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Considerations and Model Tests on the Design of River Barrages with Respect to Piping

M. Achmus*, B.G.S. Mansour**

* Institute of Soil Mechanics, Foundation Engineering and Waterpower Engineering, University of Hannover, Germany
** Director of Works, Reservoir and Grand Barrages Sector, Ministry of Water Resources and Irrigation, Cairo, Egypt

The exit gradient method is the state-of-the-art method for the design of river barrages with respect to piping. This method is compared with other methods. Questions arise concerning the magnitude of the admissible exit gradients to be considered in the design. Model tests are presented, in which favourable conditions for the beginning and the progress of a piping process under a river barrage were simulated by disturbance of the downstream soil bed. It is shown that under such conditions piping can occur with hydraulic exit gradients, determined from a two-dimensional model, significantly lower than the theoretically critical exit gradient.

I. INTRODUCTION

Piping is an erosion mechanism which is very relevant for river barrages as well as for dams and dikes. The under-seepage of such structures in soils sensitive to erosion (e.g. fine-grained, but non-cohesive soils like fine or medium sand) can lead to the development of a pipe, in which soil material is transported. Such processes usually begin at the downstream exit of the seepage flow, with the pipe development progressing from the downstream to the upstream side. At the end of this process the total failure of the barrage or dam occurs.

In Fig. 1 a schematic sketch of a piping channel developing at a river barrage is shown. The erosion begins at the downstream exit of the seepage. Here the seepage direction is nearly vertical, so that the start of the process corresponds to a local hydraulic uplift failure. In principle, this means that the hydraulic gradient at the seepage exit has to be limited in a way to avoid hydraulic failure with a sufficient safety factor. One problem in this respect is that possible disturbances in the subsoil (heterogeneities or scour holes) may lead to locally increased hydraulic gradients, which means that piping begins at lower gradients than expected based on calculations using a non-disturbed soil profile. In 1961 Terzaghi & Peck [7] already stated that piping erosion under dams can occur at water level differences much lower than to be expected due to hydraulic failure calculations.

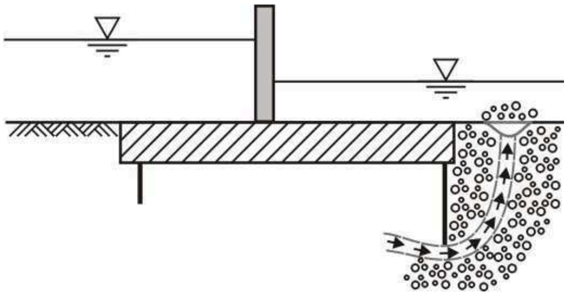

Figure 1. Schematic sketch of a piping channel occurring at the downstream end of a river barrage

Since the consideration of spatial effects of soil heterogeneity in design is usually not suitable due to limited knowledge of the subsoil conditions, admissible exit gradients have to cover such effects by means of high required safety factors.

In this paper design approaches for the consideration of piping are presented and compared for the case of a river barrage. The results of model tests are presented, which were carried out to quantify critical exit gradients under consideration of soil disturbances.

II. DESIGN METHODS FOR PIPING

The first design approach for considering piping stems from Bligh [1], who defined a seepage coefficient as follows:

$$C_B = L / H \geq C_{B,requ} \tag{1}$$

Here L is the seepage length around the structure and H is the water head. The required minimum values $C_{B,requ}$ given in Table 1 are dependent on the soil type and were derived from experience.

With theoretical considerations Sellmeijer [6] derived an equation for the critical gradient H/L which leads to piping failure. With this approach the dependence of the critical seepage coefficient on the soil type assumed by Bligh was confirmed.

Lane [3] modified the Bligh equation. He analyzed data from a large number of dams, of which a few failed due to piping, and he found out that a large vertical portion of the seepage length acts favourably. He proposed weighting the vertical portion three times higher than the horizontal one, defining the seepage coefficient as follows:

$$C_L = \frac{L_v + L_h / 3}{H} \geq C_{L,requ} \tag{2}$$

Consequently, the required values $C_{L,requ}$ are different from those given by Bligh (see Table I).

TABLE I.
REQUIRED SEEPAGE COEFFICIENTS ACCORDING TO BLIGH AND LANE

Soil type	$C_{B,requ}$ from Bligh	$C_{L,requ}$ from Lane
Very fine sand, Silt	18	8.5
Fine sand	15	7
Coarse sand	12	5
Sand and Gravel, Fine gravel	9	4

With Lane's and Bligh's methods the exact boundary conditions of the under-seepage cannot be taken into account. The actual hydraulic gradients in the subsoil are influenced, for instance, by the height of the percolated soil layer and by the locations and depths of vertical cut-offs (e.g. sheet pile walls, see Fig. 2).

Tschugajew [8] proposed to assess piping by means of a control gradient

$$I_c = \frac{H}{T\sum \zeta_i} \le I_{c,crit} \,. \tag{3}$$

The resistance coefficients ζ_i are to be calculated for the different sections of the seepage region (for details see [4]). With this the geometry of the under-seepage situation is taken into account. On the basis of a data evaluation from more than 170 dams, of which several failed due to piping, Tschugajew recommended the critical control gradients given in Table II.

With the three methods mentioned an estimation is possible for assessing the danger of piping erosion. However, in cases where piping is decisive for the design, a more exact consideration of the problem is necessary.

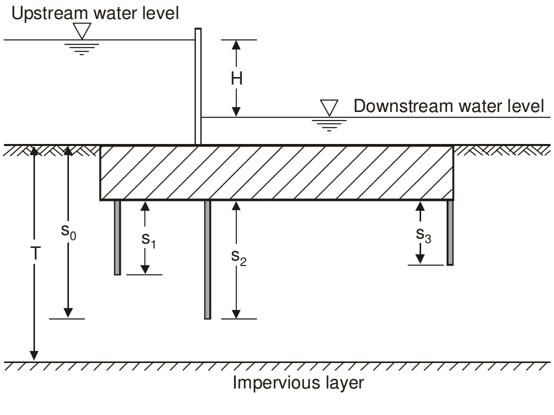

Figure 2. Geometric parameters of under-seepage flow

TABLE II.
CRITICAL CONTROL GRADIENTS ACCORDING TO TSCHUGAJEW

Soil type	$I_{c,crit}$ for cases with single cut-off	$I_{c,crit}$ for other cases
Fine sand	0.15 to 0.20	0.12 to 0.16
Medium sand	0.20 to 0.26	0.15 to 0.20
Coarse sand	0.30 to 0.39	0.25 to 0.33

As mentioned above, the process of piping erosion begins at the downstream exit of the under-seepage flow. This means that the actual hydraulic gradient at this location is decisive for the erosion design. With the exit gradient method, the hydraulic exit gradients i_{exit} are determined by means of a flow net and compared with admissible values $i_{exit,adm}$, which are again dependent on the type of subsoil. Schematically this is shown in Fig. 3.

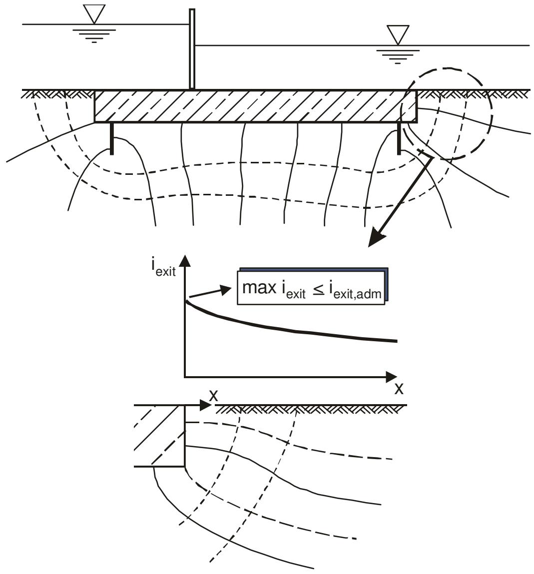

Figure 3. Exit gradient method

With numerical methods the effect of the boundary conditions of the under-seepage, e.g. different soil layers or anisotropy of the soil permeability, can be considered. Using parametric studies with a variation of input parameters a risk estimation can also be carried out, taking the uncertainties in the design parameters into account.

Instead of required seepage coefficients or a critical control gradient, admissible exit gradients have to be applied. Such values proposed by Novak et al. [5] are given in Table III.

TABLE III.
ADMISSIBLE EXIT GRADIENTS ACCORDING TO NOVAK ET AL.

Soil type	$i_{exit,adm}$
Fine sand	0.14 to 0.17
Coarse sand	0.17 to 0.20
Gravel	0.20 to 0.25

For the example of the Old Assiut Barrage on the River Nile in Egypt [4] the admissible or critical water heads have been calculated by use of the methods mentioned. The location of cut-offs (sheet piles) was varied. The results are shown in Fig. 4.

Tschugajew's method gives high water heads, because this method obviously implies no factor of safety. Admissible water heads in a similar range are obtained from Lane's and Bligh's method and from the exit gradient method. However, only the latter registers the different effectivities of the upstream and downstream cut-

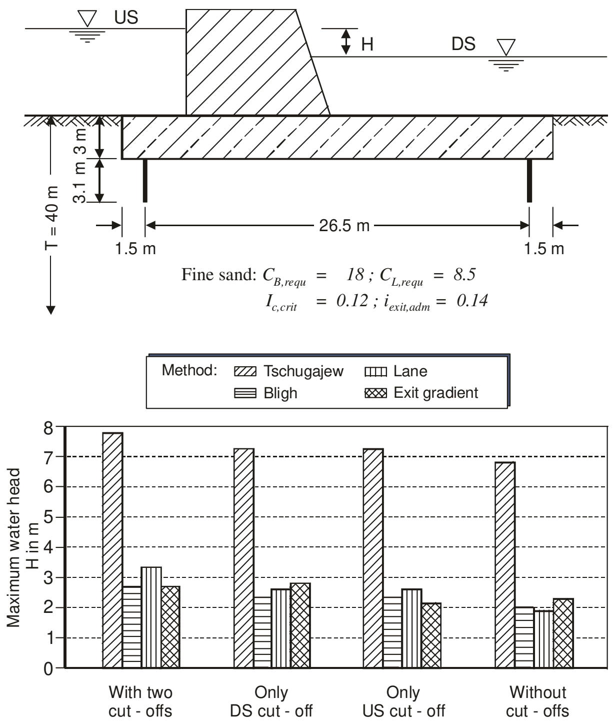

Figure 4. Comparison of calculation results for the Old River Nile Barrage at Assiut

offs. Furthermore, it is the only method which is capable of considering more complex conditions like soil layering or anisotropic permeability, which often have to be accounted for in practice.

III. CRITICAL EXIT GRADIENT

For vertical upwards-directed seepage flow the critical hydraulic gradient, for which the volume-specific seepage force equals the soil unit weight, is

$$i_{crit} = \frac{\gamma'}{\gamma_w} . \quad (4)$$

Here γ' and γ_w are the buoyant unit soil weight and the unit weight of water, respectively. Since at the under-seepage flow exit no overburden pressure acts, local hydraulic failure and with that the start of the erosion process occurs when the exit gradient reaches this critical gradient. For non-cohesive soils the buoyant unit weight normally lies in the range 9 kN/m^3 $\leq \gamma' \leq$ 11 kN/m^3, dependent on the relative density. Thus, the bandwidth for the critical exit gradient is $0.9 \leq i_{crit} \leq 1.1$. With the introduction of a safety factor η, the admissible exit gradient is

$$i_{exit,adm} = \frac{i_{crit}}{\eta} . \quad (5)$$

Novak et al. [5] derived the admissible exit gradients given in Table III from (5) using safety factors of 5 to 6. This may be justified by the fact that, at least for the example shown above, this safety factor leads to admissible water heads which are similar to the values obtained with Lane's and Bligh's methods based on experience. However, such safety factors are unusual even in geotechnical engineering and need clarification.

The background to the low admissible exit gradient is that piping erosion is a local, three-dimensional effect, whereas the exit gradients are calculated using a two-dimensional model or at least a model with homogeneous soil layers. In reality, local soil heterogeneities or disturbances (like e.g. scour holes) have to be considered, which lead to locally increased hydraulic gradients. Since it is normally impossible to take such disturbances into account, the uncertainty has to be covered by the use of high required safety factors.

However, to assess the real level of safety it should be known which are the actual critical gradients valid for most unfavourable conditions. For this reason, model tests have been carried out, in which the soil at the downstream end of a model barrage was disturbed systematically.

IV. MODEL TESTS

A. Model test set-up

In 1922 Terzaghi carried out model tests to study piping under a shallow foundation and found out that Bligh's design method incorporates high factors of safety compared with his test results. In the 1930s Davidenkoff carried out similar tests, but he inserted a small glass tube in the foundation bed to produce an artificial weak point. He established that the water head at which piping occurred was nearly halved by this measure [2].

In the tests reported here disturbance of the downstream river bed was achieved by means of a small needle which was pricked into the soil at different locations to favour the start of the erosion process.

The test set-up used is shown in Fig. 5. A model of the Old Assiut Barrage foundation on the River Nile with a scale of about 1:100 was investigated. Two foundation models, one with two cut-offs at the upstream and downstream end of the foundation and one without cut-offs, were used. Also, the depth T of the sand subsoil layer was varied between 10 cm and 25 cm.

The soil used was a uniform fine to medium sand. The grain size distribution of this material is shown in Fig. 6. The following parameters apply for the sand:

- Minimum void ratio: $e_{min} = 0.67$
- Maximum void ratio: $e_{max} = 1.09$

In two test series the sand was placed in the box once with an average void ratio of $e = 0.92$, which corresponds to a loose to medium dense state (relative density D_r = 0.40) and once with $e = 0.72$, corresponding to a dense state ($D_r = 0.88$). The loose to medium dense state was achieved by pouring the sand gently into the water, and the dense state by vibrating the box with the help of a plate vibrator whilst pouring the sand.

Starting from a constant water level, the level on the upstream side of the model barrage was increased stepwise. After each step of initially 4, later on 2 and finally 1 cm increase the evolution of stationary seepage conditions was waited for. For this the seepage discharge

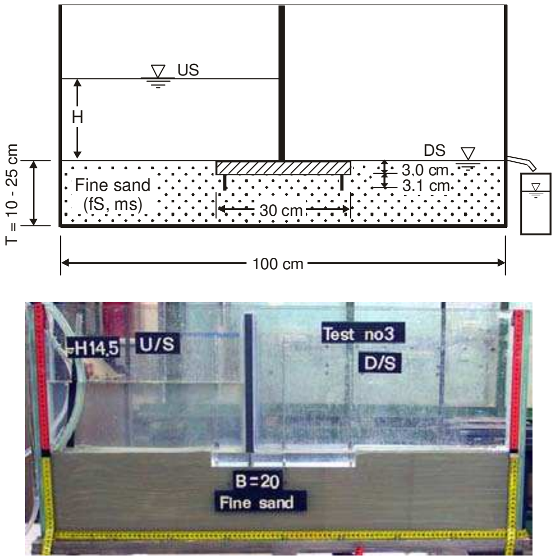

Figure 5. Model tests set-up: schematically, with cut-offs (top), photographic view (bottom, without cut-offs)

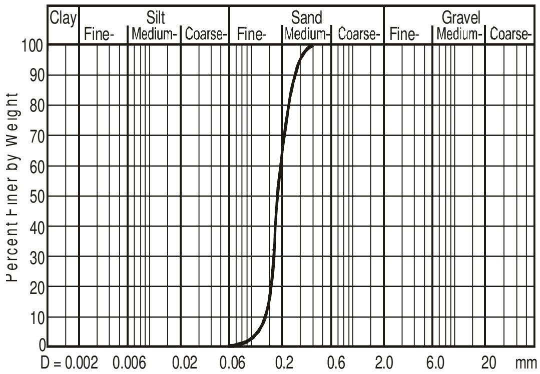

Figure 6. Grain size distribution of the sand used

and, by means of piezometers, the water pressures beneath the foundation were measured. Then the downstream soil bed was disturbed with the help of a thin needle to simulate disturbance and to create favourable conditions for the start of piping erosion. The disturbance was made at the middle and at both sides just beside the downstream end of the foundation with depths ranging from 3 to 7 cm. When this was done, at a certain water head a local 'boiling' zone indicating the start of the erosion process was observed. Afterwards, the time interval till the next water head increase of 1 cm was raised to 40 minutes in order to observe carefully the ongoing process until complete foundation failure occurred.

B. *Observed phenomena*

After reaching a certain water head on the upstream side, for both cases with and without vertical cut-offs a local erosion funnel evolved at the downstream end of the foundations. In this region the seepage force equalled the soil weight, so that the soil grains were moving around. Since this looks like as if the sand is boiling, the zone is called the 'boiling zone'. This state is stable, i.e. transportation of soil grains and a further progress of the piping channel only occurs when the water head is increased further. This was also observed in experiments by Sellmeijer [6].

Further increase of the water head leads to erosion. Due to transportation of the soil grains a small elevation in the downstream bed occurs. The boiling sometimes stopped, possibly due to blockage caused by the deposition of the sand grains, but after another disturbance with the needle it continued again. During the test, ejected sand was continuously removed to simulate the transport to be expected by the downstream water flow and to keep the erosion process in progress.

With the ongoing increase of the water head difference, in the case without cut-offs a small piping channel formed in the contact surface between the soil and the foundation, progressing towards the upstream side. This could be observed in tests using a transparent foundation model. In the top view given in Fig. 7, the boiling zone and the piping channel observed in one test are shown. During the ongoing process, a depression in the soil bed upstream of the model barrage could be observed.

For the cases with cut-offs, firstly a small depression formed at the upstream side of the downstream cut-off. Due to the depression, in the upper layer of sand between the two cut-offs the transport of soil particles to the downstream side took place. At a later stage, this material loss leads to a depression of the sand bed at the upstream end of the foundation (Fig. 7 bottom).

Finally, in all tests a complete failure of the foundation occurred with a drastic outflow of the soil beneath the foundation and a more or less instant equalization of the water levels upstream and downstream. In the tests, the

Figure 7. Observed phenomena during piping erosion: system without (top) and with cut-offs (bottom)

foundations stayed in their positions, because to avoid seepage beside the foundation, a silicone seal had been arranged between the foundation and the model box (Fig. 8). In nature, complete failure would lead to high displacements and rotations of the foundation.

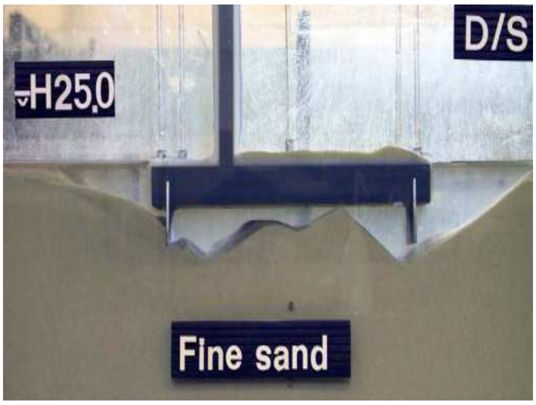

Figure 8. Final situation after complete failure

C. *Test results and analysis*

The water head differences acting at the beginning of the piping process, i.e. the first evolution of a boiling zone, and at the end of the tests reaching the ultimate failure are given in Table IV.

On one hand there is a clear influence of the relative density of the sand. For the cases with dense sand higher water heads apply than for loose to medium dense sand. On the other hand there is also a tendential influence of the depth of the sand layer. The higher the subsoil depth, the lower is the water head necessary for the begin of and the failure due to piping. This agrees with results from the exit gradient method, since a larger subsoil depth leads to higher exit gradients.

TABLE IV.
WATER HEAD DIFFERENCES MEASURED IN THE TESTS

Test case	Depth of sand layer *T* in cm	Water head difference *H* in cm	
		Piping start	Failure
Loose to medium dense sand, no cut-offs	10	13	16
	15	11	15
	20	13	14
	25	10	13.5
Dense sand, no cut-offs	10	15.5	18
	15	15	17
	20	14.7	16.5
	25	14	16
Loose to medium dense sand, with cut-offs	10	17	22
	15	14	22
	20	14	21
	25	14	20
Dense sand, with cut-offs	10	22	27
	15	20	25
	20	21	26
	25	19	25

To determine the critical exit gradients from the experimental tests, back-calculations using flow nets established for the model test cases were carried out. A homogeneous subsoil with isotropic permeability was assumed. Thus, the exit gradients belonging to the water heads measured could be calculated. In Figs. 9 and 10 the exit gradients belonging to the start of piping and determined at ultimate failure are given. The results for dense sand and for loose to medium dense sand are depicted separately.

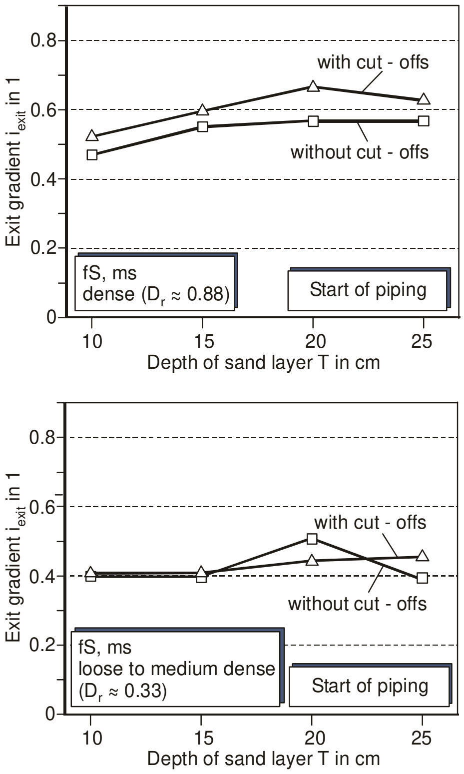

Figure 9. Exit gradients at the start of piping determined for dense sand (top) and for loose to medium dense sand (bottom)

There is a tendency, at least for dense sand, that in cases with vertical cut-offs higher critical exit gradients apply. For dense sand and a small sand layer depth of 10 cm slightly lower exit gradients are also determined.

From the experimental tests, exit gradients belonging to the start of piping between 0.5 and 0.65 are found for dense sand and between 0.4 and 0.5 for loose to medium dense sand. To induce the ultimate failure, exit gradients between 0.55 and 0.85 for dense sand and between 0.5 and 0.65 for loose to medium dense sand were determined.

V. CONCLUSIONS

The exit gradient method is the only method capable of accounting for complex boundary conditions in the design of river barrages with respect to piping. In cases where piping is decisive for the design of a structure, this method should be used.

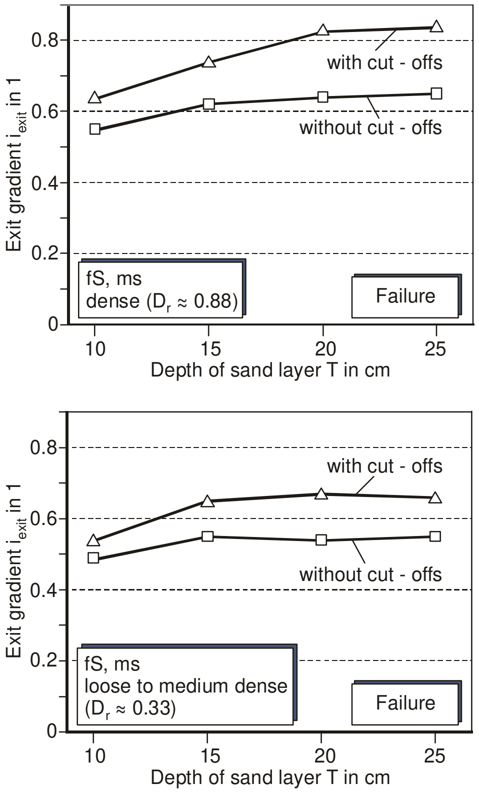

Figure 10. Exit gradients at ultimate failure determined for dense sand (top) and for loose to medium dense sand (bottom)

However, at which water head difference piping starts and failure of the structure occurs, depends strongly on soil heterogeneities or on the existence of disturbed zones in the subsoil. Thus empirical values of the admissible exit gradient are used, which imply a safety factor between 5 and 6 to the theoretically critical hydraulic gradient of about 0.9 to 1.1.

The model tests reported here make it clear that under extremely unfavourable conditions, i.e. very favourable conditions for piping, the erosion can begin at hydraulic gradients – calculated by means of a two-dimensional model – much lower than the theoretical value. Piping in fine sand was observed to begin at water head differences belonging to calculated exit gradients of about 0.4 for the loose to medium dense state and of about 0.5 for the dense state. Assuming these values to be the real critical exit gradients, the admissible exit gradients proposed by Novak et al. imply a real safety factor of about 3. Higher exit gradients are necessary to induce failure of the structure, leading to safety factors of 4 and higher.

The installation of vertical cut-offs tends to increase the critical exit gradient. The reason for this might be that the direction of seepage flow near the exit point is not really vertical but inclined for the cases without cut-offs. Also, without cut-offs, piping channels can easily course in the interface between foundation and soil. In the tests the foundation surface was relatively smooth, and the foundation pressure was relatively low.

Due to German regulations, a safety factor against hydraulic failure of 1.5 is usually required. Considering this, higher exit gradients seem to be admissible with respect to piping. However, it has to be pointed out that the critical exit gradients found should not be applied directly to practical problems. It is yet not clear to which degree the simulated disturbance of the soil bed is realistic and really covers most unfavourable conditions in nature. It must also be considered that the magnitude of soil pressures in the model tests was much smaller than in reality, which is at least of influence for the progress of the erosion after occurrence of the first boiling zone.

Thus, many questions concerning admissible exit gradients are still open. This justifies the relatively low admissible values used in practice at the present time. However, it is felt that in many cases the design with these values implies higher safety factors than necessary. To use this potential for optimization, further research has to be carried out.

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