Numerical Analysis of Penetration Dynamics into Regolith using Compressible and Non-Expanding Plastic Gas Model

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To reveal the structure and properties under the surface of a celestial object, impact probes like an impactor, a penetrator and so on are expected to play an important role. For development of such impact probes, the numerical method to simulate the flow of the regolith around a body must be established as a convenient analysis tool. To reduce the computational cost, the fluid dynamics model, rather than the particle-based model, seems promising, because the properties of the regolith are defined using the equation of state with a small number of parameters. However, the flow of the regolith is essentially different from the flow of the conventional compressible fluid from a viewpoint of the irreversibility at compression. Once the regolith is compressed, its density remains higher than that in the initial uncompressed state even after the compression force is removed. As a result, no expansion waves are expected through the impact event in the regolith.

To describe such irreversible nature of the regolith flow, the "Compressible and Non-Expanding Fluid (CNEF)" model, which can be classified into the plastic gas model, has been proposed and its solution method has been developed by the author (Suzuki, K., AIAA Paper 2016-4107, 2016). In the CNEF model, the irreversible compression is described by assuming the different speed of sound in the unloading process from that in the compression process. For simplicity of analysis, the temperature effects are ignored and the pressure is defined as function of the density. By choosing a downward convex function for the irreversible compression process, the hardening effect, by which higher resistance force is generated against compression at higher density, is easily described. When the compression force disappears, the pressure is rapidly relaxed to zero with much higher speed of sound than in the compression process. To uniquely determine the state of the fluid, the internal energy, which is defined as the work done by the compression, was introduced. The numerical scheme to solve the Euler equations for the CNEF model was constructed in the framework of the finite volume method, Godunov method and the Riemann solver. A complete set of the fundamental solutions of the Riemann problem were analytically formulated for the CNE fluid (Suzuki, K., Aerospace Technology Japan, 16(3), 2018).

First, the two-dimensional crater formation problem was solved using the CNEF flow simulation code. The crater and the rim were successfully formed with the surface tracking technique by the VOF method. The compressed regolith with high density remained in the shallow zone under the bottom surface of the crater around the impact point (Suzuki, K., 32ISTS, 2019-k-24, 2019).

In the present study, the flow of the regolith around a flat-tipped cylindrical penetrator body was numerically analyzed at the impact velocity from 100 m/s to 300 m/s, solving the axi-symmetric Euler equations on the moving coordinates fixed at the penetrator. The highly compressed regolith was formed in front of the nose just after the impact. The density of the regolith in front of the nose remained high even after the penetrator was decelerated. The body had to push the high density regolith to continue to penetrate into the regolith. Consequently, the force acting on the penetrator nose became much higher than the impact pressure in the uncompressed regolith. The radius of the crater was larger than the penetrator radius. The cylindrical side wall of the penetrator was detached from the regolith and no force was acting there. The variation of the deceleration, which is in proportion to the pressure at the nose wall,

with the velocity was similar to the variation pattern observed at the experiment of the LUNAR-A penetrator (Suzuki, K. et al., 20ISTS, 96-i-02v, 1996).
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