THE RHEOLOGY OF ACOUSTICALLY FLUIDIZED DEBRIS: EXPERIMENTS AND APPLICATION TO CRATER SLUMPING, H. J. Melosh and P. Goetz, Earth and Space Science, SUNY Stony Brook, Stony Brook, N. Y. 11794

Mechanical studies of the slumping of large extraterrestrial craters have shown that the debris surrounding a crater must be far weaker than predicted by conventional rock mechanics (1,2). The standard coulomb friction model with an internal friction angle in the observed range of 30-45° predicts that no slumping at all occurs, contradicting abundant evidence that large craters do collapse under gravity. The actual dependence of crater morphology on size is well explained if debris surrounding a crater behaves as a Bingham plastic material shortly after the impact (3). The onset of slumping occurs at a differential stress of a few tens of bars (on the terrestrial planets). The debris surrounding the crater flows as a viscous fluid ($\eta = 10^{10}$ to 10^{12} poise) when larger stresses are imposed, thus producing hydrodynamic central peaks and interior rings. The physical basis for the Bingham rheology is provided by the process of acoustic fluidization (4).

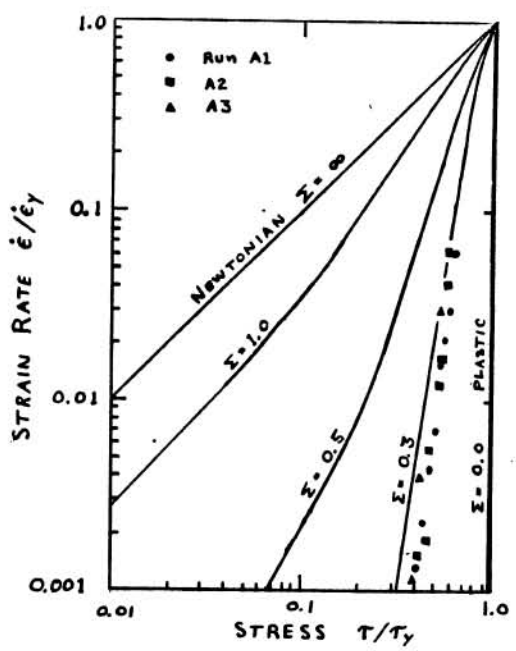
The excavation of a large crater produces an intense incoherent high-frequency sound field in the immediate vicinity of the crater. Acoustic fields of this kind (7 - 17 kHz) have been observed in explosion cratering tests (5). The fluctuating pressure field briefly relieves the overburden pressure in a region comparable in diameter to the wavelength of the acoustic wave, thus allowing the debris to creep under stresses far below the nominal yield stress. Theoretical study of this process shows that the strain rate $\dot{\varepsilon}$ is related to the applied stress τ by

$$\dot{\varepsilon}/\dot{\varepsilon}_o = T\left[2/\mathrm{erfc}[(1-T)/\Sigma] - 1\right]^{-1}$$

where $T = \tau/\tau_{static}$ is the ratio between applied stress and nominal yield stress, $\Sigma = \sigma/\rho g h$ is the ratio between the variance of the pressure fluctuation and overburden pressure, and $\dot{\varepsilon}_o = \tau_{static}/\rho\lambda c$; ρ = debris density, λ = wavelength of acoustic field, c = sound velocity in the debris. This theoretical relation between strain rate and stress is shown as solid lines in the figure. When $\Sigma = \infty$ the flow law is Newtonian, when $\Sigma = 0$ a conventional coulomb law results.

Experiments performed on sand with a range of grain sizes (100-500 μ) show a highly nonlinear relation between stress and strain rate over a range of strain rate from .001 - 10 sec^{-1} at excitation frequencies from 28 to 50 kHz. A portion of the experimental data is plotted in the figure, normalized by the measured static yield stress of 10^6 dyne/cm^2 and $\dot{\varepsilon}_o$ = 11 sec^{-1}. The data clearly fits the theoretical flow law over two orders of magnitude. The best fitting variance of the pressure field is $\Sigma = 0.263$. The data is also well fit by a power law dependence of strain rate upon stress,

$$\dot{\varepsilon}(sec^{-1}) = (2.5 \pm 1.9)\times 10^{-49}\sigma(dyne/cm^2)^{8.3\pm4.5}$$



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At large stresses or strain rates the effective viscosity of the flow approaches the theoretical value $\eta_{eff} = \rho\lambda c$. At low stresses or strain rates the power law rheology produces an apparent yield stress, thus accounting for the phenomenological Bingham plastic flow law. Yielding can be said to begin when the stress becomes large enough to produce "significant" strain on the time scale of crater collapse, $\sqrt{2H/g}$. The value of this yield stress depends upon the acoustic field strength and dominant wavelength, and may thus be quite variable from place to place on the same planet or from planet to planet. The effective yield strength is

$$\frac{\tau_{eff}}{\tau_{static}} = [\lambda c/(\sqrt{2}\,\mu\, H^{3/2}\, g^{1/2})]^{1/n}$$

where H is crater depth, g is surface gravity, μ is the normal coefficient of friction for rock sliding on rock, and n is the power law realting stress to strain rate. The effective yield stress is 20 bars if λ is a few tens of centimeters under lunar conditions when n = 8, as observed in our experiments.

References. (1) Melosh, H.J. in Impact and Explosion Cratering, 1245-1260 (1979); (2) McKinnon, W. B., Proc. Lunar Planet Sci. Conf. 9, 3965-3973 (1978); (3) Melosh, H. J., J. Geophys. Res., in press, 1982; (4) Melosh, H. J., J. Geophys. Res. 84, 7513-7520; (5) Gaffney, E. and Melosh, H. J., J. Geophys. Res., in press, 1982.