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Soils and Foundations ▮▮▮▮;▮(▮):▮▮▮–▮▮▮

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Determination of controlling constriction size from capillary tube model for internal stability assessment of granular soils

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Received 25 February 2015; received in revised form 16 November 2015; accepted 18 December 2015

Abstract

Internal instability is associated with geotechnical structures such as earth dams and dikes, and involves movement of fine loose particles through the voids of the main soil skeleton. In this study, some methods to determine the delimiting particle size (DPS) were critically reviewed. The accurate determination of the values of DPS and the diameter of the controlling constriction size ($d_{cont.}$) is essential for internal stability assessment. Here, a relationship is derived from the capillary tube model in order to determine the controlling constriction size, knowing that the diameter of the controlling constriction size should be smaller than the diameter of the loose fine particles to ensure the safety against internal stability. This derived relationship was verified with a large amount of data and it gave more accurate prediction than other methods.

Keywords: Controlling constriction size; Capillary tube model; Internal stability; Granular soils

1. Introduction

Internal instability problems are important issues in geotechnical engineering structures such as earth dams and dikes. They can lead to the improper functioning of the structures as a result of settlement or excessive seepage or even collapse of the engineering structures.

Internal stability problems are associated with widely graded or gap-graded soils, where the soils are expected to have a bimodal structure. That is, the soil has a primary skeleton composed of the coarse soil particles, and among the voids of these particles, there are finer loose particles. The main soil particles can be distinguished from the loose particles by knowing the delimiting particle size DPS, which is the particle diameter at which the grain size distribution curve (GSD) is split in to two components, primary the skeleton and fine loose particles.

The loose particles are expected to wash out under the seepage forces if their diameter is less than the “controlling constriction size”, Kenney et al. (1985), which is the predominant constriction size among the soil particles, and it is correlated to the maximum particle size that can pass through a filter. Kenney et al. (1985) obtained some relationships to determine the controlling constriction size from experimental tests. Indraratna et al. (2007) suggested the controlling constriction size as D_{c35}, which is the diameter of constriction corresponding to finer $=35\%$. Dallo et al. (2013) developed some relations to determine the controlling constriction size based on statistical analysis.

Many methods are available to assess the internal stability of granular soils, among these are Kezdi (1979) and Kenney and Lau (1985, 1986). In the method developed by Kezdi (1979)

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Peer review under responsibility of The Japanese Geotechnical Society.

http://dx.doi.org/10.1016/j.sandf.2016.02.013
0038-0806/

Please cite this article as: Dallo, Y.A.H., Wang, Y., Determination of controlling constriction size from capillary tube model for internal stability assessment of granular soils. Soils and Foundations (2016), http://dx.doi.org/10.1016/j.sandf.2016.02.013

the grain size distribution curve (GSD) is divided by an arbitrary diameter to coarser and finer components. The coarser component acts as a filter and the finer component behave as a base material. Hence, the criterion $D_{15}/d_{85}=4$ proposed by Terzaghi (1939) could be employed to assess the stability. D_{15} is the diameter of the coarser component corresponding to 15% and d_{85} is the diameter of the finer component corresponding to 85%. By the next step, another arbitrary diameter will be selected and the calculations are repeated. The soil is considered internally stable if Terzaghi's criterion is fulfilled for the whole range of selected diameters.

Kenney and Lau (1985, 1986) suggested a method (the KL method) to assess the internal stability based on the shape of the GSD curves of cohesionless soils. In this method, by determining the fines percent (*F*) corresponding to an arbitrary particle diameter (*D*), and the fines percent corresponding to the particle diameter (*4D*), the value of (*H*) can be easily calculated as the difference of the fines percent between *D* and 4*D*. The internal stability is determined by calculating the *H/F* ratios in the range of $F \leq 20\%$ for widely-graded soils, and by $F \leq 30\%$ for narrowly-graded soils. The soil is considered unstable if the ratio (*H/F*) lies below the stability boundary ($H/F=1.0$). The method assumes that the maximum possible fines content (i.e. erodible particles) for the widely graded soils (with Cu > 3) is 20% and for the narrowly graded soils (with Cu < 3) is 30%. For this reason the analysis is performed in the range of $F<20\%$ or $F<30\%$.

Li (2008) found out that the method of Kenney and Lau assesses the stability of "unstable gradations" correctly, while it provides a wrong assessment of some "stable gradations". Accordingly, the method is conservative in evaluating the potential for internal stability.

Li and Fannin (2013) suggested using the KL method to determine the delimiting particle size followed by using the capillary tube model, as suggested by Kovacs (1981), to determine the average pore size of the primary skeleton. The later value is to be compared with the diameter corresponding to finer = 85% of the fine loose particles,´ d_{85}, to assess the internal stability. Based on their results they suggested modifying the threshold boundary between stable and unstable soils.

In this study, the method of Li and Fannin (2013) was critically discussed and it was found that the KL method produced unreliable results when determining the delimiting particle size. Also, it was shown that the threshold boundary between stable and unstable gradations based on the average pore diameter is questionable. In the light of this discussion, a new procedure of analysis was suggested to use the controlling constriction size rather than the average pore diameter. A new relationship for use in determining the controlling constriction size was developed from Kovacs model and the threshold boundary between internally stable and unstable soils. The latter relationship can be used to assess the internal stability of granular soils against suffusion.

2. Capillary tube model

The capillary tube model, suggested by Kovacs (1981), envisioned the soil material and the voids among them as a solid material intersected by a series of tubes. The average pore diameter, d_0, of those tubes can be computed as

$$d_0 = 4\frac{n}{1-n}\frac{D_h}{\alpha_D}, \quad (1)$$

where n is the porosity of the soil; α_D is a shape coefficient ($\alpha_D=6$ for rounded particles, $\alpha_D=8$ for angular particles); D_h is the Kozeny's effective grain diameter, which can be computed as

$$D_h = \frac{1}{\sum \frac{F_i}{D_i}}, \quad (2)$$

where F_i is finer the percentage of particle D_i.

3. Critical review of Li and Fannin (2013) method

3.1. Using Kenney and Lau method to determine delimiting particle size

The KL method was originally suggested to assess the internal stability of cohesionless soils using the *H/F* ratio, which has a physical meaning related to the possibility that the small particles could be washed out (suffused) through the coarse skeleton of the soil. It seems that using the KL method to determine the delimiting particle size at the minimum *H/F*, as suggested by Li and Fannin (2013), has no clear physical meaning. Nevertheless, this suggestion requires comparison with some experimental tests to check its applicability and accuracy. An experimental test was provided by Binner et al. (2010) for the soil shown in Fig. 1. They found that the delimiting particle size is 4 mm at a fines percent of 23.5%. The delimiting particle size from the Li and Fannin's suggested method is 1.005 mm at $F=16.2\%$ as shown in Fig. 1. It is clear that there is a considerable difference between the computed value and the actual one. A reasonable method to determine the delimiting particle size was mathematically derived by Aberg (1992):

$$x_a = \frac{2c}{2c+1+2d}\frac{\int_{y_a}^{1}\frac{y}{x_{(y)}}dy - y_a\int_{y_a}^{1}\frac{dy}{x_{(y)}}}{\left(\int_{y_a}^{1}\frac{dy}{x_{(y)}}\right)^2}, \quad (3)$$

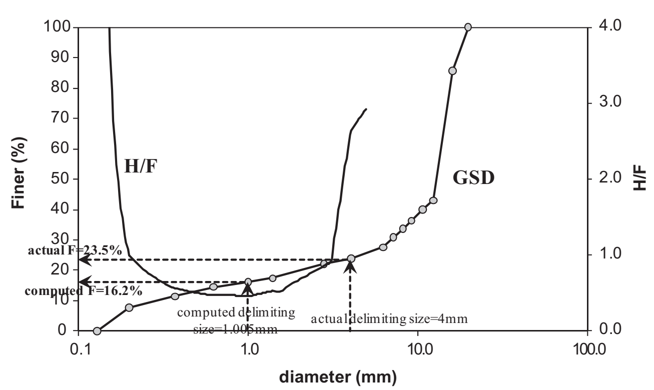

Fig.1. Grain size distribution of the soil tested by Binner et al. (2010), with the actual delimiting particle size and computed one according to the Li and Fannin method.

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