
The principal elements of simple terrestrial impact craters are an uplifted rim surrounding a bowl-shaped cavity, partially filled by allochthonous breccia. Geologic and theoretical considerations suggest that this breccia-fill is derived mainly from the inward slumping of the transient cavity walls and rim [1, 2]. Continuum mechanics calculations have provided insight into the excavation and displacement of target material during cratering [3-5]. They suffer, however, from high computational costs, are critically dependent on input parameters, and in general deal with the early stages of the cratering process. When extended to late times their reliability in predicting observed craterforms is sometimes uncertain [5]. Cratering models based on observational data also have drawbacks. They are qualitative and most of the information is concerned with the late stages of cratering [2]. By combining derivatives of the two approaches, however, it is possible to construct a simple analytical model for bowl-shaped craters. This hybrid technique uses the Maxwell Z-model, devised originally to generalize the flow field in continuum mechanics simulations of near-surface explosions [6], to approximate the cratering flow field [7, 8] and a geometric model to estimate final and transient cavity dimensions. It has been applied to Brent Crater, Ontario (D=3.8 km) and Meteor Crater, Arizona (D=1.2 km), the largest simple craters in crystalline and sedimentary targets, respectively.

A constant Z, EDOZ version of the Z-model, was used, with radial particle velocity \( \dot{R} \) given by \( \dot{R}=\alpha/R^2 \), where \( R \) is radial distance from the effective center of flow (EDOZ), \( \alpha \) is a flow strength parameter and \( Z \) defines the shape of the particle trajectory streamlines. The depth \( d_e \) and volume \( V_e \) of excavation can be estimated by considering the so-called hinge streamline, which intersects the original ground surface at \( R_e \), the estimated radius of the excavated cavity. Particles above the hinge streamline are ejected, while those below are displaced. The value of \( Z \) is \( \sim 3 \) for most of excavation stage [9] and EDOZ is approximated by the leading edge of the projectile at its maximum depth of penetration [10].

Post-excavation, transient cavity modification is modelled by an analytical version of the graphical construction in [10]. Final and transient cavities are assumed to be parabolic in cross-section. The observed depth of the final cavity \( d_{fc} \) below the original ground surface is taken as a measure of \( d_{tc} \). The transient and excavated cavity radii at the original ground surface are taken as equivalent and \( R_{tc}=2 d_{fc}^2 \) [11]. Observational data suggest an outer slope of \( 10^\circ \) for the rim of the final crater. This \( 10^\circ \) slope is extended inwards from the final rim until it intersects the upward continuation of the parabolic transient cavity above the original ground surface. The difference between the final and transient cavity rim-to-rim volumes \( AV \) is considered to be the volume of material which slumps into the crater to become the allochthonous breccia fill. The relative relationships of the geometric and Z-model are shown for Brent in Fig. 1.

Observational data for Brent indicate \( d_{fc}(\sim d_{tc})=1.1 \) km, rim crest radius \( R_{fc}(\sim 1.9 \) km, rim height \( h_{fc} \) is estimated at 200 m, and \( V_{fc} \approx 7.4 \) km\(^3\) [10]. The extension of a \( 10^\circ \) slope for the rim gives an estimated transient cavity rim crest radius \( R_{tc}(\sim 1.65 \) km, \( h_{tc}(\sim 250 \) m, \( V_{tc}(\sim 5.7 \) km\(^3\), and \( AV(\approx 1.7 \) km\(^3\). With 10% bulking [12], \( AV(\approx 1.9 \) km\(^3\), which corresponds well with the observed 2.1 km\(^3\) of breccia fill [10].

The radius of the transient cavity at the original ground surface is \( \sim 1.55 \) km. With this as an estimate of \( R_e \) and EDOZ \( \approx 240 \) m [10], a Z-model with \( Z=2.7 \) gives \( d_e \approx 480 \) m, \( V_e \approx 2.3 \) km\(^3\), and an angle...
of ejection at the hinge of 47°. \( V_e \) is \( \approx 50\% \) of \( V_{tc} \) at the original ground surface (4.2 km\(^3\)). This agrees with previous interpretations [2] and continuum mechanics calculations [13], which suggest that 50\% of the volume of the transient cavity is due to displacement. A value of \( \approx 480 \) m for \( d_e \) corresponds to a model depth to the peak stress contour of \( \approx 23 \) GPa [10]. This is equivalent to the peak pressure values estimated from shock metamorphic features, which are recorded in the "autochthonous" of the final crater floor [14].

The parameters used for Meteor Crater were \( R_{fc} = 578 \) m, \( h_{fc} = 67 \) m, and \( d_{fc} (\approx d_{tc}) = 310 \) m [15, 16]. The geometric model gives \( R_{tc} \) at the original ground surface = 438 m, \( h_{tc} = 82 \) m and \( \Delta V = 0.048 \) km\(^3\). Estimates of the volume of the breccia lens are 0.050 km\(^3\) [16], which agrees well with \( AV \). For \( Z = 2.7 \), \( R_e = 438 \) m and EDOZ \( \approx 60 \) m (a recent estimate for the diameter of the projectile [17]). \( d_e \) is \( \approx 130 \) m and \( V_e \approx 0.051 \) km\(^3\). \( V_e \) is slightly less than previous estimates of 0.063-0.076 km\(^3\) [7, 16]. Again \( V_e \) is \( \approx 50\% \) of \( V_{tc} \) at the original ground surface (0.094 km\(^3\)). A \( d_e \) of 130 m can be accommodated in the observation data, which indicate that 90 < \( d_e < 310 \) m [16]. A previous Z-model of Meteor Crater [7] gives \( d_e \approx 120 \) m, with \( Z = 2.8 \) and \( R_e = 495 \) m. This earlier model does not involve the same form of rim slumping as used here, accounting for the difference in the estimated \( R_e \) values.

It appears that for the two best documented terrestrial simple craters, the combined geometric and Z-model outlined above provides values for crater parameters which are consistent with the available observational data. The level of detail supplied by the model is highly degraded from continuum mechanics calculations. It is, however, rapid, low-cost and provides important first-order information. The model should be further tested for general applicability. Unfortunately, the required detailed observational data are generally lacking from the terrestrial data base on simple craters.