AN ANALYTICAL MODEL TO PREDICT THE EJECTA VELOCITY DISTRIBUTION AND TRANSIENT CRATER RADII K. Kurosawa[1] and S. Takada[2], [1]Planetary Exploration Research Center, Chiba Institute of Technology (2-17-1, Tsudanuma, Narashino, Chiba 275-0016, Japan, E-mail: kosuke.kurosawa@perc.it-chiba.ac.jp), [2]Earthquake Research Institute, The Univ. of Tokyo (1-1-1 Yayoi, Bunkyo-ku, Tokyo 113-0032, Japan).

Introduction: The crater size and ejecta deposits around the host impact crater could constrain the impact environment on a given planetary body throughout its history [e.g., 1]. Thus, the relation between impact conditions and their outcomes has been investigated extensively.

The π-group scaling laws have been constructed based on the late-stage equivalence [2] and dimensional analysis [e.g, 3]. It is widely believed that impact-driven processes during the late stages of impact phenomena can be described by a single quantity called as the coupling parameter $C = R_p v_{imp}{}^{\mu} \rho_p{}^{\nu}$, where R_p, v_{imp}, μ, ρ_p, and ν are the projectile radius, the impact velocity, a velocity-scaling exponent, the projectile density, and a density-scaling exponent, respectively. Using seven variables related to a transient crater diameter D_{tr}, the impact velocity v_{imp}, the projectile diameter D_p, gravitational acceleration g, the target strength Y, projectile density ρ_p, and target density ρ_t, four independent dimensionless parameters (π_D, π_2, π_3, and π_4) can be derived. By combining these parameters with C, the functional relation between a dimensionless diameter π_D and the other variables is obtained. The velocity-scaling exponent μ is one of the most influential parameters.

Since such dimensional analysis does not provide absolute values, including the ejection-velocity distribution and the transient crater radius, the scaling parameters required to determine the impact outcomes should be explored experimentally [e.g., 4]. However, the results from recent laboratory [5] and numerical experiments [6] suggested that the scaling parameter μ itself exhibits a complex dependence on the impact condition and the target property, such as internal friction and the porosity of the target. Since both laboratory and numerical experiments are highly time-consuming and expensive in terms of obtaining new scaling parameters exhaustively, we present an altarnative analytical model to predict the impact outcomes without any conventional scaling laws in this study [7].

Rationale: Our model is constructed based on impact cratering mechanics, which are the Maxwell's Z-model [8] and the concept of the residual velocity [9]. Given that the shapes of the excavation flow and the kinetic energy in a given streamtube are known, we can calculate the ejecta velocity distribution and investigate the cessation of crater growth. The peak pressure distribution is approximately given by the Croft's Γ model [10]. The peak-particle-velocity distribution $u_{p,max}(r)$ can be obtained as a similar form, which is a power-law function with respect to the distance from the impact point r under the point-source approximation, i.e., $u_{p,max}(r) \propto (r/R_p)^{-n}$. The decay exponent n has been measured to be 1.87 by using nuclear explosions [11]. The shocked materials are releaved from their high pressure after rarefaction wave arrival. During pressure release, the absolute magnitudes of particle velocities and their directions are gradually changed, resulting in the formation of an excavation flow. Thus, the residual velocities after the pressure release are the origin of the excavation flow [9]. Given that $u_{p,max}(r)$ is known, the residual-velocity distribution $u_{p,res}(r)$ can be estimated by integrating the Riemann invariant along isentropes [9, 12, 13]. Figure 1 shows a schematic diagram of the situation considered here.

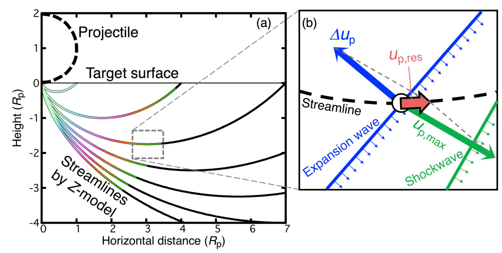

Figure 1. A schematic diagram of the situation considered in the proposed model. (a) The shapes of stream lines calculated by the Z-model. The magnitude of the residual velocity is schematically indicated as different color. (b) Close-up of the area indicated by the rectangle in (a).

If we assume the materials following a shock-release sequence are injected into an excavation flow along a streamline at velocity $u_{p,res}(r)$, we can address the energy balance of kinetic and gravitational potential energies in a given streamtube E_{kin} and E_{grav} as following volume integral in polar coordinates (r, θ),

$$E_{kin}(R) = 2\pi\rho_t \int_{R-\Delta R}^{R} \int_0^{\frac{\pi}{2}} \frac{u_{p,res}^2}{2} r^2 \sin\theta \, dr d\theta \, , \quad (1)$$

$$E_{grav}(R) = 2\pi\rho_t \int_{R-\Delta R}^{R} \int_0^{\frac{\pi}{2}} g z r^2 \sin\theta \, dr d\theta , \quad (2)$$

where R, ΔR, and $z = -r \cos\theta$ are horizontal distance from the impact point along the target surface and a small increment in R, and the height from the pre-impact surface, respectively. If E_{kin} is greater than the sum of E_{grav} at a given R, the materials in the streamtube are ejected. The ejection velocity v_{ej} is estimated from energy conservation as

$$v_{ej} = \sqrt{\frac{2(E_{kin}-E_{grav})}{M_{tube}}}, \qquad (3)$$

where M_{tube} is the mass of the streamtube between $R-\Delta R$ and R. Cessation of the growth of a crater in the gravity-dominated regime occurs when $E_{kin} = E_{grav}$. These conditions provide an absolute value of the transient crater radius R_{tr} for a given impact condition.

Results: Here, we describe the calculated results. Since the space is highly limited. We only show the results in the selected case for relatively-high velocity collision (10 km/s) of a granite sphere onto a flat granite target in this manuscript. The entire results will be appeared in [7].

Ejecta characteristics: The proposed model reproduces the "power-law behavior" in ejecta velocity distribution. For example, we show the relation between the ejection velocity and the ejecta volume as Figure 2. If we chose $Z = 3.5$, the calculated distribution is consistent with the previous laboratory [14] and numerical experiments [15]. The high/low-speed cutoffs are also consistent with the previous studies [15, 16].

Transient crater radius: The transient crater radius R_{tr} in the gravity-dominated regime is obtained by assuming $E_{kin} = E_{grav}$ as follows,

$$R_{tr} \propto R_p^{\frac{Z+1}{Z+2}} g^{\frac{1}{Z+2}} \left[A v_{imp}^{2m} + B v_{imp}^{\frac{Z+1}{n}} \right]^{\frac{1}{Z+2}}, \qquad (6)$$

where A and B are dimensional constants. R_{tr} in our model depends on the exponents n and m, indicating that the nature of the decaying shock propagation and the thermodynamic/hydrodynamic behavior of geological materials during pressure release are included to predict the resulting crater sizes. Figure 3 shows R_{tr} resulting from our model in the form of π-group scaling laws, along with the conventional scaling laws. In this calculation, Z was varied from 2.01 to 4 and v_{imp} was fixed at 10 km s^{-1}. Although results from the proposed model is sensitive to the exponent Z, the resulting π_D values are contained within the two typical scaling lines pertaining to wet and dry sands [4], strongly supporting that our model accurately predicts transient crater radii. The differences in the materials for the conventional scaling laws correspond to the differences in Z in our model.

Discussion and Conclusions: The proposed model is one of the simplest methods to predict the impact outcomes, including the ejecta velocity distribution and the transient crater radii. Thus, the new method could serve as a quick-look tool pertaining to the outcomes under a given impact condition and would significantly aid in the design of future laboratory and numerical experiments to obtain new scaling parameters. An advantage of the new model is that the mechanics of the impact cratering processes, which cannot be addressed by dimensional analysis, are included into the formulation. This allows us to predict the tendencies of the impact outcomes as a function of a range of variables.

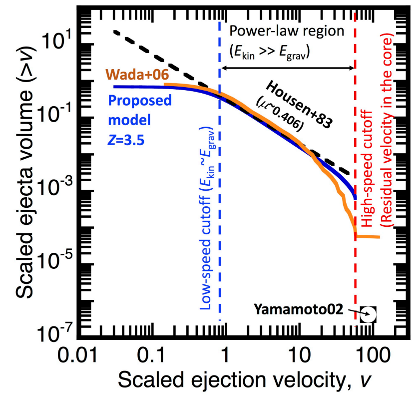

Figure 2. Relation between the cumulative volume of the ejecta launched at a given ejection velocity and the ejection velocity.

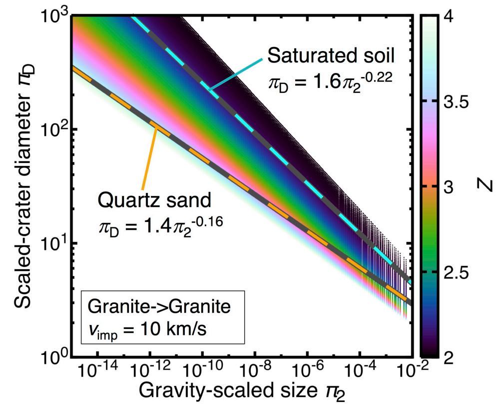

Figure 3. π_D vs π_2. The color indicates the exponent Z.

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