Segregation Index—A New Soil Parameter for Internal Erosion Assessment

Peter To and Thinh Le Van

Abstract Internal erosion is a major cause related to nearly half of dam dysfunctions and failures. This phenomenon occurs when loose soil particles are transported outwards the soil mass by seepage through a series of pores and pore constrictions. As loose particles are usually fine and embedded in the pores formed by the soil primary fabric, traditional methods often correlate the representative sizes of fine and coarse particles to indicate the susceptibility to internal erosion of an assessed soil. These methods are not very accurate because soil particle size distribution can vary widely with several identical key sizes. This paper presents a new indicator for internal erosion assessment using the probability to be transported of loose particles: the segregation index. This index is estimated experimentally and analytically for the correlation with internal erosion test results. The index also has a significant role in the estimation of real effective stress of soils.

Keywords Segregation · Internal erosion · Assessment · Dam · Soil characteristics

1 Introduction

In general, internal erosion is a common term that indicates the transportation of soil particles by seepage in a soil mass. A statistic study over recorded incidents of large dams revealed that internal erosion is related to nearly half of all dam failures and dysfunctions [1]. Based on the location of the transportation, internal erosion is classified as suffusion (inside a soil), concentrated leak (along a crack in a soil), backward erosion (piping outward a soil), and contact erosion (between two soils) [2]. In turn, these types of internal erosion can be subdivided into subcategories. For

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example, general suffusion can be divided to suffusion (with no soil volume change) and suffosion (with soil volume change) [3]. Recently, perpendicular contact erosion has been removed from contact erosion category [4]. Note that, some classification systems of internal erosion may include more types of seepage deformation, such as clogging [5]. In this paper, internal erosion is referred to as the transportation of soil particles within a soil mass.

Soils with high susceptibility to internal erosion often have a bimodal structure, where fine particles are embedded loosely in pores formed by coarser particles. These fine and loose particles can be mobilized and transported by seepage if the flow is strong enough and there is no geometrical obstacle. Hence, traditional assessment methods often correlate a few key sizes of fine and coarse particles to estimate the internal stability of soils [6, 7]. These methods may not be very accurate because soil *Particle Size Distribution* (PSD) can vary widely with the same fixed key sizes. For examples with the same d_{10} and d_{60}, a PSD can be either gap-graded or continuously graded. A recent quick method proposed to use a flexible key size to estimate the susceptibility to erosion for only continuously graded soils [8]. Some analytical and numerical studies proposed to compare the fine particles with pore constrictions, formed by coarse particles [9, 10]. The key to the success of these methods is a correct separation of fine and coarse particles from the main PSD [11]. While several studies employed a delimiting size on PSD to separate fine and coarse particles [12, 13], a recent numerical study proposed that there is an overlapping zone between these two fractions [14]. A comprehensive overview of assessment methods can be found in a recent critical review [15].

As the results of analytical assessment often come from a calculating process, they often come in the format of a “yes/no” answer rather than an index, which presents the susceptibility to internal erosion. In fact, soils are heterogeneous, so an “erodible/non-erodible” answer may not reflect comprehensively the susceptibility of soil to internal erosion. A recent study on the expended energy for internal erosion proposed a sophisticated erosion resistance index [16]. Although this index considers many aspects in an indirect compound estimation, it does not directly include the probability to be transported of fine particles. This paper presents segregation index, a new and simple index with a direct link to the transportation of particles. The novel concept is based on a probability analysis and is validated with laboratory results.

2 Probability Analysis

In general, a fine particle can be transported if two conditions are satisfied: (i) Hydraulic condition—the seepage flow is strong enough to transport the particle; and (ii) Geometric condition—no geometric obstacles are preventing the transportation. To satisfy the first condition, the hydraulic gradient must be larger than a critical hydraulic gradient [17]. Meanwhile, the second condition may be more difficult to assess. Firstly, the fine particle must not be kept in the soil primary fabric, i.e., it is loose and does not contribute to the stress transfer. Secondly, the particle must be

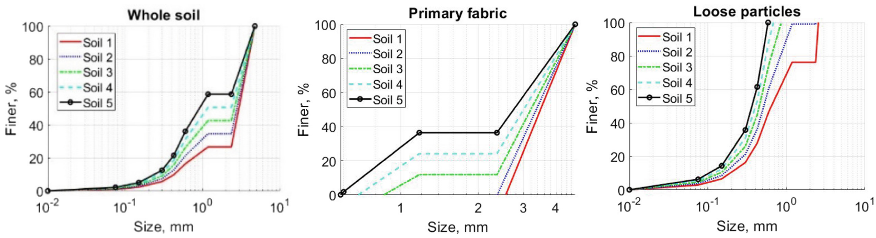

Fig. 1 Particle size distribution: whole soil (left); primary fabric (middle); loose particles (right)

smaller than the pore constriction—the narrowest dimension of the paths connecting pores. In a metaphor, furniture can be removed only if it is smaller than the door size. Thirdly, there must be room for the particle in the next pores. If the porosity is low and fine particles fully fill pores, the particle will not be transported to the next pore. A full answer to the second condition may be reached by a numerical approach, where soil samples are digitized [18] or numerically generated [19]. However, the current computational ability has not been able to facilitate the simulation and computation of a large sample yet. A 1 cm^3 soil sample may have billions of clay particles with irregular shapes. Hence, a probability analysis may be suitable to current engineering applications.

In the first step, soil primary fabric and loose particles are separated to form independent fractions. To avoid the uncertainty of the separation [15], this paper uses some gap-graded soils for analysis (Fig. 1). The gap width is not too big so that the soils are still considered as continuously graded for internal erosion assessment [8]. In this study, the gap levels are at 26, 34, 42, 50, and 59%. If the gap level is more than 35% finer, coarse particles may not be in contact with each other [17]. Hence, the delimiting point is set at d_{35}.

Then, the constriction sizes are computed based on the combination of three and four coarse particles. The size of a constriction formed by three particles, d_{c3}, is calculated by Soddy theorem [20]:

$$d_{c3} = \frac{d_{p1}d_{p2}d_{p3}}{d_{p1}d_{p2} + d_{p2}d_{p3} + d_{p1}d_{p3} + 2\sqrt{d_{p1}d_{p2}d_{p3}\left(d_{p1} + d_{p2} + d_{p3}\right)}} \tag{1}$$

where d_{pi} = size of the ith particle forming the constriction. The size of a constriction formed by four particles can be calculated from the size of the equivalent area [21].

$$\begin{aligned} A_{equal} = 0.125\big(&\left(d_{p1} + d_{p2}\right)\left(d_{p1} + d_{p4}\right)\sin\alpha + \left(d_{p2} + d_{p3}\right)\left(d_{p3} + d_{p4}\right)\sin\gamma \\ &- \left(\alpha d_{p1}^2 + \beta d_{p2}^2 + \gamma d_{p3}^2 + \delta d_{p4}^2\right)\big) \end{aligned} \tag{2}$$

where $\alpha, \beta, \gamma, \delta$ = angles at the center of the 1st, 2nd, 3rd, and 4th particle in the quadrilateral connecting centers of the four particles. β, γ, δ can be calculated from α and sizes of the particles [14]. Based on the number of occurrences, the probability of the combination of three or four particles is computed [22].

$$\begin{cases} p_{c3} = \frac{3!}{o_{p1}!o_{p2}!o_{p3}!} pf_{p1}^{o_{p1}} pf_{p2}^{o_{p2}} pf_{p3}^{o_{p3}} \\ p_{c4} = \frac{4!}{o_{p1}!o_{p2}!o_{p3}!o_{p4}!} pf_{p1}^{o_{p1}} pf_{p2}^{o_{p2}} pf_{p3}^{o_{p3}} pf_{p4}^{o_{p4}} \end{cases} \tag{3}$$

where o_{pi} = number of occurrences of particle pi in the combination, $o_{pi} = 1, 2, 3,$ (4); pf_{pi} = fraction of particle pi.

The accumulated number of probabilities shows the constriction size distribution with only three particles—the densest state—or only four particles—the loosest state. Based on the relative density, the constriction size is calculated as a combination of constriction sizes in the densest and loosest states [10].

$$d_c = d_{c3(f_c)} + f_c\left(1 - R_{dpf}\right)\left(d_{c4(f_c)} - d_{c3(f_c)}\right) \tag{4}$$

where $d_{c3(f_c)}$ and $d_{c4(fc)}$ = constriction size with the same cumulative proportion f_c in the constriction size distribution of the densest and loosest states, respectively; R_{dpf} = Relative density of the primary fabric. Note that, a more accurate estimation can be achieved by using a 3D numerical model [23]. However, that approach requires a huge computation load.

The probability to be transported of a particle will be assumed to be the fraction of constriction larger than that particle [11]. Then the total probability of loose particles to be transported can be calculated as a sum over all loose particle fraction:

$$P = \sum pf_l(1 - f_c) \tag{5}$$

where pf_l = fraction of a loose particle size; f_c = the cumulative proportion of constriction not larger than the particle size.

If the probability is not big, the transportation may be halted very quickly after several pores. The summary of the probability analysis is provided in Table 1.

It is obvious from the results that, the higher the fraction of fine particles, the lower the probability to be transported. Nevertheless, there is a reduction of P in soil 1 due to the large size of some loose particles (Fig. 1). An important note should be left here that the separation using the particle size gap is not suitable as the PSD of

Table 1 Probability analysis results

Soil	USCS	C_u	Gap level (%)	Delimiting size (mm)	P (%)
1	SW	7.54	26.7	2.56	40.47
2	SW	7.48	34.7	2.37	49.73
3	SW	7.20	42.7	0.86	30.84
4	SW	7.44	50.7	0.68	25.19
5	SW	7.42	58.7	0.58	22.91

the primary fabric and loose particles do not change. That makes P stable at 49.7% for all soils.

3 Laboratory Experiment and Segregation Index

To validate the probability analysis, several laboratory experiments have been undertaken. Soils are tested in an erosion unit [24] with a high hydraulic gradient of 5. The tests are last for 24 h. The schematic diagram of the test setup is given in Fig. 2. After the test, the soil remains in the unit is extruded by layer to find the PSD for each layer (Fig. 3). The PSDs before and after tests are shown in Fig. 4.

Fig. 2 Schematic diagram of the erosion test

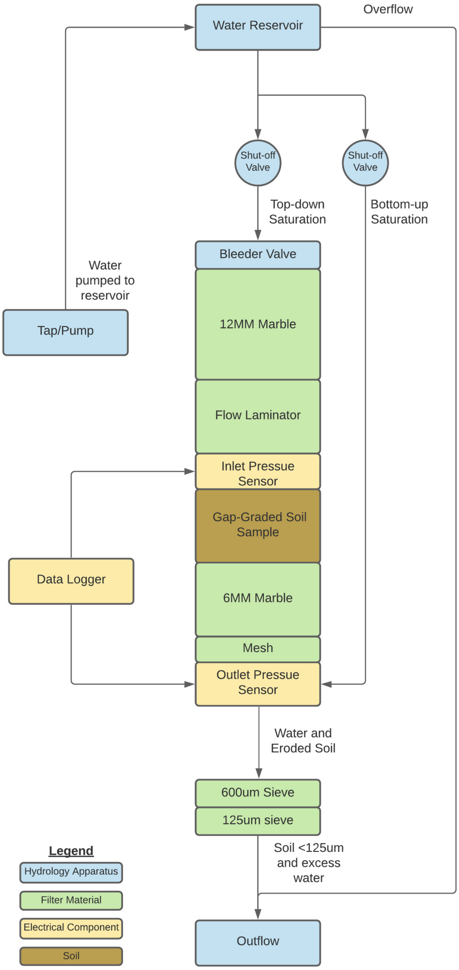

Fig. 3 Soil extrusion

The results show a striking coherence in the general trends between the predicted probability of transportation P and the actual eroded amount M (Fig. 5). In fact, P just shows only the probability to be transported to the next pores. The transportation may be halted after a few pores. Meanwhile, M shows the percentage of fines, which have been successfully washed out the soil mass.

Although P seems to be able to reflect well the susceptibility of soils to internal erosion. It may be hard to visualize its effect on the PSD. This paper proposes another index to characterize the erodibility of soil, a *segregation index* S. S is estimated as the furthest distance between a point on the original PSD to the respective point on the PSD after being eroded. In this paper, S is equal to the change of the gap level (Fig. 4). The experimental value is approximate to $2P^4$ (Fig. 6).

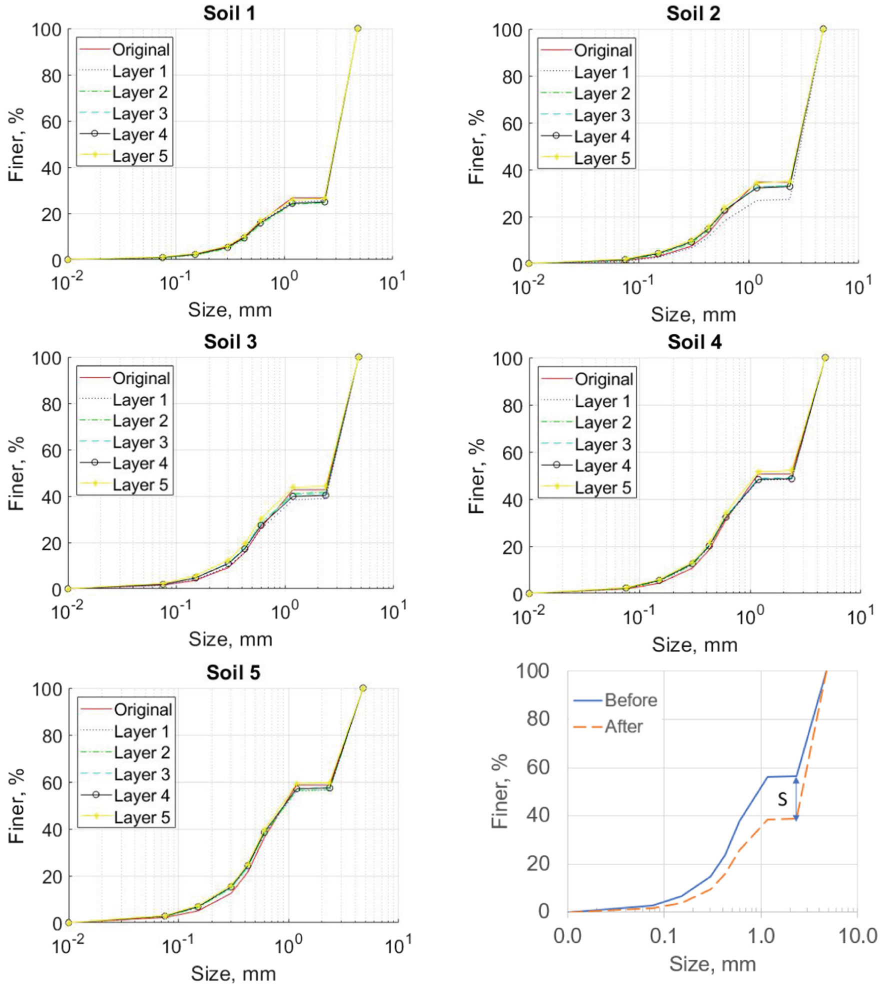

Fig. 4 PSD change in 5 soils and an exaggerated illustration of S.

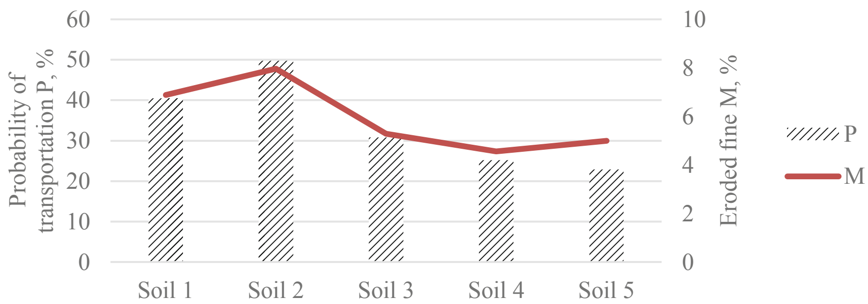

Fig. 5 Results comparison

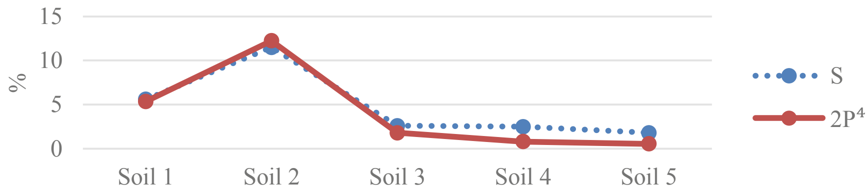

Fig. 6 Segregation index S

4 Conclusion

This paper has presented an analytical analysis on the probability of transportation for loose particles in several soils with similar PSD. The results show that the traditional separation of loose particles and primary fabric at the gap level may not be accurate. The cut at 35% shows a good coherence in trends of the probability of transportation and eroded mass. To visualize the effect of this segregation process, the paper has proposed a segregation index, which shows the change in soil PSD after the erosion test. This index can be calculated approximately as $2P^4$.

The application of the new index to clayey soils may be limited due to the irregular shape and agglomeration of super fine particles. The future study will focus on the segregation index after each layer to provide a tool for numerical simulation of the erosion/segregation process.

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