FULLY PROBABILISTIC DUNE SAFETY ASSESSMENT USING AN ADVANCED PROBABILISTIC METHOD

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In this paper, an advanced probabilistic method - Adaptive Directional Importance Sampling (ADIS) - is used in concert with a process-based dune erosion model - XBeach - to perform a dune safety assessment. The efficiency of the probabilistic method removes the restriction of only using simple empirical dune erosion models for probabilistic calculations. The proposed combination of ADIS and XBeach is able to handle complex cross-shore profiles that empirical dune erosion models cannot, as shown in several case studies.

Keywords: probabilistics; dune erosion; XBeach

INTRODUCTION

Reduction of flood risk in densely inhabited and economically valuable coastal zones is an important challenge for many coastal regions. In some countries, large parts of the coast are protected by coastal dunes. To be able to assess the present and future safety level of dune coasts, a dune safety assessment method, accounting for uncertainties in hydraulic forcing conditions, is necessary.

Currently, the accepted Dutch dune safety assessment, described in ENW (2007), uses a semi-probabilistic approach based on a dune erosion model using 1-dimensional (1D) cross-shore profiles. For a limited number of representative locations, the normative hydraulic boundary conditions are determined in a fully probabilistic manner. These normative hydraulic boundary conditions are then translated to the remaining locations through spatial interpolation. Subsequently, using these normative boundary conditions, a single deterministic 1D dune erosion model calculation is carried out for each location, to determine whether that location meets the legal normative safety level.

The prescribed dune erosion model at present for the Dutch dune safety assessment is Duros+ (van Gent et al., 2008), a relatively straightforward equilibrium profile model that calculates the post-storm beach profile and resulting dune setback, under the assumption that volume is conserved in cross-shore direction. It uses the significant wave height, wave period, storm surge level and grain size as input parameters.

PROBLEM DEFINITION

There are several issues with the semi-probabilistic approach described above. As mentioned by den Heijer et al. (2012), this approach has severe limits to its applicability. This is mainly caused by cross-shore profile shapes and configurations that lie outside the validity range of Duros+ (typical examples of these profiles will be given later on). These types of profiles can be found along a significant part of the Dutch coast.

Furthermore, the semi-probabilistic approach only yields a binary result (either safe enough or not safe enough), while a continuous result such as a failure probability would provide additional useful information with respect to the severity of an unsafe situation (or inversely, the measure of additional safety relative to the norm).

In this paper, a fully probabilistic dune safety assessment approach is proposed and used in several characteristic problem situations, the results of which are presented and discussed. This approach solves the above-mentioned issues and is applicable to a wide range of dune safety and engineering problems in an international context.

The limited applicability of Duros+ can be overcome by using a different, process-based dune erosion model that is more broadly applicable, and can resolve the situations that Duros+ cannot.

To be able to perform a probabilistic dune safety assessment, the following components are required:

1. **Dune erosion model** Predicting the amount of dune erosion under given hydraulic forcing conditions.
2. **Limit state function** Definition of the point at which a dune is considered to have failed in providing protection against flooding.

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3. **Random variables** Variables governing the dune erosion process, the value of which is uncertain on beforehand.

4. **Probabilistic method** Method that can determine the probability of failure, accounting for uncertainty in governing variables.

All of these aspects are expanded on below.

DUNE EROSION MODEL

Below, the two dune erosion models utilized in this paper - Duros+ and XBeach - are described. Both are capable of performing 1D cross-shore dune erosion calculations, using hydraulic forcing conditions as input and providing the post-storm cross-shore profile as output.

Duros+

Duros+ (van Gent et al., 2008) is a relatively simple equilibrium profile model for dune erosion. The model uses an empirical formula to describe the post-storm cross-shore profile shape. This formula uses significant wave height, wave period (both prescribed at a depth of -20 m N.A.P., Dutch ordnance datum), storm surge level and grain size as input parameters. Additionally, Duros+ is based on the assumption that volume is conserved in the cross-shore profile. This means that the post-storm profile is iteratively fitted through the pre-storm profile, to make the erosion volume match the sedimentation volume.

This prescribed profile shape is invalid when applied to pre-storm cross-shore profiles that significantly deviate from a very simple profile. For instance, in the case of multiple dune rows, extreme conditions can lead to a breach of the most seaward dune row. This often means it becomes impossible for Duros+ to fit the prescribed post-storm profile while still conserving the sediment volume. Similar problems with fitting the post-storm profile exist for profiles with very gently slopes, so that the pre-storm profile slope is less steep than the post-storm profile slope prescribed by Duros+. Also, Duros+ does not allow for non-erodible layers, which rules out any location where structures or revetments are present.

The fact that the post-storm profile is prescribed by an empirical formula means that there are implicit assumptions in place concerning wave transformation from -20 m N.A.P. towards the coastline. Because of these implicit assumptions, profiles with features that significantly affect wave transformation pose a problem for Duros+, as wave attack and subsequently dune erosion will either be under- or overestimated. Examples of these features are large bar systems or gullies that affect wave transformation.

As den Heijer et al. (2012) illustrate, the above-mentioned limitations mean that the Duros+ model is not applicable for a significant portion of the Dutch coast, because of the presence of hard structures and features affecting wave transformation, among others. Hence, there is a need for a dune erosion model that can be applied to those situations where Duros+ is not applicable.

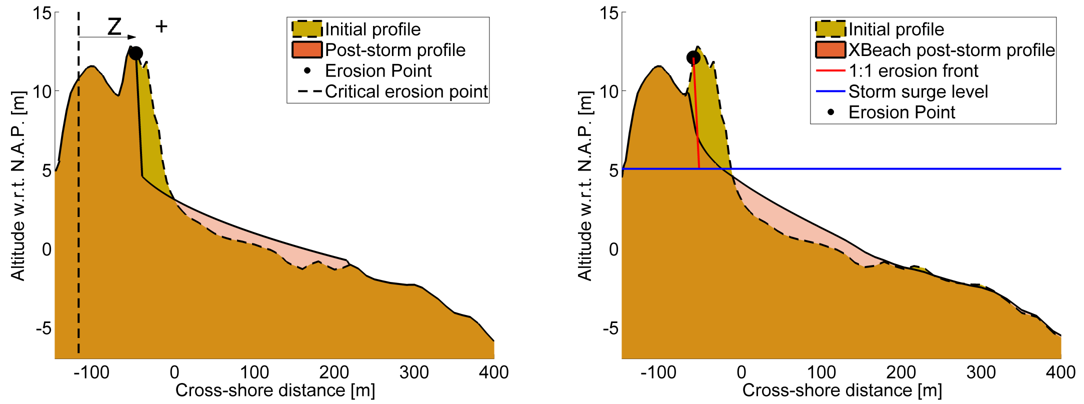
XBeach

XBeach (Roelvink et al., 2009) is a process-based storm impact model, that can be used in either 1D (cross-shore, depth-averaged) or 2DH (depth-averaged). The model equations resolve flow, wave action, sediment transport and bed level change and account for infra-gravity waves. These processes are resolved both in space and in time (contrary to the empirical Duros+, where the storm duration is implicitly assumed). By resolving many of the physical processes dominating dune erosion, this model is suitable for a wide range of near-shore situations. The prediction of dune erosion using XBeach has been extensively validated, using both experimental and field measurements for comparison (Deltares, 2014).

The fact that XBeach needs to resolve a large number of processes (and thus equations) in both space and time results in a computational demand that is much larger than that of Duros+ (which effectively only solves the post-storm profile equation and fits it through the initial profile assuming conservation of volume). This increase in computational demand is a problem when using XBeach in concert with probabilistic methods that require a lot of evaluations, since it leads to unfeasibly large computational times. Hence, an efficient probabilistic method (in terms of number of evaluations) is needed to perform probabilistic calculations using XBeach.

LIMIT STATE FUNCTION

A limit state function (LSF) mathematically defines the point at which one considers failure to have occurred. For the purpose of this paper, a fairly simple LSF is used, see Figure 1a. A critical dune erosion point is prescribed and the dune is considered to have failed when the actual dune retreat crosses the critical erosion point. Therefore, the LSF is defined as the horizontal distance (positive in seaward direction) between the critical erosion point and the erosion point resulting from the dune erosion model, see Eq. (1). Failure will occur for $Z \leq 0$, whereas for $Z > 0$ the dune is considered to still provide sufficient protection against flooding. The limit state is defined as the border between failure and non-failure, so it is comprised of all points for which $Z = 0$.



(a) Schematic depiction of the limit state function defined in Eq. (1).

(b) Derivation of $X_{ErosionPoint}$ for an XBeach post-storm profile.

Figure 1: Limit state function definition.

$$Z = X_{ErosionPoint} - X_{Critical} \tag{1}$$

Because of the prescribed shape of the Duros+ post-storm profile, the erosion point (the black dot in Figure 1a) is easy to determine. However, the post-storm profile resulting from the XBeach model can vary strongly - depending on both the initial profile and the hydraulic forcing conditions - making it harder to unambiguously determine the erosion point. Therefore, a dune face with a 1 : 1 slope (identical to the Duros+ post-storm profile) is used to determine the erosion point. This dune face is fitted to the initial profile so that it results in exactly the same amount of eroded volume above storm surge level as is measured in the XBeach post-storm profile.

MODEL INPUT

Below, the required input for both dune erosion models - Duros+ and XBeach - is reviewed. Though there are large similarities between both, there are subtle differences flowing from different model philosophies and assumptions.

Random variables

The variables governing dune erosion are water level, wave height and wave period. The distributions of these variables along the Dutch coast are described by WL|Delft Hydraulics (2007). The same probability distributions have been used in this paper, which are summarized in Table 1.

Table 1: Overview of the random variables and their probability distributions.

Random variable	Distribution type	Parameters
h, water level	Conditional Weibull	Location dependent
H_s, significant wave height	Normal	$\mu = E[H_s \mid h]$, $\sigma = 0.6$ m
T_p, peak wave period	Normal	$\mu = E[T_p \mid H_s]$, $\sigma = 1$ s

These random variables are used in Duros+ as well as in XBeach. In Duros+ these parameters are directly used in the formula describing the post-storm profile. In XBeach however, these serve as boundary and initial conditions. The H_s and T_p are used to construct a JONSWAP spectrum (Hasselmann et al., 1973) for wave generation on the offshore model boundary.

Cross-shore profile

Both dune erosion models need an initial cross-shore profile to be able to determine the storm induced dune erosion. In the case of Duros+, this initial profile does not actually influence the shape of the post-storm cross-shore profile. There is an influence on erosion volume however, since the position of post-storm profile is fitted to the initial profile, ensuring a balance between erosion and sedimentation volumes.

In the case of XBeach, the initial profile affects both the shape post-storm profile and the erosion volume, since hydro- and morphodynamics are resolved in space and time. Especially the influence of the submerged foreshore is larger in XBeach, because short wave transformation is influenced, in turn affecting the wave attack on the dune face.

PROBABILISTIC METHOD

Many of the commonly used probabilistic methods - chief among them are Crude Monte Carlo Sampling and Numerical Integration - rely heavily on a large number of LSF evaluations to reach an accurate solutions. This is problematic when dealing with limit state functions that are computationally expensive. One of the traditional solutions is to linearize the limit state in the most probable point (the point closest to the origin in standard normal space, also known as the design point) and approximate the P_f. This is known as a First Order Reliability Method (FORM) and second order alternatives are also used (SORM). While these methods do need significantly less LSF evaluations, there are limits to the shape of the limit state and the methods rely on consistent derivatives to be able to locate the design point. Hence, this approach is troubled by limit states with multiple (near) design points.

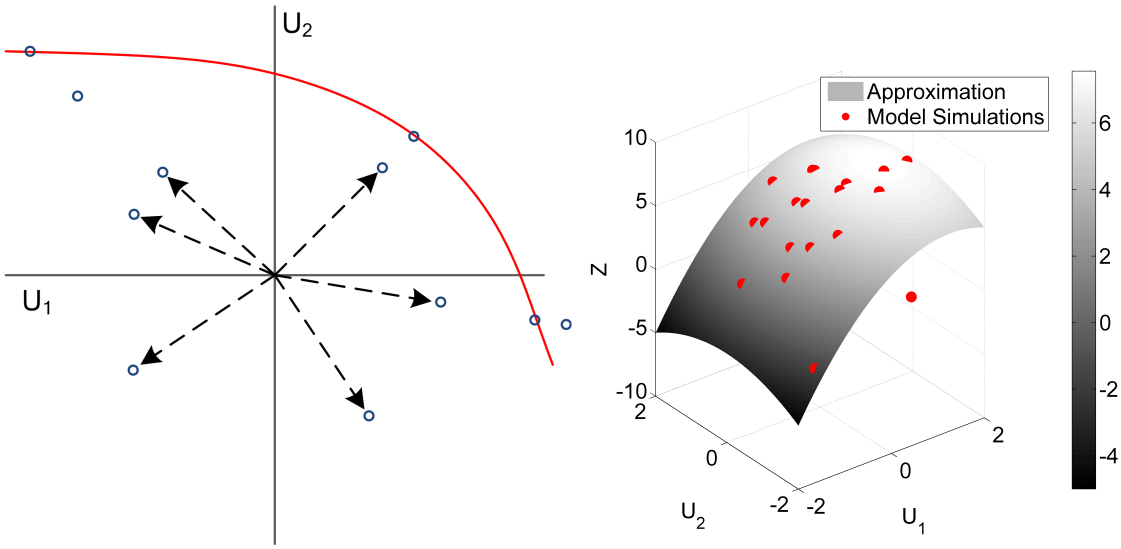
One of the consequences of resolving more physical processes in the dune erosion model is a greater computational demand per simulation, which is especially problematic in a probabilistic context, usually concerning a large number of calculations. To mitigate the increase in computation time, a more efficient probabilistic method is required in concert with the process-based dune erosion model. The proposed method, Adaptive Directional Importance Sampling (Grooteman, 2011), is an efficient probabilistic method, applicable to a wide range of problems.

ADIS

Adaptive Directional Importance Sampling (ADIS, Grooteman (2011)) is an efficient probabilistic method that combines three pre-existing principles; Directional Sampling (Bjerager, 1988; Ditlevsen et al., 1990), the use of a Response Surface and Importance Sampling. ADIS makes use of the same scheme as Directional Sampling (see Figure 2a), where directions are randomly sampled from standard normal space (which is comprised of all random variables used in the LSF, transformed to standard normal distributions). Given a random direction, a line-search algorithm is initiated, which looks for the the limit state ($Z = 0$) in that direction. When either the limit state is found or the algorithm concludes that it cannot find the limit state (not all directions necessarily intersect the limit state), a new iteration is started by selecting a new random direction.

An Adaptive Response Surface (ARS) is an approximation of the actual LSF using a (easy to evaluate) function or polynomial, an example of which is depicted in Figure 2b. This is particularly useful when the LSF is computationally demanding (for instance because it needs to perform a demanding computation using XBeach), since the approximation has an analytical solution. ADIS uses a second order polynomial as Response Surface, which is able to mimic the actual LSF close enough in all but the most strongly non-linear of limit states. A minimum number of LSF evaluations need to be available in order to fit the polynomial. For a second order polynomial the minimum number of points is $1 + n + \frac{n(n+1)}{2}$, where n is the number of random stochastic variables in the LSF. To be able to make use of the ARS as soon as possible, ADIS first tries an initial fit using a second order polynomial without any cross-terms, which only needs $2n + 1$ points. Later, when enough points are available to perform a full second order fit, the cross-terms are included.

If the ARS fits the available LSF evaluations well enough (i.e. the root-mean-squared error is small enough), the ARS is accepted and used in the Directional Sampling scheme instead of actual LSF evaluations, resulting in a drastic reduction in the computational demand. Otherwise, the ARS is rejected, a new iteration is started in the Directional Sampling scheme using actual LSF evaluations and after the iteration



(a) Schematic depiction of the ADIS method in standard normal space with 2 stochastic variables (U_1 and U_2), showing random directions (arrows), limit state (red line) and model or response surface evaluations (blue circles).

(b) Example of an ARS with LSF evaluations (red stars) and Response Surface (gray plane).

Figure 2: Examples of the Directional Sampling procedure and the ARS from the ADIS method.

another ARS fit is attempted. As soon as new actual LSF evaluations become available, the ARS is refitted, which constitutes the adaptive nature of the ARS. The number of LSF evaluations available for new ARS fits is ever greater, leading to an increasingly accurate approximation of the LSF by the ARS.

The concept of Importance Sampling is based on reducing the probability space that has to be searched by a probabilistic method, in order to increase its efficiency. To this end, usually (some of) the random variables are assigned an adjusted probability distribution in order to give more weight to the important areas; i.e. those areas in probability space that contain the limit state ($Z = 0$). Hence, a-priori knowledge of the approximate location of the limit state is necessary. If this knowledge is lacking, an adaptive sampling method is required.

Importance Sampling is applied slightly differently within ADIS, and only when ADIS has obtained an ARS with a good fit. Hereafter, the ARS is evaluated instead of the LSF, but a limited number of actual LSF evaluations is still performed to maintain the precision of the resulting failure probability. This is done for the most important contributors to the failure probability; i.e. the points that are near the limit state (so $Z = 0$) and lie relatively close to the origin (since in standard normal space, probability density increases with decreasing distance to the origin). So the concept of limiting the area to be investigated (with costly evaluations) is similar, only now the location of the important area is dynamic and follows from the method itself, so no a-priori knowledge is necessary.

CASE STUDY MODEL SETUP

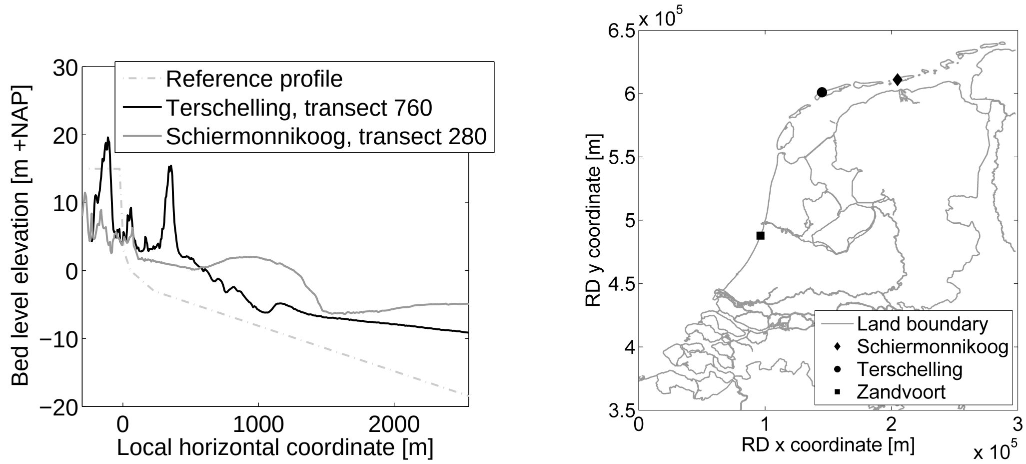
As a proof of concept, ADIS was applied in the three different test cases listed below:

1. **Reference profile** A simplified typical Dutch dune profile where Duros+ also performs well.

2. **Terschelling** A gentle barrier island profile with multiple subsequent dune crests.

3. **Schiermonnikoog** A barrier island profile with a pronounced bank affecting wave transformation.

The cross-shore profiles corresponding to these cases are depicted in Figure 3a. The reference profile will be used to demonstrate accuracy and the efficiency of the ADIS method. To this end, a comparison is made with Monte Carlo with Importance Sampling (MCIS). The strongly simplified reference profile is commonly used as a representative profile for the central part of the Dutch coast and its shape (see Figure 4) is well within the applicability range of Duros+. For this case Duros+ is used as the dune erosion model, since using XBeach with MCIS leads to very large computational times. The Terschelling and Schiermonnikoog cases will feature the proposed combination of ADIS and XBeach because they have cross-shore profiles that typically cause problems when using Duros+, since they contain characteristics like a gentle foreshore, a pronounced bank and multiple subsequent dune crests.



(a) Cross-shore profiles of the test cases.

(b) Locations of the test cases (in the local Dutch coordinate system, RD).

Figure 3: Profiles and locations of the test cases used as a proof of concept.

The model setup for the dune erosion models is similar for all test cases. The information regarding the cross-shore profiles comes from the JARKUS database (Rijkswaterstaat, 2014), which contains the yearly cross-shore profile measurements along the Dutch coast (except for the fictional reference profile). For the XBeach model, the profiles are interpolated to a discretized model grid, with a minimum cell size of 5 m (cell size increases with water depth). For both Duros+ and XBeach the boundary conditions forcing the model are provided by the hydraulic load model, using the aforementioned probability distributions, the parameters of which are location dependent (WL|Delft Hydraulics, 2007). Since the reference profile is a fictional profile, it does not have a specific location and thus no set boundary conditions. Therefore, the boundary conditions used for the reference profile in this paper are representative for a profile near Zandvoort (transect number 8006600), a city located close to the middle of the Dutch coast (see Figure 3b).

In the ADIS line-search algorithm, the tolerance for finding $Z = 0$ is set to 1 m (meaning the algorithm stops searching when the erosion point is within 1 m of the critical erosion point). Monte Carlo with Importance Sampling is used with 10^4 samples. The Importance Sampling is only applied to the water level (h), since it is the dominant variable in dune erosion (Roscoe and Diermanse, 2011). Sampling of the water level is only allowed in the range between 0 and $+6\sigma$. None of the other variables are modified.

Table 2: Overview of the case study results (* indicates a result that did not converge).

Case	Method	Dune erosion model	N_{eval}	P_f	β
Reference profile	ADIS	Duros+	36	$2.1 \cdot 10^{-2}$	2.03
	MCIS	Duros+	10^5	$1.5 \cdot 10^{-2}$	2.17
Terschelling	ADIS	XBeach	39	$5.0 \cdot 10^{-6}$	4.42
	ADIS	Duros+	31	$6.6 \cdot 10^{-7*}$	4.84
Schiermonnikoog	ADIS	XBeach	67	$2.1 \cdot 10^{-7}$	5.06
	ADIS	Duros+	70	$4.3 \cdot 10^{-9*}$	5.76

CASE STUDY RESULTS

In Table 2 the results of the case studies are presented in terms of number of evaluations (N_{eval}) and probability of failure (both in P_f and β, where $\beta = \Phi^{-1}(1 - P_f)$).

Reference profile

To demonstrate the accuracy and efficiency of the ADIS method, the Duros+ dune erosion model is used in combination with both ADIS and Monte Carlo with Importance Sampling.

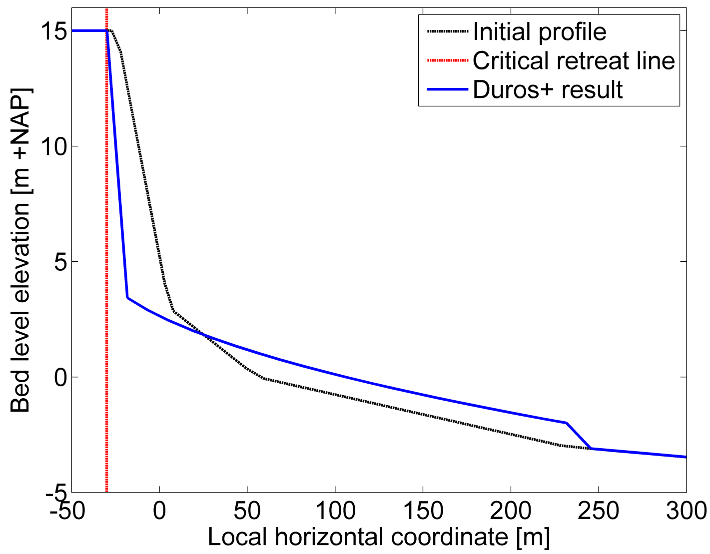


Figure 4: Design point post-storm profile (Duros+).

The relative efficiency of ADIS is apparent from the significant difference in the number of evaluations in Table 2. There is a difference in the resulting failure probability between the two probabilistic methods, but it is considered acceptably small considering the large gain in efficiency. Accuracy could be improved by using more simulations; i.e. employing a more stringent convergence criterion.

Terschelling

The cross-shore profile for the chosen transect at Terschelling exhibits two features that cause problems for Duros+; a very gentle slope of the beach and foreshore and multiple subsequent dune rows. Both Duros+ and XBeach are used in combination with ADIS.

As can be seen in Table 2, ADIS and XBeach only need a small number of evaluations to obtain a result. However, the calculation using Duros+ did not converge (the convergence criteria were not met, indicated by *), which is caused by the gentle slopes of the both the pre- and post-storm profile in Figure 5. These gentle slopes pose a problem for Duros+, since there is often no way to fit the post-storm profile while balancing erosion and sedimentation volumes. In a process-based model like XBeach, this is no problem because the shape post-storm is not prescribed.

Schiermonnikoog

The post-storm profile in Figure 6 shows that several of the smaller, more seaward dune rows have been breached, resulting in a slightly atypical profile. This atypical profile again causes problems for the prescribed post-storm profile in Duros+, not being able to converge (see Table 2). Furthermore, the very pronounced sand bank in front of the dunes induces wave breaking, significantly reducing the severity of the actual wave impact on the dune face. This reduction of the wave attack is not accounted for in the post-storm profile shape in Duros+, leading to an overestimation of erosion.

In this case, ADIS needs slightly more LSF evaluations to get to a result, it is however still very efficient compared to most other probabilistic methods.

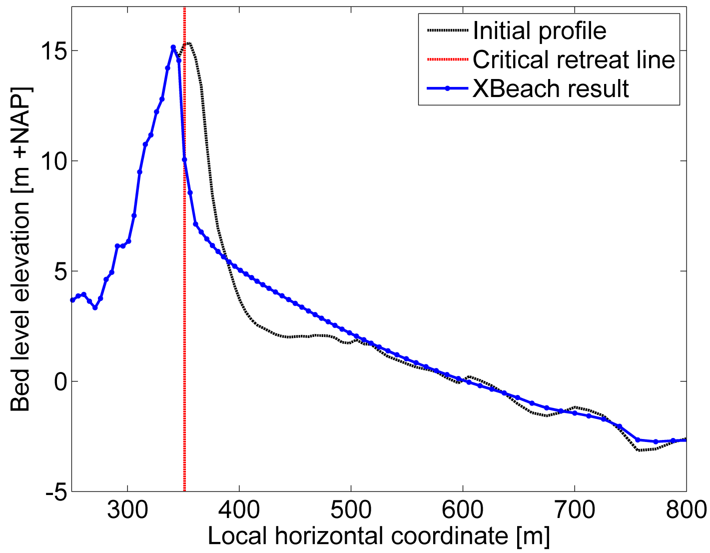


Figure 5: Approximate design point post-storm profile (XBeach).

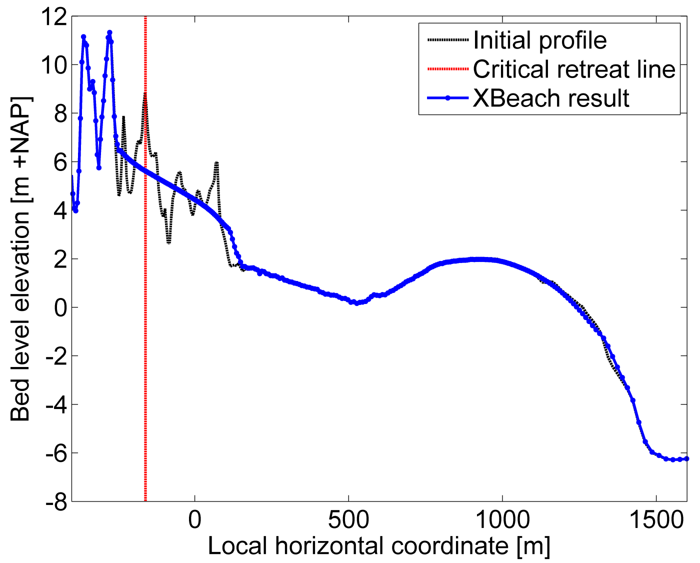


Figure 6: Approximate design point post-storm profile (XBeach).

DISCUSSION

The test cases above show the proficiency of the combination of Adaptive Directional Importance Sampling and XBeach in handling 1D cross-shore situations. The choice for the XBeach Limit State Function (depicted in Figure 1b) is primarily motivated by its consistency with the Duros+ LSF and the subsequent ease of comparison between the two. However, this argument does not apply when XBeach would be used exclusively as the default dune erosion model for dune safety assessment. In this case, it makes sense to develop a new LSF, more suitable to the stronger variation in the post-storm profiles predicted by XBeach.

Though only 1D case studies are presented in this paper, a very similar setup can also be used in concert with a 2DH XBeach model. Even if a 2DH model generally results in a larger computational demand (compared to a 1D XBeach model), ADIS is sufficiently efficient that a 2DH dune safety assessment is now within the realm of feasibility. Naturally, this would require redefining the LSF to describe dune failure in 2D, next to the addition of more random variables, such as the angle of wave incidence.

The possible applications of ADIS go much further than just dune erosion or even coastal engineering. In general, ADIS is very suitable for a Limit State Function that is dependent on a computationally expensive model, due to the methods efficiency. Despite the use of a limited number of stochastic variables in this paper, the method scales fairly well with an increasing number stochastic variables (and thus dimensions) because of the use of an Adaptive Response Surface. A higher dimensionality mostly impacts the number of evaluations needed to successfully fit an initial ARS. Once that is the case, evaluating the ARS is relatively very efficient, so the added dimensionality hardly increases computational demand. Additionally, the use of a Directional Sampling scheme makes that small failure probabilities, as often encountered in safety assessments, do not pose any problems.

The ADIS implementation used in this paper is freely available for download through the OpenEarth toolbox (OpenEarth, 2014), an open source initiative that houses a large collection of tools, models and raw data related to coastal engineering and earth sciences (van Koningsveld et al., 2010).

CONCLUSION

The 1D case studies show that the ADIS method enables the use of time consuming computational models like XBeach in probabilistic calculations. The number of required model calculations is sufficiently small that the total computational demand is feasible. The selected case studies also showcase the ability of XBeach to handle situations that typically lead to difficulties with Duros+; e.g. multiple dune rows, gentle slopes and banks affecting wave transformation. These examples act as a proof of concept of the potential of ADIS and the use of Adaptive Response Surfaces in general.

ACKNOWLEDGMENTS

This research was carried out as part of the WTI 2017 project, commissioned by the WVL department of Rijkswaterstaat, the Netherlands.

References

Bjerager, P. (1988). On computation methods for structural reliability analysis. In Frangopol, D., editor, *New directions, in structural system reliability*, pages 52–67. University of Colorado Press, Boulder, Colorado.

Deltares (2014). XBeach skillbed report. Technical report, Deltares.

den Heijer, C., Baart, F., and van Koningsveld, M. (2012). Assessment of dune failure along the Dutch coast using a fully probabilistic approach. *Geomorphology*, 143 - 144:95 – 103.

Ditlevsen, O., Melchers, R., and Gluver, H. (1990). General multi-dimensional probability integration by directional simulation. *Computers & Structures*, 36(2):355 – 368.

ENW (2007). Technical report on dune erosion (in Dutch). Technical report, expertisenetwerk waterveiligheid.

Grooteman, F. (2011). An adaptive directional importance sampling method for structural reliability. *Probabilistic Engineering Mechanics*, 26(2):134 – 141.

Hasselmann, K., Barnett, T., Bouws, E., Carlson, H., Cartwright, D., Enke, K., Ewing, J., Gienapp, H., Hasselmann, D., Kruseman, P., Meerburg, A., Müller, P., Olbers, D., Richter, K., Sell, W., and Walden, H. (1973). Measurements of wind-wave growth and swell decay during the joint north sea wave project (jonswap). *Deutschen Hydrographischen Zeitschrift*, 12:7 – 95.

OpenEarth (2014). Open source initiative: www.openearth.eu.

Rijkswaterstaat (2014). Jarkus cross-shore profile measurements database.

Roelvink, J. A., Reniers, A. J. H. M., van Dongeren, A. R., van Thiel de Vries, J. S. M., McCall, R. T., and Lescinski, J. (2009). Modelling storm impacts on beaches, dunes and barrier islands. *Coastal Engineering*, 56(11-12):1133–1152.

Roscoe, K. and Diermanse, F. (2011). Effect of surge uncertainty on probabilistically computed dune erosion. *Coastal Engineering*, 58(11):1023 – 1033.

van Gent, M., van Thiel de Vries, J., Coeveld, E., de Vroeg, J., and van de Graaff, J. (2008). Large-scale dune erosion tests to study the influence of wave periods. *Coastal Engineering*, 55(12):1041 – 1051.

van Koningsveld, M., de Boer, G., Baart, F., Damsma, T., den Heijer, C., van Geer, P., and de Sonneville, B. (2010). OpenEarth - inter-company management of: data, models, tools & knowledge. In *Proceedings WODCON XIX Conference. Beijing, China.*

WL|Delft Hydraulics (2007). Dune erosion product 3: Probabilistic dune erosion prediction method. Technical report, WL|Delft Hydraulics, Delft University of Technology and Arcadis.