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A unified expression for grain size distribution of soils

Li Yong [a,b,*], Huang Chengmin [c], Wang Baoliang [d], Tian Xiafei [a,e], Liu Jingjing [a,b]

[a] *Key Laboratory of Mountain Hazards and Surface Process, CAS, Chengdu 610041, China*
[b] *Institute of Mountain Hazards and Environment, CAS, Chengdu 610041, China*
[c] *Department of Environmental Science & Engineering, Sichuan University, Chengdu 610065, China*
[d] *School of Civil Engineering, Southwest Jiaotong University, Chengdu 610031, China*
[e] *University of Chinese Academy of Sciences, Beijing 100081, China*

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ABSTRACT

Grain size distribution (GSD) is fundamental for soils and usually described by a set of graphic parameters (e.g., median size, kurtosis, skewness, uniform and curvature coefficient). Some probability distributions (e.g., lognormal and Weibull distribution) are used for special cases, but no general expression is available. In this paper we propose a general distribution form of $P(D) = CD^{-\mu}\exp(-D/D_c)$ for various soil materials, with $P(D)$ the exceedance percentage and C, μ and D_c are parameters determined by the grain size frequency data. The power-law and exponential part of this expression respectively responds to the self-similar and random processes of grain fragmentation and accumulation in soil generation and evolution. The GSD parameters are distinct in soils and their variation reflects the changes in grain composition, such as the grain migration and segregation in landslides, avalanches, debris flows and sedimentary deposits. In addition, the GSD also fits the pore size of granular materials, confirming the grain-pore duality and suggesting an important role of the GSD expression in dynamics of soils and granular media in general.

1. Introduction

Soils of various types can be considered as a conglomerated system of particles covering a wide range of grain size, and the grain size distribution (GSD) is the most fundamental physical property (Hwang et al., 2002; Huang et al., 2012) and always the start point of soil studies. For examples, GSD has been used to predict soil hydraulic characteristics (Gupta and Larson, 1979; Arya and Paris, 1981; Tyler and Wheatcraft, 1989; Fredlund et al., 1994, 1997; Arya et al., 1999a, 1999b; Hwang and Powers, 2003; Mohammadi and Meskini-Vishkaee, 2013), trace the environments of soil genesis and sedimentary deposition (Sahu, 1964; Visher, 1969; Friedman, 1979; Fieller et al., 1984; McLaren and Bowles, 1985; Walker and Chittleborough, 1986; Tanner, 1991; Vincent, 1996; Buurman et al., 1997; Moustakas, 2012; Prins et al., 2000; Stuut et al., 2002). Moreover, GSD also governs dynamical properties in surface processes such as avalanches, landslides and debris flows (Savage and Lun, 1988; Iverson and Vallance, 2001; Barendra, 2010; Johnson et al., 2012). In general, GSD is useful in understanding the erosion, transport, and deposition of sediment, identifying the trends and patterns in response to surface processes, determining the slope stability, tracing the liquids-particles reactions, and studying fluids through the porous sedimentary deposits (Syvitski, 1991).

Conventionally, GSD is described by statistical and graphic parameters, including special sizes such as D_{10}, D_{30}, D_{60}, coefficients of sorting, uniform and curvature, and skewness and kurtosis. These are strongly dependent on the probability distributions (Folk and Ward, 1957; Koldijk, 1968; Vanoni, 1975; van Genuchten, 1980; Kondolf and Adhikari, 2000; Rubin and Topping, 2001; Dodd et al., 2003; Grunnet et al., 2004). A set of so many parameters is hard to be incorporated into any integrated description of soil property; and in practice only some are "selectively" used for special properties. Even in use, graphic method is a post mortem approach (Hartmann, 2007) and makes sense through comparisons between soil samples, taking no part in dynamical evolution of soil processes.

Various GSD expressions have been proposed, like the lognormal distribution (Gardner, 1956; Kittleman, 1964; Sparks, 1976; Buchan, 1989; Shiozawa and Campbell, 1991; Hwang et al., 2002; Labiadh et al., 2011), Weibull (or Rosin-Rammler) distributions (Shirazi and Boersma, 1984; Hartmann and Christiansen, 1988; Wagner and Ding, 1994; Zobeck et al., 1999), Gompertz distribution (Nemes et al., 1999), and log-skew Laplace distribution (Flenley et al., 1987). All these distributions appear like a parabola in semi-log scale plot (i.e., the normal percentage vs. the log-scaled size) while like a hyperbola when plotted in log-log scale, the so-called "hyperbolic distribution" (Bagnold, 1941; Bagnold and Barndorff-Nielsen, 1980; Christiansen et al., 1984;

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* Corresponding author at: Key Laboratory of Mountain Hazards and Surface Process, CAS, Chengdu 610041, China.
E-mail address: ylie@imde.ac.cn (L. Yong).

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Hartmann and Christiansen, 1992). Some researches (e.g., Deigaard and Fredsøe, 1978) suggest that the parabolic distribution could transform to the hyperbolic by sorting process; and others indicate that it is hard to distinguish the lognormal and Weibull and Gama distribution (Kondolf and Adhikari, 2000). There are also models based on soil hydraulic properties (Havercamp and Parlange, 1986; Smettem and Gregory, 1996; Fredlund et al., 2000), and derived from soil genesis processes (Bittelli et al., 1999) and from limited soil texture data (e.g., Skaggs et al., 2001). However, these distributions fit only for special cases, and no priori knowledge is available for the selection of distribution form. Their suitability relies on the content of fine or coarse grains (Hwang et al., 2002); even the most often used lognormal distribution applies only to half of the USDA texture triangle (Buchan, 1989). The really and biggest difficulty is that all the distributions fit only the unimodal pattern, but most soils have multimodal frequency distribution. Although it is possible to combine the unimodal distributions, say, in form of linear combination (Sheridan et al., 1987; Wohletz et al., 1989; Shih and Komar, 1990; Sun et al., 2002), just like using a Fourier series to fit a signal, it is hard to ascribe any meanings to the components. For example, in some cases the sediment can be associated with a certain sedimentary process (Visher, 1969; Middleton, 1976; Grace et al., 1978; Chambers and Upchurch, 1979; Bridge, 1981; Pedreros et al., 1996; Gray and Ancey, 2011), but we cannot in general relate the components to any specific phases.

More often used in GSD is the cumulative curve, which presents an S-shaped pattern in semi-log scale and derives many graphic parameters, such as the coefficients of curvature, slope and sorting. But in the log-log scale, the cumulative curve appears simply a convex curve or sometimes presents a straight segment over a certain scale. The straight log-log segment has been identified as the fractal since the late 1980s (Turcotte, 1986, 1997; Tyler and Wheatcraft, 1989, 1990; Perfect and Kay, 1991; Rieu and Sposito, 1991a, 1991b; Perfect et al., 1992; Brown and Wohletz, 1995; Taguas et al., 1999; Caruso et al., 2011), showing the self-similar hierarchical structure of grain composition (Tisdall and Oades, 1982; Jongmans et al., 1991; Dı'az-Zorita et al., 2002; Bronick and Lal, 2005). But the fractal dimension derived from the plot varies considerably with and depends sensitively on the lower cut-off and the upper limit of the scaling domain (Bird and Perrier, 2003). Moreover, a single fractal dimension cannot cover the whole soils having multiple scaling segments (Avnir et al., 1985; Tyler and Wheatcraft, 1992; Pachepsky et al., 1995; Bittelli et al., 1999; Posadas et al., 2001; Millán et al., 2003; Filgueira et al., 2003, 2006; Li et al., 2005). Still, there are conceptual difficulties as for the physical meaning of "fractal" in soil sciences (Baveye and Boast, 1998).

Literature review indicates that there has long been a "thought inertia" (or paradigm) in soil study that we are used to or even content with individual distributions or graphic parameters in expressing the GSD (e.g., Folk, 1966; Bittelli et al., 1999; Nemes et al., 1999; Hwang et al., 2002), having no idea for a general expression. In the previous studies (Li et al., 2013) we've found that a scaling form of distribution applies well to materials of landslides and debris flows. In this study we extend the distribution to a great variety of soils from different sources, confirm its universality and then make some discussions on its dynamical implication in soil evolution and mass movements.

2. Granular analysis and data sources

2.1. Granular analysis methods

Granular analysis is the basic procedure in soil studies and several techniques are widely used over the years (Poppe et al., 2014). In practice, grain size analysis consists of isolating grains and measuring the weight fraction (i.e., the frequency) of grains within a size interval. For sand and gravel grains, the fractions are determined by sieving method; and for silt and clay grains, below 0.075 mm (the No. 200 sieve size), by sedimentation methods (e.g., the pipette or hydrometer methods). Graphs of a GSD are displayed by either the fraction of a size interval (frequency curve) or the cumulative fraction. This procedure has long been operated in soil studies (e.g., Liu and Evett, 2008; Das, 2008; Knappett and Craig, 2012; Skopp, 2012) and recommended as the standard method by authorities in the world, like BS 1377–2 (UK), CEN ISO/TS 17892–4 (Europe), ASTM D 422-63 (Reapproved 2007) and ASTM D6913 (2009) (US). We do our GSD analysis following the conventional ways and the data we adopted from literatures are also obtained in the same ways.

2.2. Data collection

The data in the present study are collected by the authors and adopted from literatures, involving a variety of granular materials: soils (in the sense of pedology, geotechnique or engineering), colluviums, sedimentary deposits and materials of mass movements on earth surface (Table 1). The data set covers a wide spectrum of soil types and geographic conditions, including plain and plateau, grassland and forest, sea coast and desert, landslides and glacial lakes. In addition, we also use the UNSODA2.0 database (Nemes et al., 2015) for comparison and confirmation, involving 790 soil samples from various sources. For simplicity, hereafter we use the word "soil" to mean all the objects when no ambiguity will arise.

Although the soil samples from different authors are taken for different purposes, the grain size analysis is conducted in almost the same standard procedures as mentioned above (e.g., Su et al., 2004; Spriggs and Ray-Maitra, 2007a, 2007b); this guarantees their reliability for use. Considering the size of the dataset, the more or less uncertainties arising from the sample collection and artificial operation make little difference for our present studies focusing on the statistic feature of the grain composition.

For an example of the data form of granular analysis, we list two datasets in Table 2. Table 2a displays soil samples from Nevada (Spriggs and Ray-Maitra, 2007a, 2007b), also showing the classification of soil grains. The clay and silt grains are analyzed by hydrometer method. Table 2b lists two groups of soil samples from the Hainan Island in south China. The two groups are taken from different sites and for each site we take soils at different depths. Grains below 0.075 mm are analyzed by pipette method.

Grain frequency is defined as the weight ratio of the grains within a size interval to the total mass of the soil sample:

$$p(\Delta D_i) = \frac{\text{weight of grains within } \Delta D_i}{\text{total weight of grains in } (D_{\min}, D_{\max})} \times 100\% \tag{1}$$

where ΔD_i is the successive grain size interval for statistics, such as (0.002, 0.05), (0.05, 0.125), and ($D_{\min}$, $D_{\max}$) is the grain size range of the soil sample. From $p(\Delta D_i)$ it is easy to get the cumulative percentage $P(<D_i)$ or $P(>D_i)$ (thereafter we use $P(>D)$, the exceedance percentage, or, simple $P(D)$ in equations). Although the fractions depend on the choice of size interval ΔD_i, it matters little to the cumulative curve.

Soil grains are usually considered as grains below the gravel, up to sand grains (2 mm). But we are often encountered with much more coarse materials, such as the sedimentary materials of landslides and debris flows, with grains up to gravel or cobble size (>80 mm), according to the Field Classification of Soil Using the USCS (ASTM standards D 2487 and D 2488). Grain compositions for those wide-ranged soils are referred to our previous studies (e.g., Li et al., 2013, 2014).

3. General features of grain composition

3.1. Grain size frequency

Grain size frequency is usually displayed by the semi-log plot of $p(D)$-Log(D), which presents various patterns: unimodal, bimodal and multi-modal or their irregular combinations (Fig. 1). Unimodal and