AUTOMATED LEVEE FLOOD RISK MANAGEMENT

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ABSTRACT: The risk of flooding depends on the hydraulic load, strength of the levee and the estimation of flood consequences. To determine automatically the strength of levees, the Dike Analysis Module (DAM) has been developed. This platform is able to perform stability analysis for a large number of levees within a management area. In order to show the role of automated engineering in real-time assessments for decision support of flood control measures and emergency response, a case study is presented where the applicability of DAM is tested with real data. The added uncertainty in the results is also studied in this paper.

Key Words: Automated engineering, flood risk mitigation, data management, probabilistic piping analysis

1. INTRODUCTION

In many countries, levees play a major role in flood protection and flood risk management. Worldwide, hundreds of thousands of kilometers of levee exist. Often, these levees are old and little is known about their safety. Besides geometrical data, information on the subsoil conditions is of great importance for assessing the reliability of a levee system. In order to cope with this challenge, several programs on data management are currently being developed in the Netherlands.

Data acquired in the field or by geological analyses cannot be used directly in the calculation models that are used to assess the safety of levees. This data needs to be first processed and filtered before it can serve as input for the models. Recently, the effectiveness and efficiency of data acquisition has advanced considerably. For example, laser altimetry has enabled us to obtain topographical information (i.e. levee geometry) of large areas in a very short time. In order to advance at the same pace with the technology, it is necessary to improve the data processing to enable effective and rapid safety assessments as well. The Dike Analysis Module (DAM) is a tool that automatically processes and analyses the gathered data and can be used to support decision-making in flood risk management. The high degree of automation in DAM makes rapid analyses of levee systems on large geographical scale feasible.

The required data depends on the purpose of the assessment. The requirements during daily management differ from the data necessary for flood control or policy studies. The basic information of the levee (soil profiles, soil properties and geometries) however remain the same for the different processes. The degree of detail of the assignment depends on the goal of the analysis; from very strict in policy to a very detailed level in real-time assessments for decision support of flood control measures and emergency response.

This paper presents the application of DAM in real time assessments for decision support of flood control measures and emergency response. The framework of DAM is illustrated by a case study for the Water board Groot Salland (The Netherlands). For the piping mechanism, the real time management of uncertainties within the program in a probabilistic fashion is illustrated in this paper.

2. FRAMEWORK

In this section, a description of the Dike Analysis Module (DAM) is presented. The use of DAM to perform levee management and flood mitigation management is also discussed in this section.

2.1 Dike Analysis Module

DAM is a platform that automatically determines the strength of a levee or the failure probability based on a given hydraulic load. It involves a semi 3-dimensional determination of the levee strength. This means that cross sections are schematized from a three-dimensional terrain model and complemented with point observations of soil structure. From these cross sections, the stability can be determined.

DAM features a modular design. That is, for different applications a configuration of relevant modules can be developed. The modules are calculation models describing a specific failure mode. The applied modules are dependent on the availability of data and purpose of the analysis.

The workflow structure of DAM is based on four steps that follow the geotechnical analysis (see Figure 1), which is in principle applicable for all modes of levee failure (macro-instability, piping, erosion due to overtopping, etc). The first step comprises the collection of processed data from subsoil models, digital terrain models (DTM) and/or hydrology models. This data is schematized for stability and strength analyses in the second step. The third step is executing the stability calculation to determine the actual levee stability. This can be performed either via a deterministic or probabilistic analysis. Different models can be used to calculate the stability. The final step in the process involves the analysis, visualization and reporting of the geotechnical analysis.

Normally, for every assessment the previous four steps are followed. Every time, the analysis starts with a schematization of a representative cross section of a levee section. For the schematization, one or more cross sections are measured and several borings and cone penetration tests are performed (or already available form databases). If necessary, pore pressures and soil properties are measured (or obtained form databases).

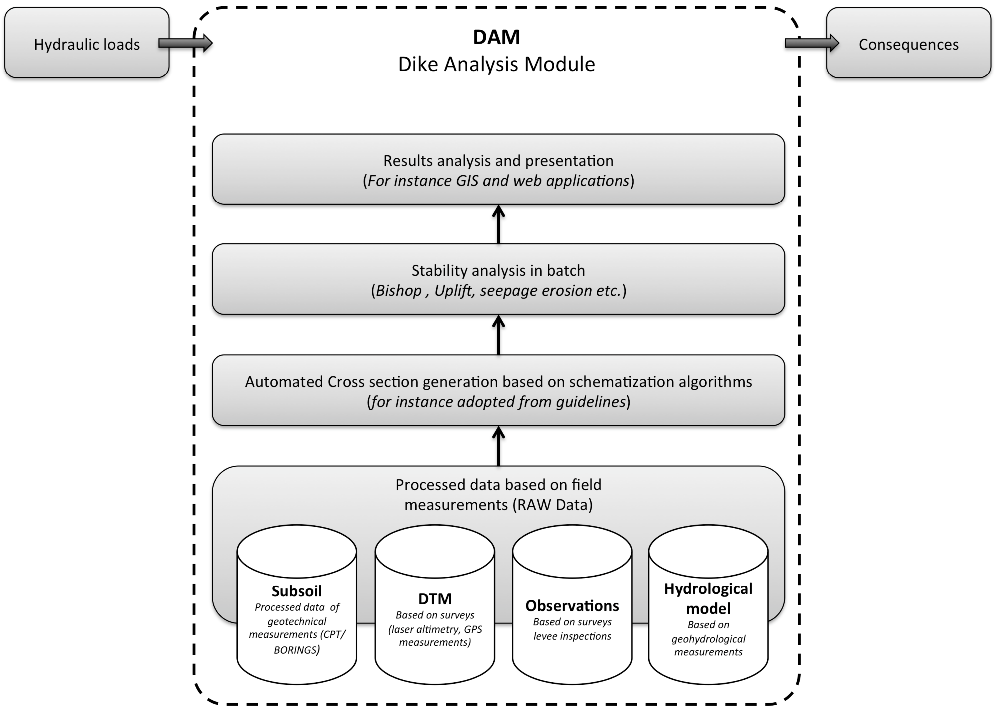

Figure 1: Structure of DAM

DAM has been developed under the assumption that in the 21st century in the Netherlands data of geometry and subsoil will all be stored in digital databases. When new data becomes available, it is simple to add to or replace the particular database in DAM. The same holds for codes, standards and calculation models. After replacing a module, it is not necessary to start the calculation process from scratch again, since the algorithms in the software performs this automatically. In this way, information obtained for a particular purpose can be used in other processes of levee management.

While using DAM as a platform to perform risk assessments for levee management, distinction is made between risk assessments for normal levee management and assessments for flood risk control (Knoeff and Vastenburg 2011). This paper focuses on the risk assessment as part of flood risk control in the standard levee management.

2.2 Flood mitigation and response

In general, four stages of disaster management can be distinguished: *Mitigation*, *preparation*, *response* and *recovery* (Godschalk, Brower and Beatley, 1989). The *mitigation* is the only stage that takes place before the flood event. The *preparation* stage includes short-term measurements to manage the flood risk and to prevent casualties and damage as much as possible. The *response* stage includes short-term emergency and assistance, such as search and rescue operation or debris clearance following the disaster. In the last stage *recovery*, post disaster actions are taken. These actions include rebuilding process and the restoration to normal life. In the *recovery* stage, the actions that have been taken to manage the flood are evaluated. The evaluation is used to improve the disaster management in the *mitigation* stage.

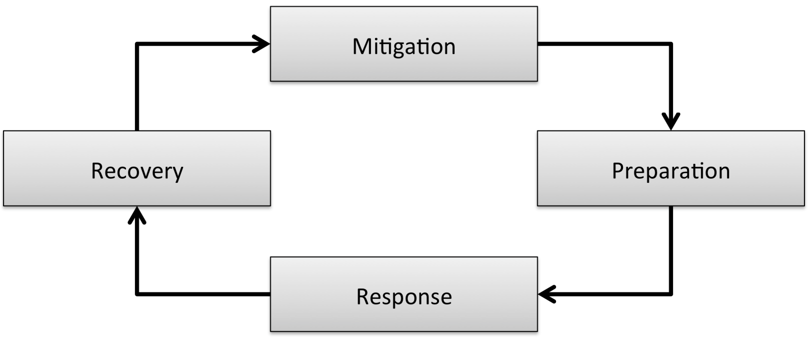

Figure 2. Stages of flood risk management and emergency response

In every stage, but especially in the first two stages, DAM can be very helpful. In the *mitigation* stage, the processed data collected during normal levee management can be used to perform risk assessments. The risk assessments can be used for prioritization of strengthening measurements along water retaining structures. The same data can be used for scenario analysis. In the same way, historical events can be recalculated and models re-evaluated. These studies provide insight in the water retaining system under critical circumstances and can be used to develop strategies and arrangements for emergency plans.

Real-time analysis of the strength of levees can be carried out in the second and third stage. The results of the real time analysis can be communicated with Flood Early Warning systems like FEWS or FLIWAS in order to have a full assessment of the situation. In the *mitigation* stage, the strength can be calculated taking into account real-time measurements or predictions of water levels. This information is used to determine the frequency of dike inspection, which is traditionally only based on water levels. Based on the results, emergency measurements may then be adjusted.

Observations by the dike inspectors can be used to automatically update the prediction of the levee strength by using real-time data assessment like Bayesian Belief Networks (BBN) or Artificial Intelligence (AI)-techniques. Which technique or DAM module is used depends on the available data. In this way, observations can be used to further prioritize emergency measures to manage the flood risk, even during flooding.

A local dike breach may affect hydraulic loads and hence dike failure probabilities at other locations. This may influence emergency and assistance plans in the *response* stage. The effects of flooding on the hydraulic load can be calculated with models such as SOBEK (Dhondia and Stelling, 2004). DAM can calculate the effect in the stability of the levees at other locations. These analyses can be done in real-time or in advance.

The possibilities to use DAM in the *recovery* stage are limited. In this stage, the actions taken can be justified and also evaluated by recalculating the event. The lessons learned are used to improve the disaster management in general and specific recommendations for the *mitigation* stage. The data collected during the flood event can also be used to improve daily levee management. In addition, one could run different scenario's of high water levels in advance, to set up different plans and protocols for extreme water events, related to the different scenario's.

Stage	**Example of application of DAM**
Mitigation	Carry out risk assessments Recalculate historical floods Develop emergency plans
Preparation	Insight in actual strength of levees Recommend and prioritize of measurements to be taken
Response	Real time updating information of levee strength in the management area
Recovery	Account for actions taken Lessons learned and recommendations to improve disaster management

Table 1. Applicability of DAM in different stages

In all stages, the induced uncertainty has to be accounted for. In the following sections, a method to manage the uncertainty is presented and an application of DAM is illustrated for the *preparation* stage and the failure mechanism of piping.

3. DEALING WITH UNCERTAINTIES

Probabilistic calculation of levee strength not only yields the probability of failure but also gives insight into the relative contributions of uncertainties of both, the hydraulic boundary conditions and the dike strength components (e.g. different failure mechanisms or strength parameters). Such information may be very valuable for decision makers in the *preparation* stage but also for developing strategies in the mitigation stage. For example: information of the degree of reduction of the probability of dike failure due to monitoring on a specific parameter such as pore water pressure can be used in both stages.

Recently a probabilistic strength model for the failure mechanism piping, based on Sellmeijer model (Sellmeijer, 2006), has been implemented in DAM for an operational setting. Piping involves the development of internal channels under the levee after sand particles are transported from its base. When one of the channels manages to connect the outside with the inside of the levee, failure occurs. In the operational setting, the failure probability is computed in real-time per cross section given a measured or predicted water level.

The calculation of the failure probability (for piping) consists of two steps: 1) Definition of limit state functions for the failure mechanism and 2) FORM analysis, where only the uncertainty of the water level is used.

3.1 Management of the uncertainty in the hydraulic load

DAM obtains the hydraulic load from Flood Early Warning System (FEWS). This software, developed by Deltares, provides a state of the art flood forecasting and warning system. The system is a sophisticated collection of modules designed for building a flood forecasting system customized to the specific requirements of an individual flood forecasting agency. The philosophy of the system is to provide an open shell system for managing the forecasting process. This shell incorporates a wide range of general data handling utilities, while providing an open interface to a wide range of forecasting models.

FEWS can import the ensemble forecasts for the meteorological conditions as provided by KNMI (Royal Netherlands Meteorological Institute). These forecasts lead to various realizations of the hydraulic load (water levels) at selected locations along the river as a function of time.

From the point of view of uncertainty analysis, it is stressed that there is no probabilistic information contained in these ensemble forecasts, that is, all members of the ensemble are supposed to be equally likely.

To determine in DAM the uncertainty in the failure probability, two different approaches can be used:

1. Run DAM for each individual realization: For each selected location, DAM is used to estimate the failure probability for a sequence of times covering the same period as the meteorological forecast. The mean and variance of the results is used to determine the uncertainty in the failure probability. The advantage of this method is that nothing is assumed about the probabilistic distribution until the last possible phase. The disadvantage is that it is computationally intensive and it may take too long in a critical moment (DAM will have to run hundreds of times the piping module).

2. Determine from the realizations the mean and variance of the hydraulic load as a function of time and use the probabilistic methods in DAM: This way, DAM has to be run for only one time series per location instead of 50 times (the nominal size of meteorological ensemble forecasts). Therefore, this is an efficient method. The main disadvantage of this method is that it is assumed a normal or log-normal distribution of the loads where the statistical aspects are simplified.

3.2 Management of the uncertainty in the strength parameters

The probability of levee failure due to piping is largely determined by the uncertainties present in the soil layers. In DAM, these uncertainties are taken into account by the so-called stochastic subsurface model. Based on a combination of subsurface information (boreholes, CPT's, etc) and expert geological knowledge, a number of subsurface scenarios are defined with a given probability of occurrence (the sum of which equals 1). For each subsurface scenario, the probability of failure (piping or slope-instability) is multiplied with the probability of occurrence. The total probability of failure equals the sum of the products of the probability of failure and probability of occurrence for each subsurface scenario.

4. GROOT SALLAND CASE STUDY

In the Groot Salland[1] case, being part of the Flood Control 2015 program[2], the strength of an entire dike ring against piping is studied for a real discharge wave. For this case study, a probabilistic module for both macro-instability and piping has been implemented in DAM. Furthermore, the connection between the programs FEWS and DAM has been established. This enables real-time forecasting for different failure mechanisms in a probabilistic environment.

4.1 FEWS-DAM coupled tool

The FEWS concept is supported by the provision of a general adapter module, which supports communication to external modules using an open XML based published interface, allowing "plugging-in" of any (forecasting) model (see Figure 3). An adapter between the native module data formats and the open XML interface is typically required. Such adapters are already available to support a wide range of hydraulic and hydrological models. For this case study, a module adapter has been developed to connect DAM with FEWS.

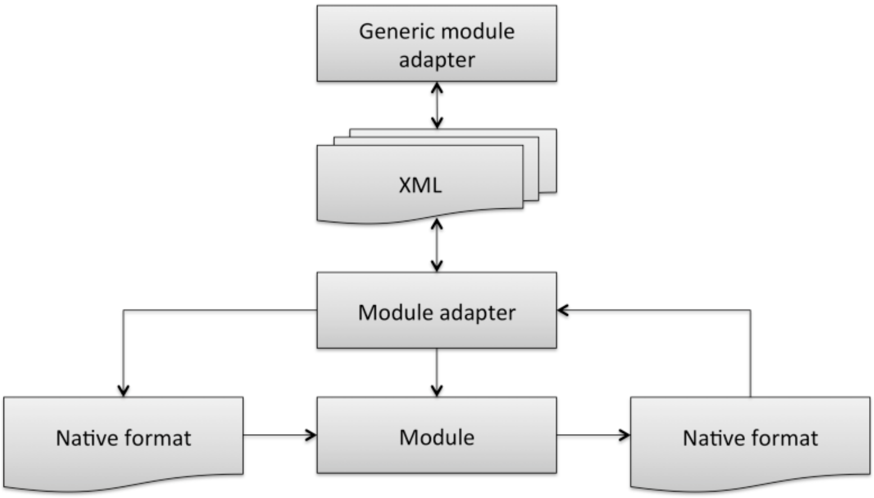

Figure 3: Overview FEWS's general adapter module

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[1] Groot Salland is a water board in the northeast of the Netherlands. The management area covers approximately 120,000 hectares. The water board manages over 4,000 km waterways. The area has a population of approximately 360,000 and a relatively large part of the area is used for light-industrial and commercial activities.

[2] Flood protection is primarily concerned in making strong dikes. The greatest gain lies in making the total system smarter: the dike, the decision-maker and their environment. Flood Control 2015 integrates these three aspects in advanced forecasting- and decision-supporting systems. Flood protection therefore becomes more transparent, quicker and more efficient.

4.2 Real-time probabilistic prediction for piping

The connection between DAM and FEWS started functioning at the end of 2010. The first results of the Groot Salland case study are here presented. It involves a back-analysis of a historical flood wave in 1995. It is important to remark that these results are solely for illustrative purposes as further research is still going on to improve the reliability of the results.

The historical discharge wave data used in this study is from 1995 (end of January and first part of February). The locations analyzed are situated along the IJssel River, from Katerveer to Kampen. A preliminary static assessment (time independent simulation) of the piping failure mechanism shows that the safety factor at these locations is insufficient for the design water levels.

Therefore, high failure probabilities are to be expected if the actual water level approaches the design level, as was the case in 1995. Start date of the "forecast" is January 22, 1995. To deal with the different uncertainties, the second approach mentioned in section 3.1 is used. Based on various realizations of the hydraulic load, the mean water level and corresponding standard deviation as a function of time are calculated. These conditions are used to determine the transient development of the failure probability.

Figure 4 shows a screen-shot of the FEWS-DAM configuration of the predicted failure probability (for one time step), along the dike ring, eight days after the start of the forecast. The color of the dots represents the probability of failure. The results can be presented in top view for different times, either by automated animation, or by manually shifting the indicator in the time bar above. To attract the attention of the operator during high water situations the probabilities of failure is represented by different colors and can be configured. In addition, when clicking on a dot, the actual water level, the water level prediction and the failure probability are shown in another window (see Figure 5).

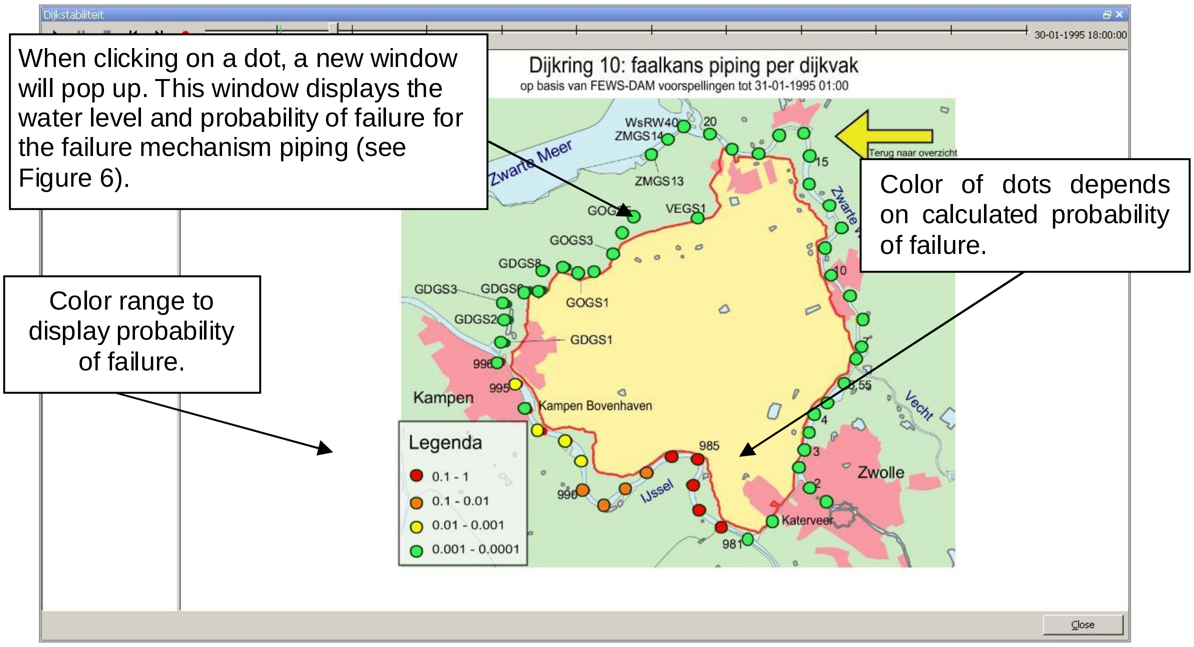

Figure 4. Piping failure probability on January 30, forecasted on January 22

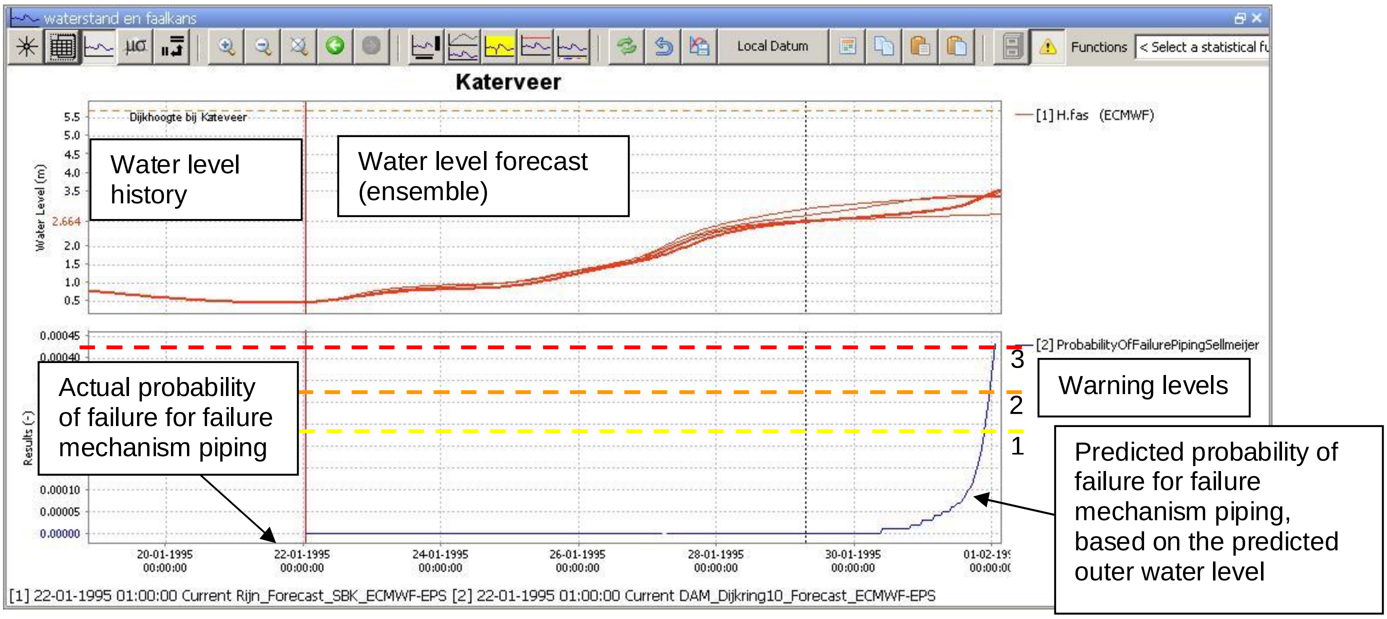

Figure 5. Example of the water level forecast and piping failure probability at location Katerveer, starting January 22

On the exact location of the analyzed cross section not always measurements (soil/water levels) are available. The failure probability of a cross-section is visualized at the position of one or more nearby locations with available measurements. In he future, the failure probability will be adjusted at the exact location by interpolating between the water levels.

Based on the results of the case study it became clear that it is technical possible to establish a connection between FEWS and DAM. This connection makes possible to set-up a system that integrates flood forecasts with dike strength analysis.

5. CONCLUSIONS

In different processes of levee management, much information about levees is collected. Taking into account that the information is obtained for different purposes, DAM shows to be an efficient tool to calculate the stability of a levee. DAM can be very helpful in every stage of disaster management, varying from preparing strategies and arrangements for emergency plans in the *mitigation* stage to real-time recommending and prioritizing of measurements to be taken in the *preparation* and *response* stages.

The results presented in this paper illustrate the possibilities of a platform that can couple real-time prediction of water levels and analysis of failure probability of the levee accounting for uncertainty in both hydraulic load and strength of the levee. This procedure enables a real-time prediction of the safety level (in terms of failure probability), for the purpose of forecasting and decision support in different stages of disaster management.

Before this method can be used in practice, further validation and possibly improvement of the implemented methods is required. An extension of FEWS-DAM for the real-time safety analysis for slope stability is already part of the FC2015 research program for 2011.

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