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Experimental Investigation of Critical Hydraulic Gradients for Unstable Soils

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ABSTRACT

The presence of unstable soils, i.e. soils in which suffusion can arise, is a potential risk to structures under which seepage occurs. It is therefore necessary to clearly identify unstable soils and to estimate hydraulic gradients at which erosion may start. An experimental study was carried out to quantify critical hydraulic gradients of unstable soils with respect to vertical upward and horizontal flow. It was found that critical gradients for unstable soils lie in the range of 0.2 both for vertical and horizontal flow, with a small dependence on the relative density. For nearly stable soils a strong effect of the relative density on the critical hydraulic gradients was found. Also, the "more stable" a soil is, the greater the difference of critical gradients for vertical and horizontal flow. The obtained results are compared to the results of other researchers.

INTRODUCTION

In the risk assessment of potential damage to dams or barrages the consideration of erosion processes in connection with under-seepage of such structures is of great significance. This is particularly valid if the subsoil consists of unstable soils. These are non-cohesive soils with a large uniformity index (non-uniform soils with uniformity index C_u >5 to 10) or irregular grain size distributions. In such soils erosion, i.e. transport of soil grains, starts at much lower hydraulic gradients than in soils with regular grain size distribution. The result of the erosion process is the wash-out of the fine-grained portion of the soil (suffusion). It has not been clear how important the effect of the soil gradation on the critical gradients in vertical and horizontal direction is and how it depends on the soil composition and its relative density. Special testing devices were therefore designed to investigate the erosion phenomenon dependent on the above mentioned factors.

OVERVIEW OF THE STATE OF THE ART

To assess whether suffusion is possible, in general the composition of the soil and the geometry of the pore channels have to be considered. Suffusion is only possible if the grains of the fine soil can pass through the pores of the coarse soil matrix. Since the pore channel geometry cannot be exactly measured, the assessment is based on the grain size distribution only. If the "geometric" criterion yields the result that suffusion is possible, i.e. the soil is potentially unstable, the minimum hydraulic gradient necessary to cause erosion and to transport the fine soil grains has to be assessed by a "hydraulic" criterion.

Geometric criteria

Suffusion is the transport and wash-out of the fine grains of a soil through the grain skeleton formed by the coarse parts: it can be considered as a contact erosion process (i.e. the wash-out of a fine soil through the pores of an adjacent coarse soil layer) between the fine and coarse parts of the soil. Based on this consideration, Kezdi (1979) proposed splitting up the grain size distribution of a soil into two distributions of the fine and coarse parts, and assessing the stability by Terzaghi's well-known contact erosion criterion applied to the two distributions. This criterion, also known as Terzaghi's filter rule, is formulated as follows:

$$d_{c,15} \leq 4\, d_{f,85} \tag{1}$$

with $d_{c,15}$ = grain diameter for which 15% of the grains by weight of the coarse soil are smaller and $d_{f,85}$ = grain diameter for which 85% of the grains by weight of the fine soil are smaller.

The Terzaghi criterion is valid only for poorly graded soil. To avoid this limitation, in the German guideline BAW (1989) the splitting method is recommended in combination with the Cistin/Ziems contact erosion criterion (see e.g. in Semar & Witt 2006), which is also applicable to non-uniform soils. In general, the grain size distribution has to be split up at several points and the resulting fine and coarse soils have to be assessed with the contact erosion criterion.

Kenney and Lau (1985) proposed transforming the ordinary grain size distribution curve to a F-H diagram. Here F is the mass percentage of grains with diameters less than a particular diameter d and H is the mass percentage of grains with diameters between d and 4d (Fig. 1). In the first version H/F ≥ 1.3 was proposed as stability criterion. In a following publication (Kenney and Lau 1986), the less conservative requirement H/F ≥ 1.0 was recommended for use.

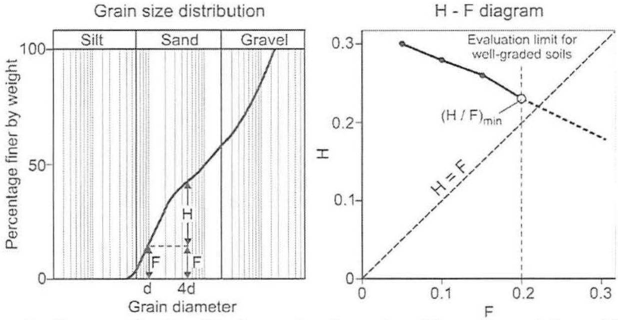

Figure 1. Geometrical suffusion criterion after Kenney and Lau (1985).

In principle, both the Kezdi and the Kenney & Lau criteria require a minimum inclination of the grain size distribution curve. Chapuis (1992) stated that the Kezdi criterion means that "the slope of the grain-size distribution is flatter than 15% per four times change in grain size", i.e. H ≤ 0.15 for all F values. In contrast, for the Kenney & Lau criterion the required minimum inclination is dependent on F. Both criteria are depicted in Fig. 2 and the test results of several authors regarding the internal stability of soils are presented. Fig. 2 shows that all soils with points lying above the Kenney & Lau line are stable and all soils with points lying below the Kezdi line are unstable. Soils with points lying in the "transition zone" ($H > F < 0.15$ and $0.15 < H < F$) can obviously be either stable or unstable. Li & Fannin (2008) proposed using the Kenney & Lau criterion for well-graded soils and the Kezdi criterion for a gap-graded soil.

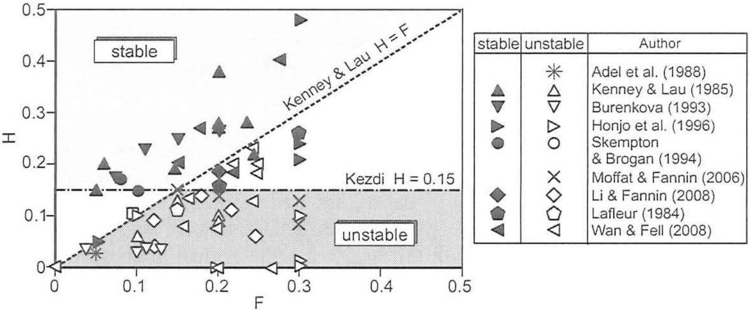

Figure 2. Compilation of test results and comparison with criteria of Kezdi and of Kenney & Lau.

For the application of the Kezdi criterion the grain size distribution has to be split up at several points and the resulting grain size distribution have to be checked with respect to contact erosion criteria. Usually the most unfavourable combination of fine and coarse soil results when the split-off point lies in the region of a small inclination of the grain size distribution. Thus, in a simplified application, the split can be done only at the point where H/F becomes a minimum ($(H/F)_{min}$). The ratio of $d_{c,15}$ and $d_{f,85}$ found for the curve splitting at that point is denoted in the following as $(d_{c,15}/d_{f,85})_{mod}$. With respect to Eq. (1), this value has to be less than 4 to indicate internal stability of the soil considered.

Hydraulic criteria

For an upward seepage flow through a stable soil without surface load the critical hydraulic gradient can be derived as follows (e.g. Terzaghi and Peck 1961):

$$i_{v,crit} = \frac{\gamma'}{\gamma_w} \qquad (2)$$

Here γ' and γ_w are the soil's buoyant unit weight and the unit weight of water, respectively.

Istomina (1957) – cited in Busch et al. (1993) – carried out tests with various soils under vertical upward flow and proposed estimating the critical hydraulic gradient dependent on the uniformity index of the soil (Fig. 3).

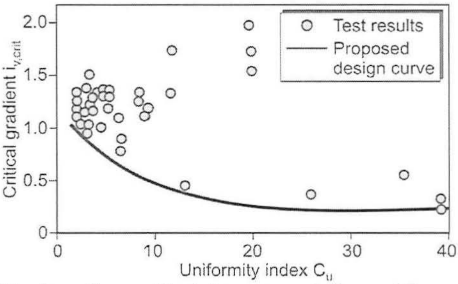

Figure 3. Critical hydraulic gradient for upward flow with respect to suffusion after Istomina (Busch et al. 1993).

Adel et al. (1988) carried out tests with stable and unstable soils (with regard to the Kenney & Lau criterion) under horizontal seepage flow. They determined critical hydraulic gradients of $i_{h,crit}$ = ca. 0.2 for three unstable soils with $(H/F)_{min} <$ 0.5. For two soils with $(H/F)_{min}$ = 1.3 the critical gradients were between 0.6 and 0.7 and for a definitely stable soil with $(H/F)_{min}$ = 1.8 the critical gradient was ca. 1.0. The results are depicted in Fig. 4.

Skempton and Brogan (1994) carried out tests with upward flow to determine the critical hydraulic gradients for unstable soils. They found that the values can be only one third to one fifth of the theoretical value according to Eq. (2). They presented the results for both vertical upward and horizontal flow (determined by Adel et al. 1988, see above) dependent on the $(H/F)_{min}$-value of the soil and suggested the connection shown in Fig. 4. Obviously, for unstable soils the difference between the vertical and the horizontal critical hydraulic gradient is rather small.

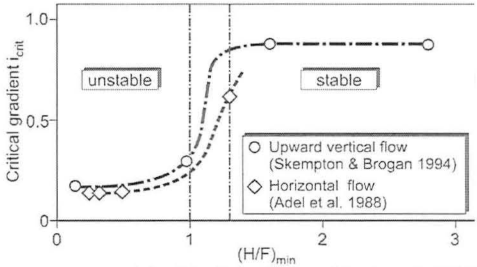

Figure 4. Relation between critical hydraulic gradient and $(H/F)_{min}$ proposed by Skempton and Brogan (1994).

Wan and Fell (2008) investigated 14 clay-silt-sand-gravel and silt-sand-gravel mixtures and found critical gradients for unstable soils less than 0.5. They also found that tendentially smaller values apply to soils in a loose state than to soils in a dense state.

Moffat and Fannin (2006) investigated the effect of vertical load acting on the sample's surface for unstable soils. They found that the critical gradients increased with an increase of the surface load.

EXPERIMENTS

Five different non-cohesive soils were tested in specially developed test devices under upward and horizontal seepage flow. The hydraulic gradient was increased slowly and gradually in order to identify the critical gradient at which erosion begins. The initial relative density of the soils was varied in the tests.

The grain size distributions of the five soils are shown in Fig. 5 and the relevant soil parameters are given in Table 1. The soils A1 and A2 are fine to medium and medium to coarse sands, respectively, which are poorly graded and stable with respect to all geometric criteria (Kenney & Lau parameter $(H/F)_{min} = 4.4$ and 5.93, respectively). The soils E1, E2 and E3 are gap-graded soils, which were produced artificially. E2 and E3 are clearly unstable soils, whereas E1 has an $(H/F)_{min}$ value of 1.1 and lies on the border between the stable and unstable region with regard to the Kenney & Lau criterion. Applying the Kezdi criterion with $(d_{c,15}/d_{f,85})_{mod} < 4$ also leads to a close decision regarding internal stability.

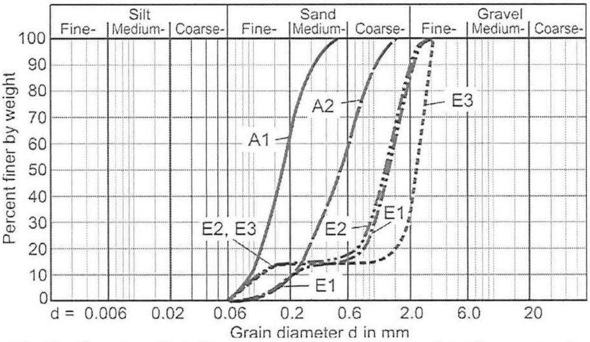

Figure 5. Grain size distributions of the soils used in the experiments.

Table 1. Properties of the soils used in the experiments

Property	Soil				
	A1	A2	E1	E2	E3
Density of grains ρ_s [t/m^3]	2.65	2.65	2.65	2.65	2.65
Minimum porosity n_{min}	0.40	0.32	0.34	0.27	0.31
Maximum porosity n_{max}	0.52	0.43	0.42	0.40	0.42
Uniformity index C_u	2.1	3.0	7.0	13.9	23.4
Index of Curvature C_c	1.0	1.0	3.3	6.7	13.8
$(H/F)_{min}$	5.93	4.44	1.10	0.20	0.03
$(d_{c,15}/d_{f,85})_{mod}$	1.31	1.50	3.30	7.20	14.40

Experiments with upward flow

A photographic view and a schematic drawing of the test device for vertical upward flow are shown in Fig. 6. The soil sample with a diameter of 28.5cm and a height of 30cm was subjected to a gradually increased vertical hydraulic gradient. During the test, the water discharge and the water pressures along the sample's height were recorded almost continuously.

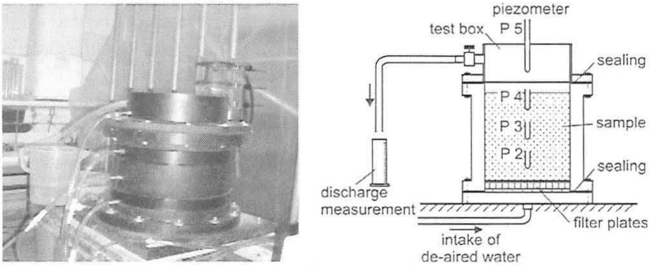

Figure 6. Test device for vertical upward flow.

The placement of the sample was carried out by pluviation under water. To prevent entrapped air falsifying the test results, the water was de-aired by boiling and cooled down to the test temperature of 20°C. A soil mass chosen with respect to the desired relative density was pluviated into the test box and compaction was then carried out by vibrating the box until the desired sample level was reached.

The determination of the critical hydraulic gradient was done by noting the water discharge and the filter velocity of the water flow, respectively. An example is shown in Fig. 7. For the internally stable soil (Fig. 7 left) the onset of erosion is connected with an immediate increase in the flow velocity and thus the permeability. Some grain movements on the sample surface already occur at smaller hydraulic gradients, but this does not lead to erosion. For the unstable soil (Fig. 7 right) the change in the permeability is more continuous. From a certain hydraulic gradient on, a strongly increased mass transport and a significant increase of the flow velocity was observed. At this state, the critical gradient was determined.

Experiments with horizontal flow

In order to grasp the directional dependence of the critical hydraulic gradients, tests with horizontal seepage flow were also carried out. A photographic view and a schematic drawing of the test device used are shown in Fig. 8. The sample had a cross section of 10cm x 30cm and was seeped horizontally on a sample length of 60cm. The placement of the material was again done by pluviation in de-aired water with the test box standing in a 90° rotated position. The sieve fabrics located at both ends of the sample were so chosen that a transport of the fine soil parts was possible.

The hydraulic gradients were increased slowly and gradually and the water discharge and the mass of eroded fines were observed almost continuously. In both curves a significant change was observed at a particular hydraulic gradient, i.e. a significant change in the permeability and an increase in the transported soil mass. At this point the critical hydraulic gradient was recorded.

TEST RESULTS

Vertical upward flow

The experimentally determined hydraulic gradients for upward flow are given in Fig. 9, dependent on the initial relative density of the soil samples.

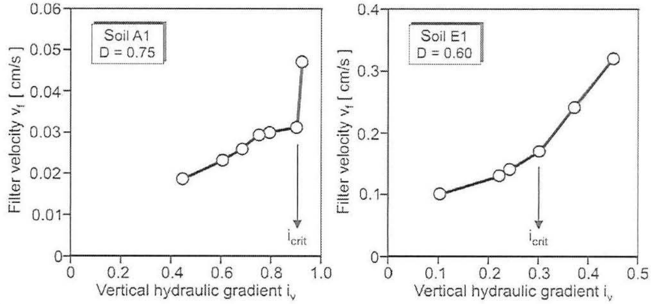

Figure 7. Development of filter velocity with the hydraulic gradient.

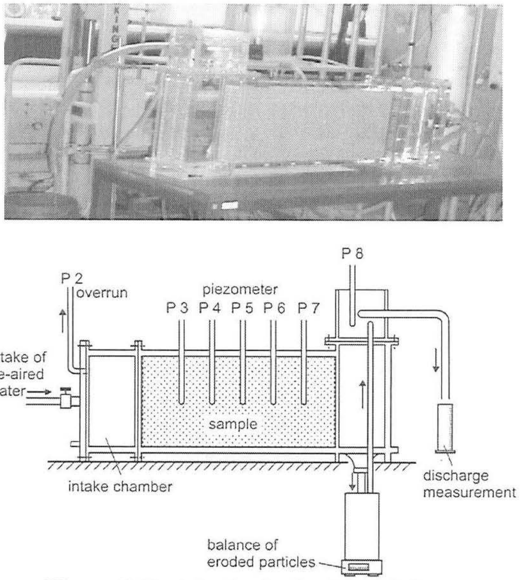

Figure 8. Test device for horizontal flow.

For the stable soils A1 and A2 the obtained critical gradients agree quite well with the theoretical values according to Eq. (2). In fact, slightly lower values were found with a maximum deviation of about 10%, which might be a result of unavoidable heterogeneities of the samples.

For the clearly unstable soils E2 and E3 very small critical gradients between 0.18 and 0.23 were measured. There is only a small dependence on the relative density of the sample. On the contrary, for soil E1, which is on the border between stable and unstable, a clear dependence of the critical hydraulic gradient on the relative densities was found. For a very dense state the critical hydraulic gradient is about double the value determined for a medium dense state. However, the value for very dense state is also significantly smaller than the theoretical critical hydraulic gradient from Eq. (2). Thus, soil E1 has to be classified as potentially unstable.

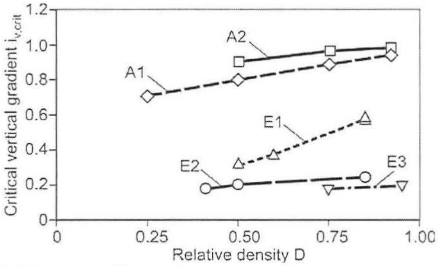

Figure 9. Critical gradients determined for vertical upward flow.

Fig. 10 shows the critical hydraulic gradients determined for the unstable soils dependent once on $(H/F)_{min}$ and once on $(d_{c,15}/d_{f,85})_{mod}$. The values obtained by Skempton and Brogan (1994) for dense sand are also depicted. The dependence on $(H/F)_{min}$ suggested by Skempton and Brogan is confirmed, with the exception of the nearly stable soil E1, where the critical gradient is very much dependent on the initial relative density. There is also a connection of the critical hydraulic gradients with the parameter $(d_{c,15}/d_{f,85})_{mod}$, but the scatter here is slightly larger. The trend lines in Fig. 11 right are suggested curves regarding the effect of relative density. Evidently, the "more stable" a soil is, the more important the relative density.

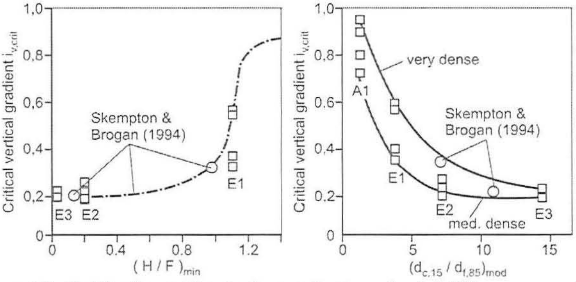

Figure 10. Critical gradients dependent on instability parameters.

Horizontal flow

In Fig. 11 the experimentally determined critical hydraulic gradients with regard to horizontal flow are presented dependent on the parameter $(d_{c,15}/d_{f,85})_{mod}$. The critical gradients for vertical flow are also given.

Tendentially, the critical gradient for horizontal flow is slightly smaller than the one for upward flow. However, the "more unstable" a soil is, the smaller the difference, and thus the smaller the critical vertical gradient. For the unstable soils E2 and E3 even slightly higher horizontal than vertical critical gradients were obtained for dense and very dense initial states. In that respect it has to be considered that in the case of vertical flow the sample surface was free and thus a certain loosening of the sample was possible due to the seepage forces acting, which of course favours internal erosion. This might also be the reason for the stronger dependence of horizontal critical gradients on the sample's relative density.

The results of Adel et al. (1988) with critical horizontal gradients of around 0.2 for unstable soils are confirmed by the tests. Unfortunately, Adel et al. did not document the relative density of the soil in their tests.

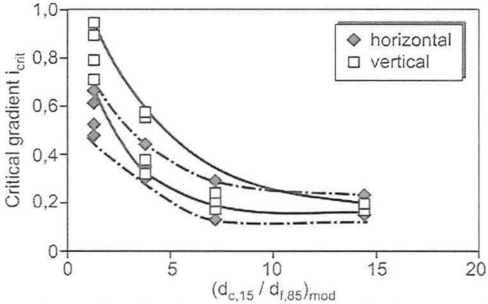

Figure 11. Comparison of critical gradients for vertical upward and horizontal flow.

CONCLUSIONS

The tests reported here show that for clearly unstable sands, i.e. with $(H/F)_{min}$-values significantly smaller than 1.0, the critical hydraulic gradients for upward flow lie at around 0.2 with only a slight dependence on the initial relative density. Also, the critical gradients for horizontal flow are nearly the same as those for vertical flow.

For clearly stable soils, e.g. poorly graded sands, the critical gradients for horizontal flow are significantly smaller than the critical gradients for vertical flow.

Sands which lie on the border between stable and unstable soils behave in a special way. For such a soil a distinct dependence of critical hydraulic gradients on the relative density was found. It can be concluded that the decision whether such a soil is stable or potentially unstable requires consideration of the compaction state.

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