICATION OF MAXWELL'S Z MODEL

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Introduction: Oblique impact ejecta curtains show evidence of an evolving flow field, such as initially asymmetric ejection angles which become more symmetric with time[1]. The subsurface flow field for vertical impacts has been successfully described by Maxwell's Z Model [2, 3], an empirical model developed using observations from explosion craters. Comparisons of predicted Z Model flow fields with impact cratering calculations [4, 5] have shown that, with a few caveats, the Z Model also may be used to describe impact cratering flow fields. Here we utilize a new experimental technique, Three-Dimensional Particle Imaging Velocimetry (3D PIV) [6, 7], to quantitatively detect ejecta particle velocities within experimental ejecta curtains. These evolving ejection velocities during oblique impacts can then be described in terms of changes in the location of the Z Model flow field origin.

At the moment of impact, a series of shock waves produced in the target impose a flow field within the target. Material is pushed downward and outward, away from the flow field origin and eventually may be ejected from the growing cavity. Understanding these subsurface material motions during impact crater formation will shed light on the energy and momentum transfer process from the projectile to the target. Moreover, it can help link the target shock pressure history with the pre-modification crater morphology, such as transient crater dimensions and ejecta deposit morphometry.

Method: One way to investigate the subsurface flow field is by observing individual ejecta particles in flight within the ejecta curtain. Here, 3D PIV images individual particles as they move within the ejecta curtain and quantitatively determines ejecta particle velocities through 360 degrees of azimuth around the impact point. 3D PIV is entirely non-obtrusive and does not affect the motion of the ejecta particles.

3D PIV utilizes sheets of laser light projected horizontally above the target surface. Ejecta particles within the laser plane are illuminated and imaged by two cameras mounted above the impact point. The system calculates three-dimensional particle velocities within this horizontal ejecta curtain cross-section. The experiments presented here were performed at the NASA Ames Vertical Gun Range (AVGR) under vacuum conditions at impact velocities near 1.0 km/s.

Ejecta Flow Behavior: As an example of 3D PIV results, Figure 1 shows a series of horizontal cross-sections of ejecta curtains, taken during vertical (90° impact angles) and 30° impact angle experiments. The left column shows a progression of 90° impacts through time while the right column shows a similar time series for 30° impacts. The very early time (2.08 msec after impact) vertical ejecta curtain cross-section appears non-uniform and patchy, most likely created by fragmentation of the Pyrex projectile. As time progresses, the vertical curtain becomes thin and circular, as expected. In the 30° impacts, the very early time (1.70 msec after impact) ejecta curtain cross-section is highly asymmetric: large amounts of ejecta moving downrange at low angles with no material apparent within the laser plane uprange of the impact

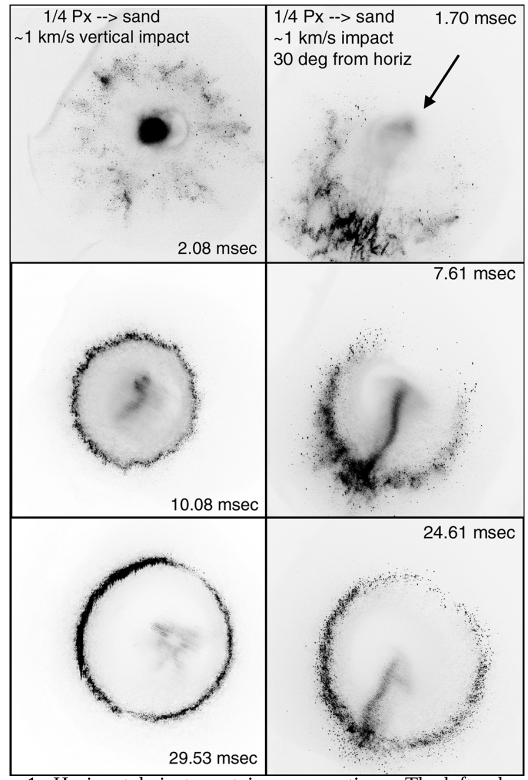

Figure 1. Horizontal ejecta curtain cross-sections. The left column is a series of vertical impacts, while the right column is a time series of oblique impacts at 30° to the horizontal (projectile trajectory shown by the arrow). The time after impact is noted for each image.

point. By about 25 msec after impact, the 30° impact curtain has become much more symmetric and closed uprange.

This ejecta flow behavior can be seen quantitatively using the derived ejection velocities and angles. Figure 2 plots ejection velocity for the very early time vertical impact and 30° impact data as a function of azimuth about the impact point. (Azimuthal angle proceeds counterclockwise from 0° in the direction of the projectile. Thus, 0° is directly uprange of the impact point and 180° is directly downrange.) Ejection velocities for the vertical impact range between 90 and 110 m/s, with scatter reflecting the patchiness of the curtain at this early time. The 30° impact has velocities that range from 90 m/s lateral to the impact point up to 130 m/s directly downrange. There is little material uprange at this early time.

Figure 3 shows the same data plotted with ejection angle versus azimuth. Again the vertical impact shows roughly constant ejection angle with azimuth, ranging between 45° and 55° from horizontal. The 30° impact shows a high degree of asymmetry in ejection angle, with very low ejection angles downrange (nearly 30°) and higher ejection angles (50°) lateral to the impact point. These asymmetries in ejection angle and velocity for the 30° impact illustrate the effect of the projectile's momentum and asymmetric initial shock wave [8] on the cratering flow field.

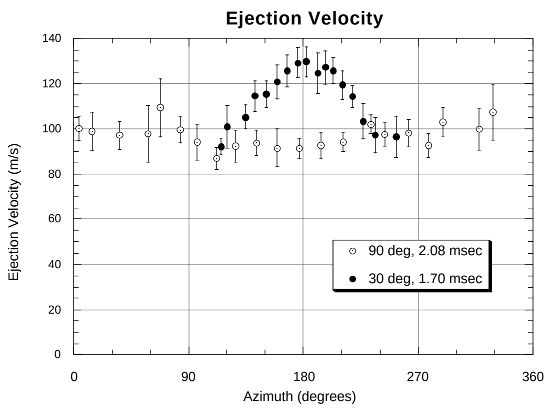

Figure 2. Ejection velocity vs. azimuth data from the earliest time images shown in figure 1. Statistical error bars are shown.

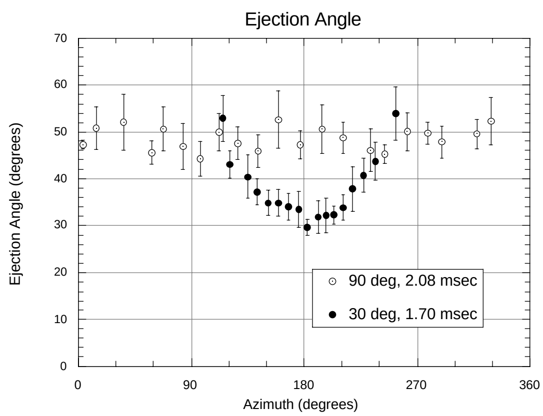

Figure 3. Ejection angle vs. azimuth, as in Figure 2.

Maxwell's Z-Model: Maxwell's Z Model is based on three main assumptions [2]: (1) Subsurface material flow is incompressible, (2) material moves along independent, ballistic trajectories after spallation at the surface plane and (3) the subsurface radial component of velocity is given by $u_R=\alpha(t)/R^Z$. Values of α and Z are usually assumed to be constant and characterize the strength and the shape of the flow field, respectively.

The value of Z characterizes the shape of the cratering flow field [2], i.e., the amount of deflection toward the surface as shown by the subsurface material streamlines. For example, material moves radially away from the flow field origin directly beneath an impact. This flow field shape is represented by Z = 2. Z = 3 characterizes a flow field that ejects material from the surface at an angle of 45^o. A flow field that ejects material at steeper angles is represented by higher Z values. Thus, an average of Z = 3 would characterize the entire flow field for a vertical impact.

Assuming that the explosive charge is resting on the target surface, Maxwell [2] derived the ejection velocity of particles at the surface plane that would be predicted by the Z Model. The horizontal ejection velocity and the vertical ejection velocity are given by:

$$u_H = \alpha / y^Z \qquad \text{and} \qquad u_V = (Z - 2)\, u_H$$

where y is the ejection range, or distance between the point of ejection and the origin of the flow field.

3D PIV determines u_H and u_V directly and therefore can be used to test the assumption that α and Z remain constant for a given impact. Figure 4 plots Maxwell's Z term as a function of azimuth about the impact point for the same data as in Figure 2. In this case, the azimuth axis has been folded over onto itself such that the azimuthal angles to either side of the trajectory range from 0^o (uprange) to 180^o (downrange). At 2.08 msec after a vertical impact, Maxwell's Z term is essentially constant with azimuth, ranging between 3 and 3.5. Maxwell's Z term around the 30^o impact, however, changes with azimuth. Directly downrange, the Z term reaches almost 2.5, whereas lateral to the impact the Z term is nearly 3.5.

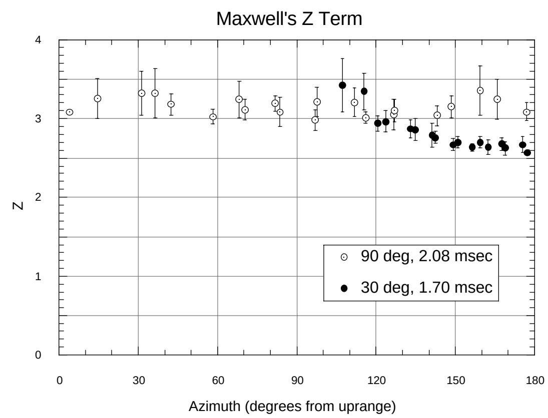

Figure 4. Maxwell's Z term plotted vs. azimuth.

In comparing predicted Z Model flow fields with numerically calculated flow fields for impacts, Thomsen, Austin and others [4, 5] found that the best correlation occurs when the flow field origin is beneath the target surface. In fact, for α and Z to remain essentially constant throughout the impact cratering process, the flow field origin must move deeper within the target over time [5]. Hence, the value of Z in Figure 4 also provides an indication of the depth of the flow field origin for oblique impacts. For example, the downrange flow field for the 30^o impact has a shallower origin (smaller Z value) than the vertical impact. Approaching the lateral and uprange regions, Z increases, reflecting a deeper flow field origin. By recognizing the strength of the Z Model to replicate different regions within oblique ejecta curtains, it will be possible to better describe the cratering process and the zone of coupling. This approach can now be applied to determining the transition from a time-varying flow field origin to a late-stage equivalent point source flow field. This evolution is exposed by ejecta asymmetries for oblique impacts, but is generally masked for vertical impacts.

References: [1] Schultz, P. H. & Anderson R. R., (1996) *GSA Special Paper #302*, p. 397-417. [2] Maxwell, D. E. (1977) in *Impact and Explosion Cratering* (eds., Roddy, D. J. et al.), p. 1003-1008. [3] Orphal, D. L. (1977) in *Impact and Explosion Cratering* (eds., Roddy, D. J. et al.), p. 907-917. [4] Thomsen, J. M. et al. (1979) *PLPSC X*, p. 2741-2756. [5] Austin, M. G. et al. (1980) *PLPSC XI*, p. 2325-2345. [6] Schultz, P. H. et al. (2000) *LPSC XXXI* #1902. [7] Anderson, J. L. B. et al. (2000) *LPSC XXXI* #1749. [8] Dahl, J. D. & Schultz, P. H. (2000) *HVIS 2000*, in press.

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