MECHANICS OF EARTH FLOWS

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ABSTRACT: Earth flows are mass movements of fine-grained soils that range from slow flows with velocities on the order of meters or less per year to rapid flows that have velocities as high as several meters per second. Slow earth flows form in deposits of fine-grained plastic clay or silt and move episodically or by sustained, relatively steady movement. Most slow earth flows move primarily by sliding on a basal shear surface, accompanied by internal deformation. Coulomb plastic-flow models may be used to describe the mechanics of slow earth flows. Most rapid earth flows form in highly sensitive clay deposits and usually progress to completion in a matter of minutes to hours by a sequence of smaller failures that spontaneously liquefy and flow out of the source area. Rapid earth flows may be modeled as non-Newtonian fluids.

1. INTRODUCTION

Earth flows are mass movements of fine-grained soils that range from slow earth flows common in plastic, fine-grained soils to relatively rapid and wetter rapid earth flows formed in highly sensitive clay deposits (Sharpe, 1938; Varnes, 1978; Cruden and Varnes, 1996). Earth flows have been recognized as a distinct type of mass movement from at least the early twentieth century; since then, many investigators have studied individual earth flows, their geology, and underlying physical processes (e.g., Keefer and Johnson, 1983; Torrance, 1987; Lefebvre, 1996). Earth flows, as defined in older classifications, such as Sharpe's (1938), cross the divisions of modern landslide classification schemes to include earth flows, earth slides, composite earth slide–earth flows, as well as liquefaction spreads, and certain debris slides (Varnes, 1978; Cruden and Varnes, 1996).

2. SLOW EARTH FLOWS

Slow earth flows are found in temperate and tropical climates around the globe, wherever clay or weathered, clay-bearing rocks occur in combination with moderate slopes and adequate moisture. Thus, earth flows are common in areas of clay-bearing sedimentary rocks and weathered volcanic rocks, as well as some areas of weathered metamorphic and plutonic rocks. Slow earth flows occur in fine-grained soils that consist dominantly of plastic silt or clay, as well as rocky soils that are supported by a plastic silt-clay matrix. Atterberg limits of earth-flow material range widely between individual earth flows, but generally are consistent with moderate to high plasticity. The materials also have low to moderate shear strength and low sensitivity.

Slow earth flows commonly have a teardrop or bulbous shape in map view, a sinusoidal profile, are elongate in the direction of down slope movement and are several times wider than thick (Keefer and Johnson, 1983). The general morphology of an earth flow is sketched in Figure 1.
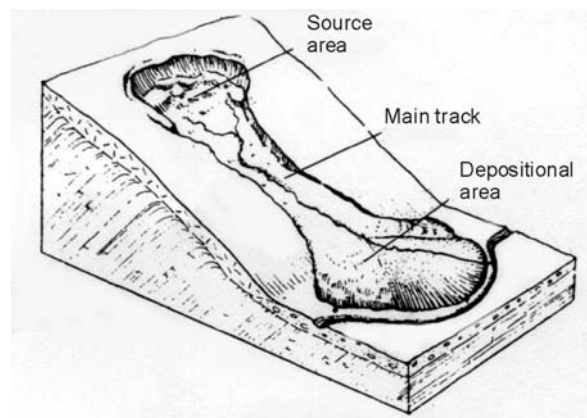

Figure 1. Sketch showing earth flow morphology. After Varnes (1978).

Figure 2A is a view of the active part of the Slumgullion earth flow, Colorado, USA (Varnes and Savage, 1996, Coe et al., 2003), a classic example of a slow earth flow. Its active part is 3.9 km long, covers an area of 1.46 km^2, and has an approximate volume of 20 x 10^6 m^3 (Parise and Guzzi, 1992). Displacement data collected during the past 40 years on the active part of the Slumgullion earth flow by surveying, photogrammetric, field-instrumentation, and GPS methods establish that nearly constant surface velocities vary seasonally from 6-7 m/yr (1.9 x 10^{-7} to 4.5 x 10^{-7} m/s) in the narrowest region of the flow to 1-2 m/yr

$(3.2 \times 10^{-8}$ to 6.3×10^{-8} m/s) in the head and toe regions. Slow earth flows move at rates ranging from 10^{-10} m/s to 10^{-3} m/s (Cruden and Varnes, 1996). In addition, recent work by Coe et al. (2003) shows that variations in surface hydrologic input are closely correlated in time with accelerations of the active earth flow, implying that pore pressures at the basal surface(s) of the earth flow respond quickly to moisture flux at the ground surface of the flow.
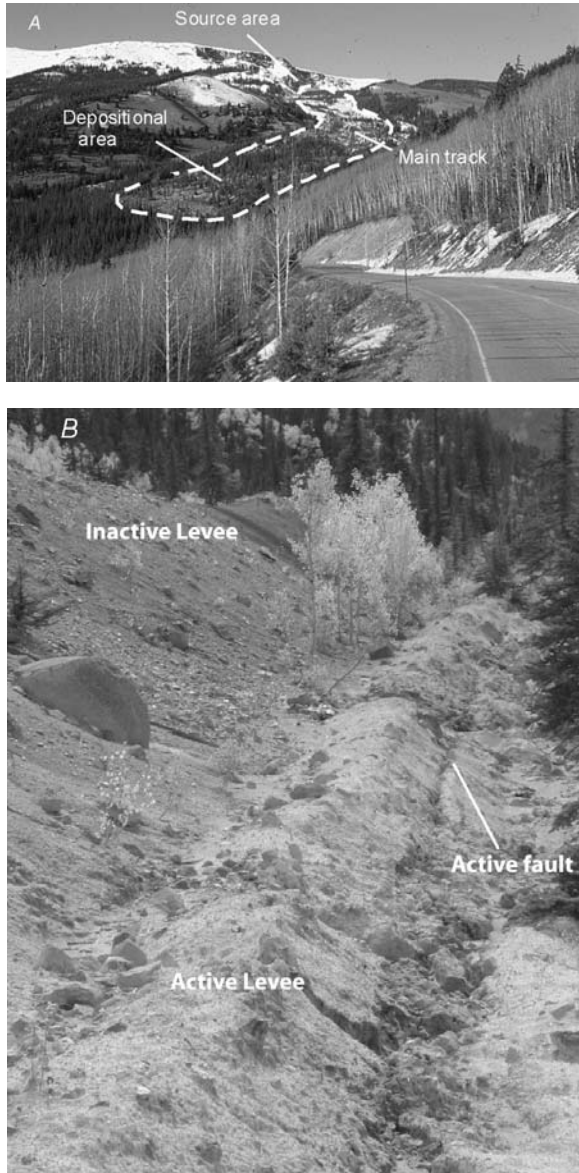

Figure 2. The Slumgullion earth flow *A*. Active part of the Slumgullion earth flow. The earth flow formed as a result of the collapse of hydrothermally altered Tertiary volcanic materials in the source or head area. This flow is about 300 m wide at the head, constricts to its minimum width of 150 m in its main track or neck, and is 450 m wide with steep slopes (average gradient of 18°) up to 40 m high in the depositional or toe area. *B*. Levees along the left flank of the Slumgullion earth flow. The inactive levee is to the left. The currently active levee is to the right and is associated with the active strike-slip fault bounding the left flank of the earth flow. View is down the earth flow.
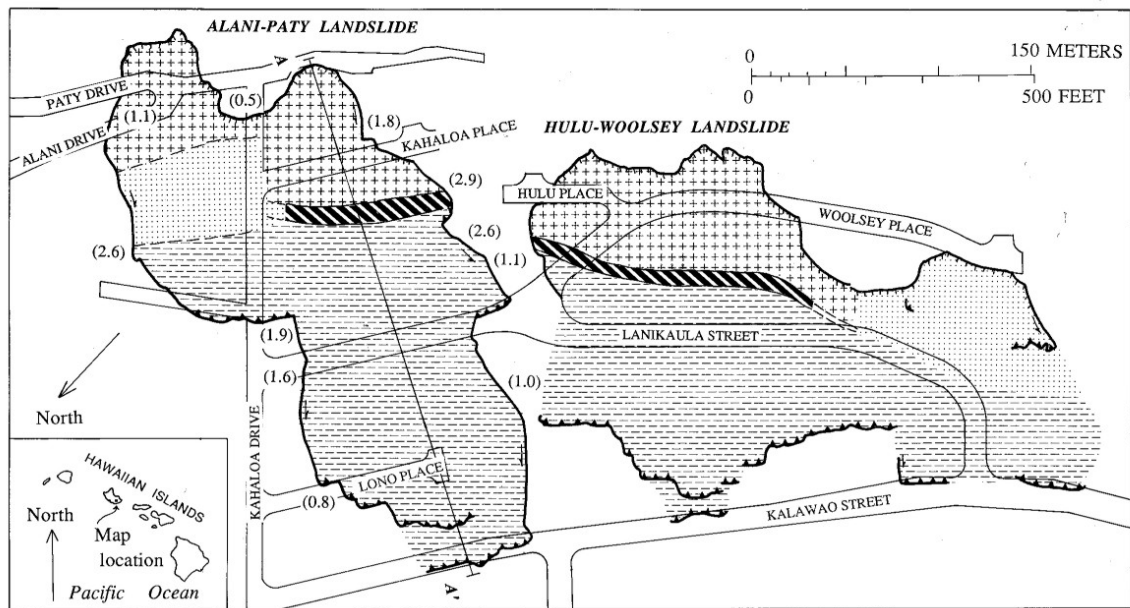
Discrete lateral boundaries, characterized by shear zones that resemble strike-slip faults, are typical of slow earth flows. Depending on the rate of movement and amount of displacement, the lateral boundaries may be manifest as en echelon cracks or as continuous shear zones. Locally, flank ridges form inboard of the lateral boundaries (Fleming and Johnson, 1989). Such ridges, also called levees (Figure 2B), form as the earth-flow mass translates down slope. Several mechanisms appear to operate in the formation of these ridges, including deposition, extrusion of material from the basal slip surface, internal deformation, and basal erosion, (Fleming and Johnson, 1989; Corominas, 1995).

The majority of slow earth flows move primarily by sliding on discrete basal and lateral slip surfaces. Distributed internal shear deformation accounts for a small fraction of the movement and contributes to the appearance of flowing movement. However, numerous measurements and observations have confirmed that sliding is the dominant mode of movement and that internal deformation is consistent with the observed mechanism of sliding (Keefer and Johnson, 1983, Zhang et al., 1991).

In addition to the distributed internal shearing of slow earth flows, a consistent pattern of longitudinal deformation has been documented in a number of active earth flows (Baum and Fleming, 1991; Fleming et al., 1993; Baum et al., 1998; Fleming et al., 1999). Longitudinal stretching commonly occurs in the upslope part of the landslide, with longitudinal shortening in the down slope section. A neutral zone, in which relatively little longitudinal deformation has occurred commonly separates the zone of stretching from the zone of shortening (Figure 3). The pattern of longitudinal deformation appears to be related to the longitudinal stresses and can be used to help constrain the interslice forces in stability analysis of landslides (Baum and Fleming, 1991) and is consistent with a model for earth flow movement developed by Savage and Smith (1986) outlined below.

The mechanics of movement of slow earth flows is well illustrated at the Acquara-Vadoncello earth flow in Senerchia, southern Italy (Wasowski, 1998, Wasowski and Mazzeo, 1998). This earth flow, a reactivation and enlargement of an older, larger earth flow, is approximately 550 m long and up to 140 m in width. Its thicknesses inferred from inclinometer and other field data are 14-17 m in the main scarp and toe areas, and 8-10 m in the main track of the flow.

Subsurface displacements (Figure 4) inferred from borehole inclinometry (Wasowski, 1998) show that internal deformation accounts for a small fraction of the movement and that sliding is the dominant mode of movement of the Acquara-Vadoncello earth flow. Slip surfaces in the head scarp and toe regions of the landslide were reconstructed using surface surveys and subsurface inclinometer observations made during retrogression of the head scarp. Reconstructed slip surfaces in the head-scarp region are shown in Figure 5. Three of the four head-scarp slip surfaces are well constrained by field data. Reconstructed slip surfaces in the toe region are shown in Figure 6. Three of the five slip surfaces in the toe region are well constrained.

EXPLANATION

Symbols

Scarp--Hachures on downdropped side

Flank--Arrows on moving ground

Toe--Sawteeth on moving ground

A ⟨ ⟩ A'   Line of section (Figure 3)

(1.1)   Displacement on landslide boundary, in meters

Patterns of deformation

Ground being stretched

Ground being shortened

Moving ground being neither stretched nor shortened

Undetermined deformation areas of shallow movement superimposed on deeper movement

Figure 3. Map showing patterns of deformation and displacements at perimeters of landslides in the Manoa Valley, Honolulu, Hawaii, USA After Baum and Fleming (1991, Figure 2a).

The configuration of slip surfaces at the Acquara-Vadoncello earth flow is consistent with a model developed by Savage and Smith (1986) that assumes landslides to be Coulomb plastic materials subject to pore pressure. In their model, landslide shear and transverse normal stresses increase linearly with depth and longitudinal stresses increase in an elliptic manner with depth under conditions of compressive or extending flow. The model predicts tensile longitudinal stresses and normal fault scarps at the surface in extending (stretching) flow, and thrust surfaces and thrust fault scarps at the surface in compressive (shortening) flow. This is shown in Figure 7, a sketch of an idealized, long, shallow landslide showing regions of compressive and extending flow. This figure shows the development of slip surfaces as listric normal faults in the region of extending flow near the landslide head (where the ground surface is convex upward) and slip surfaces as listric thrust faults in the region of compressive flow near

the landslide toe (where the ground surface is concave upward) as predicted by the model.

The translational movement of earth flows makes them prone to persistent, long-term instability; thus, earth flows commonly reactivate during periods of above-average precipitation or other disturbance, such as earthquakes, grading or irrigation (Keefer and Johnson, 1983; Skempton et al., 1989). Long-term persistence of slip surfaces at residual strength contributes to earth-flow reactivation (Hutchinson and Bhandari, 1971; Skempton, 1985).
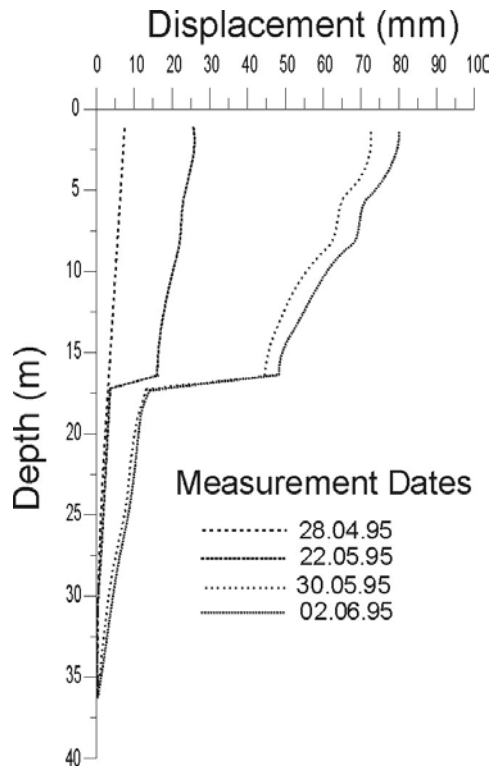
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Figure 4. Results of inclinometer measurements made in borehole I1 in the toe of Acquara-Vadoncello earth flow in Senerchia, southern Italy, in the spring of 1995. Adapted from Wasowski (1998).
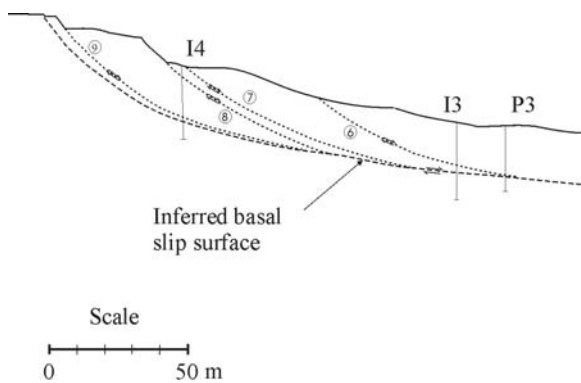

Figure 5. Slip surfaces and the inferred basal slip surface in the head scarp region of the Acquara-Vadoncello earth flow. Boreholes I3, I4, and P3, the well-constrained slip surfaces 6, 8, and 9, the less-well-constrained slip surface 7, and the inferred basal slip surface are shown. No vertical exaggeration. Adapted from Wasowski and Mazzeo (1998).
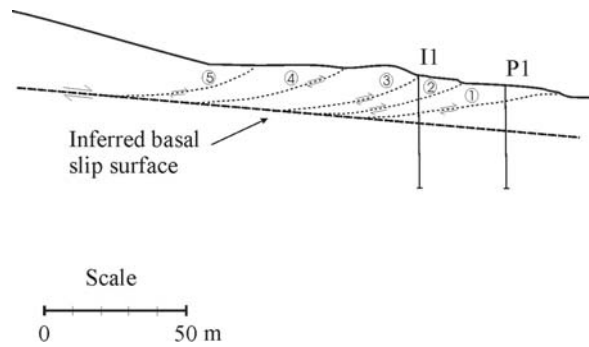

Figure 6. Slip surfaces and the inferred basal slip surface in the toe region of the Acquara-Vadoncello earth flow. Slip surfaces 1, 2, and 3, are well constrained and slip surfaces 4 and 5, inferred from surface morphology, are not as well constrained. Boreholes I1 and P1 are also shown. No vertical exaggeration. Adapted from Wasowski and Mazzeo (1998).
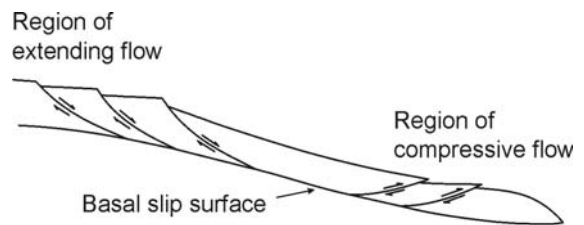

Figure 7. Sketch of an idealized long, shallow earth flow. Arrows indicate relative senses of motion along slip surfaces in extending and compressive flow.

Water is a significant factor in the movement and activity of slow earth flows. Increasing water content increases the unit weight, thereby increasing the driving stresses that tend to cause movement. Also, increasing pore-water pressure decreases the effective stress acting between soil particles, and thus the shear strength of the soil. Pore-pressure fluctuations, in combination with soil properties and shear-surface roughness, directly influence the rate of earth-flow movement (Hutchinson and Bhandari, 1971; Keefer and Johnson, 1983; Iverson, 2000; Coe et al., 2003).

Limit-equilibrium slope-stability theory alone cannot adequately explain the relationship between fluctuations in water levels and rates of movement. Deformation-induced changes in pore-water pressure near the basal slip surface may play a role in damping acceleration due to water-level increases. Baum and Johnson (1993) proposed a mechanism in which deformation of landslide material moving on an irregular slip-surface induces a secondary flow of pore water, called forced circulation. This mechanism can contribute resisting forces sufficient to maintain steady movement under rising water levels. Recent laboratory tests by Moore and Iverson (2002) indicate that dilation of deforming landslide debris can induce suctions sufficient to maintain slow steady

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movement of landslide debris until it has dilated to the critical state.

Mechanical and hydrological isolation of earth flows by clay-rich layers at their boundaries contributes to the persistent instability of earth flows (Baum and Reid, 2000). Weak, low-permeability clay layers observed at the basal and lateral shear zones of some earth flows effectively isolate the earth flow from adjacent ground. Presence of the clay layer causes the landslide to retain water, somewhat like a bathtub, and hence respond quickly to precipitation and snowmelt. Shear strength of the clay layer tends to be significantly lower than both the landslide materials and adjacent ground, thus helping to perpetuate movement on relatively gentle slopes. Observations indicate that in some cases the clay layers are pre-existing features, such as buried soil horizons or stratigraphic layers, and, in other cases, the layers appear to form by redistribution or mechanical enrichment of existing clay as a by-product of earth-flow movement (Picarelli et al., 1998).

Many attempts at modeling the movement of slow earth flows have focused on their flow-like appearance and relatively steady movement with a consequent emphasis on various viscous and viscoplastic rheologies (Savage and Chleborad, 1982; Iverson, 1986a, 1986b; Vulliet and Hutter, 1988). Evidence from field and laboratory studies outlined in the previous paragraphs points out the significance of sliding, Coulomb-plastic internal deformation, and the role of water in controlling the style and rate of movement in slow earth flows. We anticipate that recent development of a Coulomb mixture theory for fluidized granular materials (Iverson and Denlinger, 2001) may open the way to further developments in the modeling of earth flows.

3. RAPID EARTH FLOWS

Most rapid earth flows occur in areas of highly sensitive clay deposits (quick clays). The largest known deposits of sensitive clay occur in Scandinavia and eastern Canada, but deposits also exist in Alaska, Japan, the former Soviet Union, and New Zealand (Lefebvre, 1996). Most sensitive clay deposits are young marine clays deposited in bodies of salt water that existed during retreat of the Wisconsin Ice Sheet. As a result of isostatic rebound, the formerly submerged deposits have since been uplifted, subjected to fresh-water leaching, and eroded. The marine clays typically contain 30-70 percent silt and their clay-sized fractions ($<2 \mu$) typically contain more rock flour than clay minerals. The clay minerals are predominantly illite. Most workers have attributed the sensitivity to loss of salt from the pore water, an effect known to reduce the liquid limits and remolded shear strength of clays (Torrance, 1987; Lefebvre, 1996). Others have suggested that the high proportion of rock flour and resultant low plasticity of quick clays is also a significant cause of their high sensitivity (Cabrerra and Smalley, 1973). Torrance (1987) generalized this observation to a requirement that the quick clay consist of low-activity minerals (including low-activity clay minerals).

A rapid earth flow typically begins as a small landslide on a steep bank where a stream or river has eroded a valley into a sensitive-clay deposit. Excess precipitation, elevated ground-water levels, earthquakes, pile driving, long-term erosion and release of suction through desiccation cracking in periods of dry weather have triggered such earth flows (Sharpe, 1938; Lefebvre, 1996; Larsen et al., 1999). Once the initial slide begins moving, it liquefies spontaneously and begins to flow. Consequently, the scarp is left unsupported and failure rapidly extends away from the bank as a series of rotational or translational slides. The overall movement is translational and retrogressive, as the basal quick clay liquefies and flows out of the scar; the relatively dry upper soil separates into blocks that may rotate or sink into the flowing quick clay (Evans and Brooks, 1994). The entire failure process is usually completed within several minutes to several hours. Rates of movement as high as several meters per second have been observed (Torrance, 1987; Cruden and Varnes, 1996). The retrogressive failure may result in either an arcuate scar that is elongate parallel to the bank or more commonly, a so-called "bottle-neck" landslide (Figure 8), in which the quick clay has flowed through a narrow notch in the bank from an irregular landslide area. This area may extend as much as 1 km from the original bank. The earth-flow deposit is hummocky, several meters to a few tens of meters lower than the original ground surface, and slopes gently toward the stream channel.
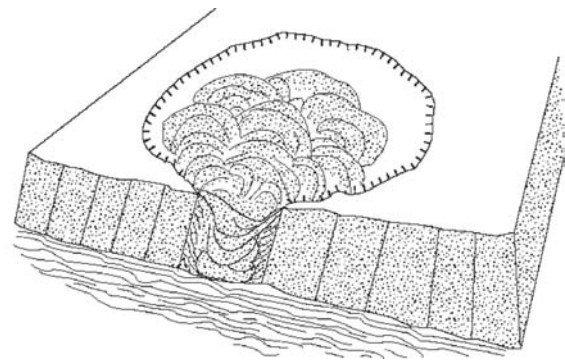

Figure 8. Sketch illustrating the morphology of a "bottle-neck" earth flow. After Karlsrud et al. (1985).

High sensitivity and low post-failure shear strength of quick clay often results in very long runout of rapid earth flows. Examples from Norway indicate that normalized runout increases as volume of the earth flow increases (Karlsrud et al., 1985). The observed ratio of runout to total drop in height along the flow path ranges from about 20 to 130, corresponding to runout angles of 3° to about 0.5°.

The post-failure rheological response of quick clays is controlled by complicated interactions among pore water chemistry, clay mineralogy, and grain size distributions (Torrance, 1999). Experimentally determined rheologies of Canadian quick clays (Bentley, 1979; Locat and Demers, 1988; Torrance, 1999) range from Bingham plastic or viscoplastic shear-thinning behaviors at depositional salinities and Bingham plastic, viscoplastic shear-thinning

and viscoplastic shear-thickening in low-salinity quick clays.

The constitutive relations for Bingham, viscoplastic shear-thinning, and viscoplastic shear-thickening flows are compared with linear viscous Newtonian flows in Figure 9. Bingham, viscoplastic shear-thinning, and viscoplastic shear-thickening flows are non-linear Newtonian fluids, and are termed viscoplastic fluids because they require shear strength to be exceeded before flow commences. Shear stress is proportional to shear strain rate through a constant viscosity in linear Newtonian fluids and in Bingham plastic fluids. Viscosity is dependent on shear strain rate in viscoplastic shear-thinning, and viscoplastic shear-thickening flows. For shear-thinning fluids viscosity decreases with increasing shear rate and for shear-thickening fluids viscosity increases with increasing shear rate.

A number of researchers have modeled rapidly-flowing landslides with non-Newtonian constitutive equations. Johnson (1970) and Edgers and Karlsrud (1986) present models for steady flow of Bingham fluids on inclined slopes. Savage et al. (1990) modeled unsteady flow of Bingham materials in an open channel. Johnson's model was applied to debris-flow movement and that of Edgers and Karlsrud was applied to model flow of three Norwegian quick-clay slides. No unsteady flow models have been applied to rapid earth flows and, to date, no general model for rapid earth-flow movement has been developed to the authors' knowledge.
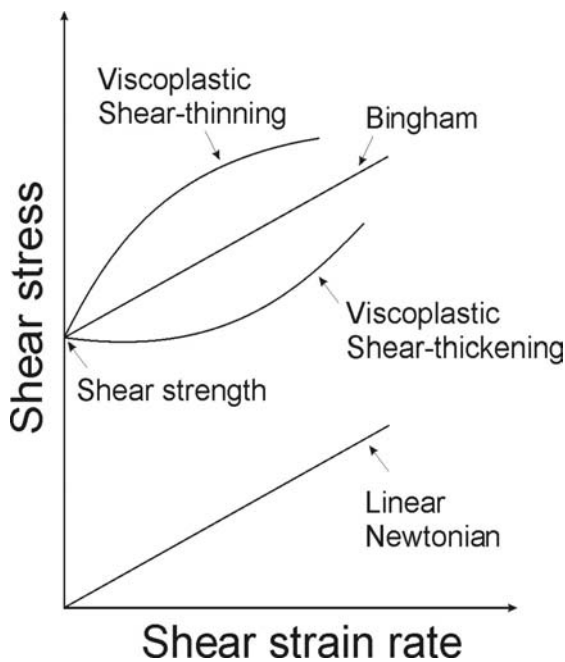

Figure 9. Constitutive relations for linear viscous Newtonian, Bingham, viscoplastic shear-thinning, and viscoplastic shear-thickening flows.

4. SUMMARY

Earth flows are mass movements of fine-grained soils that result from composite modes of failure and movement. Slow earth flows form in deposits of plastic clay or silt and progress gradually by brief episodic movements or periods of sustained, relatively steady movement. Most slow earth flows move primarily by sliding on a distinct basal shear surface, accompanied by internal deformation of the earth-flow material. Slow earth flows may be modeled as Coulomb plastic solids. Most rapid earth flows form in highly sensitive clay deposits and progress by a rapid sequence of smaller failures that spontaneously liquefy and flow out of the source area. Rapid earth flows may be modeled as non-Newtonian fluids.

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