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Effect of incident angle on crater dimensions with limestone targets

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Impact craters are common on the surface of solid bodies in our Solar system, and the majority of them are formed in oblique impacts. The effects of incident angle on impact cratering are important to derive scaling laws of impact craters and to understand the formation of secondary craters. However, there are not much experimental data of oblique impacts, especially in the strength regime. Recently, high-resolution images of the surface of planets and small-bodies allow us to see small craters in meters (e.g. McEwen et al., 2007). There are many terrestrial craters in the strength regime, such as the Carancas crater (e.g., Tancredi et al. 2009) and the Kamil crater (Folco et al. 2011). In this study, we performed impact experiments into sedimentary rock varying incident angle, to examine the effect of the angle on the crater dimensions.

Two-stage light gas gun placed in ISAS/JAXA was used. The projectiles were nylon spheres of 7 mm in diameter. The targets were blocks of limestone with 15 cm cube. The tensile strength, bulk density, and porosity of the limestone are 4.6 MPa, 2.24 g/cm^3, and ~17%, respectively (Suzuki et al. 2012). The impact velocity is ~2.5 km/s, and the incident angle (theta; measured from the target surface) is varied as 5, 10, 20, 30, 45, 90^o (vertical impact). The impacts are recorded by a high-speed digital video camera. After each shot, we measured the length (the maximum dimension of the crater along the projectile trajectory) and width (the maximum dimension perpendicular to the trajectory) with a digital caliper. We also made 'a digital topographic data' of the crater by means of a digital microscope (KEYENCE, VHX-1000), then obtained the crater volume and depth.

There is a pit in the center of the crater at the vertical impact (theta=90^o), while no noticeable pits are observed in craters of theta $<$ 45^o. The ratios of lengths, widths, depths, and volumes against the values of vertical impacts are proportional to (sin theta)$^{0.54\ +/-\ 0.01}$, (sin theta)$^{0.49\ +/-\ 0.01}$, (sin theta)$^{0.66\ +/-\ 0.02}$, (sin theta)$^{1.61\ +/-\ 0.09}$, respectively. The power of the volume ratio (1.61 +/- 0.09) is similar to those obtained by aluminum impacts into granite (Gault and Wedekind 1978; 1.80 +/- 0.16). In the strength regime, it is known that the crater volumes are proportional to the impact energy (namely, to the square of the impact velocity). Our results are consistent with the concept that crater-scaling relations can adequately accommodate the impact-angle effects by using only the vertical velocity component (Gault and Wedekind 1978; Chapman and Mckinnon 1986).

The ratio between the length and width is constant of 1.11 +/- 0.11 over the range of the incident angle from 90^o to 5^o, while the critical angle where the ratio deviate from unity is ~15^o (Gault and Wedekind 1978) and ~5^o (Burchell and Whitehorn 2003). One reason for this may be that the nylon projectile is easy to break and the top part of the projectile does not shear off (so-called 'impact decapitation' (e.g., Burchell and Whitehorn, 2003)). Without impact decapitation, the length of the crater decreases when theta decreases, in the same manner as the width decreases. However, the crater of 5^o in incident angle has a raised part in the downstream side, suggesting it would be a spall fragment when it's tore off. In the strength regime, spall fragments play a big role in shaping craters. We need a number of shots to minimize the effects of spall fragments.

Averaged diameter is defined as the average of length and width of the crater. The crater depth normalized by the averaged diameter is constant of 0.16 +/- 0.01 in the range of theta from 20^o to 90^o. The normalized depth at theta = 5^o and 10^o is smaller than the value. This trend is due to depths becoming small faster than lengths and widths, and would be because the density of the nylon projectile is about a half of that of limestone target and the projectile is difficult to penetrate the target.