Backward Erosion Piping through Vertically Layered Sands

K. Vandenboer, L. Dolphen, A. Bezuijen

***Abstract*—**Backward erosion piping is an important failure mechanism for water-retaining structures, a phenomenon that results in the formation of shallow pipes at the interface of a sandy or silty foundation and a cohesive cover layer. This paper studies the effect of two soil types on backward erosion piping; both in case of a homogeneous sand layer, and in a vertically layered sand sample, where the pipe is forced to subsequently grow through the different layers. Two configurations with vertical sand layers are tested; they both result in wider pipes and higher critical gradients, thereby making this an interesting topic in research on measures to prevent backward erosion piping failures.

***Keywords*—**Backward erosion piping, embankments, physical modelling, sand.

I. Introduction

A. Backward Erosion Piping

BACKWARD erosion piping is an important failure mechanism for cohesive water-retaining structures founded on a sandy aquifer. A local disruption of the downstream top layer leads to concentrated seepage flow towards the opening. This entails high local hydraulic gradients causing upward forces on the sand grains which may result in the onset of erosion at that location (pipe initiation). The erosion process continues in the upstream direction, resulting in the formation of shallow pipes in the sand layer (pipe progression). These pipes do not collapse because of the bridging nature of the overlying cohesive material. Eventually, the pipe forms a direct connection between upstream and downstream, which leads to a facilitated water transport and to accelerated erosion. The pipe finally reaches unbridgeable dimensions resulting in a (partial) collapse (see Fig. 1).

B. Current Formulae

Based on a large number of failures from field studies, Bligh [1] established a failure criterion which was later modified by Lane [22] to account for the vertical movement of flow lines. High safety factors are required because of the undetailed character of the criterion. An extensive experimental study led to Schmertmann's definition of the critical gradient, which requires additional groundwater flow calculations for each application [2]: More recently various design formulae were developed, which either predict piping susceptibility by correlating them to similar field cases in the past [3], [4], or have a theoretical basis [2], [5]-[7] or a combined experimental-theoretical background [8]-[11].

Some of the existing design formulae are highly sophisticated, including many influential parameters and good insights, but none of them succeeds to correctly predict the piping susceptibility for a wide range of boundary conditions. Further research is essential for understanding the phenomenon backward erosion piping and establishing a successful formula which can be applied in practice.

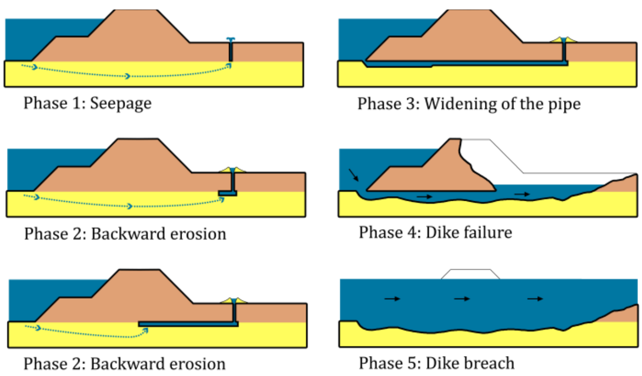

Fig. 1 Backward erosion piping [12]

Various experimental studies have led to fundamental knowledge on key aspects of backward erosion piping either by analyzing the critical gradient or by studying the pipe formation in the sand bed: [13]-[15] identified the different phases involved and described the meandering character of the pipes; [16] investigated the influence of the different downstream exit configurations on critical gradient; [17] studied the erosion and fluidization in an outflow opening; [9], [18] considered a large number of sand types in order to identify the influence of relative density, uniformity, roundness, permeability, and grain size on the susceptibility to backward erosion piping; [19], [20] demonstrated that backward erosion piping should be treated as a three dimensional phenomenon rather than a two-dimensional problem by analyzing the groundwater flow towards the exit and the pipe; [21] studied the variation of pipe widths in relation to the grain size.

In this paper, the influence of a vertically layered sand bed on backward erosion piping is examined through small-scale experiments where the pipe is forced to subsequently grow through the different layers.

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C. Measures

Obvious measures to reduce the risk of piping failure are a horizontal [1] or vertical [22] extension of the seepage length and reduction of the prevailing hydraulic head load by containment of the water downstream or with seepage dams [11]. Another possibility is the inclusion of a geotextile or a filter [23], but the installation has proven difficult.

II. Experimental Setup

In laboratory conditions, the sandy aquifer is built in a PVC box, the cohesive water-retaining structure is replaced by an acrylate plate (Fig. 2) with a fixed circular opening representing the locally punctured top layer and the hydraulic gradient is applied by means of an upstream and downstream reservoir with adjustable water levels.

The sand sample is prepared homogeneously at a relative density of approximately 80% in the box and has a total length of 0.4 m, a height of 0.1 m, and a width of 0.3 m. The distance from upstream to the circular opening (seepage length) amounts 0.3 m.

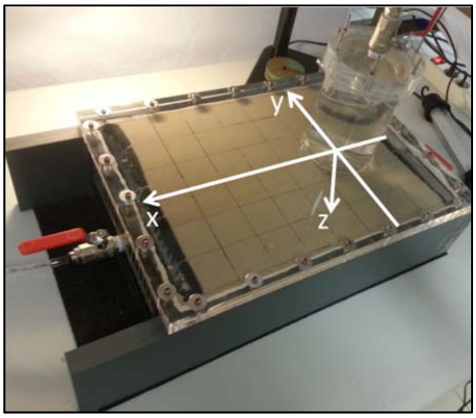

Fig. 2 Test set-up

A circular exit was chosen to obtain a reproducible pipe formation: in case of a plane or a ditch type exit [12], each pipe also originates at one point downstream, but neither the location nor the number of pipes is controllable. The hole type exit has a height h of 10 mm for practical reasons and a diameter d of 5 mm.

The initial hydraulic head difference ΔH of 0 mm is increased in steps of 5 mm or 10 mm every 5 minutes, as long as no erosion takes place. When the critical hydraulic head for initiation ΔH_{init} is exceeded, i.e. sand grains start to move and a pipe is formed, the hydraulic head is kept constant. If no erosion is observed for at least 5 minutes (equilibrium), the hydraulic head is further increased, usually resulting in progression of pipe growth. This process is repeated until the critical hydraulic head for progression ΔH_{prog} is exceeded, i.e. no equilibrium state is achieved anymore and the pipe grows until it reaches the upstream filter, and the test is stopped.

The eroded sand is deposited around the circular exit forming a submerged crater. The flow rate is continuously measured by collecting the seepage water on a balance.

In this study, two uniform and poorly graded sand types are used: 'Molsand M34' and 'Molsand M32', with an average grain size d_{50} of 0.155 mm and 0.251 mm, respectively (see Fig. 3). The hydraulic conductivity amounts $1.03*10^{-4}$ m/s for M34 and $3.28*10^{-4}$ m/s for M32 at the density that we use in our tests.

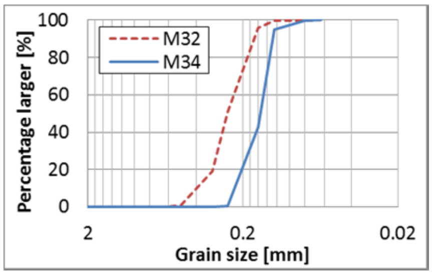

Fig. 3 Grain size distribution of the sands used in the tests

III. Results and Discussion

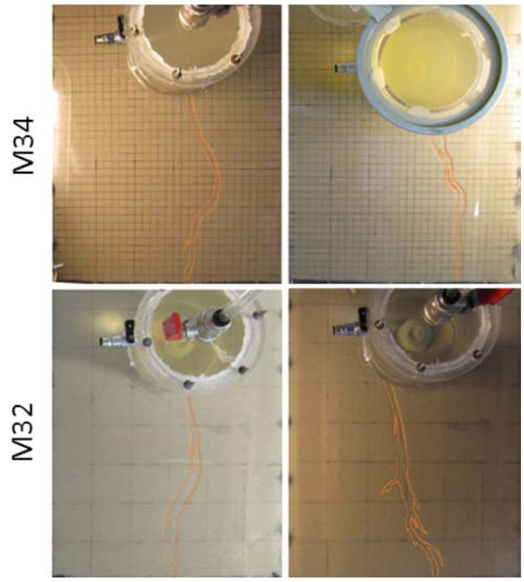

Fig. 4 Examples of pipes created in tests with a homogeneous sample of one sand type

As a reference, a series of experiments with a uniform sand sample consisting of one sand type only is performed for both M34 and M32. Erosion starts at $\Delta H_{init,M34}$ = 18 mm for M34 (4 tests) and $\Delta H_{init,M32}$ =25 mm for M32 (seven tests), after which the pipe develops gradually while the applied hydraulic head is increased a few times until the pipe reaches the upstream at $\Delta H_{prog,M34}$ = 59 mm for M34 and $\Delta H_{prog,M32}$ = 74 mm for M32. Although the smaller M34 grains are easier to erode and transport, the higher permeability of the coarser M32 sand enables a considerable water flow contributing to the erosion of the grains, so the critical hydraulic heads of the two sands are relatively close to each other. Fig. 4 shows two examples for each sand type of the pipe configuration at the end of the test. The pipes meander subtly and have an almost constant width of 9.6 mm for M34 and 12.5 mm for M32 outside the cylinder (the part inside the cylinder is not considered due to poor visibility).

The sand type has a clear influence on backward erosion piping: an almost identical but slightly coarser sand, results in a higher critical head for both initiation and progression and leads to wider pipes.

In the following, the pipe is forced to grow through a sand bed with alternating vertical layers of M32 and M34, each with a length of 0.1 m extending over the full height of the container. The hole exit is positioned at the transition of two layers so piping initiation involves both sand types. Subsequently the pipe continues in the upstream direction where it needs to overcome the first sand layer, proceed through the second sand layer and complete its course through the third layer which is the same sand type as the first sand layer; the sand layer downstream from the exit hole is referred to as the zeroth layer.

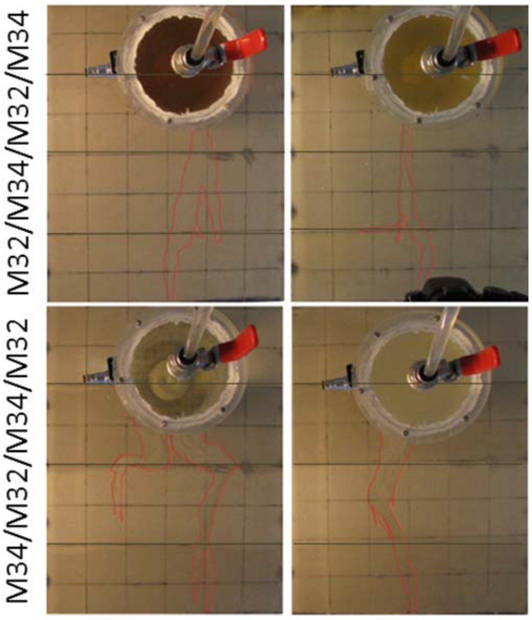

Fig. 5 Examples of pipes in tests with a vertically layered sand sample

Two configurations are tested (two tests each), from upstream to downstream: M32/M34/M32/M34 and M34/M32/M34/M32 (see Fig. 5). In all cases, both M34 and M32 are involved in piping initiation. The average permeability of the sand bed between upstream and downstream depends on the sand layers present. For M32/M34/M32/M34, this permeability is somewhat higher than for M34/M32/M34/M32, which explains why the critical head for initiation ΔH_{init} is slightly smaller (see Fig. 6).

For M32/M34/M32/M34, erosion firstly develops towards the zeroth layer containing M34 sand (not clear on the photos but clearly observed during the experiments). After a while, however, the pipes evolve in the upstream direction where the coarser M32 layer needs to be passed. As an M34 layer is present on the way from upstream to downstream, the water supply towards this pipe is reduced compared to the situation with a soil layer consisting only of M32 sand, and as a result, the critical head for progression ΔH_{prog} is 50% larger, i.e. 110 mm. The average pipe width is 21.5 mm, which is much higher than for the single layer configurations. Moreover, the average pipe width in the fine M34 layer is larger than in the coarse M32 layer (about 30.6 mm compared to 15.4 mm). The explanation is twofold: the water supply needed to erode the first M32 layer is still present when the pipe reaches the second layer and easily erodes an abundance of small M34 grains. Furthermore, the larger dimensions of the pipe in the M34 layer are needed to increase the overall permeability, so the water supply is sufficient to erode the M32 layer.

It should be noted that the dimensions of the fine M34 layer were relatively large in this study. If one wants to apply a fine sand layer in order to increase the critical hydraulic head at a large scale in practice, the beneficial effect of a smaller permeability may decrease considerably.

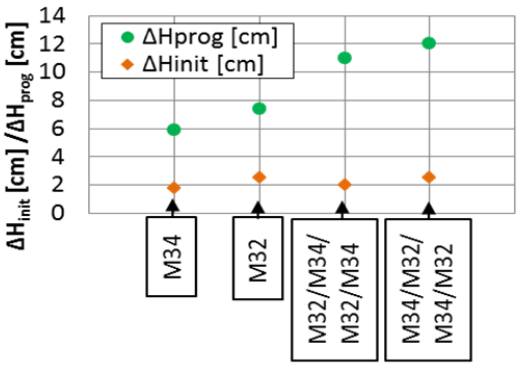

Fig. 6 Critical heads measured in the different tests

For M34/M32/M34/M32, the pipe passes the first M34 layer at an average hydraulic head of 60 mm, which is close to the critical head for progression ΔH_{prog} in case of the single M34 layer. This means that the influence of the increased permeability of the M32 layer which is present between the M34 layers is limited. In case of the single M34 layer, the pipe would continue to grow in the upstream direction without the need to further increase the applied hydraulic head. In the M34/M32/M34/M32 case, however, the water supply that was needed to erode the first M34 layer does not suffice to continue through the coarser M32 layer and the hydraulic head needs to be increased. Meanwhile, erosion continues in the first M34 layer, so the dimensions of the pipe in this layer increased considerably (see the bottom left of Fig. 5). At an average critical head of ΔH_{prog} = 120 mm, the pipe passes through both the second and third layer. The critical head for the bottom right of Fig. 5 was smaller than for the bottom left, as the latter developed two large pipes, each demanding a part of the available water supply. As a result of the enlargement of the pipe dimensions in order to overcome the second layer, an average width of 29 mm is obtained. This beneficial effect of hindering piping progression by inserting a coarser M32 layer into the fine M34 sand bed is very promising for the development of measures to prevent piping failure. More research is needed, especially on a larger scale, on the optimal location and with a relatively thinner coarse layer inclusion.

However, the results are expected to be promising as the difficulty of eroding the coarse layer remains and the effect of the increased permeability will decrease.

IV. Conclusion

This paper discusses small-scale experimental piping tests using homogeneous sand samples on the one hand, and vertically layered sand samples on the other hand. Two almost identical sand types with an average grain size of 0.155 mm and 0.251 mm are examined.

In case of a homogeneous sand layer, it is found that the critical head for both initiation and progression slightly increases with the grain size. Also, the average pipe width increases with the grain size.

Next, the same experiments are performed in case of vertical sand layers of each 0.1 m long extending over the full height of the container. One layer is present downstream from the exit hole, followed by three alternating layers between the exit and upstream where the pipe needs to pass.

The insertion of a coarse layer into a fine sand bed slightly increases the overall permeability, which is why the critical head for initiation slightly decreases. The critical head for progression however increases substantially because coarser grains of the insertion are hard to erode. Before erosion progresses through the coarse layer, the pipe dimensions in the fine sand bed increase considerably. More research is needed for applying a coarse sand layer into a fine sand bed as a measure for piping erosion in practice, but the results are very promising.

In the opposite case where a fine layer is inserted into the coarse sand, the overall permeability decreases, and consequently, the critical head for progression increases considerably as well. It is noted however that the insertion of the fine layer in our tests was relatively large, and the effect might become negligible in case of a thin fine sand inclusion.

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