Retardation of breach growth under high flow velocities

by

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Summary

People all around the world live and work in low-lying areas. Low-lying areas have to be protected against high water levels in rivers and at sea by a water protection system (e.g. dunes, dikes and barriers). Dikes are an important component within water protection systems. Generally, dikes are described as elongated naturally occurring or artificially constructed (earthen) structures, which prevent flooding of the hinterland. Dikes are mainly found along seas, estuaries, rivers, canals, lakes and water courses. Many dikes contain sand cores, which are covered by a protection layer (e.g. clay, asphalt etc.) to prevent erosion of the core. Unfortunately, there are times that one of the many known failure mechanisms of a dike causes (local) dike failure, exposing the sand core to the water (Rijkswaterstaat, 2006). A so-called initial breach is formed. Once the sand core is no longer fully covered by a protection layer, the sand core start to erode and the core is prone to fast breaching (Visser, 1998).

The water flowing through the breach is eroding the sandy sediment and the breach keeps growing, which can have significant economical consequences and can also lead to loss of human life and animal life. Several options to retard the breaching process have been investigated by Lemmens (2014). Based on laboratory experiments, especially a mixture of sand and bentonite (in the core of the dike) seems to significantly slow down the breaching process. Thus far, this theory has only been tested for relatively low flow conditions in the order of 1 m/s. However, during the breaching process high flow conditions in the order of 2-10 m/s can be reached (Visser, 1998)) and under high flow conditions dilatant behaviour of the sediment is going to play a role (Van Rhee, 2010). As a result an inward directed hydraulic gradient will hinder the erosion and is expected to have a significant impact on the breaching process. The aim of this Msc Thesis project is to find an answer to the following main question:

“How does bentonite reduce the erosion velocity of sand under high flow velocity conditions?”

A literature review has resulted in an understanding that at high flow velocities (>2 m/s) the erosion velocity depends on the properties of the soil mass and not only on the properties of a particle. Important parameters of the soil mass are the permeability and dilatancy. From the erosion experiments it can be concluded that the effect of dilatancy, which plays a role at higher flow velocities, indeed hinders erosion and thus reduces the erosion velocity at higher flow velocities. This effect is caused by a volume change, as a result of shearing of the bed. The volume change generally leads to a drop in pore pressure in the top of the sand bed. This pressure drop introduces a hydraulic gradient and thus an inflow of water that hinders the entrainment of sediment. The permeability also significantly influences the erosion behaviour. Falling head tests were executed to determine the effectiveness of adding bentonite to the core of a dike. Adding a certain amount of bentonite to sand certainly yields a high decrease in permeability. This is the result of the swelling potential of the bentonite, which is assumed to fill the empty space between the sand particles. It appears that the most significant decrease in permeability happens with bentonite contents up to 6% of the volume. Adding more bentonite still reduces the permeability, but the overall effect is starting to flatten out for bentonite contents higher than 8%. Overall, the approximate decrease in permeability is almost three orders of magnitude (from \(10^{-4}\) to \(10^{-7}\)) with bentonite volume percentages up to 10%.

Results from the direct shear tests show no significant differences between sand mixtures and sand-bentonite mixtures with a bentonite content up to 10%. The apparent cohesion is not changing drastically by adding more bentonite (< 3kPa) and the friction angle is also not significantly decreasing for higher bentonite contents. Hence, sand-bentonite mixtures with a bentonite volume content up to 10% still show sand-like behaviour. This indirectly indicates that the strength characteristics of a dike core will not be altered.

Erosion experiments were carried out in a tilting flume with a length of about 14 m, an effective height of 0.40 m, a constricted width of 0.145 m and a maximum discharge of about 0.025 m³/s. Thirteen different test runs were executed. In these tests, the volume percentage of bentonite additive, the diameter of the sand and the mean flow velocity were varied. All erosion experiments were performed under supercritical flow conditions. As a consequence of this flow regime, the preferred equilibrium flow velocities (1 and 2 m/s) were hard to regulate. In order to objectively calculate the effectiveness of a bentonite additive, the erosion velocity of the bed of a sand-bentonite mixture was compared with the erosion velocity of a sand mixture at the same mean flow velocity. This procedure was applied to two different methods. The first one related the erosion velocities to the mean flow velocities squared \(U^2\) and the second related the erosion velocities to the corrected bed shear stresses. Both methods show a similar trend. Significant reductions in erosion velocity are obtained by adding bentonite to a sand mixture. A 2% sand-bentonite mixture already reduces the original erosion velocity by about 50%, a 3% or 4% mixture by 50 to 65%...
and a 6% mixture by at least 90%. It has to be added that the reproducibility of the tests has been confirmed to be reasonably well.

A literature study concerning the erosion behaviour of sand-bentonite mixtures, has resulted in the conclusion that very few data are available. At higher flow velocities these are even non-existent. A comparison of the data that is currently present clearly indicates that it is very difficult to predict and verify the absolute reduction in erosion velocities for different bentonite mixtures. Only relative reductions in erosion velocities for different sand-bentonite mixtures make it possible to compare data from different data sets.

The observed behaviour in the experiments enhances the development of an adapted erosion function. The erosion function of Van Rhee (2010) - including the effect of dilatancy and the permeability - has been adapted to the experimental data of the erosion tests to get reasonable accurate model results. This study also discusses some possible causes of the discrepancies between the experimental data and the results predicted by the erosion function of Van Rhee (2010). The adapted erosion function includes the effect of the bentonite content on the erosion velocity. This effect is indirectly taken into account by adapting the permeability in the erosion function. The adapted erosion function has been implemented in the BRES-Visser model. The BRES-Visser model - which decomposes the breaching process in five different phases as proposed by Visser (1998) - calibrated with data from the Zwin'94 experiment, has been used to model the performance of the bentonite additives. The data from the Zwin'94 experiment has also been used as a reference scenario for a dike with a sand core. The effects of the retardant sand-bentonite mixtures have been compared to this reference scenario. The comparison is based on breach width, flow through the breach, the inundation velocity and duration of the breaching process. Significant reductions of these parameters have been realized with increasing bentonite percentages. By reducing the inundation velocity below a threshold value of 0.5 m/h, the mortality and the LIR (Localized Individual Risk), can theoretically be decreased by a factor 10. A sand-bentonite mixture with a bentonite content of 6.3% would be necessary to reduce the inundation velocity to a value below 0.5 m/h for the fictitious case of the Zwin'94 experiment. The effectiveness of the bentonite measure has also been tested in the Borssele case study.

To conclude, sand-bentonite mixtures are able to significantly reduce the erosion velocity. The effects of dilatancy and a decrease in permeability have a large impact on the erosion velocity. This is already noticeable at very low percentages of added bentonite. A sand-bentonite mixture with a bentonite volume content of 6% substantially reduces the erosion velocity (also at high flow velocities) and the mixture generally has a reasonably good homogeneity. With lower percentages of added bentonite the homogeneity is less reliable, which might be a considerable practical limitation. Sand-bentonite mixtures with a bentonite content up to 6% still show sand-like behaviour, indicating that the strength characteristics of a dike will not alter. Finally, case studies with the BRES model indicate that an increase in safety level by a factor of 10 can be achieved using sand-bentonite mixtures in the core of a dike and that the polder area has a big influence on the inundation velocity and the polder water levels. In both the Van Citterspolder I and the Van Citterspolder II the safety increases with a factor 2.5 to 10 when a 2% sand-bentonite mixture is added to the core. Higher percentages of bentonite additive increase the safety even more and in some cases even completely stop the breach growth, because the outside water level drops faster than the breach grows vertically. In the Zwin'94 case study a 6.3% sand-bentonite mixture increases the safety by a factor 10.