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Scaling and design of landslide and debris-flow experiments

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ABSTRACT

Scaling plays a crucial role in designing experiments aimed at understanding the behavior of landslides, debris flows, and other geomorphic phenomena involving grain-fluid mixtures. Scaling can be addressed by using dimensional analysis or – more rigorously – by normalizing differential equations that describe the evolving dynamics of the system. Both of these approaches show that, relative to full-scale natural events, miniaturized landslides and debris flows exhibit disproportionately large effects of viscous shear resistance and cohesion as well as disproportionately small effects of excess pore-fluid pressure that is generated by debris dilation or contraction. This behavioral divergence grows in proportion to H^3, where H is the thickness of a moving mass. Therefore, to maximize geomorphological relevance, experiments with wet landslides and debris flows must be conducted at the largest feasible scales. Another important consideration is that, unlike stream flows, landslides and debris flows accelerate from statically balanced initial states. Thus, no characteristic macroscopic velocity exists to guide experiment scaling and design. On the other hand, macroscopic gravity-driven motion of landslides and debris flows evolves over a characteristic time scale $(L/g)^{1/2}$, where g is the magnitude of gravitational acceleration and L is the characteristic length of the moving mass. Grain-scale stress generation within the mass occurs on a shorter time scale, $H/(gL)^{1/2}$, which is inversely proportional to the depth-averaged material shear rate. A separation of these two time scales exists if the criterion $H/L << 1$ is satisfied, as is commonly the case. This time scale separation indicates that steady-state experiments can be used to study some details of landslide and debris-flow behavior but cannot be used to study macroscopic landslide or debris-flow dynamics.

1. Introduction

Experimentation forms the backbone of most science, but it constitutes only a small fraction of the total body of work in geomorphology. Although controlled experiments provide a sure means of isolating the influences of key variables and performing definitive hypothesis tests, in geomorphology a question invariably arises about the relevance of experimental results. Critics commonly argue that experiments are too small, too brief, too idealized, or too restricted by artificial boundary or initial conditions to mimic the rich complexity of natural processes (e.g., Baker, 1996). To some extent these criticisms misconstrue the purpose of experimentation, which is not to imitate nature but instead to abstract it and thereby make it more amenable to systematic study (e.g., Gilbert, 1914). On the other hand, such criticisms can be valid if experiments misrepresent natural processes by abstracting them at inappropriate scales.

Scale plays a crucial role in many geomorphological experiments because it affects nearly all phenomena involving interaction of sediment and water. (One scale-dependent phenomenon is evident to anyone who builds a sandcastle. Forming damp sand into a free-standing vertical face 10 cm high is literally child's play, whereas forming a similar face 10 m high is impossible.) Many scaling issues can be addressed by careful experiment design, however. This paper emphasizes scaling and experiment design as they apply to laboratory studies of subaerial mass movements such as landslides and debris flows, but the concepts it summarizes also have relevance in a broader geomorphological context.

2. Purposes of mass-movement experiments

Experimental studies of landslides and debris flows can target several broad classes of objectives, one of which is facilitation of field observations and measurements. Field experiments differ from laboratory experiments because they generally aim to retain the scale and complexity of natural processes while controlling their location and timing (Fig. 1). A common strategy involves instrumenting a natural hillside and watering it artificially until slope failure occurs (e.g., Ochiai et al., 2004, 2007; Springman et al., 2009). Similar watering experiments that do not lead to slope failure may transition into long-term field monitoring studies (e.g., Montgomery et al., 1997, 2009). Other field experiments bypass the onset of slope failure in order to focus on the dynamics of landslide or debris-flow runout. These experiments typically involve controlled discharges of water or water − sediment mixtures onto instrumented natural slopes or channels (e.g., Rickenmann et al., 2003; Bugnion et al., 2012; Paik et al., 2012). Although field experiments

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Fig. 1. Photograph of an instrumented natural hillside being prepared for a landslide-initiation experiment, Ibaraki prefecture, Japan, 2003 (see Ochiai et al., 2004, 2007). USGS photo by M.E. Reid.

can be large enough to avoid scaling problems, and complex enough to mimic nature, no field experiment is strictly reproducible because of the idiosyncrasies of the natural settings and materials involved.

Reproducible laboratory experiments differ fundamentally from field experiments because they are designed to idealize natural processes, minimize complexity, and thereby isolate the effects of key variables. These goals are attainable in a laboratory setting because initial conditions, boundary conditions, and material properties can be closely controlled. Laboratories impose practical constraints on experiment scale, however. The largest laboratory mass-movement experiments to date have involved about 83 m^3 of material (Moriwaki et al., 2004) (Fig. 2), and many experiments have involved <2 m^3 (e.g., Eckersley, 1990; Parsons et al., 2001; Manzella and Labiouse, 2009). Scaling is therefore a crucial – albeit sometimes overlooked – aspect of experiment design.

Scaling can be particularly challenging in laboratory experiments that aim not to test specific hypotheses but rather to strip away confounding influences that are prevalent in nature and thereby reveal phenomenology that is difficult to observe or measure in the field. Designs of such exploratory experiments can be very diverse (e.g., Iverson et al., 2000; Okura et al., 2000; Bowman et al., 2012; Hsu et al., 2014; Kaitna et al., 2014; Paguican et al., 2014). Nevertheless, experiment design can be informed by using dimensional analysis to evaluate the potential scale-dependence of conspicuous physical phenomena, such as friction reduction by elevated pore-fluid pressure, and of less-conspicuous phenomena, such as apparent debris cohesion caused by electrostatic attraction of small particles or surface tension of air–water interfaces (Iverson et al., 2004).

Another class of laboratory experiments aims to test specific hypotheses that have been formalized in precise mathematical form (Iverson, 2003a). In these cases, normalization of a mathematical model's governing equations yields information about appropriate experiment scaling (e.g., Iverson and Denlinger, 2001). Experiments aimed at model testing are generally warranted only after the basic phenomenology of a process has been repeatedly observed and measured, however. A classic example of the progression from observations and measurements to systematic model development and testing is provided by the most famous scientific advances of the sixteenth and seventeenth centuries, when Galileo, Brahe, and Kepler established the empirical phenomenology that guided Newton's construction and testing of his mathematical theory of gravitation and rigid-body motion.

Physically based mathematical models of mass-movement processes apply the principles developed by Newton, but this application can be challenging because mass-movement models must account for the effects of energy dissipation. Indeed, dissipative processes produce most of the scale-dependent effects that can bedevil model formulation as well as systematic experimentation and data interpretation. For example, the energy expenditure necessary to overcome a debris yield strength of 0.1 kPa can be important in a miniaturized laboratory debris

Fig. 2. Photograph of the aftermath of a large-scale laboratory landslide experiment at the National Research Institute for Earth Science and Disaster Prevention (NEID), Tsukuba, Japan, 2003 (see Moriwaki et al., 2004). NEID photo by H. Moriwaki.