Comparison of Geometric and Experimental Models for the Assessment of the Runout and Deposition Height of a Debris Flow in Cohesive Soils

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Abstract. The objective of this paper is to validate if one dimensional runout and height deposition prediction models are suitable for large-scale landslides (debris flows in cohesive soils) based on a small-laboratory-scale test, because landslides are unpredictable hazards and involve a great quantity of triggering variables which in most cases determine the mass movement behavior during its trajectory. Due to many of these variables cannot be obtained from theoretical methods, since they are natural to the soil composition, and to the high rheological variation this soil masses suffer during all the deposition process, it is necessary finding adaptable tools and assessment methods that require simple information, such as terrain slope and soil water content. This becomes one of the main reasons for this type researches. A laboratory experiment was designed which ground slope and soil water content were involved. Several laboratory-scale trials were performed, analysed, compared and validated with one-dimensional runout prediction models as Fahrböschung model and modified gradient model, where its suitability is discussed. Regarding models that involve more advanced tools for the analysis of a landslide, like the modified gradient model, it can be affirmed that its results are reliable and clearly reflect the sliding mass behaviour in a real scenario, without mentioning the advantages using a tool like geographic information system in cases where an exhaustive analysis of all the variables that influence a landslide is needed. In conclusion, a geometric model as the modified gradient model can be used for important analysis that require runout and height deposition estimations for the calculation of a structure physical vulnerability subject to the lateral forces of a sliding soil mass. This is an important parameter to cities planning.

1. Introduction
The study and characterization of landslide, whether due to its velocity, deposition height ($h_T$) or water content (WC), temporary, spatial probability (area of occurrence) and magnitude (sliding mass runout prediction) is a matter of great importance regarding cities planning, especially in those places where the highest population concentration (both residential and industrial) are located in high mountain areas and flood valleys.

Therefore, the measurement of impact forces that a landslide can generate in a structure and the determination of potential propagation zones become the main objectives in the analysis of a landslide behaviour once its movement has happened. However, when it comes to mass movements, there are four general uncertainties that summarize the determining factors in their characterization, the spatial
component (determination of the highest landslide susceptibility zones), the temporary component (identification of those times in the year with the highest probability for the landslide occurrence), the mass movement magnitude and finally the affected area. The first three components have been widely studied worldwide [1], and have focused mainly in understanding the failure mechanisms that govern these geodynamic processes. Nevertheless, regarding the affected area analysis there are still many knowledge gaps due the variability of rheological behavior of the mass movement materials.

Parameters as viscosity, soil friction angle or other rheological parameters and pore water pressures cannot be simply measured in full-scale examples and direct measurements are rarely available for real cases [2]. This represents a difficulty when it comes to make a thorough and detailed analysis of a landslide deposition because other soil behaviors directly influence these factors and might be even harder to get.

Due to what was aforementioned, for the prediction of runout and height deposition in a mud flow, physical and geometric models have been developed, and have focused in analyse a soil mass trajectories on a determined place, taking into account mainly the slopes of the area where the movement occurs. Slope (S) is precisely the base for the simplified geometric models implementation, that aim to determine, the most probable trajectory for the landslide as well as the height deposition regardless the moving amount of soil.

2. Theoretical framework
Landslide is a general term used to describe the down slope movement of soil, rock, and organic materials under the effects of gravity and the landform that results from such movement [3]. Depending on the geological material (bedrock, debris or earth), a landslide can be classified in falls, flows, spreads, and slides and each one of these respond to different behavior regarding their composition (material and transportation agent), deposition, velocity of travel and triggering mechanisms.

A fall is mainly either a detachment of soil or rock, or both, from a steep slope along a surface on which little or no shear displacement has occurred. The material subsequently descends mainly by falling, bouncing, or rolling [3]. The slides are movements that happens mainly in high shear strain zones and rupture zones, mostly composed by soil or rock that moves down slope and increases by the motion its volume. Rotational and traslational slides are the most common types of this mass movement which principal difference can be noticeable in its surface of rupture, spoon-shaped in the first case and planar surface with little rotational movement in the second one. A spread is defined as an extension of a cohesive soil or rock mass combined with the general subsidence of the fractured mass of cohesive material into softer underlying material [3]. Block, liquefaction and lateral spreads are the types of this movement that usually occurs in plain terrains or non-steep slopes.

2.1. Flows
A flow is a spatially continuous movement in which the surfaces of shear are short-lived, closely spaced, and usually not preserved [3]. The distribution of velocities in the displacing mass resembles that in a viscous liquid. The lower boundary of the displaced mass may be a surface along which appreciable differential movement has taken place or a thick zone of distributed shear [4].

Different types of flows exist, and they all differ whether the debris composition, the size of the sliding particles, the magnitude or the velocity. Debris flow, lahars (volcanic debris flows), debris avalanche and earthflows are the most common.

Flow-like landslides movement patterns are not the same under any condition, even if they occur in the same geomorphological context, since they can all display quite different features either in coarse-grained or fine-grained soils. Experience suggests that even small details in the geomorphological
features of the slope, in soil properties or in the internal effective stress field can be responsible for one or another movement pattern, either in coarse grained or in fine-grained soils [2].

2.1.1 Debris Flow
A landslide like debris flow can be defined as a form of rapid mass movement in which loose soil; rock and sometimes, organic matter combine with water to form a slurry that flows downslope [3].

However, as researches about this type of mass movement have been developed, this basic definition has been useful as a base for new more accurate definitions that classify debris flows according the composing materials, materials properties as consistency limits, the size of particles and water content. Hence, words like debris (soil with a gravel content higher than 20% and coarse sizes), earth (unsorted clayey colluviums from clays or weathered clay-rich rocks, with a consistency closer to the plastic limit than the liquid limit) and mud (semi-liquid clayey material with clay content higher than 50%) [5] are important to understand the flow types proposed by Hungr on his book “Debris-flow Hazards and Related Phenomena”, where a debris flow is a very rapid to extremely rapid flow of saturated non-plastic debris in a steep channel, which plasticity index is less than 5% in sand and finer fractions and, a mud flow is a very rapid to extremely rapid flow of saturated plastic debris in a channel, that involves significantly greater water content relative to the source material with a plasticity index greater than 5%.

In some debris flows, the water necessary to saturate the mass comes from post failure mixing with streams or other surface water, but in most debris flows, all water necessary for mobilization exists in the mass when failure occurs. Indeed, many debris flows are triggered by changes in pore pressure distributions that result from infiltration of rain or snowmelt water that precipitates slope failure [6]. Generally, the movement is relatively shallow and the runout is both long and narrow, sometimes extending for kilometers in steep terrain. The debris and mud usually terminate at the base of the slopes and create fan like, triangular deposits called debris fans, which may also be unstable [3]. Debris flows can result from individual slope failures or from numerous small failures that coalesce downstream [6]. Nevertheless, mobilization requires failure of the mass, sufficient water to saturate the mass and sufficient conversion of gravitational potential energy to internal kinetic energy to change the style of motion from sliding on a localized failure surface to more widespread deformation that can be recognized as flow [6].

2.2. Runout assessment models
Since debris flows have become a danger for humanity, prevention a mitigation measurement design has become as well in a priority for city planning. Understanding the mechanisms that trigger a landslide and favor its movement and transport through the bed until its final deposition becomes an imperative task for such purpose. However, not so many approaches have been developed for this purpose and even less have focused in studying the affected area, because, most of the times, the magnitude of such phenomena is so extensive that available tools and information is not enough for address them correctly.

Moreover, as has been mentioned previously, measuring geotechnical parameters of the involved in mass movement materials is not as simple as saying so, and most of these available models and measurements requires advanced geotechnical parameters, that as has been stated before, it is not possible to get them from open field.

All this has led to an increasing need of creating and applying all the existent mechanisms that require simple and easy to get information to predict, more than understand, the possible run-out of a landslide and its height deposition. Nevertheless, the suitability of these models is not a granted alternative, since they exist under many limitations regarding the magnitude of the phenomena and its propagation due this same matter.
As Gruber, Hugel & Pike stated in “Modelling mass movements and landslides susceptibility”, geomorphometric models have been used for determining the affected areas and the amount of deposition that can be expected. They also mentioned the LAHARZ model [6], propagates lahar flows over a DEM to the point where the depletion of the mass halts the flow [7]. Many other models that consider multiple flow-directions, detachment and settlement capacities among other characteristics were mentioned and served as starting point for the developing of simpler methodologies.

2.2.1. Empirical models
Empirical runout models can be useful to perform slope risk assessments and aid decision-making in an operating open pit mine. Treating site-specific influences holistically is appropriate when time and geological uncertainty limit the degree of precision that can be expected. Empirical methods are quick, repeatable, and useful for bracketing site conditions where detailed data are limited [8].

2.2.1.1. Fahrböschung
This concept, which is defined by the ratio between the start–stop point elevation difference of the debris (H) and the corresponding horizontal travelled distance (L) (Equation 1), is the basis for runout prediction in landslide analysed in one direction [9].

\[
\tan \alpha = \frac{H}{L}
\]  

(1)

2.2.1.2. Hunter and Fell 2003 model
This model (Equation 2) is derived of the Fahrböschung angle (\(\alpha\)) theory, explained in the past subsection. Hunter and Fell (2003) found that the Fahrböschung angle of flow slides in loose granular fills and waste dumps had almost no dependence on volume; rather, mobility is proportional to the average travel path inclination. Slope angle-based mobility relationships that were analyzed included Fahrböschung angle, runout length, and excessive travel distance normalized to total runout length [8].

\[
\frac{H}{L} = 0.488(\alpha) + 0.117
\]  

(2)

2.2.1.3. Modified gradient
This model is a result from an investigation developed where the landslide vulnerability assessment was the objective [9]. There, the investigators developed a series of equations to landslide vulnerability estimation from the hazard intensity and the resistance ability of the elements to withstand a threat. This all led to a variable called Z (Equation 3). This variable is the modified gradient and it represents the intensity of the landslide process, that consequently, it strongly controls the vulnerability [9]. H is the start–stop point elevation difference of the debris, and d is the corresponding travelled distance considering topography.

\[
Z = \frac{H}{d}
\]  

(3)

2.3. Runout and height deposition \((h_T)\) applicability
The assessment of landslide parameters such as runout distance and deposition height is a matter of interest to the planning of cities, especially those that are located in mountainous regions. The applicability of these parameters has special importance in the assessment of a structure vulnerability that can be understood as the probability of damage when subjected to a particular effect of a natural or anthropogenic potentially damaging phenomenon, in this case a landslide [10].

The measurement of lateral forces due to the impact of a sliding mass over a structure (Figure 1), allows a thorough evaluation of its fragility and vulnerability, leading to possible implementation of mechanisms for damage decreasing. This is highly related to runout and height deposition, because these
values, especially the last one, allows the pressures diagram calculation because of the action of the sliding mass over a structure that could be located on the runout influence zone.

![Figure 1. Schematic methodology for lateral force calculation of a sliding mass](image)

Besides, having the vulnerability assessed for different structures, permits the creation of fragility curves that relate the lateral force magnitude with a mean damage ratio (MDR) that describes the probability of exceedance of an exposure limit state of the buildings facing the threat of a landslide given an intensity measure [10]. These fragility curves can be generated for different structural typologies such as scrap wood (SW-L), unreinforced masonry (URM-L), reinforced masonry (RM-L) and reinforced concrete frame (RCFL-BC), for lower floors of the structure (Figure 2).

![Figure 2. Fragility curves for different structural typologies](image)

### 3. Experiment design

The entire test were carried out at Universidad de Medellín laboratories. A metallic rectangular channel with a total length of 3.00 m and a 0.70 m x 0.50 m transversal section (Figure 3). This construction can be separated into a reservoir section and a measuring section, with a pivot gate installed at some point in the channel. The section created with this gate is 0.25 m x 0.70 m in plain view with a 0.0875 m³ volume capacity. The soil is placed in this reservoir and can be released just by unlocking the gate, imitating a dam-break scenario.
3.1. Data collecting
Each tests data were taken from the upper part of the channel with a laser device (Bosch GLM, 3mm precision) at the center zone of each cell ($n_i$) and recorded in a custom format created for such purpose. There, all information regarding water content, surface slope, soil weight and test date was reported.

In total, 16 tests were carried out, the first eight ones for procedure design purposes and an experimental protocol implementation. The remaining eight experiments were used to data collection using the proposed method in the aforementioned experimental protocol that was designed for the author of this document and some collaborators.

4. Results and discussions
4.1. Results
The collected data during the development of the assessments corresponds to distances from the edge of the channel to the spread soil layer, so, for make this data comparable with the models used for validation, it was necessary to convert this information into the spread soil layer heights. It consisted on a simply mathematical subtraction to the channel walls height $H_{channel}$ (0.50 m) and each one of the corresponding data to each cell on it ($n_i$) (Equation 4).

$$Height_{Layer} = H_{channel} - n_i$$

It is important to highlight that the measured heights collected in laboratory were taken in a perpendicular way to the bottom of the channel. Then, these measurements were decomposed in its trigonometric components for calculation purposes.

With this information, a 3D graph was generated in a Python interface where the information could be seen as if it corresponds to a real scenario landslide (Figure 4). The results are classified according the water content of the mixture used in each assessment, and for each water content, four different slopes (5%, 10%, 15% 20%) were tested. Each one of these graphics are accompanied whit a range bar that indicates, precisely, the ranges that the soil layer has after the deposition, from the starting point until the end of the measurement zone.
4.2. Discussions

The models and methodologies available for a landslide runout prediction and height deposition assessment are numerous but with many limitations. It is extremely easy to find models that allow the prediction of a landslide runout but their suitability for all the cases that can exist when it comes to mass movements is yet to discuss. As it is widely known, soils are an unpredictable particle set, is due to they are divided in big groups according to similar characteristics to make their study easier. Since landslides are soil phenomena, they are indeed, unpredictable events that are even harder to characterize because the soil is not the only factor that influences the occurrence of them. This opened an opportunity for investigations like this one, where the final objective is to determine if empirical models, based mainly on mathematical relationships are suitable for landslides, and if they can predict the run-out based on lab-scale test that simulate real scenario conditions.
An interest observation that was noticed while the model investigation process, is that many of the models found do not take into account the water content for the run-out prediction, or at least those models that have as fundamental base the Fahrböschung theory. This, due to they need, mostly, the angle surface between the lowest point of the soil deposition and the starting point of the movement, which leads to intuit, that perhaps, the obviation of such an important parameter as the water content (a statement that will be further defended), may influence, in a non-positive way, the results obtained with the mathematical models, like the Fahrböschung and the Hunter & Fell models.

These results only reinforced the interest of the analysis results obtained from the modified gradient model that was applied under a GIS environment using ArcGIS TM software with the procedures described above. This was particularly interesting because it was developed at a local university based on soils from the same area that the soil used in this assessment comes from. Therefore, the results obtained for the 45% water content could perfectly be compared with the results obtained in that investigation. It is important to highlight, as well, that for this case, it was not the runout distance the objective to analyse. However, the ratio (H/L), which is really the parameter all models are aimed to determine, because of the tools of this GIS environment offered, the values of L, known as well as the runout distance, were possible to find independent of the travel angle and the value of H.

According to [9], in several times, the calculated values of Z for different events occurred in the soils of the slopes of the Aburrá Valley, varied from 0.3 to 0.4 most of the times for landslides triggered by rainfall in similar soils, so it was the range that was taken into account to compare and validate what was obtained for the studied case. Moreover, for supersaturated landslides, this author proposes a Z value range between 0.05 and 0.1 to determine a debris flow runout. For this work purposes, the supersaturation condition of soil mass was assumed for WC=60%, but, due the limitations explained before, the validation through a geometric model could not be done for this water content. However, analysing the modified gradient Z isolines trend, it is highly probable that the flow could have reached this distance range associated to mentioned Z values. However, it was evident that this specific model tends to oversize the runout distance, because given Z range for this distance is extremely wide and in any of the cases assessed, the soil surpassed the superior range value and in some cases it barely reached it (Figure 5). Therefore, and like in the other models analysed in this paper, it is important that the available models for runout and height deposition take into account the water content, a parameter that is proved to be determining on the assessment of any topic related to debris flow like landslides.

5. Conclusions
The results obtained for runout, at first sight were the expected, since runout distance was further as the slope and water content increased. However, it was notorious the big difference obtained between runout distances for both 45% and 60% of water content. As it was mentioned before, both moisture contents are above the soil liquid limit and a similar liquid fluid behaviour would have been expected in both of them reflected in runout distances that surpassed at least the midst section of the measurement zone, in the 45% water content case. When the tests were being performed, at the first step, when mixing the water and the soil, concerns arose due the mixture seemed too dry or not wet enough to even move out the reservoir despite its weight and the channel slope, and in the 3D figures, it can be seen that the runout distance difference between slopes is almost imperceptible, even having some cases when the runout distance reached the same cells file for two different slopes.
Different models were used to validate the obtained results during the assessment of the runout distance and the deposition height of a debris flow type landslide in a cohesive soil. This opened up a series of considerations that are valuable to mention since those represented obstacles where the suitability of those models was being evaluated. It was clear the importance of the characterization of the soil because based on this, the assessed water contents were defined, in order to choose values that would lead the soil into a behavior proper of a landslide, that as said in the theory occurs because of the gravity action but also, because an over saturation of the soil causing pore pressure increments, decrease in the shear strength and the soil cohesion resulting into this phenomena. Also, the lab-scenario nature, it means, the fact the sliding surface was a channel, limited the options for suitable models, due it was not possible to apply those models that considered more than one direction/trajectory/dimension, which directly inflicted in the impossibility of determine the height deposition of the soil in any case, because it was necessary to compare between neighbor cells and one directional models do not offer that kind of analysis.

On the other hand, as stated in the discussion, the fact this same one dimensional models do not usually take in to account the water content of the soil, one of the main parameters in these assessments, influence the results, in a way yet to determine, that may lead to unrealistic analysis and that may do not correspond with the observed on the laboratory. Even when this was not the case, since the mathematical relationship was fulfilled in each one of the cases for each one of the models, a question if these models work for any type of soil still exists and demands a further investigation where coarse granular soils are involved. This specifically, refers to the mixtures made for the assessments of the 45% water content, where in each one of the cases, the soil was observed as a custardy texture mixture, capable of reach at least the middle of the measurement zone, because what it was observed, and the magnitude of the mass, but that in any of the cases, for any of the slopes assessed reached more than 0.7 m of run-out length, which is far from the middle of the flume and so even farther from the results obtained with the Fahrböschung and the Hunter & Fell model. In the author’s opinion, these models, based on mathematical relationships are not the best option to assess runout and/or height deposition accurately.
and the results should not be used for purposes different from suggest a probability for the real runout value to reach a length similar to the one obtained with these models.

For purposes such as city planning and landslide control mechanisms, is suggested to apply models that are more complex where all the factors that influence the occurrence of a mass movement event can be taken into account and gives out a more accurate result with a real case. Nevertheless, if the mathematical validation of the models is observed, where the objective was to prove both expressions, the one before and after the equal sign, fulfilled equally the model; it is obvious that one of the models were more accurate with the results, or said plain, both expressions gave as outcome almost the same value, differing if anything, in just one decimal, in the case of the Fahrböschung model case, while the Hunter & Fell model may had seemed better because the values that affected the travel angle value, but as observed this was not the case and probably, more tests involving different water contents and soil will be needed to completely define which one of the models is more suitable and accurate for the runout and height deposition assessment.

Regarding models that involve more advanced tools for the analysis of a landslide, like the modified gradient that is applied under a GIS environment it can be affirmed that its results are reliable and clearly reflect the sliding mass behavior in a real scenario. In conclusion, a geometric model as the modified gradient model can be used for important analysis that require runout and height deposition estimations for the calculation of a structure physical vulnerability subject to the lateral forces of a sliding soil mass.

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