Assessing the dynamic influences of slope angle and sediment composition on debris flow behaviour: An experimental approach

FAIRFIELD, GEORGINA

Assessing the dynamic influences of slope angle and sediment composition on debris flow behaviour: An experimental approach

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Abstract

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Debris flows are hazards that can inflict significant infrastructural damage and loss of life. Their rapid and unpredictable onset in isolated locations means that field studies are limited. Laboratory studies are therefore necessary for understanding debris flow behaviour. Despite this, fundamental uncertainties remain. This study set out to explore debris flow dynamics with an assessment of the influence of slope angle and mixture composition on flow behaviour. A novel dual-scale approach was taken, leading to an evaluation of the extent to which two different flumes (2 m and 10 m long) produced comparable results.

Results produced in the two flumes were comparable with each other. They were also comparable with natural flows, and with other experimental studies. There was some evidence of limitations imposed by rigid channel boundaries, particularly in terms of flow development. Channel slope was shown to have a significant influence on flow behaviour, particularly flow velocity; and a clear link was demonstrated between mixture composition and flow behaviour. A three-fold flow classification was developed, with flows being classified as granular, viscous or muddy. The importance of internal morphological interactions was also demonstrated, with relationships varying in strength and direction dependent on flow type. Flow velocity was influenced by both mixture composition and channel slope, while flow morphology was influenced by velocity and internal feedbacks. Conceptual diagrams were produced, demonstrating the influences and feedback dynamics relevant to each flow type.

Although limited by experimental constraints, this study has important implications for understanding the link between local environments and debris flow behaviour. The understanding of debris flows would benefit from further research examining a wider range of slope angles and sediment types, and the use of larger flumes to further explore the comparability of experimental results.

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Chapter 1 Introduction

This chapter outlines the background and rationale of this study, highlights the research aims and objectives, and gives a brief outline of the thesis structure.

1.1 Background

Debris flows are naturally occurring mixtures of earth materials and water, which move under the force of gravity. They have properties intermediate between hyper-concentrated floods and landslides (Lorenzini and Mazza, 2004; Coussot and Meunier, 1996). Coussot and Meunier (1996) produced a conceptual classification diagram categorising mass movements based on material type and solids fraction (Figure 1.1); debris flows are located in the middle of the diagram, between purely solid and purely water flows.

Certain conditions are favourable for the initiation of debris flows; most importantly an abundant supply of loose solid material and the presence of water (Selby, 1993). Flows generally occur on slopes from 15° to 40°, and with velocities varying from 0.1 m s^{-1} to 30 m s^{-1} (Sharp and Nobles, 1963; Curry, 1966; Pierson, 1980; Hirano and Iwamoto, 1981; Costa, 1984; Hungr *et al.*, 1984; Van Steijn and Coutard, 1989; Davies, 1994; Coussot and Meunier, 1996; Suwa and Yamakoshi, 2000). Mountainous areas with small, steep drainage basins and high rates of surface runoff are at particular risk from debris flows (Selby, 1993). Flows generally occur along existing drainage paths such as gullies and channels, but can also flow down hillsides (Varnes, 1978).

Debris flow behaviour is unsteady, non-uniform, and varies with water and sediment content, as well as particle size and sorting (Varnes, 1978; Takahashi, 2007). Debris flows can transport material of many sizes - from silt and clay, to boulders big enough to destroy houses (Lorenzini and Mazza, 2004). Debris flows have high mobility and can transport large volumes of material with ease (Takahashi, 2007). They have the ability to transport the volume of a large landslide (high density) with the speed and distance of a flood (high mobility), and as such have the potential to be highly destructive to both people and property.

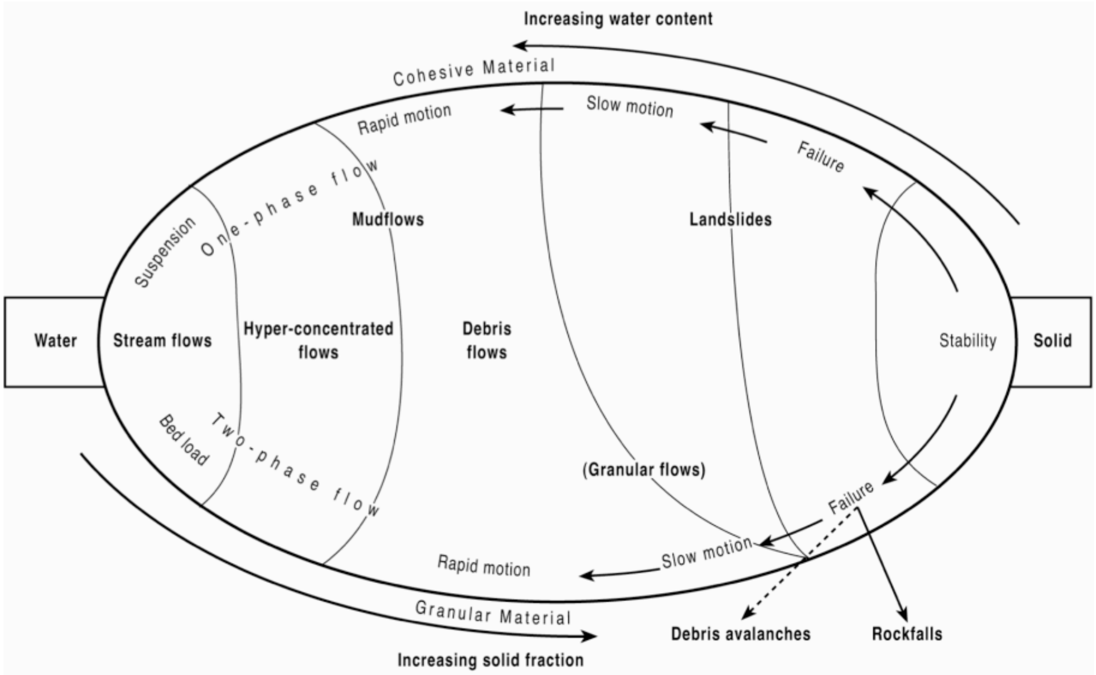


Figure 1.1: Classification diagram of mass movements based on material type and solids fraction, after Coussot and Meunier (1996 p.216).

1.2 Context and Rationale of the study

The triggering and onset of a debris flow can occur quickly and with little warning, and because of their occurrence in isolated locations witnessing a flow is rare (Davies, 1990; Major, 1997). Because of this, and despite several decades of research, the understanding of their behaviour remains limited.

With an increasing human presence in debris flow prone areas, and with their ability to cause considerable damage, debris flows are attracting increasing attention from the research community (Davies, 1993a; Perez, 2001). Experimental apparatus used to study debris flows is especially important, as it allows investigations to be carried out in a controlled, convenient and reproducible setting; enabling data to be acquired that would not be possible in the field (Mosley and Zimpfer, 1978; Iverson and LaHusen, 1993; Davies, 1994; Major, 1997; Hungr, 2000; Armanini *et al.*, 2005). A common method of debris flow study is though the use of experimental flumes because they can be used to closely replicate the natural flow environment.

Due to the devastating impact that a debris flow can have on the surrounding landscape and communities it is important to understand the feedbacks within a flow, and how they affect overall flow behaviour. Most experimental studies examine the processes and material dynamics of debris flows as a whole (Iverson and LaHusen, 1993; Armanini *et al.*, 2005; Kaitna and Rickenmann, 2005; Larcher *et al.*, 2007). However, as Major and Pierson (1992 p.841) state, "*although the geomorphological, sedimentologic, and stratigraphic characteristics of debris flows are well documented, a fundamental physical understanding of the flow mechanics of the process is lacking*". Two of the fundamental controls on debris flow dynamics are the sediment characteristics of the flow and the slope angle of the terrain.

The type and combination of material that constitutes a debris flow can have a great bearing upon debris flow behaviour. Major and Pierson (1992) found that both yield strength and plastic viscosity increase exponentially with sediment concentration. Slope angle affects flow behaviour by directly influencing flow velocity (Costa, 1984; Lorenzini and Mazza, 2004; Takahashi, 2007). It is therefore important for hazard management to understand the effects of local environments (sediment mixture and terrain) on debris flow behaviour.

Because of the broad classification of debris flows, flow behaviour can vary enormously between events; it is therefore difficult to accurately characterise flows. However, certain distinguishing characteristics are observable. These include features of flow morphology (such as a rounded snout and tapered tail), distinctive movement characteristics (such as particle segregation and transport), and the occurrence of flow surges (Johnson, 1970; Bridgewater, 1976; Takahashi, 1980; Suwa, 1988; Takahashi, 1991; Iverson, 2003; Lorenzini and Mazza, 2004; Zanuttigh and Lamberti, 2007). The present study takes a bottom-up approach by creating small-scale experimental debris flow mixtures to reproduce key characteristic debris flow behaviours. This enabled a consideration of how variations within the debris flow mixture affect flow behaviour. However, issues often arise when using scaled experiments to represent reality. Therefore, this study was innovative by generating experimental debris flows in two flumes of different sizes, and with a variety of slope angles. This allowed a comparison of the results collected in different flumes, as well as the influence of slope angle and mixture composition on debris flow behaviour. Consequently, this also allowed an assessment of the assumption (often taken for granted in experimental studies) that the results generated in small-scale experiments are representative of much larger natural events.

1.3 Aim and Objectives

This study used an experimental approach to gain a better understanding of debris flow behaviour and processes. The aim was to explore and understand the influences of slope angle and sediment composition on debris flow behaviour using experimental flumes at two different scales.

In order to meet this aim the following objectives were addressed:

1. *Test a range of sediment mixtures and determine which most closely reproduced natural debris flow behaviours, and assess the extent to which flows were comparable in different sized experimental flumes.*
2. *Assess the extent to which slope angle influenced debris flow behaviour.*
3. *Assess the relationship between mixture composition and debris flow behaviour.*

1.4 Thesis Structure

This introductory chapter has provided the background and objectives of the study. Chapter 2 expands on this; it explores in greater depth previous literature related to debris flow dynamics, and provides a review of existing experimental debris flow research. In Chapter 3, the research methods of this study are described; this includes discussion on why these were selected, and how the raw data was collected and processed. Chapter 4 summarises the results, and Chapter 5 provides a synthesis and discussion. The conclusions of this study, its limitations, and further research proposals are presented in Chapter 6.

Chapter 2 Literature Review

This chapter provides a review of the literature on debris flows. The first part of the chapter reviews the occurrence, generating mechanisms and characteristics of debris flows; including information regarding flow composition, form and behaviour. It also describes debris flow classification schemes and rheological models. The second part of the chapter focuses on the experimental studies of debris flows; experimental apparatus, types of material tested, and process representation.

2.1 What is a debris flow?

In terms of definitions the word *debris* describes a sediment based material which generally contains a high percentage of coarse grains (usually over 2 mm in diameter) (Varnes, 1978). In the context of debris flows, the term *flow* indicates a grain-fluid body which deforms continuously (Iverson and Vallance, 2001). The combined term of 'debris flow' has no formal definition, but there is general agreement that a debris flow is fundamentally transient in nature (Coussot and Meunier, 1996). In essence they are highly viscous saturated granular fluids that move in multiple surges; often described as something akin to wet concrete (Sharp and Nobles, 1953; Costa, 1988). The material within a flow varies in size and is often poorly sorted. Debris flows occur with differing degrees of sediment concentration in the fluid matrix (Takahashi, 2007). Importantly, most research shows that flow behaviour varies with sediment concentration, grain size and sorting, and with local conditions, such as slope angle (Varnes, 1978; Takahashi, 2007).

The characteristic that sets debris flows apart from other mass movements is the dynamic interaction of large sediment and boulders with a fine-grained muddy matrix. The addition of even a small quantity of water enables a debris flow it to become extremely mobile; flows can travel for long distances and at great speeds (Johnson, 1970). As Zanuttigh and Lamberti (2007 p.1) explain, "*in the absence of such interaction we can have a "rock avalanche" (when the fluid phase is dynamically irrelevant) or sediment transport by water (when the effect of the solid phase on the fluid one is dynamically irrelevant)"*.

2.2 Debris flow initiation

Debris flow initiation requires both the presence of both loose material and water. Flows often occur after high intensity rainfall or snow melt, and develop either through the mixing of water and sediment, or through the liquefaction of an already mobilised landslide (Varnes, 1978; Selby, 1993; Coussot and Meunier, 1996; Gregoretti, 2000; Lorenzini and Mazza, 2004). Debris flow initiation requires three conditions to be met simultaneously; failure of the mass, water saturation, and the translation of potential gravitational energy into kinetic energy (accommodating dispersed deformation, rather than the localised shearing associated with some other mass movements) (Lorenzini and Mazza, 2004).

Mountainous regions (small, steep drainage basins with high rates of surface runoff), and semi-arid and volcanic areas are at particular risk from debris flows (Selby, 1993; Lorenzini and Mazza, 2004). Figure 2.1 shows a debris flow channel and its surrounding landscape post-event, and highlights the widespread channel reorganisation only a few hundred metres from the point of initiation; highlighting that even in the initial stages a large debris flow has the power to destroy anything in its path. When a debris flow reaches the valley floor, and as channel slope decreases, the flow commonly spreads out into a fan, leaving thick deposits, which in themselves can lead to damage (Johnson and Rodine, 1984).

Figure 2.1: Photograph associated with the August 2005 Les Contamines debris flow in the French Alps (Fairfield, 2009). The flow was over 20 m deep, and had a significant impact on the landscape.

2.3 Debris flow classification

There have been many attempts to classify debris flows; including groupings based on flow behaviour and depositional characteristics, as well as sediment content.

The most common way to differentiate between flow types is in terms of their mechanical behaviour - which is often based on sediment characteristics (type, size and concentration) (Coussot and Meunier, 1996; Ancey, 1999; Lorenzini and Mazza, 2004; Takahashi, 2007; Sosio and Crosta, 2009). Differences in behaviour can be seen in flows with differing grain size distributions due to differing shear rates and yield strength (Whipple and Dunne, 1992; Iverson, 1997; Sosio and Crosta, 2009). Whipple and Dunne (1992) noted that yield strength and viscosity are related to sediment concentration as well as each other, and that a flow with a larger proportion of fines for a given water content will have a higher yield strength and viscosity. However, in some cases flows with high silt and clay content have a low yield strength and as a consequence are mobile (Whipple and Dunne, 1992).

Pierson and Costa (1987) created a bi-dimensional graph to classify mass movement flow types relating to sediment concentration and flow velocity (Figure **2.2**). This classification distinguishes between hyper-concentrated flows, debris flows, and granular flows. The vertical lines A, B and C represent the onset of yield strength (A), the rapid increase in yield strength which enables the static suspension of particles (B), and the end of liquefaction behaviour (C). Debris flows fall between B and C. Flows in this category show plastic behaviour, and once stopped the fine and coarse grains show no separation (Lorenzini and Mazza, 2004). This type of flow is often described by the Bingham model (section 2.4).

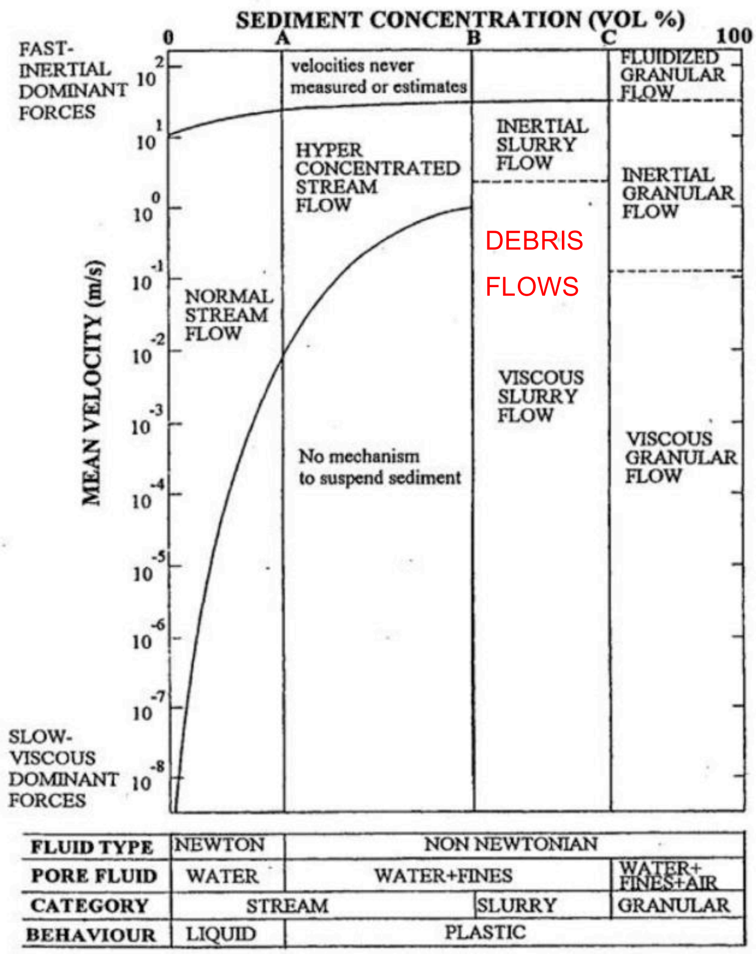


Figure 2.2: Rheological classification of water and sediment mixtures proposed by Pierson and Costa (1987).

There have also been many attempts to subdivide debris flows themselves into different categorical types. Coussot and Meunier (1996) describe two types of debris flow; muddy and granular. Muddy type flows comprise a fines fraction that is high enough to form an interstitial fluid, which lubricates the material and controls its viscous behaviour. The granular type flows, on the other hand, have a low fines content which leads to more grain to grain contact, resulting in dispersive behaviour (Lorenzini and Mazza, 2004). Takahashi (2007) also differentiated debris flows based on their sediment content; the two main types being stony and viscous. In the stony type flows the largest debris travels at the front of the flow and is followed by a long duration wet flow, with gradually decreasing discharge. Velocity is highest in the centre of the flow and erosion is the most severe in the upper channel. The more concentrated the sediment the slower the flow moves. During viscous type flows Takahashi noted a large number of surges repeatedly smoothed and scoured the channel, altering channel width, depth and slope.

There have also been studies that classify debris flows according to depositional properties. For example, Ancey (1999) classified debris flows though depositional shape, slope, cross section, grain size distribution and matrix composition. Relating different types of depositional characteristics to the mechanical properties of debris flows can lead to an understanding of the controls on flow behaviour, and ultimately determine under which conditions different flows occur. Ancey (1999) described three types of flow behaviour; visco-plastic, frictional and viscous, corresponding with three classifications of debris flow – muddy, granular and fluid.

Classifications based on parameters such as velocity or depth have often met with limited success as flow behaviour is often also dependant on boundary conditions, such as slope, and is highly variable between and during events (Coussot and Meunier, 1996). However, changes in flow behaviour do occur where parameters other than the intrinsic material properties are altered (Parsons *et al.*, 2001; Ghilardi, 2003). For example, Parsons *et al.* (2001) noted that a change in slope will alter the shear rate of a flow.

2.4 Debris flow rheology

Rheology is defined as *"the study of the properties of flow and deformation that bodies are subject to when stress is applied to them"* (Lorenzini and Mazza, 2004 p.28). Rheological properties of a mixture depend on the material composition, the relative proportion and grain-size distribution of the different materials, as well as external factors such as temperature, pressure and time (Lorenzini and Mazza, 2004). The rheology of debris flows is imperfectly understood; partly because flows are rarely observed, but also because of the difficulties of working in a laboratory with experimental sediment mixtures that contain large solid particles (Pierson, 1986).

Nevertheless, considerable progress has been made in the understanding of debris flow rheology.

The understanding of fluid motion began with Newton in the seventeenth century. A Newtonian fluid (sometimes known as the linear viscosity model) is a fluid in which shear rate is proportional to the applied stress (Johnson, 1970; Lorenzini and Mazza, 2004). A non-Newtonian fluid is one for which the relationship is not constant, leading to changes in viscosity. Non-Newtonian fluids are often described using models such as Bingham plastic, visco-plastic and dilatant. Debris flows can generally be described as non-Newtonian fluids, and are commonly placed under the heading of Bingham fluids. The Bingham model evolved in 1919 when Bingham noticed that the properties of paint did not fit with conventional rheological models, and decided that a mixed model would be a better description of the behaviour of the paint. He demonstrated that paint had yield strength similar to that of a plastic material and would not deform until a threshold was reached, but that once movement began the paint acted like a viscous material and flowed. Bingham fluids therefore share the qualities of plastic substances and viscous substances, behaving like solids when static but needing a force to induce flow (Johnson, 1970). The Bingham model has been widely proposed for debris flows.

As shown in Figure 2.3, debris flows according to the Bingham model often appear to have a non-deforming rigid plug sitting within a zone of laminar movement along the base and sides of the flow. When a flow widens the laminar zone shrinks and becomes thinner; once it completely vanishes the flow stops (Johnson, 1970). Tecca *et al.* (2003) concluded that a rigid plug could occur at any stage in the development of a debris flow as the plug is a function of flow depth, and not time.

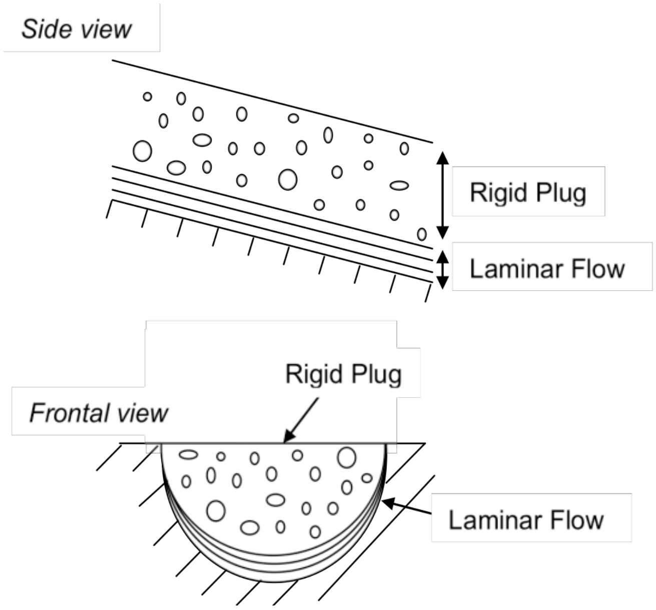


Figure 2.3: Diagram showing the rigid plug observed in debris flows according to Bingham, adapted from Johnson (1970). A zone of laminar flow close to the channel base and sides encloses a non-deforming section of material known as the plug. The rigid section of the flow stays in situ while the laminar zone shears and moves down the slope. Once a flow moves out of the channel and is no longer confined, the flow widens and the depth of the shearing zone decreases until it no longer exists and the flow stops.

In general, the Bingham model relates to flows where the solids fraction is comprised of silt and sand. It may not be appropriate for debris flows with larger coarse grained components (Lorenzini and Mazza, 2004). When the addition of large particles into a mixture results in a reduction in the fines content, the mixture may no longer display visco-plastic behaviour. However, if the fines fraction remains sufficiently high (over 10%) viscous dissipation remains dominant, and the fluid retains its visco-plastic behaviour. In this case, the Herschel Bulkley model may be more suitable (Lorenzini and Mazza, 2004). The Herschel Bulkley model can be regarded as a modified Bingham model that also takes into account the shear - thinning or - thickening behaviour of the fluid (Herschel and Bulkley, 1926; Kaitna *et al.*, 2007).

Due to the varied nature of the interactions between the solid and liquid components of debris flows it is difficult to attribute any single rheological model to the phenomenon that distinguishes them from other forms of mass movement. This stems from the fact that many different behaviours and rheological properties can be observed within a single flow (Lorenzini and Mazza, 2004). Iverson (2003 p.1) wrote that "*apparent rheologies appear to vary with time, position and feedbacks that depend on evolving debris flow dynamics*". Debris flows can also exhibit a different rheology dependent on the portion of flow being examined (Costa, 1984; Iverson, 2003; Tecca *et al.*, 2003; Kaitna *et al.*, 2007). Debris flows are thus rheologically complex. Portions of the flow may remain more mobile due to high pore-fluid pressures, while other regions of the same flow (such as the snout or margins) may, at the same time, be dominated by grain to grain contacts with high internal friction (Iverson and Delinger, 2001; Iverson and Vallance, 2001; Iverson, 2003). Tecca *et al.*, (2003) observed variations in flow velocity profiles which suggest that flow behaviour progressively approaches a Newtonian type regime in its final stages.

It has been suggested that it is not possible to characterise all debris flows with the same rheology because the range of behaviours and morphology is so varied, especially between the friction-dominated and the liquefied portions of the flow (Iverson, 2003; Kaitna *et al.*, 2007). Iverson (1997) and Iverson and Delinger (2001) have employed what is known as a rheological mixture theory; whereby the solid and fluid constituents of a flow exhibit different rheological behaviour. For example, Iverson (2003 p.10) wrote that the *"granular solids in debris flows behave as frictional materials"*, while the *"inter-granular fluids (with clay and silt carried in suspension) behave as Newtonian viscous fluids"*

2.5 Debris flow characteristics

Table 2.1 summarises debris flow characteristics (slope, sediment concentration, grain size, flow density, viscosity, depth and velocity) from locations as diverse as Europe, America and Japan. Debris flow sediment concentration by weight is generally 50% to 90% (with the majority over 70%), while silt and clay is usually less than 15% by weight. Flow densities range from 1320 kg m^{-3} to 2600 kg m^{-3}, with most around 2000 kg m^{-3}. Dynamic viscosity has a large range; from 60 Pa.s to 60,000 Pa.s. Slope angles fall within a range of 6° to 35° (also shown in Figure 2.5), while grain sizes range from several millimetres to several metres. Flow depths are generally around 1 m; but range from 0.2 m to 10.4 m, while velocity ranges from 0.3 m s^{-1} to 30 m s^{-1}.

Location/date of event and author	**Slope (°)**	**Sediment by weight (%)**	**Grain size (m)**	**Density (kg m^{-3})**	**Viscosity (Pa.s)**	**Flow depth (m)**	**Velocity (m s^{-1})**
Sharp and Nobles, 1953 California,1941	6	79-85 solids	0.15-1.8	2400	2000-6000	1.2	1.2-4.4
Curry, 1966 Colorado	15	9.9 silt 1 clay	0.02-0.8	2530	30,000	1.5	2.5
Morton and Campbell, 1974 California,1969	9	38-86 solids		1320-2130	100 – 60,000	1	0.3-3.8
Johnson, 1970 California,1917	31			2400			
Johnson, 1970 California,1969	7			2000	4500	1	
Niyazov and Degovets, 1975 Almatinka Rivers	7.1-18	58-77 solids		2000		2-10.4	4.3-11.1
Pierson, 1980 New Zealand, 1978	6	84 solids 70 gravel 20 sand 10 silt/clay	0.004	1730-2090	2100-8100	0.2-1	5
Pierson, 1981 New Zealand 1978	5-7	60-78 solids 20-70 gravel 20-54 sand 6-15 silt 4-11 clay		1730-2080			1-5
Costa, 1984 Not specified		90 solids		1800-2600			
Hungr et al., 1984 Canada	23-27						
Pierson, 1985 Washington, 1980		84-91 solids					30
Vandine, 1985 Canada	13-35	30 rocks 15 sand 35 silt/clay	< 3				
Costa, 1988 Not specified		70-90 solids		1800-2300			
Phillips and Davies, 1989 New Zealand		75-90 solids		2000			

Davies, 1993b China	5-12		0.3-1	1400- 2200			1-10
Coussot and Meunier, 1996		50-90 solids					0.5-10
Genevois et al., 2000 Italy		32-58 solids	< 2		60-1700		
Suwa and Yamakoshi, 2000 Japan	20						5-11
Perez, 2001 Venezuela, 1999	42	34-66 gravel 56-83 sand <15 silt/clay	D_{50} 0.001- 0.003			<7	

Table 2.1: The range of debris flow field data recorded in the literature. The data is listed in order of the date of appearance in the literature (gaps indicate a lack of recorded data).

2.5.1 Flow composition

Debris flows are composed of water, air, particles ranging in size from fine material to large boulders, and often detritus such as branches. By mixing clay and water a cohesive slurry is produced which creates a matrix for the fine grained particles. This matrix leads to an increase in flow density and a reduction in effective normal stresses which allows the support of larger particles; and the transportation of large boulders such as those illustrated in Figure 2.4 (Rodine and Johnson, 1976). Greater velocities produced on steeper slopes enables the transportation of even the largest boulders (Rodine and Johnson, 1976; Zanuttigh and Lamberti, 2007). Figure 2.5 shows the range of debris flow grain sizes and channel slopes identified in the literature, highlighting grain sizes of up to 3000 mm, and slope angles of 6° to 35° (Sharp and Nobles, 1953; Curry, 1966; Pierson, 1980; Vandine, 1985; Davies, 1993b).

Figure 2.4: Photographs associated with the August 2005 Les Contamines debris flow in the French Alps (Fairfield, 2009). The images highlight the large boulders transported and deposited by the flow. It is not uncommon to find boulders exceeding 2 m in diameter.

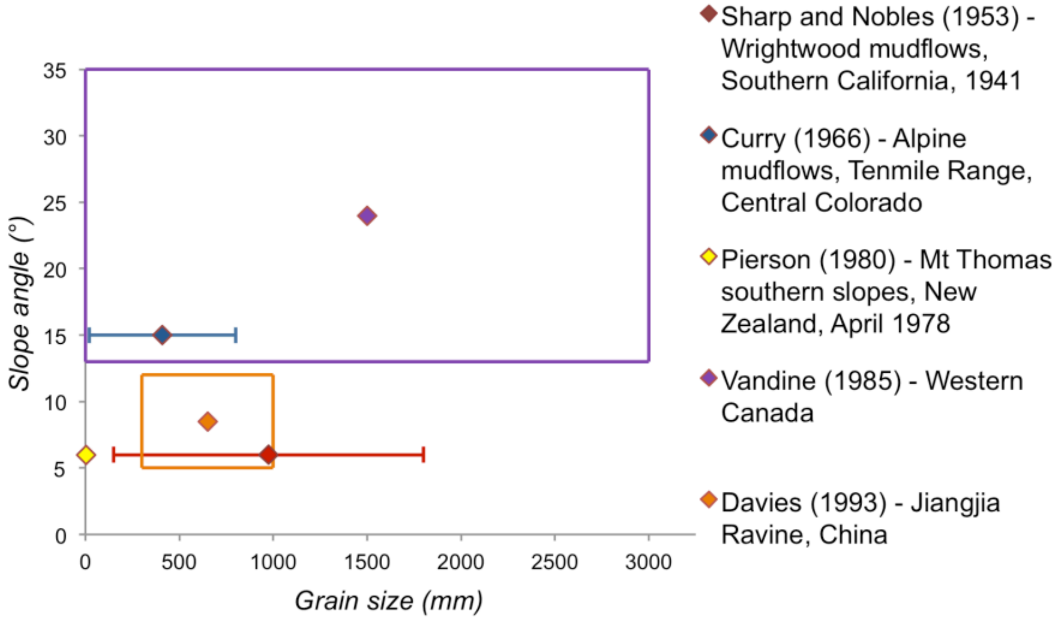


Figure 2.5: Graphical representation of debris flow slope angle and grain size ranges. There are only a limited number of studies that note both slope angle and grain size data.

The composition of a debris flow can vary from mainly silt and clay 'muddy' flows, to predominantly coarse grained flows (Johnson and Rodine, 1984). Iverson (1997) conducted rheometric investigations into debris flow deposits reconstituted with water. The experiments demonstrated that mixture behaviour varies with sediment concentration as well as grain size distribution. This was especially true for the silt and clay content, which influenced the solid-fluid interactions. It has been shown that changes as small as 2 % in sediment concentrations can lead to order-of-magnitude changes in both yield strength and viscosity in fine-grained slurries, particularly at higher ratios of silt and clay to sand (Major and Pierson, 1992).

2.5.2 Flow form

Debris flows can be divided into three distinct phases of flow. The first phase is often absent, but when it does occur it is seen as a low density, fast and turbulent flow with little particle interaction. The most common (and easily recognisable) flow phase is what Lorenzini and Mazza (2004) call the intermediate phase. This phase is what most would consider a debris flow; a high sediment density flow with extensive particle interaction. The final phase of a debris flow involves the sediment slowing and coming to a stop, forming debris flow deposits (Lorenzini and Mazza, 2004).

The intermediate phase constitutes the bulk of the flow and is therefore the most described in the literature. It is generally composed of debris flow waves, which can themselves be divided into three regions, as shown in Figure 2.6 (Hungr *et al.*, 1984; Hungr, 2000; Ikeda and Hara, 2003; Lorenzini and Mazza, 2004). Each section of a flow wave exhibits different flow behaviour. The front is comprised of a high proportion of large coarse grained sediment and boulders. Due to segregation mechanics the largest particles are usually located at the flow surface, edges and snout, causing a reduction in local water content (Curry, 1966; Johnson, 1970; Lorenzini and Mazza, 2004; Pierson, 2005). Takahashi (1991; 2007), and Lorenzini and Mazza (2004) conclude that because the snout holds most of the large boulders, and little water, the head of the debris flow tends to slow down and increase in volume. The plastic nature of the interstitial slurry can also add to this effect (Lorenzini and Mazza, 2004). As the reduction in velocity of the snout increases, its shape becomes steeper and higher (Sharp and Nobles, 1953). The debris flow snout can form a dam that is pushed along by the material behind it; which is moving at a higher velocity (Sharp and Nobles, 1953; Iverson, 2003). The middle and tail regions are proportionally thinner than the snout as the large particles give way to a more fines-laden section of flow; in a long duration event this may eventually reduce to muddy water (Johnson, 1970; Hungr *et al.*, 1984; Hungr, 2000; Ikeda and Hara, 2003; Iverson, 2003; Lorenzini and Mazza, 2004). As a consequence of these changes the tail region moves more like a fluid (Sharp and Nobles, 1953; Iverson, 2003), and the flow may alter from laminar to turbulent with distance from the snout (Johnson, 1970; Lorenzini and Mazza, 2004). The tail region with its high water content can continue to flow long after the snout has passed.

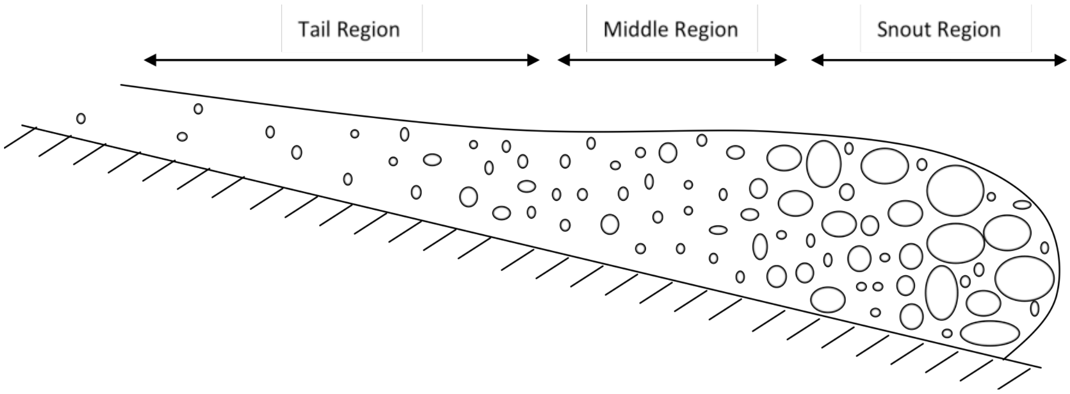


Figure 2.6: Cross sectional view of a debris flow wave, showing three distinct regions; tail, middle and snout. Each region exhibits distinct flow behaviour. There is a reduction of water towards the snout, and a subsequent reduction in velocity. Longitudinal sorting of grain size is also visible, with the largest grains found at the front and top of the flow.

2.5.3 Flow velocity

Table 2.1 highlights that debris flow velocities vary between events; from 0.1 m s^{-1} to 30 m s^{-1}. Variations in flow velocity can occur within a flow as well as between flows, and can be attributed to differences in flow composition (sediment concentration and size), as well as slope geometry (steeper channels resulting in faster flows) (Curry, 1966; Costa, 1984; Van Steijn and Coutard, 1989; Lorenzini and Mazza, 2004; Takahashi, 2007).

Velocity tends to be greatest in the centre of a debris flow, and increases in the later stages of a surge as flow depth and viscosity decrease (Pierson, 1980; Ikeda and Hara, 2003; Tecca *et al.*, 2003; Takahashi, 2007). To some extent flow velocity can be influenced by flow viscosity; a decreased viscosity leads to decreased surge height and steepness, which increases flow velocity (Davies, 1994). However, several studies have also noted that a deeper flow results in a higher velocity if the depth remains greater than the flow width (Pierson, 1980; Ikeda and Hara, 2003; Takahashi, 2007). Ikeda and Hara (2003) observed that maximum velocities can be reached during any stage of the flow. For example, they report that on July 17 1983 a debris flow reached its fastest velocity during the main flow phase, whereas on July 13 1985 the fastest velocity was seen during a late phase of the flow. Pierson (1980) and Hungr *et* *al.* (1984) suggest that flow velocity shows a strong dependence on flow depth; which is determined to some extent by whether a material is undergoing laminar or turbulent flow. Furthermore, debris flow velocity is somewhat controlled by the concentration of solids in the mixture; the denser the mixture the slower the velocity (Costa, 1984; Ghilardi, 2003; Tecca *et al.*, 2003; Takahashi, 2007).

2.6 Debris flow behaviour

2.6.1 Flow surges

Debris flows move in surges; periods of flow with high concentrations of coarse grains, interspersed with periods of watery turbulent flow or no flow (Pierson, 1980; Costa, 1984; Coussot and Meunier, 1996). Despite their variable nature, debris flows often attain a steady state as they travel over long distances (Hungr, 2000). Figure 2.7 is a schematic diagram highlighting the longitudinal and plan view of surges during a debris flow. Larger debris flows often move with more surges than smaller debris flows. In the case of smaller flows individual grains can influence behaviour, as the channels in which they flow are often the same size, if not smaller, than the largest grain. This can lead to the complete blockage of the flow if it dams behind a particularly large particle. Larger flows on the other hand generally have a more fluid appearance due to a greater channel depth to grain size ratio. They are also less likely to be influenced by individual grains (Davies, 1993b). The first surge of a debris flow is often "*characterized by the highest depth, the longest duration, the greatest erosive power, and the most symmetrical shape*" with "*secondary waves that burst on the flow tail*" (Zanuttigh and Lamberti, 2007 p.1).

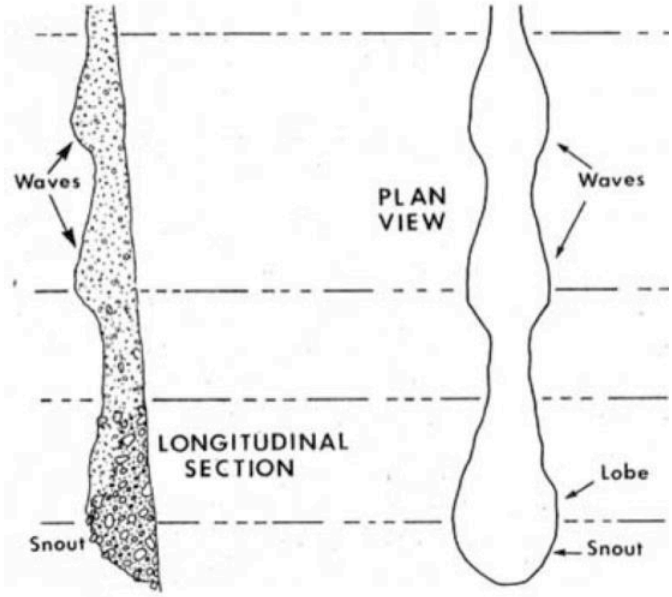


Figure 2.7: Schematic diagram of debris flow surge waves, as described by Johnson and Rodine (1984 p.435).

Debris flow surges can have depths and velocities up to three times greater than the average for a flow, and are therefore significant for understanding the devastating power of debris flows (Zanuttigh and Lamberti, 2007). The distinctive formation of surges is similar to that found in water roll waves (Davies, 1986; Takahashi, 1991). There are two types of instabilities within a flow which result in the formation of flow waves: progressive instabilities, which arise from small surface waves which amplify downstream through the overtaking and incorporation of smaller waves, and regressive instabilities, which arise from stationary or slow moving material dams, behind which sediment builds up until the increasing force sets the material in full motion again (Takahashi, 1991; Zanuttigh and Lamberti, 2007). Progressive instabilities are characterised by flows with the greatest velocity at the wave crests, whereas regressive instabilities are characterised by flows with the greatest velocity at the surge front. Surge waves will not develop without a sufficient channel length and flow instability (Zanuttigh and Lamberti, 2007).

2.6.2 Segregation mechanics

The segregation of particles within a flow is illustrated Figure 2.6. The clustering of large particles at the flow front is partly due to the mechanics of the flow, and partly due to entrainment (Iverson, 2003). Bagnold’s theory of ‘dispersive pressure’ attempts to explain longitudinal sorting (Johnson, 1970). It states that where particles are flowing alongside a rigid boundary they may either move parallel to it or away from it, but not towards it. The force exerted on the particle, per unit area, is Bagnold’s ‘dispersive pressure’, and is proportional to the shear rate. This means that when two particles are sheared together the larger one will attempt to move to an area of least shear; the surface or edge of the flow. Bridgewater (1976) later concluded that the dominant mechanism in particle segregation was a process called kinetic sieving. This occurs when void spaces develop within the flow into which the smallest particles move. This means that the finer particles percolate to the bottom of the flow, while the larger particles are found at the flow surface (Zanuttigh and Lamberti, 2007).

Takahashi, (1980) theorised that the presence of the larger particles at the front of a debris flow is the result of the faster transportation of the particles on the flow surface (the largest grains), when compared to the slower transport of the fine particles at the flow bottom (Takahashi, 1980; Lorenzini and Mazza, 2004; Zanuttigh and Lamberti, 2007). This type of movement, and the resulting increase of friction in the snout region and consequent slowing of the flow, gives a debris flow a look similar to that of a conveyor belt or caterpillar track; when a particle is transported to the front of the flow it either becomes static and is pushed along by the flow behind, or it becomes disseminated back into the flow body; if the particle is larger than those surrounding it, it will soon rise to the surface and begin its journey to the snout once again (Johnson, 1970; Iverson, 2003; Lorenzini and Mazza, 2004; Zanuttigh and Lamberti, 2007). The accumulation of boulders at the front of the flow is a consequence of the repetition of this sorting mechanism.

Suwa (1988) observed that due to the size of boulders (often nearly equal to the flow depth) carried at the front of a debris flow, dispersive pressure alone could not support their movement from the surface of the flow to the snout. Following model experiments Suwa (1988) argued that while the presence of large particles at the flow front is in part due to inverse grading (both dispersive pressure and kinetic sieving), these effects were unexpectedly small. It was determined that the greater velocity of the larger particles compared to the smaller particles played a more important role in particle segregation. Boulder velocity was much greater than fines velocity, resulting in them reaching the front of the flow faster, and because the largest boulders had a potential velocity greater than the velocity of the flow front itself, the boulders invariably collected at the flow front (Suwa, 1988; Zanuttigh and Lamberti, 2007).

2.6.3 Flow run-out

The ability of debris flows to travel long distances on relatively shallow slopes is increased by the accumulation of small amounts of clay in the mixture; clay reduces permeability and increases pore pressure, thereby increasing flow mobility (Costa, 1984). Local particle size distribution can also affect debris flow run-out. If the larger particles are much coarser than the smaller particles there is strong shear, which causes the larger particles to congregate at the flow front and increase resistance (Zanuttigh and Lamberti, 2007). This leads to the formation of lateral levees as the more liquefied flow behind the snout shoulders aside the slower coarser material. This can help to confine the flow and reduce lateral spreading resulting in a longer run out distance (Iverson, 2003; Zanuttigh and Lamberti, 2007).

2.7 Experimental debris flow studies

The need for greater understanding of debris flow dynamics and the lack of field data means that laboratory apparatus is becoming increasingly important for debris flow analysis; several studies have strongly advocated the use of experimental research. Davies (1994) concluded that it was possible to construct comprehensive working scale models regardless of the limitations of not being able to verify results with field data. Contreras and Davies (2000) surmised that there was no reason to believe that experimental material would act any differently to that in the field, and Kaitna *et al.*, (2007) state that parameters estimated independently using different rheological approaches were generally in agreement with both each other, and with field data. There is also potential in using data collected from experimental studies to calibrate and construct computer models, which may then to be used to produce unlimited data (Davies, 1994).

Experimental debris flow studies are frequently used with the aim of examining the processes and material dynamics of debris flows as a whole (Iverson and LaHusen, 1993; Armanini *et al.*, 2005; Kaitna and Rickenmann, 2005; Larcher *et al.*, 2007); often with a specific focus on material interactions (Hirano and Iwamoto, 1981; Van Steijn and Coutard, 1989; Davies, 1990; Parsons *et al.*, 2001; Ghilardi, 2003). Van Steijn and Coutard (1989) looked at the relationships between physical properties and particle orientation. Phillips and Davies (1991), and Major and Pierson (1992) explored the relationship of material viscosity with water content and sediment concentration. Ghilardi (2003) explored the link between velocity and sediment concentration values.

Many studies have also examined the rheological properties of debris flows (Phillips and Davies, 1991; Major and Pierson, 1992; Coussot *et al.*, 1998; Contreras and Davies, 2000; Hubl and Steinwendtner, 2000; Kaitna *et al.*, 2007). Parsons *et al.* (2001) examined the transition between rheological models. Iverson and LaHusen (1993) explored the dominance of Coulomb friction over shear resistance and momentum transport in water saturated sand and gravel debris flows, and the dominance of grain collisions or liquid viscosity in others. Attention has also been given to the coarse grained constituents of the flow, and flow models based around granular mechanics are often used (Kaitna *et al.*, 2007). Studies have to some extent also focused on visco-plastic flow models; where the concentration of fine material is higher (Coussot *et al.*, 1998; Kaitna *et al.*, 2007).

2.8 Experimental models

Table 2.2 summarises the range of apparatus used in experimental debris flow research; both technical apparatus (such as rheometers), and open and re-circulating flumes. Flumes are the most common method of experimentation; most range between 2 m and 10 m in length, and are less than 1 m in width. However, an important exception is the large scale US Geological Survey (USGS) flume; 95 m long and 2 m wide (Iverson and LaHusen, 1993). Flume slopes of up to 31° have been used, with most experimental designs enabling a variety of slope angles to be tested. Technical laboratory equipment includes rheometers, inclined plane tests, and viscometers.

The experimental materials highlighted in Table 2.2 include both natural and synthetic mixtures, with natural mixtures often including re-hydrated natural debris flow deposits. Two studies used synthetic particles (3.5 mm to 8 mm polyvinyl chloride - PVC). Experiments using natural materials include debris flow mixtures that have sediment by weight fractions of 50% to 80%. Of the grain sizes that were recorded all were less than 50 mm; around half the studies used grains of less than 10 mm, and half used grains of around 30 mm. Generally, the largest grains were used in open flume studies. Only a few studies noted the bulk density of their materials, and these ranged from 1400 kg m^{-3} to 2700 kg m^{-3}.

Experimental set-up	Test material	Dimensions (length x width x height) (m)	Slope (°)	Sediment by weight (%)	Grain Size (mm)	Density (kg m^{-3})
Conveyor belt flume *(Hirano and Iwamoto, 1981)*		2 x 0.1 x 0.2	0-0.5			
Not specified *(Van Steijn and Coutard, 1989)*	Coarse particles in water, silt, and clay	2-3.5 m long	10-30	0-60 <2mm 22 clay	2-5	1530-2140
Moving bed flume *(Davies, 1990)*	PVC pellets in water	2 x 0.05	5-19		4, 8	
Inverted 30° viscometer *(Phillips and Davies, 1991)*	New Zealand deposits	2 m diameter		5-9 gravel 12-24 fines 17-25 water	< 35	
Wide gap viscometer *(Major and Pierson, 1992)*	Mt St Helens deposits			62-68 <2mm 19-28 silt and clay		2650
Flume *(Iverson and LaHusen, 1993)*		95 x 2 x 1.2	2.5-31			
Flume *(Davies, 1994)*	Coal slack and wallpaper paste	10 x 0.15	6-15	0.2 wallpaper paste	<10	1400
Flume *(Major, 1997)*	Fluvial deposits	95 x 2 x 1.2	2.5-31	1-4 mud	< 32	
Rheometer *(Coussot et al., 1998)*	Moscardo deposits			80 solids 10 fines	< 50	2700
Cone and plate rheometer *(Contreras and Davies, 2000)*	Bullock Creek deposits	0.4 m diameter			< 35	
Tilting flume *(Gregoretti, 2000)*	Fractured gravel	6.75 x 0.6 x 0.25	12-20		23, 29, 34	
Conveyor belt flume *(Hubl and Steinwendtner, 2000)*	Natural deposits	2.5 x 0.12	15-30	55-69 solids	<20	1930-2150
Flume *(Parsons et al., 2001)*	Coarse material and fines	10 m long	10.7-15.2	2.5 clay		
Rectangular flume *(Ghilardi, 2003)*					5-20	

Re-circulating flume *(Armanini et al., 2005)*	Cylindrical PVC pellets in water	6 x 0.2-0.4	0-25		3.7
Vertically rotating drum *(Kaitna and Rickenmann, 2005)*	Artificial Carbopol Ultrez 10	2.5 m diameter			
Rotating flume *(Kaitna et al., 2007)*	Scala deposits	2.5 m diameter		9 fines	< 5
Re-circulating flume *(Larcher et al., 2007)*	PVC pellets in water	6 x 0.2-0.4	0-25		3.5

Table 2.2: Characteristics of experimental debris flow studies. The data is listed in order of the date of appearance in the literature (gaps indicate a lack of recorded data).

2.8.1 Specialist laboratory equipment

Specialist laboratory equipment is often the main research tool for determining the rheological parameters and material properties of debris flows. For example, Phillips and Davies (1991) used a 30° inverted cone and plate viscometer to test coarse grained materials from a New Zealand debris flow. Major and Pierson (1992) also used a viscometer (wide-gap concentric-cylinder), and used it to measure the rheology of naturally deposited slurries (Figure 2.8). Contreras and Davies (2000) followed on from the work of Phillips and Davies (1991) using a 30° inverted cone and plate viscometer/rheometer (Figure **2.9**) in order to address the issues of extreme data scatter in shear stresses observed in the 30° viscometer; finding that material behaved differently over time depending on its rheological history. Kaitna *et al.* (2007) measured material shear rates by using a ball measuring system; a rotating sphere dragged through sample material, enabling measurements of shear stress and shear rate.

Specialist laboratory equipment allows the testing of parameters otherwise un-measurable in the field. For example, the viscometer used by Major and Pierson (1992) was used because of its simplicity and the ability to conduct measurements over an extended period of time. However, there are also issues that arise from using specialised equipment, such as the physical limitations on the particle sizes able to be tested. For example, the 30° inverted cone and plate rheometer mentioned above is limited to material with a maximum size of 35 mm due to the height of the vertical inner wall (Phillips and Davies, 1991; Contreras and Davies, 2000), while the ball measuring system used by Kaitna *et al.* (2007) was limited to grain sizes of less than 10 mm.

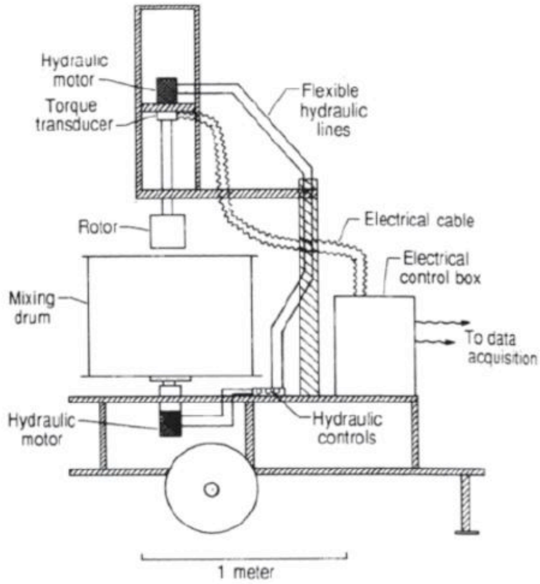


Figure 2.8: Schematic diagram of a concentric cylinder viscometer, as used by Major and Pierson (1992 p.842) to study the rheology of fine grained debris flow slurries.

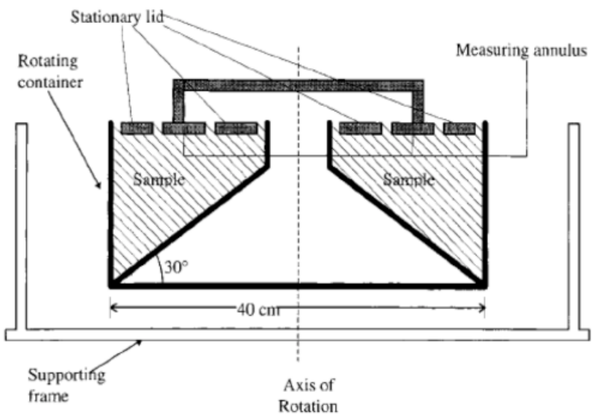


Figure 2.9: Schematic diagram of a 30° inverted cone and plate rheometer. The cone and plate apparatus shears material between a rotating lower layer and a stationary top plate, and was used by Contreras and Davies (2000 p.938) to examine debris flow rheology.

2.8.2 Flume apparatus

Flume apparatus is used in a wide range of experimental debris flow studies; a key benefit being that they can be used to replicate and represent natural flow channels. Davies (1994) constructed a 10 m long flume to examine the suitability of small scale debris flow models and concluded that the main value was that it allowed variables to be measured, such as velocity distributions, that were not possible in the field.

Both open (Figure 2.10) and re-circulating (Figure 2.11) flumes have been used to study debris flows. Open flumes generally consist of a three sided gully set at varying slopes while material is let loose to flow under the influence of gravity. As well as assessing generalised flow behaviour (Parsons *et al.*, 2001; Ghilardi, 2003), open flumes have been used to assess the more specific characteristics of debris flow initiation (Gregoretti, 2000; Blijenberg, 2007) and deposition (Major, 1997). Re-circulating flumes, on the other hand, generally consist of a conveyor belt set at different angles and speeds. Material is placed on the belt and by setting the flume bed to circulate at a set speed the flow effectively becomes fixed in space; this allows flow behaviour to be examined in more detail and over longer periods of time than is possible in a static flume. This improves measurement accuracy (Hirano and Iwamoto, 1981), and reduces the material consumption (Hubl and Steinwendtner, 2000). Re-circulating flumes, therefore, are often used to study the particular behaviours of a flow in motion (Hirano and Iwamoto, 1981; Davies, 1990; Hubl and Steinwendtner, 2000; Larcher *et al.*, 2007). For example, Davies (1990) set up a moving bed laboratory flume to study the development, behaviour and characteristics of high concentration granular flows, but found that it had its limits; concluding that obtaining data from a moving wave was problematic. However, Armanini *et al.* (2005) found that re-circulating flumes enabled the examination of rheological flow behaviour variations over flow depth; but stated that conclusions from experimental studies were bound to be revised as new techniques emerged.

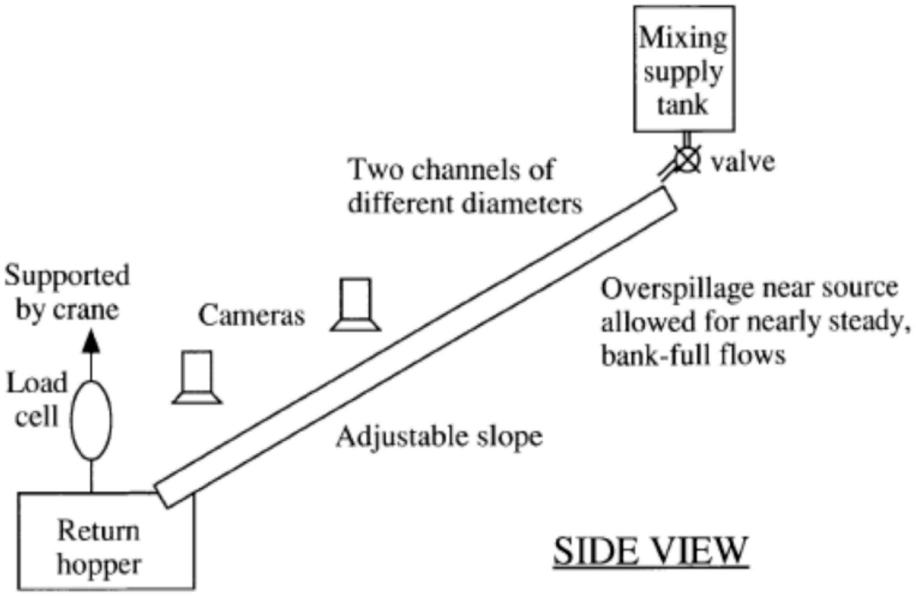


Figure 2.10: Diagram of the open channel flume used by Parsons *et al.*, (2001 p.429).

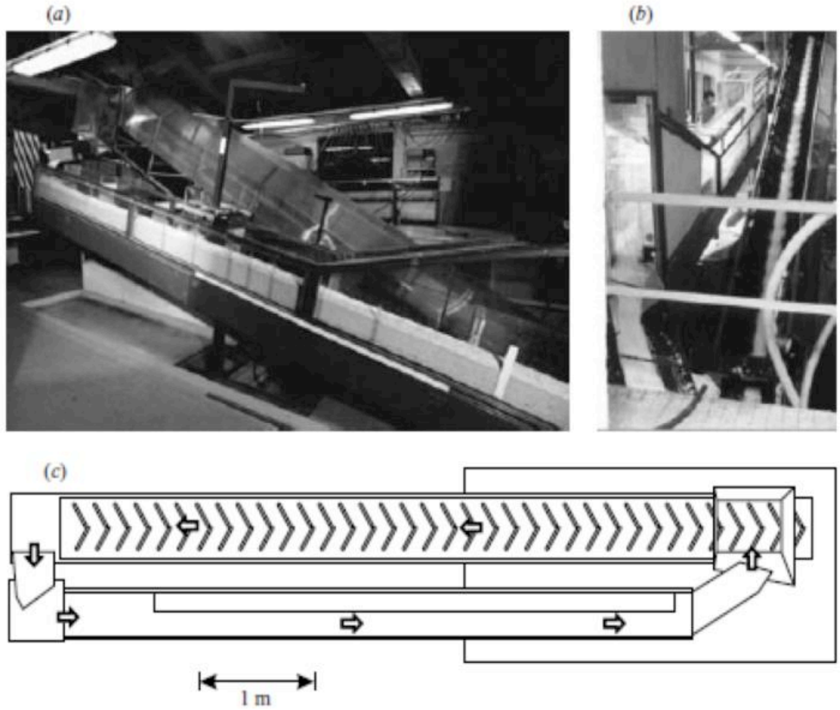


Figure 2.11: Re-circulating flume used to examine uniform debris flows by Armanini *et al.*, (2005 p.273). Figure shows a) side view, b) downstream view, and c) plan view.

Experimental debris flow flumes generally fall into three size categories; small (≤ 2 m long), medium (2 m to10 m long) and large (> 10 m long). Most early studies conducted experiments with small flumes (Hirano and Iwamoto, 1981; Van Steijn and Coutard, 1989; Davies, 1990). In the last ten years small flumes have generally been re-circulating; the ability to keep a flow effectively static removing the need for a long channel (Chow, 1959; Hubl and Steinwendtner, 2000; Kaitna and Rickenmann, 2005; Kaitna *et al.*, 2007). Davies (1994) declared that a 10 m long flume was sufficient for the creation of a steady state flow. Flumes of medium length generally have open channels (Hungr *et al.*, 1984; Davies, 1994; Gregoretti, 2000; Parsons *et al.*, 2001). The largest experimental flume to date is in the USA and was built in the 1990's by the USGS. It is 95 m long, 2 m wide and 1.5 m deep (Figure 2.12). This permitted a more natural approach to debris flow observation by enabling the use of large and realistic materials (Iverson and LaHusen, 1993; Major, 1997).

Figure 2.12: US Geological Survey outdoor flume in Oregon, America. It is 95 m in length, 2 m wide and 1.5 m deep. It slopes 31° through its upper 88 m, flattening to 2.5° over the last 7 m, making it possible to study a range of debris flow processes (Major, 1997 p.346).

Figure 2.13 highlights experimental flumes studies in which both the range of slope angle and grain size have been documented. Experimental slope angles of up to 31° have been used, with an average of between 10° and 25°; typical of real debris flows and similar to those in Figure 2.5 (Van Steijn and Coutard, 1989; Davies, 1990; 1994; Major, 1997; Gregoretti, 2000; Hubl and Steinwendtner, 2000; Armanini *et al.*, 2005; Larcher *et al.*, 2007). Generally, Figure 2.13 shows that smaller grain sizes are used in flumes with lower slope angles; although several studies used a large range of slopes and grain sizes.

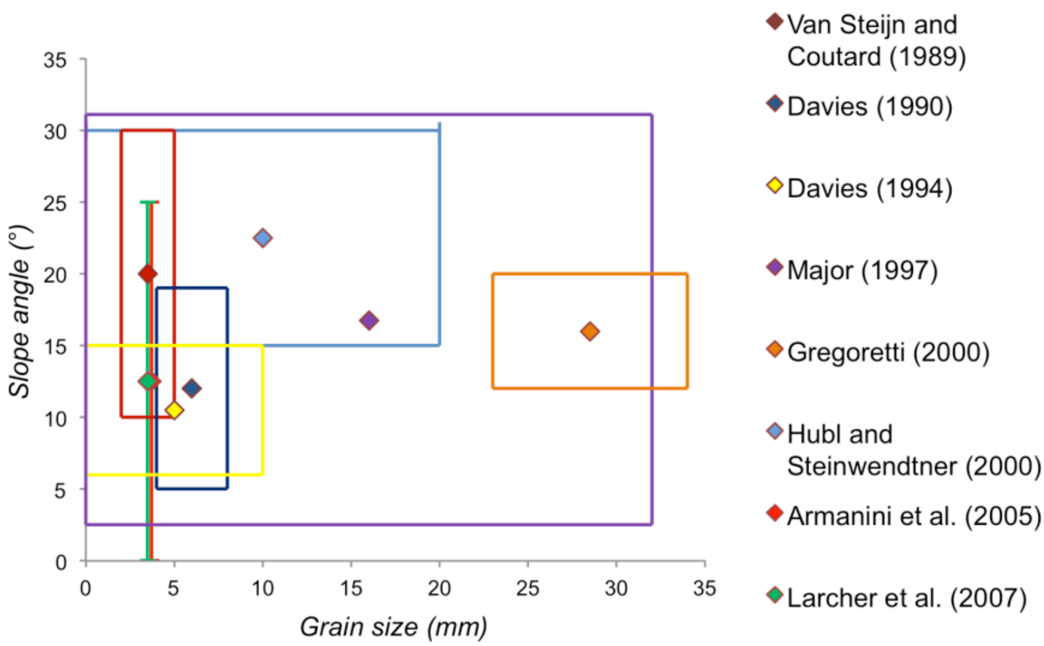


Figure 2.13: The range of slope angles and grain sizes used in experimental debris flow studies, as recorded in the literature; slope angles of up to 31°, and grain sizes less than 35 mm.

Table 2.2 also highlights the range of slope angles used in experimental debris flow studies and illustrates that in the extreme of the range Iverson and LaHusen (1993) and Major (1997) used slopes of 2.5°, although Davies (1994) found that no coherent debris flow surges developed at slopes of less than 6°. Blijenberg (2007) on the other hand used slopes of 35° to 38° to study triggering mechanisms. Depending on the part of the flow being examined higher slope angles are generally used to examine debris flow initiation, while lower slope angles are used to examine flow behaviour or depositional processes. The USGS flume has a variation in slope angle with distance down the flume in order to be more representative of natural channels (Iverson and

LaHusen, 1993; Major, 1997). However, most studies conduct experiments at different slope angles; one of the main advantages of free standing laboratory flumes being that channel slope can be altered relatively easily.

In order to help make experimental flume channels more realistic many studies roughen the channel boundary (Van Steijn and Coutard, 1989; Davies, 1990; 1994; Parsons *et al.*, 2001; Armanini *et al.*, 2005; Kaitna *et al.*, 2007; Larcher *et al.*, 2007). A basic method of roughening involves using the grooved side of a corrugated nylon belt (Davies, 1990). A more common technique is to glue particles to the channel (Larcher *et al.*, 2007). Parsons *et al.* (2001) used well-sorted sand particles of 1 mm diameter to roughen an experimental channel. Davies (1994) used crushed gravel of 3 mm to roughen a solid plane bed, while Van Steijn and Coutard (1989) used a layer of gravely loam.

Most flumes have a release gate in order to simulate debris flow initiation, and to introduce material in a steady manner (Van Steijn and Coutard, 1989; Iverson and LaHusen, 1993; Davies, 1994; Major, 1997; Gregoretti, 2000; Parsons *et al.*, 2001; Ghilardi, 2003). Release mechanisms are often synchronised with data acquisition equipment (Iverson and LaHusen, 1993). Flumes may also have catch cells at the base; although these are more common in recent studies (Gregoretti, 2000; Parsons *et al.*, 2001; Larcher *et al.*, 2007). The most common form of measurement technique for flume studies is a still- or video-camera; allowing the calculation of velocity profiles when used at several points. For example, Davies (1994) used a video camera and a 10 cm by 10 cm grid in a small scale flume in order to calculate flow velocity and depth. Other studies have made use of sensors (pressure transducers, impact plates etc.) to make direct measurements of flow characteristics. Visual tracers or painted pellets have also been used to map flow paths (Davies, 1990; Kaitna *et al.*, 2007).

2.9 Experimental materials

2.9.1 Natural material

In order to be as representative as possible, many experimental debris flow studies have used reconstituted debris from past flows (Hubl and Steinwendtner, 2000; Kaitna *et al.*, 2007). For example, Hubl and Steinwendtner (2000) used reconstituted material (varying sediment by weight from 55% to 69%) to determine which flow model best described debris flow behaviour; concluding that the best results came from the Bingham model. However, it must be remembered that due to the large range of different debris flow classifications any conclusions made using reconstituted material from a single event may not be universally representative.

Experimental debris flow mixture compositions used by Hubl and Steinwendtner (2000), Phillips and Davies (1991) and Coussot et al. (1998) are shown in Figure 2.14. All three studies used materials reconstructed from natural debris flows, and Figure 2.14 reflects the similarity of these mixtures to composition data recorded for natural debris flows. Several of the studies listed in Figure 2.14 did not record the proportion of debris flow fines, but even with limited data it can be seen that experimental mixtures may be created to reasonably represent the sediment composition of natural debris flows.

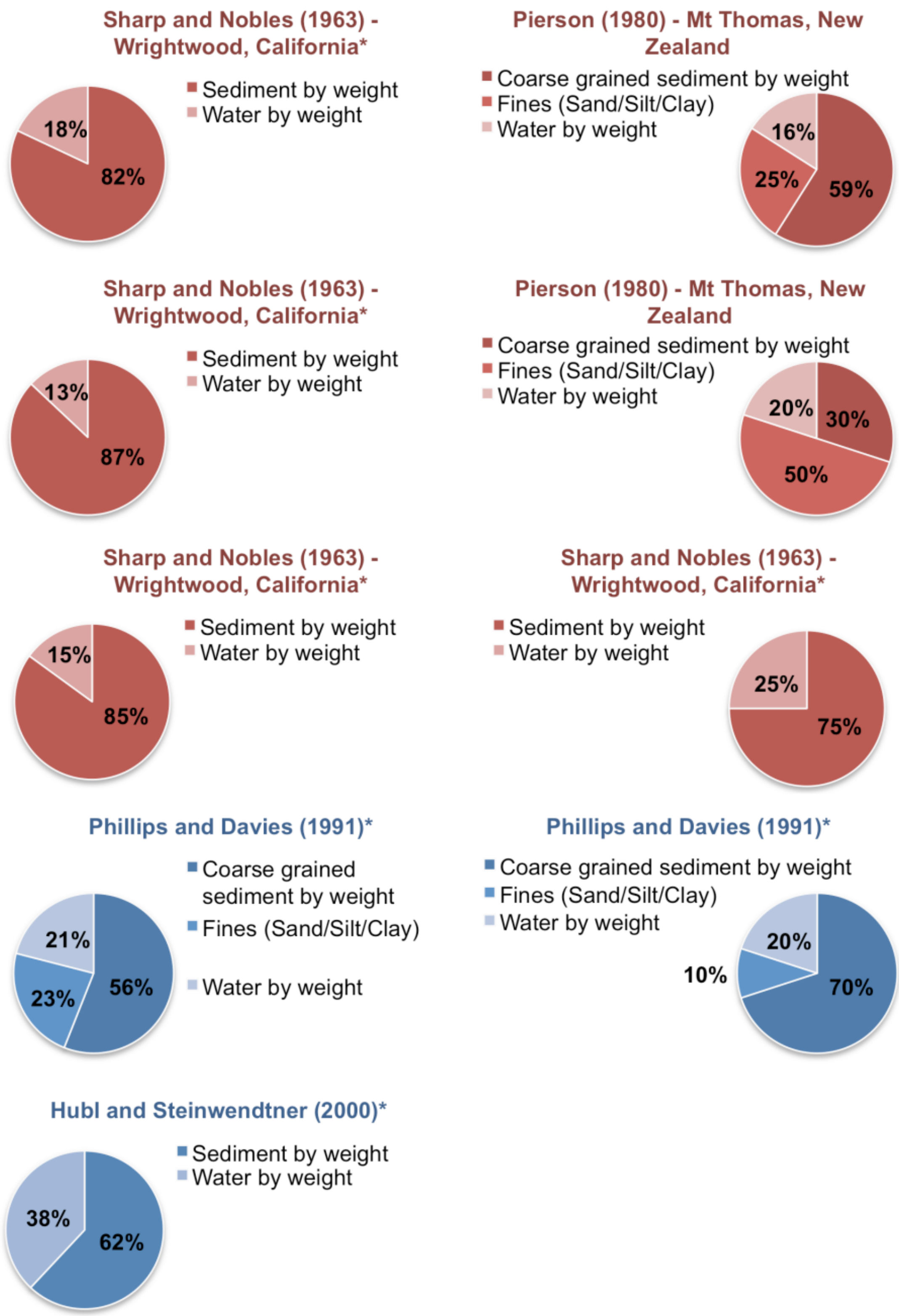


Figure 2.14: Debris flow mixture compositions; red charts show natural debris flow mixtures and blue charts show experimental mixtures. Most studies are vague; only three papers gave enough detail for charts to be produced. In cases where a range was recorded (10%-20% water by weight) the median was taken, ie.15%, and is indicated with a *.

Despite the usefulness of reconstituted material the most common experimental mixtures used in flume studies are composites of several different natural sediments mixed to represent natural debris flows (Van Steijn and Coutard, 1989; Davies, 1994; Major, 1997; Gregoretti, 2000; Parsons *et al.*, 2001; Ghilardi, 2003). The advantage of creating specific mixtures is the ability to vary sediment concentrations and examine the impact of these changes on flow behaviour (Gregoretti, 2000; Parsons *et al.*, 2001). Material mixtures are often based on field sites, with material collected from several locations. For example, Parsons *et al.* (2001) based their experimental mixtures on field studies in the Acquabona channel in the Italian Alps, and collected material from different areas in order to simulate a wide range of grain sizes – primarily by substituting sand for silt while keeping the clay content constant. The fines component was collected from US Silica, Ottawa, the coarse fraction was washed concrete sand, and the silt was derived from crushed silica fragments which produced highly angular grains representative of debris flow material.

Most studies aim to use the most realistic geological material possible; but this is difficult because natural debris flows range in particle size from fine grained silt and clay rich slurries, to coarse boulder dominated flows (Major, 1997). Debris flow sediment concentrations also vary between and during flows; Pierson, (1980) studied Mt St Thomas flows in New Zealand and concluded that there was 84% solids by weight during surges (70% gravel, 20% sand, 6% silt and 4% clay), and 54% solids by weight between surges (20% gravel, 54% sand, 15% silt and 11% clay). Most experimental studies using natural materials stay within the boundaries of mixture proportions set by natural flows. However, in order to be accommodated in scale models material sizes tend to be small; with mean diameters ranging from 3.5 mm to 50 mm (Figure 2.13). Phillips and Davies (1991) and Contreras and Davies (2000) had to remove particles larger than 35 mm from their material collected from New Zealand debris flows due to the physical size limitations of their cone and plate rheometer.

2.9.2 Artificial material

Some studies use artificial material in their debris flow mixtures. Studies using specialist laboratory equipment such as rheometers tend to focus on yield strength, viscosity values, and sediment concentrations, where the presence of natural material is necessary, and thus, it is in flume studies that artificial materials are more often found (Phillips and Davies, 1991; Major and Pierson, 1992; Contreras and Davies, 2000). For example, Davies (1994) conducted a 1:20 scaled flume study using high-viscosity wallpaper paste in water to represent interstitial fluid slurry, and coal particles to represent the coarse grains of the flow.

PVC pellets are the most commonly chosen artificial material. PVC material is lighter than natural sediment and is therefore more easily entrained in water. There is also a clear contrast in colour to water, enhancing observation (Armanini *et al.*, 2005). Armanini *et al.* (2005) used cylindrical pellets of 3.7 mm diameter in water to study the flow kinematics of high concentration granular-liquid mixtures in a re-circulating flume. The same was done by Davies (1990) using PVC pellets of both 4 mm and 8 mm diameter. Some of the pellets were painted white to act as tracers, and the study concluded that debris flow behaviour could be explained by the shearing of large grains in the fluid slurry. They also noted the distinct differences in behaviours of mixtures with differing bulk densities.

The use of artificial material in water results in a mix with well defined, and easily reproducible, properties. The creation of steady uniform flows makes it possible to estimate stresses using simple equations, enabling the extraction of statistically meaningful data at both the micro and macro scales (Larcher *et al.*, 2007). Artificial materials allow the examination of the internal flow structure of debris flows in a simplified and idealised manner; and in this sense artificial material is acceptable as a substitute to natural materials.

2.9.3 Sensitivity to material properties

The material used in experimental studies has a large influence on the experimental outcomes. For example, Phillips and Davies (1991) and Major and Pierson (1992) discovered that debris flow viscosity was extremely sensitive to water content and sediment concentration. An alteration of either property by only 1% to 2% resulted in a change in viscosity by a factor of one to two, and a change in shear stress by a factor of two. Research by Sosio and Crosta (2009) suggested that significant differences in rheological behaviour can be observed in materials with differing sediment sizes. The composition of a debris flow can also affect its mobility (Van Steijn and Coutard, 1989). Ghilardi (2003) observed that differences in sediment concentrations in flume studies resulted in variations in debris flow velocities, as well as depositional processes.

Due to the sensitivity of debris flows to only small changes within the sediment mixture there can be profound repercussions in experimental results if the material used is not representative of the processes being reconstructed. Major and Pierson (1992) concluded that due to this sensitivity a single rheological model would be unable to characterise all debris flows. Deciding upon a material (as well as the sediment concentrations) to represent debris flows in an experimental setting is therefore a very important consideration.

2.10 Experimental scale

In principle, when studies are scaled correctly there is every reason to believe that small scale models will give results comparable to those found in the nature. However, it is important that models are scaled properly and precisely, as changes to scale can affect the relationships between the properties of the model and those in reality in different ways (Chorley, 1967). Due to their reduced size there are issues with the suitability of flumes for representing natural events, especially as debris flow parameters used in a laboratory are very hard to verify; it can be difficult to determine the correctly scaled representative grain size and fluid viscosity, and in many cases the scale of individual particles is not taken into account (Parsons *et al.*, 2001). Both Major

(1997) and Blijenberg (2007) believe that small scale experiments are rarely representative of the natural environment, and are therefore limited in their insight.

Large scale flumes, such as that belonging to the USGS, can be argued to be realistic of natural events as they are able to accommodate large particles similar to those found in nature; and are therefore more adequate for simulating natural debris flows than smaller laboratory studies (Iverson and LaHusen, 1993; Major, 1997). However, small scale models can be useful in developing and testing predictive theories (D'Agostino *et al.*, 2010). For example, Davies (1994) modelled all flow aspects at a ratio of 1:20 in a small scale study. Rock material with a size of 0.2 m and density of 2650 kg m^{-3} was scaled down to 0.01 m and 1400 kg m^{-3} respectively. Davies (1994) found many similarities between debris flow waves witnessed in the field and those created in the flume, and concluded that the model design, when scaled up, would behave in a similar way to that of natural field data. Parsons *et al.* (2001) concluded that although in many cases the scale used in experimental studies may not always be relevant, the results are, by and large, relevant to the overall generalised behaviour of debris flows. D'Agostino *et al.* (2010) stated that while there may be scale issues with laboratory studies of debris flows, integrating the laboratory data with field observations can be useful in expanding the understanding of these hazardous events.

2.11 Experimental representation of prototype debris flows

Data collected in a controlled experimental setting can be much more consistent than field data (Mosley and Zimpfer, 1978). Contreras and Davies (2000) believed that results from material testing in a rheometer would be no different from the behaviour of debris flows material in the field. However, Blijenberg (2007) makes it clear that even by using field data the model used may not always be appropriate, and that relative uncertainty will always exist as so few studies can be verified with field events.

There are limitations in the design of many experimental studies. For example, few studies take into account channel bed or bank erodibility, or the fact that many natural channels have bends. Larcher *et al.* (2007) concluded that the highly idealised conditions of many experimental studies prevent them from being entirely representative of natural debris flow events, and that there can be limited validity in the results coming from them. This is especially true with studies that have used steady flow conditions, or particles no larger than a certain size. Phillips and Davies (1991) for example, concluded that standard viscometric equipment is not suitable for debris flow material due to particle size limitations.

Parsons *et al.* (2001) argued that the greatest obstacle in representing natural debris flows is the production of representative material and fluid viscosity. While natural materials can be argued to be more representative of field events, assumptions are often made that the results from one type of material are universal for all debris flows, when in fact there is a large range in natural debris flow types and materials. Despite this, many studies strive to represent debris flows as closely as possible, and to different degrees attain this; as demonstrated in Figure 2.14. However, the disparity between grain sizes (highlighted by Figure 2.5 and Figure 2.13), and the lack of studies using large grain sizes, makes comparisons difficult. Only a few studies have been able to reproduce experiments on a natural scale; such as that of the USGS facility in Oregon (Iverson and LaHusen, 1993; Major, 1997). These are especially important in their use for drawing comparisons with field events and their potential for validating the more commonly used small scale experiments.

2.12 Summary

This chapter has identified that debris flows are a complex physical phenomenon. They can be classified into many different types; from fines dominant to granular flows. However, it seems that there are common factors that link all debris flows. They can transport particles of a variety of sizes, with velocities ranging from 0.1 m s^{-1} to 30 m s^{-1}. Debris flows move in surges and are transient in nature, but also have a distinctive form; a high density coarse grained snout followed by a progressively thinning tail. Segregation dynamics of debris flows have been explained using theories such as kinetic sieving, dispersive pressure and differences in particle velocities. This chapter has shown that the composition of a debris flow (sediment type, concentration and size) can affect both the rheology and the dynamics of a flow. More specifically, it is the silt and clay content that has a large influence on solid-fluid interactions within a mixture.

This chapter has also explored the two main categories of experimental debris flow studies; those that utilise specialist laboratory equipment, and those that utilise flume apparatus (both open and re-circulating). It has shown that quantitative equipment is useful in collecting data that is normally not measurable in the field, but that due to particle size limitations results may not be representative of natural events. Flume studies have mostly been limited to dimensions of less than 10 m in length and 1 m in width. Channel slopes of up to 31° have been used; whilst in reality most natural slopes range from 15° to 40°. A range of materials have been used to represent debris flows, including rehydrated sediments from past debris flows, natural material components from around the world, and artificial materials such as PVC pellets. While natural materials can be argued to be more representative of debris flows, it is not always possible to include naturally sized sediment, such as boulders, in experimental studies. Artificial materials can be light and easily observable, but are generally only used to produce idealised flows (Larcher *et al.*, 2007).

The benefits of conducting experimental debris flow studies include the ability to produce comprehensive results in convenient, controlled and repeatable conditions. However, some of the major downfalls include the lack of studies for specific behavioural attributes, grain size limitations and the lack of channel erodibility. It is also difficult to represent a complex natural event on a small scale without introducing fundamental uncertainties. While debris flow flume experiments have been carried out at a range of scales, from the small (<2 m length) to the large (95 m length), there has been no study which has examined comparable debris flow mixtures in differently sized apparatus, and this chapter has highlighted the need to explore in more detail the similarities and differences of results produced in differently sized experimental flumes.

Past debris flow studies have shown that flow behaviour (notably flow form and velocity) is influenced by factors such as mixture composition and channel slope. However, this chapter has also highlighted the need for a study with a specific focus on understanding the interactions within a flow and the influences on debris flow behaviour. With little chance of conducting research on natural debris flows, and as long as the limitations of experimental studies are understood and accounted for, this chapter has shown that experimental flume studies can provide some useful insights into the behaviour of debris flows.

Chapter 3 Methodology

This chapter describes the methods and techniques used in this study. Two differently scaled experimental flumes were used to assess the influence of mixture composition and channel slope angle on debris flow behaviour, and to examine the extent to which results collected in different flume apparatus are comparable. The two experimental flumes are discussed; first the small flume and then the large flume. There is also a discussion on the selection of representative debris flow mixtures, data recording methods and data analysis methods.

3.1 Small scale laboratory flume

3.1.1 Experimental design

As outlined in Chapter 2, experimental laboratory studies offer the opportunities to reproduce experimental debris flow data in a controlled environment. The ability to replicate experiments is especially important for debris flow research, because the chances of directly observing even a single natural event are very rare. Having considered the advantages and disadvantages of different experimental approaches (section 2.8) it was decided that the apparatus best suited to representing and examining debris flow behaviour was the open channel flume.

For this study a simple small-scale laboratory debris flow channel was used to examine the influences of mixture composition and channel slope on debris flow behaviour. The results were then compared against those produced in a larger experimental channel (described in section 3.2) to assess whether results from two different sized flumes can be comparable. The small flume construction was based on Davies' (1994) *'Dynamically similar small-scale debris flow model'* study. It was small in size and simple in construction; a schematic diagram is shown in Figure 3.1. The channel was constructed out of semi-circular household guttering 2 m long, 0.1 m wide and 0.05 m deep. Channel slope was varied using a clamping device that allowed the flume head to be raised or lowered while the flume foot remained static. Based on the average slope angle of natural debris flow channels, the slope angle of the flume was varied between 15° and 30° at 5° intervals (Sharp and Nobles, 1953; Curry, 1966; Hungr *et al.*, 1984; Suwa and Yamakoshi, 2000).

The addition of coarse grains to a channel is a common method of creating a frictional base for a flow, and materials for this purpose in past studies have included sand, gravel and loamy deposits (Van Steijn and Coutard, 1989; Davies, 1994; Parsons *et al.*, 2001). Following the example of Larcher *et al.* (2007), the material used in this study was coarse grained sand particles (up to

2 mm diameter) glued to the inside of the flume. The use of waterproof silica glue ensured that the sand remained stable for the duration of the experiments.

To aid with data acquisition the flume channel was painted with several sets of horizontal reference markings. The flume was divided into eight equal 0.25 m sections along the channel length; each horizontal line was also divided to mark every 0.01 m across the channel width. The channel shape, roughness and markings are shown in the Figure 3.2. Material was poured into the top of the flume and collected at its base in a flat receiving tray.

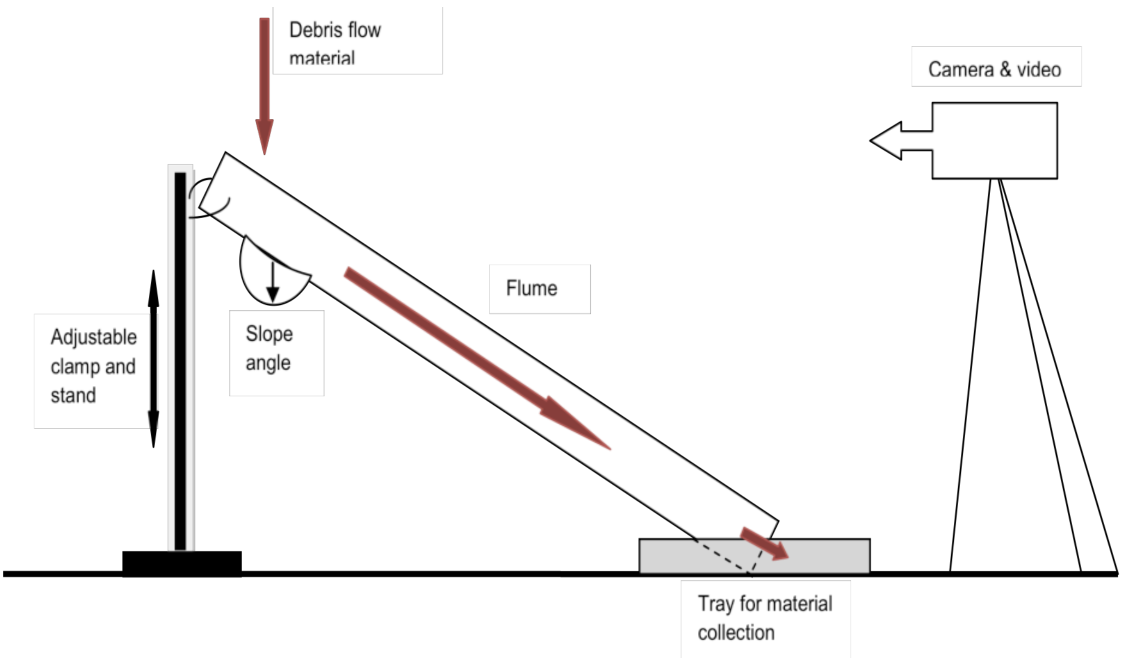


Figure 3.1: Schematic diagram of the small laboratory flume; length 2 m, width 0.1 m and depth 0.05 m. The channel is constructed out of semi-circular guttering roughened with sand.

Figure 3.2: Photograph of the small laboratory flume channel with reference markings; horizontal lines every 0.25 m along the flume length denoting every 0.01 m of the channel width.

3.1.2 Sediment mixture

Arguably the most critical aspect of any experimental debris flow study is the mixture used to represent the flow. Natural debris flows are comprised of coarse grains mixed with a selection of fine grains and water (Lorenzini and Mazza, 2004). Due to the large range of debris flow types the possible mixture combinations of a flow are highly variable, with each component affecting flow behaviour (Johnson and Rodine, 1984). Flume studies in the past have used both natural sediments and artificial materials to represent debris flows. While artificial materials can be easily reproduced and keep costs to a minimum, they are often not representative of field events (Major, 1997; Larcher et al., 2007). It is also erroneous to assume that results generated in experiments using a single sediment mixture will be universally applicable to all debris flows. For these reasons this study utilised natural sediments to create a variety of different debris flow mixtures to represent the variation in behaviour of natural debris flows – from muddy to granular. The mixtures used in this study comprised natural materials most commonly found in natural debris flows – coarse grains (represented by gravel), fine grains (represented by sand and clay), and water. Figure 3.3 illustrates typical debris flow mixtures that were used in the small laboratory flume and the sand glued to the sides of the flume to roughen the channel.

As demonstrated in Table 2.1, debris flow sediment by weight generally varies between 70% and 90%. The presence of fine sediment in a debris flow, especially clay, is important for the cohesion of the flow and the support of larger particles (Rodine and Johnson, 1976); natural debris flows tend to have a clay fraction of around 15% (Curry, 1966; Hungr et al., 1984; Iverson, 1997). These approximate values were adopted as the starting point for the composition of the experimental mixtures used in this study.

Figure 3.3: Photographs of typical debris flow mixtures used in the small laboratory flume. The roughened channel and variations in particle size are visible.

3.1.3 Sediment scaling and particle size analysis

The scaling of the sediment used in this study was similar to the approach taken by Davies (1994), which suggested that small-scale physical modelling of debris flows is both feasible and reliable. Davies (1994) took the typical debris flow properties as shown in Pierson (1980), and scaled them at an approximate 1:20 linear scale; a typical channel depth of 1 m was scaled to 0.05 m, and the average grain size of 0.2 m was scaled to 0.01 m. The results concluded that the model was comparable with field data. Therefore, the physical characteristics of the small flume and the sediment scaling in this study was broadly similar to that of Davies (1994); both have a channel depth of 0.05 m, and a coarse grained component of approximately 0.01 mm diameter. However, there is an important distinction between the two studies; Davies (1994) used coal and wallpaper paste to represent the debris flow mixtures, whereas this study utilised natural sediments (gravel, sand and clay) which make it more representative of natural debris flows.

The materials used in the small flume were analysed for their particle size characteristics. The clay fraction was analysed using a Coulter Laser Granulometer (LS 13 320), which utilises laser diffraction to determine particle size. The process involved using small samples of clay and adding hydrogen peroxide (H_2O_2) to dissolve organic matter. The sample was then centrifuged in distilled water to separate out the hydrogen peroxide. Sodium hexameta phosphate was added to the sample and left for at least 24 hours. The sample was then placed in the laser granulometer which passed the material through a broadened beam of laser light where the incident light was scattered onto a Fourier lens. The lens focused the light onto a detector array and a particle size distribution of the sample was calculated. The LS13 320 operates over a size range of 0.04 μm to 2000 μm. Several tests were conducted, and the average particle size of the clay fraction was found to be 6.21 μm.

The sand used in this study was general building sand (2 mm in diameter). It was dried at 120°C in an oven prior to use to ensure that no excess moisture was added to the debris flow mixtures.

The coarse grained component of the debris flow mixtures was represented by mixed gravel with an approximate size of 10 mm (D50 – between 8 mm and 11.2 mm). The gravel was machine sieved (sieve shaker by Fritsch) and the gravel particle size distribution is shown in Table 3.1 and Figure 3.14.

Particle size (mm)	Proportion (%)
< 2	2.5
2 - 2.8	0.5
2.8 – 4	1.6
4 - 5.6	10.5
5.6 – 8	33.2
8 - 11.2	46.6
11.2 – 16	5.1

Table 3.1: Particle size distribution of the gravel (coarse grained component) used in the debris flow mixtures in the small flume experiments.

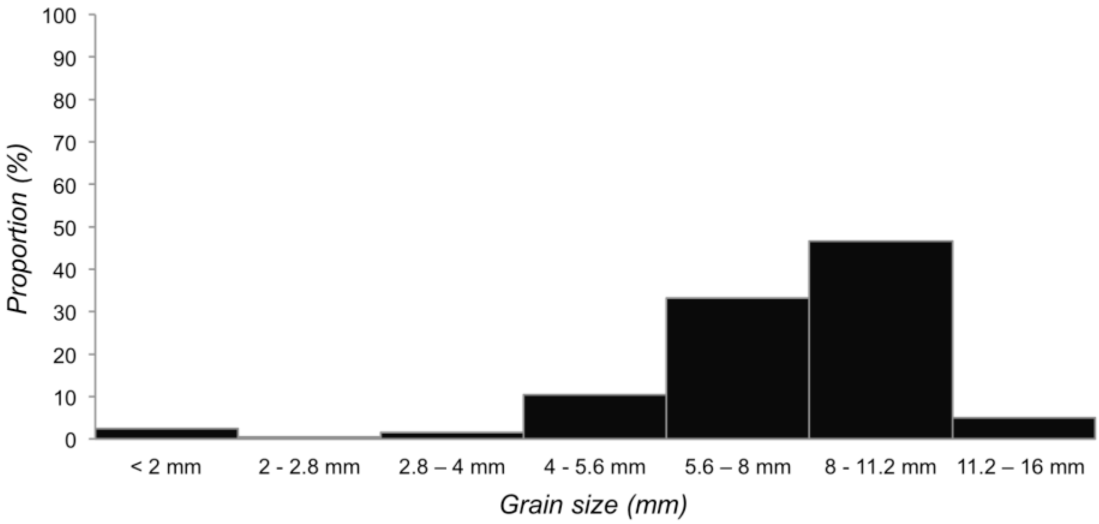


Figure 3.4: Histogram of the grain size distribution of the gravel (coarse grained component) used in the debris flow mixtures in the small flume experiments.

3.1.4 Representative debris flow mixtures

Debris flows are a distinct form of earth flow movement. Debris flow mixtures created in a laboratory must therefore model certain behaviours in order to be representative of natural flows. Most, if not all, of the following behaviours are characteristic of natural debris flows (Iverson, 2003):

- A distinction of flow behaviour between flow regions; and in some cases a change from laminar to turbulent flow with distance from the front of the flow (Johnson, 1970; Lorenzini and Mazza, 2004).
- The development of distinct surges within the flow (Takahashi, 1991; Zanuttigh and Lamberti, 2007).
- The formation of a snout at the front of the flow due to longitudinal sorting; the largest grains are located at the front and sides of the flow with a more fluid composition behind (Johnson, 1970; Bridgewater, 1976; Takahashi, 1980; Suwa, 1988; Iverson, 2003).
- A wider flow towards the snout, with a gradual reduction in the width and depth of the 'tail' behind this (Lorenzini and Mazza, 2004).
- The slowing of the frontal regions of the flow compared to the flow behind (Takahashi, 1991; Lorenzini and Mazza, 2004).
- A rolling or rotating behaviour of individual grains at the front of the flow, and/or static in-situ particles at the front of the flow pushed along from behind (Johnson, 1970; Iverson, 2003; Lorenzini and Mazza, 2004; Zanuttigh and Lamberti, 2007).
- The presence of a non-deforming rigid plug in the centre of the flow (Johnson, 1970).

The mixtures tested in the small laboratory flume were all assessed for the presence of these behaviours at the preliminary slope angles of 15° and 30°. Flows that exhibited these were re-examined with further runs and at 20° and 25°, allowing the identification of mixtures that most closely represented natural debris flow behaviour.

The key aim of this study was to gain a better understanding of debris flow behaviour and processes. This required the use of representative debris flow mixtures. Given that debris flows come in a large range of types, it was deemed sensible to examine more than one experimental mixture. Therefore, two representative debris flow mixtures were selected; one muddy/viscous in nature, and one viscous/granular in nature (section 4.1.4; Chapter 4). The experiments conducted in the small flume allowed both the examination of the influences of slope angle and mixture composition on flow behaviour, but also led to the selection of the two mixtures that were later tested in the larger flume in order to assess the comparability of results from different sized apparatus.

3.1.5 Experimental procedure

The procedure for creating debris flow mixtures for use in the small laboratory flume began with the weighing and mixing of the component materials. One kilogram of material was used in each mixture; various proportions of gravel, sand, clay and water. Components were weighed on laboratory scales and added sequentially to a beaker. The mixture was stirred to ensure complete mixing - flow initiation occurred immediately after input into the flume so settling was not an issue. Material was poured into the top of the flume and collected in a tray at its base. Each mixture left a slight residue in the mixing container; this was consistent between mixtures, and so did not bias the results to any great extent. The flume was cleaned prior to the next experimental run.

An iterative approach was applied to the design of the debris flow mixtures – the results from each flow informing the decisions relating to the composition of the next. For example, when a combination of materials resulted in a mixture that was not mobile, the next mixture may have had more water, less clay, or a combination of the two. The rationale behind this approach, as opposed to a systematic testing matrix, was to avoid the unmanageable number of permutations that would be required if all combinations of the four components of gravel, sand, clay and water were tested. Without this pragmatic approach this study would not have been feasible.

Overall, the small laboratory flume was used to test a total of 94 debris flows, comprising 38 different material mixtures. Every mixture was tested at 15° to ensure that it could flow at the lowest slope angle. This applied to all 38 mixtures except for six mixtures that were created in the first few runs of laboratory work, when only a 30° slope was used. Mixtures that displayed debris flow characteristics similar to those seen in nature were repeated up to three times at slopes of 15° and 30°. The mixtures that most closely represented natural debris flows were also tested at 20° and 25° (Table 4.2; Chapter 4). Two mixtures were selected which were representative of natural debris flow behaviour at all slope angles. These mixtures were also examined in a larger experimental flume in order to assess the comparability of results from different sized flume apparatus.

3.1.6 Data collection

The dynamics of each experimental debris flow in the small flume were recorded using a digital camera (Panasonic Lumix DMC-TZ8, wide-angle 25 mm (35 mm equivalent) lens). The camera was placed on a tripod facing the flume (Figure 3.1) and using the channel markings quantitative data was calculated. Flow velocity was calculated by measuring the time (to the nearest 0.08 seconds – one video frame) it took for the flow to travel each 0.25 m of the channel. This time divided by distance (0.25 m) enabled the production of the velocity data. Flow acceleration data was also calculated for each 0.25 m of the channel; difference in velocity divided by the difference in time. Flow width and length were measured to the nearest cm using the horizontal channel markings every 0.25 m down the channel. This gave results as a function of distance down the channel, as well as providing maximum and average data values per flow. It was not possible to directly measure flow depth, so this was calculated by dividing flow area by flow volume to produce a single average depth value per flow. Qualitative data was also noted, including flow behaviour such as the generation of surges, and the development of sediment plugs and flow snouts. Each flow was categorised into a distinct debris flow type (section 4.1.3). is a schematic diagram highlighting the characteristics of the small laboratory flume, and the debris flow morphological characteristics that were measured.

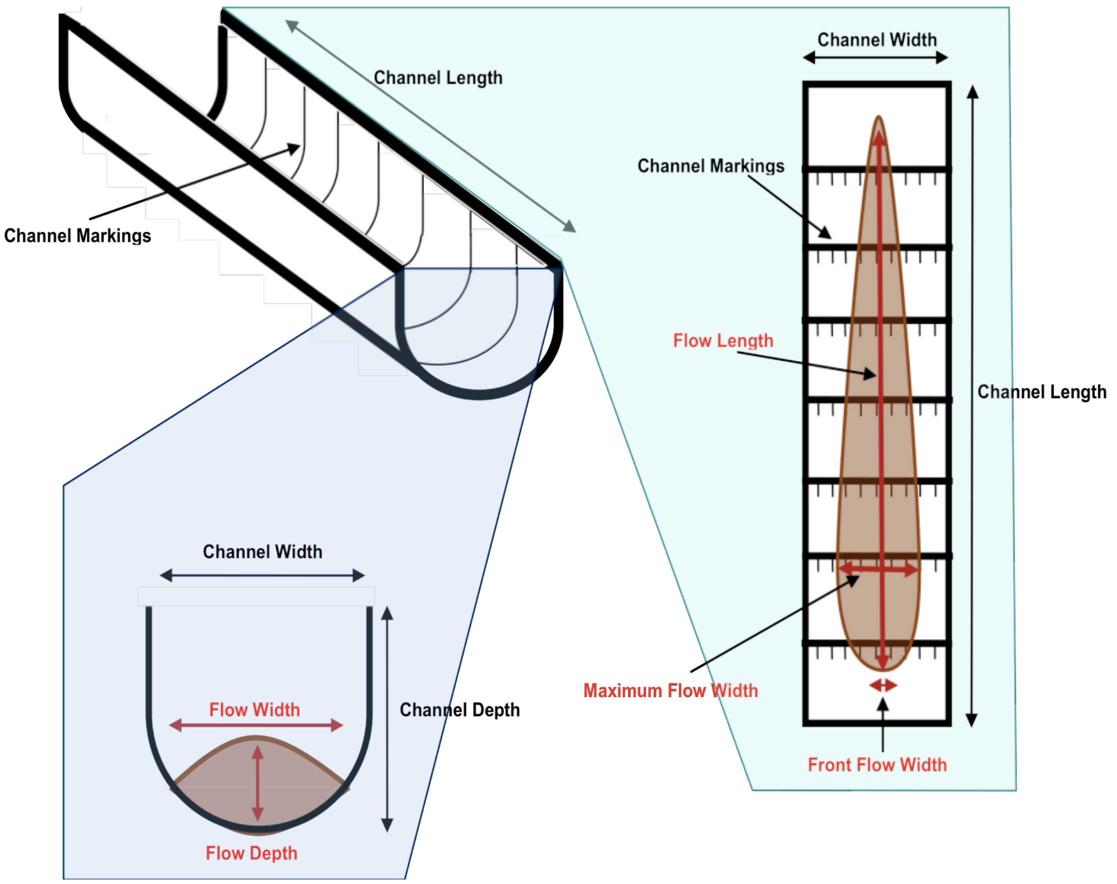


Figure 3.5: Schematic diagram of the small laboratory flume highlighting the channel dimensions and debris flow morphological characteristics (width, length and depth).

3.2 Large scale outdoor flume

3.2.1 Experimental design

The first objective of this research was to assess the extent to which flow behaviour was comparable at different experimental scales (section 1.3). This was achieved by using both the small laboratory flume described above, and a larger outdoor flume. Multiple debris flows were examined in the small laboratory flume and two mixtures were selected (based on their similarity to natural debris flow behaviour) to be scaled up, and examined in the large outdoor flume. This enabled the comparison of the results from the two different flumes, while keeping all other variables constant.

The large outdoor flume was constructed using similar materials to those used for the small flume. The flume channel was made of sturdy semi-circular plastic industrial guttering, 8 m long, 0.2 m wide and 0.1 m deep. The inside of the channel was roughened in the same manner as the small flume; coarse grained sand particles attached with silica glue.

The ratio of flume dimensions between the small and large flumes is shown in Table 3.2. In all aspects (with the exception of channel length) the large flume was twice the size of the smaller flume. In respect to the channel length, the large flume was four times larger than the small flume. In some instances during the testing of the debris flow mixtures in the small flume, the material mixtures exited the channel before they had chance to fully develop. Davies (1994) stated that a flume of length 10 m was sufficient to witness the creation of a steady state flow. Therefore, it was decided that increasing the flume length from 2 m to 8 m, rather than simply doubling it, would allow the flow characteristics of the mixtures to fully develop before exiting the channel. This study was novel in using both a small and a large flume in the same project.

	Small flume	**Large flume**	**Ratio**
Channel width (m)	0.1	0.2	2 : 1
Channel length (m)	2	8	4 : 1
Channel depth (m)	0.05	0.1	2 : 1

Table 3.2: Scaling table between the two experimental flumes.

Due to the extra length of the large flume the channel was supported within a latticed metal frame (Figure 3.6). This enabled the channel to be adjusted between 15° and 30° (the same range as the small flume) without the plastic channel deforming due to its weight. The adjustment of slope was achieved with the use of ‘feet’ at the flume head; strong metal poles holding the top of the flume off the ground whose height can be altered. The method of changing the slope angle is a common feature in previous experimental debris flow studies (Davies, 1990; 1994; Gregoretti, 2000; Hubl and Steinwendtner, 2000; Parsons *et al.*, 2001; Armanini *et al.*, 2005; Larcher *et al.*, 2007). The ability to alter the slope angle of the channel while keeping all other physical channel variables constant enabled the evaluation of the influence of slope on flow behaviour. Figure 3.6 highlights the physical features of the large outdoor flume.

Figure 3.6: Photographs showing the large experimental flume. A) Metal arm to swing camera over the flume. B) Flume release gate to hold debris flow material before it is released down the channel. C) Channel markers used to aid data collection.

The large flume had a sediment reservoir and a release gate at its head that was used to store the pre-mixed material prior to the flow (Figure 3.7). Material exiting the flume was collected in a large metal rectangular drum stationed at the bottom of the channel. The release gate that holds the mixture in place simulated the triggering of the flow, and enabled the mixture to be introduced consistently into the flume in a single pulse. The release gate was added to the large flume due to issuing arises during the small flume experiments; pouring the sediment directly into the flume sometimes produced super-elevation effects within the first 0.05 m to 0.1 m of the channel. This super-elevation may have impacted upon flow behaviour, and was obviously not constant for all mixtures. The presence of the sediment reservoir and release gate ensured that all debris flow mixtures started their journey down the flume smoothly and consistently.

Figure 3.7: Photograph of the mixture container and release gate attached to the head of the large outdoor flume.

3.2.2 Sediment mixture and scaling

With the choice of materials and sediment mixtures completed under objective one using the small flume, the main concern with the material used in the large flume was scaling it up to match the scaling of the channel. A simple approach was adopted. The fines components (clay and sand) were the same size as those used in the small flume. The coarse grained component however, was composed of gravel particles twice the size of those used in the small flume; sourced to be approximately 20 mm in diameter rather than 10 mm. This allowed the relative geometry of the coarse sediment to channel dimension ratio to be similar for both flumes (10:1 channel width, and 5:1 channel depth). The volume of sediment was also scaled up at similar ratio; 10:1 between the small flume (1 kg) and the large flume (10 kg) mixtures. Table 3.3 and Figure 3.8 show the particle size distribution of the coarse grained material (gravel) used in the large flume (D_{50} – between 16 mm and 22 mm). There is some uncertainty inherent in the scaling up of the mixtures because of particle size differences in the coarse sediment (gravel) fraction, and therefore further evaluation is required when comparing results from the small and large flume facilities.

Particle Size (mm)	Concentration (%)
< 2	0.50
2 - 2.8	0.00
2.8 – 4	0.00
4 - 5.6	0.02
5.6 – 8	0.20
8 - 11.2	7.69
11.2 – 16	40.78
16 – 22	50.82

Table 3.3: Particle size distribution of the gravel (coarse grained component) used in the debris flow mixtures in the large flume experiments.

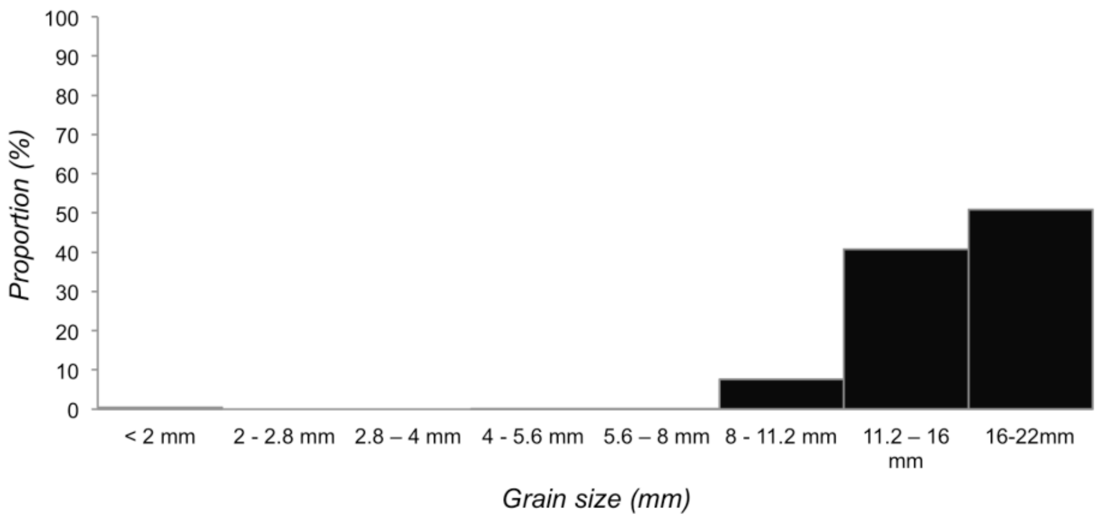


Figure 3.8: Histogram of the grain size distribution of the gravel (coarse grained component) used in the debris flow mixtures in the large flume experiments.

3.2.3 Experimental procedure and data collection

The large outdoor flume was used to test a total of 32 debris flows using two different sediment mixtures selected from the mixtures examined in the small laboratory flume; one muddy/viscous in nature, and one viscous/granular in nature (section 4.2.2). Flows were repeated four times at 15°, 20°, 25° and 30° slopes. The same quantitative and qualitative properties of each flow were measured in the large flume as were measured in the small flume; flow velocity, width, length, depth, and flow behaviours such as the generation of surges, plugs and snouts. This enabled a comparison of the results from both flumes, and allowed an assessment of whether or not the flumes produced similar results for the same mixtures. The data collection techniques in the small and large flume were the same. However, due to the large size of the outdoor flume the flows could not be filmed obliquely, as in the small laboratory flume. Instead they were filmed vertically using a metal scaffold onto which a camera was mounted (Figure 3.6). The camera mount also allowed the camera to be rotated so that it was orthogonal to the flume so that there angular distortion was minimised. Picture quality was good for the entire flow, and analysis of the flow morphology was straightforward.

3.3 Measurement Precision

Flow width, length and depth were each measured to the nearest cm using the horizontal flume markings. However, the flow velocity calculations relied on two measurements – time as recorded by the digital video camera, and the distance between each flume channel marking (0.25 m in the small flume and 0.5 m in the large flume). Two distinct factors affected the accuracy of the velocity data. Firstly, the ability to see the front of the flow as it reached each channel marking (often made difficult during afternoon filming due to shadows), and secondly, the low frame rate of the digital camera (a resolution of 0.08 seconds per frame; a frame rate of 12.5 frames per second). Because of this low frame rate the accuracy to which velocity was calculated varied according to the speed of the flow as the positioning of the material could only be differentiated by a minimum of one frame (0.08 seconds). At high flow speeds (where the number of 0.08 second frames per 0.25 m or 0.5 m marker of the channel was very low) the accuracy of measurement was in the order of ±3 m s^{-1} (one frame per 0.25 m mark) in the small flume, and ±6 m s^{-1} (one frame per 0.5 m mark) in the large flume. At low speeds accuracy increased proportionally to the number of frames between channel markings. At the lowest flow speeds, where the number of frames was high, accuracy was in the order of ±0.01 m s^{-1} for both flumes. Therefore, in order to show the greatest accuracy where possible, flow velocity was determined to the nearest 0.01 m s^{-1}. As the resolution of the velocity data was determined by the video frame rate the accuracy at high velocities is not as good as could be supposed by the reporting to two decimal places, this was done however to maximise accuracy at the lowest flow rates – this must be bourn in mind when considering the results. It must also be remembered that flow acceleration was calculated from the velocity data and therefore any associated errors are increased in the acceleration data.

3.4 Summary

This study took a novel dual-scale approach to debris flow experimental modelling. A small laboratory flume was constructed to test a variety of debris flow mixtures at different slope angles. The debris flow mixtures were created using natural sediments; gravel, sand, clay and water. An iterative approach was taken whereby each successive mixture was based on the observed performance/characteristics of the previous mixtures. Several criteria were used to design the debris flow mixtures, including the presence of typical debris flow morphology and behaviour. The results allowed the assessment of the extent to which channel slope angle and mixture composition influenced debris flow behaviour. Two experimental mixtures were also examined in a larger outdoor flume in order to examine the comparability of results collected in different sized flume apparatus.

The large outdoor flume was geometrically scaled so that it was approximately twice the size of the small laboratory flume. In order to preserve the geometrical relationship between the channel dimensions and the coarse component of the debris flows the gravel was increased in size from 10 mm average in the small flume to 20 mm average in the large flume. This gave the same ratio for channel width: grain size (1:10) and channel depth: grain size (1:5) for both flumes. The sand and clay components and flume roughness were identical between the two flumes. There were 94 experimental debris flows (38 different sediment mixtures) conducted in the small flume, and 32 experimental debris flows (two different sediment mixtures) conducted in the large flume. The results collected include flow velocity, width, length and depth, as well as qualitative recordings of flow morphology and behaviour.

Chapter 4 Results

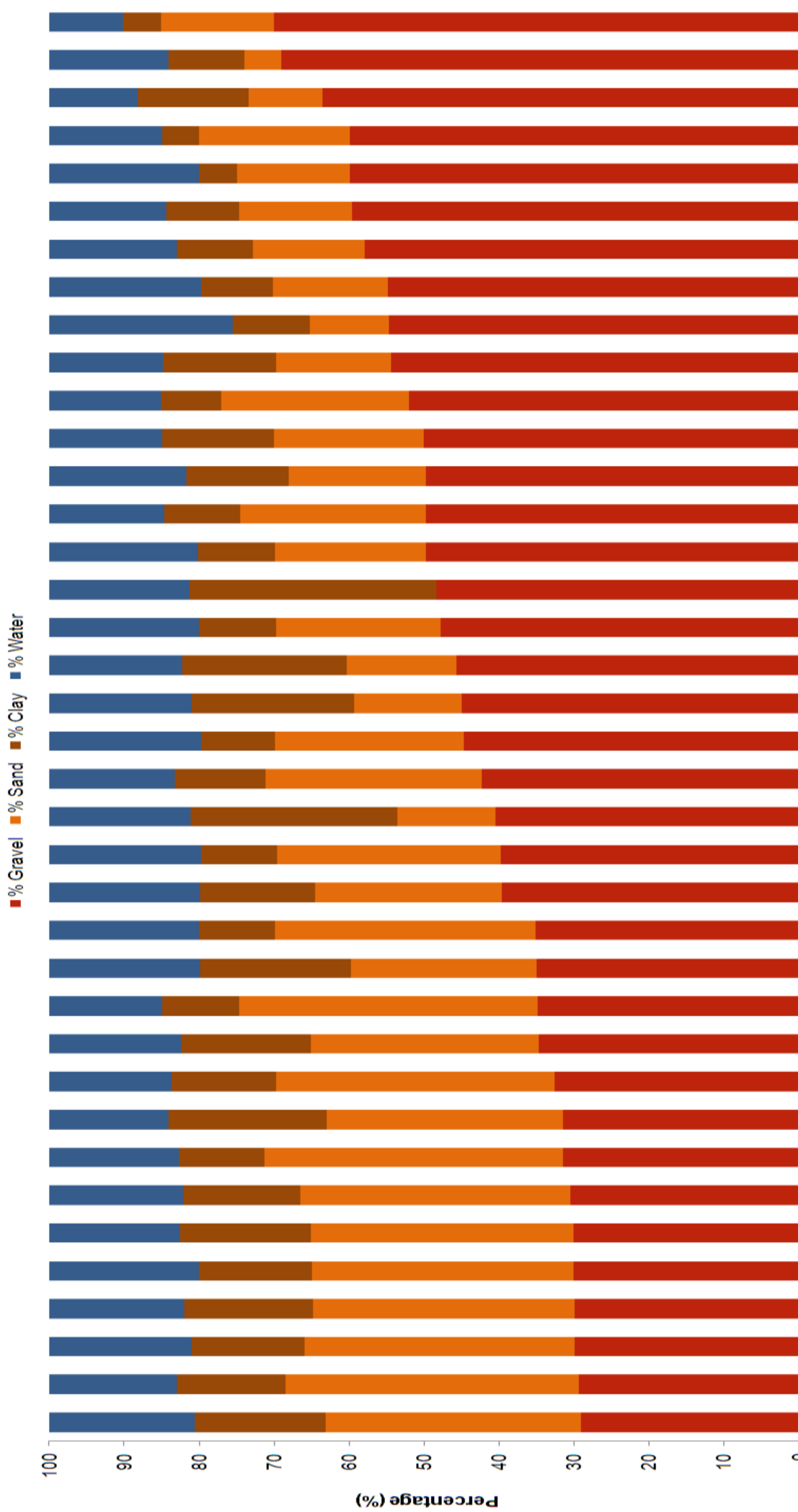
This chapter presents the results from experiments conducted in two different sized experimental debris flow flumes. The first section details the data collected from flows in a small laboratory flume, and includes a discussion regarding the selection of representative debris flow mixtures. The second section describes the data collected from flows in a large outdoor flume, and discusses the extent to which experimental debris flow behaviour is comparable between the small and large flume. Sections three and four highlight results from both flumes, and examine objectives two and three of this study; the influence of slope angle and sediment mixture composition on debris flow behaviour.

4.1 Small scale laboratory flume

4.1.1 Experimental runs

Figure 4.1 shows the range of debris flow mixtures tested in the small laboratory flume. All of the mixtures fall within the range of sediment concentrations identified in the literature for natural debris flows (usually between 70% and 90%) (Sharp and Nobles, 1953; Pierson, 1980; Costa, 1984; Pierson, 1985; Costa, 1988; Phillips and Davies, 1989; Coussot and Meunier, 1996). The debris flow mixture compositions (by weight) shown in Figure 4.1 are ordered in relation to the coarse grained fraction of the mixtures (gravel). This was the component with the most variation, ranging from 29% to 70% gravel by weight. The sand content ranged from 5% to 40% by weight, and the clay content ranged from 5% to 33% by weight. The majority of the mixtures had clay contents of less than 15%. This is similar to the generally low clay content found in natural debris flows (Curry, 1966; Pierson, 1980; 1981; Perez, 2001). However, Vandine (1985) highlighted a debris flow in western Canada with a clay content of 35%. Although this is rather unusual for natural debris flows, it is still accounted for in the small flume experiments; five mixtures had clay contents greater than 20% Figure 4.1.

In terms of the solids fraction, the proportion of gravel (as a percentage of the solids fraction) in the mixtures ranged from 35% to 83% (by weight), the proportion of sand ranged from 6% to 48%, and the proportion of clay ranged from 5% to 40%. Bulk densities varied from 1641 kg m^{-3} to 2019 kg m^{-3}, as shown in Figure 4.2. The dominant peaks in the black bars reflect the mixtures with the most experimental repeats.



	% Water	% Clay	% Sand	% Gravel
M21	19.4	17.4	34.1	29.1
M23	17.0	14.6	39.2	29.3
M36	19.1	15.0	36.0	29.9
M31	18.0	17.1	35.0	29.9
M18	20.0	15.0	35.0	30.1
M20	17.5	17.4	35.0	30.1
M22	17.9	15.6	35.9	30.5
M32	17.3	11.4	39.8	31.5
M19	16.0	21.0	31.5	31.5
M24	16.3	13.9	37.2	32.5
M25	17.5	17.3	30.4	34.8
M35	15.1	10.2	39.9	34.8
M17	20.1	20.1	24.9	34.9
M30	20.0	10.1	34.9	35.1
M16	20.1	15.4	24.9	39.6
M37	20.2	10.1	29.8	39.8
M2	18.8	27.5	13.1	40.5
M26	16.8	12.1	28.8	42.3
M29	20.3	9.9	25.1	44.8
M4	18.9	21.7	14.4	45.0
M3	17.7	22.0	14.7	45.7
M33	20.0	10.2	21.9	47.9
M1	18.7	32.9	0.0	48.4
M28	19.9	10.2	20.2	49.7
M34	15.3	10.2	24.8	49.7
M14	18.3	13.6	18.3	49.8
M15	15.1	14.9	20.0	50.1
M38	15.0	8.0	25.1	52.0
M11	15.3	15.0	15.4	54.4
M5	24.5	10.2	10.6	54.7
M12	20.2	9.7	15.3	54.8
M27	17.0	10.2	14.9	57.9
M10	15.7	9.7	15.0	59.6
M9	20.0	5.1	15.0	59.9
M13	15.1	4.9	20.0	60.0
M8	11.8	14.8	9.7	63.6
M7	15.9	10.0	5.0	69.1
M6	9.9	5.0	15.1	70.0

Figure 4.1: Comparison of the 38 debris flow mixtures (% by weight) tested in the small laboratory flume.

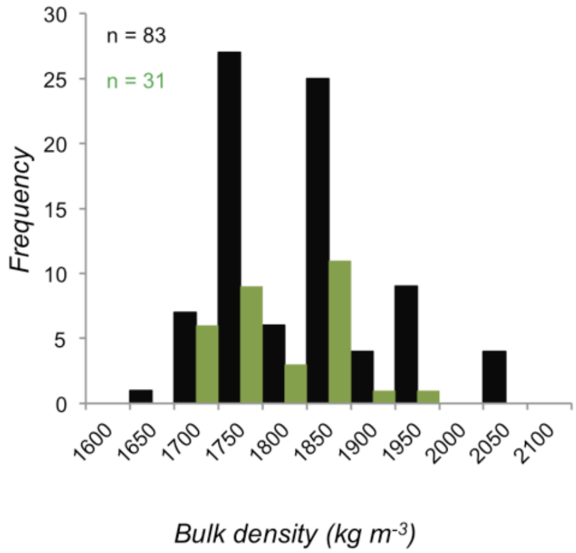


Figure 4.2: Histogram showing the bulk densities of the debris flow mixtures tested in the small laboratory flume. Black bars include all runs where mixture bulk density was calculated and includes experimental repetitions. Green bars include no experimental repetitions, therefore showing each mixture only once.

4.1.2 Quantitative data

The mixtures described above were tested multiple times in the small experimental flume. The mixtures that displayed representative debris flow characteristics (as described in section 3.1.4) were tested more frequently, and at a greater number of slope angles, than the mixtures that did not display typical debris flow behaviour. The flow characteristics of velocity, width, length and depth, as defined in Figure 3.4, were measured and collated into Table 4.1. The maximum and average values per flow are recorded. There are no maximum depth data as only average depth was calculated (section 3.1.6).

As demonstrated in Table 4.1, slope angle had an important impact on flow velocity, with both the average and maximum being greater in flows at greater slope angles. Average velocity ranged from 0.02 m s^{-1} to 1.97 m s^{-1}, and maximum velocity ranged from 0.28 m s^{-1} to 3.13 m s^{-1}. The maximum flow width was often close to the limit of the channel width (0.1 m), and several flows reached the maximum flow length of 2 m; suggesting that the flows were, at least in part, constrained by the channel dimensions. Flows that ran to the greatest lengths (greatest extension) also had the fastest average velocities.

Mixture	Slope (degrees) and run number	Average				Maximum		
		Velocity ($m\ s^{-1}$)	Width (m)	Length (m)	Depth (m)	Velocity ($m\ s^{-1}$)	Width (m)	Length (m)
5	15_1	0.94	0.04	1.03	0.0058	1.56	0.04	1.50
	30_1	1.34	0.04	0.81	0.0083	1.56	0.08	1.50
	30_2	0.86	0.04	0.38	0.0063	1.04	0.07	0.50
29	15_1	0.75	0.05	0.81	0.0078	1.04	0.07	1.25
37	15_1	1.13	0.05	1.00	0.0123	1.56	0.06	1.50
	15_2	1.28	0.04	1.09	0.0137	1.56	0.06	1.75
	30_1	1.86	0.04	1.03	0.0104	3.13	0.06	1.50
	30_2	1.90	0.04	0.97	0.0130	3.13	0.06	1.50
12	15_1	1.01	0.04	1.03	0.0083	1.56	0.06	1.50
	15_2	1.89	0.04	1.03	0.0087	1.56	0.06	1.50
	30_1	0.94	0.04	1.06	0.0120	1.56	0.09	1.75
	30_2	1.11	0.05	0.84	0.0129	3.13	0.05	1.25
16	15_1	0.94	0.05	0.91		1.04	0.07	1.25
17	15_1	1.02	0.04	1.09	0.0183	1.56	0.07	1.75
	15_2	0.79	0.03	0.40	0.0109	1.79	0.05	0.75
33	15_1	1.17	0.04	0.75	0.0092	2.08	0.06	1.00
	15_2	0.69	0.04	0.34	0.0033	1.25	0.07	0.50
18	15_1	1.07	0.05	1.00	0.0125	1.56	0.06	1.50
30	15_1	0.70	0.05	0.72	0.0096	1.04	0.06	1.00
	15_2	1.19	0.04	0.94	0.0087	2.78	0.06	1.25
	30_1	1.97	0.05	1.03	0.0122	3.13	0.06	1.75
	30_2	1.72	0.04	0.94	0.0098	3.13	0.06	1.25
9	15_1	0.72	0.04	0.87	0.0039	0.28	0.02	1.25
	30_1	1.30	0.04	1.13	0.0091	1.04	0.07	2.00
	30_2	0.28	0.02	0.25	0.0145	1.56	0.07	0.25
28	15_1	1.16	0.05	0.84	0.0157	1.56	0.07	1.50
21	15_1	1.02	0.03	1.13	0.0167	1.56	0.05	2.00
	15_2	0.79	0.04	0.40	0.0141	1.67	0.06	0.75
36	15_1	0.92	0.04	0.81	0.0091	2.78	0.06	1.00
	15_2	1.14	0.04	0.88	0.0125	2.78	0.06	1.25
	20_1	0.95	0.04	0.78	0.0091	1.56	0.06	1.00
	20_2	1.65	0.04	1.03	0.0091	1.56	0.05	1.50
	25_1	1.27	0.04	0.72	0.0091	1.56	0.06	1.00
	25_2	1.24	0.03	1.03	0.0109	1.56	0.06	1.50
	30_1	1.24	0.04	1.03	0.0070	1.04	0.06	1.50
	30_2	1.50	0.03	1.09	0.0130	2.27	0.06	1.75
4	15_1	0.89	0.04	0.94	0.0091	0.62	0.06	1.25
	30_1	0.44	0.05	0.34	0.0078	1.04	0.09	0.50
	30_2	0.31	0.05	0.50	0.0052	0.62	0.08	0.75
2	30_1	0.25	0.04	0.42		0.52	0.09	0.50
1	30_1	0.02	0.04	0.38		0.02	0.07	0.50
14	15_1	0.94	0.05	0.84	0.0091	1.56	0.05	1.25
	15_2	1.60	0.04	1.13	0.0052	0.52	0.07	2.00
	30_1	0.94	0.04	0.94	0.0091	1.04	0.09	1.25
	30_2	0.34	0.04	0.35	0.0174	3.13	0.05	0.50
31	15_1	0.67	0.04	0.81	0.0087	1.04	0.05	1.00
	15_2	0.92	0.04	0.94	0.0109	1.56	0.06	1.25

22	15_1	0.89	0.04	1.09	0.0188	1.56	0.06	1.75
	15_2	0.60	0.04	0.72	0.0075	1.56	0.06	1.00
3	30_1	0.35	0.04	0.55		0.52	0.09	0.75
25	15_1	1.12	0.04	0.97	0.0125	3.13	0.06	1.50
	15_2	0.59	0.04	0.63	0.0174	1.56	0.06	1.25
20	15_1	0.60	0.04	0.75		1.04	0.08	1.25
32	15_1	0.46	0.04	0.66	0.0072	1.04	0.07	0.75
	15_2	0.84	0.04	0.94	0.0098	2.08	0.06	1.25
27	15_1	0.75	0.04	0.45	0.0102	1.04	0.06	0.50
23	15_1	0.66	0.04	1.03	0.0163	1.04	0.06	1.50
	15_2	0.60	0.04	0.66	0.0082	1.56	0.06	0.75
26	15_1	0.38	0.05	0.44	0.0082	0.52	0.06	0.50
24	15_1	0.70	0.04	1.03	0.0150	1.56	0.06	1.50
	15_2	0.58	0.04	0.74	0.0067	1.04	0.05	1.00
19	15_1	0.35	0.04	0.42	0.0095	0.62	0.06	0.50
7	15_1	1.01	0.05	0.84	0.0036	0.35	0.03	1.25
	30_1	1.63	0.04	0.97	0.0127	1.56	0.09	1.50
	30_2	0.35	0.03	0.25	0.0091	3.13	0.08	0.25
10	15_1	0.52	0.05	0.47	0.0082	0.78	0.06	1.00
	15_2	1.89	0.03	1.09	0.0082	0.78	0.06	1.75
	30_1	0.50	0.03	0.60	0.0055	0.78	0.09	0.75
	30_2	0.51	0.04	0.64	0.0136	3.13	0.05	0.75
34	15_1	1.02	0.04	0.84	0.0114	2.08	0.06	1.25
	15_2	0.83	0.04	0.73	0.0109	2.08	0.06	1.00
	20_1	0.72	0.04	0.59	0.0089	1.04	0.07	1.00
	20_2	0.69	0.04	0.81	0.0100	1.56	0.06	1.00
	25_1	0.89	0.04	0.66	0.0068	1.04	0.07	0.75
	25_2	0.36	0.04	0.84	0.0150	0.52	0.06	1.25
	30_1	0.68	0.04	0.54	0.0030	1.04	0.06	0.75
	30_2	0.77	0.04	0.63	0.0076	0.78	0.06	0.75
11	30_1	0.31	0.04	0.44		0.52	0.07	0.50
13	15_1	1.01	0.05	0.88	0.0038	0.78	0.05	1.25
	15_2	1.20	0.03	1.13	0.0090	0.78	0.07	2.00
	30_1	0.43	0.04	0.25	0.0086	1.56	0.09	0.25
	30_2	0.58	0.03	0.81	0.0133	1.56	0.05	1.25
35	15_1	0.65	0.04	0.75	0.0082	1.56	0.06	1.00
15	15_1	0.50	0.04	0.75	0.0130	1.56	0.06	1.00
38	15_1	1.02	0.04	0.94	0.0136	2.08	0.06	1.25
	15_2	0.95	0.04	0.78	0.0125	1.56	0.06	1.25
	20_1	1.61	0.04	1.03	0.0127	1.56	0.05	1.50
	20_2	1.50	0.04	1.09	0.0123	1.56	0.06	1.75
	25_1	1.30	0.04	0.81	0.0114	1.56	0.07	1.25
	25_2	1.37	0.04	0.81	0.0124	1.56	0.06	1.25
	30_1	1.30	0.03	1.09	0.0100	3.13	0.06	1.75
	30_2	1.43	0.04	1.03	0.0152	1.56	0.07	1.50
8	30_1	0.47	0.03	0.28		0.63	0.09	0.45
6	30_1	1.18	0.04	0.81		1.56	0.09	1.25

Table 4.1: Summary of the results collected from all debris flow mixtures tested in the small laboratory flume. The results are ordered according to the percentage of solids (gravel, sand and clay) in each mixture, with the lowest percentage at the top of the table, i.e. mixture number 5.

4.1.3 Qualitative data

Chapter 2 highlights the attempts to categorise debris flows; often based around factors such as sediment concentration or flow behaviour characteristics. The flows in this study were categorised based on their qualitative appearance as they flowed down the channel, and were classified along a continuum shown in Figure 4.3. This is a hybrid of the classification systems proposed by Coussot and Meunier (1996) and Takahashi (2007). Coussot and Meunier (1996) describe two types of debris flows (granular and muddy) based on the percentage fines fraction. Takahashi (2007) described stony and viscous flow types, with the viscous flows experiencing a great number of surges, and the stony flow experiencing high levels of particle segregation.

The continuum used in this study (Figure 4.3) highlights a change in the appearance of a flow from muddy (mostly wet; closer to a flood flow than a landslide flow), to viscous (more sticky; with a greater level of interaction between the coarse grains and the interstitial fluid), and finally granular (where individual particle behaviour is much more evident).

On the whole, flows labelled as granular were dominated by grain-to-grain contact; during a granular flow it was easy to see individual grains, and in some cases it was possible to follow their progress for a short time along the channel. Viscous type flows were thick and sticky to look at; particles appeared as clumps within the flow, and it was difficult to observe individual particles. Muddy type flows were wet in nature and appeared the most fluid; dominated by the fine sediment and fluid components of the mixture.

MUDDY ⟷ VISCOUS ⟷ GRANULAR

Figure 4.3: Flow type continuum adopted for this study.

Most flows are difficult to definitively classify, so in terms of this study the flows were given the classification of the flow type they most closely represented for the greatest duration of the flow. It must also be acknowledged that within a given flow type not all flows will appear identical. This is due to the fact that debris flows occur over the entire range of the continuum highlighted above, and vary in behaviour even within the same flow type category. The relationships between flow type, mixture composition and flow behaviour will be explored later in this chapter (section 4.4).

Chapter 3 highlights several debris flow characteristics that define flow morphology and behaviour; the form and dynamics of the flow (section 3.1.4). This includes the display of a steep rounded snout with a gradual reduction in particle size towards the tail (Lorenzini and Mazza, 2004), and the presence of a non-deforming rigid plug in the centre of the flow (Johnson, 1970). A typical debris flow may also consist of several waves due to surging behaviour (Zanuttigh and Lamberti, 2007). In terms of typical particle behaviour, a debris flow often undergoes sediment sorting with the largest particles migrating to the flow surface and snout (Pierson, 2005). This is often illustrated by a rolling of the particles at the snout which gives the front of the flow the look of a conveyor belt; the resultant increase in friction can lead to a reduction in snout velocity (Takahashi, 1991; Lorenzini and Mazza, 2004; Takahashi, 2007). However, in some cases debris flows experience an overall increase in flow velocity because the flow behind the snout pushes the snout forward down the channel (Sharp and Nobles, 1953; Iverson, 2003). Each experimental run in the small flume was assessed for these qualitative behaviours, and given a flow type classification; muddy, viscous or granular. Table 4.2 documents the behavioural characteristics and flow type of each experimental flow based on video analysis of the experiments.

Mixture	Slope and run number	FLOW FORM Snout	Tail	Plug	Surges	PARTICLE BEHAVIOUR Rolling of particles	Local snout slowdown	Pushing from behind	Flow type
5	15_1								Granular
	30_1								Muddy
	30_2				■				Granular
29	15_1								Muddy
37	15_1								Muddy
	15_2								Muddy
	30_1				■				Muddy
	30_2								Granular
12	15_1	■	■			■			Viscous
	15_2				■				Granular
	30_1								Viscous
	30_2								Viscous
16	15_1								Viscous
17	15_1			■	■				Viscous
	15_2								Viscous
33	15_1								Muddy
	15_2			■					Granular
18	15_1				■				Muddy
30	15_1								Muddy
	15_2								Muddy
	30_1								Muddy
	30_2				■				Muddy
9	15_1								Granular
	30_1	■							Viscous
	30_2								Granular
28	15_1								Granular
21	15_1								Muddy
	15_2								Viscous
36	15_1			■			■	■	Viscous
	15_2	■	■			■			Muddy
	20_1	■	■			■			Muddy
	20_2	■					■		Muddy
	25_1	■	■		■	■			Viscous
	25_2	■	■		■	■			Muddy
	30_1	■	■		■	■			Viscous
	30_2	■	■			■			Muddy
4	15_1								Viscous
	30_1								Viscous
	30_2	■	■			■			Granular
2	30_1					■	■		Viscous
1	30_1								Viscous
14	15_1								Viscous
	15_2								Viscous
	30_1	■	■			■	■		Viscous
	30_2								Viscous
31	15_1	■				■			Viscous
	15_2								Viscous
22	15_1	■			■				Viscous
	15_2	■		■		■	■	■	Viscous

3	30_1								Viscous
25	15_1								Muddy
	15_2								Viscous
20	15_1								Viscous
32	15_1								Viscous
	15_2								Muddy
27	15_1								Granular
23	15_1								Viscous
	15_2								Viscous
26	15_1								Viscous
24	15_1								Viscous
	15_2								Viscous
19	15_1								Viscous
7	15_1								Granular
	30_1								Granular
	30_2								Granular
10	15_1								Viscous
	15_2								Viscous
	30_1								Viscous
	30_2								Granular
34	15_1								Viscous
	15_2								Viscous
	20_1								Granular
	20_2								Viscous
	25_1								Viscous
	25_2								Viscous
	30_1								Viscous
	30_2								Viscous
11	30_1								Viscous
13	15_1								Viscous
	15_2								Viscous
	30_1								Viscous
	30_2								Viscous
35	15_1								Viscous
15	15_1								Viscous
38	15_1								Viscous
	15_2								Viscous
	20_1								Viscous
	20_2								Viscous
	25_1								Granular
	25_2								Viscous
	30_1								Granular
	30_2								Granular
8	30_1								Viscous
6	30_1								Granular

Table 4.2: Summary of the qualitative flow behaviour of each debris flow tested in the small laboratory flume, as well as their flow type classification. Coloured spaces indicate the presence of that behaviour during the experimental flow.

Table 4.2 shows that the debris flows that developed a tail invariably also developed a snout. Snouts also developed alone, without the presence of a tapered tail but with evidence of the largest grains at the flow front and little change in flow width from the front to the back of the flow. Flows that developed a snout also almost always showed evidence of the rolling of particles at the flow front. This was similar to reports in the literature that attribute the formation of the snout to the transportation of the largest particles to the flow front with conveyor-belt like motion (Johnson, 1970; Iverson, 2003; Lorenzini and Mazza, 2004; Zanuttigh and Lamberti, 2007).

On the whole, large particle activity within the flow followed a characteristic pattern of behaviour. The rolling of particles at the snout was followed by local snout slowdown at the debris flow front, followed by the pushing of the snout from behind. However, there were cases where the rolling behaviour was followed only by local snout slowdown; and not pushing from behind. These flows were mostly granular to viscous in nature. The flows which exhibited local snout slowdown and pushing from behind, but did not show evidence of rolling behaviour, were mostly viscous to muddy in nature.

Flow behaviour in the small flume may have been influenced by channel slope and fixed channel length. For example, at greater slope angles several flows experienced snout slowdown but not pushing from behind, and when this occurred it was often that the slowdown came at the distal end of the flume. This did not allow sufficient time for the back of the flow to catch the snout and push it forward before the front of the flow passed out of the channel. This suggests that the channel length of 2 m was not sufficient for full flow development. It was also observed that several flows at 30° did not develop local snout slowdown unless the mixture was sufficiently granular; which meant that the increased friction could compensate for the steeper slope. In several flows at 15° snout slowdown was not followed by the pushing of the snout from behind because the flow velocity was not sufficient to counteract the friction at the snout. Overall, at lower slope angles the granular type flows were less likely to flow the full length of the flume compared to the viscous and muddy type flows. This was likely due to the increased internal friction within the flow, coupled with the reduced velocity as a result of the lower slope angle.

The development of multiple surges and plugs within the flow was rare, probably due to the limitations in flume length, as this restricted the full development of some of the flows. Plugs most often appeared in flows at shallow slope angles, as the lower speeds gave the flows more time to develop. The flows that developed surges tended to be viscous to muddy in nature.

4.1.4 Selecting representative debris flow mixtures

The first objective of this study was to test a range of sediment mixtures to determine which most closely represented natural debris flows; and assess the extent to which flow behaviour was comparable in different sized experimental flumes. The first step of this was to select the most representative debris flow mixtures, and after testing a variety of debris flow mixtures in the small laboratory flume, three mixtures (those exhibiting the best-defined debris flow characteristics) were selected to be retested prior to use in the large flume.

The decision as to which mixtures should be selected for repeated testing in the large flume was primarily based on the observations recorded in Table 4.2. The mixtures that were observed to have the least number of debris flow characteristics were discarded from further analysis. Other mixtures (for example, mixture 10) were discarded because they did not flow the full length of the flume on more than one occasion; this was regardless of whether the flow displayed typical debris flow characteristics. Another example of a discarded mixture was mixture 22, because although the snout reached the end of the channel, the flow was so slow that almost all of the mixture was left as deposits in the channel. In this case the mixture had high clay content (15%) and low gravel content (30%), which gave the mixture a very sticky appearance that may have contributed to the deposition.

Mixtures 34, 36 and 38 were the most closely representative of natural debris flows, and were chosen for repeated runs in the small flume. They were tested at four different slope angles (15°, 20°, 25° and 30°) in order to get a better understanding of their characteristics. Mixtures 34 and 38 had high solids content (≈ 85% sediment by weight) and were within the viscous ↔ granular range on the flow type continuum (section 4.1.3). Mixture 36 had lower solids content (≈ 81% sediment by weight) and fell within the muddy ↔ viscous range on the flow type continuum. As only two different debris flow mixtures were needed for testing in the large flume it was decided that mixture 36 would best represent muddy/viscous debris flows, and mixture 34 would best represent viscous/granular debris flows. Mixture 34 was chosen over mixture 38 because it produced flows with more characteristic debris flow properties compared to mixture 38 (Table 4.2); mixture 38 often showed a lack of the characteristic debris flow snout and tail, while mixture 34 regularly displayed it. Figure 4.4 highlights where mixtures 34 and 36 fall within the flow type continuum.

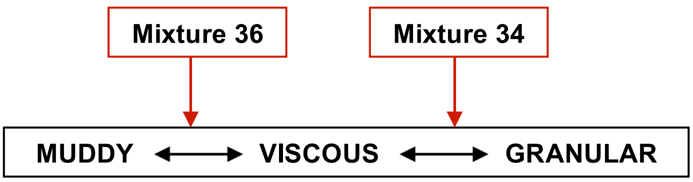


Figure 4.4: Flow type continuum adopted for this study, highlighting mixtures 34 and 36.

Table 4.2 shows that mixture 36 produced a similar number of flows with surges, but fewer flows with local snout slowdown or pushing from behind compared with mixture 34. This may be due to the constraints of the fixed flume length, or it could be linked to the fact that mixture 36 is in the muddy/viscous range with higher velocity and lower friction compared to mixture 34; which being more granular in nature (higher friction and lower velocity), showed a higher proportion of flows exhibiting all particle characteristics.

Figure 4.5 highlights the composition of the mixtures used in the small flume in terms of the proportions of gravel, sand and clay (by weight) in the mixtures as a percentage of the solids fraction. It also identifies the composition of mixtures 34 and 36, which were examined in both the small and large flumes.

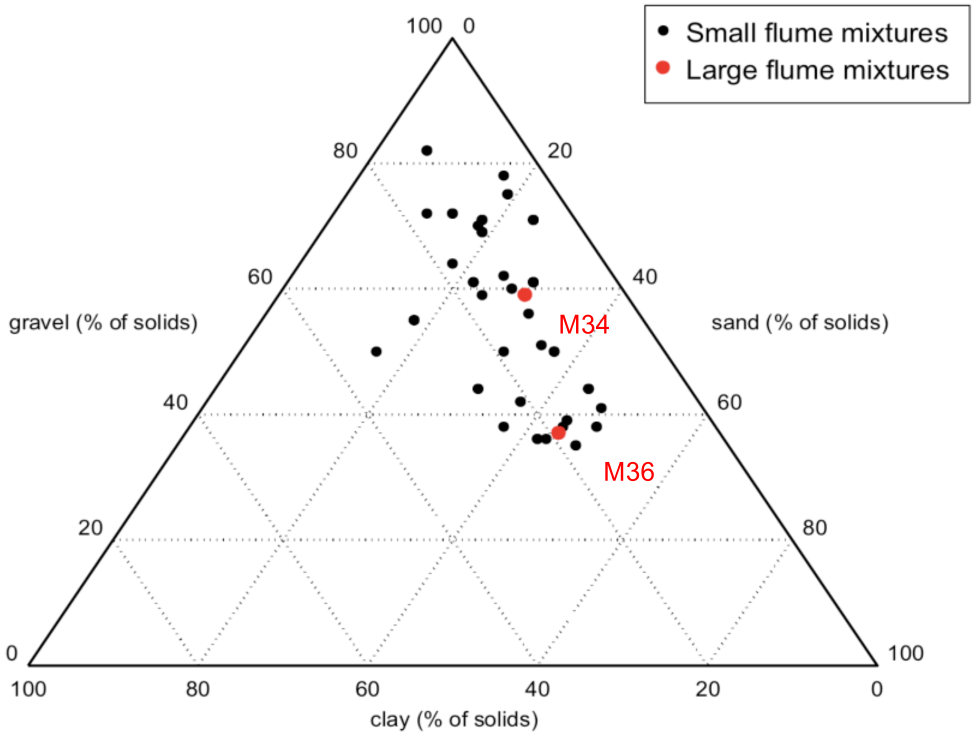


Figure 4.5: Ternary diagram highlighting the solids fraction composition (gravel, sand and clay) of the experimental debris flow mixtures (percentage by weight). Mixture 34 is represented by the higher red dot and mixture 36 is represented by the lower red dot.

4.1.5 Sediment content and flow mobility

During testing of the various debris flow mixtures in the small flume differences in the proportions of gravel, sand and clay in the mixtures produced significant differences in flow mobility. For example, mixtures with clay contents of 15% or more often had limited flow mobility; neither mixture 19 (25% clay) or mixture 21 (18% clay) had good flow mobility or developed any obvious flow form.

The results suggest that (together with less than 15% clay) a mixture requires approximately 15-20% water to flow well at a slope of 15°. In addition, an approximate 5% relative difference in the water and clay content was ideal; mixture 34 (relative difference of 5%) and mixture 36 (relative difference of 4%) both flowed the full length of the flume and displayed key debris flow characteristics. Mixture 33 on the other hand (10% relative difference), displayed limited cohesion and flowed as distinct lumps of clay and gravel in a watery mixture. Although a difference in the clay and water content of approximately 5% aided flow mobility, mixtures with a difference of 5-10% also flowed well provided that this was also accompanied by an increase in sand; this offset the tendency of the mixture to become too wet. For example, mixture 32 (6% relative difference) contained 40% sand, and flowed well.

However, the results also indicated that a high sand content led to a lack of flow mobility because of mixture dryness. For example, while 40% sand in mixture 32 aided flow mobility, in other flows (such as mixture 35) 40% sand produced a dry mixture that did not reach the end of the channel. Mixtures with lower clay content (usually below 10%) required less sand, even if the relative difference in water and clay was 5% or greater. Conversely, mixtures with higher percentages of clay, even with a low relative difference in clay and water content, required higher percentages of sand.

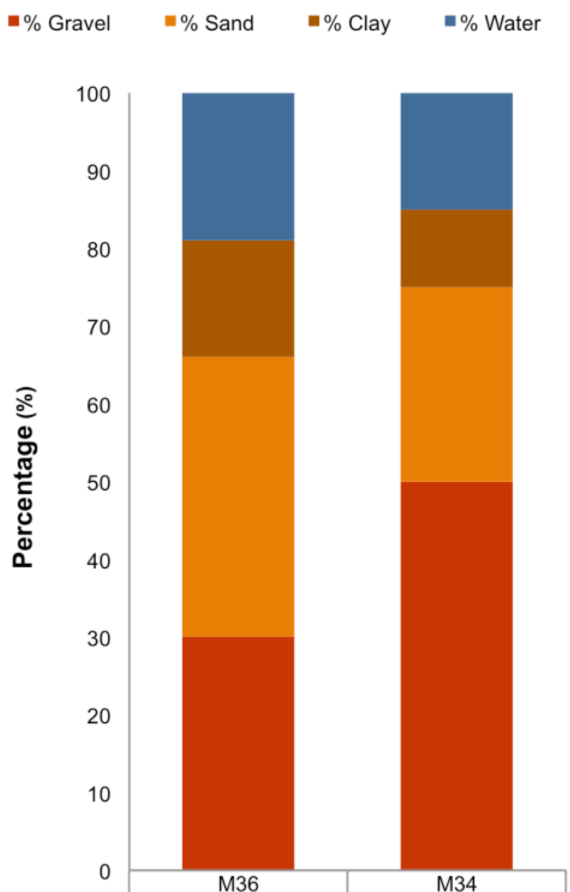
The results of this study showed that mixtures which flowed poorly because they were too dry were generally comprised of more than 35-40% sand and/or had less than a 3-5% relative difference in the clay and water content. Flows with less than 25% sand coupled with a low proportion of gravel also flowed poorly, often because they were too wet. However, mixtures with less than 25% sand were too dry if they had a high proportion of gravel. Insufficient water content also produced poor flow mobility. For example, mixture 22 (18% water and 36% sand) did not reach the end of the flume as it was too slow and sticky; suggesting that mixtures with a high sand content required more water.

It therefore seems that while clay helps to produce slurry with which to fully mix the gravel and water components of a mixture, the sand in the mixture is beneficial for reducing the cohesion produced by the clay, and thus aids mobility. In general, it seems that to flow well most mixtures required 15% or less of clay, 25-40% sand and 15-20% water. A relative percentage difference in the water and clay content of approximately 5% was also beneficial.

4.2 Small and large flume results comparison

4.2.1 Debris flow mixtures

Debris flow mixtures 34 and 36 were tested in both the small and large flume in order to assess the comparability of debris flows in different sized apparatus. The materials (gravel, sand, clay and water) were the same in both the small and large flume experiments, and the compositions of mixtures 34 and 36 were unchanged between the flumes (Figure 4.1 and Figure 4.6).



	M36	M34
% Water	19	15
% Clay	15	10
% Sand	36	25
% Gravel	30	50

Figure 4.6: Sediment concentrations of debris flow mixtures 34 and 36; tested in the both the small and large flume.

In terms of the material size, the fines component (clay up to 0.002 mm, and sand up to 2 mm) was kept constant between the flumes, while the coarse grained component (gravel) used in the large flume was increased to approximately twice the diameter of that used in the small flume. Although this was not a formal scaling exercise the size of the coarse component was increased so that the relative geometry of the coarse sediment to channel cross section was approximately similar. Only the size of the coarse grained component, and not the percentage concentration in the mixtures, was altered.

The coarse grained component of the experimental debris flows was gravel with an average of 10 mm in the small flume, and 20 mm in the large flume (Tables 3.1 and 3.3). Unlike some natural debris flows, these mixtures did not have a continuous range of grain sizes in the sand to gravel range. Therefore, the mixtures display a poorly sorted multi-modal distribution (Figure 4.7).

Figure 4.7 highlights the similarity of the particle size distributions between the debris flow mixtures; mixtures 34 and 36 in the small flume and the large flume. It also shows that mixture 36 (both small and large flume) is finer than mixture 34; similar to the mixture composition data in Figure 4.6; mixture 36 has a lower proportion of gravel than mixture 34, but a greater proportion of sand and clay.

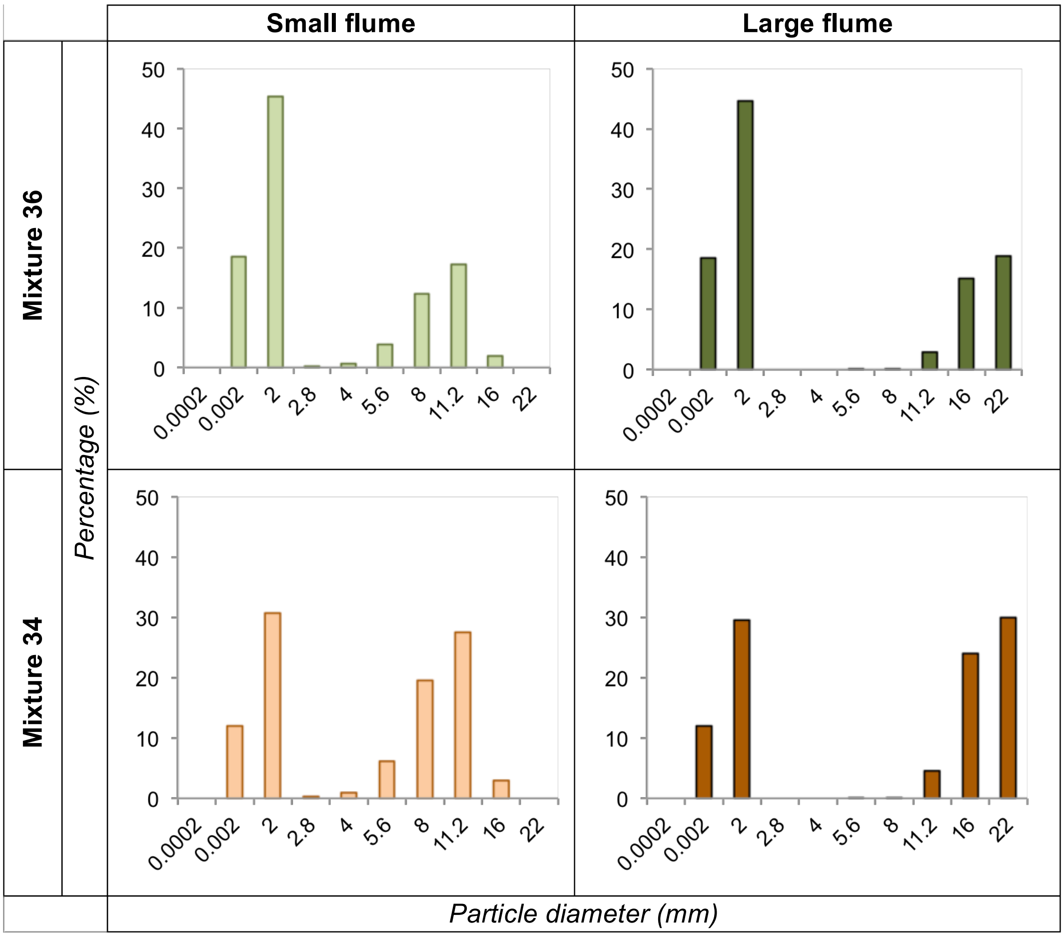


Figure 4.7: Particle size distribution of the debris flow mixtures used in both the small and large flume (mixtures 34 and 36). The clay and sand particle sizes are constant between the flumes whereas the average gravel particle diameter used in the large flume is approximately twice that of the gravel used in the small flume.

The sediment mixture ratios between the small and large flume are highlighted in Table 4.3. On the whole, the small flume to large flume sediment mixture ratio is comparable with the small flume to large flume apparatus size ratio; approximately 2:1. There is a D_{90} ratio of 1.9:1 between the small and large flumes for both mixtures 34 and 36. However, in terms of D_{50} the mixtures are quite different, with mixture 36 (both small and large flume) having a much lower D_{50} than mixture 34. The D_{50} ratio between the small and large flume is 2.15:1 for mixture 34, and 1.04:1 for mixture 36. There is very little difference in the D_{50} of mixture 36 between the small and large flume; highlighting that mixture 36 is generally finer than mixture 34.

Mixture	Grain diameter (mm)	Small flume	Large flume	Ratio
M34	D_{50}	5.6	11.9	2.15 : 1
	D_{90}	10.4	20	1.9 : 1
M36	D_{50}	1.36	1.42	1.04 : 1
	D_{90}	9.6	19	1.9 : 1

Table 4.3: Ratio table showing the particle size (D_{50} and D_{90}) ratios of mixtures 34 and 36 between the small and large flume.

Table 4.4 shows the ratio of the channel width and depth with the D_{90} of mixtures 34 and 36 in both the small and large flume. It highlights the similarity between all of the ratios; approximately 1:10 for width:D_{90} and 1:5 for depth:D_{90}, irrespective of mixture or flume size. This suggests that the increase in the size of the gravel component for mixtures used in the large flume is in proportion with the increase in channel dimensions from the small to the large flume. The volume of mixture used in the small flume was 1 kg, whereas in the large flume it was 10 kg; a ratio of 10:1. This is similar to the change in the D_{90} between the small and large flume (both mixtures), and the ratio between channel width and D_{90} in both flumes.

Mixture	Flume	Channel width (mm)	Channel depth (mm)	D_{90}	Ratio (width:D_{90})	Ratio (depth: D_{90})
M34	Small	100	50	10.4	1:9.6	1.4.8
	Large	200	100	20	1:10	1:5
M36	Small	100	50	9.6	1:10.4	1:5.2
	Large	200	100	19	1:10.5	1:5.3

Table 4.4: Ratio table showing the ratio of channel width and depth with D90 for mixtures 34 and 36 in the small and large flume.

4.2.2 Quantitative and qualitative data

Mixtures 34 and 36 were each tested 16 times in the large flume; four times at each slope angle (15°, 20°, 25° and 30°). As with the mixtures tested in the small laboratory flume the flow behaviours of velocity, width, length and depth were measured. The average and maximum results are collated in Table 4.5. Average velocity ranged from 0.41 m s^{-1} to 1.86 m s^{-1}, and maximum velocity ranged from 0.78 m s^{-1} to 3.13 m s^{-1}. In comparison to mixtures 34 and 36 in the small flume these results are very similar; in the small flume the mixture 34 and 36 average velocity ranged from 0.36 m s^{-1} to 1.65 m s^{-1} while the maximum velocity ranged from 0.52 m s^{-1} to 2.78 m s^{-1}. Velocity results were slightly higher in the large flume compared to the small flume. Average flow widths were also similar between the small and large flume; both flumes produced average widths of about half the overall width of the channel; approximately 0.04 m (channel width 0.1 m) in the small flume and 0.10 m (channel width 0.2 m) in the large flume. The higher slope angles produced flows with greater velocities and flow lengths, and the flows with the fastest velocities resulted in the greatest maximum lengths in both flumes.

Mixture	Slope (degrees) and run number	Average				Maximum		
		Velocity (m s^{-1})	Width (m)	Length (m)	Depth (m)	Velocity (m s^{-1})	Width (m)	Length (m)
36	15_1	0.68	0.08	3.81	0.0536	1.04	0.10	6.00
	15_2	0.79	0.08	3.59	0.0893	1.04	0.10	5.00
	15_3	0.64	0.09	4.00	0.1179	1.04	0.16	6.50
	15_4	0.83	0.08	3.91	0.1179	1.04	0.15	6.50
	20_1	1.19	0.09	4.25	0.0714	1.56	0.13	8.00
	20_2	1.09	0.11	3.69	0.0982	1.56	0.18	6.00
	20_3	1.04	0.10	4.13	0.0929	1.56	0.16	7.00
	20_4	0.99	0.11	4.25	0.0804	1.56	0.18	8.00
	25_1	1.42	0.12	4.22	0.0670	1.56	0.18	7.50
	25_2	1.50	0.11	4.25	0.1000	3.13	0.14	8.00
	25_3	1.69	0.12	4.06	0.0929	3.13	0.16	6.50
	25_4	0.95	0.12	3.94	0.0964	1.56	0.18	6.00
	30_1	1.50	0.12	4.25	0.0429	3.13	0.14	8.00
	30_2	1.86	0.11	3.56	0.0286	3.13	0.15	6.00
	30_3	1.82	0.11	4.13	0.0625	3.13	0.14	7.00
	30_4	1.46	0.11	4.25	0.0286	3.13	0.14	8.00
34	15_1	0.52	0.10	3.63	0.0755	0.78	0.17	6.00
	15_2	0.45	0.14	2.88	0.1019	0.78	0.16	4.50
	15_3	0.53	0.10	3.97	0.0736	1.04	0.16	6.50
	15_4	0.41	0.10	2.46	0.0509	1.04	0.17	4.00
	20_1	1.17	0.10	4.22	0.1057	1.56	0.16	7.50
	20_2	0.64	0.09	3.38	0.1132	1.04	0.16	5.00
	20_3	0.59	0.10	2.50	0.0566	1.04	0.16	5.00
	20_4	0.85	0.11	4.06	0.0736	1.56	0.17	6.50
	25_1	1.00	0.12	4.22	0.0792	1.04	0.16	7.50
	25_2	1.05	0.11	4.25	0.0925	1.56	0.16	8.00
	25_3	1.11	0.11	4.25	0.0679	1.56	0.16	8.00
	25_4	1.27	0.11	4.25	0.0528	1.56	0.15	8.00
	30_1	1.48	0.12	4.13	0.0925	3.13	0.18	7.50
	30_2	1.07	0.11	4.25	0.1057	1.56	0.14	8.00
	30_3	1.82	0.11	3.78	0.0943	3.13	0.12	6.00
	30_4	1.59	0.11	4.00	0.1226	3.13	0.14	6.50

Table 4.5: Summary of the results collected from the debris flow mixtures tested in the large flume; mixtures 34 and 36.

Table 4.6 shows the qualitative flow characteristics observed for mixtures 34 and 36 in the large flume. All but one flow reached the end of the channel. A higher proportion of flows experienced surge and plug behaviour in the large flume compared to the same mixtures in the small flume. The extended flume length and larger variation in grain sizes may be a contributing factor. Particle behaviour was similar in the both flume when comparing mixtures, with the more granular mixture 34 having a higher incidence of local snout slowdown and surging. However, at 25° and 30° mixture 34 showed less evidence of these behaviours in the large flume when compared to those witnessed in the small flume. Faster velocities in the large flume, especially at the higher slope angles, may have influenced this. Plug behaviour may also have been influenced by velocity as it was more often witnessed in the granular mixture (mixture 34) and at lower slope angles, where flow velocity is less.

Mixture	Slope and run number	FLOW FORM		Plug	Surges	PARTICLE BEHAVIOUR			Flow type
		Snout	Tail			Rolling of particles	Local snout slowdown	Pushing from behind	
36	15_1	■	■		■		■		Muddy
	15_2	■	■		■	■		■	Muddy
	15_3				■				Muddy
	15_4				■				Muddy
	20_1	■	■		■	■			Muddy
	20_2	■	■		■	■			Viscous
	20_3	■	■		■	■			Viscous
	20_4	■	■	■	■	■	■	■	Viscous
	25_1	■	■		■	■			Viscous
	25_2	■	■	■	■	■			Viscous
	25_3	■	■		■	■			Viscous
	25_4	■	■		■	■	■		Viscous
	30_1	■	■		■	■			Viscous
	30_2	■	■		■	■			Viscous
	30_3	■	■			■			Muddy
	30_4	■	■	■		■			Viscous
34	15_1	■	■	■		■	■	■	Granular
	15_2	■	■	■	■	■	■	■	Viscous
	15_3	■	■	■	■	■		■	Granular
	15_4	■	■	■	■	■	■	■	Viscous
	20_1	■	■		■	■			Viscous
	20_2	■	■	■	■	■	■	■	Viscous
	20_3	■	■	■	■	■	■	■	Granular
	20_4	■	■		■	■	■	■	Viscous
	25_1	■	■			■	■		Viscous
	25_2	■	■		■	■			Viscous
	25_3	■	■		■	■			Viscous
	25_4	■	■		■	■			Viscous
	30_1	■	■		■	■			Muddy
	30_2	■	■		■	■			Viscous
	30_3	■	■			■			Granular
	30_4	■	■		■	■			Viscous

Table 4.6: Summary of the qualitative flow behaviour of each debris flow tested in the large flume, as well as their flow type classification; mixtures 34 and 36. Coloured spaces indicate the presence of that property during the experimental flow.

4.2.3 Flow behaviour as a function of distance

Examining the average and maximum data values collected in the small and large flume can be useful in helping to explain and compare patterns of debris flow behaviour. However, flow behaviour also develops and changes throughout the duration of a flow. For example, Ikeda and Hara (2003) observed that the maximum velocity of a flow could occur at different stages of flow development. In order to address the transient and dynamic nature of debris flows Figure 4.8 and Figure 4.9 highlight the changes to flow behaviour with distance down the flume channel. Figure 4.8 details flow velocity and acceleration/deceleration for mixtures 34 and 36 in both the small and large flumes, whereas Figure 4.9 highlights changes to frontal flow width and flow length for mixtures 34 and 36 in each flume.

For most flows peak velocity was generally attained in the proximal portion of the flume channel. This peak was often followed by a velocity reduction; reflected in the acceleration/deceleration graphs of Figure 4.8. After the initial acceleration, and then deceleration, most flows seemed to reach an equilibrium velocity, reflecting the more constant nature of flow velocity in the distal part of the channel. However, several of the large flume flows also exhibited an increase in velocity and flow acceleration towards the end of the channel. This is possibly caused by the more ‘fluid’ rear of the flow reaching the slowing snout and decreasing the levels of friction at the flow front, forcing it forward. This was observed less in the small flume, possibly due to the constraints of channel length. Surges may also have caused momentary increases in flow velocity. For example, videos of flows 36_25_4 and 34_30_2 showed bursts of speed at the flow front associated with surging and pushing of the flow from behind. Both of these flows showed peaks in flow velocity in the distal reaches of the channel.

Apart from the minor differences in velocity and deceleration/acceleration between the small and large flume, all flows exhibited a similar range of data (up to 4 m s^{-1} velocity, and -10 m s^{-2} to 20 m s^{-2} deceleration/acceleration). Flows at lower slope angles seemed to display a greater reduction in velocity towards the distal reaches of the channel compared to flows at higher slope angles. The differences between mixtures 34 and 36 were more pronounced in the large flume, where the longer channel allowed more flow development before the material exited the channel. Both mixtures had relatively stable velocities for flows at 15° and 20°, but developed peaks in velocity at the end of the channel at 30° for mixture 34, and 25° and 30° for mixture 36. Mixture 36 experienced the greatest number of flows displaying this behaviour. This may be attributed to the flow type; the more viscous mixture 36 caused greater increases in flow velocity due to surging, compared to the more granular mixture 34 which had higher levels of friction.

The very high acceleration values noted in some of the graphs reflect the measuring errors produced by the low frame rate (12.5 framers per second) of the digital camera used in the calculation of the velocity and acceleration data (as discussed in section 3.3). The time interval of video frames was 0.08 seconds, thus while calculating the velocity of the faster flows the material was only visible for one or two frames of video per interval down the flume. The precision of some of these measurements was low, which explains the rapid fluctuations observed in Figure 4.8. The measurement error was not fixed, but increased as the flow rate increased (as the number of frames per measuring interval decreased) so there were larger errors in the faster flows. However, while individual measures varied in their precision, the trends down the flume remained accurate.

The data shows a clear trend towards an increase in flow length with distance down the channel. The increase in length was quite steady in most flows. However, in some flows in the small flume it appeared to plateau or reduce in the distal reaches of the channel. Flows maintained a relatively consistent frontal width along the channel as flow length increased, although an initial increase and decrease in frontal flow width was observed in the proximal reaches of the channel. In cases where the flow length decreased towards the distal end of the channel, frontal flow widths appeared to increase. The granular mixture 34 and those flows at lower slope angles seemed to experience greater reductions in flow length towards the distal reaches of the channel, likely due to increased friction levels. This often corresponded with a reduction in velocity towards the end of the channel, and was more pronounced in the large flume. In some cases the flows that experienced surging also experienced small increases in frontal width. This may be because the surges reached the flow front and momentarily increased the volume of material in the snout. On the whole, the flows in both the small and large flumes appear to have followed similar patterns.

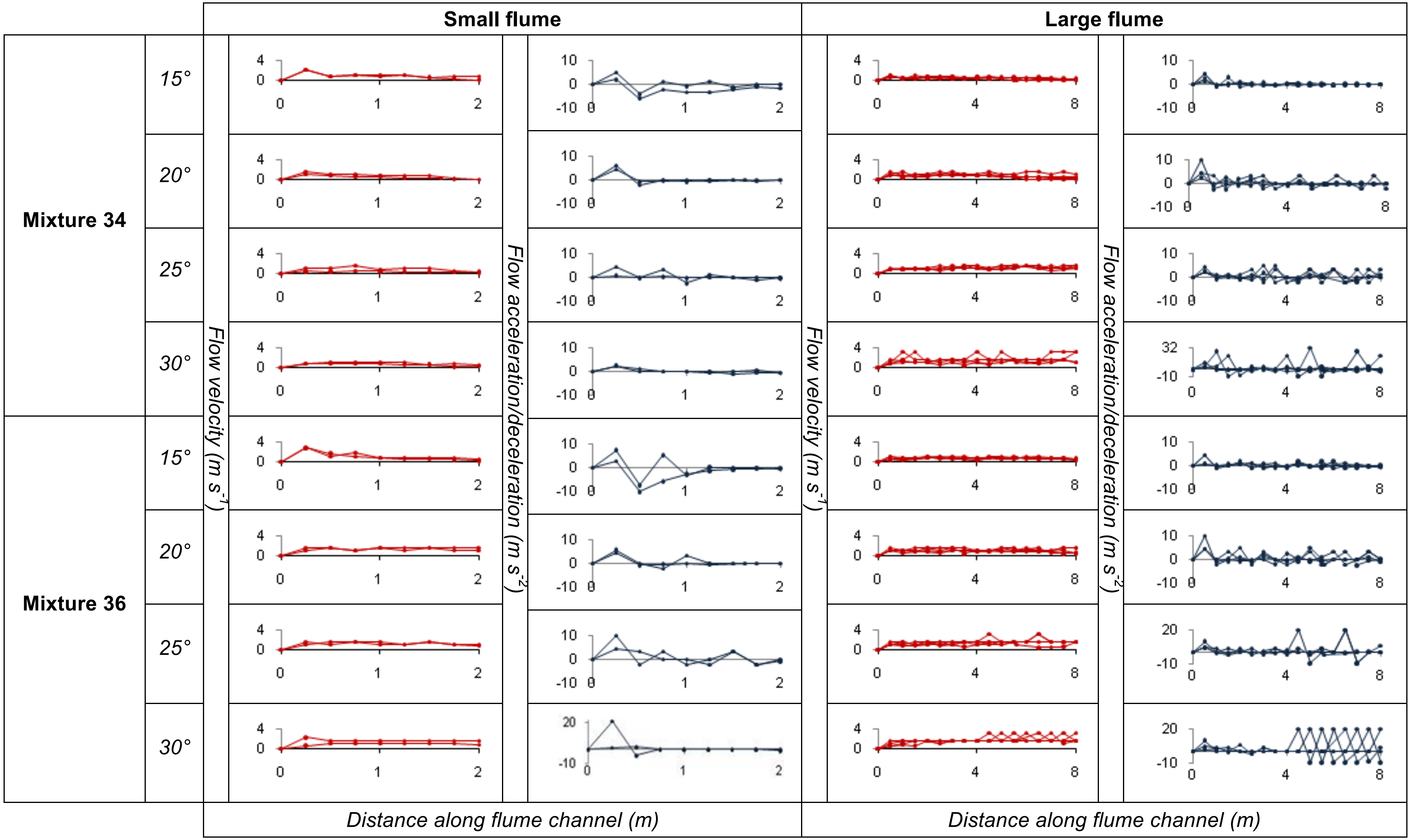


Figure 4.8: Graphical representations of flow velocity and acceleration/deceleration with distance down the flume. Acceleration has a variable y-axis reflecting the increase in values at greater slopes. Small flume; two flows per mixture per slope. Large flume; four flows per mixture per slope.

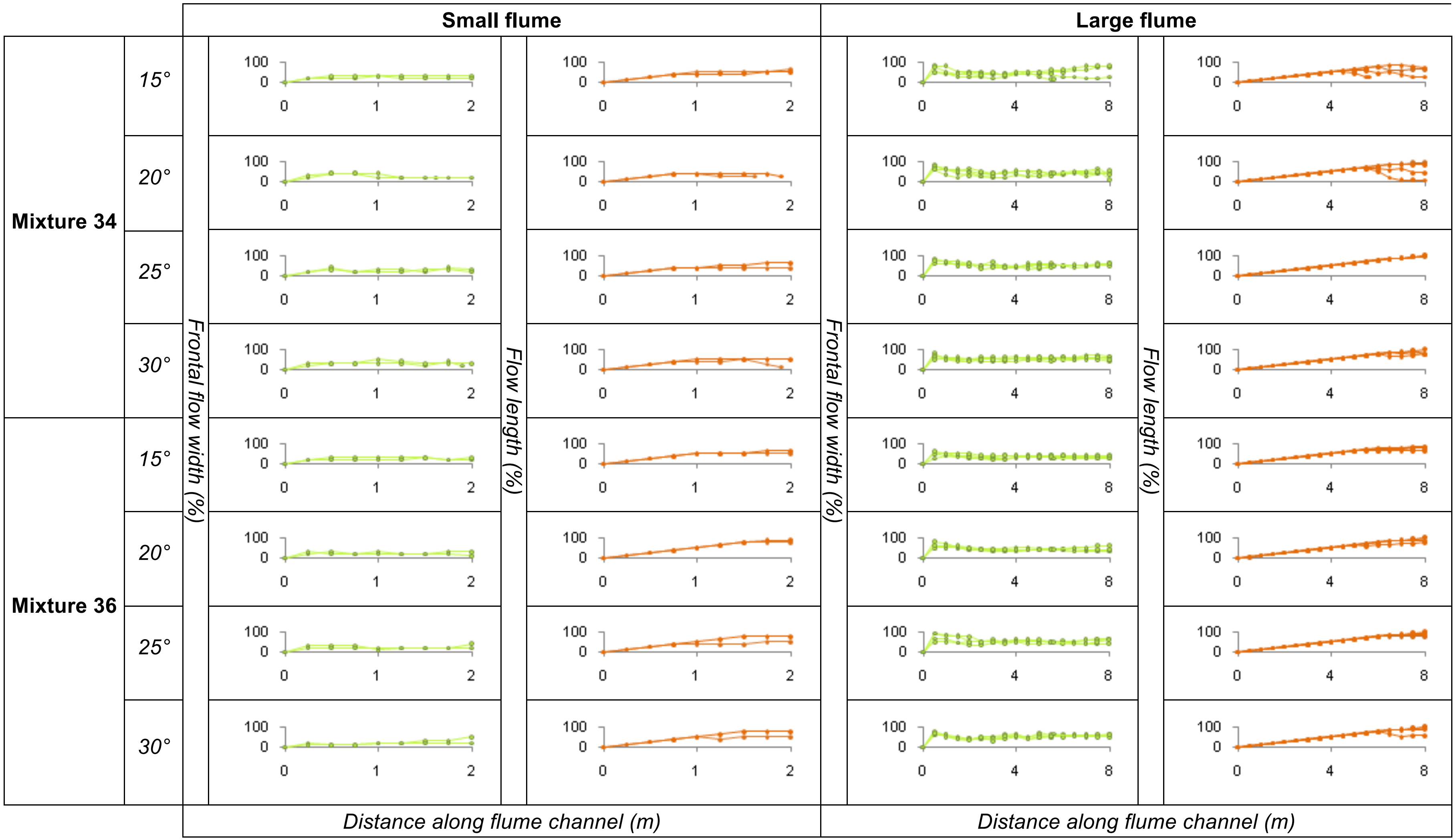


Figure 4.9: Graphical representations of frontal flow width and overall flow length with distance down the flume as a percentage of total channel width and length. Small flume; two flows per mixture per slope. Large flume; four flows per mixture per slope.

4.2.4 Direct comparison

Figure 4.10 shows histogram plots comparing the frequency of flow velocity, width and length values for mixtures 34 and 36 in the small and the large flume. Flow depth was not included as there was only one data value calculated per flow (the average), and therefore not enough to produce a detailed histogram. The histograms are constructed using every data value collected per flow (one for every 0.25 m of channel length in the small flume, and every 0.5 m in the large flume). There are therefore more values in the large flume histograms; due to the extra length of the flume, as well as the larger number of mixture 34 and 36 experimental flows. It must be noted that the mixtures used in the small and the large flume are not identical; the large flume mixtures are based on those used in the small flume, and although the mixture composition is identical, the grain size range in the gravel fraction is different (section 4.2.1).

Figure 4.10 highlights the similarity of flow velocity values in the small and the large flume, with the majority of data falling between 1 m s^{-1} and 2 m s^{-1}. The highest velocity range in the small flume was 3 m s^{-1} to 3.5 m s^{-1}, whereas in the large flume this was 3.5 m s^{-1} to 4 m s^{-1}. However, there were only a few data values above 2 m s^{-1} in either flume.

Flow width in the small flume ranged from 10% to 80%, while in the large flume this was 10% to 90%. The small flume showed the greatest frequency (around 25%) of flow widths in the 10% to 20% width and 60% to 70% width ranges, but a dip in frequency between these; 10% frequency in the 40% to 50% flow width range. The large flume showed the inverse of this, with a rising trend in frequencies up to the 50% to 60% width range (33% frequency), before frequency decreases again. This higher percentage of frequency at greater width values in the large flume is also highlighted in Figure 4.11.

Flow length in the small flume ranged from 20% to 90% of the overall channel length, whereas the large flume had a slightly larger range; 10% to 100%. The large flume had little variation in the number of values in each data range. However, the small flume plots have more variation, with a small rise in frequency for flow lengths between 40% and 60% (54% frequency), and no data values in the 60% to 70% flow length range.

Because a comparison between the data produced in the small and large flume is difficult when the data are not plotted on common axes Figure 4.11 highlights the results in dimensionless plots. This allows a direct comparison between the small and the large flume. On the whole, Figure 4.11 indicates that the relationships between maximum and average data are the same, regardless of flume size. One contradiction to this is highlighted in the width graph; the large flume producing slightly wider flows (around 20% greater). Regardless of size, the channel shape of both the small and large flume was the same, but the discrepancies between the small and the large flume results may be a function of the differing volume of mixture used in each flume (1 kg in the small flume, and 10 kg in the large flume).

Figure 4.11 also highlights the differences between mixture 34 and mixture 36. The velocity plot (A) shows higher velocity values for mixture 36 in both the small and the large flume. The same applies to the length graph (C); with slightly longer average and maximum flow lengths displayed for mixture 36 compared to mixture 34. However, in the case of the flow width plot (B), there seems to be little difference between mixtures 34 and 36.

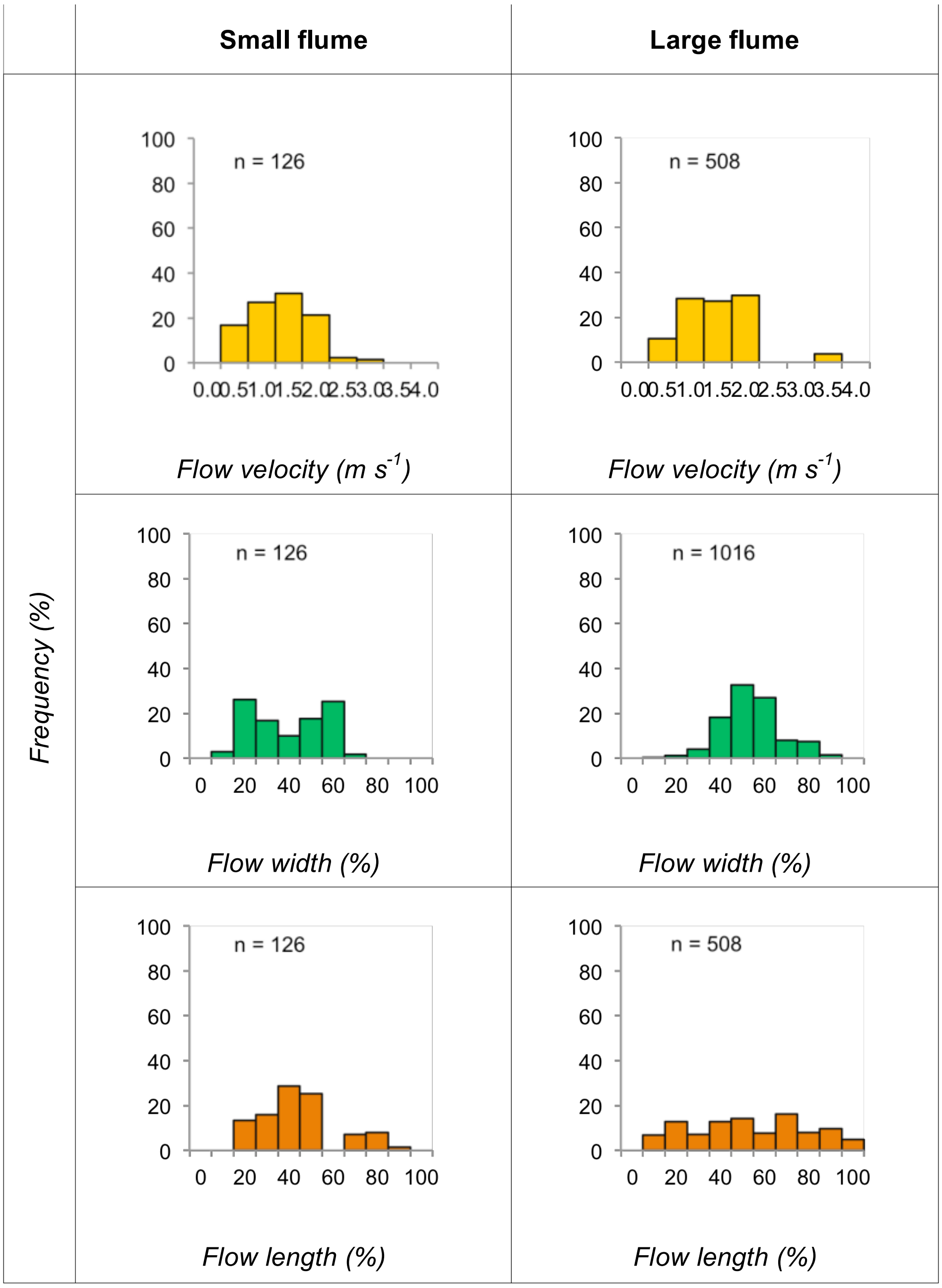


Figure 4.10: Histogram plots of flow velocity, width and length in the small and the large flume for mixtures 34 and 36. Width and length data refer to the values as percentages of total channel width and length. Each data value recorded per flow is included in the histograms (eight values per flow in the small flume and 16 values per flow in the large flume – one for every 0.25 m of channel length in the small flume, and every 0.5 m in the large flume).

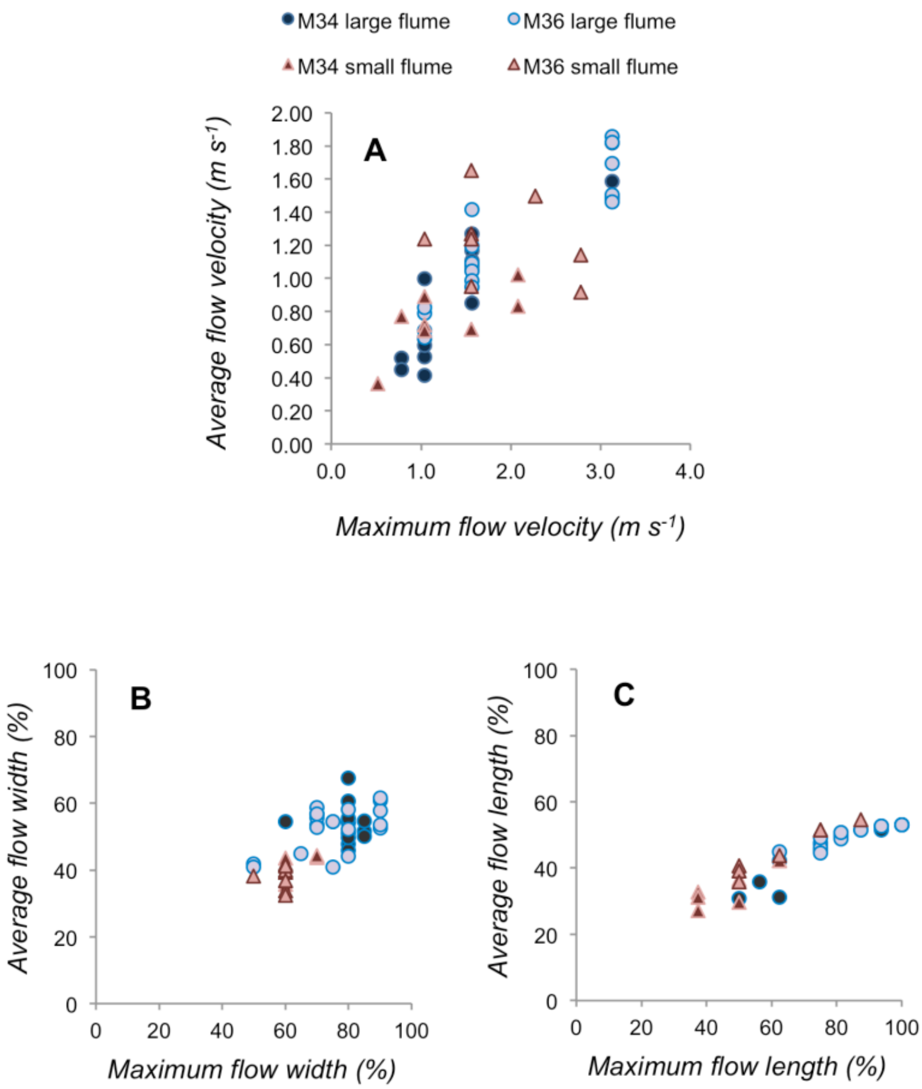


Figure 4.11: Plots of maximum and average flow velocity, width and length data for mixtures 34 and 36 in the small and the large flume. Flow width and flow length values are represented as a percentage of overall channel width and length, allowing a direct comparison of the data between flumes and mixtures.

4.3 The influence of channel slope on debris flow behaviour

The second objective of this study was to assess the extent to which channel slope angle influences debris flow behaviour. In order to achieve this, the data produced in the large flume was combined with that produced in the small flume. Figure 4.12 is a series of box and whisker plots highlighting the distribution of debris flow velocity, width, length, and depth values at different slope angles. It displays the inter-quartile range and the minimum and maximum data values for every experimental flow in this study. The mean values are displayed in Figure 4.13, and the maximum and average values are shown together in Figure 4.14.

Figure 4.12 shows a clear increase in maximum velocity with increasing slope angle, and a slight change to minimum velocity. There is also a small increase in the size of the velocity inter-quartile range as slope increases, and a negative skew for values at 20° and 25°. The data shows an increase in minimum width and width inter-quartile range values as slope angle increases, but limited change to maximum width (due to boundary constraints). The width plots also show a decrease in the size of the inter-quartile range with increasing slope angle. In terms of flow length there is limited change as slope angle increases, although maximum length is less at 15° (around 80%) when compared to the other slope angles (100%). There is little change in flow depth with slope angle in regards to the spread of the inter-quartile range, but Figure 4.12 does highlight a decrease in the minimum and maximum values. The exception to this is the maximum depth value at 30°, which is the greatest of all the maximum depth values.

The velocity and width plots in Figure 4.12 display distributions with a tighter peak than those in the flow length and depth plots; signified by the narrower inter-quartile ranges relative to the whiskers. Overall, this data highlights that flow velocity increases with slope angle, flow width increases in terms of the minimum and inter-quartile range values, flow length shows little change with slope angle, and flow depth decreases.

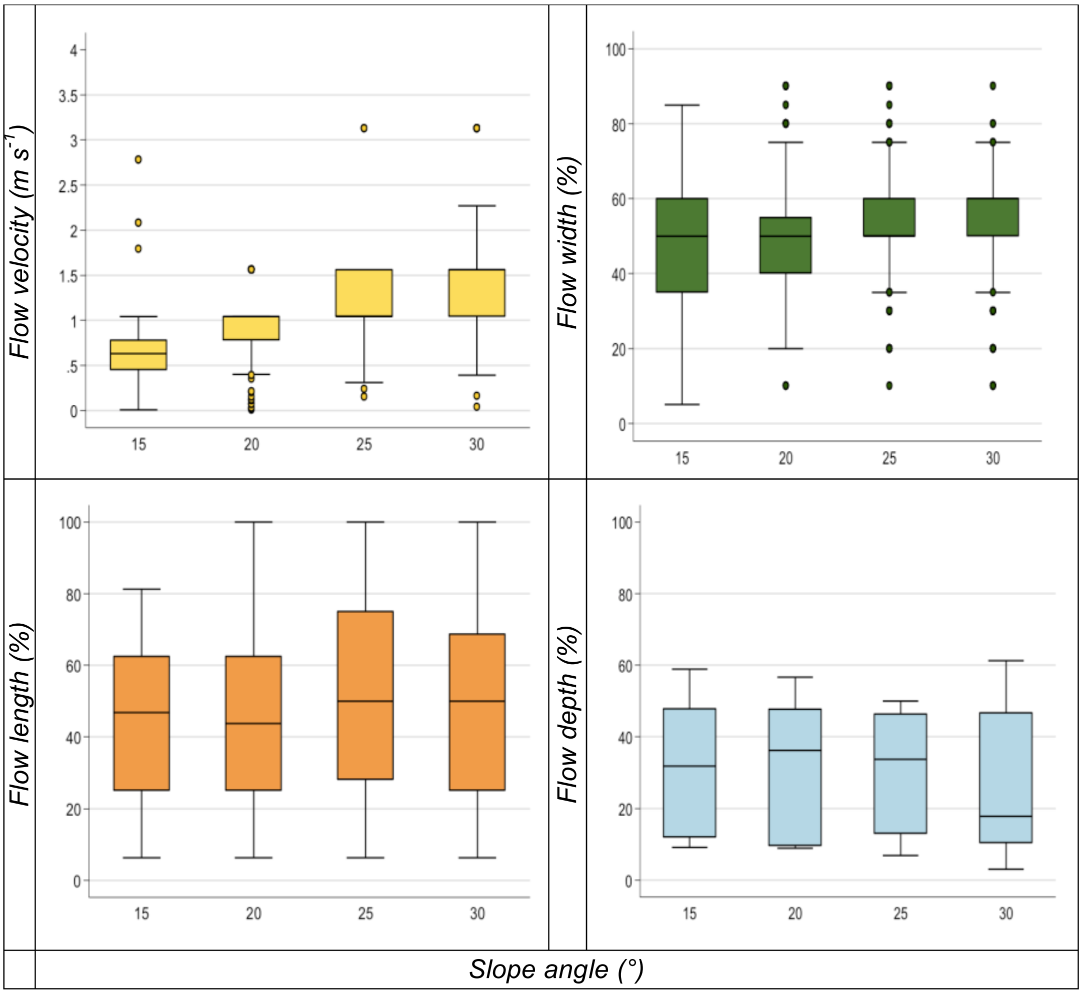


Figure 4.12: Box and whisker plots highlighting the range of debris flow velocity, width, length and depth at different slope angles (width, length and depth values are described as a percentage of overall channel width, length and depth). Each plot includes data from both the small and the large experimental flume. Each data value recorded per flow is included (eight values per flow in the small flume and 16 values per flow in the large flume – one for every 0.25 m of channel length in the small flume, and every 0.5 m in the large flume). This applies to the velocity, width and length values. The depth plots use the single average depth value calculated per flow.

Figure 4.13 demonstrates clear trends between slope angle and flow velocity, width, length and depth. The trends are similar to those highlighted in Figure 4.12. It demonstrates an increase in flow velocity and width with an increase in slope (R^2 = 0.99792 and R^2 = 0.84404 respectively), and a small increase in flow length (R^2 = 0.72025). It also highlights the decrease in flow depth with increasing slope (R^2 = 0.80679). Figure 4.13 shows little change in mean width and length from 25° to 30°; again similar to the data highlighted in Figure 4.12.

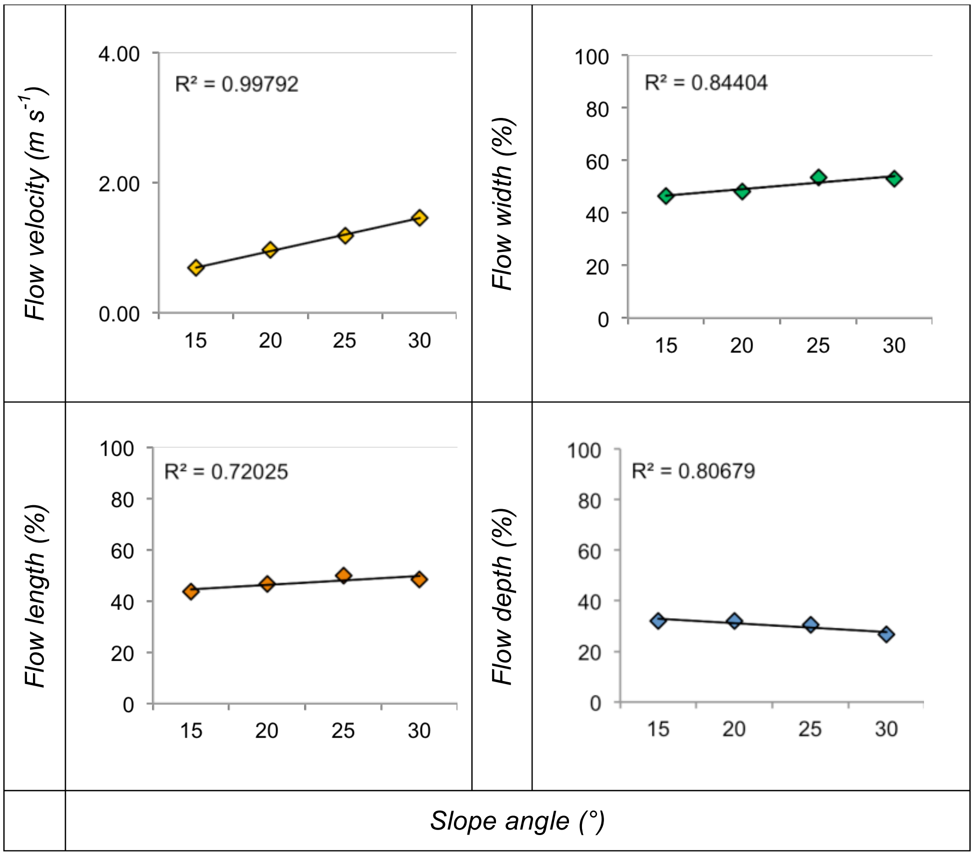


Figure 4.13: Mean debris flow velocity, width, length and depth at different slope angles (width, length and depth values are described as a percentage of overall channel width, length and depth). Each plot includes data from both the small and the large experimental flume. Each data value recorded per flow is included (eight values per flow in the small flume and 16 values per flow in the large flume – one for every 0.25 m of channel length in the small flume, and every 0.5 m in the large flume). This applies to the velocity, width and length values. The depth plots use the single average depth value calculated per flow.

Figure 4.14 demonstrates the relationship between average and maximum flow velocity, width, length and depth with slope angle. It is similar to Figure 4.12 and Figure 4.13. There is a positive correlation between slope angle and maximum and average flow velocity (R^2 = 0.17101 and R^2 = 0.38797 respectively). Average width is positively correlated with slope (R^2 = 0.05779), but there is little change in the maximum (R^2 = 0.00041) (also shown in Figure 4.12); suggesting that the rigid channel confined the flow. There is little change in average length, but an increase in maximum length with slope (R^2 = 0.05605 and R^2 = 0.07651 respectively); this is similar to Figure 4.12, and highlights the step change in maximum length from 15° to 20° from 80% to 100% of the channel length. There is no maximum depth data, but average depth decreases with increasing slope (R^2 = 0.00991).

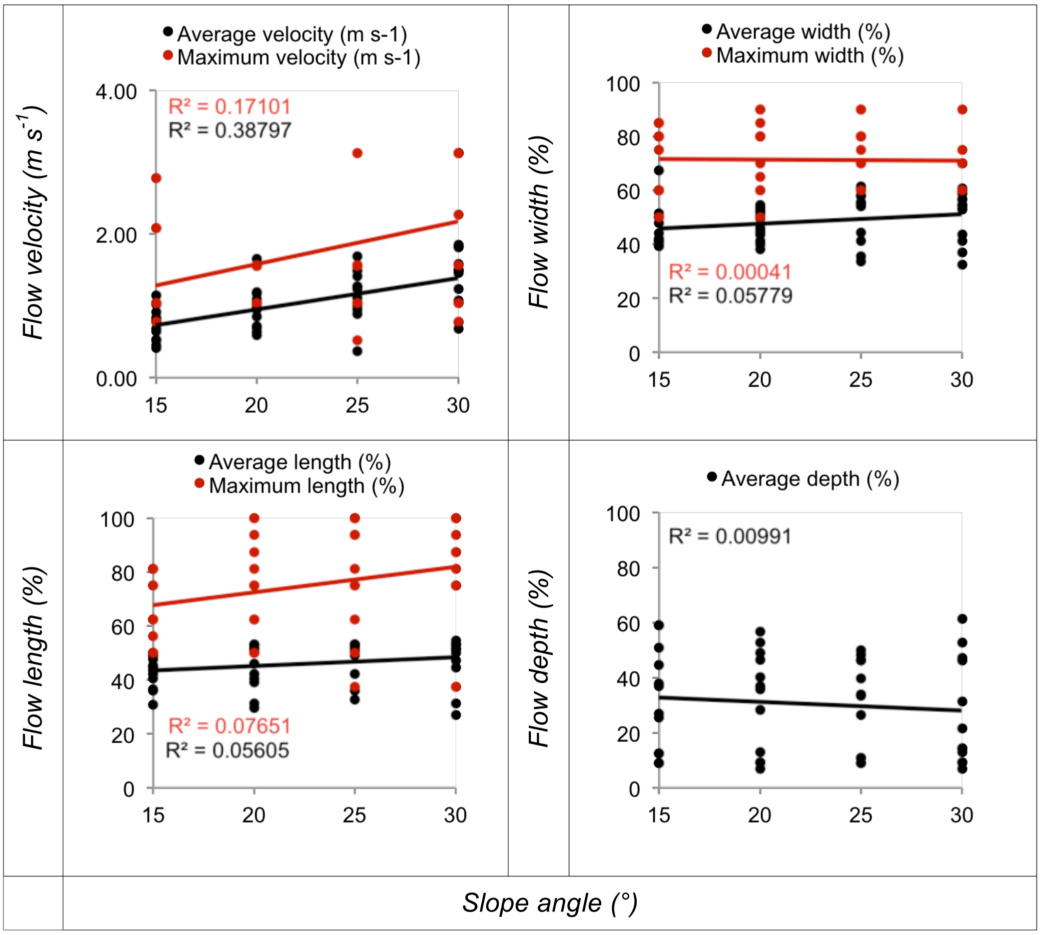


Figure 4.14: Relationship between slope angle and average and maximum flow velocity, width, length and depth (width, length and depth values are described as a percentage of overall channel width, length and depth).

4.4 The influence of mixture composition on debris flow behaviour

In order to complete objective three of this study (to assess the relationship between mixture composition and debris flow behaviour) the data produced from every debris flow in both experimental flumes was analysed.

4.4.1 Changes within the solids fraction

Figures 4.15 to 4.18 highlight the relationship between debris flow behaviour and the sediment concentrations in the solids fraction of the debris flow mixtures. The solids fraction was made up of differing proportions of gravel, sand and clay; which together made 100% by weight. Flow velocity, width, length and depth are analysed, and the figures display both the average and maximum data. Width, length and depth data were calculated as a percentage of the overall channel dimensions.

The data indicates that flow velocity, length and depth decreased as the percentage of gravel and clay became greater, and increased as the percentage of sand became greater. The changes to flow width are less than those observed with the other flow characteristics, with a total of an approximate 10% change in both the average and maximum flow width over the entire range of sediment concentration changes. Flow length showed changes of up to 20%, and flow depth showed changes of around 15%.

On the whole, the trends produced by the average and maximum values are similar to each other. However, the width plots in Figure 4.16 seem to indicate a difference between the trends of the maximum data and those of the average data; an increase in the proportion of gravel caused a slight increase in maximum width, but a decrease in average width. Also, with an increase in proportion of sand the maximum width decreased while the average width increased. Both the average and maximum width increased with an increase in the proportion of clay.

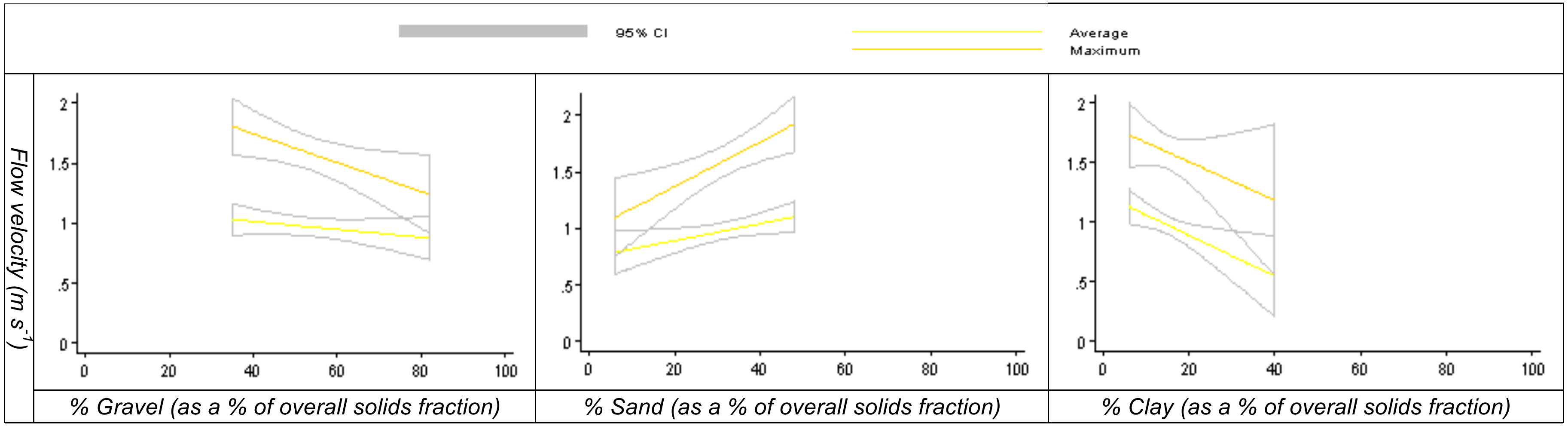


Figure 4.15: Flow velocity against sediment concentration (% gravel, sand and clay). Average and maximum data plotted, with 95% confidence highlighted.

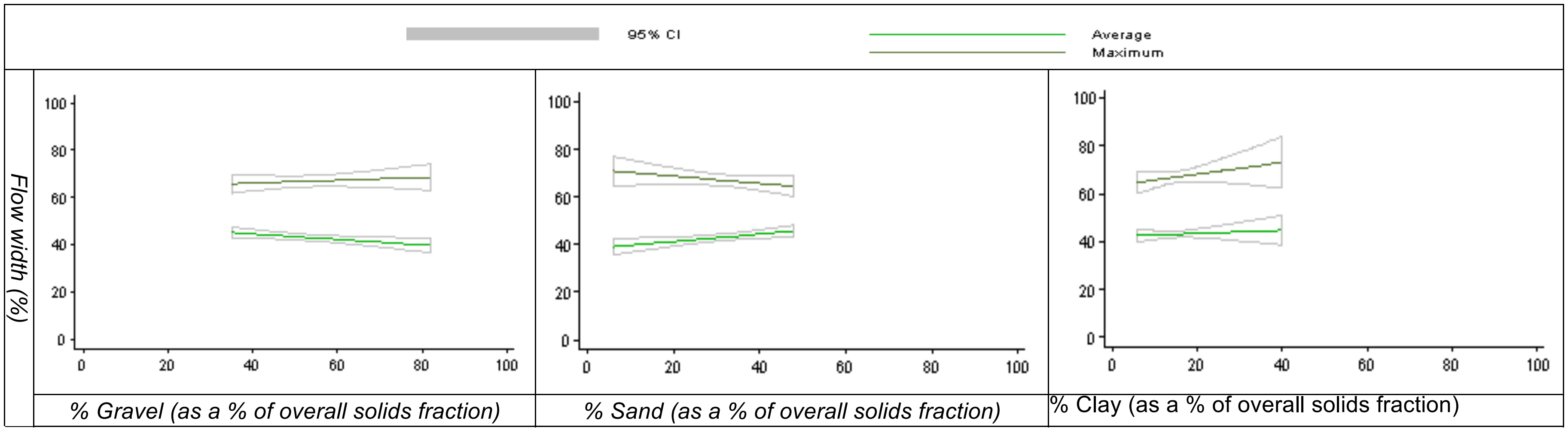


Figure 4.16: Flow width against sediment concentration (% gravel, sand and clay). Average and maximum data plotted, with 95% confidence highlighted.

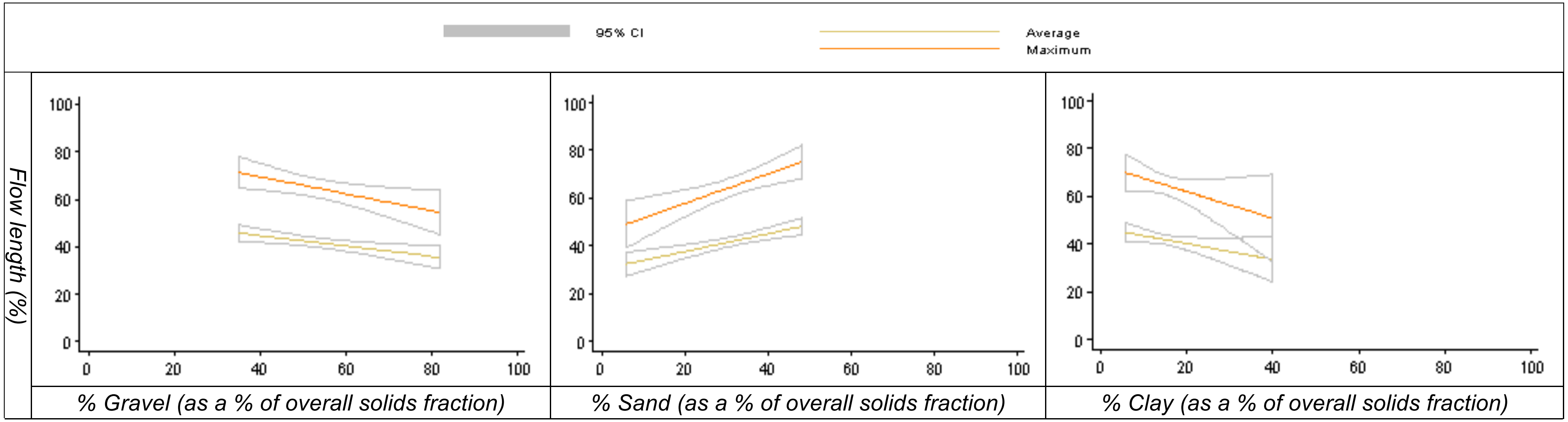


Figure 4.17: Flow length against sediment concentration (% gravel, sand and clay). Average and maximum data plotted, with 95% confidence highlighted.

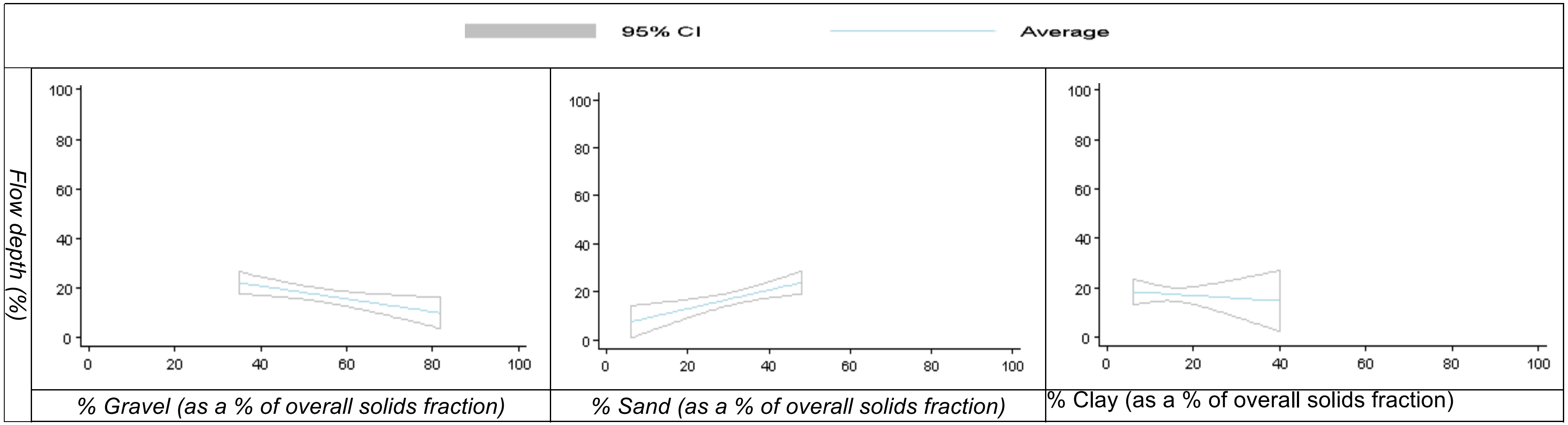


Figure 4.18: Flow depth against sediment concentration (% gravel, sand and clay). Average data plotted with 95% confidence highlighted.

4.4.2 Mixture composition and flow type

Figure 4.19 was produced to assess the relationship between debris flow mixture composition and the three flow types; granular, viscous and muddy. Mixtures with high gravel and low sand and clay proportions were dominated by granular flows, whereas mixtures with low gravel and high sand proportions were dominated by muddy flows. The viscous flows had the greatest mixture composition range and overlapped into the boundaries of both muddy and granular compositions. This validates the flow type continuum described earlier (Figure 4.3, section 4.1.3), with viscous flows in the centre linking muddy and granular flows. Figure 4.19 suggests a threshold between muddy and granular flows; the majority of muddy flows had less than 60% gravel and more than 40% sand, while the granular flows generally had of more than 60% gravel and less than 40% sand. Except for one granular flow, mixtures with more than 15% clay only produced viscous or muddy flows.

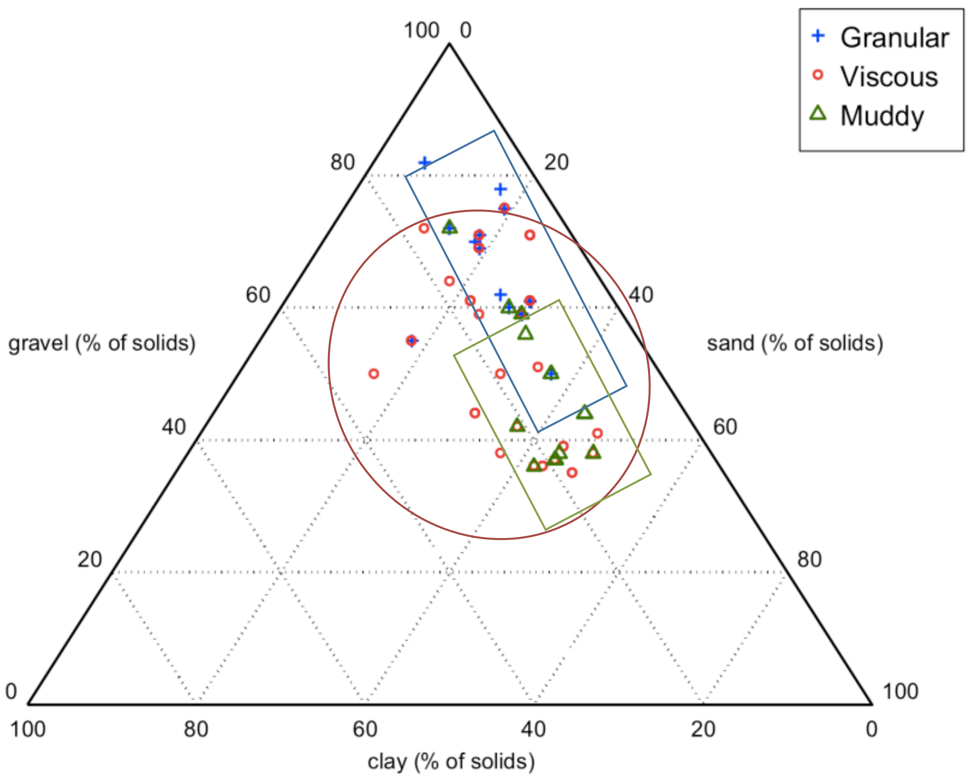


Figure 4.19: Ternary diagram highlighting the variation in experimental debris flow mixtures, and indicating a relationship between mixture composition and flow type. Viscous flows have the largest variation, and appear in the areas dominated by muddy and granular flows.

4.4.3 Flow type and flow behaviour

In order to understand how flow type (and through extension mixture composition) influenced flow behaviour, Figure 4.20 was produced; box and whisker plots of flow velocity, width, length and depth against flow type. The plots are divided into the average and maximum data. There is no maximum depth data as flow depth could not be recorded directly during the experiments. However, average depth was mathematically estimated post flow using other flow data, and this is included in Figure 4.20.

In terms of average flow velocity Figure 4.20 shows a similar range of data between the flow types; although there was a very slight rise in average velocity from the granular, to the viscous and then the muddy flows. The highest average velocity values were around 2 m s^{-1} for all flow types. The maximum velocity graph shows a much clearer trend between flow types. The muddy flows had the largest velocity values and inter-quartile range. The granular and viscous flow types generally had very similar maximum velocity inter-quartile ranges, although the viscous flow plot had higher maximum and minimum values.

In terms of flow width the average data was similar between flow types, although the viscous flows had a greater inter-quartile range (≈ 30% to 70% width) compared to the granular and muddy flows (≈ 30% to 50%).
The maximum width data, on the other hand, shows that the granular and viscous flows had similar inter-quartile ranges (60% to 80% width) and maximum values, whereas the muddy flows had a smaller inter-quartile range (60% to 70%), and maximum value; indicating a slight decrease in maximum width from the granular, to the viscous, to the muddy flows. The viscous and muddy plots had similar minimum values (≈ 50% maximum length), and the granular plot had the lowest minimum, at approximately 30% maximum width, and is negatively skewed.

In terms of flow length there was much more similarity in the trends of the average and maximum length plots concerning the different flow types; the granular and viscous plots had a larger spread of data compared to the muddy flow type, and there was a general increase in flow length from the granular to the viscous and finally the muddy flows. The average plots all had similar maximum values (≈ 55% length), and the maximum plots show maximum values near to, or at, the limit of the channel length (≈ 90% for the granular flows, and 100% for the viscous and muddy flows), suggesting that the fixed channel length was limiting the results.

The average flow depth plots also demonstrates a clear increase from granular, to viscous, to muddy flows. Average flow depth was similar between granular and viscous flows (although the viscous plot displays a slightly larger inter-quartile range and a higher maximum value). The granular plot demonstrates a range of approximately 5% to 30% depth, the viscous plot demonstrates a range of approximately 5% to 40%, and the muddy plot demonstrates a range of approximately 10% to 60% depth.

On the whole, Figure 4.20 demonstrates that along the continuum of granular ↔ viscous ↔ muddy, there were increases in maximum flow velocity and maximum flow length, and a decrease in maximum flow width. In terms of the average flow values, the data seems to follow the same trends as the maximum values, although the differences between flow types were less obvious. There is no maximum depth data, but average depth demonstrates increasing depth values from granular ↔ viscous ↔ muddy flows. On the whole, the range of data values was greater in the maximum plots compared to the average plots, regardless of flow type.

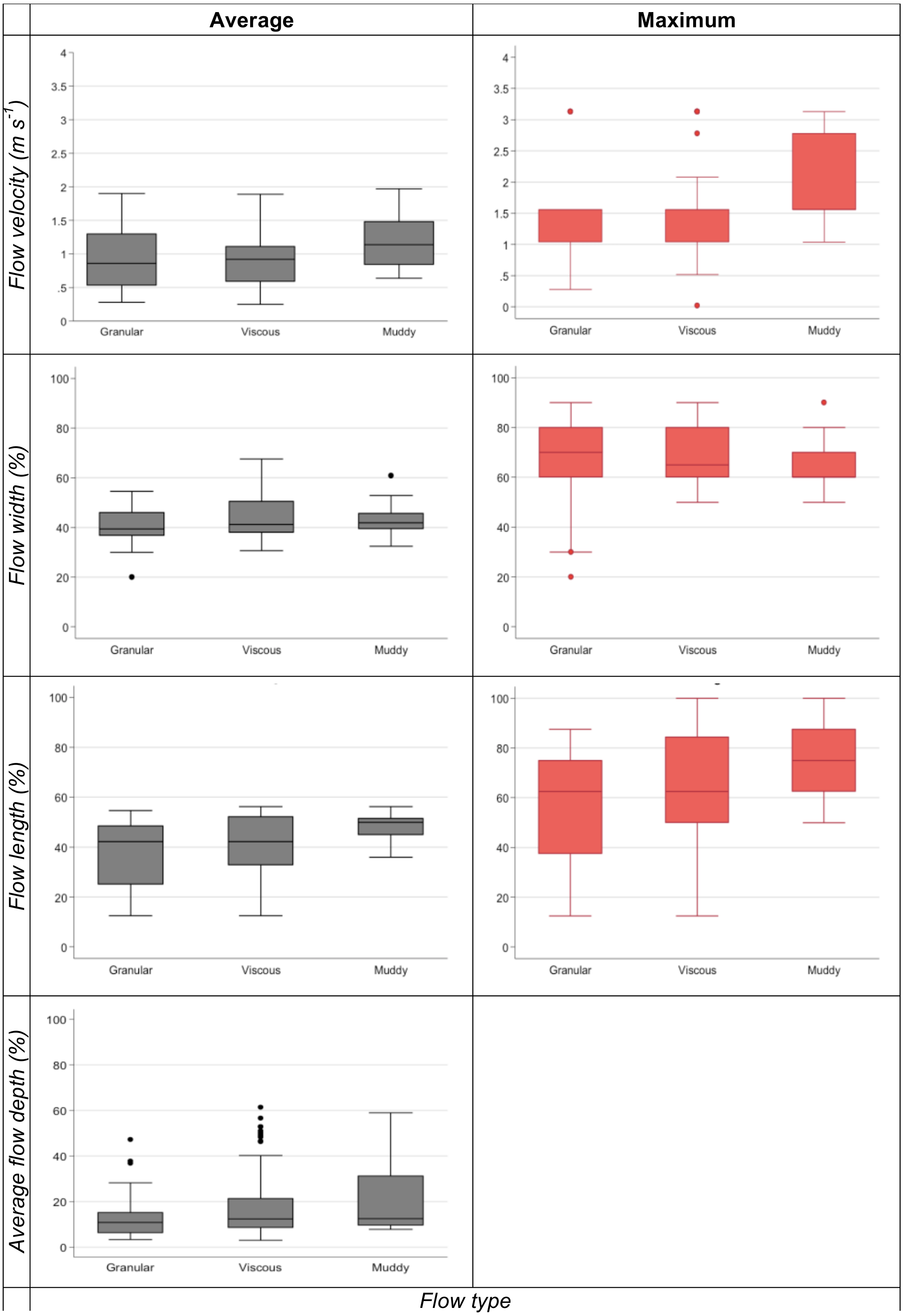


Figure 4.20: Box and whisker plots showing the range of average and maximum data for each flow type (granular, viscous and muddy) for flow velocity, width, length and depth. Each plot includes data from both the small and the large experimental flume. Width, length and depth values are described as a percentage of overall channel width, length and depth.

4.4.4 Internal interactions

It is important to understand not only how slope angle and mixture composition affect debris flow behaviour, but also how internal interactions within the flow influence behaviour. Figure 4.21 is a set of graphs indicating the relationships between flow velocity and flow length, width and depth, according to the three flow type categories (muddy, viscous and granular). It indicates a link between flow velocity and flow morphology, and shows that this varies between flow type, and therefore, mixture composition. Only data collected in the small flume was used to create Figure 4.21 because the large flume values for mixtures 34 and 36 were skewing the results.

Figure 4.21 highlights a strong relationship between flow velocity and flow length; flows with the higher velocities were longer. This was stronger in the granular (R^2 = 0.6223) and viscous flows (R^2 = 0.54), compared to the muddy flows (R^2 = 0.2319). The data also highlights a relationship between flow velocity and flow width, although this is weaker than the velocity length correlation; granular flows demonstrated a slight increase in width with velocity (R^2 = 0.0639), whereas the viscous and muddy flows demonstrated a slight decrease (R^2 = 0.023 and R^2 = 0.025 respectively). There is little correlation between flow velocity and flow depth, with only marginal increases in depth with velocity for the granular (R^2 = 0.0849) and muddy flows (R^2 = 0.0061), and a marginal decrease for viscous flows (R^2 = 0.0029).

Figure 4.22 highlights the relationships within debris flow morphology between flow width, length and depth; and how this varies with flow type. Again, only the small flume results were used. A strong correlation between flow width and flow length is demonstrated, and weaker correlations between flow width and flow depth, and between flow length and flow depth. Width, length and depth are all related, and therefore when one variable changed the others compensated. This was generally observed for the viscous and muddy flow types - although the extent to which compensation occurred varied. The data demonstrated that a longer flow would be deeper, but thinner. However, the data illustrated that for granular flows a greater length equalled both greater depth and width (although the change to depth was marginal), suggesting a possible alteration to the flow density during the flow (examined in section 5.2.4).

Figure 4.21 and Figure 4.22 demonstrate that flow velocity strongly interacted with flow length, and to a lesser extent, flow width; velocity seemed to have little interaction with flow depth. The data also demonstrated a strong correlation between flow length and flow width, and, to a lesser extent, flow width and flow depth. This suggests that the direct controller of flow depth was likely to be another flow variable, and not (directly) flow velocity. It is also clear that there were different interactions occurring within the flow, dependant on the flow type. For example, in muddy flows, the relationship between flow velocity and length (R^2 = 0.2319) was less than that for the granular (R^2 = 0.6223) and viscous flows (R^2 = 0.54), but the relationship between flow length and width was stronger for the muddy flows (R^2 = 0.1984) compared to the granular, R^2 = 0.15, and viscous flows, R^2 = 0.0507).

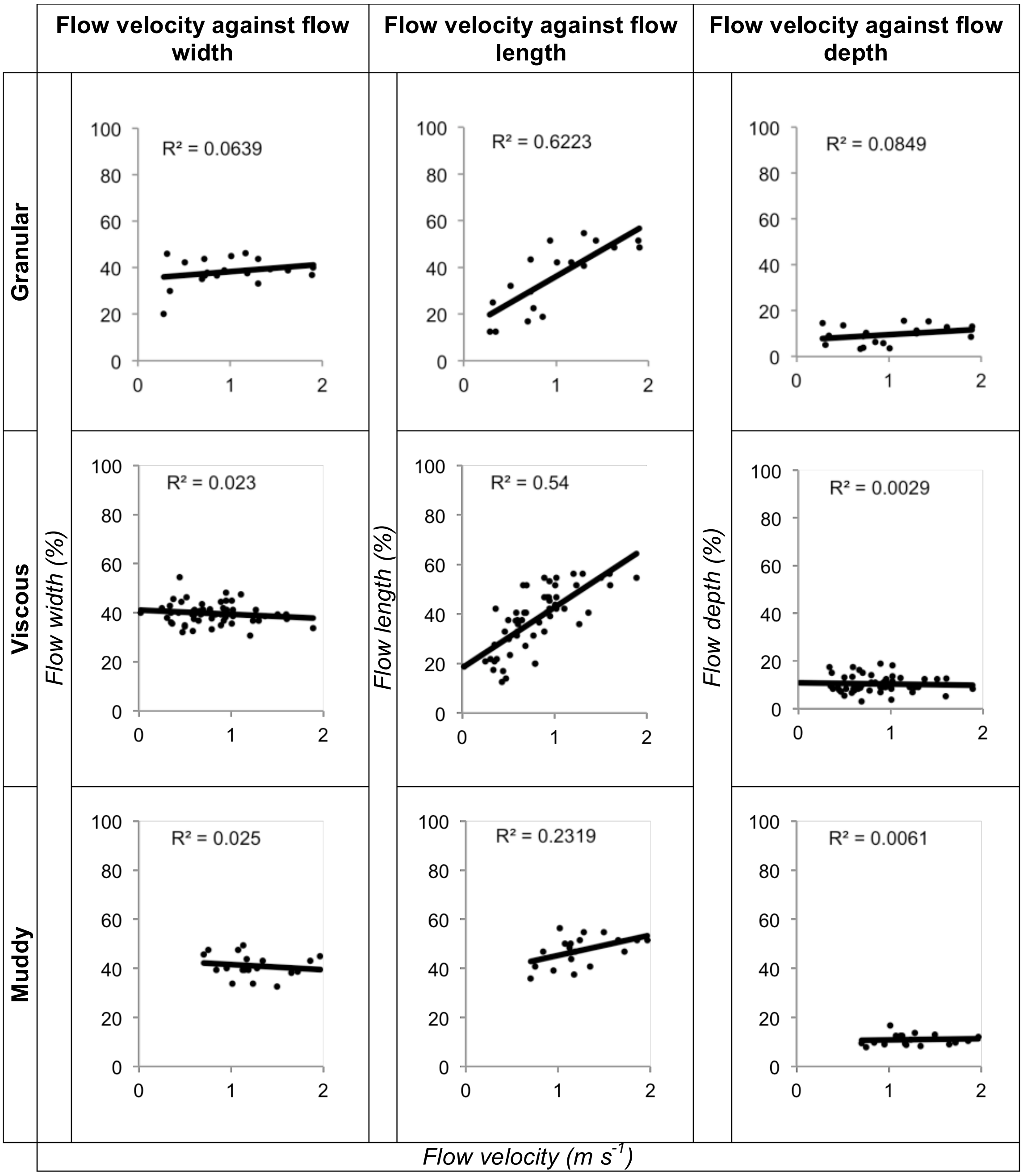


Figure 4.21: Scatter graphs depicting the relationship between average flow velocity and average flow width, length and depth according to flow type; granular, viscous or muddy. Width, length and depth values are described as percentages of overall channel width, length and depth.

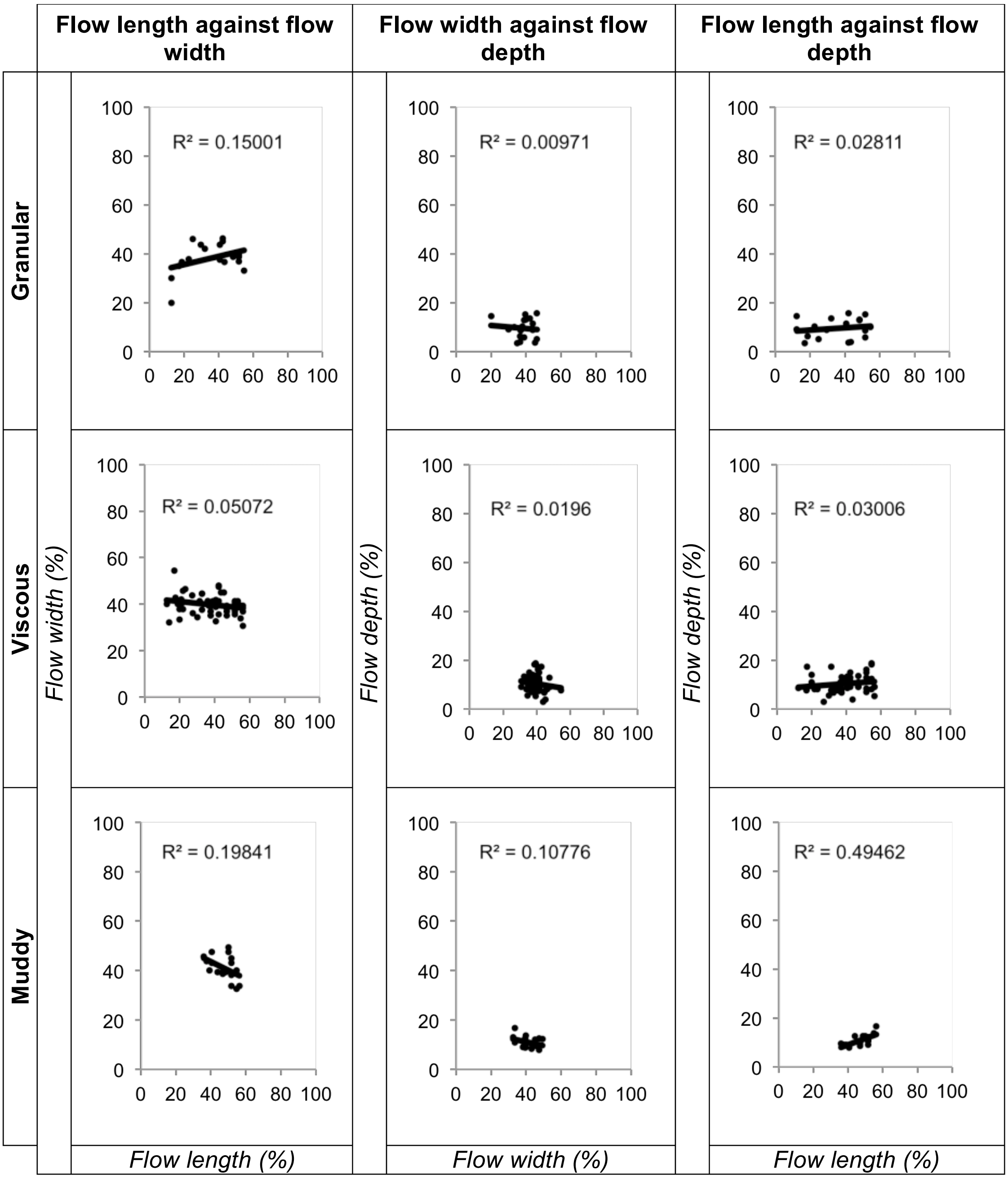


Figure 4.22: Scatter graphs depicting the relationships between average flow width, length and depth according to flow type; granular, viscous or muddy. Width, length and depth values are described as percentages of overall channel width, length and depth.

4.5 Summary

The aim of this study was to better understand debris flow behaviour and processes. This included an assessment of the influence of slope angle and mixture composition on debris flow behaviour, and the comparability of results from two different sized flumes.

This chapter has demonstrated the limitations of small-scale flume experiments in terms of the constraints of channel width and length; potentially impacting upon the full development of experimental debris flows. By utilising a small channel the debris flows may not have developed plug flow or the succession of local snout slowdown and surging from behind. Despite this, the results collected in the two different sized flumes are comparable (section 4.2). Changes to flow behaviour with distance down the channel were generally similar between the flumes. There was a sharp rise in velocity at the flume head before a gradual reduction, accompanied by a steady increase in flow length. The maximum width of a flow was observed at the point in the flume where flow length was the shortest. However, in the larger flume there was a greater level of flow development, leading to a reduction in flow velocity and length towards the distal end of the channel.

The results indicate that channel slope had significant influence over debris flow behaviour, with the steeper slopes producing flows with the greatest velocity, width and length, and the lowest depth. Slope had a strong influence on flow velocity, but had a limited influence over flow length. The results do however show several discrepancies in the relationships between slope angle and the average data (Figure 4.14), and slope angle and the maximum data, suggesting that the fixed channel boundaries may have influenced the results to some extent. The flow material was constrained by the fixed channel, therefore limiting the maximum extension of the flow (both width and length).

The results have shown that through variations in the amount of gravel, sand and clay (by weight) in the solids fraction, differences in the mixture composition influenced the flow type. Debris flow mixtures with higher proportions of gravel and lower proportions of sand and clay generally produced granular flows, whereas mixtures with lower proportions of gravel and higher proportions of sand produced a higher number of muddy flows. The data indicates an approximate threshold of sediment percentages separating the granular and muddy flow types; the granular flows tended to have over 60% gravel and less than 40% sand, whereas the muddy flows were generally comprised of less than 60% gravel and over 40% sand. It also highlighted that (except for one granular mixture) flows with a clay proportion greater than approximately 15% only produced viscous or muddy flows. This created a separation between the granular and muddy flow types, while the viscous flow types occurred with a range of mixture compositions that overlapped the boundaries of both the granular and muddy flows.

The data presented in this chapter has demonstrated that flow velocity interacted with flow morphology to differing degrees, depending on flow type. The data has also highlighted that experimental debris flows evolve with internal morphological interactions between flow width, length and depth; also dependant on flow type (and therefore mixture composition). It has shown that flow width is linked with both flow length and flow depth, whereas flow length and depth are slightly less dependent on each other. The influences of slope and sediment mixture composition on flow behaviour were analysed individually, but the results have demonstrated the complex interconnected nature of debris flows. The results in this chapter have shown that debris flow behaviour can be influenced directly by both channel slope angle and mixture composition, but can also be influenced by internal morphological interactions.

Chapter 5 Discussion

The aim of this study was to better understand debris flow behaviour and processes. This chapter will first assess the extent to which flow behaviour was comparable between two experimental flumes. It will then discuss the influence of channel slope and mixture composition on experimental debris flow behaviour, as well as the important influence of interactions within the flow. The chapter provides an overall synthesis of the interconnected dynamics of debris flow behaviour.

5.1 Experimental scale

In order to better understand debris flow behaviour and processes this study undertook the modelling of small scale experimental debris flows. The use of scale models was necessary due to the rarity of observing natural debris flows. Because scale models are designed to closely resemble a segment of the real world they must ensure that the forces acting within and upon them are the same as those found in nature (Chorley, 1967). The literature on debris flows indicates that determining similarity between debris flow models and the real world calls for both the scaling of the flow as a whole (with the length and depth of surges being the most significant), as well as of the grain-scale mechanics (where sediment composition is key) (Iverson *et al.*, 2010). However, when the scale of physical properties is altered during modelling it can result in the relationships between properties being affected in different ways (Chorley, 1967). This is especially pertinent for debris flows because their complex nature makes accurate scaling very difficult. In the past, several issues have arisen concerning scale dependant behaviours; the effects of pore fluid viscosity, the low inertia of grains, and the specific properties of interstitial water and clay (Iverson and LaHusen, 1993; Iverson et al., 2010).

For studies that must use scale models Hooke (1968) suggests they follow a ‘similarity of process’ criterion. This approach necessitates that a model meets gross scaling relationships, reproduces some morphological characteristics of the modelled system, and that the processes reproduced are logically assumed to be the same as those in nature. This approach offers a method that allows the application of experimental results to natural systems without having to scale every specific component individually.

For this study to be relevant to natural debris flows the behaviour in the model had to resemble that of natural flows as closely as possible. For most experimental studies this is difficult to demonstrate quantitatively due to a lack of comprehensive field data. The initial experimental design was therefore built upon previous studies, which have shown success in reproducing representative debris flow behaviour. As stated in Chapter 3, the experimental apparatus was loosely based on Davies' (1994) study; which gave results that when scaled up, lay within the expected range of field data. Davies (1994) based the model design on a dimensional analysis which ensured dynamic similarity between the model and nature. The main difference between Davies' (1994) study and the model used for this study was that this study utilised natural materials (gravel, sand and clay) for the debris flow mixture, rather than coal particles and wallpaper paste. By using natural sediment that mimicked the field-scale behaviour of debris flows, the difficulties of a formal scaling analysis were, to some extent, avoided.

The approximate scaling ratio between the two flumes in this study (flume dimensions and grain size) was 2:1, with the exception of channel length, which was scaled at 4:1. The channel roughness was not geometrically scaled; the sand glued to each flume was the same. The average velocities ranged from 0.36 m s^{-1} to 1.65 m s^{-1} in the small flume, and 0.41 m s^{-1} to 1.86 m s^{-1} in the large flume; similar to those recorded in Davies (1994) flume (0.2 m s^{-1} to 2 m s^{-1}). This study conducted experiments which were also similar to Parsons *et al.* (2001), who used a 10 m long flume and natural materials of sand, silt and clay (0.16 m s^{-1} to 2.45 m s^{-1}) and found that while it may not possible to accurately scale all flow properties, conclusions based on the results are relevant to the physics of natural debris flows and are therefore still of importance. The similarity between the data collected in these three different studies, as well as data collected for field debris flow events (Table 2.1), suggests not only that small scale debris flows may be used to represent natural debris flows, but also that small scale physical modelling of debris flows is not only feasible but has the potential to produce results dynamically similar to those found in nature.

5.2 Flume comparison - mixtures 34 and 36

Following initial experimentation with a large range of potential debris flow mixtures, two mixtures were examined in both the small and the large flume. Given that debris flows display such a large variation in behavioural types, it was thought sensible to examine more than one experimental mixture when assessing the similarities and differences in flow behaviour between flumes (section 3.1). Mixture 34 was chosen to represent granular/viscous flows, and mixture 36 was chosen to represent muddy/viscous flows (section 4.1.4). The same mixture compositions were used in both the small and the large flume; the only difference being the size of the coarse grained component; increased from an average of 10 mm gravel for use in the small flume to an average of 20 mm gravel for use in the large flume. The particle size distributions of these mixtures were similar in the two flumes (section 4.2.1). The up-scaling of the gravel was done in order to preserve the approximate geometry between the channel cross section and the coarse grained component of the flow (i.e. the snout geometry). However, the implications of this have not been fully evaluated; there is uncertainty in the scaling of these mixtures, with potential limitations due to the differences in the coarse grained fraction; this study was not comparing entirely like with like mixtures.

Generally, the quantitative behaviours of the two mixtures (Table 4.1 (small flume) and Table 4.5 (large flume)) were similar. Average width and length data show that both flumes produced flows with width and length values at approximately half the width and length of the channel. Although this meant that for experiments in the large flume the flows were wider and longer than those observed in the small flume. The flows exhibited similar values of both velocity (up to just over 3 m s^{-1}) and deceleration/acceleration (-10 m s^{-2} to 20 m s^{-2}) in each flume. The data also shows flows with higher velocities in both flumes experienced the greatest flow lengths. However, velocity values tended to be slightly higher in the large flume (although the spread of values was similar in both flumes). The small difference in velocity between the flumes may be attributed to the difference in the techniques used to introduce the debris flow mixtures into the experimental channels. In the small flume the mixtures were poured manually into the top of the channel, whereas in the large flume the mixtures were poured into a holding container at the top of the flume and released when the container gate was opened. This latter method ensured that all material entered the flume in a consistent manner and in a style that more closely represented the triggering of a natural debris flow. The manual pouring of the sediment into the small flume introduced greater error and inconsistencies than the method used in the large flume. For example, during some of the early small flume experiments it was observed that the mixtures displayed super-elevation in the upper channel because sediment was not poured straight down the centre of the channel. In order to avoid this, the mixture had to be poured into the flume in a steady manner that may have resulted in an artificial restriction on flow velocity. Nevertheless, all velocity values fell well within the range of natural debris flows, as shown in Table 2.1 (Sharp and Nobles, 1953; Pierson, 1980; Hirano and Iwamoto, 1981; Costa, 1984; Van Steijn and Coutard, 1989; Major and Pierson, 1992; Davies, 1994; Coussot and Meunier, 1996; Lorenzini and Mazza, 2004).

The method by which flow velocity and acceleration was measured and calculated yielded errors that affected the accuracy of the data and produced several unnaturally high acceleration values (section 3.3 and 4.2.3). The frame rate of the video on the digital camera (12.5 frames per second) meant that during velocity measurements the position of the flow in the channel could only be determined to the nearest 0.08 seconds. This was particularly problematic for experiments conducted at higher slope angles because the fast flows that were produced at these angles were only observed with one or two frames per channel section, and this resulted in low precision measurements. This lack of precision was then compounded when extrapolated into the acceleration calculations. This made it particularly difficult to quantitatively observe the development of surges towards the end of the faster flows, and surge data relied on qualitative observation from the videos. However, these issues could potentially be resolved by the use of a camera with a higher frame rate, by measuring velocity at less frequent intervals along the channel, or by utilising more precise equipment, such as a Doppler.

Despite small discrepancies both of the flumes used in this study have yielded flow morphology similar to that observed in natural debris flows (Table 4.2 and Table 4.6). There was often a clear snout and tail, similar to that described by Lorenzini and Mazza (2004). The segregation of the coarsest particles to the flow front is one of the defining characteristics of debris flows and this was present in the majority of the mixture 34 and 36 flows in both the small and the large flume. However, Table 4.2 and Table 4.6 also demonstrate that a higher proportion of flows in the large flume exhibited surging and plug behaviour. This can be attributed to the difference in channel length between the flumes. The longer channel in the large flume gave the flows more time to become fully developed, and as a consequence they displayed more of the features common to natural debris flows. It has been noted in the literature that experimental studies can be affected by enforced boundary conditions (Mosley and Zimpfer, 1978; Schumm *et al.*, 1987).

The issue of boundary conditions was again raised in Figure 4.10, which shows a selection of histograms comparing mixture 34 and 36 in the small and the large flume. The histograms are similar for flow velocity in both flumes, but both the width and length histograms show differences between flumes. The small flume shows a greater frequency of small and large flow widths, and a smaller frequency of intermediate flow widths, compared to those seen in the large flume. Due to the extended length of the large flume, flows spent more time in the channel and after a rapid increase and decrease in flow width, flows began to stabilise to around 50% of the total width, resulting in a much higher frequency of intermediate widths. This implies that there was less flow development in the small flume. There was also an increase in the frequency of large flow widths (approaching the full channel width) in the large flume. This was possibly due to the increased number of surges causing temporarily increases in the flow width.

The coarse sediment particle dynamics were also similar between the two flumes (Tables 4.2 and 4.6). Most flows, regardless of the flume, were observed to exhibit particle rolling behaviour. This type of behaviour was also observed in debris flow flume research conducted by Iverson *et al*. (2010 p.8). They described debris flow snouts as "*a form of wave breaking in which clasts reaching the crests of snouts tumbled down their forward faces, slowed when they contacted the bed, and were overridden*". They also stated that debris flow snouts "*acted to some extent as moving dams that impounded trailing, more fluid debris, the sediment constituting the dams evolving continuously*". However, the debris flows in the large flume which used mixture 34 showed less evidence of this local snout slowdown and pushing of the snout from behind at 25° and 30°, when compared to mixture 34 at the same slope angles in the small flume. It may be that these flows were influenced by the slightly faster velocities in the large flume, which were more pronounced at higher slope angles; the higher velocities reducing the likelihood of particle segregation and the development of increased snout friction, consequently producing less local snout slowdown (section 4.2.2).

This study not only examined flow behaviour as a whole, but also explored how flow behaviour developed as a function of distance down the flume channel. Figures 4.8 and 4.9 illustrate this. Flow length generally increased with distance down the channel, and flow width reduced as a consequence of this. In instances where flow length decreased towards the distal end of the channel flow width increased. However, there were also differences noticed between the two flumes. For example, several flows in the large flume displayed an increase in velocity towards the distal end of the channel, rather than the steady decrease seen in most of the small flume experiments. A possible explanation for this could be linked to the channel length constraints in the small flume; the longer channel length in the large flume gave the mixture enough time in the channel to enable surges to reach the flow front (which has slowed due to increased friction). These surges decreased the friction at the flow front, and momentarily increased the frontal velocity. When this occurred it was accompanied by a reduction in flow length (as the back of the flow caught up with the snout), and an increase in flow width. It was also observed that several of the flows in the small flume had lengths that peaked at around 50% of the overall channel length, and failed to get any longer. Figure 4.10 highlights this behaviour; showing a high frequency of flow length values in the 40% to 60% range in the small flume. This may be a consequence of the lower velocities in the small flume, which, unlike the large flume, did not enable the front of the flow to extend away from the tail.

Due to a lack of debris flow field data there may be no clear way of relating the success of the models used in this study to the behaviour of natural debris flows. It is clear that one of the disadvantages of scale models is the impact of artificial boundary conditions that would not be present during natural debris flows (Mosley and Zimpfer, 1978; Schumm *et al.*, 1987). However, Figure 4.11 confirms that on the whole the small and the large flume produced quite comparable data, especially in terms of flow velocity. But although both flumes produced similar trends, Figure 4.11 highlights the slight differences in flow width and length between the flumes. It can be argued that differences between the results are partly a consequence of model design, with the method of sediment release, differences in mixture volume and channel boundary constraints influencing flow behaviour. However, experimental models do allow the examination of processes that would not normally be possible in the field, as well as the observation and analysis of features under repeatable conditions with easy visualisation (Mosley and Zimpfer, 1978; Schumm *et al.*, 1987). Modifications to the flume design used in this study could resolve some of these issues, and potentially improve the similarity between the two flumes. However, despite some discrepancies the behaviours witnessed in this study generally compare well with both natural debris flows and those observed in other experimental studies.

5.3 Controls on debris flow behaviour

Objectives two and three of this study were to assess the influence of channel slope and mixture composition on debris flow behaviour. It has been claimed that the best route to geomorphological understanding is to structure a problem into its component parts so that the operation of each, as well as the interactions between them, can be examined; leading to a synthesis of the components as a working whole (Chorley, 1967). In order to gain a better understanding of what drives debris flows behaviour, the influence of slope angle is examined first, followed by the influence of mixture composition on flow mobility and behaviour, and finally the influence of interaction dynamics within the flow.

When examining experimental debris flow velocity, width, length and depth the flows occurred in a flume with fixed channel geometry. Therefore, although the width, length and depth of the flow could change, it was only within the constraints of this fixed boundary. The depth data used in the study was not directly measured, but was calculated by dividing flow area by flow volume; therefore only an average was obtained.

5.3.1 Slope angle

The channel slope of the experiential flumes was varied in increments of 5° from 15° to 30°. The results showing the influences of a change in slope on debris flow behaviour are set out in section 4.3; Figures 4.12 – 4.14. It is clear that slope had a major influence on flow velocity; as slope was increased both the average and maximum flow velocity increased. A relationship between debris flow velocity and slope angle has been observed in other debris flow studies (Pierson, 1986; Genevois *et al.*, 2000; Lorenzini and Mazza, 2004).

The influence of channel slope on debris flow width was less pronounced; the data demonstrated an increase in average flow width, but not of maximum flow width with an increase in slope angle. The discrepancy between the average and maximum trends (Figures 4.12 – 4.14) suggest that the flows were being constrained by the fixed channel boundaries, and did not widen as much as they perhaps would have if the channel banks were erodible; as they often are in nature. It was also noticed that neither average nor maximum channel width altered much between the slopes of 25° and 30°, suggesting a limiting response between these slope angles.

The relationship between channel slope and flow length was poor; there was little change in flow length with increasing slope angle. However, Figure 4.12 and Figure 4.14 do show an increase in maximum flow length with increasing slope; but this trend is strongly influenced by a marked increase in the maximum length from 80% at 15°, to 100% at 20°, 25° and 30°, and could be linked with the increasing velocity values at steeper slopes. This also suggests that 15° is a potential threshold after which flows have enough momentum to overcome channel friction, and as a consequence see less reduction in the flow length. This theory is supported by Figure 4.9, which shows that flows at higher slope angles are less likely to have a reduction in flow length towards the end of the channel. However, the fact that flows are reaching lengths of up to 100% of the overall channel length suggests that the flume dimensions have also placed a constraint on flow length.

The relationship between channel slope and flow depth is reasonably clear; as slope increased, average flow depth decreased (Figures 4.12 – 4.14). This is most visible in Figure 4.13. With natural debris flows, the same relationship has been observed; increased depths occur at lower slope angles due to increased friction and reduced flow velocity, which causes flow compression (Hungr, 2000; Iverson et al., 2010). However, there is limited depth data in this study and this makes it less comprehensive than that of the other flow variables.

The general influence of channel slope on experimental debris flow behaviour is highlighted in Figure 5.1. The data collected in this study revealed a clear link between channel slope and flow velocity. Channel slope and flow depth were also shown to be correlated, but to a lesser degree. The data demonstrated little correlation between flow length and channel slope, and a correlation between channel slope and average flow width only (not maximum flow width). The data also indicated that both flow length and flow width were possibly being constrained by the fixed channel dimensions.

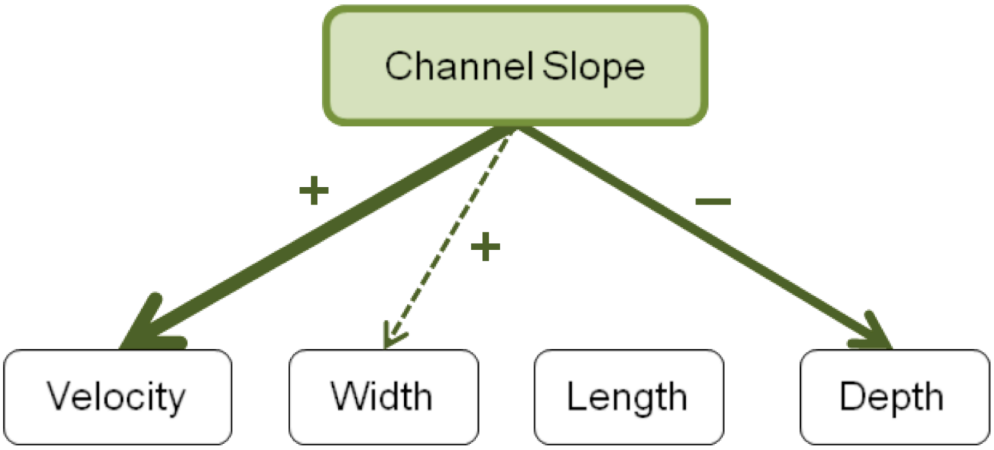


Figure 5.1: Conceptual diagram highlighting the influence of channel slope on debris flow velocity, width, length and depth. The strength of the relationship and its direction are highlighted by the width of the arrows and the increase/decrease signs; increasing slope leads to an increase in flow velocity and width, and a decrease in depth. The strongest relationship is between channel slope and velocity. The relationship with flow width is only valid for average flow width.

5.3.2 Mixture composition and flow mobility

Natural debris flows exhibit a range of different sediment compositions, all of which 'have an impact upon the flow characteristics. It has been suggested that even small changes to debris flow composition can have an effect on flow mobility and behaviour (Van Steijn and Coutard, 1989; Phillips and Davies, 1991; Major and Pierson, 1992; Iverson, 1997). By testing a range of debris flow mixtures with varying sediment compositions this study has been able to assess the extent to which mixture composition affected experimental debris flow behaviour. It was observed that the differences in the proportions of gravel, sand and clay had a significant impact on debris flow mobility (section 4.1.5). The results indicated that mixtures containing more than 15% clay had very low mobility, and in some cases failed to flow at all. It was observed that to flow freely, especially at lower slope angles, a debris flow mixture needed:

- ≤ 15% clay
- 25% - 40% sand
- 15% - 20% water

Mixtures with sand content greater than 35-40% were dry and had limited mobility, while mixtures with less than 25% sand were too wet if the gravel percentage was low; or too dry if the gravel percentage was high. Regardless of the proportions of gravel, sand and clay, if there was not enough water in the mixture mobility was limited, and the ideal was observed to be between 15% and 20%. There were also links between the sediment components. For example, for mixtures with less than 10% clay, less sand was needed than if there was a high percentage of clay in the mixture. It was also apparent that a relative difference in the clay and water content of less than 10% produced good mobility; although the best results were observed in mixtures with a relative difference of approximately 5%. For those mixtures with a relative difference of more than 5% it was possible to offset this with an increase in the sand content. On the other hand, in a mixture with a relative difference of less than 5%, a smaller percentage of sand was needed to produce a mobile flow. Therefore, this study suggests the following guidelines for the relative material components needed to produce a mobile flow:

- ≈ 15% clay requires ≈ 35-40% sand assuming the relative difference in clay/water is ≤10%.
- ≤10% clay requires ≈ 25% sand OR if the relative difference in clay/water is ≤ 5%.
- If the relative difference in clay/water is ≥ 5% more sand is required than if the relative difference is ≤ 5%.

An important conclusion stemming from this is that sand is especially beneficial for helping to mix the clay and water elements of a mixture; reducing mixture cohesion and producing a more mobile flow that can support large gravel particles. The amount of sand needed in a mixture is linked to the proportion of clay in the mixture, but also to the relative difference in the clay and water content.

5.3.3 Mixture composition and flow behaviour

As well as examining how the overall composition of an experimental debris flow influenced mobility, this study explored the influence of the solids fraction (the percentages of gravel, sand and clay) on flow behaviour; velocity, width, length and depth (section 4.4); Figures 4.15 – 4.20. The data demonstrates that experimental debris flow velocity, length and depth are all clearly affected by changes in sediment composition:

- An increase in the proportion of gravel led to a decrease in flow velocity, length and depth.
- An increase in the proportion of sand led to an increase in flow velocity, length and depth.
- An increase in the proportion of clay led to an increase in flow width, and a decrease in flow velocity, length and depth.

The influence of the gravel and sand proportions on flow width was ambiguous; there was a difference in the average and maximum trends (Figure 4.16). These relationships were poorly defined, but given the limitations of the fixed boundary conditions it is not surprising that the average and maximum results were different (also noted in Figure 4.14 when examining the influence of channel slope on flow width).

These results support the findings of previous debris flow research. For example, this study noted an increase in flow velocity with surge activity (section 4.2.3), also observed by Suwa *et al.* (1993), who state that flow mobility is a function of surges, with velocity increasing with the occurrence of surges as the concentration of gravel at the flow front is reduced. They also state that flow velocity is influenced by gravel concentration (with mobility reducing as concentration increases). The influence of sand on debris flow behaviour has also been noted (Major and Pierson, 1992; Sosio and Crosta, 2009); the proportion of sand influencing flow behaviour by affecting yield strength and plastic viscosity, aiding flow mobility.

The literature suggests that increasing the concentrations of clay within a debris flow mixture can lower yield strength and viscosity, and increase flow mobility (Rodine and Johnson, 1976; Costa, 1984; Chen, 1987; Whipple and Dunne, 1992). The results in section 4.4 of this study contradict this by suggesting that increasing the percentage of clay reduces flow velocity, length and depth, and increases flow width. However, most research studies consider debris flow mixtures with low clay contents (from 1-2% (Costa, 1984), to 8-10% (Costa, 1988)), and while their conclusions apply to these low concentrations, this study looked at clay percentages varying from 5% to 33%. This suggests that while small percentages of clay enable a debris flow to flow for long distances by increasing cohesion in the flow, there is a threshold after which an increase in the proportion of clay leads to a 'stickiness' in the flow, restricting mobility. This was noted by Iverson *et al.* (2010) who explain that some small scale experiments see an increase in flow resistance when mud content is increased because the small particles increase yield strength and viscosity. However, Figures 4.19 and 4.20 demonstrate that flows with proportions of clay above 15% were viscous and muddy in nature; the muddy flows exhibiting the most mobile flow behaviour. Muddy flows with over 15% clay also had the highest proportion of sand, suggesting that the sand increases flow mobility by lowering the yield strength of the clay. The implication is that flow behaviour is affected not only by the influence of gravel, sand and clay individually, but also by the complex interplay between the fines and the coarse grains within a flow. Pierson (1981) explained that pore fluid is able to reside in a framework of coarse grains and induce flow mobility; too many grains can lead to an increase in friction which reduces mobility. This suggests that an intermediate value of coarse grains will lead to maximum flow mobility.

This study categorised experimental debris flows into three types; granular, viscous and muddy. Figure 4.19 highlights the differences in sediment composition of the three flow types. Granular mixtures had high gravel content, and low sand and clay content, and muddy flows had lower gravel content but higher sand and clay content. The viscous flows, on the other hand, covered a large range of sediment percentages; although tended to have a lower proportion of gravel than the granular flows. Generally, along the flow continuum of granular ↔ viscous ↔ muddy, the proportion of gravel within the mixture decreased, the proportion of sand increase, and the proportion of clay increased between the granular and viscous flow types, but decreased between the viscous and muddy flow types.

In order to assess the extent to which flow type (and through extension, mixture composition) affected experimental debris flow behaviour the conceptual diagram of Figure 5.2 was produced. The changes in the composition of the mixtures between the granular, viscous and muddy flows led to an increase in flow depth and flow length the along the continuum of granular ↔ viscous ↔ muddy flows. Flow velocity and flow width were slightly more complicated as the behaviour altered between the granular and viscous, and the viscous and muddy flows; possibly influenced by changes to the clay content. Velocity decreased when the percentage of clay was increased; and increased when the percentage of clay was decreased. The opposite is true for flow width. This suggests that clay had a strong influence on flow behaviour.

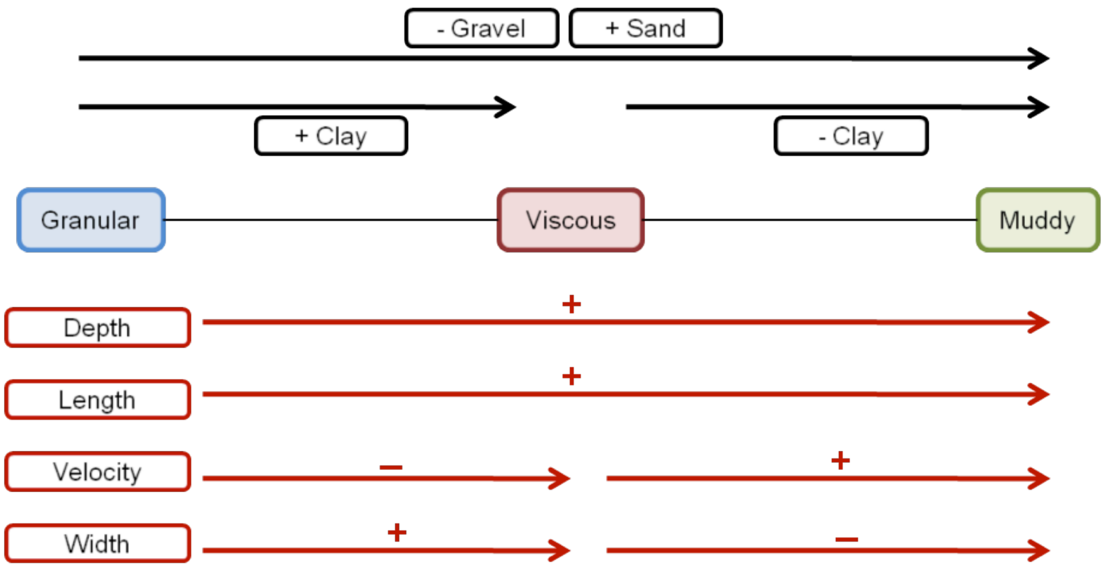


Figure 5.2: Conceptual diagram highlighting the relationship between the increase or decrease in the mixture components of gravel, sand and clay, flow types (granular, viscous and muddy) and debris flow behaviour (velocity, width, length and depth).

Different debris flow behavioural characteristics were observed depending on the flow type. The influence of mixture composition affected both the measured flow behaviour and the qualitative flow behaviour. For example, the muddy and granular flows exhibited fines dominant and grain-to-grain contact dominant behaviour respectively. This was similar to the behaviour of debris flows as described by Lorenzini and Mazza (2004), who explain that behaviour is influenced by the fines content. Mixtures 34 and 36 in this study had differing sediment contents and were seen to exhibit different particle flow behaviours (Table 4.2 and Table 4.6). Mixture 34 had higher gravel content than mixture 36, and tended to produce flows with local snout slowdown. This confirmed the observation by Iverson *et al.* (2010) where a mixture with high gravel and low sand content showed deceleration towards the flow front, and a mixture with a lower gravel and higher sand content did not.

It is clear from the literature that mixture composition has an impact upon flow velocity (Costa, 1984; Pierson, 1986; Genevois *et al.*, 2000; Lorenzini and Mazza, 2004). Greater concentrations of coarse grained sediment within a mixture lead to an increase in internal resistance, which in turn leads to a reduction in flow mobility (Pierson, 1986; Genevois *et al.*, 2000). In a study by Iverson *et al.* (2010) flows with 56% gravel and 37% sand had greater mobility than flows with 66% gravel and 33% sand. This study supports these findings. Figure 5.2 shows that as gravel content decreased, flow velocity increased; the muddy flows had lower gravel content compared to the granular and viscous flows, and exhibited higher velocity values.

5.3.4 Debris flow dynamics

This study has demonstrated that while both slope angle and sediment mixture affect experimental debris flow behaviour, the influence of internal interactions within the flow is also important. Section 4.4.4 (Figures 4.21 and 4.22) examines the relationships between flow velocity, width, length and depth. It is clear that velocity was a strong influencing factor on debris flow morphology - especially flow length; stronger in the granular and viscous flows, than the muddy flows. Flow velocity also interacted with flow width to some degree (again altering depending on flow type); granular flows showed a slight increase in flow width with velocity, whereas the viscous and muddy flows showed a slight decrease. Flow velocity seemed to have little interaction with flow depth. However, the relationship between flow velocity and flow depth can be complex, and Genevois *et al.* (2000) noted that flow velocity and depth increase at the flow front, decrease directly behind this, and then increase again towards the tail of the flow as the flow becomes more liquid.

Continuity dictates that a change in one flow variable must be compensated for by changes in other flow variables. However, the granular flows showed increasing flow width and length with greater velocity, while flow depth remained similar (Figure 4.21). It is possible that turbulence within the flow enabled air to enter the mixture, allowing changes to the dimensions of the flow without the need for compensation from one or more of the other flow variables. This may have been facilitated by the grain-to-grain contact in the granular flows; the viscous and muddy flows did not appear to experience this, suggesting that there may have been too much cohesion within the flow for any air to enter. However, this relationship between air, flow density and behaviour may be a scale dependent feature, only occurring in small debris flows and it warrants further examination.

While it is clear that velocity influenced the flow width, length and depth, it was also the case that these variables influenced each other through internal interactions within the flow (Figure 4.21). It can be seen that flow length had a strong correlation with flow width, and to a lesser extent flow depth. As velocity influenced flow length more than flow width, it could be argued that width is influenced more directly by flow length, than by flow velocity. This relationship varied depending on flow type; for granular flows, an increase in flow length led to an increase in flow width, whereas for viscous and muddy flows, an increase in flow length led to a decrease in flow width; the relationship was strongest in the muddy flows. The relationship between flow length and flow depth was simpler; depth increased with length, regardless of flow type. However, the relationship was relatively weak for all flow types; this may be linked to the limited number of depth values, the fact that depth was not independent of the other variables but calculated from them, or it could simply be that flow depth was less affected by other flow behaviours; there was also a limited relationship between flow velocity and depth. However, a relationship between flow length and flow depth was also suggested by Iverson *et al.* (2010). Figure 4.21 demonstrates a relationship between flow width and flow depth; as width increased depth decreased, and *vice versa*. Generally, the muddy flows demonstrated the smallest spread in data but the strongest relationships between morphological variables. The influence of mixture composition, and how this varied with flow type, is highlighted in Figures 5.3 - 5.5.

The data suggests that flow velocity influenced flow length, and to a lesser extent flow width (the strength and direction of the relationship dependent on flow type). Length was the main influence of flow width, again with the strength and direction of the relationship varying with flow type. Length, to a lesser extent, also influenced flow depth. Flow width and depth were correlated with each other, with an increase in width leading to a decrease in flow depth, regardless of flow type. The data in this study demonstrates that the interactions and dynamics within a flow vary between flow types, and are therefore to some extent influenced by mixture composition. These relationships are highlighted in Figure 5.3, Figure 5.4 and Figure 5.5.

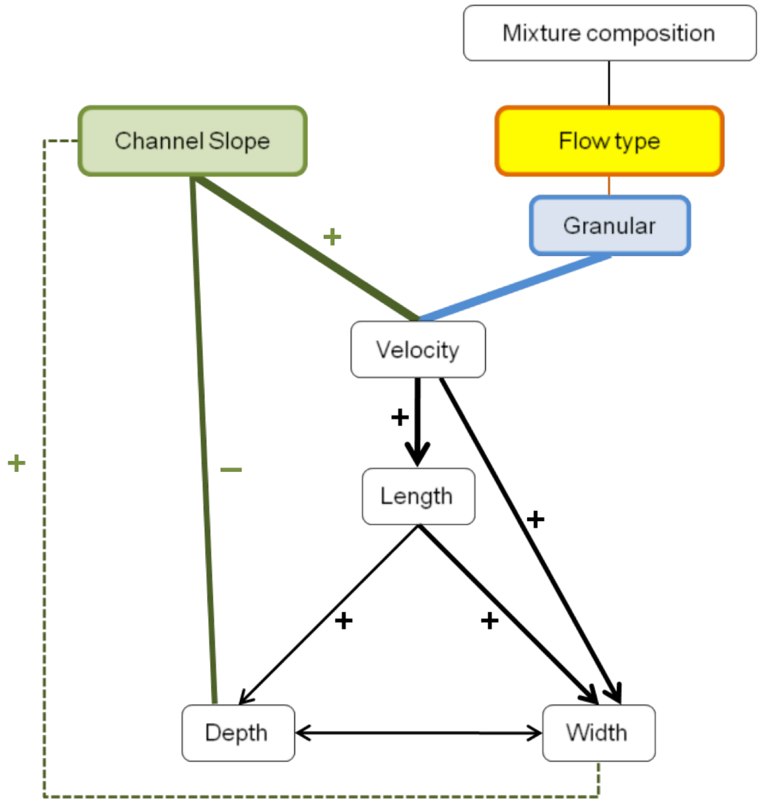


Figure 5.3: Conceptual diagram showing the interaction between debris flow mixture composition (specifically granular type flows), slope angle, and flow velocity and morphology.

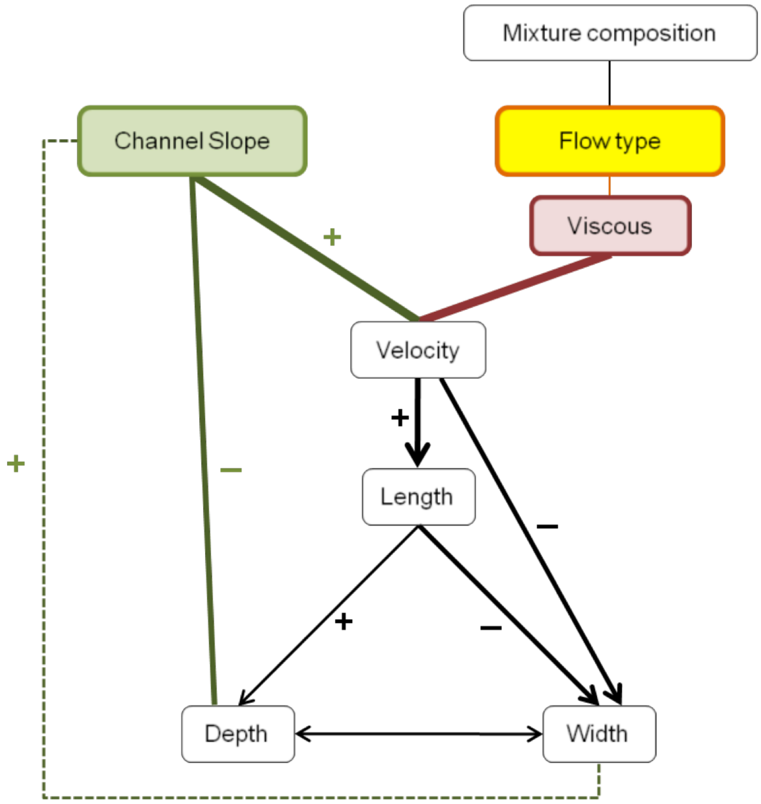


Figure 5.4: Conceptual diagram showing the interaction between debris flow mixture composition (specifically viscous type flows), slope angle, and flow velocity and morphology.

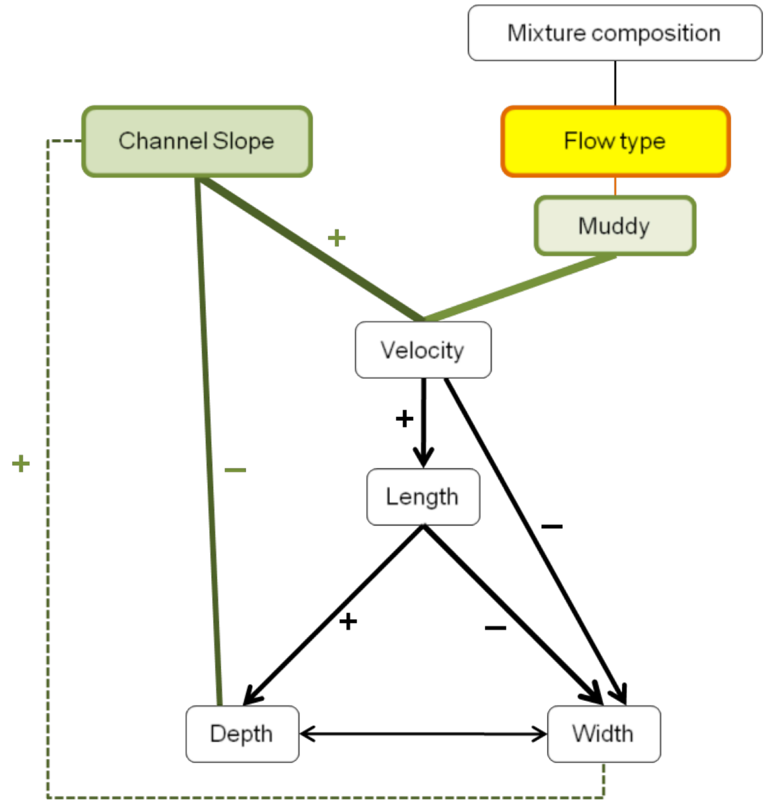


Figure 5.5: Conceptual diagram showing the interaction between debris flow mixture composition (specifically muddy type flows), slope angle, and flow velocity and morphology.

Figures 5.3 – 5.5 are summary diagrams highlighting the relationships between channel slope and mixture composition with flow velocity and morphology. They highlight how the different flow types (granular, viscous and muddy) influenced the changes in flow morphology in different ways (the strength and direction of the relationships). For example, in terms of flow morphology for granular flows, an increase in length led to an increase in width; and depth to a lesser degree. For the viscous and muddy flows, an increase in length led to a decrease in flow width, and an increase in flow depth; to differing extents. However, the influence of channel slope on flow behaviour was the same regardless of flow type.

Chapter 6 Conclusions

This chapter outlines the main conclusions of this study, and assesses the validity of the results by considering the main limitations of the work. Suggestions for future research are described.

6.1 Conclusions

The aim of this study was to explore and understand the influence of slope angle and sediment mixture composition on debris flow dynamics. This was done by using an innovative combination of experimental apparatus at two different scales. Three research objectives were formulated and tested:

1. *Test a range of sediment mixtures and determine which most closely reproduced natural debris flow behaviours, and assess the extent to which flows were comparable in different sized experimental flumes.*
2. *Assess the extent to which slope angle influenced debris flow behaviour.*
3. *Assess the relationship between mixture composition and debris flow behaviour.*

This chapter outlines the conclusions from these research objectives.

6.1.1 Similarity of behaviour in different flumes

The two experimental flumes used in this study have produced results similar to those found in natural debris flows, as well as in other experimental studies. The flows displayed the characteristics of debris flow behaviour, such as particle segregation, debris surges, sediment plug formation, and segregation into distinct phases of flow; suggesting that the results from this study can, with care, be extrapolated to represent natural debris flows. There were however, differences between flow behaviour in the small and the large flume. Principally, flows in the large flume were observed to have higher flow velocities than flows in the small flume. Flows in the small flume also displayed less longitudinal and width related flow development compared to flows in the large flume. Despite this, the two flumes produced comparable data, and it can be argued that any differences were a consequence of small differences in the sediment mixture composition and model design, such as the method by which material was put into the flume, and the fixed channel geometry.

Although this study was performed at much smaller scales than those observed in the natural environment, it provides some insight into how debris flows operate. This study included the examination of changes to debris flow behaviour as a function of distance down the flume channel. The flows showed a clear increase in flow length with distance down the channel. It was also observed that surge behaviour influenced flow velocity, width and length; when surges reached the snout they often resulted in a decrease in friction and a momentary increase in the frontal velocity of the flow. This was accompanied by local reductions in flow length, and increases in flow width.

6.1.2 The influence of channel slope

The experimental flows demonstrated a clear relationship between channel slope and debris flow behaviour. There was a strong positive correlation between slope angle and flow velocity. There was also a negative correlation with flow depth. There was little correlation between slope angle and flow length, and a weak positive correlation with flow width. Maximum flow values suggested a limiting influence of the fixed channel boundaries on flow width and length. A threshold for a change in flow behaviour was noticed between 15° and 20° for flow length, and between 25° and 30° for flow width, suggesting a link between slope angle, friction within the flow (and therefore mixture composition), and flow behaviour.

The variation in flow behaviour at different slope angles correlates well with what is reported in the literature. This study observed that channel slope had a direct influence on debris flow velocity, but less of an impact on flow width and depth, and very little correlation with flow length (Figure 5.1).

6.1.3 The influence of mixture composition

This study has demonstrated that debris flow composition can have a significant impact on flow mobility. It was observed that the most effective sediment proportions for creating a mobile experimental debris flow were:

- ≤ 15% clay
- 25% - 40% sand
- 15% - 20% water

Furthermore, there were important connections between the clay, sand and water components of the debris flow mixtures. It was apparent that sand played an important role in combining the clay and water components; reducing the effective cohesion. The data suggests that clay increased flow mobility if the proportion of sand in the flow was sufficient to compensate for the increased ‘stickiness’ of the clay content. It was also apparent that a relative percentage difference in the clay and water content of less than 10% produced flows with good mobility. The following mixture ‘rules’ are suggested to achieve good debris flow mobility:

- ≈ 15% clay requires ≈ 35-40% sand assuming the relative difference in clay/water is ≤10%.
- ≤10% clay requires ≈ 25% sand OR if the relative difference in clay/water is ≤ 5%.
- If the relative difference in clay/water is ≥ 5% more sand is required than if the relative difference is ≤ 5%.

Differences in mixture composition led to a marked difference in the appearance, as well as the behaviour, of the experimental debris flows. A three-fold classification of flows was developed; granular, viscous and muddy. The granular flows contained high concentrations of gravel and low concentrations of sand and clay and exhibited grain to grain contact behaviour. The muddy flows had lower concentrations of gravel but high concentrations of sand and clay and exhibited fines dominant behaviour. The viscous flows had a large composition range; although they tended to have a lower proportion of gravel than the granular flows. It was noted that flows with less than 60% gravel and more than 40% sand were muddy, while flows with over 60% gravel, and less than 40% sand were granular. Mixtures with a clay proportion greater than 15% generally only produced viscous and muddy flows.

This study demonstrated a clear link between debris flow composition and quantitative flow behaviour (velocity, width, length and depth). The data demonstrated the following consequences of changes to the gravel, sand and clay content within the mixtures:

- An increase in the proportion of gravel in the mixture led to a decrease in flow velocity, length and depth.
- An increase in the proportion of sand in the mixture led to an increase in flow velocity, length and depth.
- An increase in the proportion of clay in the mixture led to an increase in flow width, and a decrease in flow velocity, length and depth.

While in general these ‘rules’ are representative of the experimental debris flows, there were specific differences between the three flow types; granular, viscous and muddy. On the continuum of granular ↔ viscous ↔ muddy, flow mixtures had decreasing gravel content and increasing sand content. The clay fraction increased between the granular and viscous flow mixtures, but decreased between the viscous and muddy flow mixtures.

The influence of mixture composition affected not only the quantitative flow behaviour but also the qualitative flow behaviour. Granular type flows were dominated by grain-to-grain contact. Viscous type flows were thick and sticky, while the fine sediment and fluid components of the mixture dominated muddy type flows.

6.1.4 The influence of internal interactions

Debris flow behaviour was not only influenced by channel slope and the nature of the sediment mixture, but also by important interactions within the flow. The data in this study highlighted that velocity had a significant influence over flow length, but also (to a lesser extent) influenced flow width (the strength and direction of the relationship dependent on flow type). Length influenced flow width; with the strength and direction of the relationship also varying with flow type. Length, to a lesser extent, also influenced flow depth. The data showed that flow width and depth were correlated; an increase in width led to a decrease in flow depth, regardless of flow type.

6.1.5 Debris flow dynamics

The influences upon debris flow behaviour are complex and interconnected. Slope directly influenced debris flow behaviour, particularly flow velocity and depth. Differences in mixture composition led to different flow classifications; which in turn affected flow velocity and morphology, as well as internal interactions within the flow. It can be concluded that flow velocity was determined by both mixture composition and channel slope, while flow morphology (length, width and depth) was controlled by both flow velocity and internal interactions (with depth to some extent also influenced by channel slope); Figures 5.3 – 5.5. Internal interactions differed depending on flow type and therefore, by extension, mixture composition.

This study has shown the value of small experimental studies in assessing the influences on debris flow behaviour. Many studies in the past have made assumptions that the results from one debris flow mixture are universal for all debris flows, this study examined a range of debris flow types through the use of different mixture compositions. From a geomorphological perspective this allowed a better understanding of debris flow processes while identifying some of the controls on debris flow behaviour; which could be used to identify effective management strategies for natural debris flows.

6.2 Limitations of the study

Beveridge (1957 p65) suggests that experimental studies may be misleading: "*There is an interesting saying that no one believes an hypothesis except its originator but everyone believes an experiment except the experimenter. Most people are ready to believe something based on experiment but the experimenter knows the many little things that could have gone wrong in the experiment*". While this study demonstrated the potential of small scale modelling in assessing the behaviours of naturally occurring debris flows, the analysis has also revealed several limitations.

The study was influenced by the model limits placed on the debris flows by the fixed channel geometry, particularly in terms of flow length and width. Furthermore, there are concerns over how closely the experiments were representative of interactions in nature. For example, the debris flow flumes did not allow out-of-channel deposition, and there was no means of examining how entrainment or channel erosion affected debris flow behaviour. This study did not use debris flow materials on the scale of natural events. However, on such a small scale it is impossible to entirely replicate the natural environment, and as Hooke (1968 p.393) states "*certainty is practically impossible*". Given the fact that studying debris flows in nature is often impractical the results from this study are useful in extending the understanding of debris flows.

This study has also been influenced by experimental procedure. Differences in flow velocity and acceleration between the small and the large flume can be attributed to differences in the techniques used to introduce the debris flow mixtures into the experimental channels, the slight variations in each mixture, and the resolution of the video frame rate used to calculate the data. The manual pouring of the mixtures into the small flume left it open to human error and inconsistency, and the need to have the mixtures enter smoothly created an unnatural control on flow velocity. Using a small-scale release gate, similar to that used in the large flume, to introduce the mixtures into the experimental channel could rectify this. This study has also suffered from other data acquisition limitations. It was not possible to collect direct depth measurements; they were calculated using flow dimensions. Only one average depth value was calculated per debris flow, meaning that it was less reliable than some of the other results.

6.3 Future considerations

This study explored the influence of slope angle and mixture composition on debris flow behaviour using different sediment mixtures. However, debris flows can be composed of any number of materials with many different concentrations and this study did not examine all possible combinations. It would therefore be useful to conduct more debris flow experiments utilising a greater variety of material types, a larger range of sediment mixtures and a more detailed range of slope angles. This would give a fuller appreciation of the influences of these variables on debris flow behaviour. It would also be useful to conduct a range of studies using larger flumes as this would allow a further examination of the reliability and similarity of model results.

It is important that further research considers the wider impacts of debris flow behaviour. With a large data set it would be possible to produce a matrix detailing the likely flow behaviours produced in different landscapes. For example, it would be possible to determine what debris flow behaviours would be observed with any combination of sediment material and composition, water content and slope angle. This would go some way to understanding the overall impacts of debris flows on the surrounding environment, and would prove useful for hazard assessments in areas prone to debris flow events.

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