INTEGRATING LEVEE PERFORMANCE ASSESSMENTS INTO COMPLEX FLOOD PROTECTION SYSTEMS

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ABSTRACT

Great strides have been made in the past few years in terms of improving the characterization of levee performance and engineering assessments. The automation of several key steps in the evaluation of levees will continue to lead to improved risk assessments, targeted remediation efforts, and more effective investment by stakeholders. However, to realize the full value of these efforts, improvements in performance assessment also need to be linked to flood protection systems. The ability to identify very specific high-risk-of-failure locations on a levee can be of tremendous value to emergency management during episodic flooding hazards. Both nationally and internationally, efforts are being made to integrate the modeling of hazards of episodic events, such as hurricanes and seasonal flooding, with levee performance metrics in a "dashboard" environment. The dashboard will provide managers and operators of flood defense systems a powerful tool not only in their remediation planning but also in their efforts to deal with episodic flood events.

Geotechnical integrity is essential for levee safety assessments. Several pilot programs have been carried out in both the USA and the Netherlands to improve the geotechnical modeling of levee strength. New insights are integrated in Fugro's Rapid Engineering Assessment of Levees® (REAL®). REAL® incorporates levee geotechnical, geospatial, and geological characteristics in its assessment and allows for systematic, consistent, and repeatable evaluation at very closely spaced cross-section intervals and various water levels. This assessment and evaluation process is typically 100 times faster than conventional work flows. This paper will elaborate on some recent developments in 3-D and real-time geotechnical and geospatial levee engineering assessments.

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INTRODUCTION

Levees are generally the primary defense for lives and property against flooding. Therefore information on an actual event, forecast water levels, and the performance metrics of the levee system are of vital importance. Of even more importance is the need for a mechanism that can tie these elements together and empower flood defense managers in their efforts to mitigate the impacts of flood events.

Reliable and detailed assessment of a levee's strength and performance metrics are thus critical to this effort. It is essential to have identified locations that are at risk of failure and to understand the mechanism and criteria that could potentially cause such a failure. Armed with this information coupled with forecasted loading, management of hazards and risks can be more precise and effective in preventing or mitigating the impacts of the flood event both through long term remedial planning as well as in emergency response to episodic events.

The levee strength assessment during specific loading conditions is essential for reliable flood risk management. Table 1 shows case studies in both the US and the Netherlands where various components of a levee strength module are developed and implemented in close collaboration with the end users (water boards).

Table 1: Case Studies

Case Studies	**Levee strength module**
New Orleans HRS (SLFPAE)	Implementation in hurricane risk and safety module
California REAL® (DWR)	3 dimensional levee and subsoil model & automated geo engineering
Salland FRM dashboard (WGS)	GIS levee strength mapping & implementation in all work processes water board
IJkdijk Levee Portal (IJkdijk)	Modern sensor technology & real-time geo engineering

An important development to improve the performance and reliability of levee strength assessments are the use of 3 dimensional (3-D) levee and subsoil models and visualizations, as demonstrated in a California project using REAL®. The automated creation of levee strength maps is demonstrated in the Dutch dike ring: Mastenbroek. Another recent development is the use of modern geospatial information and communication technology (Geo-ICT) tools to upgrade to real-time levee safety assessments, using real-time data on hydraulic loads and measured levee performance, as developed and demonstrated in the Dutch IJkdijk projects.

It should be noted that although this paper discusses engineering assessments of levee performance and hazards affecting performance, these tools typically are unable to consider localized damage to a levee, such as burrows, vegetation, embankment penetrations, encroachments and riverside scour. These can dramatically reduce calculated factors of safety and alter the most likely failure location. Thus, these tools do not replace the need for periodic physical and visual inspection of levee conditions, particularly prior to a critical episodic event (when possible).

THE HURRICANE RISK AND SAFETY MODULE

The introduction of Geo-ICT tools is an important improvement in current flood risk management. During potential flood events, information can save lives. With capable and effective evaluation, monitoring, forecasting, and decision support systems, the right information reaching the right place faster could potentially mitigate the dangers imposed by the flood. Providing information on levee performance during storm conditions in a clear and logical way can significantly improve decision making.

In flood prone areas, rapid understanding of complex hydraulic and geotechnical information is required to assess levee performance and take the required mitigation measures. As a pilot project, a Hurricane Risk and Safety Module (HRS) was developed for a location in New Orleans. The importance of flood control solutions for New Orleans became clear after the catastrophic flooding caused by hurricane Katrina in 2005. More recently, hurricane Isaac in August 2012 reinforced the ongoing relevance and importance of this type of emergency preparedness. With a complex improved flood defense system in New Orleans nearing completion, there is a strong need for smart flood control solutions. Via a web-based dashboard, the HRS Module provides insight into levee performance under storm conditions.

A collaborative effort between the South Louisiana Flood Protection Authority – East (SLFPAE) and the Netherlands based flood control experts Royal HaskoningDHV, Fugro, and HKV Consultants resulted in the development of the HRS module. SLFPAE operates and maintains a large part of the New Orleans' flood defense system and is in need of clear and concise information on its performance. The HRS addresses this need for levee performance under storm conditions. The HRS is comprised of two primary data streams – storm forecasts and levee performance metrics. The evaluation of these two data streams utilizes three components (see figure 1):

1) a Storm Forecast Module (SFM), which forecasts hydraulic loading conditions for an approaching hurricane via the concept of a storm surge atlas;
2) a Levee Strength Module (LSM), which determines the levee performance based on the loads of the SFM and provides a direct overview of predicted levee strengths for a combination of failure mechanisms;
3) a Decision Support Module (DSM), which brings together the information of the SFM and LSM in a comprehensive web-based dashboard. The dashboard is adaptable to end-user preferences and brings together crucial forecast and monitoring information. An automated flood protection system assessment provides the operator with potential and preferred flood risk mitigation measures.

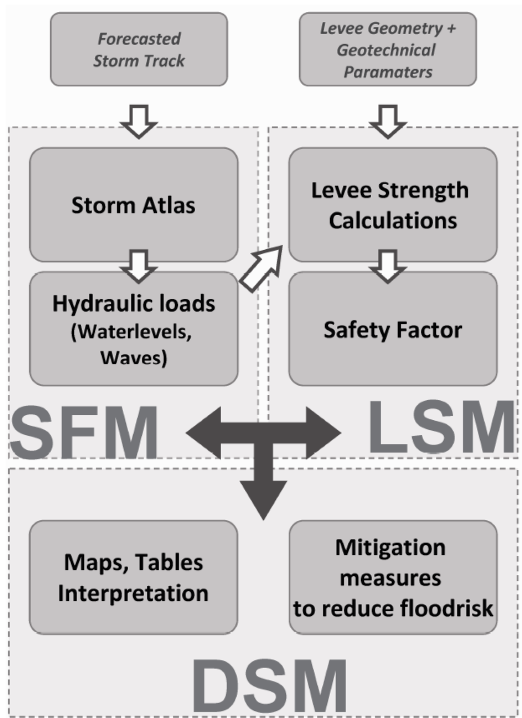

Figure 1. Workflow of the Hurricane Risk and Safety Module (HRS)

The Forecast

The Storm Forecasting Module (SFM) forecasts hydraulic loading conditions for an approaching hurricane. The output consists of best estimates for maximum storm surge levels and wave conditions for an approaching storm. The SFM uses the concept of a hurricane surge atlas and makes the results available through an interactive map. In the case of the SLFPAE project, the hurricane surge atlas for the HRS Module comprises of a set of 152 synthetic storms which vary in track, size and intensity.

By selecting the synthetic storm that closest resembles the forecasted storm in terms of track and storm parameters, the atlas immediately provides maximum still water levels and maximum wave height and peak wave period. It is possible to combine this information with the flood protection geometry to calculate possible overtopping and overflow conditions. Looking up a more extreme storm with a different track will provide instant insight in changing water levels. At the same time a storm atlas can provide a high resolution water level forecast very quickly. The atlas can be prepared before the storm season starts.

Levee Performance Assessment

The Levee Strength Module (LSM) calculates the levee strength using the forecasted hydraulic loading conditions and geotechnical calculation methodologies. The output of this module is a levee risk and safety map indicating the lowest safety factor of the geotechnical failure mechanisms per levee section during a storm.

The module consists of the pre-calculated levee reliability for any of the storms in the storm atlas. The levee reliability is calculated for two geotechnical failure mechanisms (slope stability and piping) as well as geospatial (overtopping). The calculations are based on an integrated geotechnical and geospatial database (GeoDatabase) that is comprised of topographic/bathymetric terrain data, geotechnical reports, and soil investigations for a specific levee section. This information is analyzed in conjunction with water surface elevation (WSE) data that is determined through hydraulic modeling and used in conjunction with synthetic storm impacts.

The LSM addresses this by evaluating if a levee section that is subject to a certain hydraulic load (the WSE and/or overtopping discharge rate) meets the strength criteria. If it does not meet the strength criteria, the LSM is used to determine what the likelihood is for that section to fail and cause flooding.

For each geotechnical failure mechanism a safety factor is calculated. When performing these factor of safety calculations, many choices and assumptions have to be made concerning the geotechnical conditions (e.g. soil layers, water pressures, and required safety levels). The level of sophistication of the calculations greatly depends on the choices and assumptions that are made and the information that is used as input. In general this means the less sophisticated the calculation, the more conservative the output. For example, a given project may assign a value of <1 indicating a failure and <1.5 indicating likelihood of near-failure. However, circumstances may dictate altering these figures.

The calculation results are presented as a combined safety factor, resulting in a levee risk and safety map indicating the lowest safety factor of the geotechnical failure mechanisms per levee section.

As an example, to determine the slope stability of the inner slope of the levee the theory of Bishop with the method of slices and a circular slip plane is used. The calculations are executed using the slope stability program D-Geo Stability. Based on geotechnical information from cone penetration tests (CPTs) the governing soil structure can be determined. Soil borings, CPTs, and geotechnical analyses can be used to determine the governing soil classifications. The phreatic line in the levee is based on calculations with MSeep. Figure 2 shows a typical configuration.

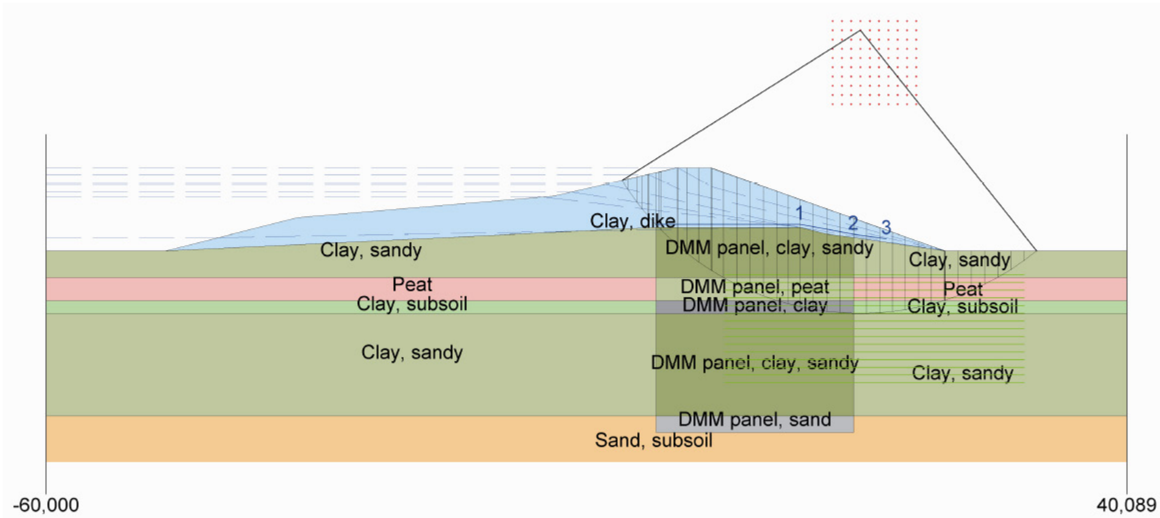

Figure 2. Typical slip circle calculation layout

Once the model is setup for each levee section that has similar geotechnical conditions, it is possible to calculate the slope stability for various water levels. The result is a slope stability safety factor that is associated with a certain water level. Since maximum Still Water Levels are available for all storms in the storm surge atlas, it is possible to calculate the slope stability safety factor for each levee section, for each storm.

Similar approaches are used for the calculation of piping (seepage) and erosion (overtopping) safety. Once the safety factor for the three geotechnical failure mechanisms is calculated for each levee section, it is possible to determine a combined safety factor. The engineer and/or flood plain manager must make a determination of an acceptable factor of safety given the potential consequences and (if available) probability of an event occurring (for example, certain failure mechanisms may vary in probability due to the presence or absence of certain hazards – often as a result of local geography and climate). To compensate for any uncertainties, the flood plain manager can choose to modify the required safety based on information at hand, such as historical evidence. In this LSM example, the required safety level has been increased in order to distinguish between three levels. The combined safety factor represents lowest calculated safety factor of the assessed failure mechanisms per levee section. The combined safety factor for a reach is presented in the dashboard and can be very helpful in decision support for specific mitigation measures.

Overall, this method does not yet consider the differences in relative consequences of failure between mechanisms. Future iterations could potentially weight the factor of safety based on the consequences of failure and factor in the probability of the critical event transpiring. However, today the LSM toolkit only provides information on the levee resiliency to a failure mechanism and the floodplain manager must still make decisions on the appropriate factor of safety based on consideration of the probability and consequences.

Decision support on a dashboard

The Hurricane Risk and Safety Module (HRS) presents the information from the SFM and LSM in a comprehensive web-based dashboard (see figure 3). In addition, the dashboard is able to collate crucial forecast and monitoring information from other third-party sources. The decision support module will provide the levee operator with a recommended action and/or mitigation plan on this same dashboard. This will provide the floodplain manager with a platform to plan for action and mitigation measures both before and after a storm event. The dashboard is adaptable to end-user needs.

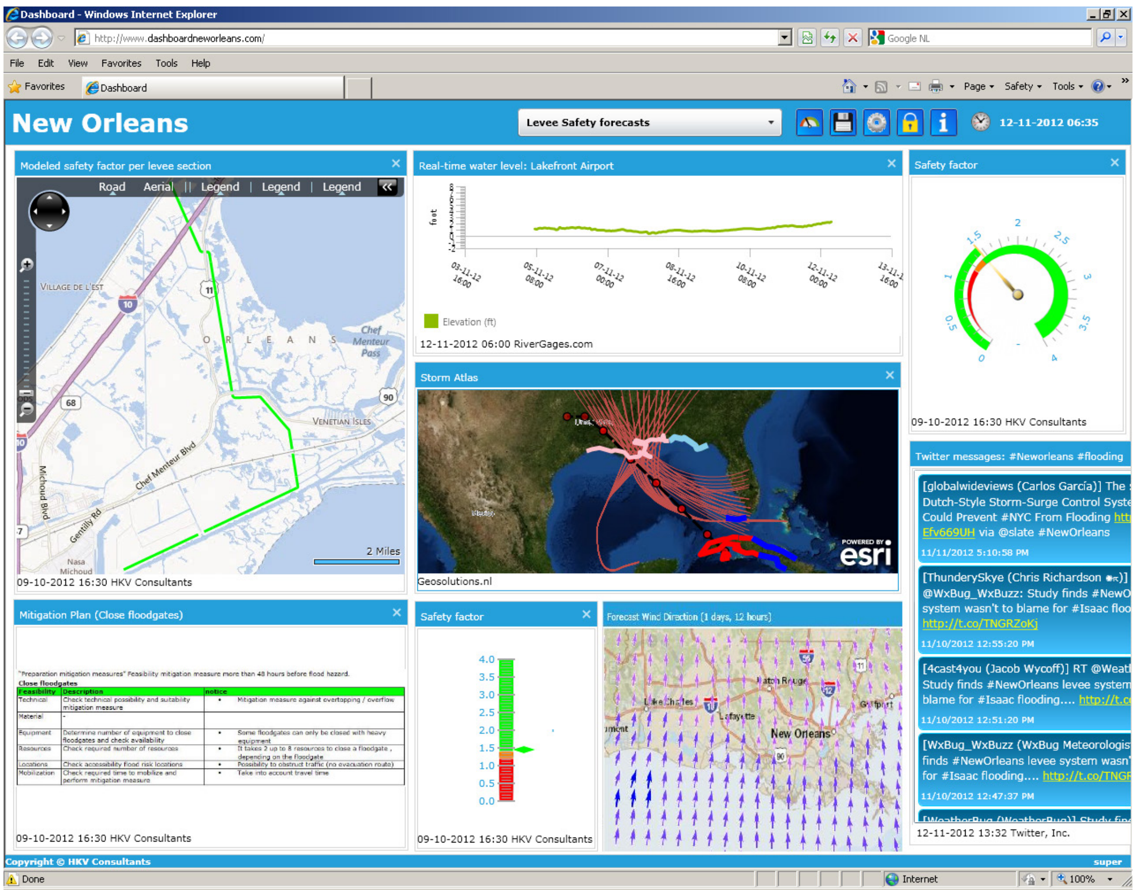

Figure 3. Dashboard Hurricane Risk and Safety Module (HRS) - New Orleans

In the case of the Dashboard New Orleans, the HRS displays several types of information: Water levels or discharges; weather and hurricane forecast information; information from the SFM and LSM; mitigation plans; Twitter feeds from the New Orleans area (tagged for #flood and #hurricane), and background documents such as guidelines. The Dashboard New Orleans presents a levee risk and safety map indicating the lowest safety factor of the geotechnical failure mechanisms per levee section. Based on the overall levee performance of a selected storm, the Dashboard recommends mitigation plans. When the overall levee performance changes (due to a new forecast), the suggested mitigation measures change accordingly.

REAL® 3-D LEVEE AND SUBSOIL MODELING: PROJECT EXAMPLE

An important trend in engineering is the application of 3-D subsoil models. Figure 4 shows a 3-D model based on aerial LiDAR, bathymetry, soil explorations and geological, geomorphical and geotechnical interpretations. The air and boat deployed remote sensing systems provide huge amounts of high quality data; frequently hundreds of gigabytes. These datasets allow an engineer to move from 2-D analyses of a limited number of levee cross sections towards analysis in almost unlimited numbers of sections. Modern data sets on levee and river geometry already provide between one and perhaps hundreds of survey observations per square meter. This permits accurate 2.5-D modeling of the surface of river bottom and levee geometry.

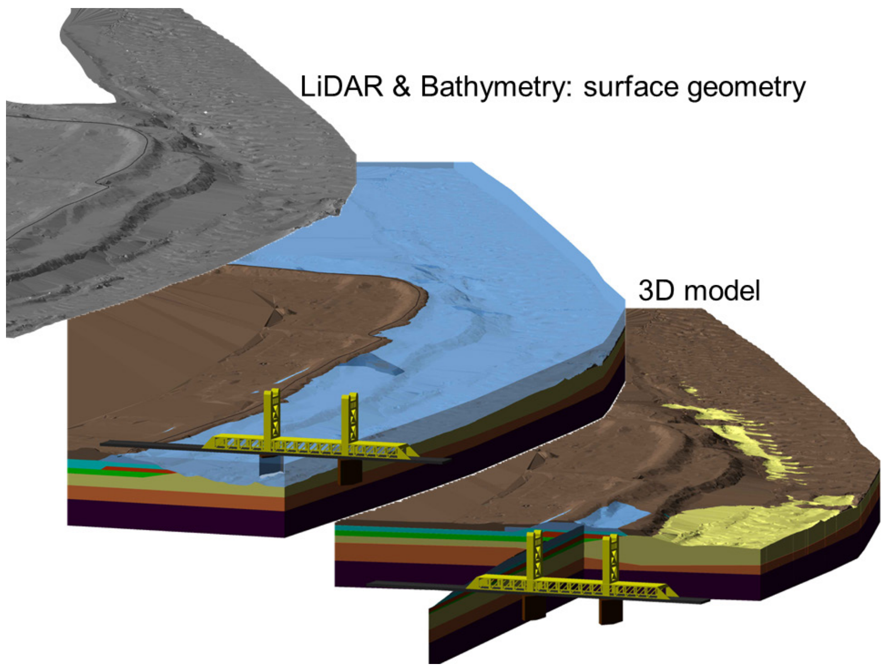

Figure 4. 3-D surface and subsurface models (West-Sacramento, California).

However, the use of only geotechnical coring and cone penetration tests gives the engineer only sporadic information regarding the subsurface conditions. Thus any subsurface model created using only this information lacks the detail of the surface model. The addition of geophysical techniques can be used to determine information about how the subsurface soils change between the physical testing locations. From down-hole logging techniques for small-scope projects to airborne geophysics for large stretches, the addition of information regarding the heterogeneity of the subsurface between conventional exploration points is essential in creating the subsurface model in 3-D.

Integrated with the highly detailed 2.5-D surface model, the resulting 3-D model offers many advantages to levee professionals in their analysis and assessment of levee performance and safety. In addition the engineers can easily provide stakeholders and decision makers supplemental *visual* information which is easier, faster and thus better to understand while also improving communication processes with the public (see Figure 4).

Recent experiences are the projects for the California Department of Water Resources (DWR). The State of California has long recognized the need to upgrade the aging levees in the Sacramento and San Joaquin River Valleys and in the Delta. The State has appropriated $500 million of funding to the California Department of Water Resources (DWR) to begin a comprehensive program of levee evaluation and upgrades. Of critical importance and highest priority are the 300 to 350 miles of levees located in the highly populated urban areas of greater Sacramento, Stockton/Lathrop and Marysville/Yuba City. The geotechnical work plan for the DWR Urban Levee project follows a logical progression of work: historic data collection, field explorations, preliminary analyses, data gap assessment, supplemental data gathering through additional field exploration, and further analyses.

Having a 3-D surface/subsurface model allows geotechnical professionals to evaluate cross-check data and interpretations more effectively, thus improving the reliability and accuracy of levee strength calculations. Also of significant importance is the ability to modernize the process through very efficient automated levee engineering assessments. One can extract levee segments from the 3-D model, have a GIS system create 2-D (or 3-D) input files (see Figure 5) for standard (off the shelf) geotechnical software and batch process these input files. With this robust 3-D model, thousands of cross-sections could be extracted instead of a statistically insignificant number, which generally is used to represent the state of a given reach (see Figure 6). The result is a vast number of geotechnical analysis results that not only represent the state of a reach, they can be used to pinpoint weak locations for emergency management as well as for planning remediation more effectively.

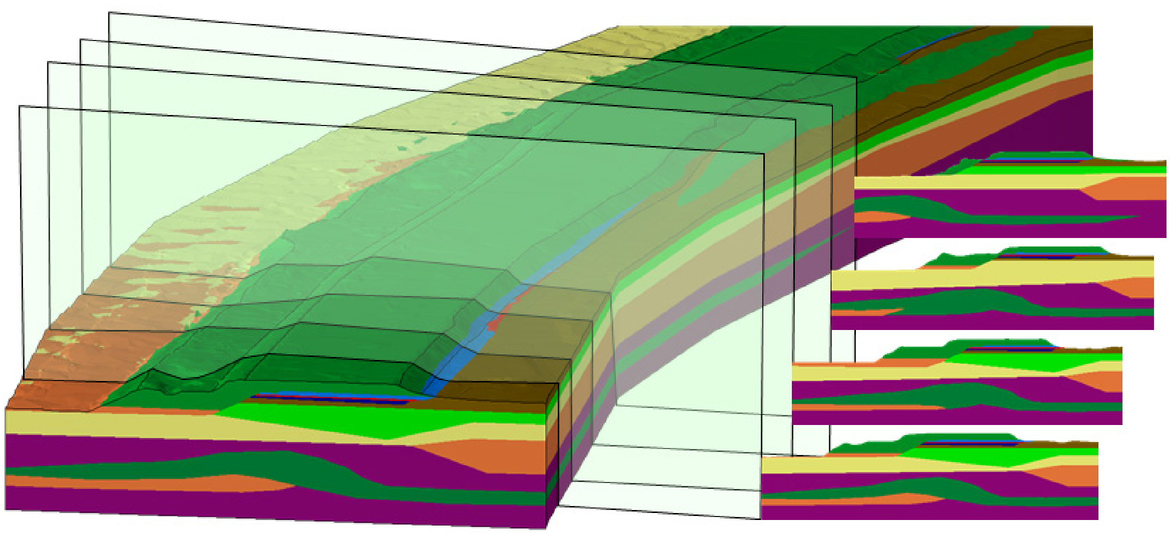

Figure 5. Continuous data 3-D model can be automatically sliced into numerous cross-sections as input into conventional levee assessment software.

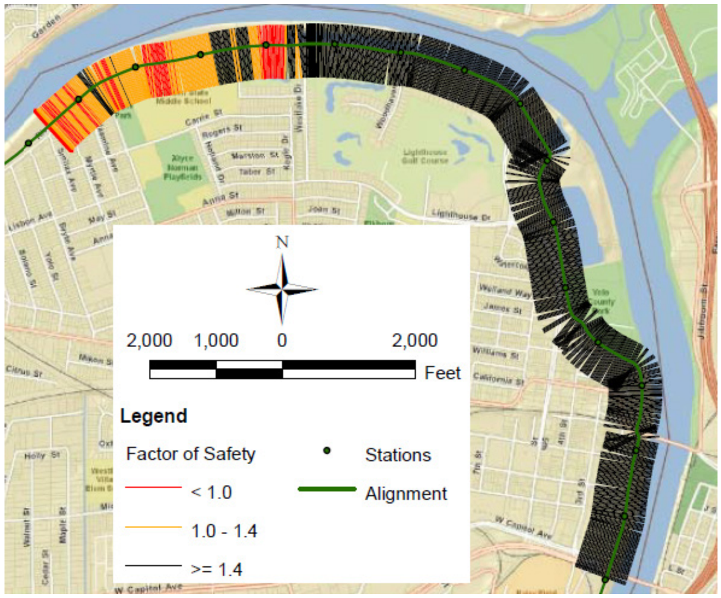

Figure 6. Automated levee cross-section analysis in planimetric view created using Fugro's REAL® system. Spencer Method used for calculation of Factor of Safety.

Execution of the analysis begins with initial runs using existing data that result in preliminary insights to the levee conditions and produce a preliminary 3-D model. The results are used to guide the project on where to focus further field studies (where required). These additional exploration efforts are carried out to improve the 3-D model. Once constructed, the LSM is used to assess the levee performance. The automation of the assessment protocols also allows the engineer to tailor the sensitivity of the analysis, which generally may include different evaluation methods and/or criteria. Experiences are being built up both in the USA and in the Netherlands employing the evaluation methods that are used and accepted in each nation respectively.

LEVEE STRENGTH MAPPING (LSM): PROJECT EXAMPLE

In the Netherlands, dike ring 10 is part of the complex water system of the delta of the river Rhine, managed by Water Board Groot Salland. The load for the levees depends strongly on the water levels of the river IJssel (a branch of the river Rhine) in the south and the river Vecht in the east and the weather conditions on the lake IJsselmeer in the northwest. Using water levels, discharges, and wind conditions the system calculates a forecast for the strength of the levee for the failure mechanisms piping and slope stability for the current (calamity) situation. Figure 7 shows the completed LSM module for the project.

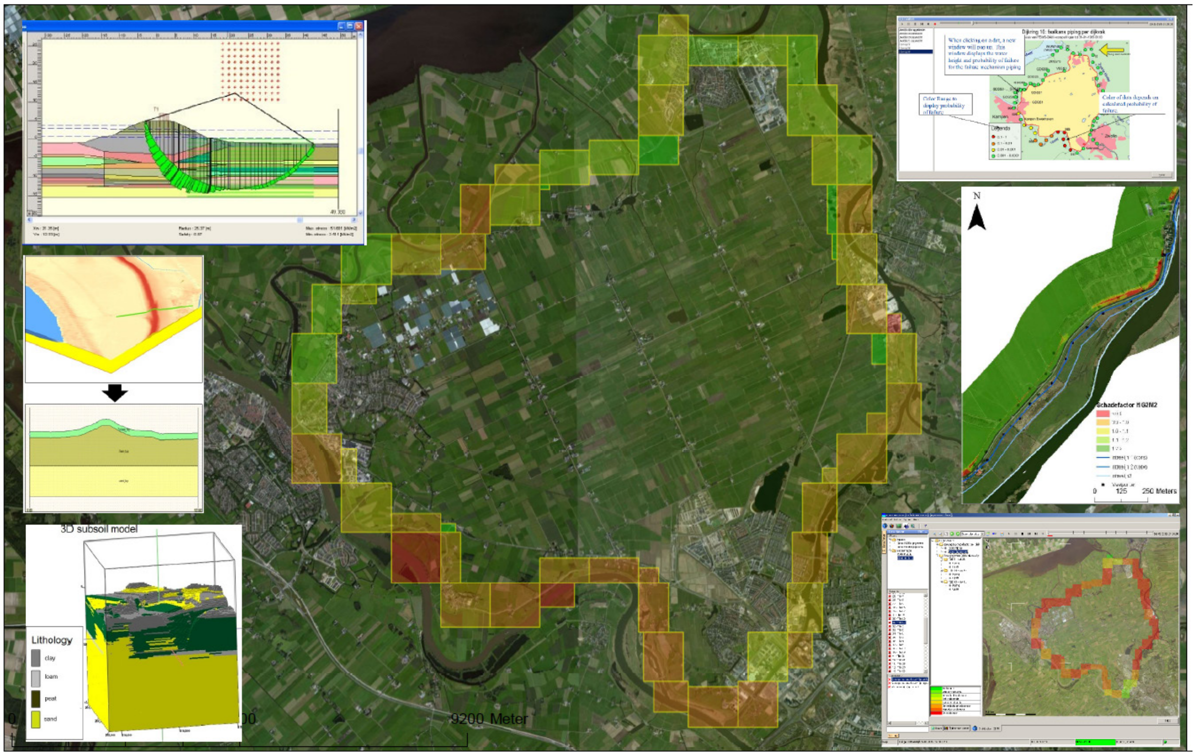

Figure 7. LSM for dike ring 10 ‘Mastenbroek’, the Netherlands (Water Board Groot Salland).

With the implementation of the LSM, the Water Board now has continuous insight into and understanding of the current and expected safety level for dike ring 10 ‘Mastenbroek’. The module discloses information, which is directly applicable in the current scaling level (assessment, maintenance, calamity and policy making). The presentation of the information is customized for the current role of the user: one system that can be used for daily operations as well as during calamities.

The LSM can also predict the impact of temporary emergency measures. For an assessment or a designed dike improvement project, the system can calculate the strength of the levees by using a theoretical load.

The results of the LSM assessments can be displayed in the Dashboard (see Figure 8). The information on the strength of the levee can be combined with measurements, forecasts, field observations and the results of the regular assessment. By implementing role specific profiles, a tailor made dashboard is defined for each role in the organization. The profiles are based on and incorporated in the regular and calamity processes in the water board.

Figure 8. Dashboard for the LSM for dike ring 10 ‘Mastenbroek’, in the Netherlands (Water Board Groot Salland).

REAL-TIME LEVEE SAFETY CONTROL: PROJECT EXAMPLE

During the IJkdijk full scale levee failure experiments in the Netherlands, performed in August/September 2012, one of the objectives was to develop a levee portal in which new insights in levee management, modern sensors, and Geo-ICT developments can be combined. The new portal would better process real-time sensor data to real-time levee safety predictions.

Real-time levee strength calculations based on all types of sensor data were carried out by Fugro, focusing on three geotechnical failure mechanisms:

- Underseepage and piping
- Instability of the top layer
- Slope instability

The latest mechanism models required for obligatory safety assessments in the Netherlands where used, with some modifications: instead of conservative parameters (design values), the most likely subsoil geometry and geotechnical parameters were used. This means also that the partial safety factors are left out, and the remaining formula is corrected to ensure that a resulting safety factor 1.0 means that there is a 50% likelihood that the mechanism will occur. A procedure is tested to combine safety predictions by using these types of modified mechanism models with additional sensor data and change detection principles.

Figure 9 shows a levee portal where Fugro’s professional data management systems is connected to a more general Dutch data management tool, named Lizard (introduced and developed by Nelen & Schuurmans). This allows dissemination of information and consultation not only by the geotechnical professional, but also by the decision makers and the public.

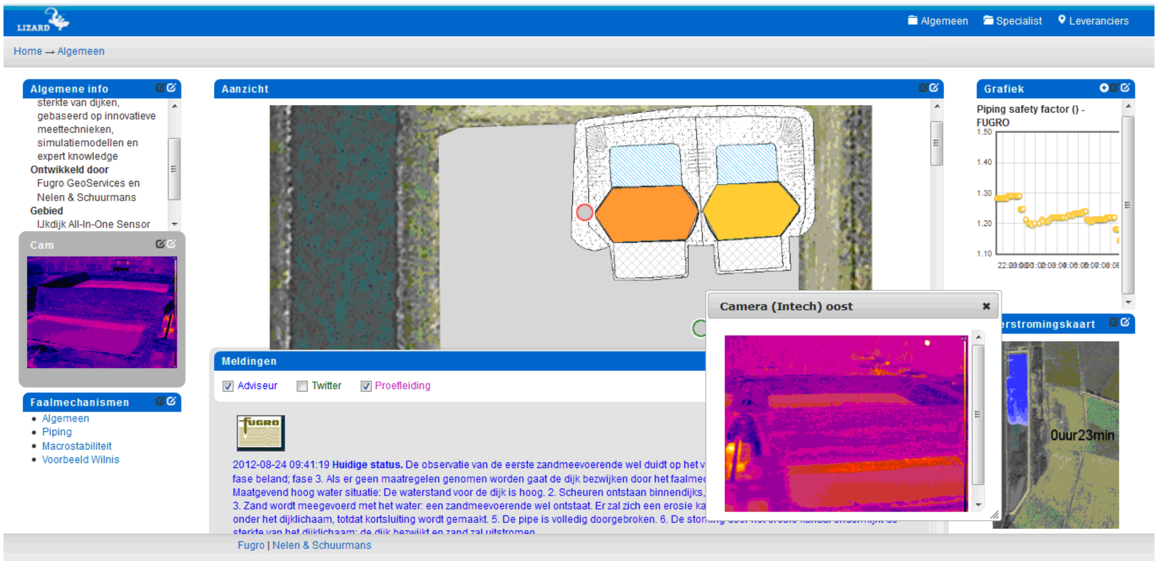

Figure 9. Levee Portal used on the IJkdijk experiments 2012.

The first experiences in the piping and micro-stability test sites are very promising. In September of 2012, another test on macro-instability was carried out (note: at the time of writing this paper, the final results were not yet available). Within the coming months the results will be studied in more detail to optimize the real-time data management, automated real-time calculations. Also the aim in the Netherlands is to implement the portal approach on real 'live dike' locations, which enables customization of the portal features to meet user's needs.

CONCLUSION AND OUTLOOK

The Hurricane Risk & Safety Module (HRS) for New Orleans links forecasted hydraulic loads with actual levee geometry and resilience resulting in a safety factor. This helps to prioritize decision making under storm conditions and allows enhancement of flood fight operation in the field. The HRS Module also provides additional insight in system performance, but at the current state the product does not replace visual monitoring of the flood defenses. During hurricane Isaac (August 2012), the HRS Module provided accurate forecasts and levee performance information, showing proof-of-concept, and its application is expected to be more effective with further development.

Potential topics for further developments use new insights in 3-D and real-time Levee Strength Modules (LSM). When a complete 3-dimensional model of the levee geometry and subsoil is compiled, it becomes possible to calculate seepage/piping safety and slope stability safety at any given cross-section for a stretch of levee. In this version of the

LSM design profiles represent levee sections. Real time data can lead to more precise calculations of actual levee safety, leading to more accurate mitigation plans that allow levee owners and emergency managers to take measures at identified hot spots along a levee stretch during an episodic event and/or to plan and prioritize remedial works as part of ongoing operations and maintenance.

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