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Parameters controlling large landslide propagation

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Abstract

Landslides are an ever-present natural hazard and understanding factors such as propagation are vital for the management of such events. This natural hazard has increased in frequency in recent history which further highlights the importance of the research. This study aims to determine which parameters contribute to large rock avalanche propagation using an experimental approach within a laboratory environment. The experiment was designed to simulate a granular flow event using equipment formed of an inclined slope and a flat horizontal plane with a confined zone. A range of material flow combinations and two different slope inclinations were used throughout. The experiment enabled the collection of data such as runout distance; maximum height and length of a flow deposit and further calculated data including the Fahrboschung angle and the velocity of different flows in order to determine the relationship between the runout and a host of parameters. By conducting this investigation, it was determined that certain parameters such as angle of slope inclination and bidisperse material all heavily contributed to a further runout of a flow. It was also concluded that having a material combination of 15% fine material and 85% coarser material provided the furthest runout distance of all the material combinations.

Keywords: Landslide propagation, granular flow, Bidisperse flow, rock avalanche propagation, Fahrboschung angle, confined flow, runout

Introduction

Introduction to landslides

Landslides are defined as large scale natural events that involve large sediment flows consisting of a sizeable amount of particulate material (Pouliquen, 1999). The term landslides are an umbrella term used to describe the general mass movement of material and cover a range of different materials and type of movement from failure (Petley, 2012). Landslides are associated with the downward and outward movement of slope-forming materials composed of rocks, soils, or artificial fills (Cruden and Varnes, 1996). This type of hazard is critical for forming landscapes, and transporting sediment throughout the fluvial system (Petley, 2012). Landslides is a generic term for the mass downward movement of material and have been classified (figure 1) by individual type (Varnes,1978) depending on the type of movement and the type of material within the flow. This classification has since been revised (Hungr *et al*, 2001).

Table 1: A table which classifies landslides depending on movement and material according to Varnes (From Varnes, D. J. Slope Movement Types and Processes. In Special Report 176: Landslides: Analysis and Control, TRB, National Research Council, Washington, D.C., 1978, Figure 2.2, p. 11. Copyright, National Academy of Sciences. Reproduced with permission of the Transportation Research Board.).

TYPE OF MOVEMENT		TYPE OF MATERIAL		
		BEDROCK	ENGINEERING SOILS	
			Predominantly coarse	Predominantly fine
FALLS		Rock fall	Debris fall	Earth fall
TOPPLES		Rock topple	Debris topple	Earth topple
SLIDES	ROTATIONAL	Rock slide	Debris slide	Earth slide
	TRANSLATIONAL			
LATERAL SPREADS		Rock spread	Debris spread	Earth spread
FLOWS		Rock flow	Debris flow	Earth flow
		(deep creep)	(soil creep)	
COMPLEX	Combination of two or more principal types of movement			

Landslide events can be triggered by several events such as earthquakes, volcanic eruptions, excess rainfall and human activity. Often, landslides occur due to multiple factors, rather than just a single cause. The general term landslides can be classified by the type of movement produced by the landslide. Movements include falls, topples, slides, flows and spreads (Varnes, 1978) and these have been subdivided further by the Varnes's (1978) classification of landslides depending on the material present into three categories: debris, bedrock and earth (table 1).

Rock avalanches are characterized by the flow consisting of a large volume of material, along with being highly mobile and harnessing a lot of energy. Rock avalanches tend to be catastrophic in nature and often lead to large scale damage compared to smaller landslide events such as rock falls which are much smaller and localised events. Rock avalanches are most commonly triggered by earthquake or rainfall events. Several theories exist to account for why this type of flow has such a high mobility. One theory dictates that increased mobility is due to the momentum shift of the mass from the rear of the flow to the front of the flow (Manzella and Labiouse, 2009). Another theory contends that fragmentation of the spreading mass (Heim, 1932; Davies and McSaveney, 1999) gives rise to high mobility. Finally, a third theory proposes that runout is affected by the destabilization of the volume of mass (Heim, 1932; Hsu, 1975; Scheidegger, 1973). These events are widespread around the globe but appear most common in areas such as the Pacific coast, USA, in States such as Washington, Oregon and California, but also commonly in areas of Asia, such as China and Japan, where extensive mountainous areas combine with high population and densely packed areas (Wang, 2015). However, the lack of frequency of rock avalanches within nature for the purposes of scientific investigation means that a more in-depth approach including laboratory experimentation is required to allow better management of such events.

Characteristics of rock avalanches

Rock avalanche events in nature have certain characteristics which distinguish them from other type of landslides. Typically, they involve the movement of a large amount of mass, as seen at the Usoi dam in Tajikistan when, in 1911, a rock avalanche occurred which led to the mass movement of 2000 $x10^{6\ m3}$ of material and is still considered as a potential risk for another catastrophic landslide event. Another trait of rock avalanche event is the capacity to be extremely rapid and contain large amounts of energy. For example, the Val Pola landslide, which occurred in Italy during 1987. Rainfall triggered an avalanche at an elevation between 2250m and 1700m above sea level (Azzoni *et al,* 1992*).* The elevation increment meant that the avalanche contained 8 $x10^{14}$ j of energy during its decent. Rock avalanches can also travel vast distances, making these events not only a risk to the local area, but also a threat to whole regions, as happened in the case of the Goldau landslide, Switzerland, which occurred during 1806 and was one of the first rock avalanche events to be studied. It travelled a total of 6.5km (Thuro and Hatem, 2010). Combining these characteristics gives rise to a range of large scale, catastrophic events that need to be better understood in order to manage such events and minimise the risks posed.

Importance of study

Landslides are an extremely dangerous and an ever-present natural hazard and appear to be increasing in frequency throughout recent decades (Weiland *et al*, 1999). Collection of data for this hazard needs to be improved, but in some respects, it is a difficult hazard to build a comprehensive database as studying physical landslides can be difficult in certain situations due to inaccessible terrain (Petley, 2012) and prediction of such, especially large landslide events, are particularly challenging. Also, landslide data collection has not been as frequent as other forms of natural hazards such as earthquakes and volcanos (Petley, 2012). Due to this difficulty of studying these events in real time for the purpose of data collection, researchers have focused on studying the behaviour of granular flow events on a much smaller scale, but in a controlled laboratory environment, recreating some of

the most common forms of landslides such as dry granular flows and subsequently recording the resulting data.
Granular flows are a common type of landslide description and can be used to describe types of flows such as volcanic ash flows, debris flows and dry rock avalanches (Yang *et al*, 2015). Granular flows are considered to be incredibly mobile and can travel great distances (Yang *et al*, 2015). Typically, granular flows will consist of more than one type of material (Phillips *et al,* 2006) and naturally this leads to segregation or sorting within the flow depending on grain size, shape and density of the grains (Phillips *et al,* 2006). This differentiation of particle size within a flow has been shown in previous studies to yield different characteristics compared to that of a single particle flow (Phillips *et al,* 2006). When segregation occurs, granular flows tend to form an inverse graded structure where larger particles will settle at the top of a flow and smaller particles will settle at the base of a flow (Denissen *et al,* 2019).

Terms of interest

Rock avalanches are very dynamic hazards, and the study of these hazards can result in many measurements and observations. When studying landslide propagation, you gain information which can be determined from the propagation itself. This information is product of the factors of influence. Calculations can then be made based on the results of the propagation and compared to the same calculations carried out consistently in other studies when trying to gain an understanding of propagation.

Runout is the most vital piece of information this study will collect. Runout dictates how far a flow will travel before being deposited. Runout can be described as the main, coherent mass of the deposit, compared to the other part of the flow that is discontinuous from the main part of the deposit (Yang *et al*, 2015). The runout is the main source of evidence which shows the impact the main factors of influence has on a flow.

First introduced by Heim (1932), the Fahrboschung angle has become one of the most frequently used calculations for landslide investigations. The Fahrboschung angle is defined by the horizontal plane and a line drawn from the origin of the material at the top of the rockfall scar slope to the edge of the subsequent deposit (Longchamp *et al*, 2016). The angle also relates to the mobility of a flow and larger landslides tend to produce lower Fahrboschung angles compared to smaller avalanches (Corominas 1996). Mobility is a critical aspect of landslide propagation, especially granular flows which are typically very mobile, and by calculating this angle, it will help understand which flows are more mobile, and build a better picture on which factors of influence create a set of conditions which lead to a higher mobility.

Approach of study

Empirical approaches have been commonly used in the study of landslide propagation (Hsu, 1975; Corominas, 1996; Li, 1983). This method consists of using previous analogous landslide events and compiling the resulting data. Although this approach remains popular within the literature on landslides, this study takes an experimental approach to the problem. Previous studies (Savage and Hutter, 1989; Weiland *et al*, 1999; Phillips *et al*, 2006; Yang *et al*, 2015) have devised experiments to recreate granular flow conditions in order to record parameters which help build an understanding of flow propagation.

The purpose of this study is to understand the effect that fine material has within a granular flow and how this effects propagation. There is yet to be an academic agreement on the figure which produces the furthest runout. As seen, many authors have investigated granular flows, but few have used a bidisperse flow (Phillips *et al*, 2006) consisting of two separate materials within a flow regime. Bidisperse flow is said to have an impact on total runout distance compared to mono-disperse flows and polydisperse flows (Phillips *et al,* 2006; Degaetano *et al*, 2013; Yang *et al*, 2015). There is yet to be an agreed threshold, but authors such as Phillips *et al* (2006) and Yang *et al*, (2015) claim that a smaller percentage of fine material coupled with coarser material leads to an increased propagation of a flow, but no overall agreement can be discerned within the literature on the percentage of fine material that yields the furthest runout distance. Each of the studies mentioned also conducted the experiments under different conditions to that of this study such as different slope inclinations (Yang *et al,* 2015) and a 2-d approach (Phillips, *et al,* 2006) rather than a 3-D approach in this study. There is a specific gap in the literature that this study hopes to fill by using different bidisperse granular flow regimes to understand how mobility is increased and how specific parameters can lead to an increased distance of flow runout.

The benefits of an experimental approach are the simplicity, repeatability, and the capacity for the experiment to be well controlled. Although an experimental approach in a laboratory is easily repeatable and crucial factors can be controlled throughout, this approach does have limitations. Recreating in a laboratory environment means the scale is considerably smaller than that of a large landslide event found in nature. Therefore, the processes operating during the experiment might behave differently compared to those in nature simply due to the much grander scale (Delannay et al, 2017). However, recreating in a laboratory and having an experimental approach remains valuable for producing a framework for important aspects of landslides such as material relationships within a flow and observing individual aspects of a flow on numerous occasions (Delannay et al, 2017).
The characteristics of a flow in this type of regulated experiment are controlled by three factors (Pouliquen, 1999):

- Gravitational force originating from the inclined slope
- The frictional force between the material and the surface of the apparatus
- Interaction with particles within a flow

There are different types of experimental approaches, but this study will be using specifically a 3-D granular approach. This approach is an effective one as 3-D terrain has a significant influence on landslides in nature (Denlinger and Iverson, 2001). Although this will be replicated in a laboratory situation, a close similarity exists with that of the previous research carried out for example by Savage and Hutter (1989) and Dellinger and Iverson (2001).

Previous research

Landslides have been studied in the literature, although compared to other natural hazards, landslides have not been as conclusively and thoroughly studied compared to other hazards such as volcanoes and earthquakes. A great deal of the literature based on landslides can be found studying past landslide events, once they have already occurred, assessing the socio damage and economic effect a landslide event has had on a region. Assessing a region prior to an event is difficult and recreating the circumstances of a landslide does not necessarily recreate real life situations but due to landslides causing large scale damage across the world, the need for as much understanding is critical, which is why previous literature have explored this. Landslides are unpreventable, and the risk can only be mitigated by understanding critical aspects of the hazard, such as its propagation. By understanding aspects like propagation, potential areas of risk can be identified with the aim being to prevent such grand disasters such as Huascarán, Peru, where a large avalanche occurred on the side of a volcano and led to the death of 15,000-18,000 people approximately. Not surprisingly therefore, scientists have conducted research with the goal of trying to understand landslide propagation, especially large landslide events, which are often the reason for catastrophic amount of damage.

Phillips *et al* (2006) conducted previous research investigating the relationship between coarse and fine particles within a granular flow regime. They concluded that the fine material acted as a lubricant at the base of the flow as the percentage of fine material increased within the flow. This theory of basal lubrication up to a certain point has since been ever prevalent within the study of experimental based granular flow regimes. Degaetano *et al* (2015) noted that the introduction of different materials led to a reduction of the amount of friction present within a flow. Most recently, Yang *et al* (2015) applied the theory of basal friction reduction to the study of poly-disperse materials of a granular flow within a flume experiment. All these studies, although the experiments had different conditions, agreed that a small range of fine material leads to a prolonged runout, although the exact amount of fine material is not in agreement. All experiments had varying factors of influence such as slope inclinations, and types of flows such as mono, poly and bidisperse flows, but the general agreement is that a low level of fine did have an influence on propagation to varying degrees.

Focus of study

The aim of this study is to determine the relationship between bidisperse material flow and the overall workings of a granular flow which result in an increased propagation. This experiment will be focused on two aspects. Firstly, factors of influence such as the inclination of the slope and the percentage of fine material within the flow. Factors of influence give direct information regarding the propagation. The second aspect of focus will be the information gained from the resulting propagation. These are parameters such as maximum runout, maximum height, length of deposit. Using this resulting data, further calculations can be made such as the Fahrboschung angle and the velocity to determine to infer more acute details about each flow. By collecting all this data, the aim is to conclusively add further information and statistics to the literature to further the general understanding of granular flows and the understanding of propagation in a section of the literature where there is yet to be a conclusive agreement.

Methodology

In this section the laboratory work performed is described.

Laboratory equipment

The apparatus employed consists of two sheets of wood measuring 2m (horizontal surface) and 1.5m (vertical inclination slope) separated along the centre of the system. One sheet remains fixed in a horizontal position whereas the second movable sheet can be adjusted using a hoist to provide the desired slope angle (see Figure 1). The upper part of the movable sheet is fitted with a box chamber (40cm x 30cm x 30cm) that holds the material and has a sliding panel used to release the material. In addition, two detachable plastic panels are position in a parallel configuration along the length of the apparatus to create confined flow conditions.

Figure 1: An image showing a view of the experiment setup along with the camera which records the side view of the flow and deposit.

Two cameras in fixed positions provide both front and side views of the experiment.

Factors of influence.

Landslide propagation is directly affected by factors of influence. Factors of influence give the resulting information on the propagation. If these factors are changed it will alter the resulting propagation and it is these factors which are critical for understanding propagation itself, along with all the resulting measurements and calculations which can be gained from the propagation.

These factors of influence are:

- Slope inclination
- Percentage of material within a flow
- Types of material within a flow

By alternating these throughout the study, the aim will be to establish the true importance of these factors and understand how these parameters affect propagation and to what degree. All three factors will be changed at different points during the experiment and all the necessary data will be collected to understand how propagation is affected and to what degree it is affected.
Materials used.
The two materials used for this project are as follows:

A) Coarse grained material = 9.5mm to 16mm classified as medium pebble gravel (Figure 2).
B) Fine grained material = 500 µm to 1mm classified as coarse-grained sand (Figure 3).

These two materials combine to create a bidisperse flow: that is the mixture of two materials within a flow.

Figure 2: An image showing the coarse-grained material used in this experiment. Grain size = 9.5mm to 16mm.

Figure 3: An image showing the fine material used in this experiment. Grain size: 500 µm to 1mm.

Table 2: A table explaining the different materials used at 40° inclination. The table highlights the change in percentage of material that make up to the total of 20kg.

EXPERIMENT NUMBER	PERCENTAGE OF COARSE MATERIAL (A)	PERCENTAGE OF FINE MATERIAL (B)
1.1	100	0
1.2	90	10
1.3	85	15
1.4	80	20
1.5	75	25
1.6	70	30
1.7	65	35
1.8	50	50
1.9	30	70
1.10	10	90
1.11	0	100

Table 3: A table explaining the different materials used at 35° inclination. The table highlights the change in percentage of material that make up to the total of 20kg.

EXPERIMENT NUMBER	PERCENTAGE OF COARSE MATERIAL(A)	PERCENTAGE OF FINE MATERIAL(B)
2.1	100	0
2.2	90	10
2.3	85	15
2.4	80	20
2.5	75	25
2.6	70	30
2.7	65	35
2.8	60	40
2.9	50	50

The first set of data at 40° inclination increased in increments of 5% and 10% to fully explore this category. When considering the second data set at 35° inclination, it was decided to have a smaller variation of combinations due to the importance of exploring fully the relationship between the two inclinations, within the critical set of data which was determined from the first set of experiments. Also, this smaller variation was decided due to time constraints.

Laboratory procedure.
The apparatus was set up manually to give a constant slope angle of 40° for the first set of data recorded and a fixed flow size of 20kg throughout the entirety. For the second data set collected the only variable changed was the inclination of the slope. The angle was altered from 40° to 35° for the second set of data collection.
The first set tested in the experiment consisted of 100% material (A) medium pebble gravel. Every care was taken to distribute the sample evenly within the box chamber to maintain a similar geometry and then three measurements were made in order to calculate the centre of mass of the material prior to release (see Figure 1). Between each experiment the material is sieved using the sieving machine. The other method of sieving is manual, using aluminium sieves to separate the material. This method was used in repeats of the experiment as the same material was re-used and then the weight was recalculated before resuming.

Measurements
For each experiment, the flow was initiated by manually lifting the sliding panel of the box-chamber. To ensure consistency of triggering, this operation was carried out by the same person throughout.
At the conclusion of each experiment the following measurements were taken:

(1) Horizontal runout distance(cm)
(2) Total length (cm)
(3) Maximum depth of material (cm)

These measurements can be observed in figure 6.

Runout

Runout will be the most important measurement for the purpose of the study. Runout is measured to the point where the deposit is densely packed with material. When gravel is unattached from the main section of the deposit it is ignored as part of the runout. The runout is measured from the start of the horizontal plane (Figure 4) and is marked by precisely using the 1cm lines drawn onto the apparatus and ruler at points in between the cm region to achieve the most accurate measurement possible. For each category of fine material, three experiments are conducted, and three runouts are recorded. This results in an average runout measured in cm for each percentage of fine material.

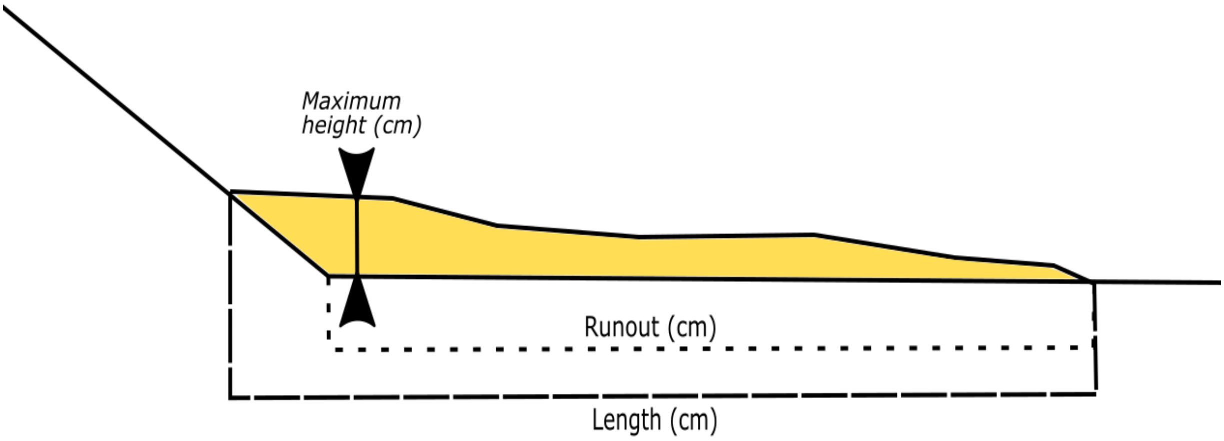

Figure 4: A sketch of the material deposited after an experiment has taken place. It shows how the runout is measured from the point of break in slope. The length is measured including material backed up onto the slope and how maximum height is manually measured.

Length

The length is the measurement of the entire deposit. Length can be defined as the horizontal projection of a deposit. The measurement of length involves the entire deposit along the horizontal sheet, rather than ignoring the unattached part of the deposit. The length can be an extension or a shortening of the runout distance (figure 4). The flow can back up onto the inclined plane causing an extension of distance. Shortening can occur if the deposit bypasses the break in slope entirely. For consistency, the measurement is always taken from the middle of the deposit.

Maximum height

The maximum height is measured manually (Figure 4). This measurement is taken immediately after the flow has deposited before any settling can take place. This measurement is taken over several points of the flow estimated as most elevated by eye level. This process is repeated up to 5 times to determine a maximum height. Maximum height will be an indicator of how much the flow has spread along the horizontal plane.

Calculations.
Calculations were made of:
- Velocity
- Fahrboschung angle
- H/L ratio

Velocity
For the duration of each experiment the cameras set up recorded each flow from positions that recorded the entirety of the flow. These enabled the calculation of velocities by using the individual time frames of the footage combined with the distance lines marked on the apparatus (see Figure 5). These calculations were aided by employing the software 'Wondershare filmora 9' which was used to slow down the footage. The measurement was taken between every 20cm along the slope and horizontal plane to build a velocity journey of the flow. The most important measurements taken included when (1) the moment the material left the box and began descending the slope (2) the moment the material reached the bottom of the slope, (3) the moment the flow passes the 100cm (1m) mark, and (4) the point where the material stops. Velocity was determined by applying the formula:

$$\boldsymbol{S = \frac{d}{t}}$$

The reason for estimating velocity was to determine two factors:

- Change in velocity as % of fine material changes
- For each % of fine category determine a speed graph highlighting points of highest velocity and how velocity altered when the flow arrived at the slope.

Investigating velocity is important in this study as granular flows can be rapid therefore studying the velocity should give a further insight into how its influenced directly by the factors of influence such as the amount of fine material.

Fahrboschung angle.
Calculating the Fahrboschung is necessary when trying to understand mobility and run out. Calculating this angle would allow the further calculation to be made of the coefficient of the Fahrboschung angle. The ratio of H/L can be calculated using this angle. Theoretically, the lower the Fahrboschung angle the higher the mobility of the flow and eventual deposition.
The equation for calculating the Fahrboschung angle is:

$$\boldsymbol{\emptyset = tan^{-1}\frac{H}{L}}$$

Where:
H=Vertical drop(m)
L= Horizontal projection(m)

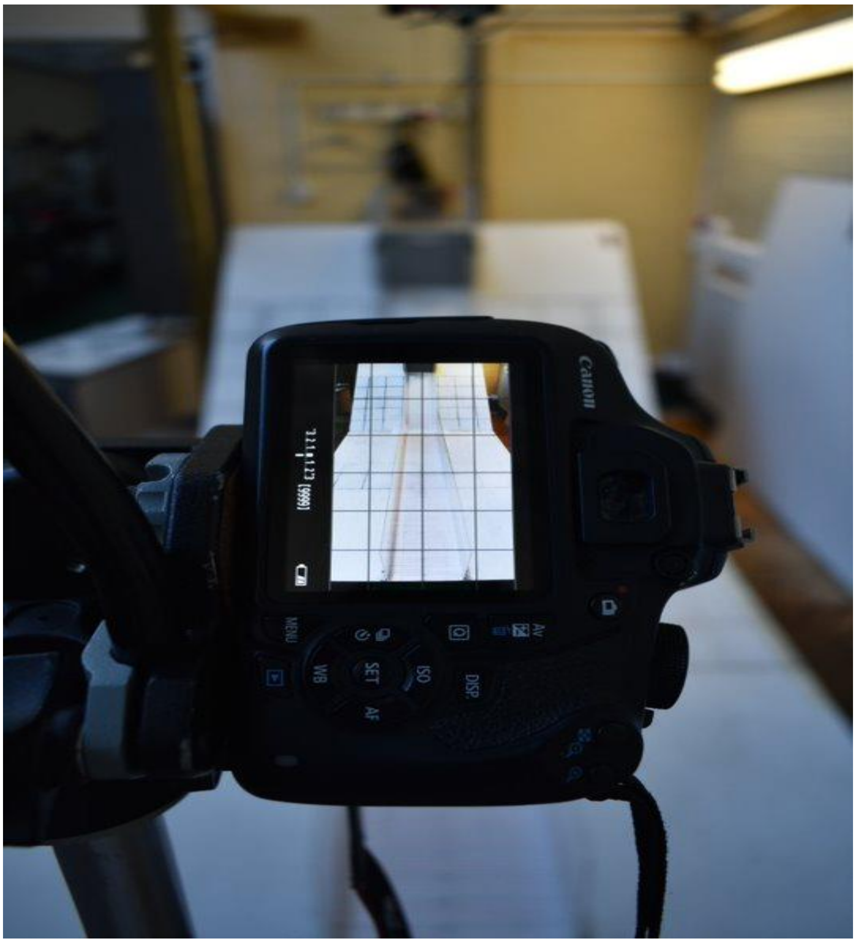

Figure 5: An image showing the view of the camera looking straight towards the flow. This records the flow, and this footage is used to calculate velocity using the 5cm and 20 cm marks along the apparatus.

Results

The experiments carried out during this research project were designed to improve clarity and generate new information in relation to parameters affecting large landslide propagation. The data set collected can be used to refine previous statistics in the literature and aid in expanding previously unknown or understudied issues within this topic.

This section of the report involves the analysis of the direct factors of influence such as varying inclination, the changing amount of fine present and the velocity of the flow. These influences will result in the analysis of propagation information such as runout, maximum height and the Fahrboschung angle.

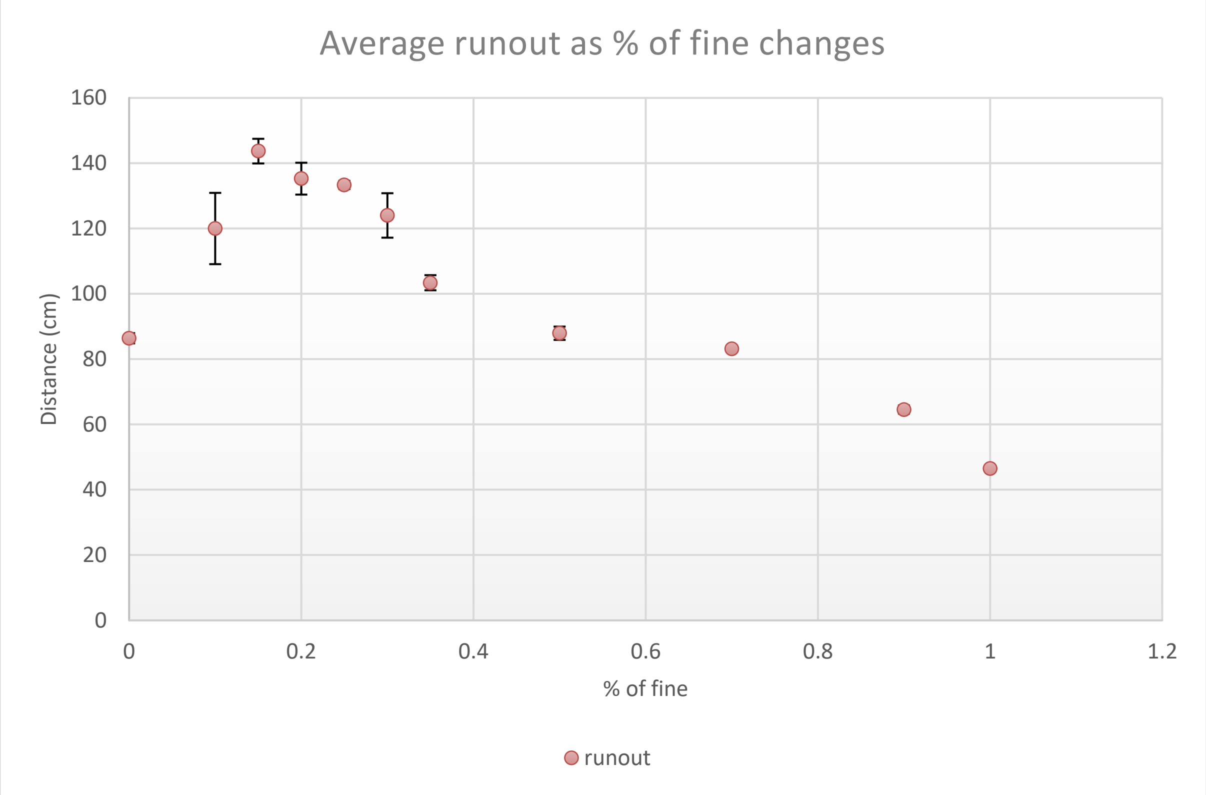

Figure 6: A graph showing the general trend of runout change as the percentage of fine material changes. This graph is based off the average runouts of three results per category, with the appropriate error bars, calculated using standard deviation. The graph displays % of fine material along the X axis and displays runout measured along the 40° slope in cm along the Y axis.

Runout (40°)
The relationship between the percentage of fine material and runout distance is depicted in figure 6. At 100% coarse material the runout distance averaged 86.4cm along the horizontal plane. Initially, as fine material was introduced making up 10% of the total flow, the runout distance increased by 33.6 cm, representing a 1.3 scaled increase compared to a flow with no fine material and suggesting that a higher percentage of fine material could correlate to increasing runout distances. An increase in the content of fine material to 15% gave rise to a runout distance of 143.7cm, the furthest distance reached during the experiment. Further increases in the content of fine material gave rise to a steady and continuous reduction in runout distance. At 20% fine material the runout distance decreased compared to 15% fine material but remained at a high figure of 135.3cm, representing only a slight decrease. However, a steady decrease occurs between 25% (133.3cm) and 30% (124cm) respectively. The introduction of greater amounts of fine material produces a pattern of ever decreasing runout distances.

The sample with 35% fine material produced the final runout distance exceeding 100cm (103.4cm). Beyond this point runout distances fall away and at 50% fine material the runout distance appears similar to the original figure associated with 0% fine material. Thereafter, the runout distance continues to reduce and finally at 100%

fine material the average runout of 46.4cm measures some 1.5 times smaller than that of the original 100% granular material and suggesting a negative influence on runout distance once finer material becomes the major component of the flow materials. The region of this data which directly affected runout distance the most was between 10%-25% fine material.

Runout compared for different inclinations

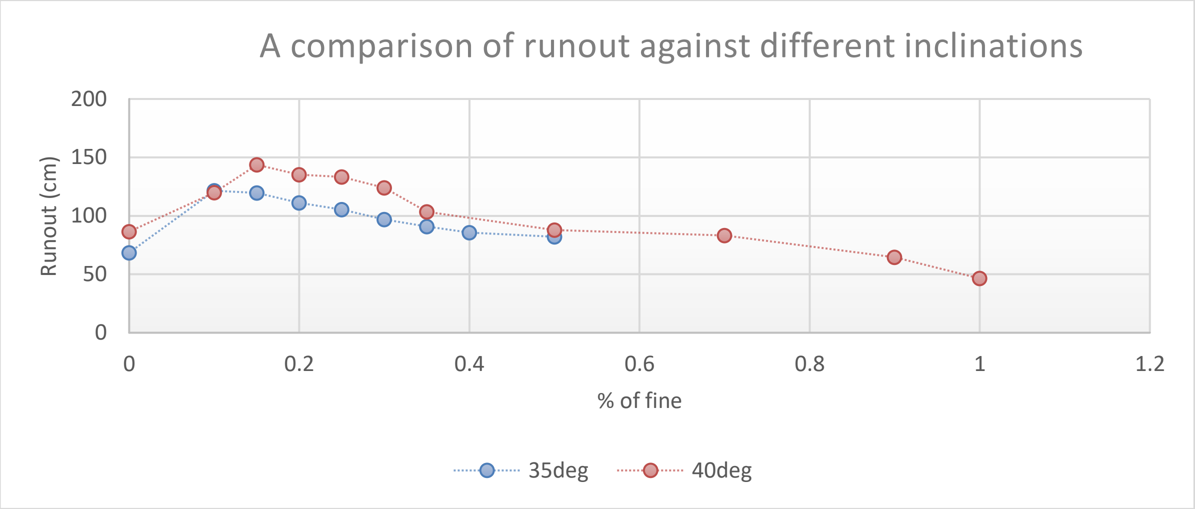

Figure 7: A Graph showing the average runout for two differing inclinations. The Orange plot shows the average runout of 40 degrees inclination. The blue plot shows the plot for 35 degrees inclination. Along the X axis is % of fine and along the Y axis is runout measured in cm.

This section will discuss how the impact different inclinations of the slope can directly affect runout distance. Figure 7 shows the results for two different inclinations: 40° and 35°. The general trend of this data is that both lines of data increase sharply to peak runout and then slowly decrease in length of runout up to 100% fine. The obvious trend to explore is that 40° inclination provides, on average, a higher runout for each experiment with the identical flow characteristics, but at 35° inclination leads to a decreased run out almost every time. The highest runout recorded at 40° inclination was 143.7cm at 15% fine material. compared to 35°, where the highest runout was recorded at 121.5cm at 10% fine material; a 22.2cm difference between peak runouts. This difference in peak runout could infer that inclination plays a role in determining runout. It could also be inferred that inclination has a direct effect on how fine material effects runout, indicating a correlation between the two factors. Experiments at 35° inclination do not have as complete a data set compared to 40° inclination because of focusing on the critical set of combinations that provide the most effective data in terms of parameters affecting landslide propagation.

Velocity

The relationship between flow velocity for the different flow materials and travel distance is depicted in figure 8. In general, the pattern for velocity reveals an increase in velocity until the flow reaches the break in slope at the 1-metre point on the x-axis of the graph. Naturally, the flow begins to lose travel velocity and eventually becomes stationary at the point of runout. Interestingly, at 10% granular material, the velocity along the slope increased markedly, unlike all the other flows.

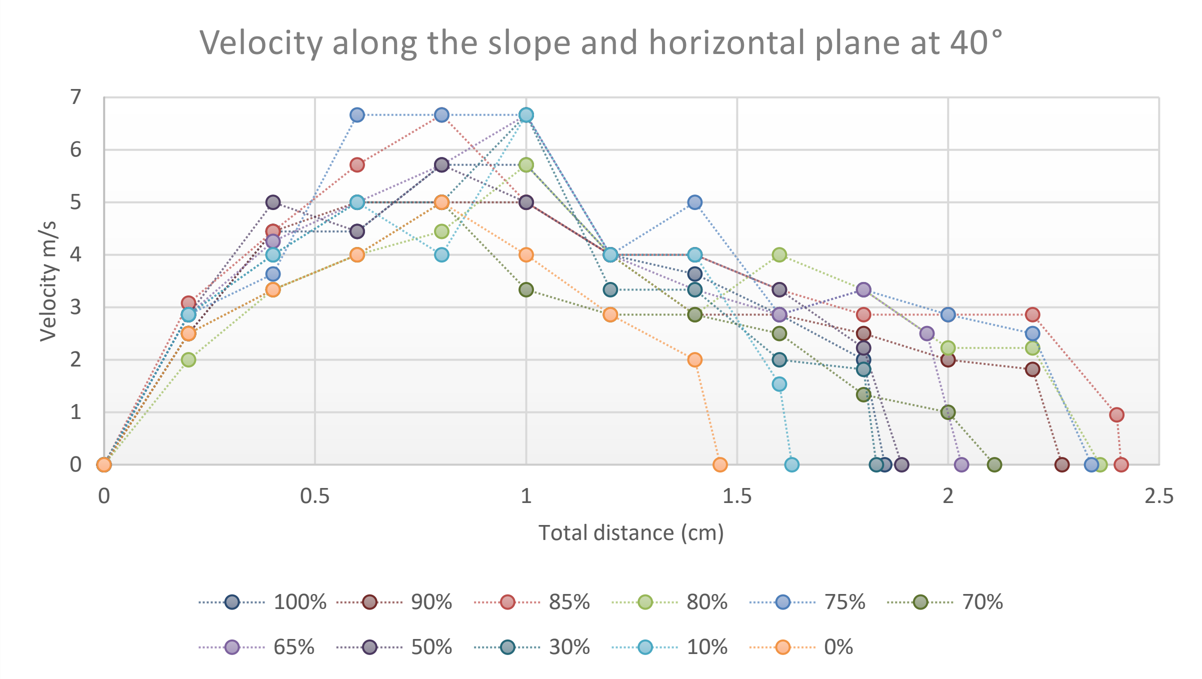

Figure 8: This graph showcases the velocity profile of the flow from origin to deposit. The plots end at the point where the flow reached maximum runout. The purpose of this graph is to show how different combinations of materials can generate different velocity. 100% represents 100% coarse material and 0% represents 100% fine material. Along the x axis is a cumulative distance and along the Y axis is velocity measured in m/s.

As this flow comprised predominantly sand, the velocity decreased rapidly as soon as it reached the break in slope and so the runout distance was considerably shorter than the other flows. However, for the most part the other flows behave in a similar and consistent manner. To focus more specially on 15% fine material, the velocity begins at 3m/s along the top of the slope, eventually reaching maximum velocity just before the break in slope at 6.2m/s. This velocity is not extraordinary, nor does it explain such prolonged runout compared to other figures. After the break in slope, this flows velocity decreases, but at a much slower rate compared to other flows and at points had a much greater velocity ranging between 5m/s to 3.3m/s the first 0.6m along the horizontal plane, this has allowed the flow to travel a greater distance compared to other flows which had a shorter runout. For example, the velocity pathway fore 100% sand shows a very similar, high velocity, along the slope but along the horizontal the velocity decreases at every 20cm point, and this results in the runout being much shorter when compared to other flows.

Although the velocity on the slope does not appear to offer any direct correlation with runout distance, a more promising pattern exists between velocity and flow along the horizontal plane. Flows which maintain velocity for a more sustained period produce longer runout distances. This observation also relates to the percentage of fine material within each flow as the previous graph highlights.

Velocity change along the horizontal plane

Figure 9 highlights the change in average velocity along the horizontal plane. The data shows a similar pattern to that of runout vs percentage of fine material. The general trend of this graph reveals a sharp increase in velocity around the critical interval (10-25%) and then a steady reduction of velocity to 100% fine material. Between the bracket of data which is considered most important (10-25%) the velocity maintained remains higher than the rest of the data. Velocity along the slope peaked at 15% and 25% fine, with both flows travelling at 3.7m/s along the horizontal.

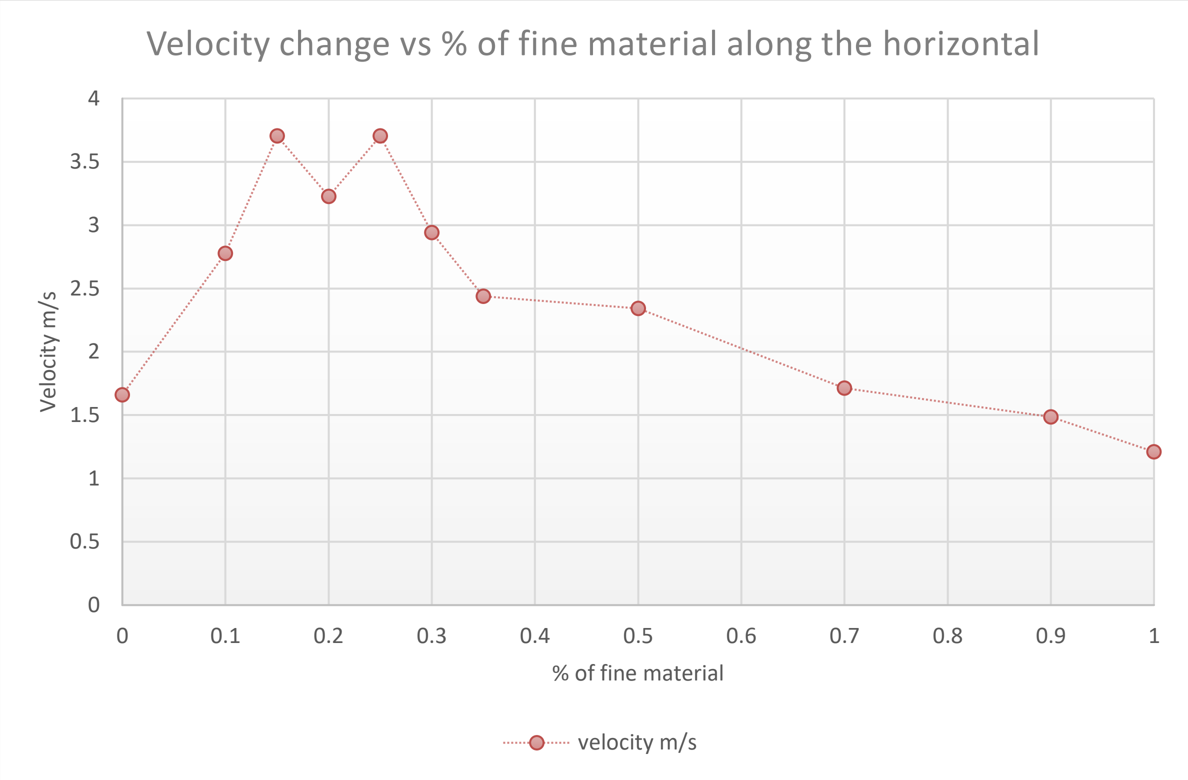

Figure 9: This graph displays the velocity of the different samples along the horizontal plane. The individual plot shows the consistent speed of each flow along the plane. Along the X axis displays % of fine and along the Y axis is velocity measured in m/s.

The slowest flow along the horizontal was 100% fine material that travelled at 1.2m/s. In comparison, 0% fine material travelled at 1.66m/s which was faster than both 90% fine material (1.48m/s) and 100% fine material (1.2m/s). 20% fine material appears to be an anomaly on the graph, but due to the velocity of the flow being 3.2m/s the flow was still the third fastest flow and still recorded a high runout distance. Velocity is being used to highlight the importance of fine material within a flow and what percentage of fine will lead to the furthest runout.

Velocity loss at the break in slope

Figure 10 illustrates how velocity decreased once the flow arrived at the break in slope. This graph expresses this loss of velocity as a percentage. Although this data reveals no obvious trend, it is important to note that all flows had a reduction in velocity once they reached the break in slope. Around the critical interval of data (10-

25%) the amount of percentage loss is generally much lower than higher percentage fine flows. The flows which produced the furthest runout (15%) appears to have the lowest velocity decrease of 20% reduction in velocity.

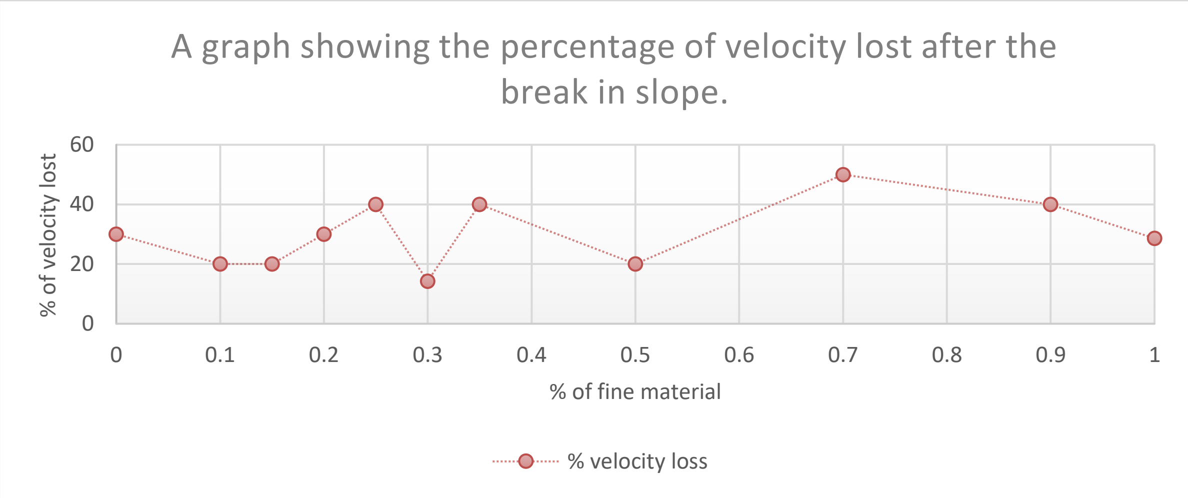

Figure 10: This graph shows the amount of velocity lost from a flow once it has reached the break in slope in the form of a percentage. This aims to highlight which flows lost more speed at this specific point compared to flows which continued at a similar velocity. Along the X axis displays % of fine material and along the Y axis is the % percentage of velocity lost at the break in slope.

Around this critical bracket velocity reduction never exceeded 40% compared to the rest of the data, for example 70% fine material had a velocity reduction of 50%. 100% coarse material had a velocity reduction of 30% and the introduction of sand to the flow appeared to reduce the amount of velocity was lost once the flow contacted the break in slope. This graph aims to show the entering velocities of each flow and how this velocity has been directly affected by the contact with the break in slope.

The Fahrboschung angle.

The Fahrboschung angle is defined as the travel angle, and theory dictates, the smaller the angle, the further the runout. The general trend of the graph (figure 11) shows how the Fahrboschung angle decreases as the content of fine material increases until the end of the critical bracket of numbers (10-25%) and then steadily increases up to 100% fine material. By correctly calculating the angle and plotting the results, the graph above shows how during the critical set of data (10-25%) the Fahrboschung angle is lower, at approximately 20°. The lowest Fahrboschung angle generated in this data set was 19.65°. This angle was calculated from the data set of 15% fine. The highest recorded angle within the data set was 30.9° at 100% fine sand. For 100% granular material, the Fahrboschung angle was 25.5°. This data will show an interesting comparison between 100% fine and 100% granular material as the Fahrboschung angle is an indicator of mobility. At 50% fine material a Fahrboschung angle of 25.5° was observed, similar to 100% granular material. Every data point past 50% fine material has an increased Fahrboschung angle compared to 100% granular material.

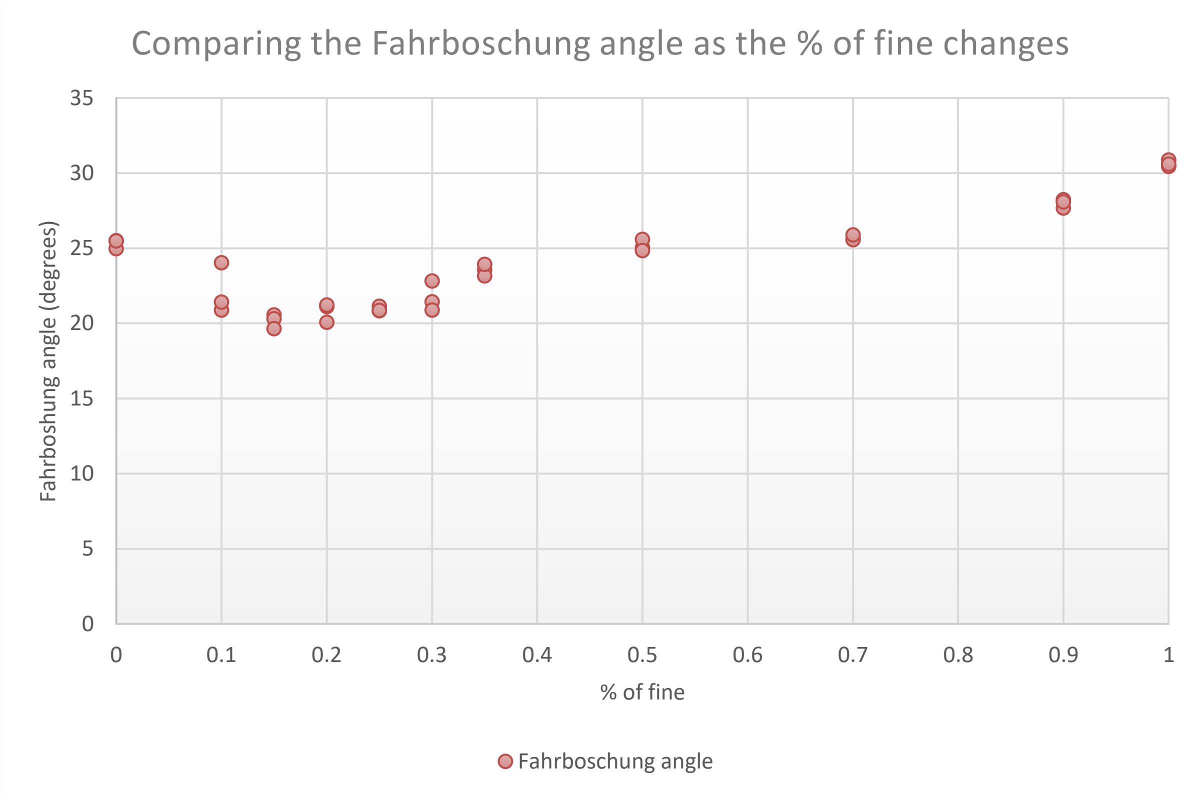

Figure 11: This graph depicts the Fahrboschung angle and how this angle fluctuates as the percentage of fine changes. The points marked on the graph show the three Fahrboschung angles generated from each set of results. Along the x axis displays % of fine and along the Y axis is the Fahrboschung angle.

Maximum Height

This graph (figure 12) shows the manual average height of the flow for each experiment.

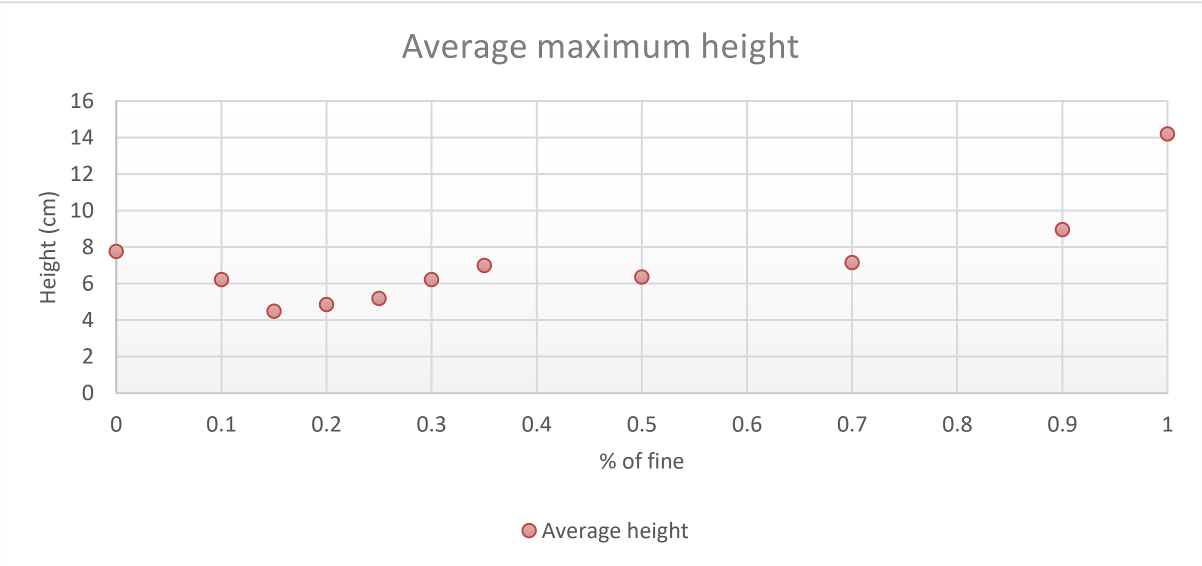

Figure 12: This graph is highlighting the manual average height of each flow for 40° inclination. Along the X axis % percentage of fine is displayed. Along the Y axis is height measured in cm.

Maximum height helps determine the degree of spreading of a flow regime. The lower the maximum height, the further the runout as the flow has spread more as the flow has longitudinally spread. The trend shown on the graph highlights 15% fine material as the flow with the lowest maximum height (4.5cm); this correlates with the rest of the data as 15% fine material had the furthest runout. Around this critical interval (10-25%) the trend is that maximum height is low compared to the rest of the data. For 100% granular material the average height was measured to be 7.7cm. Compared to 100% fine material, where the average height 14.2 cm. this is a considerable increase between the two monodisperse flows. This information indicates that the finer material has a higher spreading capacity at lower percentages within a flow.

Discussion of results

In this section the data collected will be discussed using previous literature and applying it to this individual data set. The aim is to distinguish how bidisperse granular flows behave and how grain size effects overall runout. Using the range of parameters observed, the overall aim is to conclusively determine the relationship between the factors of influence such as slope inclination, bidispersity and material combination and how these dictates and affect the runout of a flow and its velocity.

Runout

The data from runout at 40° inclination shows that 15% fine material produces the furthest runout distance. This data disagrees with Yang *et al*, (2015) who stated that highest runout was at 10% and disagrees with Phillips *et al*, (2006) who argued that the point of furthest runout occurred at 30% fine material. The data set for this project fell midway between these two previous findings reported in the literature. This could be due to different experimental conditions; therefore, some minor differences would be expected. However, this data set does agree with the previous literature in that introducing a lower percentage of fine material will give rise to an increase in the runout distance (between 10-30% of the total volume).
As granular material decreased, there was an increased amount of surface area space within the container. This excess surface area was filled in by the sand particles. In this critical bracket of data where runout was distinctly larger (10-25%) the sand fills in the excess surface area, but not entirely. This surplus surface area is a vital component of increased runout (Phillips *et al*, 2006). Within the container, the sand particles naturally migrate towards the base of the flow under gravity (Yang *et al*, 2015). Introducing the sand grains to the flow increases the mobility of the overall flow and in this excess surface area there is a general reduction of frictional stress (Phillips *et al*, 2006). Upon release of a granular monodisperse flow, the material causes frictional tension, and as the grains are not rounded, but sub-angular, mobility is lacking, which prevents a further runout. Once fine material has been introduced, the sand grains act as a lubricant at the base of the flow. This is highlighted by the huge increase in runout at the first point of fine material introduction. Runout increased by 33cm between 0% fine material and 10% fine material being present within the flow. This clearly indicates the influence fine material has within a flow.

The introduction of finer material reduces the overall frictional coefficient of the flow. Combining the lowered frictional coefficient alongside the rheological characteristic that the medium sand has a higher mobility than the granular material leads to this theory suggested by Phillips et al (2006) that the fine material lubricates the base of the flow which leads to this increased runout distance. This concept of lubrication at the base is at its maximum efficiency at 15% fine material, as the data shows, is different to the previous literature (Phillips *et al, 2006;* Yang, et al, 2015). Although there is an agreement that a smaller percentage of fine generally does create this theory lubrication at the base (Phillips *et al, 2006).*

After this point, it shows that an ever-increasing amount fine material leads to a steady decrease of run out distance. From this it can be inferred that past a certain point, fine material has a negative impact on runout distance and from the data this point was decided at 30% fine material. As fine material became the dominant material in the flow, runout reduced greatly in distance. This decline in runout is related to the proportion of sand increasing, which leads to an excess surface area, which was critical for an increased runout, being filled by the finer material. This shifted the frictional emphasis from the granular material, which had previously been eased due to the fine material, and now the emphasis was sourced from the interaction between the fine material. Previously, prior to the surface space being unfulfilled, the sand particles had room to manoeuvre and generate energy. As percentage of fine increased, it infilled all the pore spaces and the particles begin to interact to a higher degree. This interaction of particles leads to increased friction within the fine material and as a result, mobility decreases which leads to runout reducing (Phillips *et al,* 2006).

Runout for 50% fine material had a similar runout to 100% granular material. As fine increased beyond 50%, runout was shorter than 100% granular material. This would infer that the sand is having a more negative impact than just the monodisperse flow of granular material. Therefore, the sand material is generating a higher degree of friction, leading to an overall lower capacity of mobility within the flow regime. This data set shows clearly that there is a correlation between available surface area and mobility of a flow. The more surface area available allows particles to have more flexibility for manoeuvring and produce less interparticle mixing, which leads to decreased friction within the flow, and as a result, runout of the flow increases.

Bidispersity

There was also a correlation between runout and bidisperse material. The experiments consisting of 100% granular material and 100% coarse sand showcased a much lower runout as monodisperse flows, compared to the bidisperse flows. This would support the claim (Yang *et al*, 2015) that a mixture of materials leads to an increased runout. Phillips *et al* (2006) also noted that bidisperse flows lead to an increase in runout distance. Degaetano *et al* (2013) also conducted a study that discovered that a bidisperse flow was more mobile than that of a polydisperse origin. An interesting point of the data presented is that where the sand material becomes the majority type within the flow, runout decreases to a distance which is shorter than 100% granular material. This suggests two points of interest: (1) a large proportion of sand has a negative impact on runout; (2) specific combinations of material are a more important factor in terms of runout than bidispersity individually. From this data, it can be inferred that bidispersity has an efficiency range in terms of increased run out: this data would indicate that range to be between 10-25% fine material.

Angle of inclination
Two sets of data were collected, with different inclinations. This was so the relationship between runout and inclination could be analysed. Data collected at 40° inclination was the primary set of data and data collected at 35° inclination was the secondary data set.

The results indicated a strong relationship between slope inclination and runout distance of the flow. The higher the inclination, the further runout. Also, the data revealed that for 35° inclination the most efficient combination for runout was different to that of 40° inclination (15% fine material). The data demonstrated that 10% fine material produced the furthest runout for 35° inclination. This result is similar to Yang et al (2015) results, as they had concluded 10% fine material produced the furthest runout. The reason as to why 35° produced a different percentage of fine is unclear in the literature but could be potentially due to the horizontal length being longer due to a shallower inclination, along with a smoother break in slope. Combined with a general lower velocity of flows at 35° inclination these factors contributed to 10% fine producing the maximum runout. This variation highlights how inclination is a factor when considering runout.

A higher inclination produces a greater amount of force in the direction of the flow. This increased force leads to a higher acceleration of the flow upon release. As 35° inclination is lower, the resulting parallel force is reduced, and immediate acceleration of the flow is slower than that of 40° inclination. Therefore, as inclination angle increases, the resulting runout will be farther. Inclination is also an important factor when considering flow velocity. A higher inclination means the material is suspended at a greater height, this increased height will produce more gravitational energy prior to release, and therefore once the flow is released, velocity will be increased (see 4.7).

Fahrboschung
As Corominas (1996) explained, the lower the Fahrboschung angle, the higher mobility a flow will possess. The data collected in this study uses this concept to back up the results discussed that lower combinations of fine material create an overall more mobile flow (Phillips *et al* ,2006). The data shows how 15% fine material produces the furthest runout; therefore, this flow regime was the most mobile. By calculating the Fahrboschung angle of the flow, it can be concluded that 15% fine material produced the most mobile flow as it produced the lowest angle. The data also shows the importance that inclination has in the determination of the Fahrboschung angle. As the inclination lowered, the Fahrboschung changed accordingly that mobility was reduced. Although it still showed that a smaller percentage of fine had the highest mobility. As the inclination decreased, the height of which the material was suspended was reduced, which decreased the overall mobility of the flow. This shows the importance that inclination has on a flow as one of the main factors of influence. As mobility decreased with the lowered inclination, propagation also decreased. This evidence can be used to further back up the theory of lubrication at the base of the flow by the fine material, due to excess surface area within the flow itself (Phillips *et al*, 2006) and can go further in confirming the correlation that 15% fine material within a flow leads to the runout distance being the furthest.

Type of flow

Flow material combination has an impact on the depth and thickness of a flow. It should be noted that within this critical bracket of peak runout, the flow was very flat and thin and maximum height of the flow was underwhelming. This is due to a higher degree of spreading within the flow regime. The capacity of spreading of a flow correlates to a flows mobility and helps understand why flows show different runout distance. Maximum height is a resulting parameter rather than directly affecting runout. This information is critical for understanding how a landslide will behave in a natural setting. Flows outside of the critical bracket had a much lower degree of spreading within the flow, and maximum height of the flow was considerably higher. Understanding how a flow spreads will aid in managing locations at risk from potential landslide events. This information is a critical parameter of large landslide propagation, as flows that contain fine material, or more specifically within the critical set of data will produce further runout distances, and lead to larger landslide propagation.

Velocity

The velocity patterns of the data indicate that there is a correlation between the combination of material and consistently higher velocity. Flows which can maintain velocity after the break in slope tend to produce the furthest runout distance according to the data collected. The reason for certain experiments maintaining velocity is linked to a theory originated from Heim (1932) and has since been investigated further by Van Gassen and Cruden (1990), where momentum transfers within the flow, eventually arriving at the front of the flow. This momentum allows velocity to be maintained after the sharp impact with the break in slope. This momentum transfer is twinned with kinetic energy transferring to the front of the flow.

This therefore links velocity and runout distance. Material within the critical bracket, as explained previously, has an excess amount of surface area within the flow present, leading to the lubrication of the base by the sand material. This means there is a lack of frictional energy within the flow regime, and under the conservation of energy law, this excess energy must be in another form, which would be kinetic energy, as the flow is moving down the slope. Therefore, the data shows an overall higher average velocity along the horizontal, as when the flow breaks at the slope, this kinetic energy and momentum is transferred to the front of the flow upon impact with the slope. This increased kinetic energy, and overall lack of frictional force allows the flow within this critical bracket to travel further along the horizontal than other combinations of material, where excess surface area is greater, and frictional force is higher, therefore lacking in kinetic energy, compared to the critical group of data (10-25%).

This theory of momentum transfer (Van Gassen and Cruden, 1990), correlates to the data from this study. The trend in average velocity along the horizontal shows the highest velocities maintained were for 15% and 25% fine material; 15% fine material produced the furthest runout distance. This data provides an insight into the relationship between velocity and total runout distance. But the data also highlights how velocity can be influenced by different material combinations. The study of flow velocity builds on this existing evidence that lubrication of the base is a mechanism present within the flow if the percentage of material is appropriate, and that the lubrication is not just having a direct effect on overall runout distance but is also influencing the overall velocity of a flow, especially once the flow meets with the break in slope.

Along the inclined slope, the data shows a consistency in the velocity achieved by each flow. The velocity pattern rarely differs widely along this slope, and this is due to the gravitational energy prior to release. According to Lo, Bolton and Cheng, (2010) the inclination of a slope is critical when determining velocity patterns of granular material. This would indicate that at 40° inclination, the lack of variation along the slope in terms of velocity is due to the slope staying a consistent angle. An increased slope angle will lead to an increased starting velocity, due to more gravitational energy being stored prior to release.

As the material is held suspended on the slope prior to release, different combinations of material will dictate the starting acceleration of the mass due to these overall densities of each flow. Lower percentage of fine material within a flow will still have an increased density due to the overall presence of coarse material. A higher overall density will contribute to a greater starting acceleration. The reduction of friction at the base combined with the flow thickness ideal is the combination for maintaining a faster overall velocity. Whereas sand dominated mixes are less dense in comparison and have a greater amount of frictional stress present at the base which decreases the starting acceleration of the mass.

Spreading capacity

The variation of maximum height of the flows shows how different combinations of material produce different spreading patterns. The lower percentage fine deposits typically produced a shorter maximum height compared to that outside the critical set of data. This is because the deposit had a higher spreading capacity and therefore produced a much more lateral spread when deposited. The flow had not travelled as a single block, and had separated on the slope, which lead to the material spreading further along the horizontal, compared to other flows outside of the critical set of data which travelled as a single block and deposited at a much shorter length with a much higher maximum height. This occurs due to the amount of frictional stress within a flow (Legros, 2002), and flows which have a much higher amount of friction at the base present will tend to travel as a single block (Legros, 2002) and this leads to a much shorter runout distance due to the lack of motion within the flow and produces a higher maximum height as the deposit will show a low degree of spreading. Flows within the critical set of data have a higher degree of basal lubrication, this means as the flows travels, rather than travelling as a single block, the mass separates (Legros, 2002). This affects the velocity of the flow, and as the data shows, the flow will maintain a higher velocity once it reaches the break in slope as it does not hit the break in slope in one singular block, which results in momentum being halted, rather it meets the break in slope at different points which shifts momentum from the rear of the flow to the front of the flow.

The flow will begin as a singular block of mass but as it descends the slope, it transforms into more lengthy flow and this phenomenon can occur because of two factors. Firstly, the morphology of the transition-deposition zone (Storm, 2020) but in this case this is not applicable, as the slope shape does not change during the experiments, and secondly the amount of basal friction present. This is applicable, as the other evidence has shown this concept of base lubrication (Phillips *et al,* *2006)* varies as the amount of fine within the flow changes. This means that in the critical section of data, and most specifically 15% fine, the lack of basal friction is allowing the flow to extend on the slope and is contributing to the extended propagation that the data shows.

Conclusions

This research has determined three main factors of influence which directly affect landslide propagation:

- Fine material.
- Inclination of slope.
- Bidisperse materials.

This corresponds with previous research that fine material does influence the runout distance of a flow (Phillips *et al*, 2006; Degaetano *et al*, 2013; Yang *et al*, 2015). Although the comprehensive figure of peak runout was determined to be a combination of 15% fine material and 85% granular material. This combination of material is the most mobile flow regime (Fahrboschung angle) and has the lowest friction coefficient (H/L) of all the different experiments. This study reiterates the work of Phillips *et al* (2006) that flows containing a sufficient amount of fine material lubricates a flow from the base, although this study found 15% fine material to be the most impactful amount at inclinations of 40° and 35°, compared to 30% fine, with an inclination of 20° and 10° (Phillips *et al* 2006).

Inclination of a slope proved to be another direct parameter controlling landslide propagation. Comparing runout for both 40° and 35° slopes confirmed that a steeper inclination will lead to an increased runout distance of a flow. Inclination also proved to be an influencing factor when considering the velocity of a flow, which in turn influences final runout distance. Observing the results, it should be stated that bidisperse materials also have a direct relationship with a larger landslide propagation. Using bidisperse material produced a further runout on average, compared to a monodisperse flow within our experiment. This would reiterate the literature that bidisperse material is an influencing factor when considering the runout distance of a flow (Phillips *et al*, 2006; Yang *et al*, 2015).

Future work

Although this study has collected a robust data set of pertinent measurements and resulting interpretations, further experimental approaches are needed to conclusively decipher the relationship between fine material and runout distance as there is yet to be agreement on the combination of fine material that yields the furthest runout distance, albeit there is a general agreement that a certain amount of fine material of a low range does have an effect on runout with respect to bidisperse flows.
The information derived from this study aims to improve the management and understanding of future large landslide events and to understand further what factors of influence have the greatest effect on total runout distance.

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