The morphology of fresh craters on the moon shows a regular dependence on the crater's size (Howard, 1974). Small fresh craters tend to be bowl shaped, while slump terraces and central peaks appear simultaneously in the 10-30 km size range. Flat hummocky floors characterize somewhat larger craters (30-100 km). Craters larger than 200 km diameter acquire multiple mountain rings.

The transition between bowl shaped craters and craters with slumped rims and central peaks is marked by an abrupt kink in the depth/diameter curve, slumped craters tending to be shallower (Pike, 1974). The depth/diameter ratio of fresh lunar craters is close to 0.2 for all craters up to about 15 km rim to rim diameter. The depth of all craters larger than 15 km diameter lies between 3 and 5 km and is nearly independent of diameter. A small population of unslumped craters with diameters between 15 and 30 km lies on the continuation of the depth/diameter = 0.2 line.

The dependence of the morphology of fresh lunar craters on diameter has long been attributed to gravity induced mass movements (Quaide et al., 1965). Immediately after formation all craters are assumed to have the same depth/diameter ratio of about 0.2. Subsequent collapse of the larger craters produces the kink in the depth/diameter curve, explaining the coincidence of this kink with the appearance of wall slumps. The unslumped craters between 15 and 30 km diameter are accounted for by local variations in the strength of lunar rock and thus of the size at which slumping begins. Central peaks evidently develop as part of the collapse process, since they are correlated with wall slumps.

The present study evaluates the mechanical aspects of this process in more detail. The principal result of the analysis is that rather peculiar strength characteristics are required for the lunar surface rocks if collapse is to occur at all. In order for lunar craters to slump, the rock must fail with very low angles of internal friction (less than a few degrees). The best description of collapse is obtained if the rock fails as a perfectly plastic material, having no internal friction and a shear strength of only 27 bars. Granting these unusual strength characteristics, a comprehensive description of crater morphology versus diameter is obtained. These results strongly suggest that lunar craters actually do fail in a plastic mode; the difficulty comes in understanding how internal friction is eliminated.

The need for low internal friction is easily demonstrated. The average internal slope of a crater with a depth/diameter ratio of 0.2 is only 22°. This is less than the angle of repose of cohesionless rock debris (most such materials have angles of repose in the 35-45° range, see Carson and Kirkby, 1972). Thus even if the crater were produced in cohesionless rock...
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debris, we would not expect major slumping to occur, whatever the crater's diameter might be. This argument still allows a small amount of slumping near the crater rim where slopes locally exceed 35°, but it does not allow the observed large scale slump features. A very large crater may have a diameter of 300 km and a depth of 5 km, corresponding to a depth/diameter ratio of 0.017 and an average internal slope of 2°. For these proportions to have been produced by slumping, an angle of internal friction less than about 2° is required.

The appearance of slump features in lunar craters at about 15 km diameter suggests that a yield strength is exceeded by craters of this size. Presuming negligible internal friction from the preceding arguments, this yield strength is readily estimated. The weight of material excavated from a parabolic crater of diameter D and depth/diameter ratio \( H/D = \lambda \) is given by \( (\pi/6) \rho g H D^3 \), where \( \rho \) is the density of the excavated rock and \( g \) is the acceleration of gravity. If we suppose that this force acts over the surface of a hemisphere enclosing the crater, area \( \pi D^2/2 \), the shear stress \( \tau \) supported by the rock near the crater is

\[
\tau = \frac{\rho g H D^3}{4}
\]

For a 15 km diameter lunar crater this shear stress is about 30 bars, which must be nearly equal to the shear strength of the rock.

Crater modification by gravity thus requires material properties closely approximated by those of a perfectly plastic substance. Standard techniques (Scott, 1963) exist for evaluating the stability of structures in a perfectly plastic medium under conditions of plane strain. These techniques have been modified for axial symmetry and the resulting static stability criteria applied to craters. We shall find that the form of the collapse is governed almost completely by the dimensionless parameter \( (\rho g H)/c \), where \( c \) is the yield strength of the plastic substance. When \( (\rho g H)/c \) is less than 5.5, the crater is stable. For \( (\rho g H)/c \) between 5.5 and about 10 slope failures occur. Material slumps off the crater walls and onto the crater floor. This may be associated with the "swirl textured" floor morphology of craters between 5 and 40 km diameter (Smith and Sanchez, 1973). When \( (\rho g H)/c \) exceeds about 20 failure occurs throughout a volume of rock containing the crater. The crater floor rises vertically as the rim slumps down. This mode of failure may produce well marked central peaks. In all these cases the initial crater depth \( H \) decreases to a final depth \( H_f \) for which \( (\rho g H_f)/c \approx 5.5 \). This constant final depth explains the near independence of crater depth and diameter for slumped craters larger than 15 km and predicts the increasing extent of flat hummocky floors as crater diameter increases.

The accompanying figure illustrates the nature of collapse as a function of \( (\rho g H)/c \) for a variety of depth/diameter ratios \( \lambda \). To a first approximation the collapse mode is independent of \( \lambda \) (this would not be the case if internal friction were present). Also included in the figure are the \( (\rho g H)/c \) values for various lunar and terrestrial craters, where we assume that \( \lambda = 0.2 \) for the fresh crater. The strength \( c = 27 \) bars used in these computations is derived by assuming that the kink in the depth/diameter curve occurs at \( D = 15 \) km, at which diameter \( (\rho g H)/c = 5.5 \). The correspondence between predicted collapse
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Mode and morphology is clear, thus lending support to the idea that crater collapse proceeds by a plastic collapse mechanism.

References