

Physical modelling of rainfall-induced flow failures in loose granular soils

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Abstract. The tragic consequences of the March 2014 Oso landslide in Washington, USA were particularly high due to the mobility of the landslide debris. Confusingly, a landslide occurred at that exact same location a number of years earlier, but simply slumped into the river at the toe of the slope. Why did these two events differ so drastically in their mobility? Considerable questions remain regarding the conditions required to generate flow failures in loose soils. Geotechnical centrifuge testing, in combination with high-speed cameras and advanced image analysis has now provided the landslides research community with a powerful new tool to experimentally investigate the complex mechanics leading to high mobility landslides. This paper highlights recent advances in our understanding of the process of static liquefaction in loose granular soil slopes achieved through observations of highly-instrumented physical models. In particular, the paper summarises experimental results aimed to identify the point of initiation of the chain-reaction required to trigger liquefaction flow failures, to assess the effect of slope inclination on the likelihood of a flowslide being triggered, and to quantify the effect of antecedent groundwater levels on the distal reach of landslide debris with the objective of beginning to explain why neighbouring slopes can exhibit such a wide variation in landslide travel distance upon rainfall-triggering.

1. Introduction

The southern California community of La Conchita is situated on a narrow strip of land situated between the Pacific Coast and the slopes of a 180 m high bluff inclined at approximately 35° [1]. The recent history of this community has been defined by two vastly different landslide events separated in time by only ten years. In March 1995, a 120 m wide, 330 m long, deep-seated coherent slump-flow [1] destroyed nine homes at the base of the bluff. Despite this significant damage to the community, the mobility of the landslide was not exceptional for its size. The term “mobility” in this context is often used by landslide researchers (e.g. Iverson et al., [2]) to collectively describe the speed and distal reach of landslide debris, as these quantities define the threat posed by the hazard. Ten years later, however, the landslide debris from the La Conchita event remobilised as a highly fluid debris flow. This much higher mobility January 2005 event had much higher consequences for the small community as the further distal reach and speed of the debris resulted in the deaths of 10 residents and the loss of 36 houses. As noted by Jibson [1], “the movement of the same landslide mass in 1995 and 2005 by two very different mechanisms and with markedly different results is difficult to explain”;

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however, as also noted by Jibson, the 2005 landslide occurred at the end of a 15-day period of near-record amounts of rainfall. This fact indicates that antecedent rainfall may play a significant role in controlling not only the triggering, but the subsequent mobility of a landslide event.

More recently, a similar scenario in which a pair of landslides of vastly different mobility and consequences occurred near Oso, Washington, USA. In this case, the community at risk was a small neighbourhood of houses known locally as Steelhead Haven situated along the bank of the North Fork Stillaguamish River at the base of a 180 m high slope inclined at approximately 20°. In 2006, a landslide occurred on the slope on the opposite side of the river from the neighbourhood which exhibited non-exceptional mobility. Although the debris from this event travelled approximately 100 m and partially blocked the river, the landslide mass came to rest before reaching the Steelhead Haven neighbourhood [3]. Less than ten years later, on 22 March 2014, this same slope remobilised as a high mobility flowslide (Figure 1) of a volume of approximately $8 \times 10^6 \text{ m}^3$ which overran the full 1 km width of the floodplain, demolished the Steelhead Haven neighborhood, buried highway SR530, and resulted in 43 fatalities [2]. Again, antecedent rainfall was identified as a leading potential factor causing the vast difference in mobility between these two events. As noted by the GEER team [3], the cumulative precipitation for the three weeks prior to the high-mobility 22 March 2014 event corresponds to a return period of almost 100 years and the wettest early March on record for a nearby rain gauge. Seismic signals recorded during the landslide event have been interpreted to infer that failure occurred in two stages. However, the exact sequence of events through which a higher antecedent rainfall could lead to such an exceptional mobility landslide event is currently unclear, with different mechanisms proposed by the GEER team [3] and Iverson et al. [2] to explain the cascading sequence of events which led to liquefaction of the base of the landslide.



Figure 1. Photograph of the Oso Landslide after the 2014 flowslide.
Photo taken by Spc. Matthew Sissel, U.S. Navy.

The two pairs of tragic landslide events at La Conchita and Oso clearly underline the increased threat posed by high mobility landslides. In so doing, these events also demonstrate the importance of understanding how and why some landslides transition from slide to flow. In particular, research is needed to further investigate the sequence of triggering conditions needed to generate high mobility flows, the influence of antecedent groundwater on the likelihood of their triggering, and the range of slope inclinations susceptible to this type of failure. The objective of this paper is to present an overview of the findings of a 10 year research program using physical model experiments to begin to seek answers to these questions.

2. Physical modelling test program

Geotechnical physical modelling provides an avenue of experimental landslides research in which nominally identical slopes can be created and brought to failure under different highly controlled boundary conditions. This permits factors such as antecedent groundwater flow, or slope angle to be varied in the models whilst keeping all other factors constant. As a further advantage, slope geometry and soil properties within physical models can be sufficiently simplified to permit subsequent analysis of the observed landslide behaviour in the form of quantitative data capturing transient pore water pressures and landslide movement. Thus, rather than to explicitly attempt to model the more complex geological sequences at La Conchita, Oso or from another historical landslide, the physical modelling test program focused on capturing the transition from slide to flow for a simple idealised slope geometry to investigate how this much simpler system works as a first step.

The geometry used for the testing program consists of a 50 mm thick soil layer overlying bedrock, which when subjected to a centrifugal acceleration of 30 g in a geotechnical centrifuge, corresponds to a layer of 1.5 m in thickness (Figure 2). The decision to include an impermeable bedrock layer was made for a number of reasons, which have been fully described by Take [4], and as such will only be briefly summarised here. The primary reason for this permeability contrast layer relates to the difficulty in replicating static liquefaction events in physical models. Despite being observed in triaxial tests and field events, static flow liquefaction events within physical model tests has proved to be an surprisingly difficult experimental task. As described in the recent keynote lectures investigating the deformation and failure mechanisms in loose and dense granular slopes by Ng [5,6], static liquefaction has been seen in some physical model tests of homogeneous loose fill slopes (e.g. Zhang and Ng [7]) but not in others (e.g. Take et al. [8]). The primary difference between these two cases is the need for a high degree of saturation for liquefaction to occur. Whereas the saturated loose slope of Zhang and Ng [7] liquefied during inundation, the unsaturated homogeneous granular slope model reported by Take et al. [8] simply experienced minor volumetric collapse upon application of intense model rainfall. In other words, although the unsaturated slope experienced rainfall-induced instability, a flow failure was not triggered in this case through the mechanism of static liquefaction. Instead, the low degree of saturation of the granular slope prior to rainfall permitted the model slope to accommodate the volumetric strains associated with the wetting collapse through the compressibility and ease of migration of the pore air [8]. Although the slope material was contractile, and a triggering event was provided in the form of a rainfall-induced wetting collapse, this test result indicates the importance of a high degree of saturation to permit the development of shear-induced pore water pressures if the mechanism of static flow liquefaction is to be triggered [4]. The impermeable bedrock layer in the follow-on testing programme described here therefore permits the development of a water table within the potential slide mass, in order to create the pore network of contractile saturated voids filled with an incompressible fluid (water) which is prone to significant positive excess pore water pressure generation upon shearing. Thus, the presence of the impermeable bedrock layer is simply a strategy to encourage saturation of the potential slide mass.

The 50 mm thick layer of soil consisted of fine uniform sand (U.S. Silica F110 Ottawa Sand of d_{50} of 0.12 mm), mixed at a gravimetric moisture content of 7%, and rained through a sieve from an elevation of approximately 125 mm to create a very loose sand layer resting on a roughened impermeable base intended to model impermeable bedrock. A series of miniature PDCR-81 pore water pressure sensors were mounted into this base layer to capture both the static and transient pore water pressure response of the slope prior to and during failure. In this model, water was introduced as a seepage flux, Q_{in} , at the top of the model using a metering flow pump. The response of the slope was then monitored using a Phantom V9.0 high-speed digital camera recording at 1000 frames per second (fps) to capture the deformation of the soil at toe and base region of the slope. Readers interested in the full details of the physical model, soil properties, and instrumentation are referred to Take and Beddoe [9].

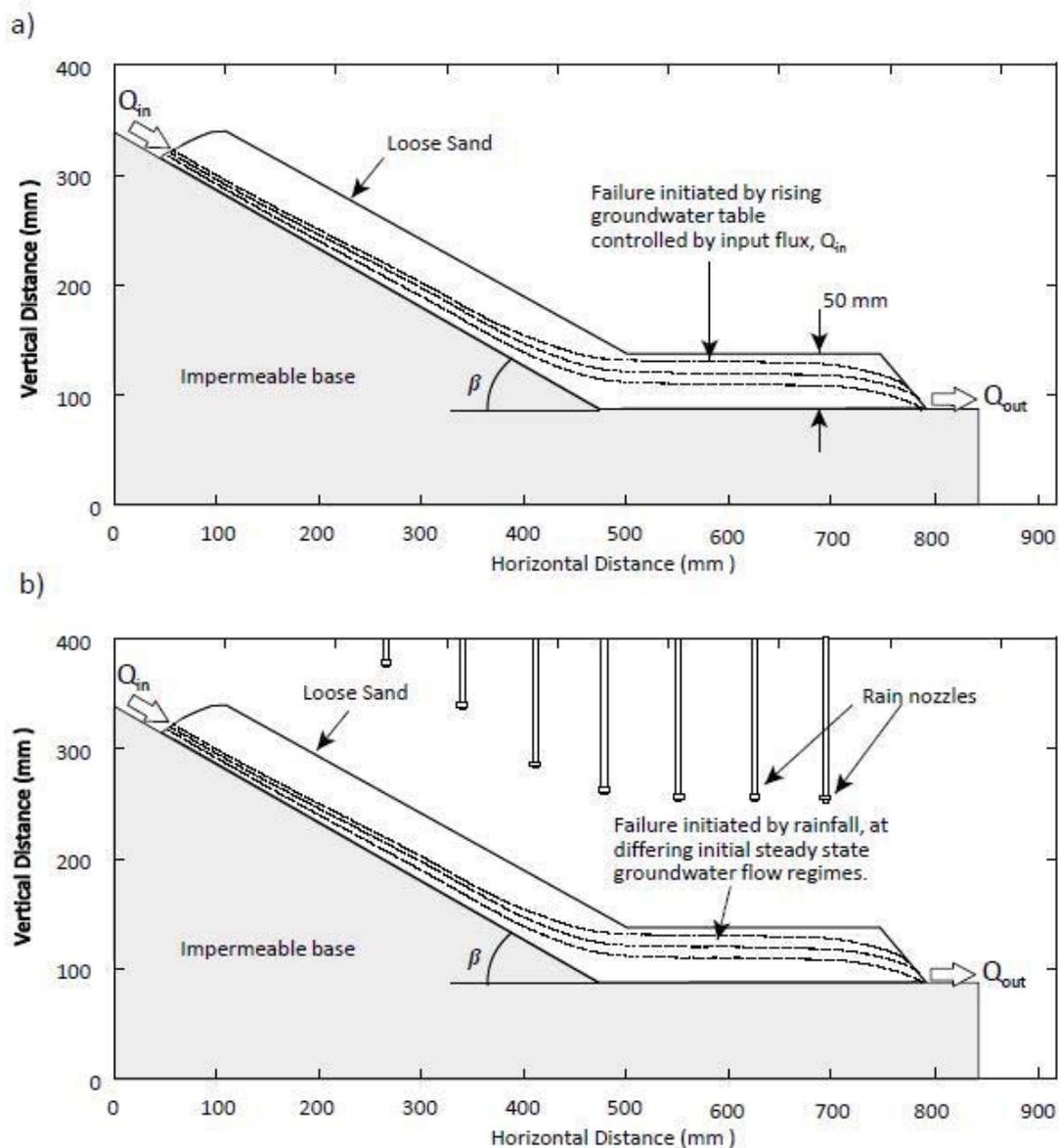


Figure 2. Imposed flux boundary conditions on the physical models, where a) a failure event was initiated by a rising groundwater table controlled by input flux, Q_{in} , and b) failure was initiated by rainfall at differing initial steady state groundwater flow regimes. Model scenarios were conducted at a slope angle, β , of 20 and 30 degrees.

Once constructed, the model was subjected to the test acceleration of 30 g on the C-CORE centrifuge in St John's, NL, Canada. The testing program aimed to investigate the sequence of triggering events leading to high mobility flows (Take and Beddoe [9]), the influence of antecedent groundwater on the likelihood of triggering high mobility flows (Take et al. [10]), and the range of slope inclinations susceptible to this type of failure (Beddoe and Take [11]). An overview of the findings from these investigations are presented in the following sections, with the objective of

combining the observations of slope behaviour from these recently published papers to reach overarching conclusions from the entire combined dataset of physical model test results.

3. Triggering sequence

In order for the deviatoric strain-softening associated with static liquefaction to be generated, the soil must be contractile, be subjected to a monotonic loading trigger, and be sufficiently saturated to permit the generation of excess pore water pressures upon shearing. However, as proposed by Take and Beddoe [9], it is this third condition that is perhaps the most difficult to achieve for granular soil slopes. If one considers an infinite slope of granular material inclined at 30° , a significant seepage flow rate would be required to saturate even a small thickness of the layer. Instead, Take and Beddoe hypothesised that a more likely location of saturated soil could be located in regions where the inclination of the soil layer locally reduces, as this change in geometry can impose a lower hydraulic gradient resulting in a thicker zone of saturated soil for the same groundwater flux. One extreme case of a change in slope inclination is the toe of a slope. As shown in Figure 2a, water entering the top of the physical model slope with a flux Q_{in} will result in only a thin zone of saturated flow on the slope, but a significantly thicker zone at the base due to the reduction in hydraulic gradient. Thus, the change in soil layer inclination at the toe creates the hydraulic conditions that favor saturation at a lower flow rate than would be required to trigger liquefaction failure in an infinite slope of the same inclination. If this soil was sufficiently loose, and if a rainfall or seepage induced local toe failure were to provide a monotonic shearing trigger, it is theoretically possible that the base of the landslide may be at higher risk of experiencing static liquefaction than the better drained inclined portion of the slope [9]. To test this hypothesis, Take and Beddoe [9] carried out a physical model test of geometry described in Figure 2a in which the groundwater flux, Q_{in} , was incrementally increased until failure was triggered.

The sequence of failure observed by [9] in a rising groundwater experiment in a 30° physical model slope is shown in Figure 3. This figure contains displacement vectors, calculated using the image processing technique of digital image correlation [12] on image frames captured in the toe / base region of the slope every 0.001 s of the experiment. As the groundwater flux was increased in small increments, no significant landslide deformation was observed in the slope. However, once the groundwater flux was sufficient to saturate the sand layer at the base of the slope (i.e. note the total head values and measurement locations in Figure 3a), a small initial slip surface developed at the toe of the slope. This failure then rapidly sheared the highly saturated volume of soil in the base layer, causing the generation of positive excess pore water pressures (signified by the total head values significantly above the soil surface in Figure 3b) consistent with the undrained shearing of a contractile material. This then permits the failure surface to deepen, a larger volume of material to be entrained, and the debris to flow nearly horizontally as the toe region removes its buttressing support of the remainder of the material left on the inclined portion of the slope (Figure 3c). Although a highly idealised geometry, this failure sequence highlights the need for a small monotonic failure to be co-located with a zone of saturated, contractive soil for the system to be prone to liquefaction.

These observations illustrate that the sequence of failure illustrating the transition from a small localised slide to a more widespread flow can be captured in a physical model. But can physical models be used to explain why lower antecedent groundwater conditions led to lower mobility landslides? To answer this question, we present the results of a physical model test conducted using the same geometry as the previous experiment, but this time, brought to failure by the application of model rainfall using mist nozzles. This slightly revised testing configuration is shown in Figure 2b, and in this case that will be discussed in detail, no steady-state antecedent groundwater flow was induced in the model prior to rainfall application. Therefore, this test represents the extreme case of a landslide being brought to failure with the same rainfall event, but with very low initial groundwater levels. The sequence of failure observed by [10] for this case is presented in Figure 4. As the test aimed to have very low antecedent groundwater volumes, the pre-rainfall total head values presented in Figure 4a are consistent with the drainage of moisture from the slope during gravity turn-on (i.e.

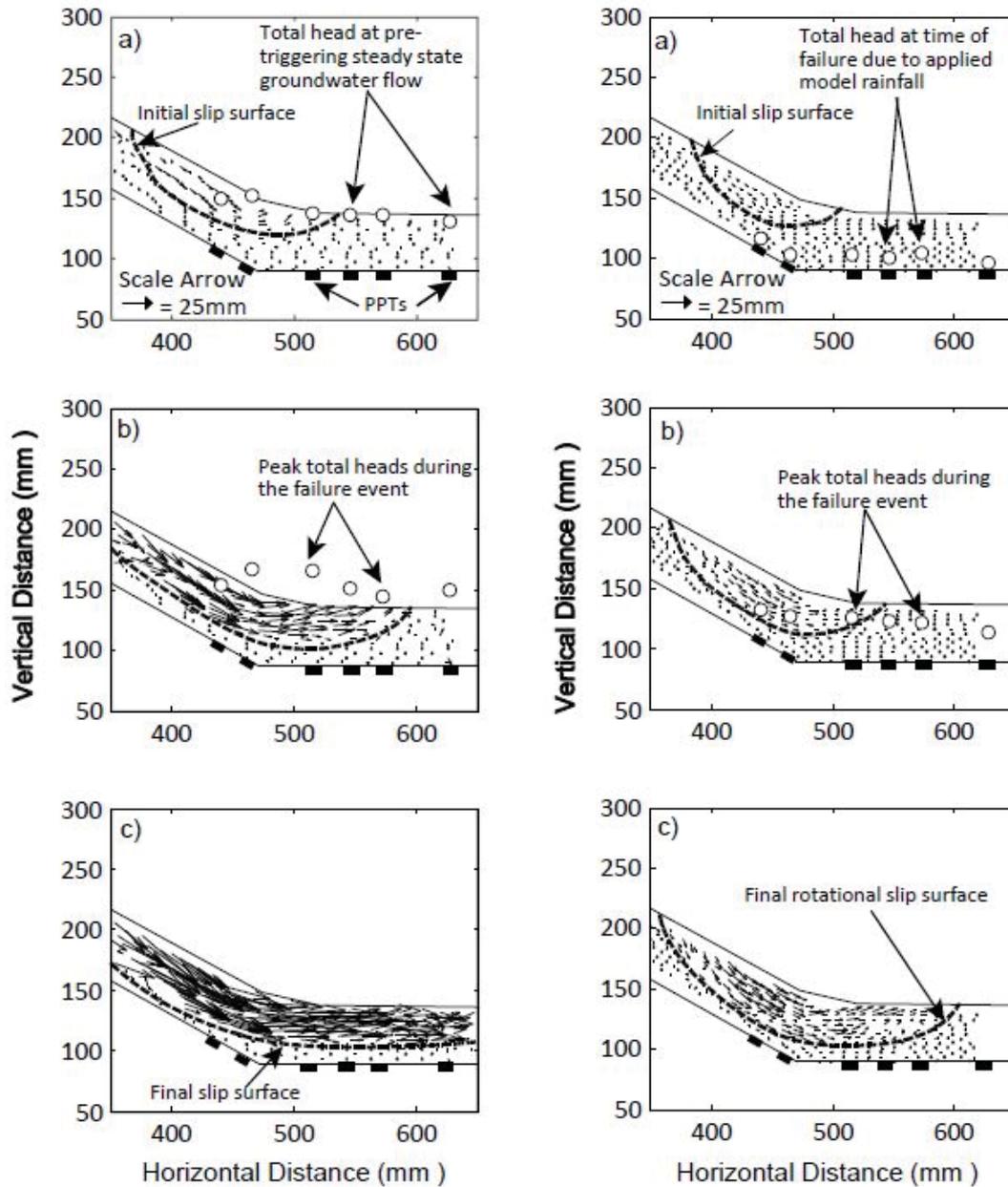


Figure 3. Evolution of the failure event for rising groundwater scenario, highlighting, a) pre-triggering total heads measured by the porewater pressure transducers (PPTs) super imposed on the initial failure event, b) mid failure event, when peak total heads are reached, and c) final vector displacement of the landslide.

Figure 4. Evolution of the failure event for the rainfall only scenario, highlighting, a) pre-triggering total heads from rainfall event imposed on the initial failure event, b) mid failure event, when peak total heads are reached, and c) final vector displacement of the landslide.

recall that the soil was placed at a gravimetric water content of 7 percent). As model rainfall was applied, the reduction in suction associated with the infiltration front caused an initial localised failure surface at the toe, consistent with the first physical model. However, the consequences of this monotonic shearing event on the base layer are dramatically different in the second case. Although shear-induced pore water pressures are generated (Figure 4b), the lower saturation of this layer has the consequence of reducing the magnitude and duration of these total heads, resulting in a landslide of much lower mobility (i.e. The full extent of the difference between the landslide travel distance can be assessed by comparing Figures 3c and 4c as the displacement vectors are plotted to the same scale).

4. Effect of antecedent groundwater flow on mobility

The differences in mobility between the high and no antecedent groundwater flow cases in Figure 3 and 4 is drastic. But what is the nature of the relationship between antecedent groundwater flow and mobility? Is it linear? Or is there a threshold value of flux required to trigger the high mobility liquefaction landslides? To attempt to answer this question, Take et al. [10] performed additional experiments at intermediate antecedent groundwater levels prior to rainfall infiltration. As illustrated schematically in Figure 2b, this was achieved physically in the model, by controlling the metering flow pump to provide different groundwater fluxes to the top of the model, thereby creating different initial positions of the water table (i.e. thicknesses of saturated soil) along the base of the model. Frames captured every 0.001 s from each experiment were then analysed using digital image correlation to measure the total distal reach of the landslide debris and the maximum velocity. The results from the five experiments performed on a 30 degree slope are presented using solid markers in Figure 5 in model scale. The x-axis for this figure reports the antecedent groundwater condition of each experiment, as expressed by the steady-state flux applied prior to rainfall infiltration. Therefore the two tests already discussed in this paper correspond to 175 mm/min (i.e. the test failed by groundwater seepage alone) and 0 mm / min (i.e. the test with no pre-existing groundwater table prior to rainfall). Superficially, the results illustrate that the landslides that experienced the highest travel distance also experienced the highest peak velocity. This is both a logical and expected observation. More importantly, these results illustrate that the effect of antecedent groundwater flow on landslide travel distance and peak velocity is highly non-linear with seepage flux. For example, the increase in travel distance provided by a 75 mm/min increase in seepage flux from 0 – 75 mm/min is marginal; whereas an additional increase by the same 75 mm/min increment from 75 – 150 mm/min results in an enormous increase in mobility. Further, this data indicates that for the simple idealised geometry investigated in this research program, high antecedent groundwater conditions can increase the mobility of the landslide debris by a factor of eight.

5. Effect of slope angle

The average inclination of the slope at La Conchita was approximately 35°, whereas the inclination at Oso was only 20°. As noted by Iverson et al. [2], “landslides that transform into mobile, high-speed flows almost invariably begin on slopes >20°, and initiation sites steeper than 30° are typical [13,14]”. In this context, the high mobility of the Oso landslide underscores the importance of defining the range of slope angles susceptible to high mobility liquefaction events. To this end, Beddoe and Take [11] performed a series of physical model tests at a lower inclination (20°) to enable a direct comparison to the test results already presented for 30° slope models. Intuitively, higher slope inclinations correspond to higher downslope components of gravity, which may lead to the conclusion that steeper slopes are more susceptible to large distal reach landsliding. However, as noted by Beddoe and Take [11] more gently inclined slopes require higher pore water pressures to trigger failure, which could possibly lead to higher mobility due to a larger region of saturated soil at the moment of triggering.

The sequence of failure observed in a rising groundwater experiment in a 20° physical model slope is shown in Figure 6. Once again, similar to the more steeply inclined soil layer, increasing

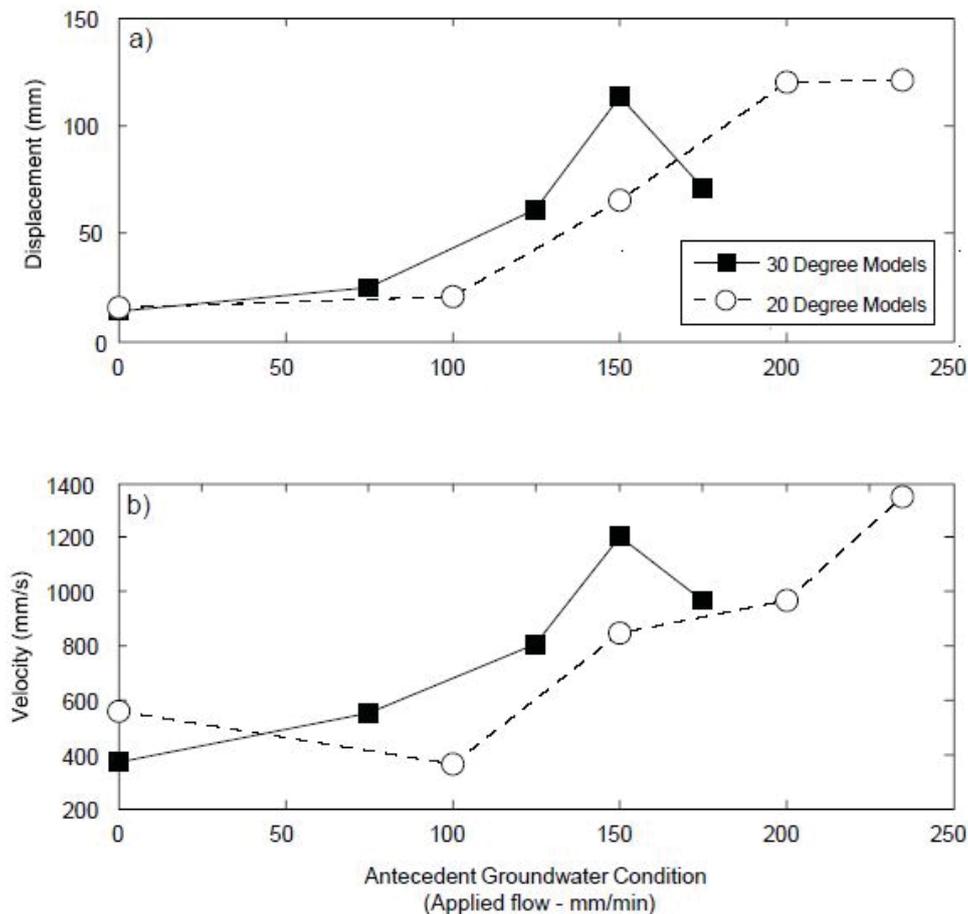


Figure 5. Comparison of landslide mobility observed in 30° [10] and 20° [11] slopes, where a) maximum displacement, and b) maximum velocity.

groundwater flow had the effect of saturating the base of the landslide prior to a small localised failure at the toe of the slope (Figure 5a). This monotonic shearing event then generated significant excess pore water pressures within the slope (Figure 5b) sufficient to liquefy the soil layer, and experience significant horizontal flow. These observations indicate that although more water was needed to trigger failure (230 mm/min rather than 175 mm/min flux), high mobility flow slides can still be initiated at slope angles as low as 20°.

The relationship between landslide mobility (i.e. maximum velocity and distal reach of debris) and antecedent groundwater conditions (expressed as a pre-rainfall imposed groundwater flux to the model) reported by Take et al. [10] for the 30° slopes and Beddoe and Take [11] for the 20° slopes are combined in Figure 5. This data clearly illustrates that a 20° slope can exhibit higher landslide mobility than a more steeply inclined soil layer subject to a lower groundwater seepage flux. Further, it is important to note that the relationship between mobility and groundwater seepage flux remains non-linear for the 20° slopes. Therefore, given the non-linearity of this relationship in both datasets, this data illustrates the enormity of the challenge posed by the prediction of the triggering of high mobility flows from meteorological data alone.

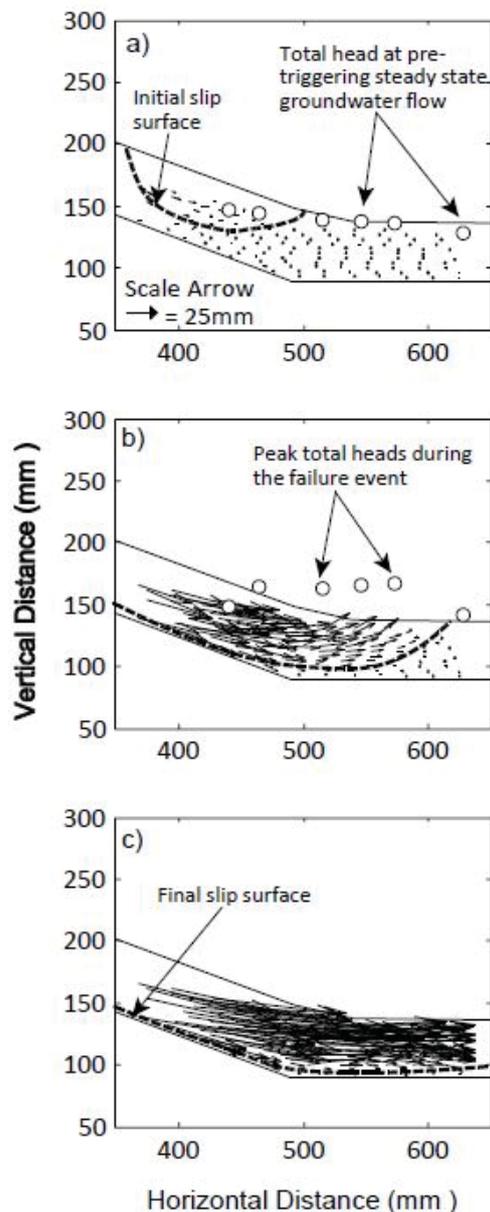


Figure 6. Evolution of the failure event for a 20 degree test, highlighting, a) pre-triggering total heads along with the initial failure event, b) mid failure, when peak total heads are reached, and c) total vector displacement of the landslide.

To further illustrate this point, the rainfall duration required to initiate failure as a function of antecedent groundwater condition for all tests are summarised in Figure 7. As all tests brought to failure using a constant intensity rainfall, the y-axis of the graph represents short-term rainfall (i.e. the rainfall duration required to trigger rainfall expressed in seconds), whereas the x-axis represents the antecedent groundwater seepage conditions prior to rainfall. This data underlines the metrological conditions required to trigger failure, with the lower inclination slope requiring more infiltration to initiate failure. However, what is completely lost in this treatment of the data is that not all of these landslide events have the same mobility, and therefore do not pose the same threat to life and livelihood.

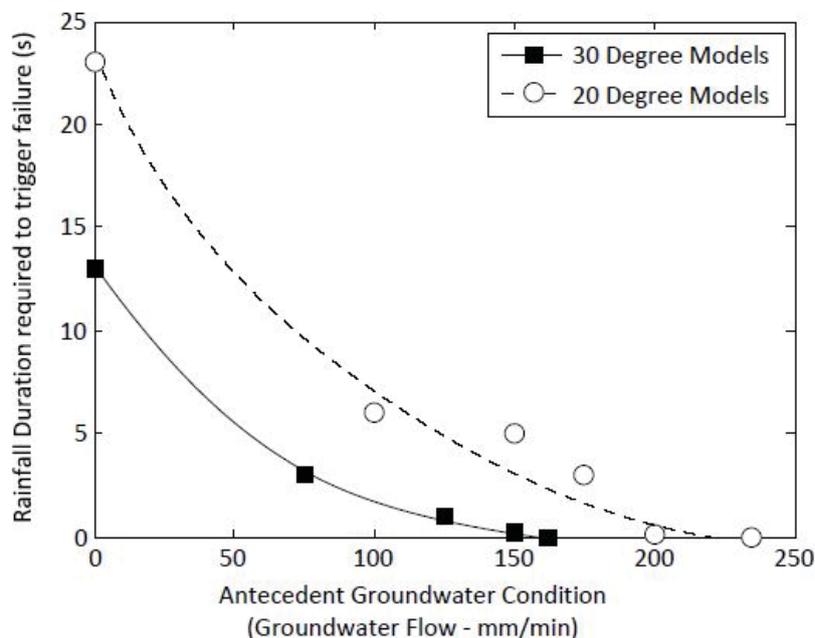


Figure 7. Comparison of the rainfall duration required to initiate failure for the 30° slope and 20° slope physical model tests. The curves emphasize a landslide warning rainfall threshold, however this type of intensity-duration curve does not capture the resulting landslide mobility.

6. Conclusions

The tragic landslide events in the communities of La Conchita and Oso clearly demonstrate the increased threat posed by high mobility landslides. Geotechnical centrifuge testing, in combination with high-speed cameras and advanced image analysis has now provided the landslides research community with a powerful new tool to experimentally investigate the complex mechanics leading to high mobility landslides. In this paper, an overview of the findings of a 10 year research program using physical model experiments aimed at better understanding these complex failure processes has been presented. These experiments have been successful in initiating deviatoric strain-softening associated with the cause of the extreme mobility (static liquefaction) in physical models under a wide range of different hydraulic boundary conditions.

The first contribution of these physical model tests to our understanding of these events is to illustrate one particularly highly-successful scenario in which high-mobility landslides can be generated. This scenario begins with a small initial slip surface developed at the toe of the slope. This failure then rapidly sheared the highly saturated volume of soil in the base layer, causing the generation of positive excess pore water pressures consistent with the undrained shearing of a contractile material. This then permits the failure surface to deepen, a larger volume of material to be entrained, and the debris to flow nearly horizontally as the toe region removes its buttressing support of the remainder of the material left on the inclined portion of the slope. Although a highly idealised geometry, this failure sequence highlights the need for a small monotonic failure to be co-located with a zone of saturated, contractive soil for the system to be prone to liquefaction. For the case of field events, heightened pore water pressures due to permeability contrasts associated with adverse layering or local bedrock exfiltration (e.g. Rüdlingen landslide experiment [15]) could potentially create other locations in addition to the toe of the slope where an initial localized failure event could trigger the onset of static liquefaction of a zone of saturated, contractive soil.

Secondly, the high mobility La Conchita and Oso landslide events were both hypothesized to be related to the extremely high antecedent rainfall that preceded both events. This hypothesis was tested using physical models of various antecedent groundwater levels prior to the application of model rainfall. The results from this testing program indicate that the effect of antecedent groundwater flow on landslide travel distance and peak velocity is highly non-linear with seepage flux. Further, this data indicates that for the simple idealised geometry investigated in this research program, high antecedent groundwater conditions can increase the distal reach of the landslide debris by a factor of eight. Therefore, these results confirm the enormous role that antecedent groundwater levels play in determining whether the landslide mass is sufficiently saturated to experience full liquefaction.

Finally, the influence of slope angle was investigated to contrast the evolution of the slide to flow mechanism at slope angles thought to be typical of flow slide generation (30°) and more gently inclined slopes (20°) consistent with the average slope at Oso. The physical model results indicate that liquefaction can indeed be triggered in more gently inclined slopes (20°), and in certain circumstances, can result in higher mobility landslides than those triggered on steeply inclined slopes (30°). However, higher groundwater flow seepage rates and durations of rainfall infiltration were required to achieve the pore water pressure required to trigger failure, consistent with expectations from a frictional effective stress framework to predict triggering.

It should be noted that all physical modelling experiments performed in the testing program were conducted at a void ratio that was very loose and exceedingly contractile under loading. As noted by Iverson et al [2] a critical void ratio exists that defines whether a landslide deposit is sufficiently contractile to generate the high excess positive pore water pressures required to experience liquefaction. The next step of the physical modelling research program is therefore to investigate the variation in mobility of landslides at different initial void ratio (and therefore state parameter).

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