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Piping Phenomena in Heterogeneous Sands - Experiments and Simulations

PIPING PHENOMENA IN HETEROGENEOUS SANDS – EXPERIMENTS AND SIMULATIONS

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Piping in or under levees and dams is a phenomenon that may cause significant safety threats. To predict the occurrence of piping underneath levees, several computational models are available. However, all these models use the properties of a single type of sand in which the channel formation takes place. In the real world, heterogeneities, like the co-occurrence of different types of sand with different properties, exist. This contribution describes an attempt to establish this influence by conducting laboratory experiments and numerical simulations for a situation where the piping channel is formed serially through zones of different types of sand, which is an essential difference with earlier experiments on a system of layers of different types of sand with a parallel system of fine sand above coarse sand, described in literature (Hanses, Müller-Krichenbauer et al.).

Our experiments have been performed in a sandbox, subjected to a horizontal water gradient. During the test the hydraulic head over the sand was raised until piping occurred. The process of formation of small channels was observed through a transparent cover.

Groundwater flow simulations have been performed with MSeep, a groundwater model extended with a piping module, based on Sellmeijer's rule (Sellmeijer, 1988; TAW, 1999).

Two types of sand were used for the tests. The tests were performed on both sands individually, tests on fine sand downstream and coarse sand upstream, and tests on fine sand with an intermediate zone of coarse sand. All experiments have been simulated with MSeep.

It was found that a piping channel that developed in the fine sand stopped at the interface between the coarse sand and the fine sand. Total failure took place only after a significant increase of the hydraulic head. It appeared that combination of different sands appeared to resist the growth of piping channels stronger than each of the homogeneous sands. This result has not been found in the results of the groundwater simulations in MSeep. The critical gradient of the heterogeneous sands, calculated in MSeep did not deviate significantly from the calculations of single sands.

This outcome stimulates further investigations. These investigations will include aspects of heterogeneity of natural sands and their impact on the factors influencing pipe development.

Key Words: *Piping, Erosion, Heterogeneity, Experiments, Simulations*

1. INTRODUCTION

According to recent studies on the safety of levees in the Netherlands, piping is one of the most relevant failure mechanisms in the water retaining structures along the rivers in the Netherlands. The existing models used have been proven successful but are likely to overestimate the risk. Therefore, a need exists to investigate improvements.

Mark that the current models available for the prediction of piping are based on homogeneous single sand layers. The effect of heterogeneities on piping has been studied by several researchers. Müller-Kirchenbauer (1978) has tested a multi-layer system with either two or four layers of fine and course sand. Following this, Hanses et al. (1985) described the influence of the thickness of the water bearing sand layer on the piping process, in both homogeneous and layered situations.

In reality the sand channel will be formed through various types of sands. Heterogeneities are present in the horizontal direction. To assess the influence of this kind of serial heterogeneities, experiments and simulations have been performed with zones of different sands. The preliminary experiments are performed on a small scale, using two commercially available sands. The simulations are performed in MSeep, a groundwater flow model developed to evaluate the occurrence of piping channels.

2. SET UP

The experiments are performed in a small box with dimensions of 0.5x0.4x0.1m. The box can be filled with sand, which is retained by two filters. A constant head can be applied to the sand, with a range of 0-1m.

The transparent perspex cover allows for the observation of the formation of piping channels. A camera has been placed above the set up to monitor the formation of channels. The set up is shown in Fig 1.

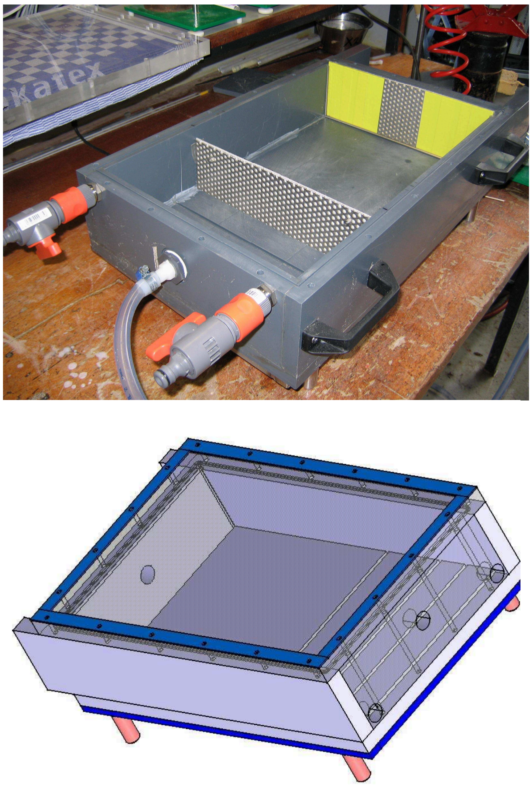

Fig 1 Experimental set up

3. CONDUCT OF TESTS

Several tests have been conducted in the experimental set up, comprising testing of single sands and different combinations of sands. To test and optimize the set up, the first tests were executed with a well known type of fine sand, so-called Baskarp sand. After this, two types of sand were selected to perform the heterogeneous tests. The selected sands are Playground sand and Masonry sand, which are sands from a DIY store. The grain size distribution of these sands is shown in Fig 2.

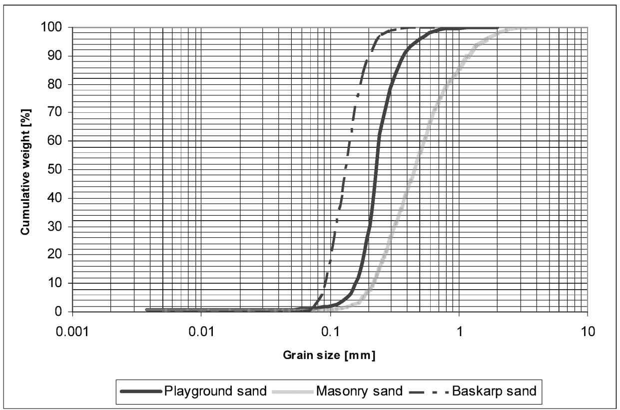

Fig 2 Grain size distribution

With these sands the following tests are conducted:

- Individual sands
- Coarse Masonry sand upstream and fine Playground sand downstream
- Fine Playground sand with a small intermediate zone (5cm) of coarse Masonry sand

4. RESULTS OF SINGLE TESTS

The critical heads obtained for piping formation in the individual sand tests are given in Table 1. In Fig 3 the channel formation in Baskarp sand is shown. The results have been compared with calculations using Sellmeijer's rule (1999) in the same table.

Table 1 Critical heads for individual sands

Test	Permeabillity [m/s]	Length [cm]	Critical head Sellmeijer [cm]	Critical head experiments [cm]
Baskarp 1	6.4E-5	34	15	18
Baskarp 2	6.5E-5	35	15	16
Masonry sand 1	4E-4	35	31.4	26
Masonry sand 2	2.5E-4	35	36	62
Play-ground sand 1	1.4E-4	35	18.5	24

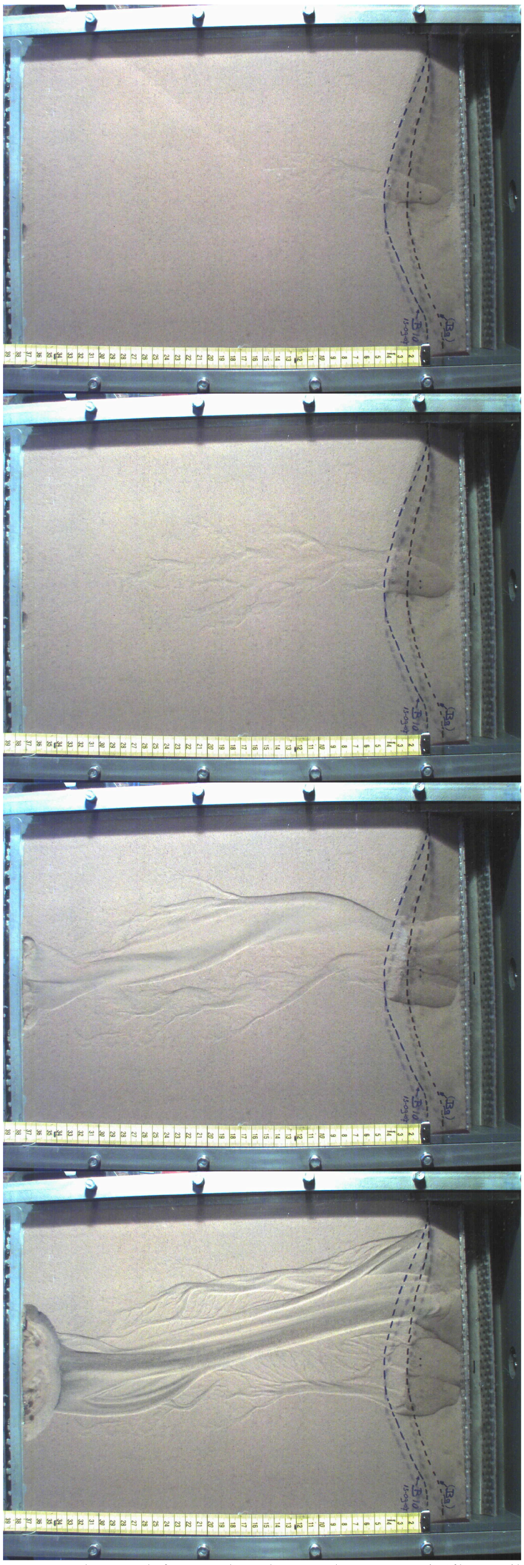

Fig 3 Channel formation in Baskarp sand (flow direction to the right).

It is observed that the prediction using Sellmeijer agrees rather well with the two obtained critical heads for Baskarp sand. The test with Masonry sand, however, is not well reproduced. This might be caused by the fact that this sand is well graded, which complicates the preparation of the sample. The Playground sand is tested only once and therefore the reproducibility is not established.

It is noted that due to scale effects the observed gradients should be considered as qualitative results and they are not realistic for field situations.

5. TESTS ON HETEROGENEOUS SANDS

Two types of heterogeneous tests have been conducted:

- Masonry sand upstream and Playground sand downstream; a coarse to fine test (CF)
- Playground sand with an intermediate zone of Masonry sand (FCF)

Both tests have been conducted twice.

During the CF tests it was observed that channel formation in the finer sand took place at a relatively low gradient. It stopped at the interface with the Masonry sand, resulting in equilibrium conditions without further transport of sand. Increase of the gradient resulted in deepening and widening of the channel in the finer sand, both in flow direction as well as parallel to the interface of both types of sand (Fig 4)

Fig 4 Channel formation in Masonry sand and Playground sand.

A significant increase of the head was necessary to cause channel formation to progress in the Masonry sand. The results are shown in Table 2.

Table 2 Critical heads CF test

Test	Critical head [cm] Playground sand	Critical head [cm] combined sands
13	12	51
14	12	40

The FCF-tests consisted of fine Playground sand with an intermediate zone of 5 cm of coarser Masonry sand. As in the previous test, channel formation in the Playground sand took place at a relatively low head. Since the stack did contain less coarse sand, the permeability was lower and channel formation took place at a higher gradient compared to the previous test.

Channel formation in the intermediate coarse sand layer took place only after a considerable increase of the gradient. The fine sand layer, however, stayed in place until the head was raised even further, up to about 80 cm (which is a gradient well over two). It is assumed that clogging occurs at the fine-coarse interface (Fig 1).The results of these tests are shown in Table 3.

Table 3 Results FCF tests.

Test	Critical head [cm] lower Playground sand	Critical head [cm] Masonry sand	Critical head [cm] combined sands
15	22	70	82
16	22	66	76

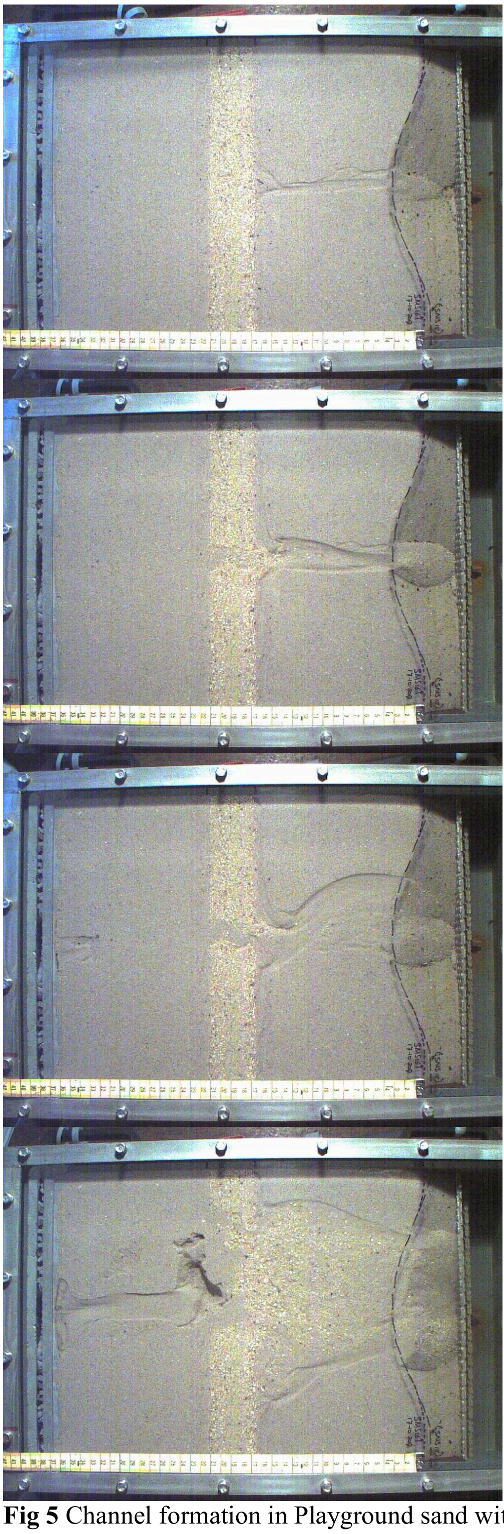

Fig 5 Channel formation in Playground sand with zone of Masonry sand

6. COMPUTER SIMULATIONS WITH MSEEP

Few computational models are available to evaluate the occurrence of piping phenomena. Most of these models, like Sellmeijer's rule, do not specifically allow for calculations with heterogeneous subsurface conditions. However, the groundwater flow calculation model Mseep has been extended with a code for internal erosion, based on the theory of Sellmeijer (1988) and allows for the calculation of a more complex subsurface configuration.

The piping facility in the MSeep model has not been validated earlier for heterogeneous conditions. It is therefore unknown to which degree the computations will match the experiments. However, the original concept is tested for various conditions.

In order to test the ability of MSeep to predict the results from the experiments, all experiments have been simulated numerically (Fig 6).

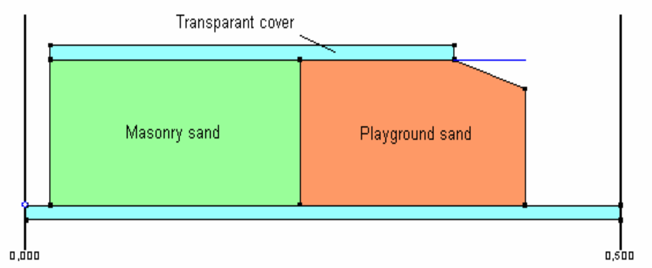

Fig 6 Example of MSeep configuration.

In these simulations it was found that the obtained critical head for single sands agreed well with the Sellmeijer's rule. The combinations of Playground sand and Masonry sand resulted in a poor performance in terms of critical head (15 cm and 18 cm, versus significantly higher values found in the experiments).

Next to the combination of Masonry sand upstream and Playground sand downstream, the situation of Masonry sand downstream and Playground sand upstream has been simulated in MSeep. This can be compared to a filter construction. As expected, it has been found that this combination resulted in a high critical head of 72 cm.

7. COMPARISION BETWEEN MSEEP AND EXPERIMENTS

In Table 4 an overview is given of the critical heads for both the experimental work and simulations.

Table 4 Overview of critical heads

	C*	F**	CF	FC	FCF
Experiment 1[cm]	26	24	51	-	82
Experiment 2 [cm]	62	-	40	-	76
MSeep simulation [cm]	32	17	15	72	18

* C: coarse Masonry sand
** F: fine Playground sand

It appears that the critical head for combinations of different sands is significantly underestimated in simulations by MSeep. This might be caused by a difference in the impact of channel formation on bulk permeability. The influence of channel formation on the bulk permeability over the sand-filled box during channel formation is shown in Fig 7. It can be seen that the change in overall permeability caused by the formation of a channel is overestimated in MSeep in comparison to the experiments.

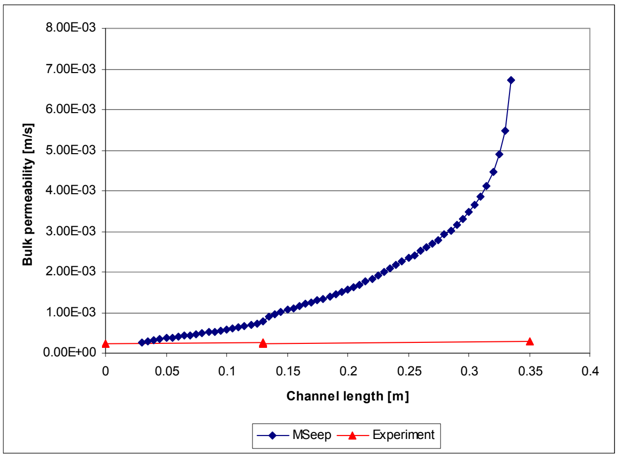

Fig 7 Impact of channel formation on bulk permeability.

8. CONCLUSIONS AND RECOMMENDATIONS

In general it is concluded that heterogeneous sands appear to resist the formation of piping channels better than each of the individual sands. It is found that a discrepancy exists between the results of the experiments and the results obtained from the groundwater model MSeep. This discrepancy is most likely caused by the difference in impact of the channel formation in the downstream sand. With increasing length of the channel the bulk permeability increases significantly in the calculation model, whereas in the experiments this effect is negligible, which is a surprise.

The reproducibility of the tests on Masonry sand appeared to be poor.

It is therefore recommended to conduct more research on the behaviour of heterogeneous sands. Further investigations will aim for reproducibility, broadening the range of sand properties and upscaling.

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