DEBRIS FLOWS: Disasters, Risk, Forecast, Protection

Proceedings
of the 5th International Conference

Tbilisi, Georgia, 1-5 October 2018

Editors
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Publishing House “Universal”
Tbilisi 2018

СЕЛЕВЫЕ ПОТОКИ: катастрофы, риск, прогноз, защита

Труды
5-й Международной конференции

Тбилиси, Грузия, 1-5 октября 2018 г.

Ответственные редакторы
С.С. Черноморец, Г.В. Гавардашвили

Издательство Универсал
Тбилиси 2018

ღვარცოფები: კატასტროფები, რისკი, პროგნოზი, დაცვა

მე–5 საერთაშორისო კონფერენციის მასალები

თბილისი, საქართველო, 1–5 ოქტომბერი, 2018

რედაქტორები
ს.ს. ჩერნომორეც, გ.ვ. გავარდაშვილი

გამომცემლობა "უნივერსალი"
თბილისი 2018

УДК 551.311.8
ББК 26.823

Селевые потоки: катастрофы, риск, прогноз, защита. Труды 5-й Международной конференции. Тбилиси, Грузия, 1-5 октября 2018 г. – Отв. ред. С.С. Черноморец, Г.В. Гавардашвили. – Тбилиси: Универсал, 2018, 671 с.

Debris Flows: Disasters, Risk, Forecast, Protection. Proceedings of the 5th International Conference. Tbilisi, Georgia, 1-5 October 2018. – Ed. by S.S. Chernomorets, G.V. Gavardashvili. – Tbilisi: Publishing House “Universal”, 2018, 671 p.

ღვარცოფები: კატასტროფები, რისკი, პროგნოზი, დაცვა. მე–5 საერთაშორისო კონფერენციის მასალები. თბილისი, საქართველო, 1–5 ოქტომბერი, 2018. გამომცემლობა "უნივერსალი", თბილისი 2018, 671 გვ. პასუხისმგებელი რედაქტორები ს.ს. ჩერნომორეც, გ.ვ. გავარდაშვილი.

Ответственные редакторы С.С. Черноморец, Г.В. Гавардашвили
Edited by S.S. Chernomorets, G.V. Gavardashvili

Верстка: С.С. Черноморец, К.С. Висхаджиева, Е.А. Савернюк
Page-proofs: S.S. Chernomorets, K.S. Viskhadzhieva, E.A. Savernyuk

При создании логотипа конференции использован рисунок из книги С.М. Флейшмана «Селевые потоки» (Москва: Географгиз, 1951, с. 51).
Conference logo is based on a figure from S.M. Fleishman’s book on Debris Flows (Moscow: Geografgiz, 1951, p. 51).

ISBN 978-9941-26-283-8

Brazilian tropical residual soils as the solid phase sources of local occurring mud and debris flows due to heavy rains

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Residual soils result from a complex "in situ" weathering, decomposition and disintegration processes of several rock types and classes. Residual soils represent an accumulation of regolitical mass where the upper layer is a mature residual soil, represented by a totally decomposed rock mass matrix located on terrains surface and extending to more profound and deep situated saprolitic rock masses these less attained by the mentioned transformation process. The profile defined by the mentioned extremes soil materials constitutes lithosphere's regolitical cover. All regolith's properties, such as density, permeability, strength, deformability and other physical/mechanical features are conditioned by intensity and duration of geophysical and geochemical reactions that develop in rocky milieu. Residual soils, in a simplified first approach, are constituted by: a) granular frictional, non-cohesive soils represented by coarse grained gravel and sandy soils as acid rocks weathering products, and b) cohesive fine grained silt and clayey plastic soils resulting mostly from basic rocks weathering processes. Rock mass weathering occurs due to high temperatures and intense rainfall rates of tropical and subtropical environment. During the intense long duration rains, in mountainous regions of the country, hillside slope failures occur very frequently. Many of them result in mud and debris flows. Bingham's rheological model is usually employed to simulate stress-strain behavior of fine grained clayey soils and respective water admixtures that occurs as shallow or deep slides upon local conditions. Deep slides involve saprolitic and/or less decomposed rocky material. Bagnold's macro viscous, or eventually inertial models, represent well the rheological behavior of such solid-liquid phase mixtures. Some characteristic of residual soils grain size curves is commented. Recently occurred accidents in country's mountainous regions, involving properties and human life losses, are mentioned and briefly discussed.

brazilian tropical residual soils, weathering processes, residual soils properties and characteristics, rainfall induced mud and debris flows, representative rheological models

Тропические остаточные почвы как источник твердой составляющей селевой массы для селей ливневого типа в Бразилии

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Остаточные почвы являются результатом комплексных процессов выветривания, разложения и дезинтеграции нескольких типов и классов горных пород in situ. Остаточные почвы представляют собой скопление реголитической массы, где верхний слой представляет собой зрелую остаточную почву, представленную полностью разложенной матрицей горных пород, расположенной на поверхности и простирающейся до более глубоко расположенных сапролитовых породных масс, которые меньше подвергаются упомянутым процессам трансформации. Профиль, определяемый указанными экстремальными почвенными материалами, представляет собой литосферный реголитический покров. Все свойства реголита, такие как плотность, проницаемость, прочность, деформируемость и другие физико-механические особенности, обусловлены интенсивностью и продолжительностью геофизических и геохимических реакций, которые развиваются в твердой среде. Остаточные почвы при упрощенном подходе представляют собой: а) гранулированные фрикционные, несплошные почвы, представленные крупнозернистыми гравийными и песчаными почвами как продуктами выветривания кислых пород; б) сплошные мелкозернистые иловые и глинистые платстичные почвы, образующиеся в основном в результате выветривания основных пород. Выветривание горных пород происходит из-за высоких температур и интенсивных осадков, характерных для тропического и субтропического климата. Во время интенсивных продолжительных дождей в горных районах страны очень часто происходят склоновые процессы. Многие из них приводят к грязевым и грязекаменным потокам. Реологическая модель Бингхэма обычно используется для моделирования поведения стресс-деформаций мелкозернистых глинистых почв и соответствующих водных примесей, которые происходят в виде мелких и глубоких оползней в местных условиях. Глубокие оползни включают сапролитный и / или менее разложившийся каменистый материал. Макро-вязкие, или, в конечном счете, инерционные модели Багнольда хорошо отражают реологические свойства таких смесей твердой и жидкой фаз. Прокомментирована некоторая характеристика кривых размера зерна остаточных почв. Упоминаются и кратко обсуждаются произошедшие недавно в горных районах страны события, связанные с имущественными и человеческими потерями.

тропические остаточные почвы Бразилии, процесы выветривания скальных пород, свойства и характеристики остаточных грунтов, грязевые и каменно-грязевые сели ливневого типа, представительные реологические модели

Tropical soils

At a first glance tropical soils are associated to their geographic location which occurs in tropical belt range of earth's sphere limited in northern and southern hemispheres by the tropics circles latitudes.

The tropical belt is defined as earth globe's regions of:

a) Humid tropical zones where the year's rainy season period is greater than seven (7) month and the yearly rainfall precipitation rate is larger than 2000 mm/year;

b) Sub-humid tropical zones with four (4) to seven (7) month long rainy season with precipitation rates superior than correspondent evapotranspiration rates in the same period as mentioned by Silva Dias (2001).

A more detailed characterization of earth's tropical zones is given by Ayoade (1983), with some geographic, astronomic, climatic and meteorological properties of earth surface, cited as:

1 - Area of the earth sphere which is situated between the Cancer and Capricorn tropics circles or 22°30′ latitudes of both hemispheres;

2 - Sites on the earth surface where the apparent trajectory of the sun attains zenithal point of the celestial hemisphere.

3 - Earth surface locals where mean annual temperature value is equal or smaller than the mean daily temperature range.

4 - Earth surface sites at sea level where the mean temperature of the year's coldest month is equal or greater than 18ºC.

5 - Earth surface regions characterized by absence of an accentuated cold season (winter period).

6 - Earth surface areas with total annual rainfall amount larger than 2000 mm.

Some important and particular aspects conditioned by former mentioned characteristics and properties are regarded as main factors in relation to tropical soils formation.

They are mainly:

a) The solar activity resulting as an sun irradiation of greater intensity and duration, that results in higher temperatures actuating on lithological and regolitical mantle and on surrounding them air or water environment;

b) A greater rainfall rates which occur as consequence of intense atmospheric dynamic processes situated in tropics range what results in more frequent, intense and long duration precipitations;

c) The resultant increased runoff, infiltration and subsuperficial percolation rates; and

d) A resulting dense vegetal cover recovering earthen tropical surface areas which include: rain forests, bush and shrubs lands, and grass specimens covered prairies areas.

Tropical residual soils

The tropical residual soils and their weathered original underlayed rock strata constitute the regolitical mantle of the upper layer of the lithosphere in tropical environment as characterized before.

In a strict sense mentioned tropical residual soils are sufficiently thick accumulated strata of “in situ” weathered, as will be discussed later, decomposed and/or disintegrated rock matrix and mass which recovers the sound original rock.

Weathering processes occur mainly by variable cyclic temperature’s variation (heating/cooling) and also cyclic and variable water content (saturating/drying) actuating on the superior regolitical cover.

As proposed by Deere and Patton (1971) rock weathering processes involve two distinct class of mutation.

The transformations of chemical and physical-mechanical nature that occurs as: a) - rocks matrix or constituent’s decomposition, and b) - rocks mass structural disintegration. Dearman (1974) offers a detailed study of both weathering processes with elucidative Figures that are not presented here. Both weathering processes reduce in individual or integrated form, the mechanical strengths of the rock matrix material and the overall structural strength of the rock mass. In this way residual soils genesis process essentially transforms the solid state sound rock, in another solid state material of reduced cohesion and consequently mechanically less resistant characteristics and properties.

The regolitical strata profile are sequential horizons named from the top to the bottom sound rock, as:

a) mature residual soil (top covering humus layer and upper layer soil layer);

b) immature residual soil or developed saprolitic soil (upper intermediate depth);

c) residual saprolitic soil with reliquary original rock structures (lower intermediate depth);

d) weathered rock (deep placed layers), and

e) original sound rock (bottom layer), as presented by Vargas (1978), on the following Fig. 1.

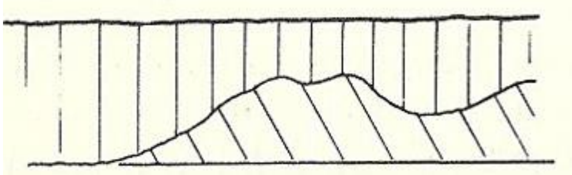
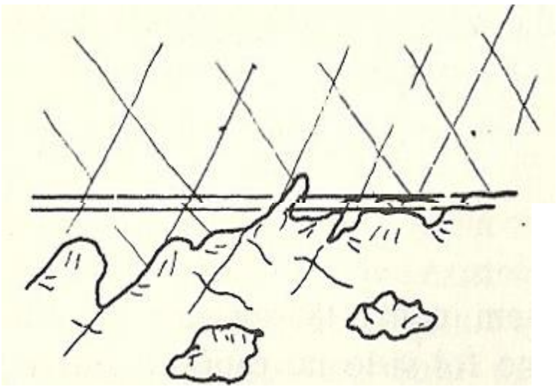
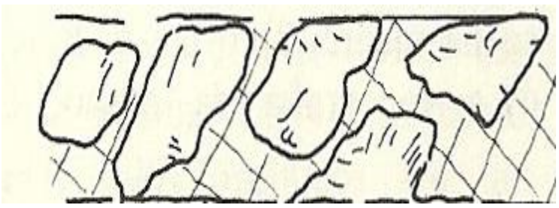
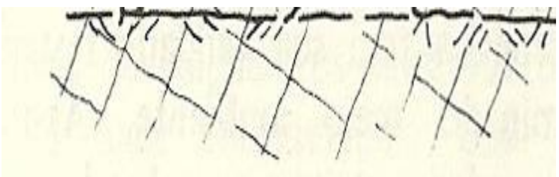
Horizont I (a) 0-10 m.		Humus and porous sand or clay; Slopes covering colluvial soil or mature residual soil with limonitic concretions at the bottom.
Horizont II (b) 5-15 m.		Brown, red or yellow clay; Stiff residual soil or residual saprolitic soil.
Horizont III (c) 0-70 m.		Clayey sand, with gravels and cobbles which maintain the rocks original structure; Slightly weathered rock.
Horizont IV (d) 0-100 m.		Intensively weathered rock with numerous boulders permeated by decomposed rock components.
Horizont V (e) >100 m.		Sound (fractured/fissured) original rock.

Fig. 1. Typical residual soil profile resultant from weathered gneiss or granite in Southern Brazil. [*Vargas, 1977. Introduction to Soil Mechanics*], translated and adapted by the author.

The weathering processes in Brazil attain sometimes significant and large extension (depth) values reaching about one hundred meters deep in some extreme cases (see Fig. 1).

The sound underlying rock's horizons, due to local conditions, transform in a weathered rock maintaining original structural features, or in amorphous saprolitic/lateritic shallow rock or soil shell strata of a moderate depth and small thickness.

The ultimate stage of a completely weathered rocky material is a residual fine grained sand or clayey mature soil that forms a shallow regolitical cover of moderate about one meter thick depth.

Rock mass weathering and decomposition or disintegration processes

Distinct lithological rock classes

The representative rocky materials media is formed by macro volumes of a specific rock matrix that include the pertinent families of discontinuities and constitutes the overall rock mass media.

Normally differentiated lithological strata are encountered and are represented by different sets of rock types and classes.

They are:

a) igneous or magmatic;

b) metamorphic; and

c) sedimentary rocks.

Either, mineralogical and chemical, or estratigraphic and textural, or physical and mechanical properties and characteristics of mentioned rock type, constitute quite heterogeneous media presenting between them some important and substantial differences.

A short overview of the different genetically constituted rock types is presented as follows.

Rock types upon their genetic origin

There are three types of rocks grouped upon their geological genetic, chemical and physical-mechanical characteristics and properties:

a) Igneous-magmatic rocks; spread as large extended extrusive layers (batholiths) or as vertical and/or sub vertical diaphragms (dikes) or intrusive chimneys. The melted rock mass is submitted to rapid or slows cooling processes and result in more or less fractured and discontinuous mass;

b) Metamorphic rocks with different mineral origins; are subjected to tectonic movements and/or crust volcanic thermal action of variable intensity, duration and frequency. Large tectonic deformations and an intense geothermal action contribute to a formidable number of metamorphisms which attaint the original igneous-magmatic masses and create a very large number of different and specific metamorphic rock classes.

c) Sedimentary rocks; are depositional products of sediments in a fluid (liquid or gaseous) environment. These rocks are an assembling of different size fragments, with a distinct cohesion or cementation level between them, resulting in variable strength products. They are deposited as successive horizontal/sub horizontal layers, in sub aquatic or sub atmospheric environment.

The three mentioned rock types are all submitted to weathering and to the superimposed mass transport processes by gravity, hydraulics or both, and result in different kinds of residual soils.

The first attempt of a genetic classification and description of residual soils in Brazil was done by M. Vargas (1951), with the valuable professors K. Terzaghi's consultancy and assistance, during the high head (~800m) Cubatão Hydroelectric Plant design and construction at Sao Paulo-Brazil, in the late 50th years of the past century.

A tentative specific approach to residual soils from gneisses was established at this time in regard to a regolitical material quite different from materials of glacial origin originated in colder and temperate zones of the earth (moraines).

Some time later Brazilian residual soils were classified, upon their silica content, as citied by Teixeira Guerra (1966) represented by:

a) acid, light colored or leucocratic matrix, with high silica content (Si > 65%);

b) neutral, with a medium silica content (65% < Si < 52%);

c) basic, with a moderate silica content (52% < Si < 45%); and

d) ultra basic, dark colored or melanocratic matrix, with low silica content (Si < 45%) and predominant iron (Fe) and magnesium (Mg) components.

It is easy to see that the acid rocks, of high silica content, result in more resistant weathered products and generate easily large sized sediments such as boulder, cobbles, gravels or a granular and sand rich cohesion less soils.

On the other side, the basic and ultra basic rocks, with low silica content, submitted to weathering processes, result in less strong but cohesive and fine grained, clay and silt rich, residual soils.

The two extreme situated igneous rock classes that represent either acid or ultra basic rocks are the family of granites, with high silica content (Si) and the peridotites or basalts and diabases with high iron (Fe) and magnesium (Mg) content.

The mentioned igneous rocks classes and their derivates metamorphic and sedimentary lithological classes are largely encountered in the Brazilian territory, mainly located at the southeastern mountain ridges (Serra do Mar, Mantiqueira, Paranapiacaba, and others) of the country.

Coincidently the above mentioned places contain also the highest elevation peaks of Brazil's mountains and encompass the largest observed rainfalls sites of the country.

The conclusion is that at such points the occurrence of large (deep) and as well of small (shallow) hill-side slopes ruptures are very common events. Slope ruptures transform frequently in severe mud and debris flow events upon large pluvial precipitations.

Rock's mass weathering, as was mentioned, is strongly related to decomposition and disintegration processes which are produced by distinct and different chemical attacks and physical/mechanical reactions.

The decomposition of original rock matrix encompasses chemical agent's action such as oxidation, oxides reduction, hydration, carbonation and some time vegetations or animal's chemical action.

As result original rock matrix material passes through color and texture changes, mechanical strengths, hardness and soundness reduction, and other minor transformations.

Rock mass disintegration processes are mostly structural changes that result due to temperature and water actions that develop principally along rock mass discontinuities.

Resulting infiltration and percolation through discontinuities, with saturation and super saturation state of whole rock mass with some physical vegetal and animals caused effects, contribute all to the disintegration processes in variable degrees.

A typical example of weathering process is done by *Worcester* [1949] mentioned by Vargas (1951). It is an attack of mixture of water and carbonic acid on any rock mass/matrix composed by iron, calcite, magnesium, sodium or potassium.

An orthoclastic granite rock is mentioned by the author as example:

$$K_2O\ Al_2O_3\ 6SiO_2\ (orthoclast \rightleftarrows) + H_2CO_3(carbonic\ acid) + 2H_2O(water) \rightarrow$$

$$\rightarrow K_2CO_3\ (so\,lub \rightleftarrows \rightleftarrows le\ potassium\ carbonate) + Al_2O_3\ 2SiO_2\ 2H_2O\ (kaolinite) + 4\ SiO_2\ (silica).$$

Disintegration processes are rock mass size reduction by the increase of rock mass discontinuity and permeability by percolation, what results in friability of rock matrix and includes particles shape, modification beside other structural changes [*Dearman, 1974*].

Resulting products are an extended and large range of solid particles, with dimensions varying from rock fragments (blocks, cobbles, gravel and debris) to fine and very small sized particles of cohesion less sediments (sand, silt, clay and colloids).

Granulometric studies on residual soils samples or precisely of their fine grained fractions, identify two sorts of grain size curves: a)- apparent, and b)- real, both referring to the same soil sample.

The cluster and honeycomb structures of fine grained residual soils hide the real and/or actual granular composition or meritics spectrum.

Strong mechanical action, as such that occurs during mud and debris flow discharges, destroy the original soil structure. The result is a remolding process of whole soil mass.

Laboratory test recurs to the use of deflocculating substances which individualize the solid grains reducing cohesive bond tensions between them.

The mixture of the solid and liquid phase produces dispersed biphasic systems or the stony, muddy and viscous flows (upon Takahashi 1991) of variable dispersed content (different volumetric/weight concentrations) and of large and variable sediments grain size range.

Distinct grain size fractions are easily associated with different mud and debris flow types as was observed by *Znamensky and Gramani* [2000] and proposed by *Takahashi* [1991].

The coarse and medium grains size domains (M) and (m), or in other words, blocks, cobbles, or gravel and sand fractions of residual soil are classified by American Geophysics Union (AGU) [*Gottschalk*, *1964*] and are responsible for its frictional characteristics.

Resulting solid-water mixture discharges in these cases are inertial stony debris flows or macro viscous mudflows containing (acid) rocks coarse sediments.

On other side clay mineral constituents of residual soils are originated from basic rocks and result as small sized sandy granular domain (μ), or as cohesive fines fraction sediments (silt, clay, colloids).

They confer to the solid-water mixtures plastic and viscous characteristics with a turbulent behavior at presence of excessive water content (supersaturated state).

The graphical representation of the grain size domains is presented on the Fig. 2 of this text.

Mass transportation process of "in situ" residual soils deposits.

Both overlapped decomposition and disintegration processes of the rock mass and of the rock matrix produce "in situ" residual soils.

Regolitical soils are classified upon their specific topographic locations on hill side slopes and receive specific geomorphologic designations.

The "in situ" generated residual soils are transported either by gravity force or by hydraulic forces as erosion processes, both observed on the hillside slopes.

This way the residual soils are classified as: 1)-stables or no transported (static state), and as 2)-mobilized and transported (moving dynamic state):

(1) Eluvial or top placed strata, without any significant or only a slight mass transport, mostly as salt solutes that form residual soil lateritic horizons.

(2) Coluvial or slope deposits, commonly designated as talus, result mostly from gravitational mass movements along the hillside slopes but also include water transported sediment masses as an erosion product.

(3) Alluvial or fluvial deposits of transported sediments occurring on terraces of water course plains, as large mass transportation process due to high exceeding surface flow or runoff.

A brief summary of stables (non-transported) and of mobilized (transported) soils is presented here:

a) "In situ" generated elluvial regolitical products or mature residual soils represent mudflows solid phase sources;

b) Eluvial regolitical products are transported on slopes by gravity and/or hydraulic force actions as initiation process of geotechnical or hydraulic phenomenon's but are rapidly extinguished on the slopes;

c) Larger transportation modes occur where morphologic aspects of natural terrain, local hydrological regime of the water basins and soils geotechnical properties define the coluvial process classes as slides or/and flows resulting in mud or debris flows.

d) Deposited products concentrate on distinct locations at the lower part of hill side slopes or even at their bottoms already in the channels.

An elucidative example of hypothetical residual soil profile is reproduced in previous presented in the text Fig. 1. The pictured details correspond to a hypothetic soil profile with a maximal 100 meters depth (Vargas 1978) derived from highly weathered, decomposed and disintegrated, metamorphic rock (gneiss) a very common lithological feature in southern Brazil (Serra do Mar).

Physical and mechanical characteristics of granular and cohesive residual soils

Tropical residual soils characteristics and classification and their description is performed using the ordinary formulas from classical Soil Mechanics. Some basic concepts of the saturated Soil Mechanics, proposed in the past by several researchers are extended to the tropical residual soils and are applied to engineering problems solution, some times with only slight modifications.

The two large domains of the tropical residual soils are:

a) Granular or no cohesive soils, represented by blocks, cobbles, gravel and/or sand particles fractions, and

b) Plastic cohesive soils represented by fine sand, silt and clay fine grain particles fractions.

Granular no cohesive (frictional) residual soils

Granular and no cohesive residual soils are represented by sand and/or gravel particles fractions. Considering in the first place granular non-cohesive soil represented by gravel and/or sand fractions, their solid skeleton's relative density D_R, is figured alternatively in terms of void ratio (e), porosity coefficient (n) or dry unit weight (γ_D).

The relative density D_R parameter is figured in the two first citied cases as dimensionless quantity and is written as void ratio or porosity quotients functions as follows [*Maslov, 1987; Lambe, 1979; Vargas, 1978; Sowers 1963*]:

$$D_{R\,(\text{Void Ratio})} = \frac{e_{max} - e}{e_{max} - e_{min}} \quad , \qquad (1)$$

$$D_{R\,(\text{Porosity}-\text{Coefficient})} = \frac{(n_{max} - n)}{(n_{max} - n_{min})} \cdot \frac{(1 - n_{min})}{(1 - n)} \qquad (2)$$

Another way to represent relative density of granular non-cohesive fraction of soils establish the relative density parameter D_R, as function of specific dry weight of solid skeleton ($kg \cdot m^4/seg^2$), or as analogous functions of (ρ) dry unit mass or solid grains absolute density (kg/m^3) and/or (δ) grains relative density or specific gravity (dimensionless parameter).

$$D_{R\,(\text{Specific Weight})} = \frac{\gamma_{Dmax}}{\gamma_{Dnat}} \left\{ \frac{(\gamma_{Dnat} - \gamma_{Dmin})}{(\gamma_{Dmax} - \gamma_{Dmin})} \right\} \qquad (3)$$

Both parameters (1) and (2) components are expressed either in terms of the void ratio (e) or porosity coefficient (n) and are detailed in sequence: $e=V_v/V_s$, is natural soils void ratio, where, V_v represents soil skeleton's voids and V_s solid grain's volumes (m^3); e_{max} and e_{min} are respectively maximum and minimum void ratio or voids and solids volumes quotients all figuring as dimensionless parameters; $n= V_v/V_T$, is natural soils porosity coefficient, with $V_T=V_s+ V_v$, or sum of previously defined components volumes (m^3); n_{max} and n_{min} are respectively maximum and minimum porosity coefficients both dimensionless parameters.

In Equation (3) figured symbols mean: $\gamma_{Dnat}=g\rho_{Dnat}/V_s$, is dry soils (grains skeleton) specific weight ($kg \cdot m^4/seg^2$), or alternatively $\rho_{Dnat}=\gamma_{Dnat}V_s/g$, is unitary mass or absolute density of dry solid grains mass (kg/m^3) with gravity acceleration g (m/seg^2), or $\delta_{Dnat}=\rho_{Dnat}/\rho_W$, that is solid grains dimensionless relative density or specific gravity with water's absolute density as ρ_W =1 (kg/m^3).

The relation between the relative density parameter D_R and specific weight γ_{Di}, and alternatively unitary mass parameter $g\rho_{Di}$ or δ_i, is also written upon [Maslov, 1982] as:

$$\gamma_{Dnat} = \frac{\gamma_{Dmax} - \gamma_{Dmin}}{\gamma_{Dmax} - (\gamma_{Dmax} - \gamma_{Dmin}) D_R} \qquad (4)$$

The extreme values for specific granular material, together with the actual relative density value, assess the necessary specific weight and unit mass or specific gravity of a particular granular soil mass.

It is observed that $\gamma_{Dmax}=g\rho_{max}$ and $\gamma_{Dmin}=g\rho_{min}$ values refer to physically possible maximal and minimal extreme values of dry grains skeleton arrays that are established by different particles package features.

It is worthy to observe the great difficulties of field and/or laboratory evaluation of the mentioned parameter values.

The great difficulty of a current use of (Eq. 1), (Eq. 2) and (Eq. 3), as applicable design data, is to specify and also to obtain, by a laboratory (or field) testing, reliable extreme values of all next mentioned parameters such as: a) void ratio (e_{max}, e_{min}), b) porosity coefficient (n_{max}, n_{min}), c) specific weight (γ_{Dmax}, γ_{Dmin}) or d) unit mass (ρ_{Dmax}, ρ_{Dmin}).

Table 1. Designation, Relative Density range (D_R) and correspondent penetration resistance (SPT) of residual granular incohesive soils [*Terzaghi, Peck, 1948*] and [*Maslov, 1982*].

Designation	**Relative density ratio D_R (%)**	**Number of blows N (SPT)**
Extremely loose	0-20	0-4
Loose	20-40	4-10
Medium	40-60	10-30
Dense	60-80	30-50
Very Dense	80-100	>50

The geotechnical practice in Brazil uses a standardized qualitative designation set associated with field exploratory data (SPT) to assess quantitative values of relative density ratio D_R (see Table 1).

Tropical cohesive residual soils

Conventional and arbitrary water content as determined by some easily performable tests in field or by classical procedures adopted in laboratory establish various characteristic of mechanical behavior of the tropical residual soils.

They are known as:

(1)- Shrinkage limit (LC);

(2)- Plastic limit (LP);

(3)- Viscous limit (LV), and

(4)- Liquid limit (LL).

The well known Atterberg's limits are: shrinkage limit (LC), plastic limi (LP) and liquid limit (LL). The relatively unknown parameter viscous limit (LV) mentioned here is situated between (LP)<(LV)<(LL) and corresponds to semi-solid or plastic and to semi-fluid or liquid behavior and state of the soils and water mixture.

Determination of (LV) and its relation to degree of saturation (Gs) is important as it corresponds to soils water content when the saturated regolitical mass begins to creep in irreversible and unlimited way.

Or in other words, if soils water content increases mixture of soil and water yielding becomes more and more plastic and ultimately transforms in a Newtonian fluid discharge.

Table 2. Soil water content and the respective limits and indexes of soil/water biphasic mixtures [*Holtz, Kovacs, 1981*], in Venezuelan Disaster; [*Umeya, 1983*], Advances in Mechanics and Flow of Granular Materials.

Soil states	Soil dispersed in gas (fluid)	Solid-plastic state	Solid Plastic viscous state	Fluid Liquid viscous state	Soil dispersed in liquid (fluid)
Water content	Super Dry	Humid	Unsaturated	Saturated	Super Saturated
Limit	<LC	LL–LP	LP<LV	LV<LL	>LL
Consistency	IC>>1	IC≥1	IC	IC≤1	IC<<1
Fluidity or Liquidity	IF<<0	IF≤0	IF	IF≥1	IF>>1

The Komamura and Huang [*1974*] proposed viscous limit (LV) did not get a large use as an expedite measure of practical value and get not an acceptance between the geotechnicians. Some ambiguous use of IL and IF is still occurring due to indefinite meaning of solid unsaturated (LP) or fluid saturated (LL) state of the soils mass.

Consistence index IC of tropical residual cohesion less and cohesive soils

Residual soils are classified upon their consistence figured as consistence index below.

$$I_C = \frac{LL - h_{nat}}{LL - LP} = \frac{LL - h_{nat}}{IP} \qquad (5)$$

Where: h_{nat} is the soils natural humidity, figuring as a dimensionless ratio between the interstitial water and the dry soil weights ($h=P_a/P_s$), and (IP=LL–LP), as plasticity index parameter largely employed by *Casagrande* [1948] in his Unified Soil Classification System.

Table 3. Soil state description, consistence index and unconfined compression strength ranges of tropical residual soils

Soil state description	IC Consistence index (dimension-less)	(R_{Uas}) Axial unconfined strength (kPa)
Fluid (Liquid)	IC=0	R_{Uas}=0 $R_{Uas} < 0,5$
Soft plastic	0<IC<0,50	R_{Uas}<0,5
Medium plastic	0,50<IC<0,75	0,5<R_{Uas}<1,5
Stiff plastic	0,75<IC<1,00	1,5<R_{Uas}<4,0
Solid (Hard)	IC≥0	R_{Uas}≥4,0

Vargas [1977]. Introduction to Soil Mechanics.

The consistence index IC classify in qualitative way the bond and toughness of tropical residual soils relating axial unconfined compression strength of cohesive clayey soils and the confined relative density of cohesion less granular sandy soils by Atterberg limits and Casagrande’s IP index.

Fluidity index IF of cohesive soils (silts, clays and colloids)

If the water content of a soil mass results in a fluid (liquid) state of regolitical body its liquidity or fluidity index is obtained as follows:

$$IF = \frac{h_{tot} - LP}{LL - LP} = \frac{h_{tot} - LP}{IP} \qquad (6)$$

Where: $h_{tot}=h_{nat}+h_{plu}=h_{nat}+\Delta h$, or the natural soil water content plus the introduced rain water during the saturation processes.

A comparison between consistency and fluidity index of residual soils is figured in the next Table 4.

Saturation (S) and Aeration (A) degree indexes of granular and cohesive tropical residual soils

The partial air/water replenishment of the voids origins residual soils at aerated or dry, unsaturated or partially saturated, completely saturated and at super saturated (submerged) state with exceeding water content as pounding (static) or flowing (dynamic) surface water.

Soils void volume is can be occupied only by air (a practically weightless fluid-gas mixture) V_G (m3), or by water (a fluid-liquid mixture of known density) V_w (m^3), or as a complementary and simultaneous replenishment of soil voids by air and water.

$$S = V_W / V_V \qquad (7)$$

$$A = V_A / V_V \qquad (8)$$

The figured parameters of saturation (S) and aeration (A) define and describe quantitatively the soil voids occupation by anyone of the fluids.

Between the parameters S and A exist the relation S+A=1, as can be easily verified.

Toughness and Liquidity indexes of cohesive soils (clays and silts).

The relation between the parameters IC and IF is proposed by many researchers [*Maslov 1982; Holtz and Kovacs 1981*], and is figured as an ultimate saturation or super saturation state as a sum of IF+IC=1, when IC≤0 (liquefied and supersaturated mixture).

$$IF + IC = \left[\frac{h_{tot} - LP}{IP} + \frac{LL - h_{nat}}{IP}\right] = \frac{LL - LP + \Delta h_{plu}}{IP} - \frac{h_{nat} - LL}{IP} = 1 + \frac{\Delta h_{plu}}{IP} \qquad (9)$$

$I_F = 1 - I_C$ The ratio between IC and IF, is the toughness index IT of a mixture of cohesive residual soil and water and Figures as:

$$IT = \frac{IC}{IF} = \frac{(LL - h_{nat})/(IP)}{(h_{tot} - LL)/(IP)} = \frac{LL - h_{nat}}{h_{tot} - LL} \qquad (10)$$

Similarly, an inverse ratio as figured in (Eq. 10) is the liquidity index Il=IF/IC of the same mixture of cohesive residual soil and water [*Lambe, 1979*].

Table 4. Comparison between consistency and fluidity indexes of tropical residual soils *[Vargas, 1977*]. Introduction to Soil Mechanics

Consistency index (IC)	Fluidity index (IF) or Liquidity index (IL)
IC=0 (Liquefied saturated soil)	IF<1,00 (Supersaturated mixture)
0<IC<0,50	1,00>IF>0,50
0,50<IC<0,75	0,50>IF>0,25
0,75<IC<1,00	0,25>IF>0,00
IC>1,0 (Solid stiff soil)	IF<0,00 (Stiff and rigid solid mixture)

Grain size curves of microgranular cohesive and macrogranular non-cohesive frictional residual soils

Tropical residual soils very often present a liaison between their individual grains due to variable strengths cementation.

The resultant flocculated or honeycombed structure is formed by a random grains association that masks the soils real granular specter.

Lateritic soils with a strong ferruginous cementation are a typical example of that phenomenon.

But there is also residual soil that are only weakly cemented and are ready to suffer desegregation and so changes of grain distribution spectra even under small loads.

The dissolution of chemical components of the cements by water saturation of mineral particles is another cause.

The general result in accumulated grain size curves graphical representation is a shift toward the side of fine diameters as pictured (see Fig. 2.).

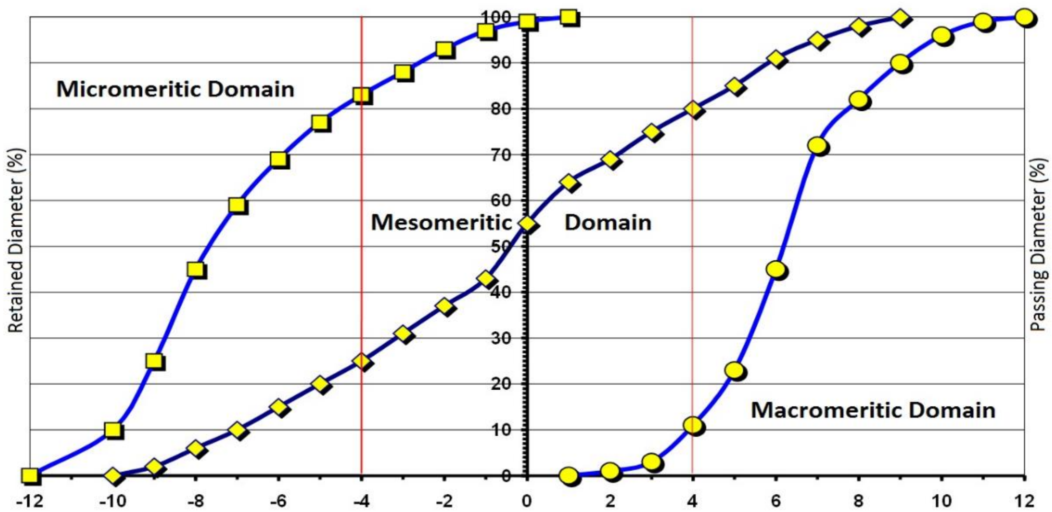


Fig. 2. Deflocculated or remolded soil structure move and increase the grain size curves toward fine grains content

If debris flow is submitted to size reduction processes there is a trend of the coarse grain assemblies to become transformed in a finer grain size fraction. Impact shocks and shearing frictional mechanical effects are responsible for such kind of transformation.

In concern to a smaller size grains assembly's the cements dissolution and/or chemical desegregation action is present at sandy mud and clayey viscous type's mudflows.

In a general way it is assumed that the grain size transformation occurs as M→m→μ what is exemplified in following pictures (Figures 3 and 4).

The debris and mudflow grain size curves present a coarse grain size (apparent specter) at the beginning of the flow process and (real specter) at final stage of the movement.

Grain size reduction occurs chemically by deflocculating admixtures use but also by water interaction with solids. Small sized particles (μ) intermingle easily with the water and produce a more or less viscous fluid matrix that is responsible for the flow movement of the mud.

A resume of regolith's movement is presented on next Table 5, connecting and overlapping geotechnical and hydraulic processes created by heavy rain falls.

Resultant saturation and/or super saturation result in rapid surface runoff flow (erosion) or in slow and time lagged subsurface seepage flow (rupture and flow).

The predominance of the first or second mode determines geological or hydraulic oriented regolith's mass movements and different mitigation measures proposed by Vargas (1999).

Fig. 3. Stony type debris flow with fragmented blocks of sienite (acid) rock increasing medium and small size grains content (M.F. Gramani)

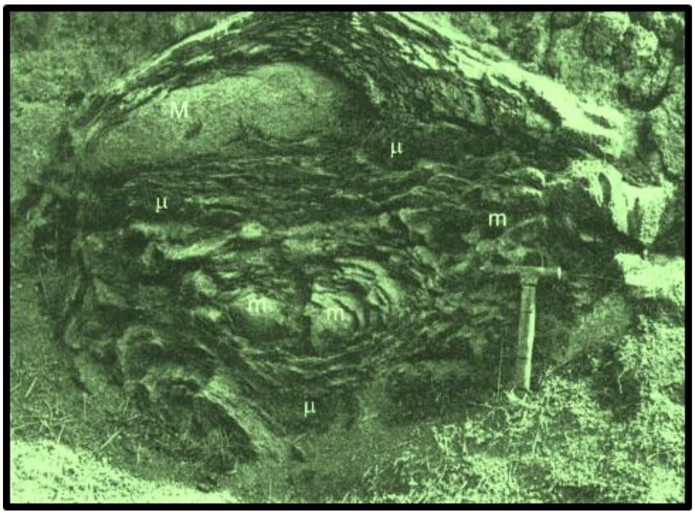


Fig. 4. Weathered basalt block (basic) rock with saprolitic "onion shale" features of fine grained residual soil (μ) and larger particles (M, m) (A. Teixeira Guerra).

Fig. 5. Typical weathered gneiss/granite eluvial and residual talus soil mud flow and fresh rock debris flow on hillside slope at Rio de Janeiro coast (W. A. Lacerda).

Fig. 6. Mudflow on hillside slope and debris flow at river channel due to heavy rains in Santa Catarina state.

Table 5. Regolith's movements in the tropical mountainous regions of the Southeastern Brazil (Serra do Mar), caused by typical observed rainfall thresholds (*)

Movement	**Class**	**Occurrence**	**Causes**	**Prevention**
Slow plastic and viscous soil movements	Creep of surface layers	Slow creep movements mobilizing partially the regolith's shear resistance	Constant movement accelerated during the rainy seasons	Surfaces drainage and impermeability
	Hillside slopes deposits slides	Continuous movement mobilizing former slides slope deposits	Slopes toe cuts performed during the rainy seasons	As in the previous case plus drainage by deep horizontal holes or galleries
Slides along rupture surfaces	Planar slides	Shallow slides on soil-rock contacts slopes	Sudden ruptures during or after rains with a rate superior to 100 mm/day (*)	Idem as in both previous cases plus hill sides slope reductions with toe berms construction. Gravity or anchorage retention structures
	Rotational slides	Residual or saprolitic soils slides with eventual cobbles or rock blocks inclusions	Ruptures occurring at rainfall end periods	
Rock mass structural slides	Rock wedge slides	Slides along slopes planar discontinuities	Sudden ruptures during or after rains with a rate superior to 100 mm/day (*)	Anchoring of rock blocks.
	Highly fractured rock mass slides	Slides of discontinued rock mass blocks with eventual intermixed mud component		Anchored structures
	Rock falls	Unstable rock mass blocks stability loss	Ruptures occurring not necessarily at rainfall end periods	
Earth and Rocks Avalanches	Mudflows	Erosions and liquefaction of regolith's upper mantles	During heavy rainfalls with a rate superior to 50 mm/hr (*) at rainy periods of the rainy years	Not existent
	Debris-flows	Hydraulic induced ruptures of heavily fractured and weathered rock masses.		

Vargas [1999]. Historic and conceptual revision of the Serra do Mar slides.

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