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Empirical methods to predict the travel distance and mobility of landslides

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Abstract

Landslides and damages derived from these processes have required the efforts of professionals and researchers in the area of geotechnics through the implementation of tools such as Hazard, Vulnerability and Risk Assessment. One of the topics that has received special attention in recent years is the analysis of travel distance, through simple models or more sophisticated models that involve more detailed analysis. A review of empirical methods around the world is presented along with the description of the factors that influence the reach of landslides, which may include variables such as slope geometric properties, mechanical properties of materials, environmental configuration, geology, terrain conditions, etc., and that are evaluated by statistical analysis from robust databases. Some of the conclusions reached by the authors are described in the article as well as the advantages of using certain methods for the study of mass removal processes. Different examples of application of the use of empirical relationships are also discussed and the statistical tools from which the equations for predicting the mobility of landslides are obtained are reviewed.

1 INTRODUCTION

Mass removal processes are phenomena that cause many disasters around the world, and that can represent losses in terms of lives, economy and infrastructure. The causes associated with landslides and the patterns under which they are triggered depend on the geological, hydrogeological and geomorphological conditions of the region of the site where the movement occurs, as well as the mechanical characteristics of the materials that make up the slope and its geometry, in this sense, it is essential to study its effects; within this area, it is important to perform a risk assessment, which is defined as the product of the hazard and vulnerability; thus, in terms of probability:

$$R(DI) = P(H) * P(S|H) * P(T|S) * V(L|T) \quad (1)$$

Where R (DI) is the risk, P (H) is the annual probability of occurrence of the event, P (S│H) is the probability of spatial impact given the event, P (T│S) is the probability of temporal impact given the spatial impact and V (L│T) is the vulnerability.

Within the risk assessment, one of the most important aspects that may be difficult to determine is the probability of spatial impact, more specifically the travel distance, defined as the horizontal projection of the line linking the upper part of the landslide source and the outermost edge of the landslide deposit (Grupo de Estándares para Movimientos en Masa, 2007). For the analysis of travel distance, empirical, analytical or numerical methods can be used. Empirical methods are based on field observations and movement characteristics, meanwhile, analytical and numerical models are based on continuous or discrete models that use more complex parameters; in all cases, it is convenient that the models be calibrated with mass movement inventories close to the study area. Empirical models, unlike analytical ones, take into account simpler parameters, which is why these are used as a preliminary evaluation of travel distance as the result of the non-requirement of rheological parameters or mechanical details of movement, in addition they are a simple tool that offers a practical method of prediction (Guo et al., 2014).

The aim of this article is to present the worldwide panorama for the analysis of the travel distance of landslides, starting with the different approaches, the empirical models, the statistical tools for their evaluation and some applications that are important within the evaluation framework of risk.

2 LANDSLIDES MOBILITY ANALYSIS

Landslide mobility prediction is one of the most important issues in risk assessment. This depends on many specific factors of each site where the events take place, so calculating the travel distance remains a difficult task for professionals and researchers. Mobility is expressed in terms of the distance traveled by the displaced mass, although some authors prefer to use other mobility indexes, and these are generally analyzed using 3 different approaches: empirical, analytical and numerical. Empirical methods often relate the travel distance of the slide material (exposure) with geomorphological parameters of the slope, such as the volume of the slide and the height of fall (zones of origin) through statistical methods to making predictions, which are simple and easily applicable, also, these relationships can help better understand the nature of the extreme mobility of many movements (Chen et al., 2015). On the other hand, empirical methods do not explicitly include the rheology of the material and the failure mechanism. There is an inherent limitation to empirical techniques, given the dependence of prediction on an adequate database of field observations for the development of the model (Fannin and Wise, 2001). The analytical methods include models of concentrated mass and methods of conservation of momentum or balance of energy, these may somehow include the rheology of the material, and the mechanics of the movement to some extent, but they do not do it in detail and do not take into account the internal deformation of the mobilized mass (Chen et al., 2015). The input parameters for the analytical models may not be so trivial, they also require simplifications that can lead to physical inconsistencies in their development, so these parameters need to be calibrated with events close to the study site. Numerical methods include finite elements, methods of distinct elements, the smoothed particle hydrodynamics method, and these can describe the movement and rheology in detail, but require a lot of information, and in an area where landslides can be generalized, it is not very adequate (Chen et al., 2015), in addition to the fact that the mechanism of failure of the different movements is not yet fully understood. On the other hand, it is well known that the parameters required for its implementation change during the movement, which makes it less efficient in situations where time is a key factor for decision making.

With the above, empirical models are considered as a solution that can be fast, efficient and useful for bracketing the conditions of the site where detailed information is limited (Whittall et al., 2017). It should be noted that the uncertainties of the data required to use these relationships, as well as the uncertainties of the models limit their application, although the results derived from the empirical models can be taken as preliminary values or framed within a probabilistic framework for evaluation of the hazard.

3 EMPIRICAL METHODS TO EVALUATE TRAVEL DISTANCE OF LANDSLIDES

The Elm landslide on September 11, 1881, which claimed the lives of 115 people and destroyed 83 buildings, motivated the study of the reach of the landslides that was born with the introduction of a mobility index known as the fahrböschung angle or angle of reach, by Albert Heim in 1932 and is the angle of the line that connects the head of the slide to the distal margin of the displaced mass (H/L) (Chen et al., 2015). Its reciprocal is known as mobility and is defined as L/H, although it is less used in practice. Other indexes are the deposit area, the affected area, the travel distance, the shadow angle, the deposit width, the excessive travel distance, runout (used only for flows and is the distance from the crest of the fan and the most distal point of the displaced mass), among others. The physical sense of the reach angle has been debated for decades, Shreve (1968), called this angle the equivalent coefficient of friction, while Scheidegger (1973) said that for a body that slides, the tangent of the reach angle, is, in fact, the coefficient of friction of the contact surface between the sliding mass and the soil (Corominas, 1996). Some authors have expressed that the assumption is valid only when the centers of gravity of the source and the reservoir are connected (Corominas, 1996), although for practical purposes it is not very suitable since the position of the centers of gravity is only available for detailed studies of large events and this measure does not represent the total horizontal travel distance, which is much more useful in risk assessment (Strom et al., 2019). From the definition of Scheidegger (1973) the following relation can be written:

$$H/L = \tan \emptyset' \quad (2)$$

Where H is the height of the landslide, L is the total travel length and $\emptyset'$ is the internal friction angle of the soil. Regarding this assumption, Hsü (1975) defined the excessive travel distance as the horizontal projection of the travel distance beyond what is expected of a rigid mass that slides down a sloping plane with a coefficient of normal friction, that is, $H / (L \tan \varphi') = 1$ evidences a landslide that moved in drainage conditions on a surface of the same material and without obstacles. $H / (L \tan \varphi') \neq 1$ indicates a deviation from this reference pattern (Vaunat and Leroueil, 2002). It has been shown that the reach angle for very large events can result in very low values, which could show a relationship with the volume of the displaced mass; it was initially defined for rock avalanches that under certain volume intervals, the equivalent coefficient of friction could be assumed constant (Scheidegger 1973; Hsü, 1975).

It should be noted that the H/L ratio is not only influenced by the size of the landslide, other factors must also be taken into account, the endogenous ones that are properties of the landslide such as the height of fall (H), the slope angle, the properties of the material, velocity of movement, type of landslide, potential energy, etc., and exogenous, which are properties of the environment such as water content, geology, vegetation, path of travel, confinement of the material, the trigger factor, etc. (Whittall et al., 2017).

Empirical models seek to relate mobility indexes with endogenous and exogenous factors, either through one-to-one relationships, or through a combination of variables independent by mean of multiple regressions. It is important to keep in mind that when the parameters included in the model are qualitative, they can be taken into account as categorical variables (e.g. Guo et al., 2014) or analyze as many models as categories have the variable (e.g. Qiu et al., 2017).

Next, the influence of some factors on the best known mobility indexes is reviewed according to the analyzes carried out by different authors who are experts in the field around the world, showing some examples derived from their research, although it should be noted that there is not a consensus as to how each parameter affects the reach of the landslides, since each model depends on the specific database for each site, however, these results can serve as a guide to establish or calibrate new models in countries where still these tools for risk management have not been developed.

3.1 Effects of volume on landslides mobility

One of the first authors to note the relationship between the equivalent coefficient of friction and the volume was Scheidegger (1973), which established that the decrease in the reach angle occurred when the volume exceeded 10^5 m^3, for smaller volumes a coefficient of constant equivalent friction could be established (0.57-0.83) in most cases, Hsü (1975), showed the volume threshold below $5x10^6$ m^3, where most rocks exhibit a constant coefficient of 0.6. Later Corominas (1996) confirmed this effect of size in the H/L ratio for other types of landslides such as rock falls, earth flows, debris flows and translational landslides, although it was established that it was not appropriate to use coefficients of friction constants for small events, as these can also exhibit excessive mobility. On the other hand, Legros (2002) found that there are the same increasing trends in travel distance with increasing volume for volcanic and submarine landslides, despite the different environments, Budetta and Riso (2004) also found a good correlation between those two parameters. Okura et al., (2003) found no relationship between volume and H/L due to the study of a limited volume range. Hunter and Fell (2003) found that the angle of fahrböschung in landslides in loose granular landfills and garbage dumps almost did not depend on volume; rather, mobility is proportional to the average inclination of the travel route (Whittall et al., 2017). Some authors, such as Skermer (1985), state that there is no clear relationship between the angle of reach and the volume, and that the mobility is given by the height of fall, greater heights of fall should correspond to longer horizontal displacements (Corominas, 1996). There is a lack of agreement among researchers about the findings of the dependence of travel distance with volume. Consequently, different conclusions have been derived from these simple relationships although it is clear that there is a tendency to decrease H/L with volume, but a specific relationship can only be used in the place where the data is collected (Bashart and Rohn, 2015), for example, in Figure 1 the results of analysis of different debris flows in a region in southern Italy are shown (Budetta and Riso, 2004) where it is clearly observed, how the travel distance increases with a larger volume.

Although these trends exist in most studies, field observations show that simple Coulomb friction (equation 2) cannot predict the high mobility of events because the volume of events must be combined with the topography of the flood area and other physical parameters (Pudasaini and Miller, 2013). A problem with this approach is that the data dispersion is too large to allow reliable use for travel distance predictions, except the most preliminary, but in places where information is limited or in situations where time does not play in favor, it can be quite useful.

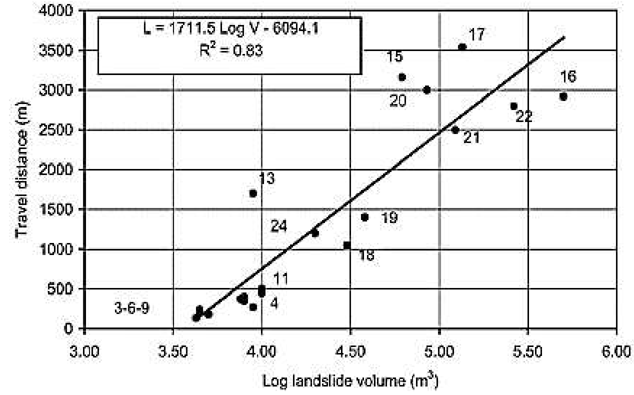


Figure 1. Relationship between travel distance and volume for debris flow in Italy (Budetta and Riso (2004)).

Sometimes, the movement can not only spread forward, but also can do so laterally if the forces in this direction that occur during the movement overcome the basal friction of the ground (Strom et al., 2019). This requires introducing the total affected area, one of the mobility indexes widely used by some authors and that correlates well with the volume of the slip through a power law. In example, Iverson et al. (1998) derived an Area-Volume relationship for lahars in Washington, USA, additionally a relationship for unobstructed rock falls in Colombia from data from the CGS (Colombian Geological Service) collected by the author is shown in Figure 2 where the two equations are compared. These relationships are useful to the extent that they only require the volume as input to establish the value of the affected area with good accuracy, knowing the type of event beforehand. In addition, Figure 2 evidences that for the same volume, exist difference between the mobility of different types of movements, therefore it is necessary to properly characterize the landslides if it is required to apply some existing empirical relationship.

3.2 Effects of height on landslides mobility

Some studies ensured the effects of topography on the mobility of landslides (Finlay et al., 1999; Hunter and Fell, 2003). The fall height governs the potential energy, which makes it responsible for the velocity of the landslide and its travel distance, therefore, a higher fall height leads to a higher velocity and, therefore, to a greater travel distance (Corominas, 1996; Guo et al., 2014). On the contrary, other authors indicate that the vertical height from which a given volume was released had no influence on the travel distance, and this only depends on the volume, since the kinetic energy gained during the initial fall dissipates rapidly (Hsü, 1975; Legros, 2002); Davies (1982) established that vertical height is of secondary im-

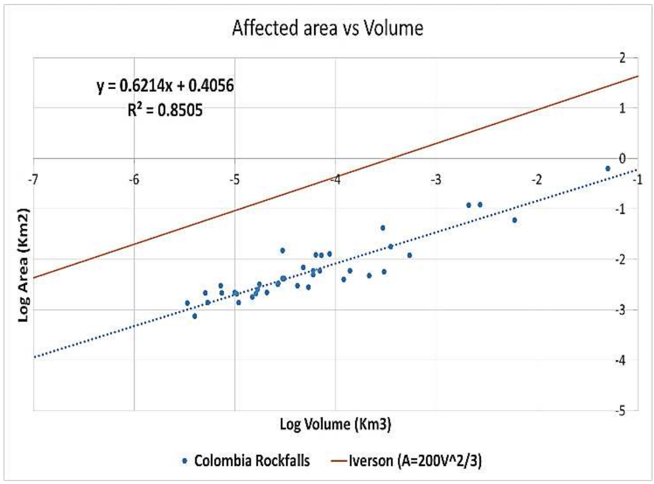


Figure 2. Difference in mobility between lahars and rock falls.

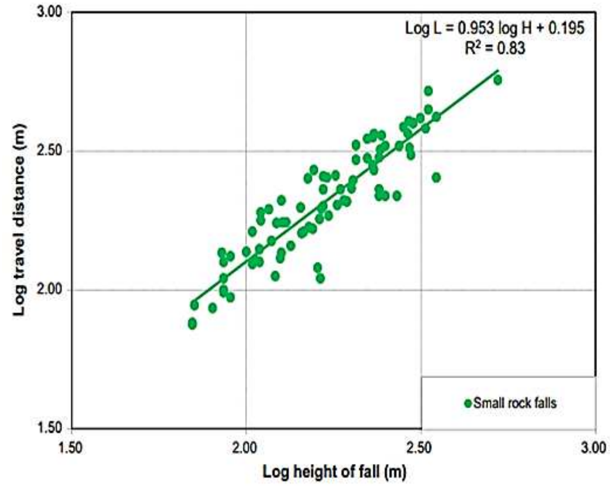


Figure 3. Relationship between travel distance and fall height for rock falls in Pakistan. (Bashart and Rohn (2015)).

portance, simply adding dispersion to the analyzes. Although there is no agreement between researchers, Corominas (1996) used a comparison of the fall height with the length of the horizontal path to show that, if two identical failures occur from different fall heights, the one with the biggest fall will travel further. One of the advantages of using the height of fall as a predictor variable is that it can be approximated as the height of the slope that has slipped, while the volume values reported in the field observations are usually accompanied by great uncertainties (Qiu et al., 2017). Bashart and Rohn (2015) show the relationship of travel distance to fall height in a log-log graph applied to events in earthquake-induced rock falls in northeast of the Himalayas, Pakistan, which supports the appreciations of some authors cited above (Figure 3).

3.3 Effects of slope angle on landslides mobility

High inclination is associated with high shear stress on hillside materials. Hattanji and Moriwaki (2009) showed that the equivalent coefficient of friction increases with increasing slope inclination, i.e., for gentle slopes, the travel distance is greater. Okura et al. (2000) verified the positive relationship by performing numerical simulations and experiments (Qiu et al., 2015). Considering the kinematics of a landslide it can be said that a gentle slope has a lower residual strength, which determines the gradient of the mass displaced after the landslide (Hattanji and Moriwaki, 2009). Another reason that supports these results is that a steeper slope leads to a greater gravity component to accelerate the sliding mass and greater consumption of kinetic energy due to the impact at the foot of the upper slope (Guo et al., 2014).

A study by Changwei et al (2013) in Figure 4 of Wenchuan earthquake-induced landslides in China shows that clear dependence.

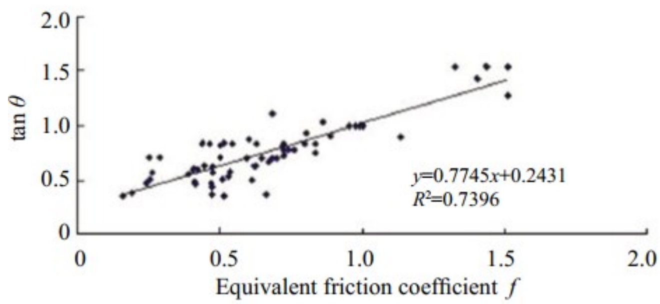


Figure 4. Relationship between the slope angle (tan) and the equivalent coefficient of friction (f=H/L) for earthquake-induced landslides in China (Changwei et al (2013)).

3.4 Effects of pore pressure on landslides mobility

Rickenmann (1999) observed that rock falls have comparatively smaller travel distances than debris flows, which can possibly be explained with smaller water contents in the flowing masses. In addition, when comparing the same type of landslide, in this case, flows, a greater travel distance is also observed by the movements that involve more water, examples of this are the Nevado del Ruiz mudflow and the Mount St. Helens lahars (Rickenmann, 1999). Fast undrained load is a common long travel distance mechanism for landslides, although it should not be forgotten that some dry events have also exhibited excessive mobility (Hungr and Evans, 2004; Corominas, 1996). Wong et al. (1998) carried out a study on the relation between the angle of reach and the sliding mode and concluded that the angle of reach is affected by the amount of water involving the movement. Hutchinson (1986) showed the influence of the initial pore pressure ratio (pore pressure on total vertical stress) in the mobility of the Aberfan disaster in South Wales through a back-analysis, the results shown in Figure 5 make evident that greater pore pressures make the reach angle smaller, i.e., the landslides have greater travel distance.

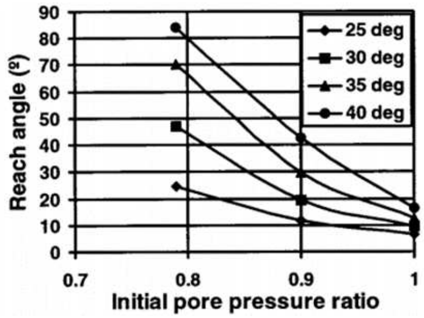


Figure 5. Effect of pore pressure on debris flow mobility in Aberfan, Wales. (Vaunat and Leroueil (2002)).

3.5 Effects of confinement on landslides mobility

It must take into account that different authors who analyzed databases from different regions reached controversial conclusions. For example, Shaller (1991) found that channeling (lateral confinement) had no significant effects on mobility characterized by the H/L ratio. Nicoletti and Sorriso-Valvo (1991) reached an opposite conclusion, since they discovered that the channeling of the landslides allowed a greater travel distance (L), which increased mobility (Strom et al., 2019); this is a logical or expected result, since the displacement of a debris flow (and its path) is very sensitive to water content (Chau et al., 2000), and it is obvious that, in general, the valley-confined debris flows are likely to have higher water discharges than the hillslope debris flows (Lorente et al., 2003). Edgers and Karlsrud (1982) had reached the same conclusion studying soil flows generated by submarine slides. Strom et al. (2019) tested the effect of confinement for rock avalanches in Central Asia, showing that for the same volume, laterally confined movements have greater mobility than unconfined, or frontally confined movements (Figure 6).

3.6 Other factors that influence the mobility of landslides

The analysis of the databases of different authors has made it clear that the mobility of landslides can be affected by factors such as the type of landslide and the properties of the slope material. Some lithology are expected to produce extremely fast movements: quick clays and loess (Souisa et al., 2018); Zhuang et al. (2018) shows that for China landslides triggered by earthquakes, the finest mate

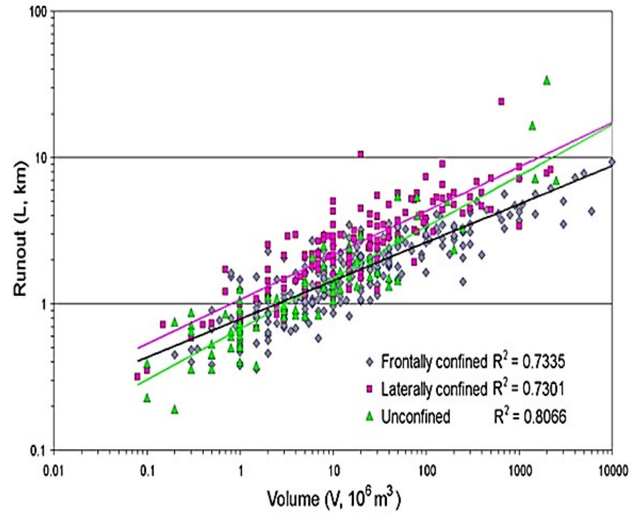
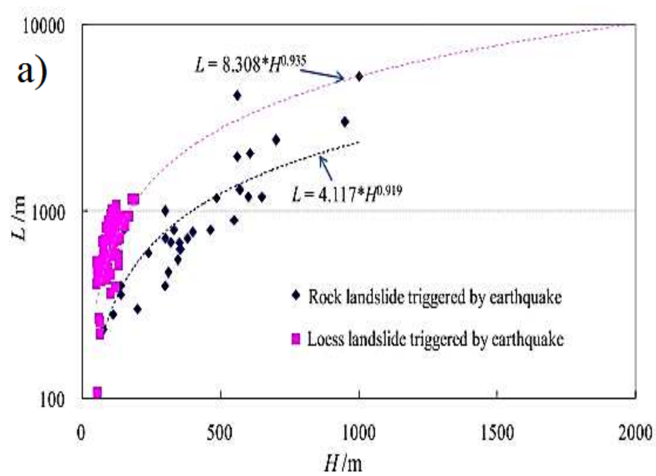


Figure 6. Effects of confinement on runout for rock avalanches in Central Asia. (Strom et al. (2019)).

rials usually cause events with greater travel distances (Figure 7a). Fleming et al. (1989) found that contractive soils move further than dilatant soils. Whittall et al. (2017) analyzed the influence of the type of landslide for movements in open pit mines (Figures 7b); likewise, Corominas (1996), classified some movements worldwide according to that parameter without reaching a definitive conclusion, since the dispersion of the data is evident and more bases are needed to confirm the effects of that factor, although the figure suggest certain trend where falls may be less mobile than flows, in any case, these results should be used with caution and with the judgment of an expert.

Other factors that influence the mobility of landslides and that are generally not taken into account in empirical methods include grain size distribution, type of obstruction, degree of saturation, strength parameters, slope shape, topography, vegetation, velocity of landslide and trigger factor.



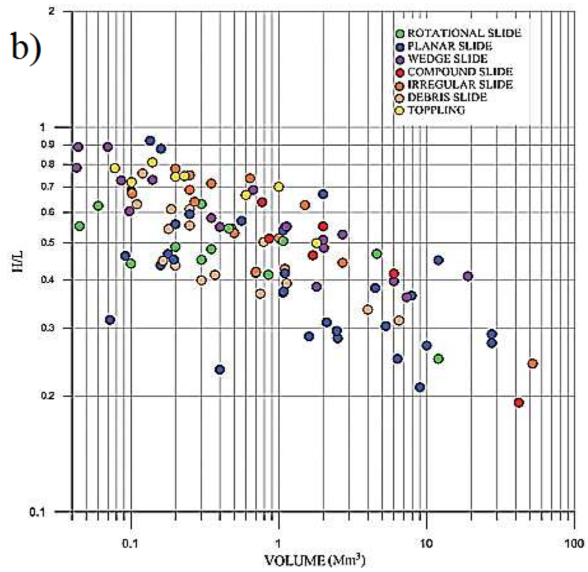


Figure 7. Effects of some factors on the mobility of landslides: a) Influence of the type of material. b) Influence of the type of landslide. (Zhuang (2018); Whittall et al. (2017)).

4 EMPIRICAL METHODS IN THE WORLD

Given the different mobility indexes and the exogenous and endogenous factors around the movement, many authors have developed empirical models for the prediction of mobility through simple (bivariate) regressions or multiple regressions, using statistical tools to validate each of the models. The author is advancing a database that compiles the most important empirical models that have been developed in the world, which covers different regions and events that take place in different geological conditions, including some parameters that have been described in this article. The database will be presented in subsequent works (for more details contact the author) and include the region where the data was obtained, the type of landslide where each model applies, the mobility index used, the independent variables, the empirical equation, the coefficient of determination R^2 and the reference. That work aims to be a guide for researchers or professionals to establish the best model that fits the study of landslides given a region, since sometimes the information is very limited, although it is always better to develop a new model if the necessary data is available.

5 STATISTICAL TOOLS FOR TRAVEL DISTANCE ANALYSIS

To obtain the travel distance models of landslides from the different databases collected by the researchers, some statistical techniques are used, which must be chosen with a good criterion since the same results are not always obtained if one or the other is used, for this reason it is advisable to use all possible tools, as long as it is convenient with respect to the time available for the development of the model. Generally, we begin by finding one-to-one relationships between mobility indexes (dependent variable) and the other endogenous and exogenous variables (independent variables), i.e., there are as many models as independent variables are available. The most common model is the simple linear regression model given by:

$$y = \alpha + \beta x + \varepsilon \quad (3)$$

Where y is the response variable, x is the predictor variable, α is the intercept of the line with the y axis, β is the slope of the regression line and ε is a random error. The α and β coefficients can be found using the least squares method or the maximum likelihood method that are not detailed in this article but can easily be found in any basic statistics book. The models obtained by simple regression are evaluated by hypothesis tests on the slope and the intercept, using "t-tests" and "F-tests", in addition to the coefficient of determination R^2 that may be more known to readers and that measures the goodness of fit of the regression model found. Finally, the model is also evaluated by analyzing the residuals, it must be ensured that these show normality, constant variance and absence of trends when they are plotted. Sometimes it is required to use non-linear models to adjust the variables, which may result in better adjustments with higher coefficients of determination.

If simple models are not sufficient and there are more than one independent variable that influences the dependent one, it is more appropriate to use a multiple regression model, which in the linear case is given by (Walpole et al., 2007):

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + \cdots + b_kx_k + \varepsilon \quad (4)$$

The constants b_0, b_1, ..., b_k called regression coefficients are found by the method of least squares, and using n observations of the form: yi, x_{i1}, x_{i2}, ..., x_{ik} where i = 1, ..., n. In the same way as in the simple regression, the models obtained are evaluated using the same statistical tools (for more details see for example Walpole et al., 2007).

When there is a model with more than one independent variable, it is necessary to evaluate which parameters are the ones that most influence the model and what parameters can be omitted, this is done through a subset analysis, where the following methods can be found (the most used): Backward elimination starts with the model that includes all potential predictor variables. Variables are eliminated one-at-a-time from the model until we can obtain an adequate model. The forward selection strategy is the reverse of the backward elimination technique. Instead of eliminating variables one-at-a-time, we add variables one-at-a-time until we cannot find any variables that improve the model. The elimination or introduction of variables is carried out with some criteria, of which the most common are the p-value criterion and the R^2 criterion (for more details see, for example, Cetinkaya-Rundel et al., 2019).

6 APPLICATIONS OF THE EMPIRICAL EQUATIONS OF TRAVEL DISTANCE OF LANDSLIDES

One of the most important applications of empirical models is the ability to improve landslide hazard maps. The majority of hazard and risk management studies only contemplate the levels of susceptibility of landslides in a given area, this in terms of probabilities of failure of a certain slope, and very rarely there is an analysis of the mobility of materials when the movement occurs, it is here that the empirical equations come into play, since from these methods, it is possible, together with the digital terrain models and other inputs, to define danger zones and thus have a better panorama of the risk at that both buildings and people are exposed. One of the application examples is Chen et al., (2015), which derives an empirical equation for the calculation of travel distance from a database for surface rain-induced landslides in a region of China, and they uses data from the terrain, rainfall, infiltration and slope stability analysis to delimit the reach of events, both for the upper and lower limits. Berti and Simoni (2007) implement an algorithm (DFLOWZ) to predict the flood zone from an empirical area vs volume relationship for debris flow data in the Italian Alps using a digital terrain model. (Dahl et al., 2010) uses the reach angle approach to delimit, not only the areas of susceptibility, but also the areas of deposition of materials, this for flows in the Faroe Islands. Another application is aimed at the design of structures to mitigate the risk of landslides, and this is achieved by establishing models that allow predicting the hazard zones of the most dangerous potential events.

7 CONCLUSIONS

Hazard and risk studies must be accompanied by a component that analyzes the extent or mobility of landslides, so that the most exposed areas can be known and strategies can be created to mitigate or manage the effects derived from these events

The evaluation of the travel distance requires understanding different mechanisms and the interaction between the processes involved in the movement and the endogenous and exogenous factors, this is done through statistical models that incorporate several parameters according to the quantity and quality of information of each specific site where the study is carried out.

Although different authors have reached different conclusions about the influence of certain parameters on the mobility of landslides, there are trends that are common in most analyzes, which serve as a guide for the calibration of new models.

Empirical models for the evaluation of the mobility are practical tools that do not require detailed information about the materials involved in the events and represent a quick and precise solution when the necessary time for more complete studies is not available.

Travel distance models improve hazard maps and can be incorporated into computer programs along with more complex models for more accurate and adequate studies.

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