A preliminary Disintegration evolution Model for Weak Rocks and Intermediate Geomaterials IGM Cutting Slopes

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Abstract

Nowadays, Geotechnical engineers are facing a great challenge to interpret the data retrieved from IGM slopes with advanced stages of disintegration. This challenge is even greater when they need to define design parameters to be used in modeling software based on limit equilibrium, finite element method or discrete method. The complexity increases when to simulate the future performance based on the present disintegration state of the material is necessary. Thus, in order to help designers in the decision-making process relating to disintegration evolution, a preliminary general model that depicts the disintegration mechanism and the life cycle in weak rocks cutting slopes was stated. In the first instance, the model was stated as a descriptive observational model that could depict the Cycle Life of cutting slopes on weak rocks. Second, a detailed analysis of physical evolution phenomenon on the field was contrasted with the evolution at the laboratory level, in order to identify the most significant properties and variables related to disintegration evolution. Afterward, this descriptive model was combined with experimental data a general model was proposed. This stated model was weighed against experimental data and with the results of some bulk sample DEM simulations. Subsequently, based on the observed results, a mathematical function was chosen to look for a better fit with the observed disintegration evolution. The stated model was contrasted using the experimental data retrieved from the application of computer vision analysis for experimental setups.

1 INTRODUCTION

Every material in nature suffers disintegration; this process starts due to changes in its equilibrium state with the environment produced by external agents (weather, biological and anthropic). Disintegration rates and effects are not the same for all materials because of composition and microstructure that influences response at any given stimulus. Pointing to rocks, we can observe diverse disintegration behaviors in different rocks according to their lithological characteristics and diagenetic features. Mostly, the worst performance and the higher disintegration rates and susceptibility correspond to clay-bearing rocks, argillaceous rocks, shales and mudstones, Rocks denominated as weak rocks as well. Rincon *et al*., (2016)

In spite of, the variety of studies made over the last five decades about disintegration in weak rocks or slake as is usually recognized; some aspects about this phenomenon are not entirely elucidated yet. For instance, Chapman (1975) made recommendations to solve the lack of correlation in classification systems based on the slake durability test with the field performance. Since that time, this problem with suitability and representativeness of common static and dynamic slake tests results and the classification systems about observed field behavior have continued being reported over the years (Cano & Tomás, 2014; Erguler & Ulusay, 2009; Gautam & Shakoor, 2013; Heidari, 1983; Sadisun, Shimada, Ichinose, & Matsui, 2005; Santi, 1998). It exposes some weaknesses in the current state of knowledge about the process related to slaking, durability and disintegration, which has not allowed fulfilling this goal in a satisfactory way.

The disintegration of weak rocks, soft rocks, very weak rocks or intermediate geomaterials, occurs quickly after the rock is exposed to the environment. It generally occurs in a short time after the slope excavation process was started. It has generated several instability problems during infrastructure construction and operation, causing significant budget increments. A good example about this phenomenon is the Highway between Briceño Tunja Sogamoso located in the central zone of Colombia on the Andes Mountain Range. On that highway, one segment of about 80 kilometers was built in these types of materials. Since the construction project beginning, about 50 slope instability problems have appeared and nowadays some of them are still not solved; despite of a great variety of mitigation strategies applied such as retaining walls, anchors, piles, massive walls, etc. It occurs mainly because an accurate geotechnical characterization for these types of Geomaterials with different degrees of disintegration is not an easy labor, and simulate during the design the disintegration evolution with the time is complicated with the available constitutive models. This design limitation generates great uncertainties in the performance and stability valuation of the proposed structures. In some cases because of the high sensibility due to the low diagenesis of these types of rocks, just during the lapse time between geotechnical exploration and mitigation structures design the disintegration state has changed significantly making the designed structure not functional.

At the present, still, laboratory tests and classification systems are mainly focused in to stablish rock slake susceptibility or potential. However, test results do not allow knowing what is the current disintegration state or its future performance; it makes hard the labor for formulating coupled models that involve physical, mechanical, chemical, and thermodynamic properties combined with environmental variables for these type of materials with high slake rates. In general, the seeking of the disintegration models in geomaterials has been limited due to the majority of research works have been mainly focused on fragmentation evolution, mechanical properties variations related to saturation states, mineralogical variations or change in physical conditions. On the other hand, only few works combine field and laboratory data; it is mainly due to the difficulty of getting and keeping good samples, reducing the availability of good quality data in order to formulate general models of behavior.

Consequently, in order to seek models that help to simulate disintegration evolution on cutting slopes (formed by rocks with massive fabric as claystones and mudstones). This research project was trying to develop an in-situ and laboratory framework that affords to understand this process in all its possible stages, to be used as support for future works based on multiphysical models. The paper presents different theoretical, empirical approaches, made to define a general model of behavior for these type of materials, combining previous expert knowledge with observational and laboratory data getting from this research combined with Computer Vision and Microtremors measurements. Those technologies have not used before in this field of knowledge. The results indicated significant correlations between the degree of disintegration of the cut face, the dominant frequency estimated from the microtremor H/V ratio, and the image entropy values, suggesting that H/V ratio and image entropy can be reliable techniques for quantifying the degree of disintegration. So applying these novel methods was possible to make a consistent survey of disintegration evolution in laboratory and field that provides elements to state and validate a model for disintegration evolution. The stated model was weighed against experimental data and DEM simulations.

2 OBSERVATIONAL FRAMEWORK

Disintegration refers to break or decompose into constituent elements, parts, or small particles or to destroy unity or integrity (Merriam-Webster Inc., 2016). Scrutinizing this definition, a first query appeared, it was about the role of the object or substance under breaking or decomposing process. In other words, disintegration requires the existence of a body; thus, it can refer to the disintegration of some organism, some substance or element. Referring to geomaterials in a first view, the disintegration could be addressed with the change between an initial state **(i)** defined by a fragmentation condition **FS (i)** to a further material state **(i+1)** with a major fragmentation condition expressed as **FS(i+1)** (Fig. 1).

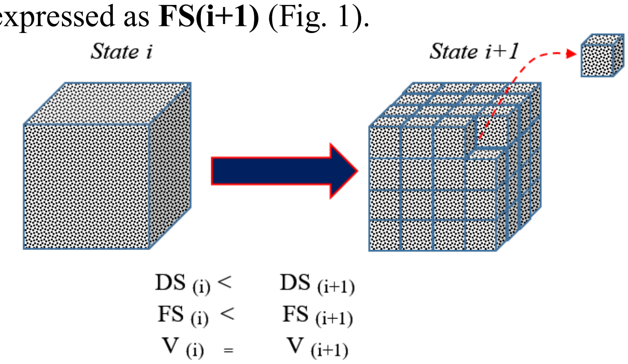

Figure 1. Disintegration states representation.

Here some interrogations appear: first ¿how many disintegration states a weak rock exhibits?, second ¿are the properties of the produced fragments equal to the original rock mass properties?, third ¿is the disintegration rate the same during the entire process?, and fourth ¿are the disintegration patterns the same at different scales?. Thus, in order to start to solve those questions an observational process was applied in field and laboratory upon cutting slopes on weak rocks and intermediate geomaterials IGM, developed over almost three years in the study zone. Thus, according to this process, three main disintegration states were identified for these type of materials (Fig. 2). The first state (**DS_1**) corresponds to the interval between time **t_0** when the material does not exhibit disintegration, and the time **t_1** when visible disintegration features appear on the material surface. The second state (**DS2**) corresponds to the interval between time **t_1** and time **t_2** when the material fragmentation is too high so the rock mass behaves like granular material; in other words, the material starts to behave as a soil. Finally, the third disintegration (**DS_3**) would correspond to the further time from **t_2** when slope material fragmentation continues evolving to lesser sizes, corresponding to sand and silt sizes.

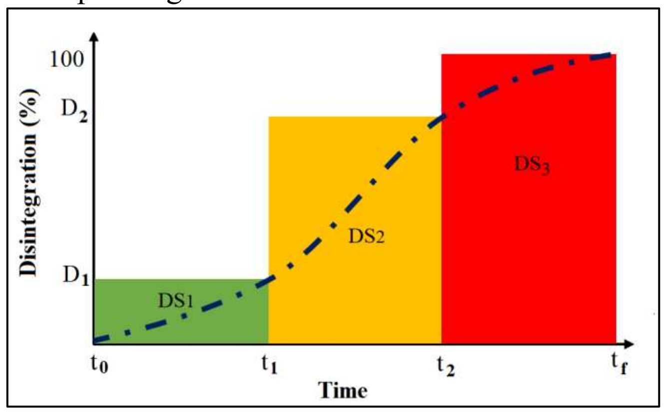

Figure 2. Sketch of disintegration evolution based on observational process.

Figure 3 depicts these three stages; so, in the initial state (**DS_1**) fragmentation and cracks are not observed; therefore, the material pores would be the main descriptor of the void spaces in the rock mass, and the material behavior can be considerate such as a continuum material with a low disintegration rate. On the second stage (**DS_2**), cracking process starts and subsequently voids begin to reduce due to shrinkage process on the clod zones, formed among cracks; thus, at this moment, cracks would be the main descriptor of the void spaces on the material and it starts to behave as discrete in some zones. Finally, on the third state, the crack density is too high making clods break and converting on isolated fragments, therefore, the rock mass lost continuity becoming in a discrete media; at this moment, the relation between size and fragment position will be the main descriptor of the void spaces on the material; in other words, its packing density.

On the other hand, through a careful monitoring and examination of slopes during three years, two disintegration evolution rates were identified on the assessed slopes, a high disintegration and low disintegration rates. These rates are associated with the slope exposed cutting surface disintegration state. Hence, when slope disintegration state corresponds to **DS_1** (very good initial state), disintegration evolves at low speed, when slope disintegration state corresponds to **DS_2** (medium disintegration), disintegration speed increase to a higher rate; it corresponds to the time interval when the material suffers more alterations and physical changes. Finally, when the exposed material reaches the high disintegration state **DS_3**, the disintegration rate decrease again to a low rate, because the relationship between fragment size and environment is different due to its scale and size, the fragment behaves as new independent material from the rock mass.

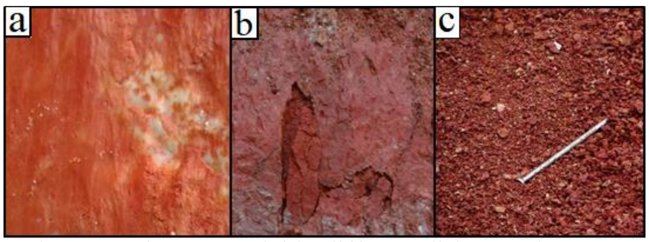

Figure 3. Slope Material in different disintegration states, after the cutting process a) DS_1 b) DS_2 c) DS_3

3 MODEL CORROBORATION

3.1 COMPARISON WITH WEAK ROCKS DISINTEGRATION CLASSIFICATION SYSTEMS

In order to get a better comprehension about the three identified stages, they were related with two of the most relevant weak rocks disintegration classification systems The Slake Durability Rating **SDR** (Erguler & Ulusay, 2009) and the disintegration ratio **Dr** (Erguler & Shakoor, 2009). Therefore, comparing with the stated **SDR** classes, the low disintegration level **DS_1** would corresponds to materials with field classification **IA** and **IB** (SDR 100-95%); medium disintegration level **DS_2** would corresponds to materials with field classification II-II-IV (SDR 94.9-40%); and high disintegration level **DS_3** would corresponds to materials with field classification V and VI (SDR 39.9-0%).

Furthermore, considering the disintegration results reported by Gautam and Shakoor (2013), applying **Dr** index upon several clay-bearing rocks exposed to environmental conditions during one year, was possible to recognize these rates of disintegration as well. They reported that the samples, extensively crumbled after one month (it would be the time **t_1**, corresponding to the end of **DS_1**); after three months they informed the samples did not have any intact pieces left (it would be the time **t_2**, corresponding to the end of **DS_2**). Finally, they informed that during the remaining nine months, the sample continued to slake but at a gradual rate (corresponding to **DS_3**). It confirms that the identified disintegration trends are present in similar materials.

3.2 EXPERIMENTAL VERIFICATIONS

Afterward, through the experimental results obtained from several rock samples with dissimilar disintegration states collected during a three years period, it was possible to identify correlation among the disintegration states and rock properties such as color, fragmentation, density, activity, thermal parameters, and wave velocity. For instance, Figure 4 shows the thermal conductivity results from 130 samples, the data are arranged according to the three ranges. A comprehensive report about it is presented on Rincon *et al*. (2016) that includes relations between image entropy, microtremors fundamental frequency measured upon cutting slopes and the three disintegration states for these rocks.

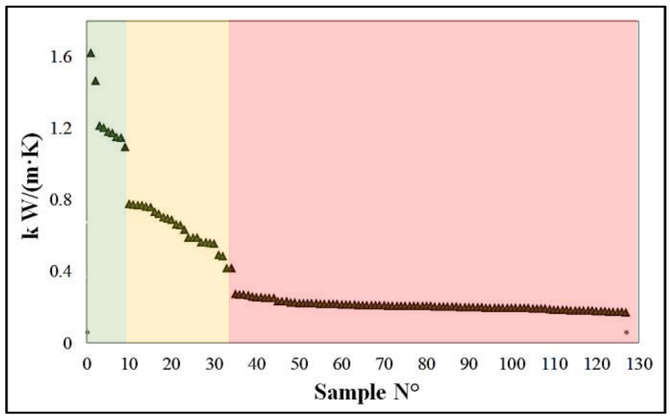

Figure 4. Relation of disintegration ranges and thermal conductivity *k*.

4 MODEL DEFINITION

According to the associations made among disintegration states **DS_1, DS_2, DS_3** and the experimental results, it was possible to infer that the disintegration evolution resembles an S shaped curve or sigmoid curve. Therefore, this trend suggests that the application of S curves would be useful for an adequate representation of the disintegration evolution process. Thus, considering that the logistic function (known as Sigmoid function as well) introduced by Verhulst in 1845, is represented by these type of curves, and the effectiveness reported on simulations process involving temporal evolutions (Weisstein, 2016); therefore, the logistic function was selected as a good model to link both mechanical and temporal scales referring to disintegration process in weak rocks. The logistic equation is known in two forms: continuum (Eq. 1) and discrete (Eq. 2); the discrete equation has become a paradigm of nonlinear equations including various states of the system. The discretization of the continue equation was made through Euler algorithm, looking for a major representativeness on certain temporal phenomena not achieved through the continue function (Ausloos & Dirickx, 2006).

$$D(t) = \frac{1}{1 + \left(\frac{1}{D_i} - 1\right) e^{-rt}} \qquad (1)$$

$$D(t+1) = rD_t(1 - D_t) \qquad (2)$$

Although, both functions offer great possibilities for their use in disintegration modeling just the continue function was applied to this research. Therefore, to test the function and to establish the possible correspondence with the stated observational model, a numerical sensitivity analysis was made considering different disintegration states **D(t)** and different disintegration growth rates **r** (Fig. 5) looking to select the adjust parameters. Therefore, three common numerical values (Table 1) were identified in all simulated sequences, and these values fitted with the S shape inflection points (that define the boundary between the three disintegration states.

Table 1. Parameter obtained for logistic model

Parameter	Fitted Value
D (t_1)	0.023730137742326
D (t_2)	0.211318986383594
D (t_3)	0.986386775414630

These three values correspond to irrational numbers, just how they appear in every simulation; it suggests that maybe they could be assimilated as mathematical attractors; in other words, as a set of states points in the phase space and invariant under the dynamics, towards which the system state tends to evolve. So, it implies that if those values are almost such a certain type of invariant, then they could be used as rough milestones to adapt the logistic model to represent disintegration evolution and the change in associated properties on the materials in an approximately way. Hence, to validate that supposition, different analyses were developed with experimental data acquired. For instance, Figure 6 shows the thermal conductivity data normalized, trying to observe the reduction in this parameter associated with disintegration evolution. The obtained curve shows how around 20% reduction corresponds with the transition zone between high disintegrated samples and middle disintegrated samples; it seems to be close the value of the number D(tb) 21.13%, if well the match is not perfect is close. The same trend was observed on other measured properties such as ultrasonic velocity.

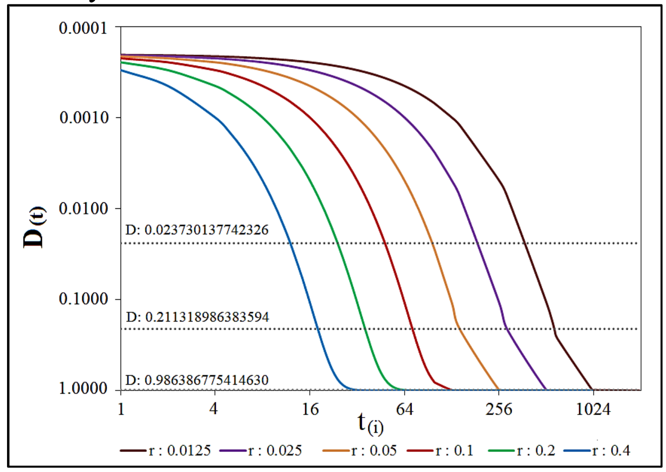

Figure 5. Sensitivity analysis results applying continue logistic function.

Therefore, in order to verify this trend, and looking for a better appraisal of this phenomena, different experimental setups were developed monitoring the temporal evolution of properties in the material under controlled conditions. Figure 6 shows the results from an experimental setup controlling wetting process in dried claystone, afterward kept it in an environmentally controlled chamber until it reaches the equilibrium water content again ; the entire process took 100 days; the temporal wetting plot shows a strong correlation r^2=0.99. Hence, analyzing the temporal evolution was possible to observe a clear sigmoidal trend, with the first transition around 21%, a value close to the D(t2) value and the second transition near 98% close to the value of D(t3)=98.63%. Figure 7 shows an inference realized from the reported **Dr** data presented by Gautam and Shakoor (2013), from a temporal evolution obtained during a one year exposure to natural climatic conditions for three Claystones. Despite, the initial disintegration condition (before the exposure), for the three samples was not reported; so, eyeing the obtained normalized plots, a transition is observed for the three curves around a 21% as well. It is a rough approximation, having in account that the temporal series reported were incomplete and Dr data-scarce for the early weeks where the affectation is greater for these type of rocks; however, for the three materials the disintegration evolution trajectories converge around D(t_2). Consequently, the trends suggest that the logistic function could be useful in order to estimate disintegration temporal evolution, and D(t_2) and D(t_3) could be used as numerical constants to estimate their properties.

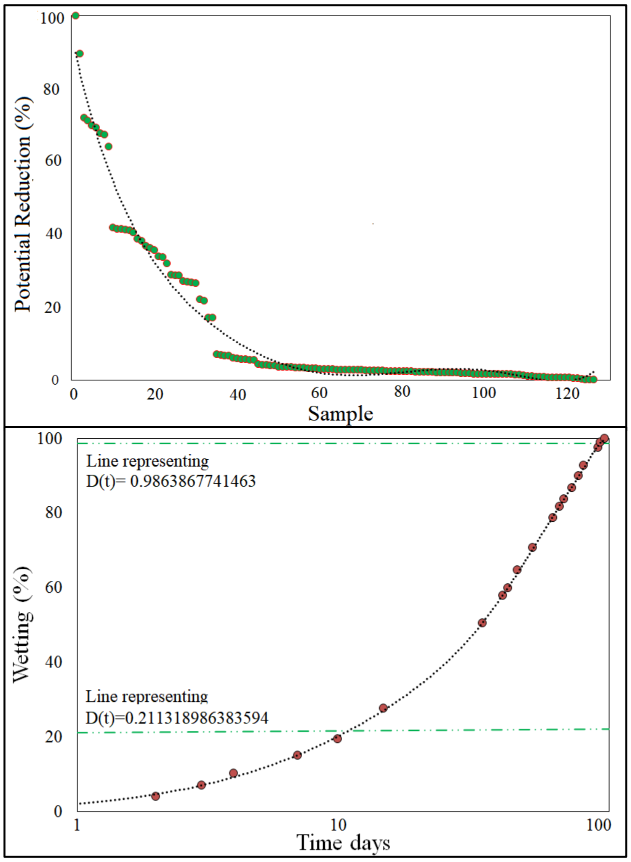

Figure 6. a) Thermal conductivity reduction b) Temporal wetting variation curve claystone Tilata formation.

Finally, an interesting feature was found assessing the ratio $D(t_3)/D(t_2)$; the obtained value is (4.6677), number almost equal to the Feigenbaum constant (4.6692); that is related with the chaotic behavior of systems, and representing period-doubling bifurcations on the logistic map that has been widely studied through logistic discrete equation (Eq. 2). Therefore, it could suggest that the disintegration process could be considered as a chaotic system, and it possibly predicted through the application of chaos theory; so, this path emerges as an alternative in order to make disintegration predictions and describe different states of the weak rock system. Hence, a new research branch appears here; so future experimental work and modeling will be required to understand it better.

5 ADDITIONAL CONSIDERATIONS

As a final point, in order to get a reliable model, textural changes on rock mass during disintegration advance should be considered; thus, the two principal textural related features for these types of rocks are crack frequency (λ) and particle or blocks size produced by fragmentation. Hence, conventional modeling tools based on limit equilibrium or finite elements do not guarantee a suitable representation of these two features during disintegration. Therefore, the discrete element method DEM was selected as an alternative for modeling, because this method offers capabilities through it would be possible to overcome those drawbacks. Thus, looking for a good way to represent disintegration states using a discrete model, the two disintegration descriptors aforementioned **SDR** (based on crack frequency λ) and **Dr** (based on fragmentation) were assessed and pondered considering which would be the better indicator to be used as control parameter into discrete models.

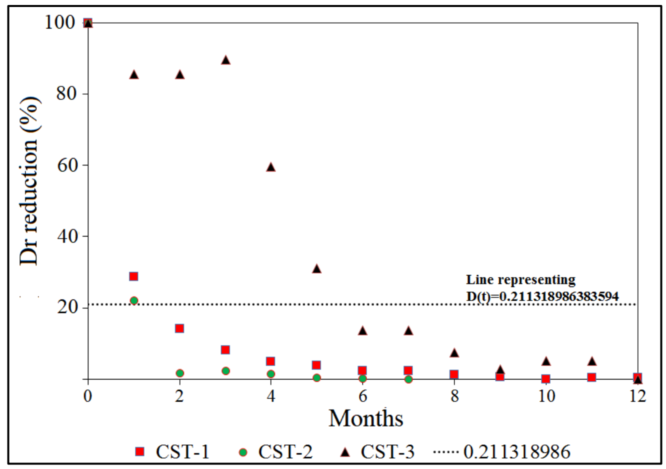

Figure 7. Dr temporal reduction for three Claystones, adapted from data presented by (Gautam & Shakoor, 2013)

The **SDR** index has problems with crack representation at the slope mass scale because it was developed using a 100 mm reference length. Therefore, if the slope in an early disintegration stage in which crack frequency is between 20 to 25 cm, using a 10 cm length measurement window probably none cracks are falling into the observation window; consequently, the fracture frequency assigned would be zero (λ=0), and the SDR value would be 100%. Then, the material would be classified as non-degraded material, valuation inconsistent with the real disintegration observed on the slope. Additionally, when fragmentation state is high, the frequency is hard to determine. Therefore, this parameter would not the better choice to depict and control disintegration evolution. On the other hand, because **Dr** parameter was stated based on fragment size evolution during disintegration, it makes it more reliable as a reference indicator and does not have scale issues as SDR parameter has; additionally, it could be easily measured and supervised on DEM simulations. According to the observed behavior during three years on the slopes constituted by weak rocks with non-fissile fabric, it was possible to establish that rock fragmentation would be considered the most important feature that depicts and influences disintegration behavior. If well, some cracks were present during the early disintegration stages, they would be incorporated when great size fragments are considered. Thus, the **Dr** would be more useful to map disintegration evolution into DEM models.

Afterward, an appropriate transitional rule that helps to depict fragmentation evolution for DEM was defined tracking disintegration evolution on materials in laboratory and field under various scales and conditions (Fig. 8). Through image analysis was possible to discover how the reduction of size between two consecutive disintegration states is. The observed trends suggest that the rock fragmentation roughly follows some self-similar patterns. Besides, combining with gradation results was possible to identify how the average size of the particles or blocks changed during different disintegration evolution stages. As a result, a transition fragment rule was stated; it is about a third of the diameter between successive fractions. Therefore, this relation was validated with the disintegration patterns observed upon laboratory-disintegrated samples and field exposed samples as well. Based on all these patterns, a mathematical artifact was developed to get an approximate fragmentation simulation. It was coded in Visual Basic® for Applications VBA. It works with a given initial fragment, and three parameters proposed from the observational process: the transitional diameter relation value **Tdr,** the value for the transition probability **Tpf**, and the transitional delay factor **Tdf** (a factor that defines the dissimilar behavior of the fragments aforementioned). Figure 9 shows a simulation of disintegration sizes for eight disintegration stages; the simulated distribution of particles matched pretty well with the distributions measured from slopes during the three years. As a result, the transition rule was adjusted and a transition probability matrix for size changes among disintegration sizes was stated; it allows simulating fragment evolution considering nonlinear behavior. Finally, the effectiveness of the stated model approach to be used on DEM models was analyzed.

Therefore, different slope configurations and particle arrangements were evaluated; for instance, Figure 10 shows the application of the suggested approach for two slopes geometries. This figure shows different disintegration states representing the progressive disintegration evolution acting from its surface to inward of slope mass. Different parameters were verified such as particle number, size and void increase (porosity). The progressive evolution was achieved applying the transformation relation proposed for each particle; the disintegration cycles were limited to three for each zone on the profile; the porosity evolution was between 0.102 (low disintegration) and 0.276 (high disintegration), and the granulometric distributions obtained match very well with the measured from samples in different fragmentation stages. To finish, the proposed transition rule was integrated with the other criterions necessary for DEM simulation such as contact model, crack frequency, and failure controls for slopes in these type of rocks on the study zone that were defined by Buenahora and Bravo (2014).

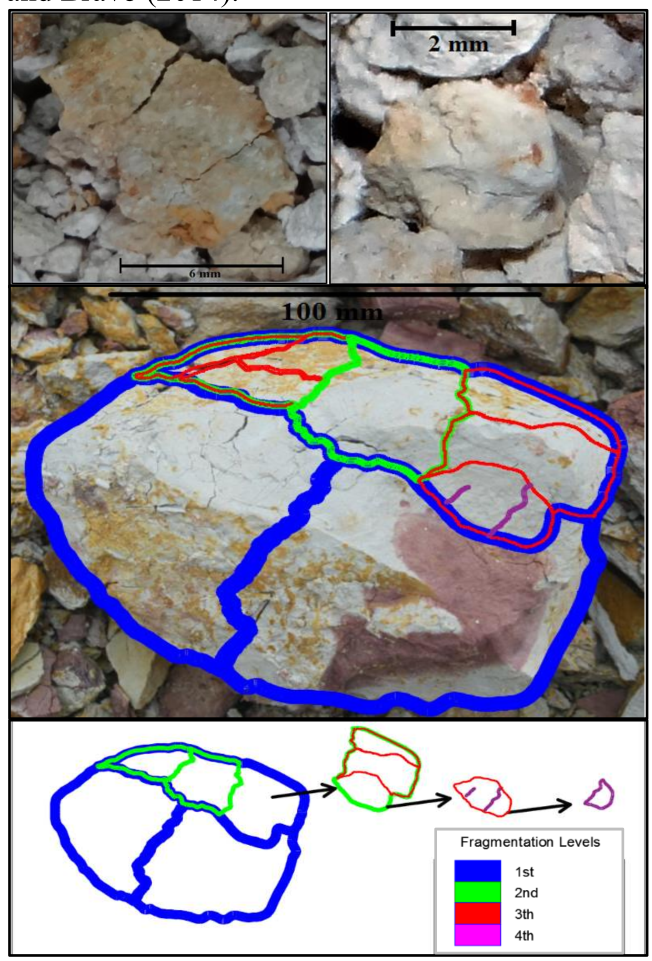

Figure 8. Inferred disintegration sequence different sizes, laboratory and field samples.

6 CONCLUSIONS

The combination of field and laboratory observations, combined with experimental results and different modeling tools, was useful to state a model that allows reliable disintegration simulations for slopes on weak rocks and IGMs.

The better disintegration index to be used as a control parameter on disintegration simulation on the slopes constituted by weak rocks with non-fissile fabric is the Dr ratio, because it controls changes in particle size distributions of slaked material.

According to the experimental results and the simulations developed was found that the logistic function could be useful in order to estimate the temporal evolution of disintegration phenomenon and the properties of the materials at different disintegration states; even evidence was found that it could be useful to model disintegration as dynamical system or chaotic system considering bifurcation states.

Weak rock disintegration could be associated as a progressive process, in which the material changes repeatedly from an unstable condition to a more stable condition; it means that weak rocks with early diagenesis are not in a stable state, because they are in intermediate lithification process; so when material is exposed after cut, their equilibrium is lost and the geomaterial must evolve toward a more stable form (soil) in which the predominant minerals attain their most stable forms.

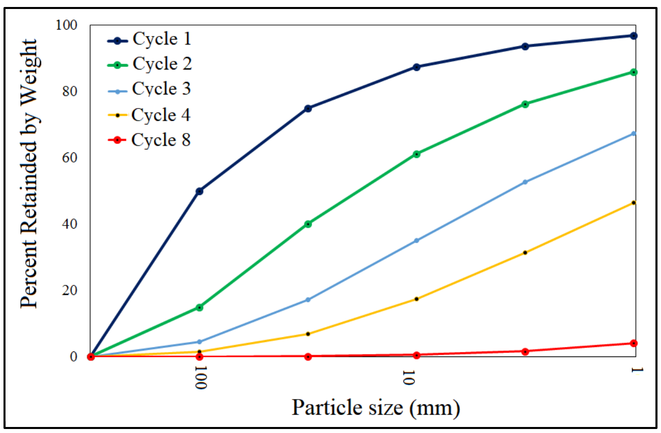

Figure 9. Grain size evolution disintegration simulation

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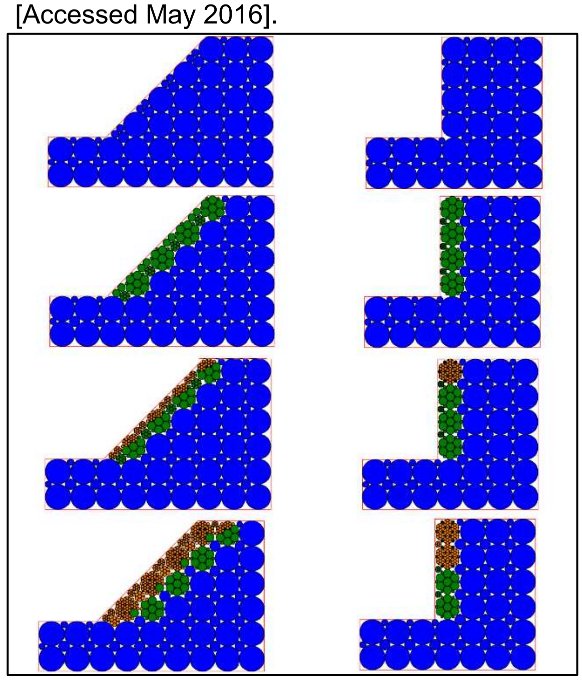

Figure 10 Simulation disintegration evolution two slopes