SPATIAL AND TEMPORAL ANALYSIS OF COMPENSATIONAL STACKING AND GRADUAL MIGRATION OF AN EXPERIMENTAL DEBRIS-FLOW FAN

by

Hayden Edward Brown
A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geological Engineering)

Golden, Colorado
Date____________________

Signed:________________________
Hayden E. Brown

Signed:________________________
Dr. Paul M. Santi
Thesis Advisor

Golden, Colorado
Date____________________

Signed:________________________
Dr. M. Steve Enders
Interim Head
Department of Geology and Geological Engineering
ABSTRACT

Understanding sediment transport across debris-flow fans is crucial for assessment and mitigation of debris flow hazards in mountainous communities. To gain a better understanding of sediment transport, an experimental debris-flow fan was developed from 30 successive experimental debris flow events. The debris flow material was a kaolinite sand slurry consisting of 19% kaolinite, 48% sand and 33% water (all percentages are by mass), designed to model the Bingham plastic properties of natural debris flow. This experimental debris-flow fan was developed to analyze compensational stacking, which is the tendency of a deposit to fill a topographic low to reduce the overall potential energy of the system, and to evaluate overall flow directions of debris flow events as a debris-flow fan evolves. Specifically, the spatial variation of compensational stacking was analyzed longitudinally, by mapping 32 cross-sections from the apex of the fan to the toe of the fan, and calculating the modified compensation index for each cross-section. The overall flow directions and altering of flow direction was analyzed from video data, oblique birds-eye photographic data, and from a developed metric called net migration. Net migration evaluates, in two-dimensions, how much of a debris-flow mass is to the left or right of an assumed central axis to depict gradual migration of the experimental debris flow trials throughout the experiment. Several geometric and physical properties of the flow events were measured in order to perform various correlation analyses with the modified compensation index and the net migration metric. The analyses were used to identify what influences movement and propagation of debris-flow events across the fan surface. Also, time series as related to net migration, were analyzed using cross-correlation, autocorrelation, partial autocorrelation, and autoregressive integrated moving average (ARIMA) modelling to evaluate evolution of the debris-flow fan surface over time. It was found that the modified compensation index and net migration metric exhibit exponential decay as one moves closer to the apex of the debris flow fan. Also, it was found that net migration exhibits cyclical amplified behavior. These findings are valuable for engineers and scientists, because they can help better predict locations of future debris-flow events on fan surfaces, and more effectively implement and locate mitigation structures.
# TABLE OF CONTENTS

ABSTRACT ........................................................................................................................................... iii

LIST OF FIGURES.................................................................................................................................. viii

LIST OF TABLES...................................................................................................................................... xii

CHAPTER 1: INTRODUCTION ................................................................................................................. 1

1.1 Scope of Work................................................................................................................................. 3

CHAPTER 2: BACKGROUND .................................................................................................................... 4

2.1 Debris Flow and Debris fans/Alluvial Fans in Nature................................................................. 4

2.2 Debris Flow Fluid Mechanics and Various Representative Models....................................... 9

2.3 Alluvial Fans and Debris-Flow Fans in the Laboratory............................................................ 14

2.4 Compensational Stacking and the Modified Compensation Index....................................... 15

2.5 Scaling of Models......................................................................................................................... 21

2.6 Importance of Current Experiment in Regards to Previous Work...................................... 22

CHAPTER 3: THE PHYSICAL MODEL .................................................................................................. 24

3.1 Geologic Setting........................................................................................................................... 24

3.2 Experimental Debris-Flow Fluid and Fluid Scaling................................................................. 24

3.3 Scaling Considerations............................................................................................................... 29

3.4 Limitations of Model.................................................................................................................. 35
3.5 Model Diagram, Set-Up and Execution.................................................................35

CHAPTER 4: RESULTS..............................................................................................40

4.1 Video Data: Flow Direction and Frontal Velocities........................................40

4.1.a Flow Directions.........................................................................................40

4.1.b Frontal Velocities.....................................................................................46

4.2 Birds-Eye View Photographic Data: Spatial Distribution, Run-Out Lengths, and Length to Width Ratios.................................................................47

4.2.a Spatial Distribution..................................................................................47

4.2.b Run-Out Lengths......................................................................................50

4.2.c Length to Width Ratios...........................................................................51

4.3 Cross-Section Data: Modified Compensation Index, Longitudinal Slopes and Margin Slopes..................................................................................52

4.3.a Cross-Sections........................................................................................52

4.3.b The Modified Compensation Index..........................................................56

4.3.c Longitudinal Slopes of Central Axis..........................................................64

4.3.d Margin Slopes of Cross-Section 22.........................................................68

CHAPTER 5: ANALYSIS.........................................................................................70

5.1 Assessing the Change in Lateral Movement of Experimental Debris Flows.................................................................................................................70

5.2 Correlation Analyses......................................................................................77
5.3 Analysis of Cross-Section 22: Attempting to Correlate Compensation to Height and Slope

5.4 Time Series Data Analysis

CHAPTER 6: DISCUSSION

6.1 Avulsion versus Migration

6.2 Modified Compensation Index

6.3 Correlation Results and Implications

6.4 The Importance of Time

6.5 Implications of Findings for Hazard Mitigation

6.6 Ideas to Consider

6.7 Future Works

CHAPTER 7: CONCLUSIONS

REFERENCES CITED

APPENDIX A

APPENDIX B

APPENDIX C

APPENDIX D

APPENDIX E

APPENDIX F
LIST OF FIGURES

FIGURE 2.1: SCHEMATIC DIAGRAM OF THE CHANNEL, LEVEE AND LOBE MORPHOLOGIES FOUND IN DEBRIS FLOW DEPOSITS...........7

FIGURE 2.2: DIAGRAM REPRESENTING THE MORPHOLOGICAL DIFFERENCES IN FLUVIAL DOMINATED AND DEBRIS FLOW DOMINATED FAN.................................................................8

FIGURE 2.3: SCHEMATIC GRAPH REPRESENTING THE BEHAVIOR OF A BINGHAM PLASTIC.............................................................................................................10

FIGURE 2.4: SCHEMATIC SHOWING THE RELATIONSHIP BETWEEN THE VELOCITY PROFILE OF BINGHAM PLASTIC AND THE RIGID PLUG AND LAMINAR FLOW REGIMES EXISTING IN BINGHAM PLASTICS.................................................................11

FIGURE 2.5: SCHEMATIC DIAGRAM DEPICTING THE DIFFERENCE BETWEEN THE HIERARCHICAL GROUPS OF BEDS, STORIES AND ELEMENTS.................................................................20

FIGURE 3.1 PARTICLE SIZE DISTRIBUTION CURVES OF SAND USED IN EXPERIMENT...........................................................................................................29

FIGURE 3.2 NAIP IMAGE OF CHALK CLIFFS IN COLORADO.................................32

FIGURE 3.3 RESULTS FROM DELINEATING DRAINAGE BASINS AT CHALK CLIFFS USING GIS........................................................................................................33

FIGURE 3.4 DIAGRAM OF THE MODEL FOR CONSTRUCTING THE EXPERIMENTAL DEBRIS FLOW FAN.................................................................38

FIGURE 3.5 PHOTOGRAPH OF ACTUAL MODEL SETUP USED FROM AN OBLIQUE LONGITUDINAL VIEW............................................................................39

FIGURE 3.6 PHOTOGRAPH OF MODEL SET UP FROM A DOWN CHANNEL VIEW...........................................................................................................39

FIGURE 4.1 DIAGRAM DEPICTING THE FLOW DIRECTIONS OF TRIAL 2........41

FIGURE 4.2 DIAGRAM DEPICTING THE FLOW DIRECTIONS OF TRIAL 5........42

FIGURE 4.3 DIAGRAM DEPICTING THE FLOW DIRECTIONS OF TRIAL 15.........................................................................................................................43
FIGURE 4.4 DIAGRAM DEPICTING THE FLOW DIRECTIONS OF TRIAL 20........44
FIGURE 4.5 DIAGRAM DEPICTING THE FLOW DIRECTIONS OF TRIAL 26........45
FIGURE 4.6 DIAGRAM DEPICTING THE FLOW DIRECTIONS OF TRIAL 30........46
FIGURE 4.7 GRAPH PLOTTING FRONTAL VELOCITIES AGAINST TRIAL NUMBER.................................................................47
FIGURE 4.8 DIAGRAM DEPICTING THE SEQUENCE OF EVOLUTION OF EXPERIMENTAL DEBRIS FLOW FAN.................................49
FIGURE 4.9 DIAGRAM DEPICTING THE SEQUENCE OF EVOLUTION OF THE EXPERIMENTAL DEBRIS FLOW FAN (CONTINUED)...............50
FIGURE 4.10 GRAPH PLOTTING RUN-OUT LENGTH AGAINST TRIAL NUMBER.............................................................................51
FIGURE 4.11 GRAPH PLOTTING LENGTH TO WIDTH RATIO OF EACH TRIAL.....52
FIGURE 4.12 DIAGRAM SHOWING LOCATIONS OF CROSS-SECTIONS MAPPED OF DEBRIS FLOW FAN...........................................53
FIGURE 4.13 IMAGE OF CROSS-SECTION 7..................................................54
FIGURE 4.14 IMAGE OF CROSS-SECTION 10...............................................54
FIGURE 4.15 IMAGE OF CROSS-SECTION 18.............................................55
FIGURE 4.16 IMAGE OF CROSS-SECTION 32.............................................55
FIGURE 4.17 MODIFIED COMPENSATION INDEX RESULTS FOR BED SCALE FOR CROSS-SECTION 7 AND 10........................................58
FIGURE 4.18 MODIFIED COMPENSATION INDEX RESULTS FOR BED SCALE FOR CROSS-SECTION 12 AND 15........................................59
FIGURE 4.19 MODIFIED COMPENSATION INDEX RESULTS FOR BED SCALE FOR CROSS-SECTION 20 AND 22........................................60
FIGURE 4.20 MODIFIED COMPENSATION INDEX RESULTS FOR BED SCALE FOR CROSS-SECTION 32.............................................60
FIGURE 4.21 IMAGE ILLUSTRATING THE ELEMENTS USED FOR CALCULATION OF THE MODIFIED COMPENSATION INDEX AT THE ELEMENTS SCALE.........................................................60
FIGURE 5.9 ILLUSTRATION SHOWING ORIGINAL GRAPH USED FOR CALCULATING MODIFIED COMPENSATION INDEX OF CROSS-SECTION 22, GRAPH DIVIDED BY TRIAL, GRAPH CATEGORIZED BY EARLIER TO LATER TRIAL, AND GRAPH PLOTTING AVERAGE MARGIN SLOPE AGAINST TRIAL NUMBER OF CROSS-SECTION 22.................................................................83

FIGURE 5.10 MODIFIED COMPENSATION INDEX GRAPH CATEGORIZED BY EARLIER TO LATER TRIAL FOR CROSS-SECTION 22.............................................84

FIGURE 5.11 GRAPH PLOTTING RATIO OF LEFT MARGIN SLOPE AGAINST RIGHT MARGIN SLOPE OF CROSS-SECTION 22........................................85

FIGURE 5.12 GRAPH PLOTTING LONGITUDINAL SLOPES OF CROSS-SECTION 22 THROUGH TIME.................................................................86

FIGURE 5.13 GRAPH PLOTTING RATIO OF LONGITUDINAL SLOPE TO MARGIN SLOPE OF CROSS-SECTION 22..................................................87

FIGURE 5.14 TIME PLOT FOR ARIMA MODEL OF AVERAGE NET MIGRATION USING A PERIOD OF 19.................................................................88

FIGURE 5.15 ACF PLOT OF RESIDUALS FOR ARIMA MODEL WITH PERIOD 19.................................................................................................102

FIGURE 5.16 PACF PLOT OF RESIDUALS FOR ARIMA MODEL WITH PERIOD 19.................................................................................................102

FIGURE 5.17 RESIDUAL PLOTS FOR ARIMA MODEL WITH PERIOD OF 19......103

FIGURE 5.18 TIME PLOT OF ARIMA MODEL FOR AVERAGE NET MIGRATION WITH A PERIOD OF 21.................................................................103

FIGURE 5.19 ACF PLOT OF RESIDUALS FOR ARIMA MODEL WITH PERIOD 21.................................................................................................104

FIGURE 5.20 PACF PLOT OF RESIDUALS FOR ARIMA MODEL WITH PERIOD 21.................................................................................................105

FIGURE 5.21 RESIDUAL PLOTS FOR ARIMA MODEL WITH A PERIOD OF 21.................................................................................................105

FIGURE 6.1 A SCHEMATIC OF A DEBRIS FLOW FAN AND PARAMETERS THAT COULD BE USED TO CLASSIFY MOVEMENT OF DEBRIS FLOW EVENTS WITHIN THE FAN........................................111
LIST OF TABLES

TABLE 2.1 COMMON PHYSICAL PROPERTIES OF DEBRIS FLOWS……………………5
TABLE 2.2 COMPARISON OF VARIOUS DEBRIS FLOW MODELS AND THEIR APPLICATION………………………………………………………………………………………………………13
TABLE 3.1 QUALITITATIVE TRIALS FOR COMPOSITION SELECTION………….26
TABLE 3.2 TRIAL 2 PROPERTIES USED TO CALCULATE FROUDE NUMBER…………………………………………………………………………………………………………………………28
TABLE 3.3 SCALING PARAMETERS USED FOR EXPERIMENT………………………31
TABLE 3.4 C:D RATIOS USED FOR CHOISING CHANNEL WIDTH OF MODEL………34
TABLE 4.1 MODIFIED COMPENSATION INDEX RESULTS FOR BEDS, ELEMENTS, AND FLANK MORPHOLOGY…………………………………………………………………………61
TABLE 5.1 TABLE SUMMARIZING CROSS-CORRELOGRAM RESULTS…………90
TABLE 5.2 TABLE SUMMARIZING RESULTS OF AUTOCORRELATION AND PARTIAL AUTOCORRELATION RESULTS…………………………………………92
TABLE 5.3 TABLE SHOWING ITERATIVE APPROACH TO ARIMA MODELLING AVERAGE NET MIGRATION OF TRIALS ACROSS THE FAN SURFACE………………………………………………………………………………………96
CHAPTER 1: INTRODUCTION

Debris flows are sediment gravity flows consisting of poorly sorted material ranging from clay to boulder sized clasts that have high velocities and large impact forces (Ritter et al., 2006). These properties, coupled with the fact that they are extremely difficult to predict, increase the hazard of debris-flow events on mountainous communities. One geomorphic location where debris flows pose great risk and hazard to humans is on debris-flow dominated alluvial fans. It is common for humans residing in steep mountainous terrain to construct structures and residences on these alluvial fans due to their relatively gentle gradient compared to the surrounding steep terrain. Many debris-flow mitigation strategies such as catchment dams and fences are only effective if they are built in the path of future debris-flow events. This makes the study of how debris-flow events move and alter direction across an alluvial fan surface of critical importance for preventing and mitigating dangers for human developments located on these fans.

How debris flows move and change direction on alluvial fans is mainly examined through the study of avulsion, which is the tendency for a debris-flow event to plug or overtop the channel in which it travels and rapidly change flow direction. Very few studies have been performed to analyze this phenomena of avulsion on debris-flow fans. Pederson (2014) compiled a minimal database of subaerial debris-flow fans in Colorado. His work addressed the need to understand and predict likely paths and avulsion tendencies of debris flows to further enhance debris-flow hazard mitigation. He used the modified compensation index to analyze compensational stacking, which is the tendency for a deposit to fill topographic lows, on alluvial fans. The modified compensation index varies between 0.0 and 1.0, where 1.0 indicates pure compensation, 0.0 indicates pure anti-compensational behavior, and 0.5 indicates a random stacking pattern (Straub et al., 2009). It should be noted that the modified compensation index is an analogous version of the compensation index, and it uses length the dimensions instead of...
time. Pederson (2014) evaluated three debris-flow dominated fans in Colorado. Researchers have studied compensational stacking and avulsion of other sediment transport systems (Straub et al., 2009; Wang et al., 2011; Straub & Pyles, 2012), but few studies have been done to evaluate compensational stacking, avulsion and movement of debris flows across debris-flow fans. Bradford (2016) evaluated additional debris-flow fans in Colorado to add to Pederson’s data and to develop a logistic regression for better predicting compensational tendencies of debris flows. McLain (2015) attempted to use various statistics to discern whether compensational behavior can be seen in borehole investigations. However, research is limited in this area, therefore this work is an important contribution to further assess the patterns of debris flow movement across fans.

This current experiment was conducted to advance the understanding of avulsion tendencies and flow directions of debris flows across fan surfaces. This experiment evaluates two modes of changes in flow direction: avulsion and migration. For this study, avulsion is defined as the rapid change in flow direction due to debris-flow material evacuating the channel and altering its course of direction, and migration is defined as a debris flow’s gradual change in direction over time as more events occur. This work used a physical model to build a scaled debris-flow fan through successive debris flow events, allowing each event to deposit on top of the previous event. These events were videotaped and photographed to evaluate the evolution of the experimental debris-flow fan, to analyze spatial distribution of the debris-flow events on the fan surface, and to observe the flow directions on the fan surface.

In this study, various parameters were compared to the modified compensation index results and net migration results to see if any of these parameters affect avulsion tendencies and to track how debris-flow events move across the fan surface. It should be noted that net migration is a parameter that was developed in this study to evaluate the gradual change in depositional direction of debris-flow events, rather than the rapid or instantaneous change
caused by avulsion. Net migration compares quantitatively how much of the two-dimensional extent of an event is on either the right or left side of an established central axis. Measured parameters were collected at successive times to evaluate their evolution as the debris-flow fan forms. Observations were then used to speculate on the manner in which successive events behave, and how they combine to form the overall fan structure. These observations can be used to mitigate hazards associated with these types of fans.

These comparisons and general observations on flow directions can enhance the understanding of avulsion and migration tendencies of debris flows, and can help predict locations of events to decide where to apply mitigation measures on a debris-flow fan surface.

1.1 Scope of Work

This study relies on data collected from the video and photographs. The data collected were:

1. Flow directions of the surges of the debris flow events
2. Frontal velocities of the debris flow events
3. Overall spatial distribution and overlapping of deposits
4. Maximum run-out distances of the deposit from each event
5. Maximum length to maximum width ratios of the deposit from each event
6. Net migration of each event (this parameter will be explained in the analysis portion of this thesis).

32 cross-sections of the final debris-flow fan were also constructed from toe of the fan to the apex of the fan. These cross-sectional displays of the deposits were used to calculate:

1. The modified compensation index for various cross-sectional lines along the fan
2. Longitudinal slope for the central axis of the fan
3. Margin slopes for the fan.
CHAPTER 2: BACKGROUND

This section outlines previous research performed on debris flows and alluvial fans pertaining to geometries, mechanics and modelling. This section shows the breadth of work completed in these two areas to justify the need for the research performed in this thesis, and to justify model properties used in experimentation.

2.1 Debris Flow and Debris Fans/Alluvial Fans in Nature:

*Physical properties and Classification of the Debris Flow Phenomenon:*

Subaerial debris flows are a group of episodic sediment gravity flows that are known to occur in a range of settings from the deep ocean to arid and semi-arid regions (Ritter et al., 2006; Boggs, 2006), and are one of the dominant geomorphic processes in steep mountainous terrains (May & Gresswell, 2004). They are highly concentrated mixtures of granular solids, water and air. Clasts in the flow are supported by buoyancy, dispersive pressure, excess pore fluid pressure and the cohesive strength of the matrix of the slurry (Kim & Lowe, 2004). These rapid mass movements contain a large variety of grain sizes ranging from clay to boulders and have varying water content. Table 2.1 lists some common ranges of physical properties of debris flows. As can be seen from table 2.1, debris flows have a high shear strength, high viscosity and high density. Flow properties of debris flows vary considerably based upon sediment concentration, particle size distribution, water/clay content, flow thickness and permeability of the flow (Kim & Lowe, 2004). Studies performed at Owens Valley, California found debris-flow deposits to be matrix rich with 60 to 80 percent coarse material (Kim & Lowe, 2004). Velocities are affected by grain concentration, particle size distribution, and shape of the channel through which the debris flow is travelling (Takahashi, 1981).
Table 2.1: Common Physical Properties of Debris Flows (Adapted from Ritter et al., 2006)

<table>
<thead>
<tr>
<th>Velocity (m/s)</th>
<th>Slope (%)</th>
<th>Bulk Density (g/cm³)</th>
<th>Newtonian Viscosity (poise)</th>
<th>Depth (m)</th>
<th>Solids (% by Weight)</th>
<th>Shear Strength (dn/cm²)</th>
<th>Flow Character</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5-31</td>
<td>5.8-47</td>
<td>1.4 – 2.6</td>
<td>200-60,000</td>
<td>0.5-12</td>
<td>60-90</td>
<td>&gt;&gt; 400</td>
<td>Laminar</td>
</tr>
</tbody>
</table>

Source, Initiation, Progression and Cessation of Debris-Flow Events:

Most debris flows are sourced from within small drainage basins, with steep slopes, which helps to concentrate run-off and sediment supply (Ritter et al., 2006). Debris flows typically follow pre-existing channels but they can also flow across un-channeled alluvial fans. In the later scenario debris flows tend to build up levees along their margins, which confines the flow and allows them to proceed down fan (Ritter et al., 2006). Debris flows commonly initiate on slopes between 27 to 56 degrees. Slopes greater than 56 degrees lack the colluvial mantle necessary to feed a debris flow, and slopes less than 27 degrees have less potential for failure of the colluvial mantle and thus initiation of flow downslope (Blair & McPherson, 2009).

Debris flows commonly come to rest due to decreasing gradient and decrease in flow. However, with confinement they are known to flow over slopes as low as 1 to 2 degrees (Ritter et al., 2006; Boggs, 2006). Some debris flows come to rest after short transport distances, stopping on relatively steep slopes ranging from 4 to 6 degrees, while other debris flows can transport sediment down the entire length of the fan stopping at gradients of 1 to 2 degrees (Whipple & Dunne, 1992).

Deposition of debris flow material occurs by either *en masse freezing* or by incremental aggradation of longitudinally segregated flows (Kim & Lowe, 2004). This second mechanism can be thought of as surges of flow that make up the entire mass of the debris-flow deposit. Subsequent surges of the debris flow penetrate and push previous surges laterally, causing inverse grading (Major, 1997).
Debris Flow Mobility:

High yield strength debris flows typically travel the shortest distances, while low yield strength debris flows are capable of travelling the farthest distances and can deposit on any part of the fan (Whipple & Dunne, 1992). For viscous fluids such as debris flows, yield strength is the shear stress that must be attained to initiate and maintain flow. Water content of the flow has been shown to have a first order control on the mobility of the flow, thus low sediment concentration debris flows with lower yield strengths travel farther down fan and further laterally compared to high sediment concentration flows (Whipple & Dunne, 1992).

Debris-Flow Morphologies:

Debris flows depositing onto alluvial fans exhibit morphologies ranging from thin and lobate to digitate and narrow. Debris flows typically exhibit a channel, levees and a distal lobe (Figure 2.1). The exact nature and location of each of these morphologic parts of a debris flow may vary from fan to fan. Kim & Lowe (2004), examining a debris flow at the South Dolomite Fan, noted that the levee and channel morphology exists on slopes between 6 and 26 degrees, and the lobe morphology existed at 3 degree slopes. In this same study, the authors noted that the lobate morphology tends to be finer grained than compared to the levee morphology (Kim & Lowe, 2004). Blair and McPherson (2009) working in a range of debris flows note that the various morphologies are in part a product of the surface slope, with the levee-dominated sections occurring on slopes of 9-12 degrees, clast-rich lobes occurring on 3-5 degree slopes, and clast-poor lobes developing on 2 to 3 degree slopes.
Figure 2.1. A schematic diagram of the channel, levee and lobe morphologies found in debris-flow deposits. Channel and levees exhibit convex transverse profiles, while lobe morphology exhibits concave down transverse profiles. The lobe regime is finer grained than the channel and levee morphologies (Altered from Kim & Lowe, 2004)

Classification of Alluvial Fans:

Alluvial fans can either be debris flow dominated or fluvial (i.e. stream) dominated (Boggs, 2006). In all alluvial fans, debris flow is the most important sediment-gravity process with respect to the volume of sediment delivered to the fan structure (Blair & McPherson, 2009). Debris flow dominated fans are characterized by poorly sorted lobate deposits (Fig. 2.2). Usually on alluvial fans, debris-flow deposits are radially elongated lobes 1-100m wide and 0.05 to 2 m thick (Blair & McPherson, 2009). The lobes of these debris-flow deposits can be
continuous for hundreds of meters down fan, and can begin at the apex, active depositional lobe or distal ends of levees (Blair & McPherson, 2009).
Alluvial Fan Geometry and Shape:

It has been shown that fan slope does not control the aggradational process, but rather results from the aggradational process (Blair & McPherson, 1998). Alluvial fans that are dominantly composed of clast poor debris flows have slopes of 2 to 4 degrees. (Blair & McPherson, 2009). Deposition along debris-flow dominated alluvial fans is episodic, and avulsion at the apex is very likely to occur in conjunction with large flows (Blair & McPherson, 2009). Alluvial fans are typically cone shaped or arcuate in shape. Longitudinal profiles of fans from the apex of the fan to the toe usually exhibit concave upward shapes, with the greatest slope at the apex and slope decreasing down fan (Boggs, 2006). It has been shown that fan morphology varies due to fan setting, in other words whether it is located along a mountain front or intramontane valley. Fan form is controlled by fan constructional processes, and seem to be more regular in constrained mountain fronts (Sorriso-Valvo, 1998). Sorriso-Valvo also showed that the influence of constructional processes is greater in the intramontane valley setting. Smaller fans are located in more rugged basins, and larger fans are located where water flow is the predominant constructional process (Sorriso-Valvo, 1998). Some of these alluvial fans are underlain by almost flat valley floors, such as the case of Owens Valley, California, where the South Dolomite Fan is underlain by flat Holocene lake beds (Kim & Lowe, 2004).

2.2 Debris-Flow Fluid Mechanics and Various Representative Models:

Debris flows tend to flow downslope as many unsteady and non-uniform surges (Iverson, 1997). Debris flows are considered non-Newtonian fluids and are often represented as a Bingham plastic, in which a particular yield stress must be met before the material will begin to flow (Johnson, 1970) (Eq. 2.1)(Fig. 2.3). Overall, in debris flows, sediment is supported by a matrix which has a finite yield strength (Dagsupta, 2003). In Bingham plastics, the strength and viscosity are finite, and they behave as a combination of a rigid solid and a Newtonian fluid (Middleton & Wilcock, 1994). Representing debris flows as a Bingham plastic results in debris
flows having a zone of laminar flow at the base of the flow with a rigid “plug” in the middle and top of flow. This “plug” occurs due to shear stress being less than the shear strength of the material, causing a portion of the material to remain rigid (Johnson, 1970). In other words the shear stress within the rigid plug is very low, and so this portion does not deform. This behavior is proven in natural flows when relatively fragile objects within the center of a debris flow, such as fractured boulders and tree limbs remain un-deformed, even after travelling long distances (Johnson, 1970). Since one portion of the material exhibits laminar flow and the other portion exhibits rigid plug movement, the velocity profile will be parabolic within the laminar regime, and uniform and constant in the rigid “plug” regime (Johnson, 1970) (Fig. 2.4). Bingham plastics come to rest when the shear stress at the base is no longer great enough to exceed the shear strength of the debris (Middleton & Wilcock, 1994). When trying to represent Bingham plastic properties experimentally, it has been shown that kaolinite-sand slurries exhibit this exact fluid behavior (Johnson, 1970), because they have a finite cohesive strength (Dagsupta, 2003).

![Graph of shear stress vs. rate of strain](image)

Figure 2.3. Schematic graph representing the behavior of a Bingham plastic. As can be seen a yield shear stress must be met before the fluid begins to flow represented by the rate of strain.
Figure 2.4. Schematic showing the relationship between the velocity profile of Bingham plastic and the rigid plug and laminar flow regimes existing in Bingham plastics (adapted from Johnson, 1970).

\[ \tau = k + \mu \frac{d\varepsilon}{dt} \]

Equation 2.1 Equation representing a Bingham plastics behavior. \( \tau \) is shear stress, \( k \) is the yield stress needed to initiate flow, \( \mu \) is the plastic viscosity, and \( \frac{d\varepsilon}{dt} \) is the strain rate.

*Limitations of the Bingham Model:*

Some aspects of debris flow do not follow this Bingham plastic model. One problematic observation is that many debris flows have predominantly sandy matrixes, and it is difficult to understand how this sandy matrix can possess enough strength to make the Bingham plastic...
model valid (Middleton & Wilcock, 1994). Also, some debris flows “freeze” from the bottom up, but in the Bingham model stress increases linearly and is greatest at the base, hence a debris flow should freeze from the top down (Middleton & Wilcock, 1994). Also, the Bingham plastic model does not consider the momentum exchange caused by grain collisions (Middleton & Wilcock, 1994). Even though the Bingham plastic model may cause discrepancies in explaining initiation and deposition of debris flows, the rest of the flow process is well accounted for by the Bingham plastic model, meaning that this model can be useful in understanding debris flow dimensions, velocity and travel or run-out distance (Middleton & Wilcock, 1994). The limitations of this model were further investigated by Major & Iverson (1999) and Iverson (2003), where it was observed that debris flow behavior can vary from almost rigid to a highly fluid material based on variations of pore-fluid pressure and mixture agitation across space and time.

Other Representative Models:

Other fluid models have been proposed to help describe the flow, initiation and deposition of debris flows (Takahashi, 1981; Iverson, 1997; Iverson, 2003), but these models are much more complicated and still have limitations in predicting the initiation, movement and deposition of all debris flows.

Based on Iverson’s (1997) dimensional analysis of debris flow momentum transport, five processes of momentum transport or stress generation are important in debris flow motion. These are inertial grain collisions, grain contact friction, viscous shear, inertial fluid velocity fluctuations and solid fluid interactions (Iverson 1997). With so many aspects affecting momentum transport, it is difficult to define one model that accurately defines all of the stresses generated in a debris flow. Table 2.2 lists some of the various models used to represent natural debris flows, and what these do and do not accurately portray.
Table 2.2: Comparison of various debris flow models and their applications (adapted from Iverson, 1997). X’s signify where model is applicable.

<table>
<thead>
<tr>
<th>Phenomenon</th>
<th>Bingham Plastic Model</th>
<th>Bagnold Grain Flow Model</th>
<th>Coulomb Grain Flow with Variable Pore Pressure Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow mobilizing from rigid slope failure without change in constitutive properties.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Fluid pressures can differ from average pressure and affect apparent strength and flow resistance.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Flow exhibits rigid plug of undeformed material.</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Flow can lack a rigid plug.</td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Flow is unsteady and non-uniform with blunt snout and tapered tail.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Flow can transport up to boulder size clasts that do not settle.</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Flow produces segregation of grain sizes.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flow agitation can affect apparent strength and flow resistance.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Boundary slip occurs at bed.</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Flow strengthens and halts rapidly when pore fluid is drained from beneath.</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Interior of deposit can remain weak and unable to support loads while perimeter of deposit becomes rigid.</td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

Based on the goals of this research (i.e. evaluate spatial distribution and not necessarily evaluate deposition and initiation mechanics) the simplest mechanical model was chosen, which is the Bingham plastic model. Bingham plastic models are good for experiments at laboratory scales (Iverson, 1997). However, this model does not account for the interaction of coarse grained sediments with each other or for observed debris-flow behavior (Iverson, 1997). As
stated above, Johnson (1970) found that kaolinite-sand slurries follow this Bingham plastic behavior.

2.3 Alluvial Fans and Debris-Flow Fans in the Laboratory:

Alluvial fans have been extensively evaluated experimentally to research many aspects of the fan morphology; however, a majority of these experiments assume continuous sediment deposition (i.e. fluvial dominated) rather than episodic deposition, which would be characteristic of debris flow dominated fans. Some researchers have looked at debris-flow fans experimentally (Tsai, 2011; Cui, 1997), but research in this area is minimal. This sections describes some of these experiments to show what has been researched and what can be learned from studying fluvial dominated alluvial fans, and how these principles and findings could be used in evaluating debris-flow fans experimentally.

*Experimental Stream Dominated Alluvial Fans:*

Clarke et al. (2010) evaluated an experimental stream dominated alluvial fan following a similarity of processes approach, and found that within fluvial dominated alluvial fans with continuous sediment supply, there is an autogenic transition from sheet-flow to channelized flow as evolution of the fan progresses, and this is a result of the decline of aggradation rate over time. Clarke et al. (2010) also demonstrated that autogenic mechanisms (i.e. internal forcing) can impact aggradation, incision, avulsion, and changes in fan morphology. The evolution of their experimental fluvial dominated fan started with sheet-flow, transitioning to unstable channels, then to lateral migration of stable channels, and finally to the construction of an entrenched single channel. Their findings show that observed changes in fan morphology cannot be automatically attributed to allogenic response (i.e. external forcing such as environment) (Clarke et al., 2010).
Clevis (2003) developed a numerical model of drainage basin evolution and found that the alluvial fan surface could be characterized by rapidly shifting braided streams. They found that the switching of depositional lobes appeared to be non-periodic and occurred between 20,000 to 60,000 years (Clevis, 2003).

Another numerical model created by De Chant et al. (1999) using a diffusive sediment transport model and unsteady radial flow found that dimensionless morphology of alluvial fans is controlled more by the principles of diffusive sediment deposition rather than environmental and basin characteristics (De Chant et al., 1999).

**Experimental Debris-Flow Dominated Fans:**

Tsai (2011) found that the non-dimensional longitudinal and transverse profiles of experimental debris-flow fans are accurately depicted by Gaussian curves, and the non-dimensional planform of debris-flow fans is approximately fitted by a circular curve. These findings can help in volume calculations to help decipher hazardous zones near debris-flow fans.

All of these experiments show that both physical and numerical modelling of varying types of alluvial fans can provide valuable insight into their formation, sediment transport and controls on fan morphology.

**2.4 Compensational Stacking and the Modified Compensation Index:**

Compensational stacking is the tendency for a flow-like deposit to preferentially fill topographic lows (Straub et al., 2009). This process smooths out topographic relief, compensating for the localization of the deposition (Straub et al., 2009). Compensation is believed to occur due to continuous or periodic changes to the sediment transport field to decrease the potential energy created by increasing elevation gradients (Straub et al, 2009). It is believed that a dominant mechanism for this compensational stacking behavior is avulsion
Compensation indicates that the deposition of a thin bed is statistically more likely to be succeeded by a thick bed (Straub et al., 2009). Compensational stacking has commonly been used to analyze deep marine systems, turbidites, fluvial systems, and deltaic deposits.

**The Compensation Index:**

When sedimentary deposits are composed of discrete elements (i.e. lobes and channels, debris), then a characteristic depositional architecture is created. Straub et al. (2009) found that for several depositional environments (river deltas and deep water minibasins), the decrease in standard deviation of sedimentation, $\sigma_{ss}$, (Eq. 2.2) divided by the subsidence of the basin followed a power law trend (Eq. 2.3) (Straub et al., 2009). He termed the exponent of this trend the compensation index, $K$. This ranged between 0 and 1, where 0 indicates anti-compensation or aggradation, 1 represents pure compensation and 0.5 represents random stacking of deposits. Based on their analysis of various sedimentary basins, Straub et al. (2009) deduced that a global average for $K$ may be 0.75, and that most basins probably range between 0.5 and 1.0 (Straub et al., 2009). However, they note that this does not indicate that all basins have a $K=0.75$, and that for cases with significant depositional persistence $K$ could be less than 0.5 (Straub et al., 2009). They also found that $K$ increases logarithmically as the frequency of avulsions increase, and that compensation is stronger where sediment transport is strongly slope driven (Straub et al., 2009). They also note that some systems may be anti-compensational over short time scales. This is assumed to occur whenever depositional elements acts as “attractors”, rather than local “repellers” (Straub et al., 2009). Straub found that as long as the depositional event (i.e. debris flow or other flow event) is no more than half as large as the model domain, then $K$ will be unaffected by changes in size (Straub et al., 2009).
Equation 2.2 Equation for standard deviation of sedimentation which represents compensation in a system. \( r(T; x, y) \) is the local sedimentation rate measured over a stratigraphic time difference. \( \hat{r}(x, y) \) is the local long term sedimentation or subsidence rate. This serves as a measure of the extent of subsidence control in a basin.

\[
\sigma_{ss}(T) = \left( \int_A \left[ \frac{r(T; x, y)}{\hat{r}(x, y)} - 1 \right]^2 dA \right)^{1/2}
\]

Equation 2.3 Equation for the power law trend exhibited by the standard deviation of sedimentation. The exponent in this trend is the compensation index.

\[
\sigma_{ss} = \alpha T^{-k}
\]

Deciphering Allogenic and Autogenic Controls on Compensational Stacking:

A problem arising in analyzing compensational stacking is that allogenic signals may be obscured by autogenic signals (Wang et al., 2011). Allogenic responses are stratigraphic responses caused by external factors, such as environment and tectonic activity. Autogenic responses are those characteristics preserved in the stratigraphic record that are caused by internal factors related to the dynamics of the system itself. Wang et al. (2011) suggests that the transition to where stratigraphy is partially influenced by autogenic forcing to being completely controlled by allogenic forcing occurs at the time necessary to generate a mean thickness equal to the maximum topographic relief of the transport system. This transition can be estimated by equation 2.4. This was proven by plotting \( \sigma_{ss} \) with time showing that \( K \) increases from 0.28 to 1.0 and then becomes a constant 1.0 indicating the transition from autogenic to allogenic responses. Wang et al. (2011) also demonstrated that the measurement window does not have to be time, but can be spatial as well, and can correspond to the average thickness of the deposit between to stratigraphic surfaces (Wang et al., 2011). This is important, because stratigraphic horizons can be used instead of timelines where deposits lack age control (Wang et al., 2011). Wang et al.’s work shows that the strength of compensation is scale dependent.
Equation 2.4 Equation depicting the time scale at which compensation index reaches unity, which signifies the shift from stratigraphy that record autogenic process to stratigraphy determined by regional sediment supply and accommodation. $T_c$ is the compensation time scale, $l$ is the roughness length scale and $\bar{r}$ is the long term basin wide subsidence rate.

\[ T_c = \frac{l}{\bar{r}} \]

*Development of the Modified Compensation Index:*

Based on the fact that Wang et al. (2011) showed that spatial parameters can be used in place of temporal scales, Straub & Pyles (2012) proposed a modified compensation index $K_{cv}$ through the investigation of hierarchical organization of sedimentary units. Before discussing the modified compensation index, a short discussion on hierarchical sedimentary units will be presented, so that the research used to develop the modified compensation index is better understood.

Dividing deposits based on hierarchy subdivides deposits based on distinct scale-dependent changes in characteristics such as duration of deposition, and size (Straub & Pyles, 2012). This version of categorization of units splits them into hierarchical classes called beds, stories and elements. Beds are inferred to be constructed of a single depositional event (Straub & Pyles, 2012). Stories group beds into a larger package that has similar lithofacies associations, and the location of the axes of vertically adjacent stories are approximately superimposed (Straub & Pyles, 2012). Elements are even larger groups, and record abrupt and large changes in location of the axes of the elements, lithofacies, bedding style and paleocurrent direction (Straub and Pyles 2012) (Fig. 2.5). Straub & Pyles found that by subdividing sedimentary systems in this fashion, that some characteristics of the system are hierarchical and some are fractal, or scale invariant (Straub & Pyles, 2012), and that compensation is not fractal. They also found that lobe elements tend to be more
compensational than channel elements (Straub & Pyles, 2012). They found that increase in hierarchical level increases the strength of compensational behavior.

To analyze the propensity for hierarchical groups to display compensational tendencies, a modified compensation index was developed, because quantifying subsidence over time is rather difficult especially with sedimentary systems that have short time spans or minimal subsidence (i.e. alluvial fans and debris-flow events) (Straub & Pyles, 2012). So, the Kcv looks at a statistical parameter that is analogous to $\sigma_{ss}$, which is the coefficient of variation (CV) in deposition between two stratigraphic surfaces (Straub & Pyles, 2012). The equation for CV is shown below in equation 2.5. CV compares the local deposit thickness between two stratigraphic surfaces at discreet intervals divided by the mean deposit thickness in between those surfaces across the length of the cross-section. This allows for the characterization of the variability in local deposit thickness standardized by a fraction of mean thickness (Straub and Pyles, 2012). This further allows for the comparison of deposit stacking patterns across a variety of thickness scales. The actual modified compensation index parameter is the exponent of equation 2.6, which is the assumed power law decay of CV with increasing mean deposit thickness. As is the case with the compensation index, 0.0 represents pure anti-compensation tendencies, 0.5 represents random stacking patterns, and 1.0 represents purely compensational behavior. This version of the compensation index assumes uniform and constant subsidence rates, meaning that the shape of the deposit is solely influenced by the morphodynamics of the sediment routing system (Straub & Pyles, 2012). This assumption is good for sedimentary systems that exist on a relatively short time scale (i.e. alluvial fans).
Figure 2.5. Schematic diagram depicting the difference between the hierarchical groups of beds, stories and elements. Beds are indicated with red dashed lines, stories are indicated by blue dashed lines, and elements are represented by the green wedges. Figure adapted from Straub & Pyles(2012).

$$\text{Equation 2.5. Equation for CV which is a statistical parameter used to represent compensation tendencies in sedimentary systems.}$$

$$\text{\(CV = \left( \int_{L}^{0} \left[ \frac{\Delta \eta(x)_{A,B}}{\Delta \eta_{A,B}} - 1 \right]^2 dL \right)^{1/2} \)}$$

Equation 2.5. Equation for CV which is a statistical parameter used to represent compensation tendencies in sedimentary systems. \( \Delta \eta(x)_{A,B} \) is the local deposit thickness between to stratigraphic surfaces A and B. \( \Delta \eta_{A,B} \) is the mean deposit thickness between surface A and B over the length, L, of the cross-section.

$$\text{\(CV = a \Delta \eta_{A,B}^{-k_{CV}}\)}$$

Equation 2.6 Equation for the power law trend exhibited by CV. The exponent in this trend law is the modified compensation index.
Compensational Stacking in Regards to Debris-Flow Fans:

Pederson (2014, 2015) applied the above concepts of compensational stacking and the modified compensation index to three debris-flow fans in Colorado to evaluate what parameters affect compensational behavior in debris-flow fans. Parameters evaluated included percent stream flow material, percent clay by mass in matrix, percent volume of pebble sized clasts, percent volume cobble sized and greater clasts, maximum unit thickness, unit width to thickness ratio, fractional outcrop distance from the fan apex, and absolute distance from fan apex. His fans had modified compensation index values between 0.63 and 1.03, indicating a preference for compensational stacking amongst the studied debris-flow fans. These results followed assumptions made in Straub et al. (2009), Wang et al. (2011), and Straub & Pyles (2012), indicating that the modified compensation index is a viable tool in analyzing avulsion tendencies of debris-flow fans. The only statistically significant parameters that correlated to the modified compensation index were percent cobble sized clast and greater, and percent pebble sized clasts by volume. Both were positively correlated indicating that increase in these parameters causes an increase in the modified compensation index. Pederson assumed that based on these two parameters larger debris-flow events are more compensational (Pederson, 2014).

2.5 Scaling of Models:

Dynamic similarity of experimental debris flows requires scaling for the flow as a whole and for the grain-scale mechanics that generate stresses in the fluid (Iverson et al., 2010). This dynamic similarity is governed by seven dimensionless parameters. $\varepsilon = \frac{H}{L}$, $R = \frac{\rho}{\rho_0} R_f = \frac{\rho_f}{\rho_0} C = \frac{\tau_s}{\rho_0 g H}$, $Y = \frac{\tau_y}{\rho_0 g H}$, $N_R = \frac{\rho_0 g H \sqrt{\gamma}}{\mu}$, $N_P = \frac{\sqrt{L/g}}{H^2/D}$. In these dimensionless parameters $H$ is the height of a surge of debris, $L$ is the length of a surge of debris, $\rho$ is the bulk density of the flow, $\rho_0$ is the reference value to the bulk density at static limiting equilibrium, $\rho_f$ is the density of the fluid involved in the debris flow, $\tau_s$ is shear stress, $\tau_y$ is the yield strength, and $g$ is the acceleration.
due to gravity. $\varepsilon$, R and $R_f$ imply no inherent scale dependence and should be much less than 1, similar to 1 and similar to 0.6, respectively (Iverson et al., 2010). C also implies no scale dependence since $\tau_s$ depends on effective normal stress which scales with $\rho g H$. These above parameters show that experimental debris flows can be geometrically similar, but the scale dependence of $Y$, $N_R$, and $N_p$ shows that dynamic similarity is likely not possible. This can be seen in the fact that miniature debris flows are likely to exhibit disproportionately large effects of fluid yield strength, viscous flow resistance, and grain inertia, and they will exhibit disproportionately little effects of pore fluid pressure (Iverson et al., 2010).

Since dynamic similarity cannot exist, $Y$, $N_R$, and $N_p$ were not used in designing of the experiment. Also, C was not used because shear strength of the fluid was not measured for this experiment. Along with these scaling parameters, Froude scaling was used as well for the attainment of some sort of fluid similarity to compare to the natural world.

2.6 Importance of Current Experiment in Regards to Previous Work:

While compensational tendencies have been studied for fluvial, deltaic and deep-marine systems, the mechanism of compensation in debris-flow fans has not been evaluated directly, and the trends and laws of compensational tendencies in debris-flow fans is assumed from other depositional environments. This study will give a more accurate depiction of compensational tendencies of debris-flow fans.

This study also evaluates the differences between depositional processes on debris fans and alluvial fans. The previous studies of alluvial fans focus almost entirely on the evolution of fluvial dominated alluvial fans. It cannot be assumed that fluvial and debris-flow dominated fans act the same due to the difference in their fluid properties and due to the difference how they are deposited (i.e. continuous deposition versus episodic deposition). Studying debris-flow fans
at a small scale can help better portray how sediment is transported, distributed and diverted along the surface of a debris-flow fan.

Previous research shows that experimental physical modelling is a good resource to study autogenic processes, because one can eliminate the influence of allogenic forcing in a controlled laboratory setting.
CHAPTER 3: THE PHYSICAL MODEL

This section describes the model used to analyze and evaluate avulsion and migration tendencies of debris flows across debris-flow fans, and discusses considerations that were taken into account to ensure that the model effectively portrayed natural debris-flow phenomena.

3.1 Geologic Setting:

The intention of this model is to represent an alluvial fan setting that is debris-flow dominated with episodic events, where there is steep mountainous terrain transporting sediment onto a broad shallow sloped valley. This particular model represents a fan developing through the discharge of sediment from only one source or channel, and the channel is fixed and not moving. The fan itself is intended to represent a lobe dominated regime. An analog to this type of geologic setting could be regions around Aspen Colorado, where there is steep mountainous terrain with abundant fan structures developed on broad, shallow-sloping glaciated valley floors. This setting would also be typical of the area surrounding the Chalk Cliffs near Buena Vista Colorado, which was a location used in geometric scaling of channel dimensions. Also, the alluvial fan is intended to represent a debris-flow fan where sediment transport is heavily dominated by episodic events rather than a more continuous alluvial stream sediment transport mode.

3.2 Experimental Debris Flow Fluid Composition and Fluid Scaling:

This section describes the material used to represent the debris-flow phenomena during experimentation. This section will justify the choosing of this material and its composition.
**Previous Work:**

Kaolinite-sand slurry is a very common material used to represent debris flows experimentally. It has been used to evaluate the difference in mobility of subaqueous and subaerial debris flows, the ability for debris flows to remobilize antecedent deposits, the dependence of flow behavior on sand:clay ratio, and the various debris-flow mechanics models (Johnson, 1970; Mohrig et al., 1999; Illstad et al., 2004). Mohrig et al. (1999) found that subaerial debris flows travelled a shorter distance compared to subaqueous debris flows of similar rheology, and that subaerial debris flows had greater propensity to remobilize antecedent deposits compared to subaqueous debris flows. They hypothesized that this was due to the water of subaqueous flows creating a lubricating layer between the base of the deposit and the channel, allowing the subaqueous debris flow to hydroplane across the surface. Johnson (1970) used the kaolinite-sand slurry to analyze the application of the Bingham plastic model to the fluid properties of natural debris flows.

In regards to fluid scaling, research has been performed to analyze the Froude numbers of various debris-flow material. The Froude number is a dimensionless parameter used in fluid mechanics to describe flow regimes and helps relate model flow properties to natural world flow properties. It is a ratio of inertial to gravitational forces helping to describe momentum transfer. Kaitna & Rickenmann (2007) found experimental debris-flow material to have Froude numbers varying from 0.2 to 4.1.

**Qualitative Trials:**

Several qualitative trials were performed to choose the composition of the kaolinite-sand slurry used during the experiment. Kaolinite was chosen because it is an inactive clay, so that the activity of the clay would not affect the rheology of the slurry. Table 3.1 lists the percentages of sand, kaolinite and water attempted, and a qualitative justification of why they were or were not
chosen. It should be noted that at first, compositions were developed using total percent volume, but upon trial of this method it was deemed too hard to account for pore space within the clay fraction of the composition. It was difficult to compact the clay enough to remove the pore space between the grains to accurately assess the volume of clay within the slurry. Therefore the composition was measured by mass percent.

Table 3.1: Qualitative Trials for Composition Selection:

<table>
<thead>
<tr>
<th>% Water (by vol.)</th>
<th>% Kaolinite (by vol.)</th>
<th>% Sand (by vol.)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>30%</td>
<td>20%</td>
<td>50%</td>
<td>Extremely Viscous, no downslope movement, hard to keep homogenous, High percentage of sand allows for drainage of water out of deposit (i.e. dilates then contracts too quickly)</td>
</tr>
<tr>
<td>30%</td>
<td>40%</td>
<td>30%</td>
<td>Not viscous enough (i.e. flows too similar to water), extremely soupy or watery</td>
</tr>
<tr>
<td>30%</td>
<td>50%</td>
<td>20%</td>
<td>Extremely viscous, no downslope movement</td>
</tr>
<tr>
<td>47%</td>
<td>20%</td>
<td>33%</td>
<td>Too viscous, may be error in volume calculation</td>
</tr>
<tr>
<td>35% (by mass)</td>
<td>20% (by mass)</td>
<td>45% (by mass)</td>
<td>Low viscosity, Appears to exhibit stream flow rather than debris flow</td>
</tr>
<tr>
<td>30% (by mass)</td>
<td>20% (by mass)</td>
<td>50% (by mass)</td>
<td>Low Viscosity, Appears to exhibit stream flow rather than debris flow</td>
</tr>
<tr>
<td>25% (by mass)</td>
<td>20% (by mass)</td>
<td>55% (by mass)</td>
<td>High viscosity, Not enough downslope movement</td>
</tr>
<tr>
<td>30% (by mass)</td>
<td>15% (by mass)</td>
<td>55% (by mass)</td>
<td>Low viscosity, Sand drains too quickly</td>
</tr>
</tbody>
</table>
Table 3.1 Continued

<table>
<thead>
<tr>
<th>Composition</th>
<th>Consistency</th>
<th>Behavior</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% (by mass)</td>
<td>20% (by mass)</td>
<td>60% (by mass)</td>
</tr>
<tr>
<td>20% (by mass)</td>
<td>25% (by mass)</td>
<td>55% (by mass)</td>
</tr>
<tr>
<td>27% (by mass)</td>
<td>20% (by mass)</td>
<td>53% (by mass)</td>
</tr>
<tr>
<td>29% (by mass)</td>
<td>20% (by mass)</td>
<td>51% (by mass)</td>
</tr>
<tr>
<td>30% (by mass)</td>
<td>21% (by mass)</td>
<td>49% (by mass)</td>
</tr>
<tr>
<td>31% (by mass)</td>
<td>22% (by mass)</td>
<td>47% (by mass)</td>
</tr>
<tr>
<td>33% (by mass)</td>
<td>19% (by mass)</td>
<td>48% (by mass)</td>
</tr>
</tbody>
</table>

Final Composition:

Based on the qualitative observations above, it appeared that the composition consisting of 33% water, 19% clay and 48% sand seemed to best represent natural debris flow. To justify this choice the Froude number was calculated for this trial (Eq. 3.1) to represent the fluid properties of natural debris flows as a homogenous one phase flow regime. In this case, the Froude number should be less than 1, signifying subcritical flow. Homogenous one phase flow was desirable, because non-uniform two phase flow may have had complicating effects on the experiment. Based on trial 2 of the experiment, the Froude number was calculated to be 0.866 which is less than one, and deemed acceptable for this experiment. The Froude number was
calculated by dividing the frontal velocity by the square root of the acceleration due to gravity multiplied by the maximum height of the fluid. Frontal velocity was measured from video data, and maximum height was measured from use of a meter stick. The parameters of trial 2 used to calculate the Froude number are listed in table 3.2.

\[ F_r = \frac{v}{\sqrt{gL}} \]

Equation 3.1. Equation for the Froude number (Scheidl et al., 2013). V is the maximum velocity, g is acceleration due to gravity, and l is the maximum flow height.

Table 3.2: Trial 2 Properties used to calculate Froude number.

<table>
<thead>
<tr>
<th>Debris Flow Slurry Properties</th>
<th>Water</th>
<th>33%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (% Total Mass)</td>
<td>Sand</td>
<td>48%</td>
</tr>
<tr>
<td></td>
<td>Kaolinite</td>
<td>19%</td>
</tr>
<tr>
<td>Average Density (kg/m^3)</td>
<td>1614 kg/m^3</td>
<td></td>
</tr>
<tr>
<td>Maximum Velocity</td>
<td>43 cm/s</td>
<td></td>
</tr>
<tr>
<td>Maximum Flow Height</td>
<td>2.4 cm</td>
<td></td>
</tr>
<tr>
<td>Froude Number</td>
<td>0.886</td>
<td></td>
</tr>
</tbody>
</table>

The slurry used is a high density fluid, representative of natural debris flows. The average density of the fluid was 1614 kg/m^3 and the standard deviation of the density was 17.3. A discussion pertaining to the densities and a table of the density of each trial can be found in appendix A.

Also, to check to see if variability in the particle size distribution of the sand used in the slurry could affect results, grain size distribution curves for the sand were plotted. Figure 3.2 shows that the grain size distribution of the sand remains relatively constant throughout the experiment. A short discussion on methodology and effects of grain size sorting can be found in Appendix A.
Figure 3.1. Particle size distribution curves of sand used in experiment. The sand used is well sorted and grain size ranges from approximately 5 mm to 0.07 mm.

3.3 Scaling Considerations:

A variety of scaling techniques were used in this experiment including dimensionless parameters discussed in section 2.5, Froude scaling and a ‘similarity of processes and performance’ approach (Iverson et al., 2010; Pyles et al., 2013; Scheidl et al., 2013; Clarke et al. 2010). It should be noted that all of these scaling considerations are based on trial 2, which is the first trial used in development of the experimental debris-flow fan.

A distorted Froude scaling approach was used where vertical and horizontal dimensions are looked at independently. The thickness of natural or prototype debris flows can be on the order of tens of meters as seen in section 2.1 of this thesis. The thickness of debris flows during experimentation was on the order of centimeters. Applying equation 3.2 gives a scaling factor of 100 for the vertical dimensions based on the above assumptions.
\[ \lambda_v = \frac{H_p}{H_m} \]

Equation 3.2. Equation for the vertical scaling parameter, \( \lambda_v \). \( H_p \) is the prototype height or thickness of deposit, and \( H_m \) is the height or thickness of deposits in the model.

The length of prototype debris flows can be estimated at a magnitude of hundreds of meters based on research reviewed in section 2.1 of this paper. The length of debris flows during experimentation was on the order of tens of centimeters. Applying equation 3.3 gives a scaling factor of 1000 for the horizontal dimensions based on these assumptions.

\[ \lambda_H = \frac{L_p}{L_m} \]

Equation 3.3. Equation for the horizontal scaling parameter, \( \lambda_H \). \( L_p \) is the prototype horizontal length of deposit, and \( L_m \) is the horizontal length of the deposit in the model.

One can derive what the natural world slopes would be on the system based upon the experimental slopes on the experimental fan using equation 3.4. To make sure that velocities in the experiment can represent velocities in the natural world for debris flows, the Froude number should be less than 1 (Eq. 3.1).

\[ \frac{S_p}{S_m} = \frac{\lambda_v}{\lambda_H} \]

Equation 3.4. Equation for comparing slopes in the model to slope in nature. \( S_p \) is the prototype slope, and \( S_m \) is the model slope.

A ‘similarity of processes and performance’ approach was evaluated as well for scaling considerations of this experiment. This approach to scaling is based on the assumption that aspects of a natural system can be reproduced in a laboratory setting, and that processes that
produce features in nature will be similar to those in a laboratory setting (Clarke et al., 2010). This approach requires that: 1) a number of gross scaling relationships be met, 2) the system reproduces some morphological characteristic of the landform in question, 3) processes producing this characteristic in the experiment can logically be assumed to have the same effect on the natural landform (Clarke et al., 2010). The first requirement is met through the use of the dimensionless parameters and Froude scaling described above. The second requirement is met by the fact that the experimental debris flows exhibit lobe morphologies, which could be representative of lobate debris flow features found in the natural world. The third requirement is met through the use of kaolinite-sand slurry that exhibits Bingham plastic behavior, which has been accepted as a suitable model to represent debris-flow behavior at a basic level. The third requirement is also met by the fact that both the experimental debris flows and natural debris flows exhibit surges of flow rather than one homogenous flow. Table 3.3 lists the values of scaling parameters used in the experiment.

Table 3.3. Scaling parameters used for experiment. Fr should be less than 1, $\varepsilon$ should be much less than 1, R should be similar to 1 and $R_f$ should be approximately 0.6.

<table>
<thead>
<tr>
<th>Fr</th>
<th>$\lambda_V$</th>
<th>$\lambda_H$</th>
<th>$\varepsilon$</th>
<th>R</th>
<th>$R_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.866</td>
<td>100</td>
<td>1000</td>
<td>0.027</td>
<td>1</td>
<td>0.62</td>
</tr>
</tbody>
</table>

*Other Geometric Scaling and Similarity Considerations:*

Debris-flow channels and debris-flow deposit width were analyzed to determine the width of the channel used in the model. To do this, channel width to deposit width (C:D) were calculated for a limited number of debris-flow fans in literature and from a 3m Digital Elevation Model (DEM) and National Agriculture Imagery Program (NAIP) image (Fig. 3.2) of the Chalk Cliffs near Buena Vista Colorado. The DEM was processed in GIS to delineate deposits within the fan structure evaluated at Chalk Cliffs (Fig. 3.3). The fan that was used for calculating C:D is
represented in figure 3.3. It is the fan that is the far westerly fan in figure 3.2. This one was chosen, because it appeared to experience the least effect from the coalescing of individual fans. The deposit width was measured at the widest extent of the deposit. Literature used to calculate C:D ratios are Blair & McPherson, 1998 and Whipple & Dunne, 1992. In this literature the dolomite fan and other alluvial fans were mapped in Owens Valley, California. To calculate C:D in the literature the scaled maps of the fan surface with mapped debris-flow deposits were used. Table 3.5 lists these C:D ratios.

Figure 3.2. NAIP image of the Chalk Cliffs in Colorado. Radial conical fan structures are present along the mountain slope valley interface. Fans appear to be coalescing.
Figure 3.3. Results from delineating depositional lobes at Chalk Cliffs using GIS. The different colors or shades of gray represent delineated depositional lobes, which were assumed to follow the margins of debris-flow deposits.
Table 3.4: C:D ratios used for choosing channel width of the model.

<table>
<thead>
<tr>
<th>Location</th>
<th>Channel Width: Deposit Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chalk Cliffs, CO</td>
<td>0.0747</td>
</tr>
<tr>
<td>Chalk Cliffs, CO</td>
<td>0.172</td>
</tr>
<tr>
<td>Chalk Cliffs, CO</td>
<td>0.110</td>
</tr>
<tr>
<td>Chalk Cliffs, CO</td>
<td>0.0821</td>
</tr>
<tr>
<td>Dolomite Fan, CA</td>
<td>0.139</td>
</tr>
<tr>
<td>Dolomite Fan, CA</td>
<td>0.107</td>
</tr>
<tr>
<td>Dolomite Fan, CA</td>
<td>0.117</td>
</tr>
<tr>
<td>Owens Valley, CA</td>
<td>0.169</td>
</tr>
</tbody>
</table>

It can be seen from table 3.4 that C:D ranged from approximately 7.5% to 17%. The runout platform for the model was built from a standard 4ft by 8ft piece of plywood, so to make sure that the experimental debris-flow deposits did not exceed this width as a boundary condition, a channel width of approximately 8% of the plywood width was used. The channel was chosen to be four inches in width to obtain this eight percent C:D ratio.

It should also be noted that the greatest width of trial 2 was approximately 36.5 cm and that the model domain (i.e. plywood run-out platform) was approximately 122 cm wide. Straub et al.(2009) found that as long as the depositional element (i.e. debris flow or other flow event) is no more than half as large as the model domain, then the K will be unaffected by changes in size. Since the deposit width is significantly less than the model domain in this experiment, it is deemed that this experiment is applicable for the use in compensational behavior studies.

Channel and run-out platform angles are based upon several sources (Shieh, 1997; Ancey, 2001; Iverson, 2010). Shieh (1997) calculated that theoretical debris flow regimes exist between 13.3 degrees and 21.6 degrees. Theoretically bed slopes larger than this cause
sediment mixture to slide but not flow down slope and bed slopes smaller than this allow individual particle transport, but not a debris flow mass. Shieh, 1997 used a run-out surface slope of 2 degrees and Iverson (2010) used a run-out surface slope of 2.4 degrees. Iverson, 2010 used a slope of 31 degrees for the channel, because this angle is comparable to angles of many debris flow initiation locations. Ancey (2001) describes how the transition of two-phase flow to a single-phase flow occurs at approximately 12 degrees. At this slope, debris flow mixtures take on the appearance of a viscous homogenous fluid (Ancey, 2001). Based on these results, a value of 25 degrees was chosen for the channel slope based on visual observation, as it appeared to evacuate sediment most effectively out of the channel and onto the run-out surface without causing turbulence to develop in the fluid. The run-out surface was sloped at 3 degrees.

3.4 Limitations of the Model:

Based on section 2.5 of this thesis, dynamic similarity cannot be attained with small scale debris flow experiments. The effects of pore fluid viscosity and diffusion of pore fluid pressure are greatly exaggerated in small scale experiments of debris flows (Iverson et al., 2010). Also, there is no one single model for portraying debris-flow mechanics that represents all aspects of debris flow motion, so one type of fluid and viscosity cannot portray all aspects of a debris flow experimentally.

3.5 Model Diagram, Setup, and Execution:

Figure 3.4 is a diagram of the model setup used during experimentation. The run out platform was constructed out of ½ in. thick plywood and 2X6 pine construction grade lumber. One end of the plywood top was attached to the 2X6 lumber rectangular base with hinges, and the other end left unattached so that the slope of the platform could be adjusted. The platform was gridded into 1cm by 1 cm squares with red lines at 10 cm intervals, so that measurements...
of velocity and dimensions of each trial run could be taken from photographic and video data. This run-out platform was left unconfined to permit lateral spreading of the experimental debris-flow slurry. Bed roughness was added to the run-out platform using spray contact adhesive and spreading sand on the wet adhesive. This gave the run-out platform a texture similar to sandpaper. The "channel" portion of the model was constructed out of a 4 in. diameter PVC pipe and a 5 gallon plastic bucket, and sloped at approximately 25 degrees. This steep slope helped promote one-dimensional flow. The pipe was attached to the bucket via epoxy. The bucket acted as a hopper for the slurry material that would be used in the development of the experimental debris-flow fan. The entrance to the channel was blocked by a sluice gate built from Plexiglas, so that during execution of trials the slurry could be released instantaneously out of the channel. While the slurry was in the hopper it was continuously mixed with a paddle bit and drill at a constant revolution rate to ensure that the kaolinite sand slurry remained homogenous once the trial was initiated. Figure 3.5 and Figure 3.6 are photographs of the model setup.

The slurry for each trial was dyed with mason stain so that individual trials could be discerned in cross-section and in photographic and video data. This allowed for measurements of extent and thicknesses of the deposits.

To initiate each trial, the slurry was prepared by mixing the water and kaolinite first for approximately one minute with a drill with an attached paddle bit. The clay and water were mixed first to ensure that homogeneity was achieved before addition of the sand, so that clumps of dry material would not exist in the slurry mixture. Next, the sand was added and mixed with a paddle bit and drill once again for approximately one minute or until homogeneity of materials in the slurry mixture was achieved. Next the depth of the slurry at five points was measured and averaged so that volume and density calculations could be performed to ensure that these two parameters remained relatively constant throughout the execution of the experiment. Once the
slurry was prepared, it was poured into the hopper of the channel. The execution of each trial required two people; one person had to continuously mix the slurry in the hopper to ensure homogeneity, and the other had to pull the sluice gate out of the hopper to allow the slurry to flow through the channel and out on the platform. The slurry in a trial was continuously mixed until all of the slurry had exited the hopper and channel and had flowed out onto the platform. The trial was then allowed to dry and harden for at least 24 hours to ensure that subsequent trials would not erode the antecedent deposit. These steps were repeated for a total of 30 trials which made up the experimental debris-flow fan. It should be noted that each trial was photographed from an approximately orthogonal birds eye view, and videotaped at an oblique birds-eye view. This allowed for the measurement of dimensions for each trial, the calculation of frontal velocity for each trial, and the evaluation of flow directions of each trial.
Figure 3.4. Diagram of the model used for constructing the experimental debris-flow fan.
Figure 3.5. Photograph of actual model setup used from an oblique longitudinal view. Grids on the platform are 1 square cm and red lines denote 10 cm intervals.

Figure 3.6. Photograph of model set up from a down channel view.
CHAPTER 4: RESULTS

This section describes the results of the 30 successive experimental debris-flow trials used to develop the experimental debris-flow fan. This section is divided into data that was acquired from video, photographs and cross-sections.

4.1 Video Data: Flow Direction and Frontal Velocities

Each experimental debris-flow trial was recorded from an oblique birds eye view to calculate frontal velocities and evaluate flow directions of the debris-flow masses. It was observed that the experimental debris flows moved via a surge flow mechanism whereby the mass exited the channel in subsequent pulses. Appendix B contains figures depicting the flow directions of the trials. The flow direction vectors in figures of appendix B depict only relative magnitude and direction. The flow direction vectors are approximate estimates of major pulses or surges of mass movement. The longer the vector, the more of the debris-flow mass that flowed in that particular direction. The number next to the vector gives a relative time line of when a particular surge occurred, where one indicates an early surge and a greater number indicates a later surge.

4.1.a Flow Directions:

The following section discusses the flow directions of representative trials in the experimental debris-flow fan. The flow direction figures depict relative flow vectors, whereby length depicts relative magnitude compared to subsequent surges of mass flow during deposition of the trial. The numbers next to the vectors indicate a relative chronology of the flow direction of the trial where 1 indicates the first direction of the flow of mass, and subsequent numbers represent direction of flow of later surges of mass in the trial. These figures were produced to preserve the video record of the trials. A subset of the 30 trials is presented to illustrated general trends.
Trial 2:

Figure 4.1 depicts the flow directions of trial 2. It can be seen that the initial surges flowed approximately straight and farthest from the channel exit. Initially, the surges of flow were equally dispersive, dispensing mass on either side of an imaginary center line of the deposit. Later surges favored depositing mass on the left side of the deposit. The surges of flow deposit mass farthest from the channel initially and successively deposit mass a shorter distance from the channel as the trial is near completion. The third surge of mass travelled farthest in trial 2.

Figure 4.1. Diagram depicting the flow directions of trial 2. It should be noted that trial 2 is the initial deposit of the subsequently developed debris-flow fan.
Trial 5:

Figure 4.2 depicts the flow directions of trial 5. Once again, flow of mass is radially dispersive from the channel in which deposition of mass occurs simultaneously on both sides of the center line. The trial does not avulse to either side of the center line. Mass appears to be equal on either side of the center line. Surge one of mass travelled furthest and exhibited bifurcated flow during trial 5.

Figure 4.2 Diagram depicting the flow directions of trial 5.
**Trial 15:**

Figure 4.3 depicts the flow directions of trial 15. The first surge of mass of trial 15 travelled approximately down center line of the deposit and then subsequent surges exhibited preferential flow to the right. Surge 5 and surge 6 of mass flow dispersed mass equally to either side of the center line. The last surge of mass, once again, heavily favored the left side. The flank morphology of the left portion of the developing fan was further enhanced by the preferential flow to the left.

![Diagram depicting the flow directions of trial 15.](image)

**Trial 20:**

Figure 4.4 depicts flow directions of trial 20. All surges of mass flow except for the final surge preferentially deposited mass to the right side of the centerline of the deposit. The last surge dispersed mass preferentially along the left side flank morphology of the developing fan. The second surge of mass flow travelled farthest from the channel.
Figure 4.4. Diagram depicting the flow directions of trial 20.

**Trial 26:**

Figure 4.5 depicts the flow directions of trial 26. Surge one through surge three dispersed mass down centerline of the deposit. Surge three of mass flow travel the farthest. Surge four and surge five of mass flow exhibited bifurcated flow in which mass was slightly preferentially deposited toward the right. The last surge exhibited bifurcated oblique backwards flow toward the channel. It should be noted that this occurred, because the fan sloped backwards towards the apex at the locality of the last surge. Once again, flow preferentially deposited mass longitudinally rather than laterally.
Figure 4.5. Diagram depicting the flow directions of trial 26.

**Trial 30:**

Figure 4.6 depicts the flow directions of trial 30. The initial surge of mass flow travelled down centerline. All surges of mass flow, after the initial flow down centerline, exhibited extreme bifurcated flow, where flow was close to perpendicular or directly perpendicular to the center line of the deposit. Earlier surges preferentially dispersed mass to the left, and later surges preferentially dispersed mass to the right, creating two distinct masses within the entire deposit. Overall, flow predominantly dispersed mass laterally rather than longitudinally. Surge two of mass flow travelled farthest from the channel.
4.1.b Frontal Velocities:

Frontal velocities for each trial were calculated from video data recorded for each trial. The frontal velocities are calculated from the farthest distance travelled by the first surge of mass flow, and the time required to reach that distance.

Frontal velocities of the trial range from 43 cm/s to 102.5 cm/s. Appendix C contains a table listing the frontal velocity for each trial in the experiment. The average velocity was 72.86 cm/s. Based upon figure 4.7, velocities during the experiment appear constant, but need further statistical analysis to verify. Velocities increased and decreased, but the trend in increase and decrease appears to be random.
Figure 4.7. Graph plotting frontal velocities against the trial number.

4.2 Birds-Eye View Photographic Data: Spatial Distribution, Run-Out Lengths, Length to Width Ratios

For each trial birds-eye view photographs were taken upon completion of the trial run. These photographs were scaled and dimensioned in CANVASX 16, so that various dimensions of each trial could be measured. The greatest width and greatest length were measured to calculate length to width ratios for each deposit. Also, maximum run-out lengths for each deposit were measured. The photographs of each trial were overlaid upon each other to evaluate the overall planar spatial distribution of the trials within the experimental debris-flow fan.

4.2.a Spatial Distribution:

Using the overlaid photographs, the deposits of the trials were outlined to assess the overlaps, aggradation and avulsion tendencies of each trial. Figure 4.8 and figure 4.9 depicts the sequence of development of the debris-flow fan as subsequent trials were deposited.
Based upon figures 4.8 and 4.9, one can qualitatively see that migration of deposits appears to be in a cyclical fashion where trials migrate right for some time, trend back towards the center, migrate left and then repeat the process. It appears that between cycles of progressive migration to the right or left, deposits tend to directly aggrade on top of one another, and then after several trials of aggradation, the trials avulse. It also appears that predominant heads of the deposits indicate overall migration direction. Another pattern that seems to develop from these diagrams is that deposits tend to follow a cyclical run-out pattern. The pattern is such that an initial trial will have a long run-out and subsequent trials will have progressively shorter and shorter run-out distances, until some threshold is met and a trial overruns the length of the previous deposits. Also trials appear to overall widen over time, but a widening to narrowing cyclical pattern also appears to exist qualitatively based upon figures 4.8 and 4.9.

4.2.b Run-Out Lengths:

Maximum run-out length of each trial was measured. This was measured from the apex of the fan to the greatest longitudinal extent of the trial. It should be noted that the apex of the fan is approximately 10 cm longitudinally down fan from the exit of the channel. This parameter was measured so that it could be compared to other parameters to identify correlations and regression models that might explain what factors affect avulsion or migration.

Appendix D contains a table listing the run-out distances for each trial originating from the apex of the experimental fan, and figure 4.10 depicts a plot of these compared to trial number. Based on figure 4.10, it appears that a cyclical component to run-out distance may exist, but the pattern is not strong enough to deduce this without further analysis (performed in the next chapter).
Figure 4.8. Diagram depicting the sequence of evolution of the experimental debris-flow fan. Images are to scale. Trial 2 is in the upper left hand corner and trial 17 is in the lower right hand corner.
Figure 4.9. A continuation of figure 4.8 depicting the evolution of the experimental debris-flow fan. Images are to scale. Trial 18 is in the upper left hand corner and trial 31 is in the lower right hand corner.
4.2.c Length to Width Ratios:

Length to width ratios of each trail were calculated. The length used in the ratio was the longitudinally farthest extent of the trial, and the width used was the greatest lateral extent of the trial.

Appendix E contains a table listing the length to width ratios of each trial, and figure 4.11 depicts a graph of these ratios plotted against trial number. Figure 4.11 shows a rapid decrease in length to width ratio of the trials over time until approximately trial 10 where length to width ratios are approximately constant. Then at trial 23 a break in length to width ratios exist where the ratio increases initially and then decreases linearly until the end of the experiment.
4.3 Cross-Section Data: Modified Compensation Index, Longitudinal Slope and Margin Slope

32 cross-sections were mapped from the experimental debris-flow fan. The first six cross-sections were taken at 1 cm intervals, and after that they were taken at 3 cm intervals. The cross-sections were taken from the toe of the debris-flow fan to the apex of the fan. Data collected from these cross-sections included longitudinal slope of the central axis, margin slopes of deposits within a particular cross-section (cross-section 22), and the modified compensation index for each cross-section.

4.3.a Cross-Sections:

All 32 cross-sections are located in appendix F. Only a few representative cross-sections will be discussed in this results section. Figure 4.12 shows the locations of the cross-
sections mapped. Cross-sections used are a result of stitching multiple photos of the cross-section using the program Microsoft ICE.

Figure 4.12. Diagram showing locations of cross-sections mapped of debris-flow fan. The grid present is 1 cm by 1 cm. The red lines on the grid indicate 10 cm intervals.
**Toe of the Debris-Flow Fan:**

Cross-section 7 (Fig. 4.13) and cross-section 10 (Fig. 4.14) demonstrate representative behaviors at the toe of the debris-flow fan. From these cross-sections, one can see that deposits appear to stack in a compensational manner, and aggrade on top of each other as well.

![Image of cross-section 7](image1.png)

**Figure 4.13.** Image of cross-section 7. Tops of deposits are outlined according to color of dye used in trial run. This cross-section contains trials 2, 7, 18, 19, 20 and 21.

![Image of cross-section 10](image2.png)

**Figure 4.14.** Image of cross-section 10. Tops of deposits are outlined according to color of dye used in trial run. This cross-section contains trials 2, 3, 6, 7, 9, 12, 13, 15, 16, 17, 18, 19, 20, 21, 23 and 26.

**Middle of the Debris-Flow Fan:**

Cross-section 18 (Fig. 4.15) is representative of behavior in the middle of the debris-flow fan. Cross-sections in the middle of fan show deposits that aggrade on top of each other, with minimal compensational stacking within the individual deposits or at the bed scale. However, when looking at the central axes of the beds, one can see that there are distinct changes in this central axis, indicating several sedimentary packages that can represent the element scale.
These elements appear to be more compensational than the bed scale. Also, deposits appear to be thicker at their flanks compared to the apexes of each deposit.

Figure 4.15. Image of cross-section 18. Tops of deposits are outlined according to color of dye used in trial run. This cross-section contains trials 2, 3, 4, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30 and 31.

Apex of the Debris-Flow Fan:

Cross-section 32 (Fig. 4.16) is representative of behavior near the apex of the debris-flow fan. This cross-section shows that the sedimentary packages seen in the middle of the fan begin to amalgamate into one individual package, with central axes aligning. Also, there is a greater accentuation of the thickening of the flanks of the deposits compared to the apexes. Also, slopes on the margin of the later trials are much steeper compared to the toe and middle of the fan.

Figure 4.16 Image of cross-section 32. Tops of deposits are outlined according to color of dye used in trial run. This cross-section contains all trials of the experiment.
4.3.b Modified Compensation Index:

To calculate the modified compensation index ($K_{CV}$), the deposits were outlined using CANVASX 16 to export coordinate data for each deposit in a particular cross-section. This coordinate data was used to calculate the modified compensation index ($K_{CV}$) for each cross-section. This index number was calculated using a Matlab program which calculates the coefficients of variations (CV) for each deposit and mean interval thickness. These CV and mean interval thicknesses are plotted against each other for each deposit in a particular cross-section (appendix G). The points are assumed to fit a power law trend discussed in section 2.4, and a trend line is fitted to the data. The slope of this line represents the modified compensation index for that particular cross-section (appendix G). The modified compensation index was calculated for the bed scale (i.e. for individual trials) and the elements scale (i.e. packages of deposits that appear to exhibit common behavior). The elements or sedimentary packages were chosen based on qualitative distinction, where it appeared that certain trials followed similar avulsion or aggradational behavior. Also the central axes of deposits in these larger units appeared to align, and the axis of the larger unit as whole was not superimposed on top of the next distinct element, which indicates different flow direction compared to the next element, justifying the choice of particular deposits to represent a particular element. The elements chosen were element 1 consisting of trials 2 through 12; element 2, consisting of trials 13 through 22; element 3, consisting of trials 23 through 28; and element 4, consisting of trials 29-31 (Fig. 4.21, Fig. 4.22). It should be noted that the element scale of classification began to be discernible at approximately cross-section 10. Also, it was observed that a flank morphology developed during building of the debris-flow fan, and that this flank may exhibit a forcing effect on compensational behavior, so the compensational index of the flank morphology was calculated independently of the rest of the cross-section to analyze this assumption (appendix G). The flank morphology persisted in cross-section 23 through cross-section 27. The modified compensation index for the beds, elements, and flank morphology are listed in table 4.1.
One can see from the plots of CV against mean interval thickness that the power law trend lines used to calculate the modified compensation index fit poorly to the data (Fig. 4.17-Fig.4.20). Also, between cross-section 13 and cross-section 15 (Fig.4.18, Fig. 4.19), distinct populations of data begin to develop indicated by breaks in the data points. These distinct populations remain persistent in the data until about cross-section 29 or cross-section 30, where the data converges into one population (Fig. 4.20).

Figure 4.23 depicts the modified compensation index compared to longitudinal distance from the apex of the fan for the bed and element scale. The modified compensation index is greater for the elements compared to the beds. The bed scale appears to follow an exponential trend, where the modified compensation index increases exponentially as one moves farther from the apex. There also appears to be cyclical sharp increases in the modified compensation index along the entire longitudinal length of the fan. Figure 4.24 depicts the modified compensation index for the flank morphology compared to longitudinal distance from the apex of the fan. The flank morphology was a portion of the fan on the left-hand side that appeared to develop separately from the rest of the fan structure. The modified compensation index for this section was calculated by establishing a discreet base depositional surface only for this morphology. The rest of the fan structure was essentially neglected and depositional surfaces of trials were only delineated for this portion of the fan. The modified compensation index results for the flank morphology appear to change at random along the longitudinal length of the fan.
Figure 4.17. Graphs plotting mean interval thickness against CV for cross-section 7 and cross-section 10.
Figure 4.18. Graphs plotting mean interval thickness against CV for cross-section 12 and cross-section 15.
Figure 4.19. Graphs plotting mean interval thickness against CV for cross-section 20 and cross-section 22.
Figure 4.20. Graphs plotting mean interval thickness against CV for cross-section 32.

Figure 4.21. Image illustrating the elements used for calculation of the modified compensation index at the elements scale. Element 1 is red, Element 2 is blue, Element 3 is purple and Element 4 is dark grey. This is an image of cross-section 12.

Figure 4.22. Image illustrating the elements used for calculation of the modified compensation index at the elements scale. Element 1 is red, Elements 2 is blue, Element 3 is purple and Element 4 is dark grey. This is an image of cross-section 16.
Table 4.1: Modified compensation index results for beds, elements, and flank morphology. $R^2$ (log) statistic indicates how well power law trend line fits the data, where 0.0 is a poor fit and 1.0 is a good fit to the trend line.

<table>
<thead>
<tr>
<th>Cross-Section No.</th>
<th>Distance from Apex (cm)</th>
<th>$K_{CV}$ Beds</th>
<th>$R^2$ (log)</th>
<th>$K_{CV}$ Elements</th>
<th>$R^2$ (log)</th>
<th>$K_{CV}$ Flank</th>
<th>$R^2$ (log)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>83</td>
<td>1.68</td>
<td>0.71</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2</td>
<td>82</td>
<td>1.62</td>
<td>0.71</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>3</td>
<td>81</td>
<td>1.62</td>
<td>0.71</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>4</td>
<td>80</td>
<td>1.56</td>
<td>0.71</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>5</td>
<td>79</td>
<td>1.55</td>
<td>0.71</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>6</td>
<td>78</td>
<td>0.979</td>
<td>0.78</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>7</td>
<td>76</td>
<td>0.655</td>
<td>0.66</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>8</td>
<td>73</td>
<td>0.550</td>
<td>0.52</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>9</td>
<td>70</td>
<td>0.396</td>
<td>0.35</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>10</td>
<td>67</td>
<td>0.562</td>
<td>0.39</td>
<td>0.517</td>
<td>0.70</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>11</td>
<td>64</td>
<td>0.295</td>
<td>0.29</td>
<td>0.252</td>
<td>0.44</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>12</td>
<td>61</td>
<td>0.289</td>
<td>0.30</td>
<td>0.543</td>
<td>0.84</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>13</td>
<td>58</td>
<td>0.299</td>
<td>0.33</td>
<td>0.633</td>
<td>0.96</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>14</td>
<td>55</td>
<td>0.341</td>
<td>0.38</td>
<td>0.579</td>
<td>0.95</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>15</td>
<td>52</td>
<td>0.450</td>
<td>0.46</td>
<td>0.474</td>
<td>0.91</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>16</td>
<td>49</td>
<td>0.259</td>
<td>0.32</td>
<td>0.483</td>
<td>0.87</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>17</td>
<td>46</td>
<td>0.205</td>
<td>0.27</td>
<td>0.557</td>
<td>0.78</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>18</td>
<td>43</td>
<td>0.185</td>
<td>0.25</td>
<td>0.565</td>
<td>0.72</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>19</td>
<td>40</td>
<td>0.239</td>
<td>0.31</td>
<td>0.530</td>
<td>0.71</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>20</td>
<td>37</td>
<td>0.280</td>
<td>0.35</td>
<td>0.609</td>
<td>0.64</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>21</td>
<td>34</td>
<td>0.259</td>
<td>0.33</td>
<td>0.369</td>
<td>0.58</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>
Table 4.1 Continued

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>31</td>
<td>0.241</td>
<td>0.33</td>
<td>0.338</td>
<td>0.49</td>
<td>N/A</td>
</tr>
<tr>
<td>23</td>
<td>28</td>
<td>0.231</td>
<td>0.32</td>
<td>0.321</td>
<td>0.45</td>
<td>0.498</td>
</tr>
<tr>
<td>24</td>
<td>25</td>
<td>0.233</td>
<td>0.33</td>
<td>0.300</td>
<td>0.40</td>
<td>0.147</td>
</tr>
<tr>
<td>25</td>
<td>22</td>
<td>0.184</td>
<td>0.27</td>
<td>0.269</td>
<td>0.40</td>
<td>0.100</td>
</tr>
<tr>
<td>26</td>
<td>19</td>
<td>0.163</td>
<td>0.26</td>
<td>0.364</td>
<td>0.55</td>
<td>0.283</td>
</tr>
<tr>
<td>27</td>
<td>16</td>
<td>0.203</td>
<td>0.31</td>
<td>0.480</td>
<td>0.64</td>
<td>0.107</td>
</tr>
<tr>
<td>28</td>
<td>13</td>
<td>0.255</td>
<td>0.37</td>
<td>0.495</td>
<td>0.61</td>
<td>N/A</td>
</tr>
<tr>
<td>29</td>
<td>10</td>
<td>0.220</td>
<td>0.33</td>
<td>0.483</td>
<td>0.62</td>
<td>N/A</td>
</tr>
<tr>
<td>30</td>
<td>7</td>
<td>0.161</td>
<td>0.25</td>
<td>0.367</td>
<td>0.65</td>
<td>N/A</td>
</tr>
<tr>
<td>31</td>
<td>4</td>
<td>0.121</td>
<td>0.17</td>
<td>0.200</td>
<td>0.47</td>
<td>N/A</td>
</tr>
<tr>
<td>32</td>
<td>1</td>
<td>0.0823</td>
<td>0.13</td>
<td>0.138</td>
<td>0.35</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Figure 4.23. Graph of modified compensation index plotted against longitudinal distance from apex. Includes data for the beds and elements scale. Power trend line applied to elements scale, and exponential trend line applied to beds scale based on R² values that represent best fit.
Figure 4.24. Graph plotting modified compensation index of flank morphologies against longitudinal distance from apex.

4.3.c Longitudinal Slope of the Central Axis:

A central axis was established for the entire experimental debris-flow fan (Fig. 4.25). This central axis was established based upon an imaginary extended centerline of the channel. This axis was assumed to be fixed so that data collected from this central axis were consistent and could be used for establishing comparative trends during analysis of the data. The longitudinal slopes calculated are referenced to this central axis.

Figure 4.25 is the longitudinal profile for the experimental debris-flow fan along the central axis for each trial. As can be seen from this profile, the slopes of the deposits are shallow throughout the middle of the fan, longitudinally, and steepen greatly near the toe. The slope near the apex of the fan becomes steep beginning at trial 28. The upper and lower deposits appear to be thicker compared to the deposits in the mid-height of the fan.
Appendix H contains tables of longitudinal slopes of the trials for each cross-section and tables of longitudinal slopes categorized by distance from the apex. This slope is the slope of the top of the depositional surface of a particular trial. These slope are calculated for discreet locations and do not represent overall slope for the trial’s depositional surface. They can be thought of as distinct, incremental slope vectors.

Figure 4.26 plots the average longitudinal slope against the longitudinal distance from the apex. A polynomial trend line indicates slight periodicity in the data, and the linear trend line indicates that within this periodicity there is a general increase in average longitudinal slope as one moves farther from the apex. Figure 4.27 shows that the average longitudinal slope of each trial exhibits a gradual linear increase as the experimented progressed.

4.3.d Margin Slopes of Cross-Section 22:

The slopes of the margins of the deposits in cross-section 22 were measured. Cross-section 22 was chosen because it contained all of the trials, was located in the middle of the fan, so that deposition was well established, and because the graph used to calculate the modified compensation index appeared to exhibit a data set that contained several different populations that could be analyzed during analysis. These were measured to evaluate whether trends exist between margin slope and compensational behavior. This analysis will be discussed in the analysis section. The margin slopes were calculated by assuming that the deposits exhibit a triangular or trapezoidal simple geometry. A line was fitted to the deposit on either side of the apex of that deposit to estimate an average margin slope for the right side and left side of the deposit. Appendix I contains a table listing these margin slopes. Appendix J contains a diagram that depicts the lines used to approximate average margin slopes for the deposits.
Figure 4.25. Longitudinal profile of the constructed experimental debris-flow fan. Longitudinal profile is located along a fixed central axis which extends from the center of the exit of the channel. Colors in the longitudinal profile are correlated to the color dye used in that particular trial. Longitudinal profile constructed from cross-section data.
Figure 4.26. Graph plotting the average longitudinal slope derived from the longitudinal profile against longitudinal distance from apex.

\[ y = 0.242x - 0.131 \]
\[ R^2 = 0.5864 \]

\[ y = -0.0003x^3 + 0.0308x^2 - 0.642x + 4.7547 \]
\[ R^2 = 0.7127 \]

Figure 4.27 Graph plotting the average longitudinal slope for the entire surface of the trial from channel to the toe of the deposits.
Figure 4.28 shows how the margin slopes of the trials on the left and right side of the central axis varied as the experiment progressed. In the beginning of the experiment, the left and right slopes increased at an approximately linear trend, and remained similar in value. This trend existed until trial 15. At this point the left margin slopes continued to increase linearly, and the right margin slopes began to decrease, and remain constant until trial 28, where the linear increase in slope resumed. It should be noted that the left margin slopes experienced a marked decrease at trial 22, but after this trial the linear increase resumed. Also, at trial 15, the left margin slope starts to become far greater in value compared to the right margin slope.

![Margin Slopes of Cross-Section 22](image)

Figure 4.28. Graph plotting the margin slopes of each trial against trial number. Since these are episodic events, the trial number is representative of development of margin slopes through time.
CHAPTER 5: ANALYSIS

This section evaluates the data collected in the results sections. Analyses include assessing migration and lateral movement of deposits, correlation analysis of various parameters, analysis of the margin slopes in cross-section 22 in relation to the modified compensation index, and correlation analysis of time series data collected.

5.1 Assessing the change in lateral movement of experimental debris flows:

It was observed that during development of the experimental fan, the debris flows did not always avulse rapidly, but rather incrementally migrated laterally with successive runs. Based upon the modified compensation index results for the cross-sections trending to aggradational behavior quickly as one moves towards the apex, it is believed that the modified compensation index may not be robust enough to quantitatively assess this trend of gradual migration, so a net migration parameter was developed. This metric establishes a fixed central axis that extends down centerline of the exit of the channel. Next, the lateral extent of material of a particular trial is measured on either side of the fixed central axis at discreet points down the central axis. Measurements taken to the left of the central axis were assigned a negative value and measurements taken to the right of the central axis were assigned a positive value. These two values were added together at each discreet point down the central axis for each deposit to get a net migration value. This net migration value indicates whether a greater extent of material was either on the left or right side of the central axis, where by a negative value shows that a greater extent of material was left of the central axis, and a positive number indicates that a greater extent of material was to the right of the central axis. This net migration metric can be thought of as tracking mass of a particular trial in a two-dimensional view. These net migration values at discreet distances down the central axis for each trial were then averaged for each trial to get an average net migration value for each trial in the experiment. This average net
migration value indicates whether a particular trial’s mass was predominantly on the right or left side of the central axis, indicating extent of lateral migration of that particular trial.

Figure 5.1 through figure 5.4 depicts the net migration of each trial within the experiment. All of the plots in figure 5.1 through 5.4 have the same axis intervals to show how magnitude of migration changes over time. One can see that the first trial of the experiment exhibited almost no migration, which is good because this means that the model setup was not influencing migration to a great degree. One can also see that the greatest migration occurred farthest from the fan apex. Starting at trial 13 or trial 14 migration appeared in the middle portion of the fan as well as the toe. Migration starting at these trials appears to increase relatively linearly towards the right side along the middle portion of the fan, and at the toe begins to migrate slightly back to the left portion of the fan. Starting at trial 22 migration of material heavily favors the right side of the fan until about trial 26 where migration becomes relatively constant, indicating no preferential lateral movement. At trial 27, a shift occurs where the trial migrates back towards the centerline of the fan, and starting at trial 29, trials begin to exhibit a migrational behavior where a sinusoidal pattern is exhibited as one moves longitudinally down fan, indicating that trials are depositing mass on both sides of the centerline of the fan. Figure 5.5 depicts the average net migration of each trial plotted against time, which in this case is each successive trial. This figure shows a sinusoidal amplification of migration away from the central axis of the fan as the development of the fan moves through time. Figure 5.6 shows that the magnitude of average net migration follows an exponential trend with longitudinal distance from the apex, whereby migration increases dramatically as one moves towards the toe of the fan structure.
Figure 5.1. Graphs showing net migration of each trial as a function of longitudinal distance from apex. A positive net migration value indicates a greater portion of mass to the right of the central axis, and a negative value indicates a greater portion of mass to the left of the central axis.
Figure 5.2. A continuation of figure 5.1 of graphs showing net migration of each trial as a function of longitudinal distance from apex. A positive net migration value indicates a greater portion of mass to the right of the central axis, and a negative value indicates a greater portion of mass to the left of the central axis.
Figure 5.3. A continuation of figure 5.1 and figure 5.2 of graphs showing net migration of each trial as a function of longitudinal distance from apex. A positive net migration value indicates a greater portion of mass to the right of the central axis, and a negative value indicates a greater portion of mass to the left of the central axis.
Figure 5.4. A continuation of figure 5.1 through figure 5.3 of graphs showing net migration of each trial as a function of longitudinal distance from apex. A positive net migration value indicates a greater portion of mass to the right of the central axis, and a negative value indicates a greater portion of mass to the left of the central axis.
Figure 5.5. Average migration plotted against trial number, polynomial trend line shows periodicity in migration of mass of trials through time. Also, there is apparent amplification of migration through time. Overall this graph shows that sinusoidal amplification of migration of mass exists in the experiments as the experimental debris fan experiences more debris-flow events over time.

Figure 5.6. Magnitude of average migration plotted against longitudinal distance from apex. Trend line indicates an exponential increase in migration as the debris-flow event moves from apex to toe. This is similar to the relationship exhibited between Kcv and longitudinal distance from apex. Both theses indices exhibit this increasing exponential trend as one moves farther from the apex.
5.2 Correlation Analyses:

Various parameters measured from the video, photo and cross-section data were plotted against each other and various types of trend lines fitted to the data to assess whether or not correlations existed between various parameters. These possible correlations could help predict avulsion and migration tendencies of debris flows within a debris-flow fan structure.

Many of the comparisons yielded no correlations. The graphs showing these correlation attempts are in appendix K. The following comparisons exhibited no corollary trends:

- Run-out length versus length to width ratios
- Run-out length versus frontal velocity
- Frontal velocity versus length to width ratios
- Average net migration versus run-out length
- Average net migration versus length to width ratio
- Average net migration versus frontal velocity
- Average net migration versus length to width ratio of previous deposition
- Average net migration versus previous deposit’s run-out length
- Standard deviation of net migration versus modified compensation index
- Standard deviation of longitudinal slope versus modified compensation index
- Ratio of margin slope to longitudinal slope versus net migration
- Modified compensation index versus longitudinal slope

Figure 5.7 shows a moderately strong correlation between the modified compensation index and the average net migration. Both linear and power law trend lines show a positive strong correlation between the two indices, with $R^2$ values of these trend lines between 0.76 and 0.77. This correlation means that the average net migration parameter could possibly be used as an analog to the modified compensation index, if the modified compensation index does not appear to be robust enough to represent flow directions and alteration of flow direction.
of a debris-flow event. Also, the modified compensation index can only be categorized by
distance since it evaluates an entire cross-section, then the average net migration could allow
for categorizing the modified compensation index with respect to the number of events rather
than the distance from apex. It should be noted that some of the modified compensation index
values are above 1. This occurs because these cross-sections had very few deposits, which
causes the modified compensation index equation to breakdown and give results that are
greater than one. These cross-sections are entirely compensational.

Figure 5.7. Graph plotting the average net migration at a particular longitudinal distance from
apex against the modified compensation index at that distance.

Figure 5.8 shows a moderate positive correlation between average longitudinal slopes at
a particular longitudinal distance compared to the average net migration at that distance. The

78
exponential and linear trend lines show a moderate positive correlation between these two parameters with $R^2$ value ranging from approximately 0.58 to 0.64. This could mean that an increase in longitudinal slope could cause an increase in net migration.

Figure 5.8. Graph plotting average longitudinal slope at a particular distance from apex against average net migration at that distance.

### 5.3 Analysis of Cross-Section 22: Attempt to correlate compensation to height and slope

For cross-section 22, the margin slopes, longitudinal slopes and compensation of each trial involved in the cross-section were evaluated to attempt to correlate compensation tendencies with height and slope to use as an analog for the rest of the fan structure. Cross-section 22 was chosen because it was in the middle of the fan, indicating that it was a well-developed cross-section that could possibly display evolutionary traits of the fan structure. Also, it contained all trials present in the experiment and the graph plotting CV against mean interval
thickness appeared to have distinct populations in the data set (Fig. 5.9). These different populations of data in the CV-mean thickness plot were attempted to be deciphered by removing subsequent trials from the cross-section, and replotting the CV-mean interval graph. This was performed systematically until all trials were removed, then these individual plots were overlaid on top of the original plot and marked in various colors to indicate which data points corresponded to which set of trials. This allows for the comparison of compensation of each trial to the margin slopes and longitudinal slopes of the trial at the cross-section.

One can see from figure 5.9 that if one was to apply a power law trend line to this graph it would change as the trials progress. At first, this trend line would appear to have a steeper slope than compared to the later trials associated with the graph. This steeper slope would relate to a higher modified compensation index number and therefore a greater propensity to exhibit compensational behavior. As trials progress, as seen in this graph, the slope shallows indicating that later trials appear to be less compensational. The graph in the lower right corner shows margin slopes increasing in a polynomial trend as the trials progress. One could deduce that this increase in margin slope causes the decrease in compensational behavior in the lower left graph as trials progress. This shows that compensation actually decreases with increased height of the cross-section, because for the most part successive trials stacked on top of each other increase the height of the cross-section, and the slope of the power law trend line would decrease. Also, if one were to view the successive trials as progression through time, one could deduce that the compensational tendency of this cross-section decreases over time according to these graphs.
Figure 5.9. Illustration showing original graph used in calculating modified compensation index, graph used to calculate modified compensation index dividing data amongst trial intervals, graph used to calculate modified compensation index dividing data amongst groups showing evolution of graph through time through the classification of early trials and late trials, and graph plotting average margin slope against trial number for cross-section 22. The light brown dots of the graph in the lower left corner signify early trials, and dark brown signify later trials. An enlarged version of the graph in the lower left corner is presented in figure 5.10, so that the variation in hues of brown are more discernible.
Figure 5.10. Enlarged version of graph plotting mean interval thickness against CV categorized by progression from early trials to later trials.
Figure 5.11 shows how the ratio of the left margin slope to the right margin slope of the trials varies through time. This ratio decreases until trial 10 and linearly increases until trial 26 and then decreases again. The data best fit a fourth order polynomial trend, which could indicate periodicity in the trend because polynomial trends can approximate sine and cosine curves.

Figure 5.11. Graph plotting the ratio of the margin slopes of the right and left sides of the deposits in cross-section 22 against the trial number. This ratio is the left margin slope in degrees divided by the right margin slope in degrees to provide a unitless number which provides an indication of which margin slope is greater at a particular cross-section locality.

Figure 5.12 shows how longitudinal slopes changed as subsequent trials were performed. This plot shows that the longitudinal slope exhibited periodicity whereby it increased and decreased repetitively until trial 18. At this point some threshold must have been met, and the longitudinal slopes increased in a fairly linear pattern until the end of the experiment.
Figure 5.12. Graph plotting longitudinal slopes at the discreet location of cross-section 22 through time.

Figure 5.13 shows how the ratio of the longitudinal slope to the average margin slope of deposits changed through time. One can see that there is no clear trend between this ratio and progression of trials. This relationship was explored because it was hypothesized that the relationship between these two types of slopes might affect compensation and net migration. It was thought that larger ratios may lead to greater compensation and migration, because this would allow for the fluid to flow farther down fan, and create a greater chance for compensation to occur. This was based on the previously observed relationship between longitudinal distance from the apex and net migration and the modified compensation index shown in figures 5.6 and 4.23, respectively.
5.4 Time Series Data Analysis:

When evaluating the results of this experiment it was observed that some of the data exhibited time series trends if the progression of trial numbers was thought of as progression through time. A time series is a sequence of measurements that follow non-random orders, and analysis of this type of data is based upon the assumption that successive values in the data represent consecutive measurements taken at equally spaced intervals of time. With time series data analysis the goal is to identify the nature of the phenomena and also forecast the data into future time intervals. Time series are described using the terms “trend” and “seasonality.” Trend refers to the general increase or decrease in the data, and seasonality refers to the repetition of systematic intervals over time. Parameters that appeared to experience time series trends were: average net migration, run-out length, frontal velocity, longitudinal and margin slope of cross-section 22, average longitudinal slope of trial numbers, length to width ratios of trial numbers,
and ratio of right margin slopes to left margin slopes of cross-section 22. Autocorrelation and partial autocorrelation were calculated for some of these parameters to see if seasonality truly existed in the data. Also, cross correlations were conducted between these various time series trends and the time series trend of net average migration, to identify which parameters may affect the migration of mass of the experimental debris flows through time.

In the next few paragraphs, these analysis techniques will be described in minor detail to give a better understanding of what these analyses are conveying about the data.

Cross correlation is useful in determining if one set of time series data leads to or precedes another set of time series data. It is the measure of the similarity of two time series as a function of the lag of one relative to the other. It is a standard method for evaluating the degree to which two series are correlated. If the peak of a cross correlation function is at lag 0, then correlation does not exist between the two series. If the peak of a cross correlation function is at some lag, then a potential correlation exists between the series whereby one series is preceded by the other.

Autocorrelation and partial autocorrelation analyze whether or not a series exhibits seasonality. Autocorrelation calculates the autocorrelation function (ACF), which looks at a correlation between the series and a lagged version of the same series. If this correlation is high, then periodicity or seasonality is likely in the time series. This seasonality is evaluated graphically using an autocorrelogram, which displays the ACF at consecutive lag intervals. Along with autocorrelation analysis, a t statistic and LBQ statistic is calculated. The t statistic looks at whether or not the lag between the series and the lagged version of itself is zero. Typically it is assumed that if the absolute value of the t statistic is greater than 1.25 for lag intervals 1 through 3 or greater than 2 for lag intervals 4 and beyond, then the lag is not equal to zero. The LBQ statistic looks at whether or not the observations are random and independent over time. If the observations are not independent, then one observation in the series may be
correlated with another observation in the series at a specific time units later. In other words, if the observations are not independent but are dependent, then autocorrelation likely exist within the series, and therefore seasonality is exhibited in the series. If the LBQ is greater than some critical value, then autocorrelation may exist in the data.

Partial autocorrelation is also used to measure whether observations in a series are dependent or independent, and is an extension of autocorrelation where dependence on the intermediate elements, or those within a particular lag, are removed. All of the autocorrelations within a lag are cancelled out. This provides a more evident conveyance of dependence in a series for individual lags. It should be noted that if a lag of 1 has the greatest peak in a partial autocorrelogram, then a first order autoregressive process exists within the time series. An autoregressive process is a process where past values have an effect on current values. If a process is a first order process, then the current value or observation is based on the immediately preceding value or observation. Both autocorrelation and partial autocorrelation are used in the development of autoregressive integrated moving average (ARIMA) models, which are used for forecasting time series data, and will be discussed further later in this section.

Cross-correlation, autocorrelation, and partial autocorrelation analyses:

Table 5.1 shows the summarized results of the cross-correlation analyses. Appendix L contains the cross-correlograms pertinent to the analysis. It should be noted that these correlations are in regards to time.

One interesting finding from the cross-correlation analyses is that the right margin slopes may have had a greater impact on propagation of debris flows compared to the left margin slopes of the fan surface through time. This was surmised from the fact that the lag peak of the cross-correlogram of the right margin slope was much greater than the peak of the left margin
slope’s cross-correlogram. Another interesting finding was that the increase of average margin slope and increase in longitudinal slope were independent of each other.

Table 5.1: Table summarizing cross-correlogram results. The strength of correlation is a qualitative assessment based on the difference in the peak lag compared to the other lags in the cross-correlogram.

<table>
<thead>
<tr>
<th>Cross-Correlation Comparison</th>
<th>Peak Cross-Correlation Function Lag</th>
<th>Parameters Cross-Correlated?</th>
<th>Strength of Correlation</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Margin Slopes of Cross-Section 22 and Average Longitudinal Slopes of Trials</td>
<td>0</td>
<td>No</td>
<td>N/A</td>
<td>None</td>
</tr>
<tr>
<td>Left Margin Slopes and Right Margin Slope of Cross-Section 22</td>
<td>0</td>
<td>No</td>
<td>N/A</td>
<td>None</td>
</tr>
<tr>
<td>Average Net Migration and Ratio of Margin Slopes of Cross-Section 22</td>
<td>4 and 6</td>
<td>Yes</td>
<td>Strong</td>
<td>Ratio of margin slopes impacts migration of flows through time.</td>
</tr>
<tr>
<td>Average Net Migration and Average Margin Slopes of Cross-Section 22</td>
<td>8</td>
<td>Yes</td>
<td>Weak</td>
<td>Peak is similar to values of other lags.</td>
</tr>
<tr>
<td>Average Net Migration and Average Longitudinal Slope of Trials</td>
<td>-2</td>
<td>Yes</td>
<td>Weak</td>
<td>None</td>
</tr>
<tr>
<td>Average Net Migration and Left Margin Slopes of Cross-Section 22</td>
<td>4 and 6</td>
<td>Yes</td>
<td>Moderate</td>
<td>Left margin slope has impact on migration of flows through time.</td>
</tr>
<tr>
<td>Average Net Migration and Right Margin Slopes of Cross-Section 22</td>
<td>-5</td>
<td>Yes</td>
<td>Strong</td>
<td>Right margin slope has impact on migration of flows through time.</td>
</tr>
</tbody>
</table>
Table 5.1 Continued

<table>
<thead>
<tr>
<th>Average Net Migration and Run-Out Lengths of Trials</th>
<th>-2 and 9</th>
<th>Yes</th>
<th>Strong</th>
<th>Run-out lengths affect migration of flows through time. Has both a positive correlation and negative correlation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Net Migration and Length to Width Ratios of Trials</td>
<td>-5</td>
<td>Yes</td>
<td>Moderate</td>
<td>Length to width ratios affect migration of flows through time.</td>
</tr>
<tr>
<td>Average Net Migration and Frontal Velocity</td>
<td>-1 and 2</td>
<td>Yes</td>
<td>Weak</td>
<td>Peak lags are similar to value as lag 0.</td>
</tr>
<tr>
<td>Average Margin Slopes of Cross-Section 22 and Discreet Longitudinal Slopes of Trials in Cross-Section 22</td>
<td>0</td>
<td>No</td>
<td>N/A</td>
<td>Each type of slopes develop independently through time.</td>
</tr>
</tbody>
</table>

Table 5.2 shows the results and summary of the autocorrelation and partial autocorrelation analyses. Appendix M contains the autocorrelograms, partial autocorrelograms and tables of t-statistics for the analyses. The red lines and curves on the correlograms indicate 95 percent confidence intervals, whereby if an autocorrelation function or partial autocorrelation function at a particular lag extends beyond these thresholds, then the function value indicates statistically significant seasonality for the data at that particular lag. Also, a partial autocorrelation having a statistically significant peak at lag 1 indicates that the parameter exhibits first order autoregressive processes.

An interesting discrepancy arises in the autocorrelation and partial autocorrelation of the frontal velocity. The correlograms for frontal velocity show statistically insignificant seasonality for all lags, but the t-statistics for the partial autocorrelation and autocorrelation contradict this finding since the t-statistic is greater than 1.25 for lag 1 and lag 3.
Table 5.2: Table summarizing results of autocorrelation and partial autocorrelation analyses.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Does a Lag Exceed 95% Confidence Limits?</th>
<th>If yes, Which Lag?</th>
<th>t-statistic for Lag Exceeding 95% Confidence</th>
<th>Autoregressive Behavior/Seasonality?</th>
<th>Parameter</th>
<th>Does a Lag Exceed 95% Confidence Limits?</th>
<th>If yes, Which Lag?</th>
<th>t-statistic for Lag Exceeding 95% Confidence</th>
<th>If Autoregressive Behavior, What is Order?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Net Migration</td>
<td>Yes</td>
<td>1 and 2</td>
<td>4.29 and 2.68, respectively</td>
<td>Yes</td>
<td>Average Net Migration</td>
<td>Yes</td>
<td>1</td>
<td>4.29</td>
<td>1st Order</td>
</tr>
<tr>
<td>Run-Out Length</td>
<td>No</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>Run-Out Length</td>
<td>No</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Frontal Velocity</td>
<td>No</td>
<td>N/A</td>
<td>N/A</td>
<td>No</td>
<td>Frontal Velocity</td>
<td>No</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Length to Width Ratio of Deposits</td>
<td>Yes</td>
<td>1</td>
<td>2.78</td>
<td>Yes</td>
<td>Length to Width Ratio of Deposits</td>
<td>Yes</td>
<td>1</td>
<td>2.78</td>
<td>1st Order</td>
</tr>
</tbody>
</table>
Autoregressive integrated moving average (ARIMA) model for average net migration of debris flows across experimental debris-flow fan:

An autoregressive integrated moving average (ARIMA) model was produced for the average net migration of the trials in the experiment to produce a forecast model for the experiment. This was done so that future experiments could possibly be validated by these forecasts. An ARIMA model is a time series forecasting model that includes autoregressive and moving average parameters. This model uses correlation techniques. Appendix N contains a brief discussion on ARIMA modelling in regards to details, fitting the model and evaluating the model.

It should be noted that it is recommended that input data contain at least 50 observations. Since the data set of this experiment only contains 30 trials, this criterion is not met, but ARIMA was performed to get a rough understanding of the time series behavior of the average net migration of the trials.

ARIMA Model Results:

Based upon the correlograms for the autocorrelation (ACF) and partial autocorrelation (PACF) functions for the average net migration in appendix M, a first order autoregressive process is present within the data. Also, this indicates seasonality and is verified by figure 5.5, which shows an apparent periodic trend for the average migration of trials. The period, or time intervals required for the cycle to repeat itself, appeared to be between 19 and 21. Based on the seasonality and autoregressive nature of average net migration, a seasonal model was fit to the ARIMA model and was differenced at a lag of 1 to accommodate for the seasonality. The PACF decayed quickly with an exponential decay and a statistically significant lag at lag 1, while the ACF appeared to decay at an intermediate rate between exponential and linear, and had statistically significant lags at lag 1 and lag 2. Based on these observations it appeared that average net migration could possibly fit rule 1, rule 4 or rule 5 listed in appendix N, so an iterative approach was taken where each of these were applied. In summary, ARIMA models
with a seasonal difference of 1 were attempted with: 1 autoregressive (AR) parameter and zero moving average (MA) parameters, 1 AR parameter and 1 MA parameter, and zero AR parameters and 2 MA parameters. Even though it was observed that the period of the seasonality existed somewhere between 19 and 21 time units, different periods were attempted to evaluate how picking the wrong period could affect the results of an ARIMA model. Table 5.3 summarizes the findings of this iterative approach to picking an appropriate ARIMA model for the data. Based on table 5.3, one can see that the two most appropriate ARIMA models were the ARIMA model with a period of 19, containing 1 AR parameter and 1 moving average parameter (Fig. 5.14), and the ARIMA model with a period of 21 containing 1 AR parameter and 1 MA parameter (Fig. 5.18). Both of these had p-values less than the desired alpha value of 0.05 for the AR parameter and MA parameter, meaning that these parameters are statistically significant. Also, the forecasts including the 95% confidence interval forecasts were close to each other and appeared to converge, making them adequate forecasting models. However, it should be noted that there was not enough data after the 19 and 21 time intervals to calculate p-values for the residuals. The p-values are calculated because for the model to be adequate the residuals should not be statistically significant and should be close to normally distributed, and should only represent noise in the data having no systematic pattern. Also the ACF and PACF plots of the residuals should not have any lags that are statistically significant. Even though there were no p-values for the residuals, the plots of the residuals (Fig. 5.17, Fig. 5.21) show that they are somewhat normally distributed and there appears to be no systematic order in the plots. Also, the ACF and PACF plot of the residuals for the two models (Fig. 5.15, Fig. 5.16, Fig. 5.19, and Fig. 5.20) showed no statistically significant lags, indicating no autoregressive behavior in the residuals. Based on these findings, the two models appear to be adequate, even though p-values for residuals could not be calculated. Both models exhibited forecasts that contained seasonality, but both exhibited an overall trend where average migration of the future trials would favor migrating and depositing mass on the right side of the fan. This means that
possibly during experimentation some threshold was met that caused the average net migration
to cease its seasonal behavior, and instead preferentially favor one side of the fan surface. This
could indicate another future step in the evolution of a debris-flow dominated alluvial fan.

It is interesting to note, from table 5.3, how choosing the wrong period can cause the
forecasts of the model to diverge indicating an inadequate model, but p-values for the AR
parameter, MA parameter, and residuals can yield statistically significant results that could lead
one to believe these are adequate models.
Table 5.3: Table showing iterative approach to ARIMA modelling of average net migration of trials across the fan surface. P-values and observations highlighted in green indicate that these are values that could make the model adequate, ones highlighted in red indicate values that could make the model inadequate, and values highlighted in orange indicate that judgement would need to be taken with the result.

<table>
<thead>
<tr>
<th>No. of Autoregressive (AR) Parameters</th>
<th>p-value for Significance of AR</th>
<th>No. of Moving Average (MA) Parameters</th>
<th>p-value for significance of MA</th>
<th>Period</th>
<th>No. of Differences</th>
<th>p-value for Significance of Residuals</th>
<th>Qualitative Observation of Forecasts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>9</td>
<td>1</td>
<td>0.000</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.657</td>
<td>9</td>
<td>1</td>
<td>0.000</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.000 0.001</td>
<td>9</td>
<td>1</td>
<td>0.024</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.519</td>
<td>10</td>
<td>1</td>
<td>0.262</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>10</td>
<td>1</td>
<td>0.175</td>
<td>95% confidence forecasts diverge</td>
</tr>
</tbody>
</table>
Table 5.3 Continued

<p>| | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.005</td>
<td>10</td>
<td>1</td>
<td>0.062</td>
<td>95% confidence forecasts diverge slightly</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>11</td>
<td>1</td>
<td>0.034</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.192</td>
<td>11</td>
<td>1</td>
<td>0.018</td>
<td>95% confidence forecasts remain a constant distance apart</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.404</td>
<td>11</td>
<td>1</td>
<td>0.161</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>12</td>
<td>1</td>
<td>0.013</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.000</td>
<td>12</td>
<td>1</td>
<td>0.013</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.614</td>
<td>12</td>
<td>1</td>
<td>0.025</td>
<td>95% confidence forecasts diverge</td>
</tr>
</tbody>
</table>
Table 5.3 Continued

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>13</td>
<td>1</td>
<td>0.075</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.071</td>
<td>13</td>
<td>1</td>
<td>0.121</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.445</td>
<td>13</td>
<td>1</td>
<td>0.203</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>14</td>
<td>1</td>
<td>0.610</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.003</td>
<td>14</td>
<td>1</td>
<td>0.242</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.088</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.835</td>
<td>14</td>
<td>1</td>
<td>0.534</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>15</td>
<td>1</td>
<td>0.204</td>
</tr>
</tbody>
</table>
Table 5.3 Continued

<table>
<thead>
<tr>
<th></th>
<th></th>
<th>0.000</th>
<th></th>
<th>0.669</th>
<th>15</th>
<th>1</th>
<th>0.224</th>
<th>95% confidence forecasts diverge</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td></td>
<td>0.034</td>
<td>15</td>
<td>1</td>
<td>0.115</td>
<td>95% confidence forecasts remain a constant distance apart</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>0.000</td>
<td></td>
<td>N/A</td>
<td>16</td>
<td>1</td>
<td>0.596</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>0.000</td>
<td></td>
<td>0.746</td>
<td>16</td>
<td>1</td>
<td>0.658</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td></td>
<td>0.000</td>
<td>16</td>
<td>1</td>
<td>0.705</td>
<td>95% confidence forecasts remain a constant distance apart</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>0.000</td>
<td></td>
<td>N/A</td>
<td>17</td>
<td>1</td>
<td>0.833</td>
<td>95% confidence forecasts diverge slightly</td>
</tr>
</tbody>
</table>
Table 5.3 Continued

<table>
<thead>
<tr>
<th></th>
<th>0.000</th>
<th>1</th>
<th>0.214</th>
<th>17</th>
<th>1</th>
<th>0.789</th>
<th>95% confidence forecasts diverge</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.163</td>
<td>17</td>
<td>1</td>
<td>0.502</td>
<td>95% confidence forecasts remain a constant distance apart</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>18</td>
<td>1</td>
<td>N/A</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.865</td>
<td>18</td>
<td>1</td>
<td>N/A</td>
<td>95% confidence forecasts diverge</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.005</td>
<td>18</td>
<td>1</td>
<td>N/A</td>
<td>95% confidence forecasts remain a constant distance apart</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>19</td>
<td>1</td>
<td>N/A</td>
<td>95% confidence forecasts diverge</td>
</tr>
</tbody>
</table>
Table 5.3 Continued

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>95% confidence forecasts remain a close constant distance apart, and slightly converge.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.007</td>
<td>1</td>
<td>0.000</td>
<td>19</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.110</td>
<td>19</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.036</td>
<td></td>
<td></td>
<td>95% confidence forecasts diverge slightly</td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>0</td>
<td>N/A</td>
<td>20</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>95% confidence forecasts diverge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.725</td>
<td>20</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>95% confidence forecasts diverge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.048</td>
<td>20</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.044</td>
<td></td>
<td></td>
<td>95% confidence forecasts remain a constant distance apart</td>
</tr>
<tr>
<td>1</td>
<td>0.001</td>
<td>0</td>
<td>N/A</td>
<td>21</td>
<td>1</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>95% confidence forecasts diverge</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5.3 Continued

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>95% confidence forecasts remain a close constant distance apart, and slightly converge.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.000</td>
<td>1</td>
<td>0.016</td>
<td>21</td>
<td>1</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>N/A</td>
<td>2</td>
<td>0.122 0.063</td>
<td>21</td>
<td>1</td>
<td>N/A</td>
<td>95% confidence forecasts remain a constant distance apart</td>
</tr>
</tbody>
</table>
Figure 5.14. Time plot of ARIMA model of average net migration containing a period of 19 and its predicted forecast of future migration. The blue colored data is the original dataset. The red colored data is the ARIMA prediction results. The middle red data are the actual results and the red data above and below are the 95% confidence limits. These confidence limits should be close to the original results and should not diverge from original prediction.
Figure 5.15. ACF plot of residuals for ARIMA model with a period of 19.

Figure 5.16. PACF plot of residuals for ARIMA model with a period of 19.
Figure 5.17. Residual plots for ARIMA model with a period of 19.
Figure 5.18. Time plot of ARIMA model of average net migration containing a period of 21 and its predicted forecast of future migration. The blue colored data is the original dataset. The red colored data is the ARIMA prediction results. The middle red data are the actual results and the red data above and below are the 95% confidence limits. These confidence limits should be close to the original results and should not diverge from original prediction.
Figure 5.19. ACF plot of residuals for ARIMA model with a period of 21.

Figure 5.20. PACF plot of residuals for ARIMA model with a period of 21.
Figure 5.21. Residual plots for ARIMA model with a period of 21.
CHAPTER 6: DISCUSSION

The purpose of this experiment was to achieve a better understanding of the avulsion tendencies and overall modes of propagation of debris-flow events on a debris-flow fan. The next few sub-sections will discuss some of the more important findings of the study.

6.1 Avulsion versus Migration:

Based upon the two parameters used to evaluate flow direction of debris flows (i.e. Kcv and Net Migration), avulsion is not the only mechanism by which debris flows change direction. The Kcv does show avulsion tendencies for the toe portion of the experimental debris-flow fan, but this index number decays exponentially toward zero as one moves towards the apex, indicating anti-compensational regimes. For these anti-compensational sections in the middle and apex of the fan, it was observed through photographic data (Fig. 4.8, Fig.4.9) and video data (appendix B) that significant change in flow direction occurred, but this was not captured by the modified compensation index. However, a “net migration parameter” did pick up on this more subtle change in movement (Fig. 5.1- Fig. 5.4). It showed that debris flows gradually change their flow direction through time, and this change in direction is not necessarily instantaneous. This was also shown in figures 4.23 and 5.6, with an exponential increase of Kcv or net migration, respectively, as one moves from apex to toe. While both of these graphs show exponential increase, the fit of this trend is better for the net migration indicated by its r^2 value of 0.93 and the Kcv fits r^2 value of 0.73. This shows that one should not only be concerned with the rapid avulsion mechanism seen in debris-flow events on fans, but should also pay attention to changes in flow direction caused by gradual migration of successive events. It was also noticed from the video data that the experimental debris-flow fan exhibited long periods of gradual migration, where the events slowly shorten in runout length and gradually move laterally. In between these periods of gradual migration avulsion occurs, causing the flow events to radically change direction. It has also been shown that debris-flow fans may
be a positive feedback system (Fig. 5.5). This phenomena is indicated by the amplification in the wave shape as the fan develops through time. It should be noted that more trials should be executed to see if this cycle continues or dies out.

6.2 Modified Compensation Index:

Looking at figure 4.23, the Kcv at the beds scale increases exponentially as one moves farther from the apex. There also appears to be cyclical increases in the Kcv that occur through longitudinal distance as well. This periodic change could be caused by the cyclical shortening of the run-out lengths of the trials, so where the events involved at that particular distance reaches a minimum threshold run-out length, the subsequent trial avulses over the previous aggraded deposit, and diverts in another direction increasing the Kcv of that cross-section. The Kcv was always higher for the elements compared to the beds except at lengths 64cm and 67 cm, further verifying the conclusion by Straub and Pyles (2012), that Kcv increases with hierarchical scale. There could be inherent differences in how compensation behavior works at these different hierarchical levels due to the different types of trend lines fit to the data.

The Kcv for the flank morphology still remained in the anti-compensational regime in which the overall cross-section Kcv existed in at those longitudinal distances from the apex. This could possibly show that there is no significant difference in compensational behavior laterally in a debris-flow fan cross-section, and that the Kcv for the entire cross-section is a good approximation for tendencies at one specific discreet location within the cross-section itself.

It was observed that the plots used to calculate the Kcv of a cross-section exhibited different populations. The plot for cross-section 22 (fig 5.9) was used to decipher these populations by classifying trials in different colors to examine if trends existed. This analysis showed very rough trends in the data. The overall slope of the data for the earlier trials appears to be steeper than the overall slope for the later trials (Fig. 5.9), indicating a higher Kcv and
compensational tendency for the earlier trials. If one considers earlier trial numbers to be lower in elevation, compared to later trials, then it could be assumed that increasing the elevation or height at which a trial is occurring decreases the compensational tendencies of that event. However, this change in slope of the graph though time (i.e. trials) could be explained by the findings of Wang et al. (2011), in which they found this change in slope to represent the transition from autogenic to allogenic responses in the sedimentary structure of the deposits. This means that these earlier trials are being controlled by internal factors of the deposits themselves, and the later trials could be controlled by external forcings, such as slope. This could be significant for engineers, because it could indicate that for young fans autogenic forcings will control flow direction when trying to predict the location of the next event, and for old fans allogenic forcings should be considered when trying to predict location of the next flow event.

6.3 Correlation Results and Implications:

As discussed in section 5.2, few parameters correlated with the modified compensation index or net migration parameter.

An interesting correlation that was identified is that between the modified compensation index and the net migration parameter. This correlation was moderately strong. This indicates that even though the two values evaluate different processes (i.e. avulsion and gradual shifting of flow direction), the processes themselves are inherently related. This means that one could possibly be used as a proxy for another, when analyzing flow directions of debris-flow events.

The average longitudinal slope and net migration showed a moderate positive correlation. This is helpful, because longitudinal slope could help in identifying the migration of debris-flow events across a fan. One could assume that a steeper longitudinal slope could cause greater migration of events.
It can be seen from the above discussion, appendix K, and section 5.2, that many of the geometric, and physical properties evaluated do not correlate with compensation and migration. The author of this paper assumes that this is because compensation and migration are not controlled by these types of properties on a first order level. It is believed that time, or fan maturity, is the first order control on migration and compensation, as discussed below.

6.4 The Importance of Time:

It appears that time and the relative stage of maturity of a debris-flow fan is more important than the actual physical properties of the fan. When one evaluates the time series developed during the experiment, there appears to be various correlations between time and how the debris-flow events alter direction. It should be noted that this assumes that the successive trials represent episodic events through time. Findings in section 5.1 indicate that the change in flow direction of debris-flow events is more dramatic and larger through time. This is important for scientists and engineers, because if one can constrain the age of the debris-flow fan in question, and understand where the development of the fan is through time, then one can better predict where a future debris-flow event will go. It also indicates that an older fan may tend to disperse debris-flow material farther (in regards to lateral movement) from the center line of the fan structure, while younger fans will disperse debris-flow events in closer proximity to the center line of the fan structure.

The ARIMA model forecasts showed a general increase in migration to the right side of the fan as time progressed. This could indicate a threshold being met in the experiment, whereby a fan will experience cyclical migration up to a certain time, and then the fan will preferentially deposit material to one side of the fan.
6.5 Implications of Findings for Hazard Mitigation:

The above findings involving avulsion, gradual migration and time affect how engineers predict flow directions of debris flows on a debris-flow fan.

Based on conversations with some consultants who deal with debris-flow mitigation, some firms attempt to predict where debris flows will go using a statistical and volume approach, focusing entirely on avulsion. This experiment shows that flow direction models should be more robust, and not only incorporate the avulsion mechanism, but also incorporate the gradual migration mechanism. It is the author’s opinion that this experiment involving an experimental debris-flow fan shows that the gradual migration of debris flows in the lobe regime may be more important than the rapid avulsion process of the channel regime. This means that instead of using the statistical volume approach, models should use a more deterministic approach using physical laws, such as diffusion equations, at least for the lobe regime of the fan structure. Also, time series forecasting may be a viable approach to deciding the location of future debris-flow events, based on the seasonality and time series dependence exhibited for migration and some geometric properties of the debris-flow fan.

6.6 Ideas to Consider:

Overall, the modified compensation index appeared to not pick up on the subtle gradual migrations of the debris-flow events, which could be important for hazard mitigation. This means that other possible indices or classification schemes to categorize fans in regards to the migration and avulsion potential should be developed.

One idea for classification of migration and avulsion potential could be to calculate centroids for each deposit in the cross-section, and measure the distance between subsequent centroids of later deposits (Fig. 6.1). The standard deviation of this distance could then be
calculated and categorized into groups based on standard deviation intervals based on field observations of debris flow direction.

Figure 6.1. A schematic of a debris-flow fan and the parameters that could be used to better classify movement of debris-flow events within the fan. XY is the centroid in the x and y direction. This would be an indication of the center of mass of the deposit in a two-dimensional cross-section view. The variable d shown is the distance between the centroid of each successive trial. This d variable could be used to classify avulsion and migration potential. One way to classify d could be through the standard deviation.

The sensitivity of the modified compensation index to cross-section and deposit geometry could be of great insight into the understanding of avulsion tendencies of debris-flow fans.
6.7 Future Works:

The execution of this experiment brings to light other works that should be performed in regards to avulsion and migration tendencies of debris-flow events within debris-flow fans. One is that exponential decline in the modified compensation index as one moves closer to the apex indicates that other indices should be researched and developed to better constrain subtle changes in debris flow direction, which could impact developments. Also, a sensitivity analysis should be performed on the modified compensation index, where random cross-section geometries are developed to see how much this index changes with different geometries and possibly allow for a field guide estimation of compensation based solely on observing the shapes and distributions of debris-flow events in cross-section. This could be done in a software such as CANVAS16X where coordinate data can be extracted from drawn polylines. Also, it would be good to look at how different ratios of sand, clay and water involved with the experimental debris-flow slurry affect the modified compensation index. Also, analyzing slopes in greater detail by altering channel and run-out platform slopes could be beneficial to a better understanding of compensation and migration tendencies.
CHAPTER 7: CONCLUSIONS

Overall, the goal of this experiment was to better understand the development of debris-flow fans and how debris flows move within the fan structure using a small scale physical model. This experiment provides insight into how debris flows alter direction, primarily in the lobe regime. This can help in predicting location of future debris-flow events, allowing for better placement of mitigation efforts. A key finding is that fan maturity is an extremely important factor when determining flow direction of debris-flow events. The cyclical amplified nature of migration of the experimental debris flows accentuates this importance. If one can constrain a recurrence interval for debris flows and possibly identify the stage of development of a debris-flow fan, then one could use the time series relationships shown in this thesis to better predict events. However, it should be noted that this is a small scale experiment, and debris flows are mechanically and dynamically very complex, making it hard to accurately portray all aspects of debris flow. This means that relationships and findings discovered during this experiment should be applied only in a broad sense, but these broad observations can help guide studies in the field.

Also, this experiment shows that avulsion is not the only mechanism for altering of flow direction that should be considered when evaluating debris-flow events. The gradual migration of events through episodic time across the debris-flow fan surface plays a major role in the development of the fan, and in altering direction of events. Both compensation and migration were shown to increase as one moves farther from the apex, which was expected. However, the rapid exponential increase in these two mechanisms as one moves toward the toe of the fan is of great importance. This means that close to the apex and upper middle of the fan, avulsion is not predominant, but developments near the toe of a fan should worry about avulsion and migration tendencies.
REFERENCES CITED


Mohrig, D., Heller, P.L., Paola, C., & Lyons, W.J. (2000). Interpreting avulsion process from ancient alluvial sequences: Guadalupe-Matarranya system (northern Spain) and


APPENDIX O

SUPPLEMENTAL ELECTRONIC FILES

Included in the supplemental electronic files are all the appendices for the above thesis. Some of the appendices had to be oversized pages, and this is why they are in this separate section. They contain discussion on densities of slurry used, tables of the data used, images of the constructed cross-sections, graphs used to calculate the modified compensation index, graphs proving non-correlations, detailed discussions on time series analyses. These files are organized as alphabetic appendices. Below is a table listing the files, and a short description of what is contained in each.

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appendix A</td>
<td>Contains discussion on densities of trials.</td>
</tr>
<tr>
<td>Appendix B</td>
<td>Contains figures showing flow directions of trials.</td>
</tr>
<tr>
<td>Appendix C</td>
<td>Contains table of frontal velocities of trials.</td>
</tr>
<tr>
<td>Appendix D</td>
<td>Contains table run-out lengths of trials.</td>
</tr>
<tr>
<td>Appendix E</td>
<td>Contains table of length to width ratio of trials.</td>
</tr>
<tr>
<td>Appendix F</td>
<td>Contains cross-sections used in analyses.</td>
</tr>
<tr>
<td>Appendix G</td>
<td>Contains graphs used to calculate modified compensation index.</td>
</tr>
<tr>
<td>Appendix H</td>
<td>Contains table of longitudinal slopes of trials.</td>
</tr>
<tr>
<td>Appendix I</td>
<td>Contains table of margin slopes of cross-section 22.</td>
</tr>
<tr>
<td>Appendix J</td>
<td>Contains figure of cross-section 22 used to measure margin slopes.</td>
</tr>
<tr>
<td>Appendix K</td>
<td>Contains graphs proving non-correlations.</td>
</tr>
<tr>
<td>Appendix L</td>
<td>Contains cross-correlograms of analyses.</td>
</tr>
<tr>
<td>Appendix M</td>
<td>Contains auto-correlograms and partial auto-correlograms of analyses.</td>
</tr>
<tr>
<td>Appendix N</td>
<td>Contains discussion on ARIMA modelling.</td>
</tr>
</tbody>
</table>