

Assessing the Potential of Internal Instability and Suffusion in Embankment Dams and Their Foundations

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Abstract: Suffusion is the process by which finer soil particles are moved through constrictions between larger soil particles by seepage forces. Soils susceptible to suffusion are described as internally unstable. This technical note describes a method for assessing the potential of internal instability of silt-sand-gravel or clay-silt-sand-gravel soils based on their particle size distribution based on laboratory tests carried out by the writers and results published by others. It is shown that some commonly used methods are conservative for these soils.

DOI: 10.1061/(ASCE)1090-0241(2008)134:3(401)

CE Database subject headings: Soil erosion; Dams, embankment; Dam foundations.

Introduction

The writers set out to investigate the factors affecting piping and internal erosion processes in embankment dams and their foundations as part of a research project funded by industry and the Australian Research Council. Findings by the writers on erosion in cracks in embankments were presented in Wan and Fell (2004b,c). This technical note summarizes the findings of the investigation on another internal erosion process called suffusion. Suffusion is the process by which finer soil particles are moved through constrictions between larger soil particles by seepage forces. Soils susceptible to suffusion are usually described as internally unstable. Internally unstable soils are usually broadly graded soils with particles from silt or clay to gravel size, whose particle size distribution curves are concave upward, or gap-graded soils.

Suffusion occurring within an embankment core or the foundation of a dam will result in a coarser soil structure, leading to increased permeability and seepage, likely settlement of the embankment, and a higher likelihood of downstream slope instability which may result in failure of the dam. A filter constructed of internally unstable materials will have a potential for erosion of the finer particles, rendering the filter coarser and less effective in protecting the core materials from erosion so piping failure may result.

The phenomenon of suffusion of sand-gravel soils has been studied by a number of investigators, including Kenney and Lau (1984, 1985, 1986), Sun (1989), Burenkova (1993), Skempton and Brogan (1994), Lafleur et al. (1989), and Chapuis et al. (1996). The soils investigated by most of these authors are sand-

gravels free of silty fines. The exception is Burenkova (1993) who investigated silt-sand-gravel soils and Sun (1989) who investigated clay-silt-sand soils but tested them under very high gradients which will not occur in dams or their foundations.

This research on sand-gravel soils indicates that for suffusion to occur, the following three criteria have to be satisfied:

1. The size of the fine soil particles must be smaller than the size of the constrictions between the coarser particles, which form the basic skeleton of the soil;
2. The amount of fine soil particles must be less than enough to fill the voids of the basic skeleton formed by the coarser

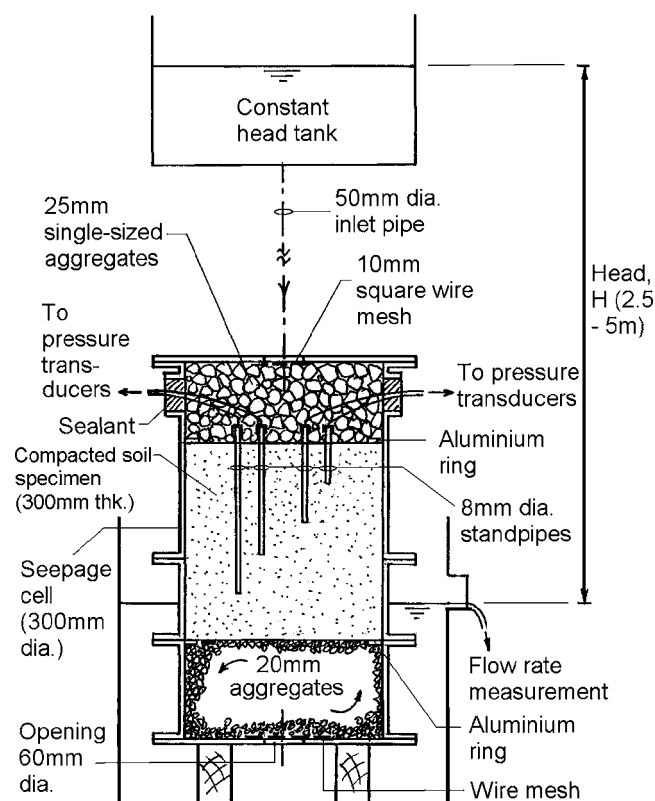


Fig. 1. Schematic diagram of downflow seepage test apparatus

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Note. Discussion open until August 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this technical note was submitted for review and possible publication on January 26, 2006; approved on March 5, 2007. This technical note is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 134, No. 3, March 1, 2008. ©ASCE, ISSN 1090-0241/2008/3-401-407/\$25.00.

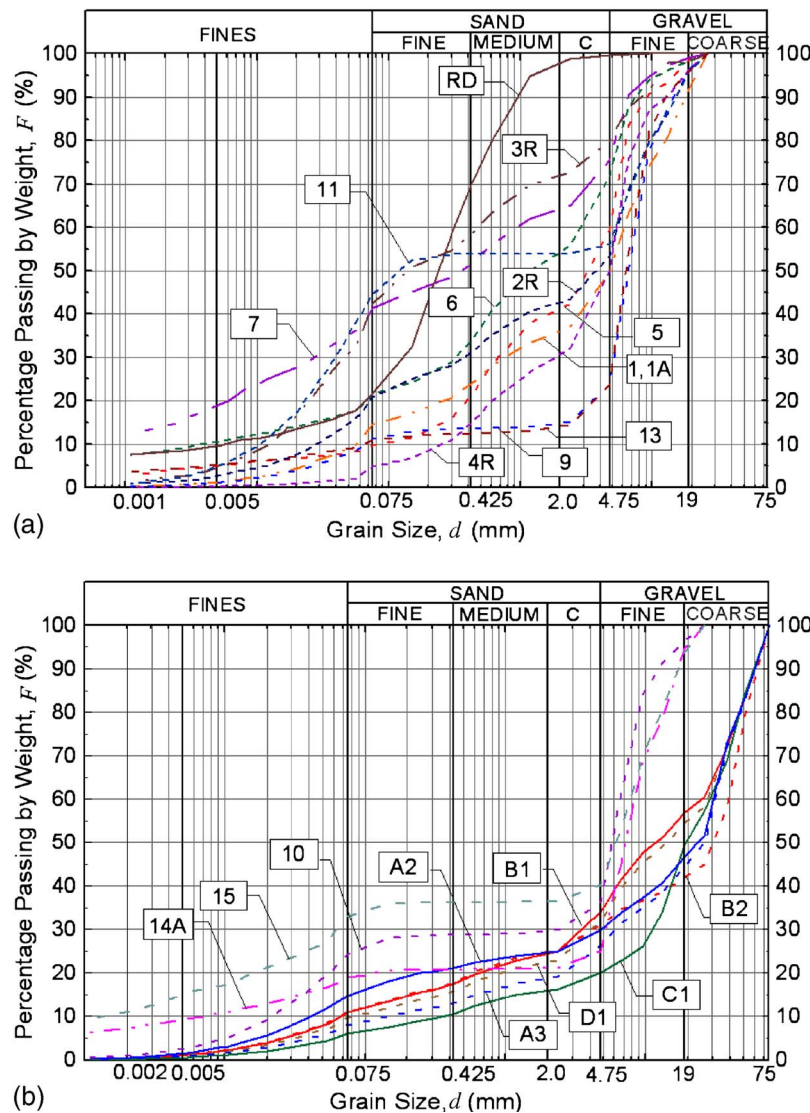


Fig. 2. Soil samples tested by UNSW: (a) internally stable soil samples; (b) internally unstable soil samples

particles. If there are more than enough fine soil particles for void filling, the coarser particles will be “floating” in the matrix of fine soil particles, instead of forming the basic soil skeleton; and

3. The velocity of flow through the soil matrix must be high enough to move the loose fine soil particles through the constrictions between the larger soil particles.

It is the writers’ experience that most dam engineers in Australia and the United States use the methods of Kenney and Lau (1985, 1986) or Sherard (1979) to assess whether the soils in a dam or its foundation are internally unstable, even if the soil is silt-sand-gravel, or clay-silt-sand-gravel. This is because there are no other well accepted methods. They do so not knowing if the methods they are using are conservative or otherwise.

This technical note presents improved methods for assessing whether silt-sand-gravel, or clay-silt-sand-gravel soils are internally unstable. The methods are based on laboratory tests carried out by the writers, and results of testing by others. The results of the writers’ tests are used to assess the validity of the Kenney and Lau (1985, 1986) and Sherard (1979) methods for these soils.

Laboratory Suffusion Tests

A schematic diagram of the laboratory tests carried out by the writers is shown in Fig. 1. The flow is downward, and the upstream water head is maintained constant at 2.5 m corresponding to a hydraulic gradient of about 8 across the 300-mm-thick compacted soil sample. The gradient is higher than would normally be expected in the core or foundation of a dam but may be experienced across filters or transition zones. The tests were carried out until no fine particles were seen washed out from the test sample and the pressures at various depths of the sample, and the rate of water flow through the sample attained steady values.

Figs. 2(a and b), show the particle size distribution curves of the 20 test samples. Samples 5, 6, 7, 13, 14A, and 15 contain kaolin in the percentages shown in Table 1. Other samples were nonplastic. Test samples were compacted in the seepage cell to the specified degree of compaction and water content (typically at 95 or 90% of the standard maximum dry density, and at optimum water content). This was to replicate the likely range of densities in the core of dams, and in gravelly soils in dam foundations.

Table 1. Summary of Results of Downward Flow Tests and Assessment of Internal Instability Using Methods by Others

Test sample	Percentage of kaolin	UNSW test result ^a	Sherard (1979)	Kenney and Lau (1985, 1986)	Burenkova (1993)
1, 1A	0	S	U	U	S
2R	0	S	U	U	U, M
3R	0	S	U	S, M	S
4R	0	S	U	U	S
5	5.9	S	U	U	U, M
6	11.2	S	U	U	U, M
7	21.8	S	U	U	S
9	0	S	U	U	S
10	0	U	U	S	U
11	0	S	U	U	S
13	5.5	S	U	U	S
14A	10.9	U, M	U	U	U
15	21.5	U	U	U	U
RD	0	S	U	U	S
A2	0	U	U	U	U
A3	0	U	U	U	U
B1	0	U	U	U	S
B2	0	U	U	U	U
C1	0	U	U	U	U
D1	0	U	U	U	S

^aS=stable; U=unstable; M=marginal. Boldface means incorrect prediction.

There was no discernible difference in performance within this range of density ratios. More details of the tests and the analysis of the results are given in Wan (2006), and Wan and Fell (2004a).

Prediction of Internal Instability by Existing Methods

The 20 soil samples tested at the University of New South Wales have been assessed for internal instability using methods of Sherard (1979), Kenney and Lau (1985, 1986), and Burenkova (1993). The results are summarized in Table 1. It can be seen that the Sherard (1979) and Kenney and Lau (1985, 1986) methods are conservative in that most of the soil samples tested to be internally stable are predicted as internally unstable by these methods. The Burenkova (1993) method provides better but not totally accurate predictions of the internal stability of the University of New South Wales soil samples.

In fact it is not surprising that the Sherard (1979) method does not predict well. It was empirically based and designed to identify soils which will not self-filter, which is a different process to internal instability as defined here. Self-filtering is the process where the coarse particles of a cohesionless soil prevent erosion of the medium sized particles, and the medium size particles in turn prevent erosion of the fine particles. The filter therefore only has to prevent erosion of the coarse particles (usually represented by d_{85} size) to be effective. However there is no requirement that the eroded particles are from within the voids between the coarse particles and that there is no erosion of the coarser particles forming the matrix as is required for internal instability and suffusion as defined here.

Proposed Methods for Prediction of Internal Instability

In view of the poor predictive ability of the existing methods for silt-sand-gravel and clay-silt-sand-gravel soils, improved methods for assessing whether these soils will be internally unstable have been developed. A number of different approaches were trialed using statistical methods, varying the combination of particle size parameters, and compaction density. In order to increase the size of the database on which the methods are based, laboratory test data from other authors have been included with the University of New South Wales test data. These includes data from 20 tests on sand-gravel soils by Kenney et al. (1983, 1984) and Kenney and Lau (1984, 1985); three tests on mixtures of ballotini beads by Lafleur et al. (1989); eight tests on silt-sand gravel soils by Burenkova (1993); four tests on sand-gravel soils by Skempton and Brogan (1994), and three tests by Chapuis et al. (1996). Particle size distributions for the samples are shown in Figs. 3–5. These data are based on similar testing procedures although there are differences in gradients, the size of the containing filter at the base of the sample, and some tests were vibrated and others not. Details are given in the referenced papers of Wan (2006) and Wan and Fell (2004a). The following methods were best able to identify internally unstable soils.

Modified Burenkova Method for Broadly Graded and Gap-Graded Soils

The Burenkova (1993) method is based on d_{90}/d_{60} and d_{90}/d_{15} ratios where d_{90} is the sieve size for which 90% of the sample by weight passes. The d_{90}/d_{60} ratio represents the slope of the coarse part of the particle size distribution plot. High values represent near single size coarse particles which will have large constriction spaces compared to a well graded soil. The d_{90}/d_{15} can be regarded as a measure of the filter action between the coarse fraction and the finer fraction. The method does not give a clear-cut boundary between internally stable and unstable soils in the data set. To model this logistic regression was used to define contours of equal probability of internal instability as shown in Figs. 6 and 7. Fig. 6 is to be applied to silt-sand-gravel and clay-silt-sand-gravel mixtures with a plasticity index less than 13% and less than 10% clay size fraction (percent passing 0.002 mm), and Fig. 7 to sand-gravel soils with less than 10% nonplastic silt fines passing 0.075 mm. The probability contours in Figs. 6 and 7 are defined by the following equations:

$$P = \exp(Z) / [1 + \exp(Z)] \quad (1)$$

$$Z = 2.378 \log(h'') - 3.648h' + 3.701 \quad (2)$$

for Fig. 6 and

$$Z = 3.875 \log(h'') - 3.591h' + 2.436 \quad (3)$$

for Fig. 7 where P represents the probability of internal instability.

Alternative Method for Broadly Graded Soils

Experience in using the modified Burenkova method led the writers to realize that soils with a steep slope on the coarse fraction, and a flat slope on the finer fraction were likely to be internally unstable. After some trials it was determined that these could be represented by d_{90}/d_{60} and d_{20}/d_5 . Fig. 8 shows the data with two

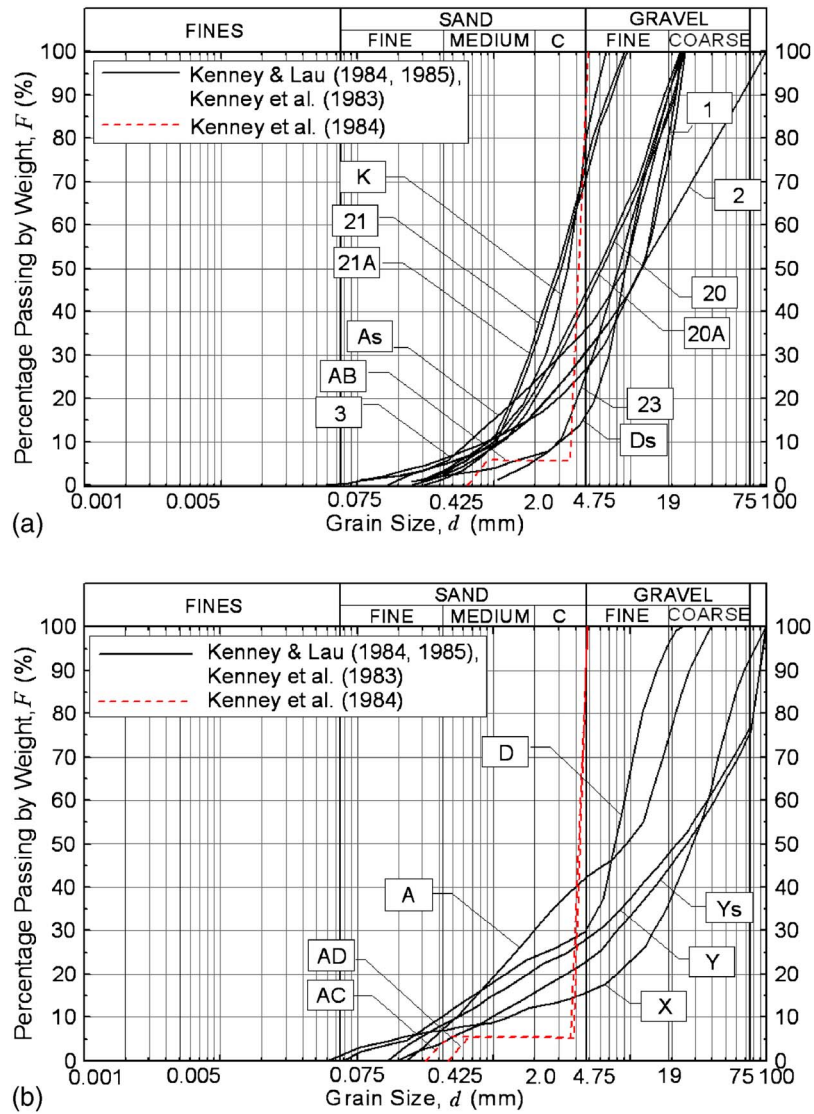


Fig. 3. Soil samples tested by Kenney and Lau (1984, 1985) and Kenney et al. (1983, 1984): (a) internally stable soil samples; (b) internally unstable soil samples

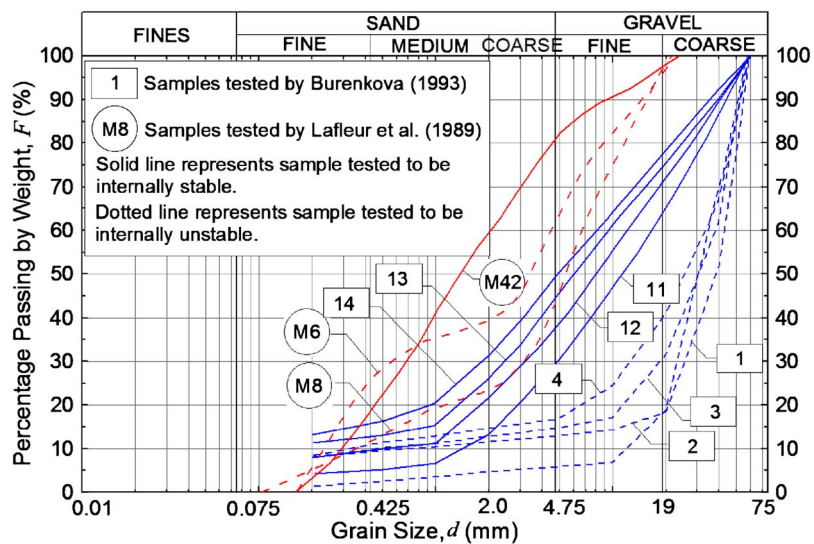


Fig. 4. Soil samples tested by Burenkova (1993) and Lafleur et al. (1989)

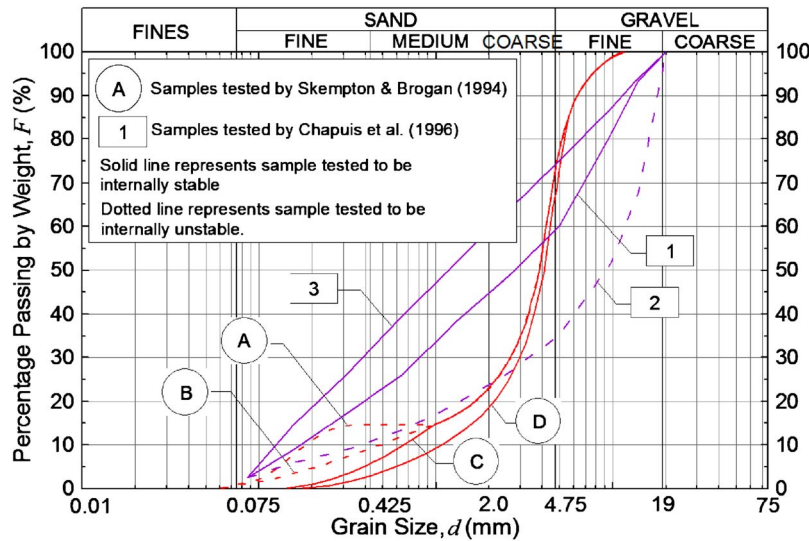


Fig. 5. Soil samples tested by Skempton and Brogan (1994) and Chapuis et al. (1996)

boundaries: one beyond which the likelihood of internal instability is low, and the other defining an area in which soils are highly likely to be internally unstable. This method is not able to identify the internal instability of gap graded soils.

Maximum Fraction of Erodible Material in Internally Unstable Soil

Wan (2006) and Wan and Fell (2004a) give details of a method to determine what fraction of the soil will be eroded. The writers have found that in practical terms it can be assumed that 50% of the finer fraction as defined by the point of inflection of broadly graded soils and the fine limit of the gap in gap-graded soils is eroded, and the particle size distribution replotted. This is based

on the results of laboratory testing. For a more conservative approach it may be assumed that the entire fine fraction is eroded.

Seepage Gradient at Which Erosion Will Begin

The writers' laboratory tests and those by Skempton and Brogan (1994) show that erosion will begin in internally unstable soils at a gradient lower than the critical or zero effective stress gradient. For the internally unstable soils tested, all began to erode with upward gradients of 0.8 or less, with several less than 0.3. There is a general trend that soils with a higher porosity begin to erode at lower hydraulic gradients. Loose higher porosity soils tested began to erode at gradients less than 0.3. Soils with plastic fines required higher gradients to begin to erode. Gap-graded soils

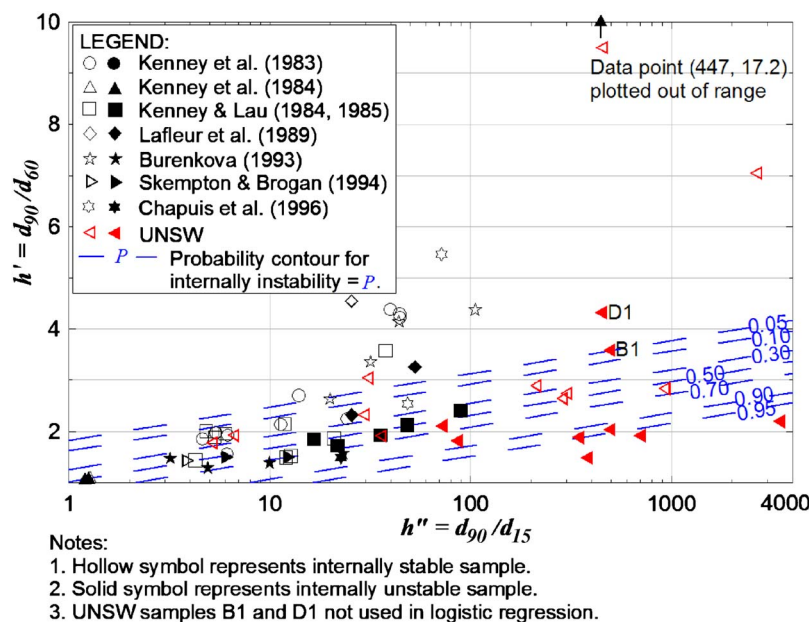


Fig. 6. Contours of probability of internal instability for silt-sand-gravel soils and clay-silt-sand-gravel soils of limited clay content and plasticity

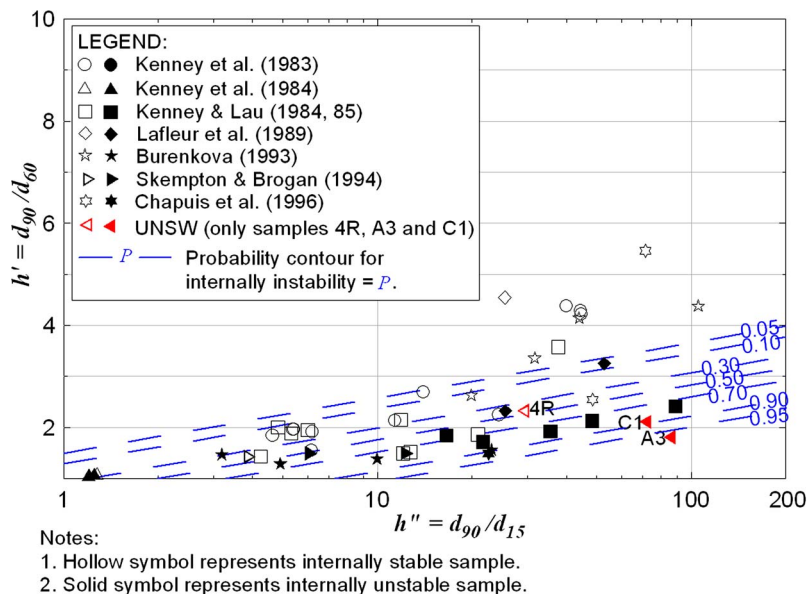


Fig. 7. Contours of probability of internal instability for sand-gravel soils with less than 10% nonplastic fines passing 0.075 mm

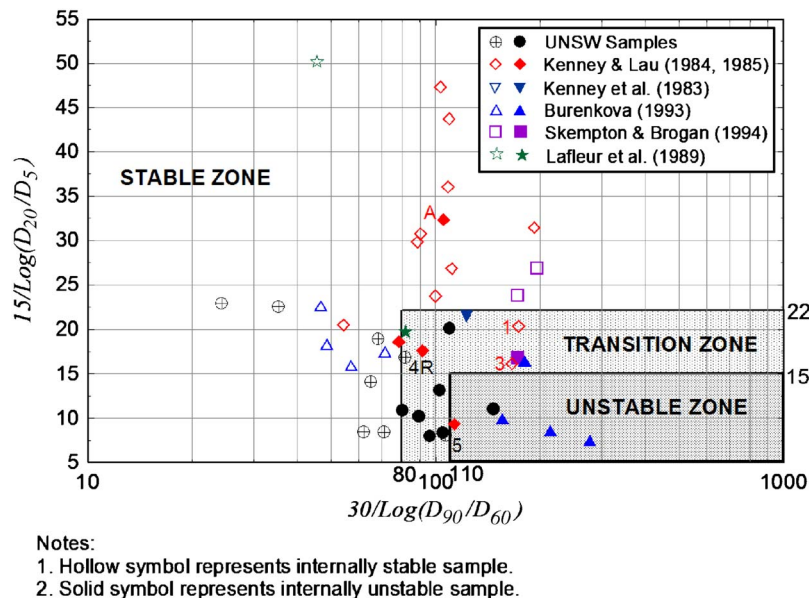


Fig. 8. Alternative method for assessing internal instability of broadly graded silt-sand-gravel soils

tended to begin to erode at lower gradients than nongap-graded soils with the same fines content.

Conclusions and Comments

Improved procedures for predicting the internal instability of sand gravel soils with silty and clayey fines based on particle size distribution are proposed. It is shown that the most widely used methods to assess whether a soil is internally unstable are conservative. Minor differences in the shape of the particle size distribution affect whether a soil is internally stable and it is recommended that for important projects laboratory tests be carried out on the soils which are tested in the marginal areas to confirm the

assessments made by the methods suggested here.

Soils that have less than 15% finer fraction (20% for the alternative method) may not be adequately assessed by these methods. While it has not been proven by tests, if the slope of the finer fraction is used in lieu of the d_{20}/d_5 ratio the alternative method should be applicable.

Acknowledgments

The writers wish to acknowledge the support of the Australian Research Council, and the 17 industry sponsors for research into internal erosion and piping failure of embankment dams.

References

- Burenkova, V. V. (1993). "Assessment of suffusion in noncohesive and graded soils." *Proc., 1st Int. Conf. Geo-Filters*, Karlsruhe, Germany, Balkema, Rotterdam, The Netherlands, 357–360.
- Chapuis, R. P., Constant, A., and Baass, K. A. (1996). "Migration of fines in 0–20 mm crushed base during placement, compaction, and seepage under laboratory conditions." *Can. Geotech. J.*, 33(1), 168–176.
- Kenney, T. C., and Lau, D. (1984). "Stability of particle grading of compacted granular filters." *Publication No. 84-06*, Dept. of Civil Engineering, Univ. of Toronto, Toronto.
- Kenney, T. C., and Lau, D. (1985). "Internal stability of granular filters." *Can. Geotech. J.*, 22(2), 215–225.
- Kenney, T. C., and Lau, D. (1986). "Internal stability of granular filters: Reply." *Can. Geotech. J.*, 23(4), 420–423.
- Kenney, T. C., Lau, D., and Clute, G. (1983). "Filter tests on 235 mm diameter specimens of granular materials." *Publication 84-07*, Dept. of Civil Engineering, Univ. of Toronto, Toronto.
- Kenney, T. C., Lau, D., and Clute, G. (1984). "Stability of particle gradations tests on mixtures of narrowly graded materials." *Publication No. 84-08*, Dept. of Civil Engineering, Univ. of Toronto, Toronto.
- Lafleur, J., Mlynarek, J., and Rollin, A. L. (1989). "Filtration of broadly graded cohesionless soils." *J. Geotech. Engrg.*, 115(12), 1747–1768.
- Sherard, J. L. (1979). "Sinkholes in dams of coarse, broadly graded soils." *Trans., Proc., 13th Congress on Large Dams*, Vol. 2, New Delhi, India, 25–35.
- Skempton, A. W., and Brogan, J. M. (1994). "Experiments on piping in sandy gravels." *Geotechnique*, 44(3), 449–460.
- Sun, B. C. B. (1989). "Internal stability of clayey to silty sands." Dr.Phil. thesis, dissertation, Univ. of Michigan, Ann Arbor, Mich.
- Wan, C. F. (2006). "Experimental investigation of piping erosion and suffusion of soils in embankment dams and their foundations." Ph.D. thesis, Univ. of New South Wales, Sydney, Australia.
- Wan, C. F., and Fell, R. (2004a). "Experimental investigation of internal instability of soils in embankment dams and their foundations." *UNICIV Rep. No. R 429*, The Univ. of New South Wales, Sydney, Australia.
- Wan, C. F., and Fell, R. (2004b). "Investigation of rate of erosion of soils in embankment dams." *J. Geotech. Geoenviron. Eng.*, 130(4), 373–380.
- Wan, C. F., and Fell, R. (2004c). "Laboratory tests on the rate of piping erosion of soils in embankment dams." *Geotech. Test. J.*, 27(3), 295–303.