PRELIMINARY RESULTS OF THE SAFELEVEE PROJECT*

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1. INTRODUCTION

A significant proportion of the global population is located in flood prone areas. The consequences of these areas being flooded can be severe. [1]. The EU Floods Directive 2007/60/EC was developed and published in October 2007 [2] and aims to reduce and manage flood risk with respect to public health, environment, cultural heritage, and economic activity. To evaluate the risk associated with floods, flood spreading models have been developed. For accurate modelling of the consequences of a flood, the flow rate of water entering a flood area needs to be accurately predicted. This requires an accurate prediction of when and how a levee would fail when subjected to extreme loading conditions. Empirical breach relationships have been developed using available data on breaches [3]. However, the large variety in loading conditions on levees, levee design, and failure modes, combined with limited data available on failed levees, make empirical models inaccurate which highlights the need for further research into the processes of breach formation. For the purpose of levee management, continuous monitoring of the condition of levees is crucial as well as difficult. Current conventional levee inspection methods rely on expert observers, which are infrequent, qualitative and labor intensive [4], [5]. Furthermore, many failure modes of flood defenses are usually preceded by small and slowly changing modification of their geometry and structure, which are not possible to detect by visual inspection. Hence, innovative monitoring techniques are welcome to support authorities in fulfilling their maintenance tasks.

The SAFElevee project at Delft University of Technology focuses on levee performance and failure, and analyses the interrelated processes of (initial) failure of a levee and breach development, both at a system-macro scale as well as for individual failures. To support the different work packages of this project an international levee performance database has been developed. Section 2 provides more details on the database and the type of information provided by the database.

One of the project objectives covered by the work packages is to improve the understanding of breach formation and breach initiations processes. As part of this work new equations have been developed which describe the erosion process from a process point of view. Section 3 of this paper elaborates on the outcomes and general approach taken to develop these equations. When water overflows an unsaturated levee infiltration occurs, which causes for a decrease in shear resistance of the soil. An analysis of the processes of breach initiation and formation hence must account for the effects of saturation. Section 4 provides the results of a review that has been performed on existing infiltration models and the effect of saturation on the change in potential gradients at the levee surface which in turn influence the erosion rates. The final preliminary outcome of the SAFElevee project presented in Section 5 of this paper is the answer to the question of whether satellites can be used to monitor the behaviour of levees under a range of loading conditions. If so, information obtained from satellites could then be used to better predict the behaviour of levees when subjected to extreme hydraulic loads. Satellite Radar Interferometry can thereby also complement existing approaches for assessing levee deformation and failure investigations (e.g. expensive field tests) at relatively low cost. In Section 6 conclusions are drawn and recommendations are made.

2. INTERNATIONAL LEVEE PERFORMANCE DATABASE

Systematic documentation and analyses of international levee performance data serves to improve the understanding of how levees behave when subjected to extreme loading conditions and supports the study of processes related to breach formation in levees. Besides, a database would support the identification of the individual processes that lead up to failure by means of hindcasting historical levee failures, and other performance observations such as monitored near-failures or field observations during extreme loading [6]. Individual efforts have been undertaken to document failures of levees after disasters (e.g. [7][8][9]). Several databases have also already been developed for levee dam breaches in table format [10][11]. Characteristic for these databases is that only generic information on failures is provided, e.g. information on the dam geometry, protection layer, peak discharge, and time at which the peak discharge occurs. Neither any information on the breach outflow hydrograph, nor detailed geotechnical information is provided by these databases. Therefore, these databases are not suitable for detailed analysis of processes that initiated failure or for validation of process based models. To fill this gap, an online available international levee performance database has been set up to facilitate sharing of data on levee characteristics, failure modes, geotechnical investigations, breach initiation and formation. The database thereby includes time dependent data like breach hydrographs. More specifically, the International Levee Performance Database (ILPD) systematically provides data on:

- Actual failures during extreme catastrophic events, like in New Orleans [7];
- Failures in large-scale (prototype) experiments [12];
- General investigations on the performance of flood defense systems [13];
- Near failures of levees to determine the proven strength;
- Detailed data for validation of individual processes modelled by breach models;
- Information on the consequences per extreme event.

The dataset has been made available online via http://leveefailures.tudelft.nl. Here datasets can be selected for manual downloads. Upon selection for downloading of the data automatically a file is created, containing all data sources to which should be referenced when using the data. This way the original owner is always credited for the data. To accommodate automated validation of models and for rapid statistical analysis the data has also been made accessible via an Application Programming Interface (API). With this database structure the SAFElevee project offers a cooperative data and knowledge platform for usage by governments, researchers and companies in the field of levee safety. It is thereby expected to contribute to more effective and innovative levee reinforcements and large potential cost savings in design and safety assessments.

3. DESCRIBING THE EROSION PROCESS OF LEVEES

For breach models to provide accurate predictions, it is essential that model approximations are understood and that the model is not applied outside sensible parameter limits. Nowadays, nearly all breach models describe the breach process according to the simplified steps of breach formation [12][14][15]. The following stages have been identified for levees failing due to overtopping, with the possible exception of Stage 3:

1. Levee is stable and functions well.
2. Levee starts to overflow and water percolates into the levee. Material is progressively removed and the landside slope retreats towards the waterside slope.
3. Erosion of the landside slope reaches the waterside slope and the flow slowly starts to increase. The increased hydraulic head over the levee leads to higher flow velocities through the breach, and an increased horizontal flow contraction besides the already present vertical flow contraction.
4. Rapid increase in flow velocity with erosion of the waterside slope and simultaneous widening of the breach. Flow velocities are super critical.
5. Breach flow becomes affected by the rise of the downstream water level, and/or the fall of the upstream water level, and the breach flow starts to decrease to the point that the flow velocities become so small that the erosion process stops.

These stages have been observed in several large- and small-scale breach experiments [16]. However, differences in breach behavior have been found in the rate, and manner of breach formation. Although researchers agree on these stages, yet no explanation has been offered for why the rates of erosion are significantly higher down the landside slope than over the crest as observed during Stages 2, and 3. Although the erosion process is often described by the erosion equation, this equation is not able to explain the higher rates of erosion on the landside slope. As part of the SAFElevee project a new process based erosion equation has been developed which does explain why the erosion rates along the landside slope are significantly higher than over the crest which has been outlined below.

Morris et al. [16] and Hanson and Hunt [17] commented that the susceptibility of material to erosion depends on material texture, compaction moisture content, and compaction energy. Morris et al. [16] noted that in order to break the cycle and improve the reliability of breach models it is necessary to:

1. Understand the role that material type, compaction efforts and moisture content play in determining soil erodibility.
2. Include spatial and temporal variability in soil properties.

Erosion due to high velocity has also been a field of research for the dredging industry. Van Rhee [18] and Bisschop et al. [19] identified that the erosion rate of dilatant soils depends on the initial compaction and the hydraulic conductivity of the soil. The influence of dilation thereby already becomes significant for flow velocities in excess of 1.5 m/s [20]. When sand is subjected to higher flow velocities the erosion process of the material is no longer described by the pick-up of individual particles but by the shear failure of layers of soil. For soil layers to shear, soil needs to dilate. For highly compacted soils the degree of dilation needed for the layers to fail due to shear is higher leading to smaller rates of erosion. The increase in pore volume associated with dilation requires for an inflow of water into the bed. The inflow of water requires a head difference over the bed which adds to the effective stresses between the particles and hence the shear resistance. This theory of dilation corresponds well with the observation that soil erodibility depends on material texture, compaction moisture content, and compaction energy [16][17]. Although the impact of dilation has been identified [18][20][21], accounting for the effects of dilation has been challenging. Sediment transport formulas have been developed [18][21][22] for flow velocities up to 3 m/s which give better predictions for the pickup flux than the original equilibrium sediment transport equations by Van Rijn [19][23] but still have a predominant empirical nature. In the field of Dredging Engineering the water level is thereby often assumed to be horizontal, limiting the range of applicability of these formulae. During breach formation in levees the water level usually follows the bed slope. By applying empirical relationships developed for the dredging industry, to the erosion of levees, it is inherently assumed that no groundwater gradients are present to contribute to the erosion of soil. Groundwater flows parallel to a sloping bed nevertheless reduce the shear resistance of soil [24]. Especially in the case of erosion at high flow velocities, during which layers of soil are sheared at once, a groundwater head gradient parallel to the bed slope could lead to an increase in erosion rates. Experiments to high speed erosion are also often performed on horizontal beds whereas for sloping beds the effects of gravity provides less stability due to the reduced normal stress component and increased shear stress component. The importance of the effects of dilatency on erosion [18][20][21] fits well with the steps identified by Morris et al. [16] as a higher degree of compaction requires a higher degree of dilation to occur, leading to a corresponding reduction in erosion rates [18]. Hence, this warrants the inclusion of the effects of dilation when developing an erosion formula for levees.

The fact that erosion can be described by the failure of soil layers also agrees with the temporal variability in soil erodibility. Due to infiltration of water in the levee the effective stresses in the soil reduce [24] making it more susceptible to erosion which is consequently expected to be time dependent. Capturing all these influences in empirical models would be challenging. Hence a more process based approach is welcomed to better predict the erosion rates of levees.

As high speed erosion is described by the failure of layers of soil, a direct link is found with debris flow mobilization. Debris flows initiate when the shear stress applied to a layer of soil exceeds the shear strength [25][26][27][28]. During the erosion process particles and water are exchanged with the bed. With this exchange of mass also momentum is exchanged. Over the depth at which the shear stresses exceed the shear strength, the bed starts to move. The movement of the bed itself causes for the flow velocities at the interface of the flow and the bed to increase as well [29]. Based on the mass and momentum balance equations describing the exchange between the water flow and the levee material a new process based erosion equation has been developed which explains why the erosion rates of course sands are higher than in fine sands, why the erosion rates along the landside slope are significantly higher, and why more densified materials erode slower than loosely packed materials. Key for the derivation of this relationship was the discovery that the soil thrives towards that situation for which the average reduction in pore pressure, multiplied by the depth over which the particles shear over each other, is minimum. This corresponds with the situation for which the shear resistance of the soil is maximum. The erosion relationship has been validated against erosion experiments which were performed under high flow velocities.

Thus far the relationship has been developed for fully saturated bed materials. However the effects of infiltration of water into the bed could easily be included. The rate of infiltration both affects the shear strength as well as the shear stress acting on the bed. The increase in shear strength could easily be accounted for in the erosion relationship. The increase in shear stress may be more difficult to capture but could be captured by including some empirical relationships.

4. THE EFFECTS OF INFILTRATION ON CHANGES IN POTENTIAL GRADIENTS

The effects of infiltration on breach formation are multiple. First the shear resistance of soil decreases due to infiltration. The shear stresses acting under the slope thereby increase when the soil becomes increasingly saturated. The shear resistance of soil is hence expected to depend on time. In order to accurately determine the effects of infiltration on erosion it is important to determine the potential gradients over the soil during infiltration. To determine this first a critical review was performed on the current state of the art infiltration relationships.

Soil is characterized by a random distribution in pore sizes. During water infiltration water menisci form at the interface of water, soil grains, and air in the pores, inducing suction due to surface tension. Differences in suction and friction inside pores give a diffusing infiltration front whereby at the infiltration front the infiltration rate is higher in the smaller pores than in the larger pores. This process of infiltration is often simulated by solving Richards' Equation [30] which follows from substituting Darcy's law in the mass balance equation. Darcy [31] discovered that for fully saturated porous media the specific discharge of water in soil is described by multiplying the deterministic potential gradient with the expected value of the frictional forces, denoted by the hydraulic conductivity.

Unlike saturated soils, unsaturated soils are characterized by the presence of water menisci in pores at the interface of air, water, and soil particles. At the location of water menisci the surface tension of water induces a drop in pressure head resulting in suction. Pore radii in the soil are randomly distributed. As a direct consequence the pressure head becomes a stochastic parameter. Hence both the effects of friction and the potential gradients now stochastic parameters. For Richards equation to be valid the mean friction in the pores must be independent on the average effect of the pressure gradients experienced in the pores. This assumption is however in direct conflict with the fact that in unsaturated porous media the viscous contributions to the friction and the potential gradients are both dependent on the random distributed pore radius. Logic now dictates that the expected value for the water flux should follow from the product of the expected value of the hydraulic conductivity and the pressure gradient plus the covariance of the hydraulic conductivity and the pressure gradient [32].

Other studies have also identified that Richards Equation might not accurately describe the infiltration process [33][34][35]. New methods have been developed to improve the predictive capacity of Richards Equation. However these methods are all still based on substituting Darcy's law in the mass balance equation, and inherently do not yet account for the contribution of the covariance. As part of the STW project SAFElevee a new method for simulating flows in partially saturated porous media has been developed, which a) captures the effects of the covariance, and b) provides the time dependent distribution in potential gradient at the soil surface during the process of infiltration. The results are promising and are correctly able to explain the time dependent nature of the diffusion often observed in experiments.

5. INVESTIGATION OF SEASONAL PATTERNS IN LEVEE DEFORMATION BASED ON SATELLITE RADAR INTERFEROMETRY

Common remote sensing and stability monitoring methods are costly and time-consuming, and thus usually applied only to locations considered to be at high risk by visual inspection [36]. Hence, in countries with an extensive network of flood defense infrastructure, such as the Netherlands, innovative and cost-effective techniques to monitor levee stability are welcomed. In recent years, satellite radar interferometry, also known as Interferometric Synthetic Aperture Radar (InSAR), has become a widespread and efficient tool for monitoring surface topography and deformations, providing abundant and frequent observations with high spatial resolution and accuracy at reasonably low costs. A sub-method of InSAR is Persistent Scatterer InSAR (PS-InSAR, or PSI) [37], which is a processing technique using millions of observations with a repeating period of 6 to 35 days. Radar satellites allow day and night observations. Current abailable measurements span a period of 25 years, from 1992 till today. Historical analyses are performed using the archival radar data, whereas the recently launched satellites (e.g. Sentinel-1a) can be used to monitor the surface deformations continuously. PS-InSAR has been successfully applied to monitor land deformations in a large variety of contexts, such as railways, urban areas and large dams.

In particular, previous studies [38], [39], [40] have shown that PS-InSAR is able to provide dense sampling of flood defense systems and high precision measurements of long term deformations, and that the stability of more than 90% of flood defenses in the Netherlands could be monitored on a weekly basis. These studies have shown that PS-InSAR can be successfully applied to continuous levee monitoring. Therefore, it is expected to become a useful tool especially for early detection of potential problems. Due to the different loading conditions experienced on levees, weak spots are best identified when it becomes possible to determine if the observed deformation is in line with expectations. Predicting the behavior of a levee therefore also forms the basis for the development of an automated early warning system. To accommodate the development of such a system, here it has been assessed whether the variation patterns in levee deformations obtained from PS-InSAR are related to seasonal variations.

To evaluate whether levee deformations are predictable and related to seasonal patterns, a case study area (10x10 km) South of Delft was selected, which is located in the South-Western part of the Netherlands (See Fig. 1). The levees used in this study are flood defenses situated along regional rivers and canals. The canals in this area, serve to drain excess water from the lower-lying polder to the main rivers and the sea. Water levels in these canals typically exceed surface levels of adjacent polders. Therefore, it is important to monitor the levee behavior and detect anomalies and levee deterioration in preliminary stages.

The levees in this area have been monitored using high resolution data from TerraSAR-X descending orbit in order to estimate the line-of-sight deformation time series of each PS between 2009 and 2015. This satellite provides high resolution data with a pixel size of 3x3 meters and a repeat cycle of 11 days. The PS interferometry [41] procedure has been implemented on the radar images in order to estimate the line of sight deformation time series for each measurement point.

Fig. 1 Monitored levees South of Delft, The Netherlands. Right: White rectangle shows the TerraSAR-X descending stack. Green rectangle represents the location of the monitored area. / Surveillées de digues a Delft Sud, Pays Bas. À droite, le blanc rectangle montre la voie descendante de TerraSAR-X. Le vert rectangle representé de l'emplacement de la zone surveillée.

The deformation map of the canal levees over a period of 6 years is given in Fig. 2. In the figures, steady state deformation rates are depicted for convenience, but every point has a complete time series of deformation estimates (Fig. 4).

Fig. 2 Deformation velocity maps of the regional canal levees South of Delft, the Netherlands. / Cartes de vitesse de déformation de digues régionaux a Delft Sud, Pays Bas.

A part of a levee segment in the monitored area, of which soil profiles from different locations are also available, has been investigated further in order to analyze the levee behavior from the time series of PS points in detail (Fig. 3). The method is illustrated for a training area that shows similar deformation behavior. Meteorological conditions result in a change in phreatic level and also a change in pore water pressures inside the levee. As soil saturates the matrix suction due to the capillary action of water in the pores, reduces. The change in pore pressures in turn leads to an elastic swelling and shrinkage behavior of the soil which behaviour was clearly identifiable from the data.

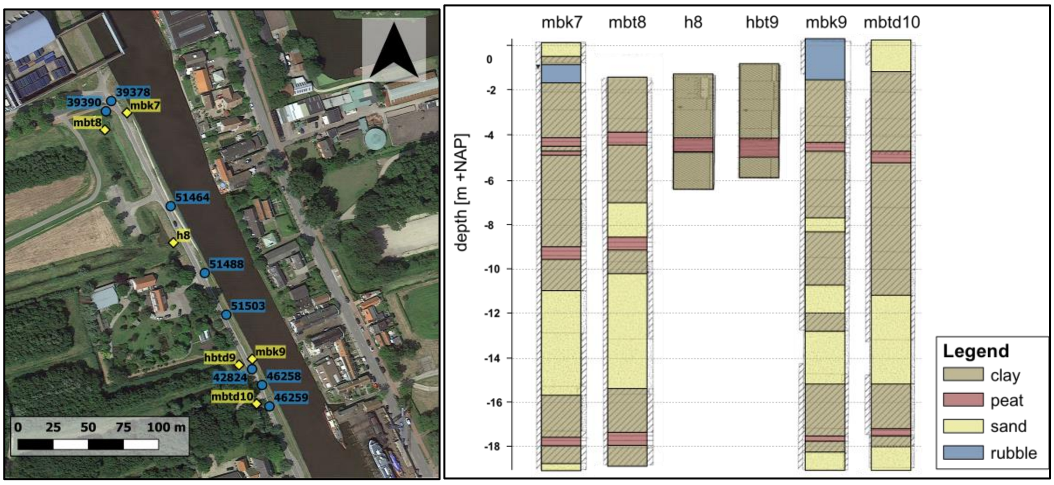

Fig. 3 Location of the 8 PS points (blue) and soil profile stations (yellow) at the detailed levee segment. Right: Soil profiles for each measurement station given in the Left. / Localisation des 8 points de PS (bleu) et les stations de profil du sol (jaune) sur le segment de digues détaillée. À droite: profils de sols pour chaque station de mesure donnée dans la gauche.

The long-term linear trend of the deformation observations over the satellite period has been removed to evaluate the behavior of the levee to seasonal variations which would result in swelling and shrinkage of the levee. Deformation time series of 8 PS points in the given area have been averaged assuming a homogeneous behavior in order to reduce the signal noise (Fig. 4a).

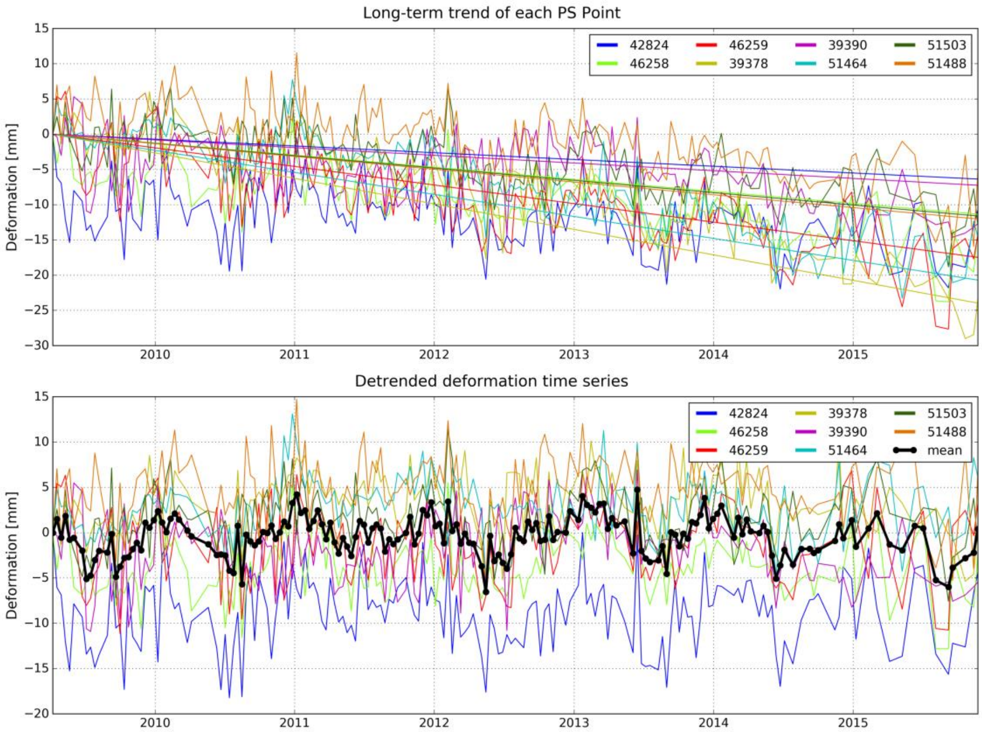

Fig. 4 (a) correction of deformation time series for long-term trend, (b) Time series of the mean deformation of 8 de-trended PS points. / (a) correction des séries chronologiques de déformation pour la tendance à long terme, (b) Les séries chronologiques de la déformation moyenne de 8 points de-PS affiché une tendance.

As it can be observed from the Fig. 4b that during the winter months, the average time series shows swelling behavior, whereas in summer periods the soil shows a shrinkage behavior periodically. Hence, the seasonal patterns can be easily observed from these datasets.

6. CONCLUSIONS & RECOMMENDATIONS

The preliminary results of the SAFElevee project presented here form the first step in better determining the strength of levees. The online, and easily accessible database which has been developed as part of SAFElevee forms a useful foundation for further analysis and provides insight into the most occurring failure mechanisms. The coming years an effort will be made to fill the database with more data. The erosion relationship developed as part of the SAFElevee project gives a fundamental explanation of erosion and can be applied to a wide range of dilatant soils. Eventually the method could be used to accurately predict breach growth rates and rates of breach formation. An innovative infiltration model has been developed as part of the project. This model could be used to more accurately determine the increase in shear stresses and reduction in shear strength during infiltration of water into the levee. Finally the preliminary results of the SAFElevee project have also shown that deformations in line of sight direction obtained from monitoring a levee with the PS-InSAR technique are sensitive to seasonal changes. The monitoring technology could thereby help to understand the normal behavior of levees and therefor also forms a platform for identifying unexpected degrees of deformation and adopt this in an early warning system.

ACKNOWLEDGEMENTS

This research was performed as part of the NWO TTW project SAFElevee (Project number 13861).

SUMMARY

This paper described outcomes of the Dutch research project SAFElevee which focuses on levee performance and failure, and analyses the interrelated processes of (initial) failure of a levee and breach development, both at a system-macro scale as well as for individual failures. One project objective is to improve the understanding of breach formation and breach initiations processes. The second objective is to investigate whether remote sensing by satellites can be used to monitor the behaviour of levees under a range of loading conditions.
To support the project an online international levee performance database has been developed which contains data on breach (related) experiments that have been performed but also information on the (near) levee failures that have occurred worldwide. Preliminary results of the SAFElevee project have provided a better understanding of the breach growth through the development of a process based erosion relationship for erosion under high flow velocities. The positive effects of potential gradients over the soil surface on the shear resistance of the soil could also be accounted for in this method. To determine these potential gradients a new infiltration model has been developed. Seasonal variations in the degree of saturation of levees and their effect on the swelling of the levees were successfully observed with satellites.

RÉSUME

Ce papier présente les résultats du projet Néerlandais SAFElevee, qui étudie la performance et la défaillance des digues, et analyse les processus interconnectés de dégradation initiale de la digue et de développement de brèches, aussi bien à l'échelle macroscopique qu'à celle des ruptures individuelles. Un premier objectif de ce projet et d'améliorer notre compréhension des mécanismes menant à la formation de brèches. Un second objectif est d'évaluer le potentiel des images satellites pour étudier le comportement de digues soumises à une large gamme de contraintes et prévoir le comportement en cas de conditions extrêmes. Pour atteindre ces objectifs, une banque de données internationale a été mise en place. Celle-ci contient des données expérimentales de ruptures de digues, mais aussi des informations sur les (quasi-)ruptures de digues qui ont été observées à l'échelle mondiale. Le projet SAFElevee nous a déjà permis d'acquérir de nouvelles connaissances sur le développement de brèches grâce au développement d'un modèle décrivant le phénomène d'érosion en présence de fortes vitesses de courant. Les effets du phénomène d'infiltration a été prise en compte facilement dans la méthode mais les gradients qui se développent a la surface du sol. Un nouveau modèle d'infiltration a été développé. Les variations saisonnières de degré de saturation des digues et leur effet sur le gonflement des digues ont été observées avec succès avec les satellites.

Keywords: Groundwater flow, Erosion, Monitoring, Failure

Mots Clés: Debit de la nappe phreatique, Erosion, Auscultation, Rupture

REFERENCES

[1] ABC NEWS. Flood costs tipped to top $30b. *Retrieved from http://www.abc.net.au.* 2011, Jan 18.

[2] EUROPEAN PARLIAMENT. Directive 2007/60/EC of the European parliament and of the council, on the assessment and management of flood risk. *Official Journal of the European Union*, Vol 288, pp27-34.

[3] VERHEIJ, H.J. AND VAN DER KNAAP, F.C.M. (2002). modification breach growth model in His-om. *WL| Delft Hydraulics Q*, 3299, 2002.

[4] RIJKSWATERSTRAAT, *Hydraulische randvoorwaarden 2001 voor het toetsen van primaire waterkeringen*. *Technical report, Rijkswaterstraat, DWW, Delft, The Netherlands (in Dutch),* 2001.

[5] HANSSEN R.F. AND VAN LEIJEN F.J. monitoring water defense structures using radar interferometry. *Radar Conference, RADAR'08, IEEE* 1-4, 2008.

[6] SCHWECKENDIEK T., VROUWENVELDER A.C.W.M. AND CALLE E.O.F. Updating piping reliability with field performance observations. *Structural Safety*, 2014, Vol 47, pp13–23.

[7] SEED R., BEA R., ATHANASOPOULOS-ZEKKOS A., BOUTWELL G., BRAY J., CHEUNG C., COBOS-ROA D., HARDER L. JR., MOSS R., PESTANA J., RIEMER M., ROGERS J., STORESUND R., VERA-GRUNAUER X., WARTMAN J. New Orleans and Hurricane Katrina. III: The 17th Street Drainage Canal. *Journal of Geotech. and Geoenviron. Eng.*, 2008, Vol 134, Nr 5, pp740–761.

[8] SEED R., BEA R., ATHANASOPOULOS-ZEKKOS A., BOUTWELL G., BRAY J., CHEUNG C., COBOS-ROA D., EHRENSING L., HARDER L. JR, PESTANA J., RIEMER M., ROGERS J., STORESUND R., VERA-GRUNAUER X., WARTMAN J.. New Orleans and Hurricane Katrina. II: The Central Region and the Lower Ninth Ward. *Journal of Geotech. and Geoenviron. Eng*. 2008, Vol 134, Nr 5, 718–739.

[9] HEYER, T. AND HORLACHER, H. B. Analyse der Deichbrüche an Elbe und Mulde während des Hochwassers 2002 im Bereich Sachsens "Flussdeiche – Bemessung, Dichtungssysteme und Unterhaltung". In *Proceedings of the DWA Seminar, Fulda, Germany (in German).* 2007.

[10] FROEHLICH D.C. Embankment-dam breach parameters. In Hydraulic Engineering, *Proceedings of the 1987 ASCE National Conference*, 1987, pp 570-575.

[11] DANKA J. AND ZHANG, L. Dike Failure Mechanisms and Breaching Parameters. *Journal of Geotech. and Geoenviron. Eng*., 2015 Vol 141, Nr 9, 04015039.

[12] VISSER P.J. *Breach growth in Sand-Dikes*. *PhD dissertation, Delft University of Technology* 1998.

[13] SILLS G.L., VROMAN N.D., WAHL R.E. AND SCHWANZ N.T. Overview of New Orleans levee failures: lessons learned and their impact on national, 2008.

[14] ZHU, Y. *Breach growth in Clay-Dikes. PhD dissertation, Delft University of Technology* 2006.

[15] MORRIS M., HASSAN M., KORTENHAUS A., GEISENHAINER P., VISSER P.J., AND ZHU Y. Modelling breach initiation and growth. *FLOODsite Report*, 2009, pp1-127.

[16] MORRIS, M., HANSON G., AND HASSAN M. Improving the accuracy of breach modelling: Why are we not progressing faster? *Journal of Flood Risk Management,* 2008 Vol 1, Nr 3, pp150-161.
[17] HANSON, G. AND HUNT, S. Lessons learned using laboratory JET method to measure soil erodibility of compacted soils." *Applied Engineering in Agriculture*, 2007, Vol 23, Nr. 3, pp305–312.
[18] VAN RHEE, C. "Sediment entrainment at high flow velocities*." Journal of Hydraulic Engineering*, 2010, 572,582.
[19] BISSCHOP, F., MIEDEMA, S., VISSER, P., KEETELS, G., AND VAN RHEE, C. Experiments on the pickup flux of sand at high flow velocities. *Journal of Hydraulic Engineering*, 2016, Vol 142, Nr 7.
[20] VAN RHEE, C. Erosion of Granular sediment at high flow velocities, Hydrotransport 17, *Conference on the Hydraulic Transport of Solids*. 2007.
[21] WINTERWERP, J., BAKKER, J., MASTBERGEN, D., AND ROSSUM, V. Hyperconcentrated sand water mixture flows over erodible bed*. Journal of Hydraulic Engineering,* 1992, 118.
[22] MASTBERGEN, D. AND VAN DEN BERG, J. Breaching in find sands and the generation of sustained turbidity currents in submarine canyons. *Sedimentology*, 2003, Vol 40 Nr. 4, pp625–637.
[23] VAN RIJN, C. L. Sediment Transport, Part II: Suspended Load Transport.
[24] VERRUIJT. Soil Mechanics. Delft University of Technology, http://geo.verruijt.net/, 2001.
[25] IVERSON, R. AND GEORGE, D. A depth-averaged debris-flow model that includes the effects of evolving dilatancy. I. *Physical basis. Proceedings of the Royal Society A.* 2014.
[26] IVERSON, M. R., REID, M., AND LAHUSEN, R. . Debris-flow mobilization from landslides. *Annual Review of Earth and Planetary Sciences*, 1997, pp 85–138.
[27] IVERSON, M. R. .Landslide triggering by rain infiltration. *Water Resources Research*, 2000, Vol 36, pp1897–1910.
[28] TAKAHASHI, T. A review of Japanese debris flow research*. International Journal of Erosion Control Engineering*. 2009.
[29] IVERSON, R., REID, M., LOGAN, M., LAHUSEN, R., GODT, J., AND GRISWOLD, J. Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment. *Nature Geosciences*, 2010.
[30] RICHARDS L.A. Capillary conduction of liquids through porous mediums. *Journal of Applied Physics*, 1931, Vol 1 Nr. 5,pp 318-333.
[31] DARCY, H. Les Fontaines Publiques de la Ville de Dijon, Paris. 1856.
[32] DEKKING, F., KRAAIKAMP, C., LOPUHAA, H., AND MEESTER, L. *A Modern Introduction to Probability and Statistics, Understanding Why and How. Springer Science & Business Media*, 2005.
[33] NIELSEN D.R., BIGGAR J.W., DAVIDSON J.M.. Experimental consideration of diffusion analysis in unsaturated flow problem. *Soil Science Soceity of America* 1962, Vol 26, Nr. 2, pp107–111.
[34] BELL M.L., NUR A. Strength changes due to reservoir induced pore pressure and stresses and applications to Lake Oroville. *Journal of Geophysical Research*,1978, Vol 83, pp 4469–4483.
[35] ROELOFFS E.A. Fault stability changes induced beneath a reservoir with cyclic variations in water level. J*ournal of Geophysical Research* 1988, Vol 93, pp 2107–2124.
[36] OZER I.E., VAN DAMME M., SCHWECKENDIEK T. AND JONKMAN S.N. On the importance of analyzing flood defense failures. E3S Web of Conferences, Vol. 7, EDP Sciences, 2016.
[37] FERRETTI, A., PRATI, C., AND ROCCA, F., "Permanent scatterers in SAR interferometry", *IEEE Transactions on Geoscience and Remote Sensing* 2001, Vol 39 Nr. 1, pp 8–20.

[38] DENTZ, F., HALDEREN, L., POSSEL, B., ESFAHANY, S., SLOBBE, C. AND WORTEL, T. “Poseidon. on the potential of satellite radar interferometry for monitoring dikes of the Netherlands,” *Delft University of Technology*, 2006.

[39] DIXON, T.H., AMELUNG, F., FERRETTI, A., NOVALI, F., ROCCA, F., DOKKA, R., SELLA, G., KIM, S.-W., WDOWINSKI, S. AND WHITMAN, D. “Space geodesy: Subsidence and flooding in New Orleans, *Nature*, vol. 441, no. 7093, pp. 587–588, 2006.

[40] HANSSEN, R.F. AND VAN LEIJEN, F.J. Monitoring water defense structures using radar interferometry, *IEEE Radar Conference*. 2008, pp. 1–4.

[41] VAN LEIJEN, F.J. “Persistent scatterer interferometry based on geodetic estimation theory,” Ph.D. dissertation, *Delft University of Technology*, 2014.