# Automated levee inspection and control: from coarse to fine

## Inspection et contrôle automatisée des digues : d'une approche générale à une plus détaillée

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ABSTRACT: As the levees are degrading in time as a natural process, the hydraulic load of the river/sea will remain the same or will even increase. A safety assessment of the levees is getting more important to determine the actual stability of the levee. This paper describes the different levels of assessment based upon the available information and the desired outcome supported by actual assessments performed. In order to speed up the calculations there will be made use of automatic embankment calculations. Level 1 describes the quick scan of a long levee stretch with ample information. The aim of this assessment is, among other things, to determine the weak spots and to address them. The Level 2 assessment is intended for a more detailed based research. Level 3 is conceived for real-time monitoring of levee profiles based on sensor networks installed in a levee, whereas Level 4 includes also a forecast of dike strength based on fragility curves or groundwater models.

RÉSUMÉ : Pendant que les digues se dégradent au cours du temps à travers les procès naturels, la charge hydraulique des rivières ou de la mer reste la même ou peut même augmenter. Une évaluation de la sécurité des digues devient encore plus important à fin de déterminer la stabilité effective des digues. Cet article décrit les différents niveaux d'évaluation basés sur les informations disponibles et sur le résultat désiré, supporté par des projets réalisée. Pour accélérer la procédure de calcul, il est possible d'utiliser des calculs automatiques des digues. Le niveau 1 décrit une analyse rapide d'une longue portion de la digue. Le but de cette évaluation est, entre autre, de déterminer les sections les plus faibles de la portion considérée de la digue. Le niveau 2 d'évaluation est prévu pour une recherche et une analyse plus détaillée, basée sur plus de données. Le niveau 3 est conçu pour un monitorage en temps réel, basé sur des réseaux de capteurs installés dans la digue, tandis que le niveau 4 inclue aussi des prévisions de stabilité basées sur de courbes de fragilité ou sur des modèles eau souterraine.

KEYWORDS: Levee, stability, piping, automated calculation, flood forecasting, assessment, fragility curves, China, USA

## 1 INTRODUCTION

Worldwide countries have safety issues with levees. The levees are old and need to be maintained. To assure that the levees will carry out their main purpose, which is to protect against flooding, much information is needed (e.g. information about the geometry, the subsoil parameters and the groundwater pressure).

Unfortunately, not everywhere a sufficient amount of information is available for this purpose. Therefore, a platform for automatic calculations of levee assessments was developed. This allows for assessing levee stretches even when low amount of local data are available. This paper presents how this platform can be used for levee assessments, proposing different levels of analysis based on the required needs and available information.

## 2 AUTOMATED LEVEE CALCULATIONS

DAM (Dike Analysis Module) is a software platform for automated levee calculations (Knoeff, 2011). In this software platform several levee failure mechanisms can be analysed with customary software programs, tools or models. These calculation programs, tools or models are implemented in the platform for batch processing of the calculation. Also implemented in the platform are the adjustable algorithms to schematize the levee by the available information for the different failure mechanisms.

The software platform of DAM makes it possible to perform large amount of levee calculations. It allows for fast recalculations for changing conditions in hydraulic load or in availability and density of the levee information. The possibilities of DAM are suitable for operational purposes in monitoring the actual stability of levees with installation of water pressure sensors in the levees. This application of DAM is called DAM-Live and it can be implemented in an operational system like Delft-FEWS.

The ease to perform levee (re)calculations gives opportunities to tailor made the need for levee information by the state of levee stability. By introducing different levels of stability monitoring, the collection of levee information can be phased. Depending on the amount and the density of the levee information, the obtained insight gives a degree in accuracy of in the levee stability.

Coarse levee information leads to rough insight in the levee stability (level 1), while detailed levee information combined with pore water pressure sensors combined with a FEWS (Flood Early Warning System) gives a precise insight in the levee stability and a forecasting of the stability (level 4). See also figure 1 for the different levels of levee assessment.

## 3 DIFFERENT APPROACHES FOR ASSESSING LONG STRETCHES

An assessment of a levee is very useful during all episodes of his existence. In this chapter the different approaches (levels) for assessing a levee will be described including worldwide examples of assessments.

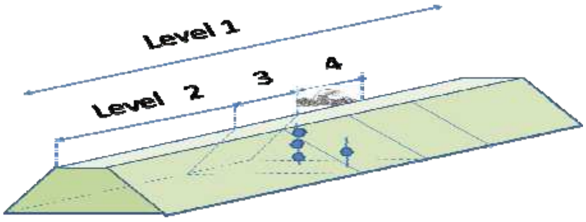


Figure 1. Example of the different levels of stability monitoring for a levee

### *3.1 Level 1 Long stretch assessment with coarse information*

For a lot of levee stretches around the world ample information is known, but the water safety issues keep increasing. To get a quick impression of the stability of levee stretches a (partly) automated analysis can be carried out with little information. This procedure has been executed in 2014 for the south bank of the Xinyi river in China. (Van den Berg, 2014).

Shuyang is a rapidly growing city north of Shanghai and is located south of the Xinyi River. Due to the increasing population and economic activities, there is need for adequate security of the surrounding levee. The assessment was conducted to assess the strength of the leveebased on minimal data of the levee. The length of the assessment from Shuyang to the Yellow Sea was approximately 110 km.

For this assessment, two representative cross sections (cross-sections 48+000 and 67+500) and the information of some borings and ground parameters (cohesion and angle of internal friction) were provided. A stochastic subsurface model (Hijma, 2015) was specifically developed to do an automated DAM analysis, whereas the subsurface was schematized using layer scenarios. This method provides scenarios for possible types of build-up of the subsurface and their change of occurrence in a certain levee stretch. The calculations to determine the strength of the levee were performed with different river level heights and resulted in a safe levee for the failure mechanism of macro-stability.

For this assessment it was possible to collect the data, perform the stochastic model and the calculations within one week. This assessment showed that with relative little data, time and local knowledge it is possible to set-up a quick scan using an automated levee assessment. This quick scan approach allows for detecting the weak spots in the levee stretch, where more data can be collected for further analysis in a more detailed level.

Next step (level 2) includes a more detailed local analysis to obtain more accurate results, as described in the next paragraph.

### *3.2 Level 2 Long stretch assessment with detailed information*

When more information is available, the accuracy and reliability of the assessment will increase. The level 2 assessment is intended for a more detailed based research.

In 2014 an assessment was carried out alongside the levees of the Mississippi, USA. (Van, 2015) The goal of this assessment was to compare the US and Dutch assessment methods with respect to piping and slope stability. One of the topics was the inquiry of damping of the waterpressure in the aquifer which was connected directly to the river.

The collected information consists, among other things, of LIDAR[1] data to extract dense amount of cross sections, which are needed for the calculations. Hydraulic boundaries, subsoil and soil characteristics were provided. Also for this assessment a stochastic model was made. Figure 2 shows the Mississippi delta with the subsoil segments based on the stochastic model. The research was mainly focused on the damping factor.

The results of the assessment with a detailed density were recognized by the local levee districts. The assessment showed that once the data is available very quickly and with a low threshold, variation studies can be performed to estimate the sensitivity of parameters on the safety assessment.

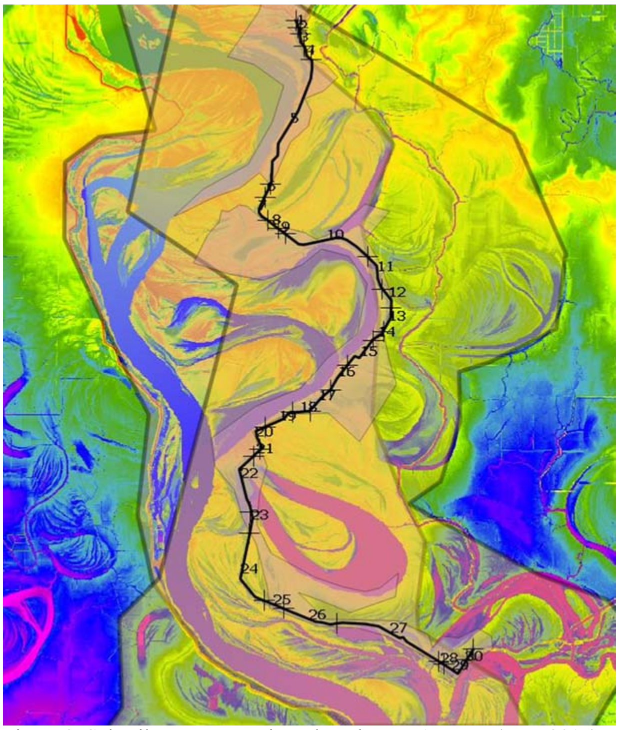

Figure 2. Subsoil segments projected on the LIDAR map (Van, 2015)

### *3.3 Level 3 Small stretch assessment with sensors*

For levee stretches that need to protect sensitive areas, it is possible to increase the level of control with an early warning system based on sensor networks installed in levee bodies. This provides relevant real-time data in the prevention and protection from flood events (Pyat et al., 2013; Melnikova et al., 2015).

A pilot project for a real-time monitoring of dike strength has been executed along the Ommelanderzeedijk, a primarily levee in the region of Groningen (The Netherlands). Water pressure sensors installed along specific levee sections provide real-time information of the water level inside the levee. This information is coupled to the DAM-Live module to perform a levee strength analysis in real-time. Data are imported and visualized hourly in the Delft FEWS-DAM-Live software system (Ponziani and Bachmann, 2016). The inputs for the stability calculations are the phreatic line, the subsoil schematization including the geo-mechanical properties of each layer and the model parameters.

The phreatic line is built with values of water levels measured by the sensors and other fixed water levels that can be

[1] LIDAR (Light Detection And Ranging or Laser Imaging Detection And Ranging) is a technology which determines the distance to an object or surface by means of the use of laser pulses.

provided in the schematization (e.g. the polder level). The output of the calculations for each levee section is a safety factor of the most critical slip circle of the levee schematization, which is based on the input of water levels and soil properties. The system is flexible in the use and applicability of the models and source data. It is thus possible to perform the stability calculations with different models and to update the input values (e.g. modify soil properties or add water levels).

A pilot project alongside the Yellow River (China) was executed to study the effectiveness of a levee monitoring system for early warnings (Van den Berg, 2012). In figure 3 the pilot location is depicted.

Figure 3. Assessment location alongside the Yellow River during the installation of the sensors.

A multi-level solution consisting of three types of sensors has been applied. A TenCate GeoDetect® fibre optic fabric installed on the perimeter of the dike provides the water level, pore pressure sensors installed at different depths provide information of the inner levee and a camera positioned on the adjacent levee visually monitors the levee. All the data are collected and processed to provide real time information about levee strength (macro stability) and deformation. The real time macro stability was calculated hourly based upon the data which are imported and visualized with DAM-Live.

These solutions proved a number of benefits for the real time safety assessment and monitoring of levees. The system can look inside and outside the dike. It provides constant information on the levee strength that can be used for early warnings and to monitor weak sections of the dike before/after improvements. Moreover, the more accurate assessment will lead to prevent unnecessary costs of reinforcements, allocating thus the resources to the exact locations that need improvement.

### *3.4 Level 4 Small stretch assessment with flood forecasting*

A Further step in levee assessment is to predict the levee behaviour based on the forecasted water levels outside of the levee. For a levee section not equipped with sensors, the forecast of levee strength can be expressed in terms of failure probabilities derived from pre-calculated fragility curves. These curves relate the forecasted water levels to the failure probabilities and have been applied to the flood management system since 1991 (USACE, 1991).

In the pilot project of the Ommelanderzeedijk (chapter 3.3), a forecast system based on fragility curves was combined with a real-time monitoring system based on sensors (Ponziani and Bachmann, 2016). Fragility curves for this case study were generated for different failure mechanisms: overflow, wave overtopping, wave impact, wave erosion, piping in combination with heave, micro- and macro-stability of the landward slope (Bachmann et al., 2013).

A total fragility curve is derived from the combination of the single failure probabilities (Figure 4). This system provides thus both monitoring and forecasting of dike strength and it can be used for the planning and intervention in both regular and emergency situations.

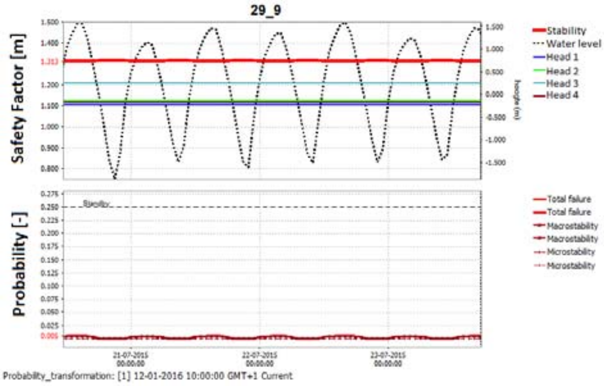


Figure 4. Example of a fragility curve

A forecast of levee strength can be obtained from stability calculations (i.e. using the DAM-Live module) when also a forecast of the water level inside the levee is produced. The piezometric field can be simulated from hydrological/hydraulic models (e.g., PLAXIS, iMod, DG-FLOW) and provided as input for the stability calculations.

An alternative solution when measurements of sensors are available is to derive direct relationships between the water level measured by each sensor and the outside water level. For this purpose, a statistical analysis of the Voorhavendijk (The Neherlands) was performed based on three years of sensor data.

For the sensors installed in the deep aquifer it was possible to derive a straight relationship between the sensor measurements and the outside water level. For the sensors installed in the levee body a better correlation was found with the moving average of the outside water level, therefore including also the time dependence on the duration of the events.

## 4 CONCLUSION

A level based approach has been presented for assessments of levees. The approach is based on recent international practical experience. Aim is to decide for every assessment beforehand which level is useful for which situation. In table 1 a summary of the level based approach for levee assessments is given.

Level 1 will give for long stretch with ample information a coarse insight of the stability of the levee. A rough division of strong and weak spots can be made in level 1. The weak spots can be assessed in the next level. The collection of the levee information needed for a detailed level 2 assessment can efficiently focus on the weak spots. Level 2 will give more insight in the stability of the levee and again a further division of strong and weak spots.

More insight can be obtain for small stretches in level 3 by real time strength calculations based on a sensor network inside the levee body. This refine insight of the stability is sufficient detailed to associate stability thresholds with local calamity operations or measures.

For the most critical stretches or critical hinterland maximum insight and operational prospects can be obtained in level 4 by forecasting the levee stability related to the forecasted water levels.

The availability of the software platform DAM which support automated levee calculations makes such level based approach possible. Effort and levee information needs can be optimized and phased in time which makes levee control come in reach.

Table 1. Level based approach for levee assessments

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|---|---|
| Level 1 | Long stretch assessment with ample information |
| Level 2 | Long stretch assessment with detailed information |
| Level 3 | Small stretch assessment with sensors |
| Level 4 | Small stretch assessment with flood forecasting |

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