Debris-flow mechanics

Richard M. Iverson

6.1 INTRODUCTION

Debris flows involve gravity-driven motion of solid–fluid mixtures with abrupt surge fronts, free upper surfaces, variably erodible basal surfaces, and compositions that may change with position and time. These complications pose great challenges in efforts to understand debris-flow mechanics and predict debris-flow behavior. Recently, however, a combination of observational, experimental, and theoretical research has begun to yield a coherent picture of debris-flow mechanics. To help build a foundation for future research, this chapter emphasizes principles of debris-flow mechanics that are relatively well established and also highlights areas where critical knowledge is lacking. The chapter does not provide a comprehensive review of debris-flow mechanics literature, which has become voluminous during the past decade. An entree to this literature is provided by the proceedings of three International Conferences on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment (Chen, 1997; Wieczorek and Naeser, 2000; Rickenmann and Chen, 2003).

6.2 MECHANICAL DEFINITION OF DEBRIS FLOW

Debris flows encompass a broad and imprecisely defined range of phenomena intermediate between dry rock avalanches and sediment-laden water floods, but to limit the scope of mechanical analysis, it is necessary to identify some distinguishing traits. Although debris flows are largely saturated with water, they differ from surging water floods in which sediment is held in suspension almost exclusively by fluid mechanical phenomena (e.g., viscous drag, buoyancy, turbulence). In such floods the presence of suspended sediment is mostly incidental to the dynamics of the flood wave as a whole. At the opposite extreme, although debris flows have sediment
concentrations comparable to those of rock avalanches, they differ from avalanches in which grains interact almost exclusively through solid-contact phenomena (e.g., collisions, adhesion, friction), perhaps mediated by intergranular air. In such avalanches the presence of water is mostly incidental to the dynamics of the avalanche as a whole. In contrast, strong interactions of the solid and liquid constituents are an essential element of the mechanics of debris flows. The magnitude and character of solid–liquid interactions may vary from flow to flow and within an individual flow, but the interactions always play a definitive mechanical role.

Typically, solid grains and intergranular liquid constitute roughly equal percentages (30–70%) of the volume of a debris flow. Rock avalanches can transform into debris flows through entrainment of water or water-rich sediment, and debris flows that entrain additional water can become so dilute that they transform to surging floods. Subaqueous debris flows can undergo a similar transformation as a result of entrainment of ambient water, thereby forming buoyancy-dominated gravity currents.

This chapter focuses on the mechanics of relatively simple subaerial debris flows in which average compositions remain more-or-less constant. Although the chapter emphasizes debris-flow motion, it presents a mechanical framework that also applies to quasistatic processes such as liquefaction during debris-flow initiation and consolidation of debris-flow deposits (cf. Iverson et al., 1997; Major and Iverson, 1999; Iverson et al., 2000; Iverson and Denlinger, 2001; Denlinger and Iverson, 2001). The conceptual continuity provided by this framework is important because debris-flow motion begins and ends in static states. In this respect debris flows have more in common with rock avalanches than with water floods.

6.3 MACROSCOPIC DYNAMICS

Any mechanical assessment of debris flows must begin with identification of the scale of behaviour of interest. This chapter adopts a continuum perspective, which considers behaviour on scales no smaller than that of representative elemental volumes (REVs) containing large numbers of individual solid grains (see Figure 6.1). The number of grains in an REV must be great enough that spatially and temporally averaged continuum quantities such as stress are meaningful and measurable, and are not subject to significant fluctuations due to the motion of individual grains. Drew and Lahey (1993) discuss mathematical issues regarding continuum averaging of fluctuating phenomena in grain–fluid mixtures. Iverson (1997) presents data that show how continuum stress fluctuations at the base of debris flows diminish as the size of the measurement device (or REV) increases to include the simultaneous effects of many thousands of grains.

An alternative approach to debris-flow mechanics considers behaviour at the scale of individual grains. Advances in computational power have facilitated progress in this area (e.g., Campbell et al., 1995; Asmar et al., 2003), but such a “discrete-body” approach appears unlikely to supplant continuum mechanics in the foreseeable future, as even laboratory-sized debris flows (~10 m³) commonly contain