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ProDeich - a tool for assessing the safety of coastal dikes in Denmark

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ABSTRACT: *Denmark, nestled between the North Sea to the West and the Baltic Sea to the East, boasts a coastline stretching approximately 7300 kilometres. Along the Danish shores, coastal protection primarily revolves around a combination of sea dikes, spanning about 1200 kilometres, complemented by dunes, beaches, and cliffs. The ProDeich tool operates failure modes for sea dikes on the principles of serviceability limit states (SLS, such as wave overtopping) and ultimate limit states (ULS, such as grass and clay erosion). It is using a fault tree methodology where the aforementioned failure modes are structured according to failure observations of sea dikes from the past. The model also features a breach prediction model, the results of which will be fed into the SFINCS model (by Deltares) for flood prediction. This article describes some technical details of ProDeich and its applications to two case studies from both the East and West coasts of Denmark, each of which with distinct challenges. Furthermore, the discussion extends beyond Denmark's borders, contemplating the transferability of these methodologies to other coastal regions with similar challenges.*

KEYWORDS: coastal dikes; dike safety; flood prediction; climate change adaptation

1. INTRODUCTION

Denmark, nestled between the North Sea to the West and the Baltic Sea to the East, boasts a coastline stretching approximately 7300 kilometres. This expansive coastal stretch has necessitated robust coastal protection measures to safeguard against the threats posed by the elements. Along the Danish shores, coastal protection primarily revolves around a combination of sea dikes, spanning about 1200 kilometres, complemented by dunes, beaches, and cliffs.

In the aftermath of recent flooding events in Denmark, Germany and Norway, the government of Denmark has tasked the Danish Coastal Authority (DCA) to reassess the safety of Denmark's sea dikes and to provide comprehensive flood maps to anticipate and prepare for potential storm surges. To fulfil this mission, DCA is using state-of-the-art tools and methodologies.

One of these tools, SFINCS, developed by Deltares (Leijnse et al., 2021), is used to predict flood maps as a consequence of predicted storm surges. This tool and its application are further described in a parallel paper to this conference (Geertsen et al., 2024). Meanwhile, the second tool, ProDeich, has been tailored specifically for the Danish sea dikes. Initially conceived as a probabilistic design tool for North Sea dikes (Kortenhaus, 2003), ProDeich has undergone significant adaptations to embrace the varieties of Denmark's coastal dikes.

The key objective of the ongoing project at DCA is to develop a real-time forecast tool for potential flooding with which potential losses of lives and material damages can be avoided during upcoming storm surges. The tools are triggered by forecast data from the Danish Meteorological Institute (DMI) and are planned to run within about two hours for the endangered coastal areas. This will allow the Danish emergency systems to plan and execute mitigation measures in time before the storm peaks.

The aim of this paper is to describe some of the technical details of ProDeich and its collaboration with SFINCS (see chapter 2). The paper will also briefly describe the two selected case studies (chapter 3) which the project will use for testing the tools before they will be applied and rolled-out for the whole coast of Denmark. Some lessons learnt from earlier results of ProDeich will also be discussed.

2. BACKGROUND AND TECHNICAL DETAILS

ProDeich operates failure modes on the principles of serviceability limit states (SLS, such as wave overtopping) and ultimate limit states (ULS, such as grass and clay erosion). The fault tree for the Danish coastal dikes is displayed in Figure 1 where the aforementioned failure modes are structured according to failure observations of sea dikes from the past.

In Figure 1, the failure modes used for ULS, starting with initial conditions at the bottom, and leading to breaching of the dike at the top of Figure 1, are shown in three branches, depending on the critical failure path (seaward slope, crest, or landward slope). Failure modes are connected by ‘gates’ where three types are used: an OR-gate connects two (or more) failure modes in a way that either the one or the other failure mode leads to failure, an AND-gate means that both failure modes need to fail to lead to branch failure, and an IF-gate means that one condition (failure mode) has to be fulfilled first before the calculation of the other failure mode is started.

For all failure modes the relevant safety factor, expressed as the ratio of resistance R over stress S , is indicated in Figure 1 by the number provided in the boxes underneath each failure mode. A typical failure mode calculation is shown in Figure 2, using a Bishop slip circle for the seaward side of the dike as an example.

The larger boxes in Figure 1 where several failure modes are brought together are time-dependent processes and therefore calculated in a time-based approach, each time-step memorising and using the end result of the previous time-step (typical time-step is one hour, but can be reduced to any shorter steps as well). In addition, each time-step is using updated information of the boundary conditions such as water level and wave predictions.

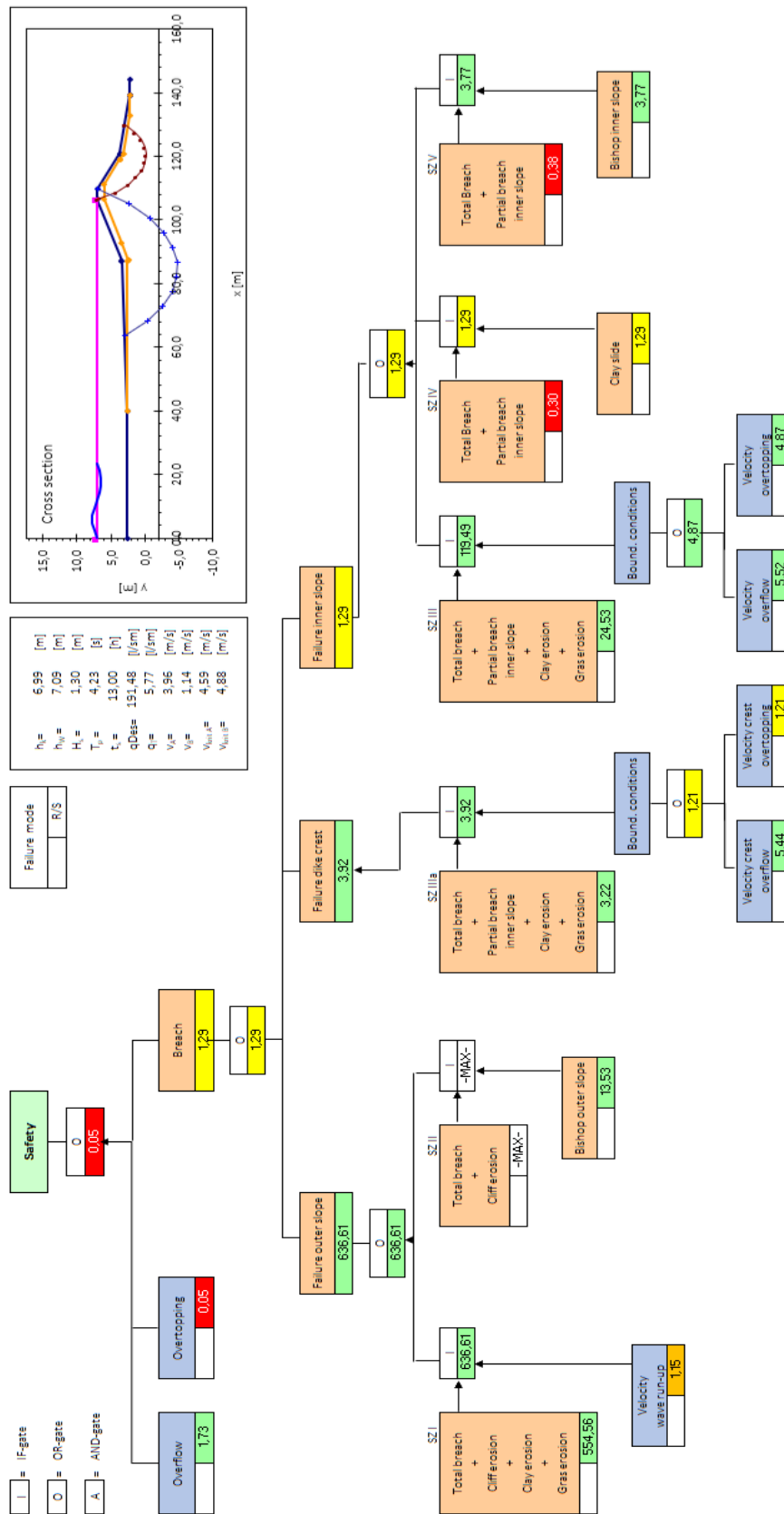


Figure 1: Fault tree for the Danish coastal dikes

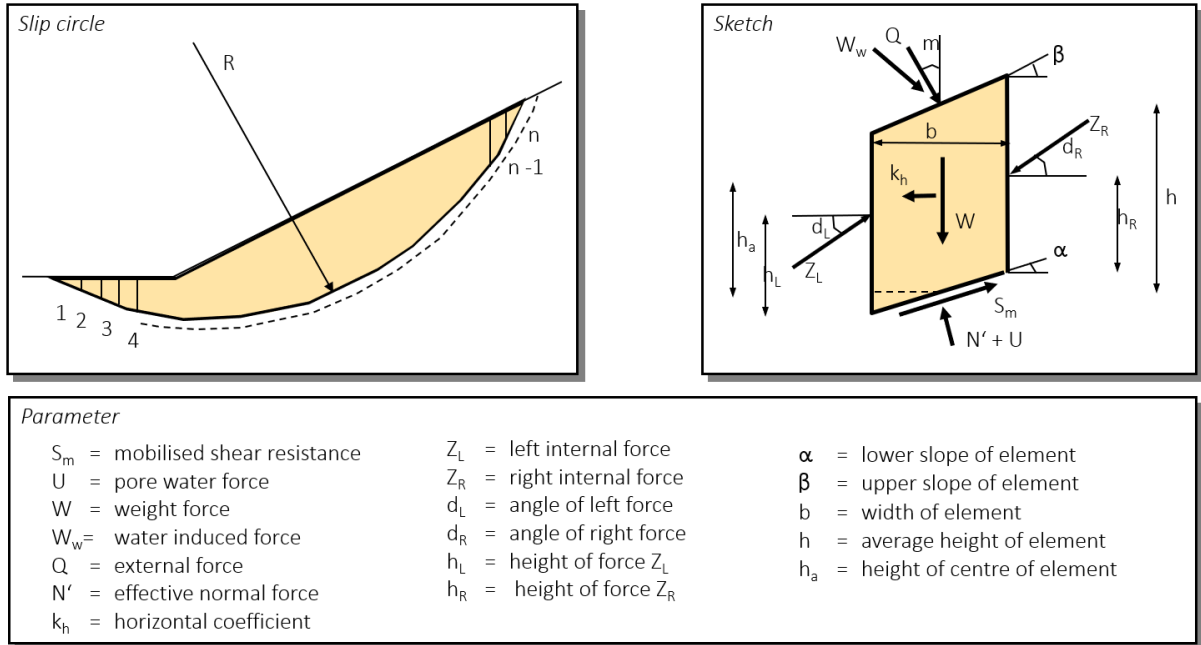


Figure 2: Example of a failure mode calculation, here: Bishop slip circle seaward slope

Whilst ProDeich is principally able to also calculate failure modes for revetments or impacts by breaking waves on the seaward slope, these failure modes have been disabled for the Danish coastal dikes since these dikes do not feature revetments and have very mild seaward slopes which principally exclude impacts induced by breaking waves.

ProDeich spans two distinct calculation modes: the 'scenario approach' and the 'forecast approach'. The former uses historical data to assess dike safety under various water level and wave scenarios, yielding tabular results for reference. Conversely, the 'forecast approach' relies on prediction data provided by the Danish Meteorological Institute (DMI) to forecast potential safety issues during upcoming storm surges.

Both approaches rely on the integration of survey data, soil investigations, and drone-assisted assessments of dike and grass quality which are being performed in 2024 and will improve the current knowledge about the state of the Danish sea dikes. It should be noted that these investigations will be limited at this stage to certain dike stretches where no or hardly

any information is available yet. The assessment of grass quality, in addition, is to a certain extent, dependent on seasonal variations (grass growth, water content, temperatures, etc.) and on the maintenance conditions of these dikes. As compared to the currently available knowledge, however, these components, together with a detailed elevation and bathymetry model of the Danish coastline, will furnish the tools with the necessary inputs to generate accurate safety assessments.

The model also features a breach prediction model (Visser, 1998 for sand dikes), the results of which will be fed into the SFINCS model for flood prediction (for more details about SFINCS, see Geertsen et al., 2024). Additionally, a colour-code system will be used to show predictions of weaker dike sections for potential mitigation measures. Figure 3 shows a preliminary sketch how the two models are combined.

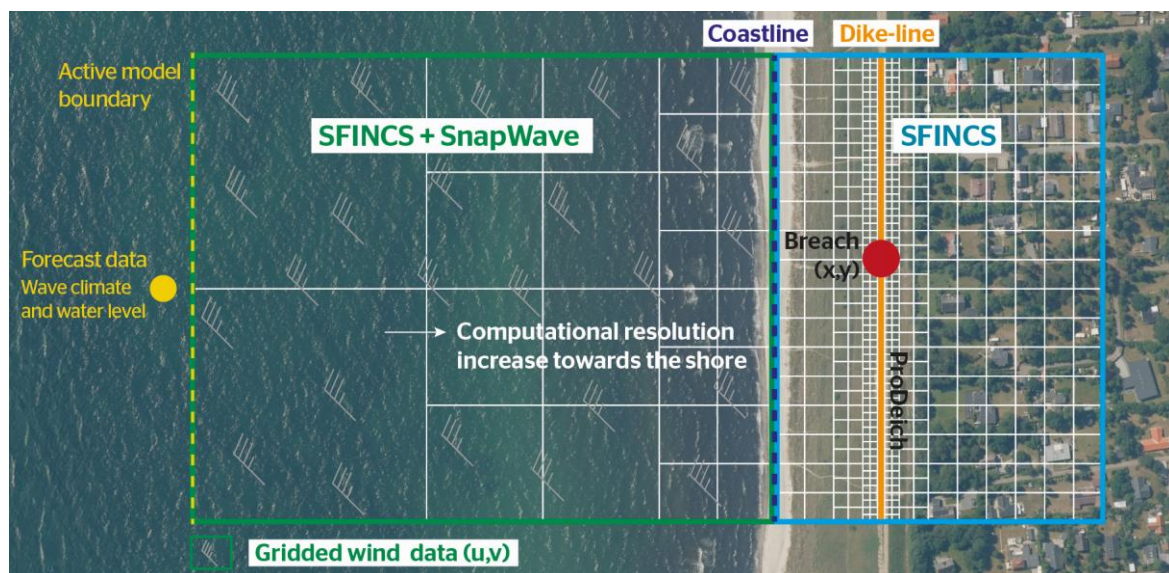


Figure 3: Sketch of SFINCS and ProDeich working together for the Danish safety assessment (source: Geertsen et al., 2024)

Figure 3 shows that SFINCS, together with SnapWave (both from Deltares), will use the DMI input data and calculate the wave propagation until the toe of the sea dikes. These data will then be transferred to ProDeich, but also used as input for the calculation of the

flooding. ProDeich will calculate the dike safety for the relevant dikes and will also determine breach locations, together with the development of breaches over time. The latter is then used in SFINCS again to calculate the flood extension from these breaches.

ProDeich can also run probabilistic fault trees (based on Monte-Carlo simulations) where the total result is no longer a safety factor, but a failure probability. Due to the necessary amount of simulations in this case, the aforementioned project has developed the safety factor approach as a suitable and feasible option, especially for the forecast approach.

3. APPLICATION AND RESULTS

First applications are made to two case studies from both the East and West coasts of Denmark, each of which with distinct challenges. The first application is to the East coast of Denmark, Hejsager, a small coastal village in the South of the city of Haderslev and protected by a grass-covered sea dike (see Figure 4).



Figure 4: Photo impression of the dike in Hejsager (source: own photos)

The dike in Hejsager is a small, grass-covered dike protecting the small community against storm surges from the East. The area has been flooded during the most recent storm surge in December 2023 where the dike was breached at one location. Cross sections of the dike at different locations are available together with geotechnical investigations and will be used for a hindcast exercise of the storm surge.

The second application is made to the dike of Rejsby, located at the West coast of Jutland, close to the island of Rømø (Figure 5).



Figure 5: Photo of the dike at Rejsby (source: Hjart, [WikiCommons](#))

The reason for selecting this case study is due to its typical location at the West coast of Denmark, close to the Danish Wadden Sea. The dike has failed during the storm surge on 3rd December 1999, where some documentation is still available. Together with geotechnical data and an already available SFINCS model for the region, the Rejsby dike was selected as second case study and will also be used for calibration.

Results for both case studies have already been generated for the ProDeich model using its ‘scenario approach’. Input boundary conditions for this approach was not taken from DMI predictions, but from statistical information derived for so-called MetOcean stations all around the coast of Denmark. These stations feature historical information of water levels, wave data, including return periods and typical time series. In addition, the scenario approach goes beyond historical information and also uses water levels which are physically possible, but have not been observed in the past. Based on these calculations, the dike segments show some sensitivity to the following dike / boundary conditions:

- steep shoreward slopes together with a clay cover and a high water content
- longer storm durations and low grass quality (e.g. due to low maintenance efforts)
- pre-eroded grass covers

This analysis, amongst other findings, has triggered further and more detailed investigations of the dike layers and the grass conditions. For the former, geotechnical investigations are being performed for about 300 km of dikes in Denmark, and the latter will be further analysed using drone flight campaigns where an algorithm for its analysis will be developed by DCA. It is expected that these additional data will improve some of the previously achieved results and hence the prediction ability of ProDeich in its ‘forecast approach’.

The methodology used in this paper can be extended beyond Denmark's borders where coastlines with similar challenges are found. Due to its modular approach and real-time calculations, the authors believe that a similar methodology can be applied to many coasts worldwide.

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