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Analysis of Dune Erosion on the Coast of South Baltic Sea Taking into Account Dune Landslide Processes

Piotr Szmytkiewicz, Lesław Zabuski

Institute of Hydro-Engineering, Polish Academy of Sciences, Kościerska 7, 80-328 Gdańsk, Poland,
e-mails: p.szmytkiewicz@ibwpan.gda.pl, lechu@ibwpan.gda.pl

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Abstract

An analysis was carried out to determine the influence of landslide process at a few meters depth under the dune surface on the rebuilding of the dune. In the first step, calculations were done using the XBEACH model to determine seabed rebuilding as well as shore and dune undercutting for the assumed hydrologic and hydrodynamic conditions. Next, the obtained tachymetric profile of the dune and beach was fed into the FLAC2D program, and calculations of stress distribution, displacements and stability conditions were made. In this way, landslide movement was identified. The theoretical investigations clearly prove that waves attacking the dune not only cause surface erosion, but also trigger a landslide within the dune mass to a maximum depth of about 5 m. It results in a lowering of the dune crown by about 0.6 ÷ 0.7 m. Numerical models such as XBEACH, SBEACH or CSHORE do not take into account landslide occurrence, and thus underestimate dune erosion.

Key words: South Baltic coastal zone, dunes, erosion, landslide process

1. Introduction

The aim of the paper is to prove that the erosion of the dune exposed to attacking waves can be additionally induced by landslide process occurring a few meters under the dune surface, regardless of superficial soil avalanching along the scarp of the dune. This phenomenon additionally lowers the surface of the dune, which has not been formerly considered in the analysis of dune erosion.

The paper presents a calculation procedure aimed at determining the effect of landslide deformations occurring in the dune mass on its rebuilding. The computer code FLAC2D was used for these calculations (FLAC2D Manual 2000). The analysis has a numerical character, and measurements of deep dune deformations are still necessary to verify its results.

The problem analyzed in the paper has important significance for the determination of dune erosion on the South Baltic shores, as dunes cover approximately 75% of the Polish sea shores. According to estimates, the average annual retreat of the dunes at the end of the 20^{th} and the beginning of the 21^{st} century was about $1 \div 2$ m, and as much as 8 m in extreme cases (Pruszak 1998, Zawadzka-Kahlau 1999, Frankowski et al 2009).

A well-developed, stable nearshore bar system, wide beaches, highly positioned dune toes and their proper shape constitute the natural protection of shore zones against erosion and sea floods. Under the Polish sea shore protection programme (published in *Dziennik Ustaw* [*Journal of Laws*], 2003, No. 67, item 621), the local erosion of the coast is reduced and offshore zones are protected against sea floods by the so-called artificial replenishment. It consists in increasing the beach height and extending the dunes. In order to adjust the shore profile to environmental conditions, taking into account the assumed return period, it is necessary to predict beach and dune reconstruction. This involves dune erosion calculations.

The stability and erosion of dunes depends on

– seawater level,
– duration of extreme events, including direct exposure of the dune toe to waves,
– height of wave run-up onto the beach/dune,
– occurrence of infragravity (long) waves affecting the dune toe,
– groundwater level,
– precipitation height and intensity,
– wind conditions (aeolian transport),
– geomechanical properties of beach and dune sediments,
– geological structure and geomorphological parameters of the nearshore region (including the slope of the shore, beach width and dune height),
– parameters of landslide deformations within the dune mass,
– type and rate of vegetation and land use patterns.

The latest methodology for the determination of dune erosion is featured by the XBeach (eXtreme Beach behavior) model. It was tested in the Delft Flume (Roelvink et al 2009, van Thiel de Vries 2009), as well as under natural conditions (Roelvink et al 2010, McCall et al 2010). It is widely used nowadays for computing the foreshore and backshore evolution of coastal segments with dunes (Vousdoukas et al 2011, Harley et al 2011, Bolle et al 2011, Splinter, Palmsten 2012, Bugajny et al 2013, 2015).

The Xbeach model consists of the following computational modules:

– wave module, where an energy flux conservation equation is applied to determine nearshore wave breaking and transformation (incl. empirical wave run-up formulation),
– current module, where mass and momentum conservation equations are employed to determine nearshore flow fields (flow velocity and direction),
– sediment transport module, where an advection-diffusion equation is used to determine sediment concentration and transport,
– morphological evolution module, where morphological changes in the nearshore region are determined.

The routine dune evolution algorithm includes verification, in each computational time step, whether the current dune configuration does not exceed the maximum permissible angle of dune face inclination. If this condition is no longer met, avalanching is introduced until the new dune slope is milder than the prescribed maximum angle of repose.

None of the currently available models considers landslide movements of the entire dune massif.

2. Study Site – the Topography of the Coastal Zone

The dune under analysis is located on the South Baltic coast in the Lubiatowo region (Choczewo Community, Pomeranian Voivodeship), (Fig. 1). The seashore in this region is characterized by a gently inclined seabed ($\beta \approx 0.015$). It is composed of fine-grained quartz sand with an average grain diameter of $d_{50} \approx 0.22$ mm. The thickness of sand sediments in the backshore zone is $3 \div 5$ m. In the seashore profiles, $3 \div 4$ nearshore bars occur. The first of them, R_{I}, is located at a distance of about $100 \div 120$ m from the shoreline, the second (R_{II}) at about 200 m, the third (R_{III}) at about $300 \div 350$ m, whereas the fourth (R_{IV}) and a possible fifth at about $550 \div 850$ m (Fig. 2).

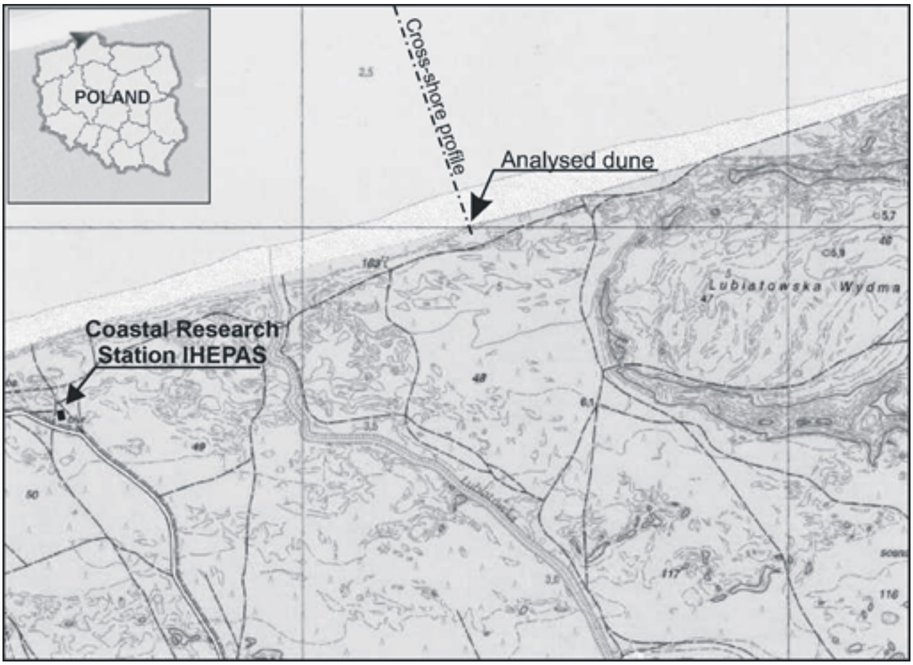

Fig. 1. Location of the dune and cross-shore profile (map from http://www.geoportal.gov.pl/, modified)

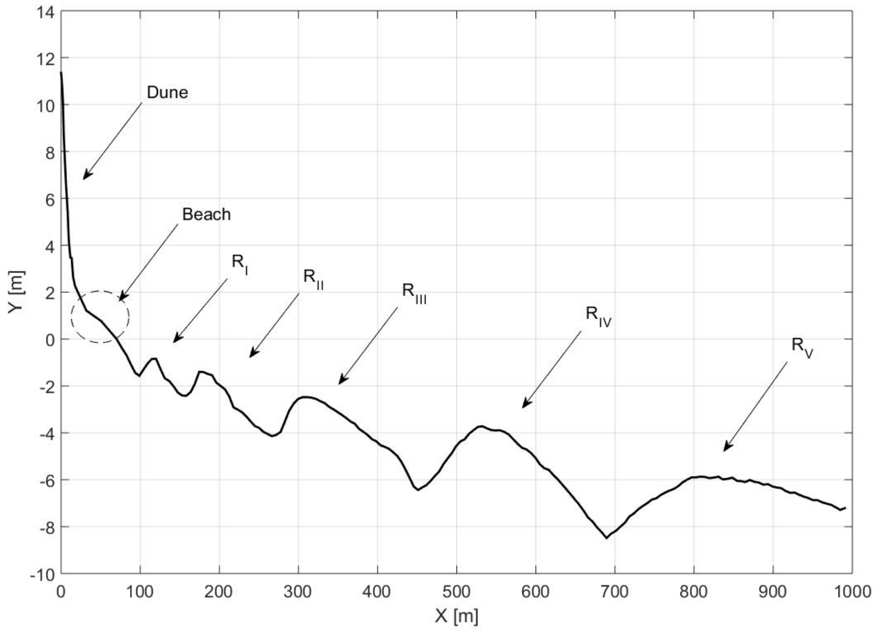

Fig. 2. Cross-shore profile

Fig. 3. View of the dune

In addition, the so-called ephemeral bar R_0 occurs in the form of a flat underwater shallow. It migrates towards or away from the coastline, depending on transient hydrologic and hydrodynamic conditions. A significant proportion of the coast section under analysis is built of irregular dune nipples with height differences of $10 \div 15$ m. The dune toe ordinate in the profile analyzed is about 2 m (Fig. 2), and the beach is about 50 m wide. The dunes in this region are protected by twig fences and reinforcing plants (Fig. 3) (Pruszak et al 2008, Ostrowski et al 2016, Szmytkiewicz, Różyński 2016).

3. Nearshore Zone Hydrodynamics

Wave climate measurements at the site have been performed since 1997 by IBW PAN using a directional wave buoy located at a depth of $16 \div 20$ m. Table 1 shows that waves from the western sector (SW-W and NW) occur over 50% of the year, those from the eastern sector (NE, E, SE) over ca. 32%, and those from the shore-normal sector over ca. 13.5%. The most frequent waves are those from the $0.5 \div 1.5$ m height class, occurring over ca. 47% of the year. Table 2 presents the rates of occurrence [in %] of significant wave heights for particular height classes and azimuths of wave direction.

Table 1. Significant wave height occurrence [in %] for different wave height classes and wave directions

Significant wave height classes [m]	N	NE	E	SE	S	SW	W	NW	Total
0.0÷0.5	3.06	6.84	5.72	0.32	1.31	0.38	8.35	3.19	29.18
0.5÷1.5	5.90	12.60	2.75	0.11	0.18	0.04	21.74	4.00	47.32
1.5÷2.5	3.06	3.22	0.02	0.00	0.00	0.00	10.94	2.23	19.47
2.5÷3.5	0.99	0.20	0.00	0.00	0.00	0.00	1.73	0.50	3.42
>3.5	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.61
Total	13.5	22.9	8.50	0.43	1.49	0.41	42.76	10.03	100.0

Table 2. Deepwater wave climate parameters for particular return periods for the CRS Lubiatowo (Boniecka et al 2013)

Recurrence period [years]	Significant wave height H_s [m]	Peak period T_p [s]
20	5.85	9.0
50	6.45	9.5
100	6.88	9.8
200	7.32	10.1

Wave heights and periods for the assumed recurrence periods were selected according to the procedure suggested by Boniecka et al (2013). This procedure assumes that the representative wave parameters are related to a design storm lasting 3 hours, in which the significant wave height H_s and wave spectrum peak period T_p can be regarded as constant according to Det Norske Veritas (2013) and Kamphuis (2010) recommendations.

Boniecka et al (2013) employed the parameters computed by the WAM4 model. The results of those computations made it possible to reconstruct the Baltic wave climate for 44 years between 1958 and 2001. That reconstruction is described in Cieślikiewicz and Paplińska-Swerpel (2008). The input wind field data for the computations of the wave climate originated from the regional atmospheric model REMO. The grid resolution was set at $5' \times 5'$ (ca. 9 km). Interpolated wind field inputs were introduced into the wave model at an hourly time step, and then within that model they were interpolated every 300 s. As a result, hourly estimates of wave parameters (significant wave height, wave period and angle of incidence) were obtained. The wave parameters were calculated for a point located at about 20 m depth near Lubiatowo. Table 2 contains the deepwater wave climate parameters identified for particular return (recurrence) periods.

4. Sea Level (Storm Surges)

The representative water levels corresponding to a given probability of occurrence for the CRS Lubiatowo are adopted from the nearby mareographic station at the Ustka port (Boniecka et al 2013). The long-term mean water level amounts to about 500 cm. The absolute maximum seawater level at Ustka between the mid 19^{th} century and 2007 was 668 cm. Seawater levels, based on the analyses done by Wiśniewski and Wolski (2011) and by Wolski et al (2014) and of the greenhouse effect by Stramska and Chudziak (2013) are provided in Tab. 3.

Table 3. Seawater levels at Ustka with a given probability of occurrence, including the greenhouse effect (Wiśniewski and Wolski 2011, Stramska and Chudziak 2013) (the seawater levels below were referenced to the Amsterdam gauge)

Recurrence period [years]	Seawater level [cm]
20	648
50	676
100	707
200	721

5. Method of Analysis

A three-step analysis was carried out to determine the influence of the landslide process at a depth of a few meters under the dune surface on the rebuilding of the dune. In the first step, calculations were done using the XBEACH model to determine seabed rebuilding as well as shore and dune undercutting for the assumed hydrologic and hydrodynamic conditions. In the second step, the profile obtained was fed into the FLAC2D program (Zabuski et al 2015, Kulczykowski et al 2015, Marcato et al 2012, FLAC2D Manual 2000), and stress distribution, displacements and stability conditions were calculated, which made it possible to identify landslide movements. In the last step, the rebuilt dune profile in which only superficial erosion and soil avalanching had been considered (previously calculated by the XBEACH model), was compared with the profile affected by a deeper landslide.

5.1. Hydrologic and Hydrodynamic Computation Scenario

Calculations were performed for six independent hydrologic and hydrodynamic scenarios. The first was a typical storm occurring each year. The second were storm conditions during the "Ksawery" hurricane, which took place on the South Baltic shore on December 5–7, 2013. The other scenarios were the mutual combinations of storms with different assumed return periods, determined by Boniecka et al (2013). Storm conditions generated waves with various parameters, and depending on these parameters, different dune undercutting occurred. Six trials were performed, presented in Table 4.

Table 4. Parameters of hydrologic and hydrodynamic scenarios used in the calculations of dune undercutting

Trial No.	Type of events	Water level [m]	Significant wave height H_s [m]	Wave peak period [s]
1	Typical South Baltic storm conditions	5.50	2.50	5.9
2	"Ksawery" hurricane, which occurred at South Baltic sea on Dec. 5–7, 2013	5.85	4.98	10.5
3	Recurrence period of wave height = 50 years Recurrence period of water level = 100 years	7.07	6.45	9.5
4	Recurrence period of wave height = 100 years Recurrence period of water level = 50 years	6.76	6.88	9.8
5	Recurrence period of wave height = 50 years Recurrence period of water level = 50 years	6.76	6.45	9.5
6	Recurrence period of wave height = 100 years Recurrence period of water level = 100 years	7.07	6.88	9.8

As a result of these calculations, new profiles were obtained (Fig. 4). Only three curves representing the undercutting, those for trials 2, 3 and 6, are presented in Figure 4. Trials 1, 4 and 5 did not cause any changes in the dune shape (no undercutting).

6. Method of Landslide Simulation – FLAC2D Model

FLAC2D (Fast Lagrangian Analysis of Continua) is a two-dimensional continuum code for modelling the behaviour of soil (and rock). The explicit finite difference formulation of the code makes it ideally suited for modelling multi-stage geomechanical problems, such as sequential excavation and loading. The Lagrange formulation can

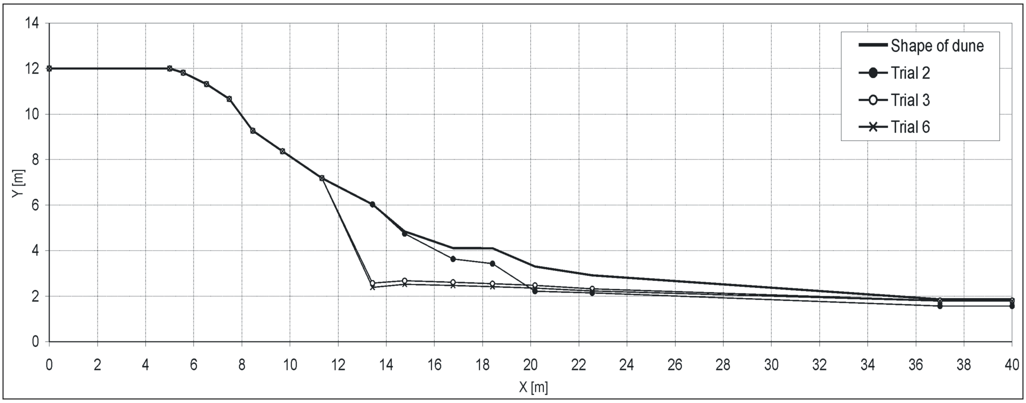

Fig. 4. Changes in the dune profile due to the undercutting of the dune toe by waves

accommodate large displacements and strains and non-linear material behaviour, even if yield or failure occurs over a large area, or if total collapse occurs.

Two geomechanical and numerical models of the dune for FLAC2D analysis were elaborated for trials 2 and 6 on the basis of the geometry and geomechanical properties of the soil (sand) mass forming the dune and the shape of the undercutting. Trial 3 was not considered, as the shape of the undercutting for this trial is very similar to that for trial 6 (see Fig. 4).

In each case, the model was divided into finite difference zones (Figs 5a and b), and stress, displacement, state (elastic, elasto-plastic), failure mode (shear, tension), etc. were calculated in each zone or in nodal points

The following parameters of the sand were assumed:

Density	$\rho = 1.9$ t/m^3
Angle of friction	$\phi = 30°$
Cohesion	$c = 1.25$ kPa
Shear modulus	$G = 34.2$ MPa
Bulk modulus	$K = 74.2$ MPa
Tension strength	$s_r = 0.0$

Sand cohesion $c > 0$ results from the fact that the dune surface, especially its upper part, is overgrown with trees, shrubs and grass (see Fig. 3), whose roots generate some cohesion.

The calculations were performed in two steps:

1. Stress distribution and displacements were calculated in the model with parameters assumed for the dune without undercutting.
2. Stress distribution and displacements were calculated in the model with parameters assumed for the undercut dune (height of the undercut zone of about 450 cm – see Figs 4 and 5, trial 6).

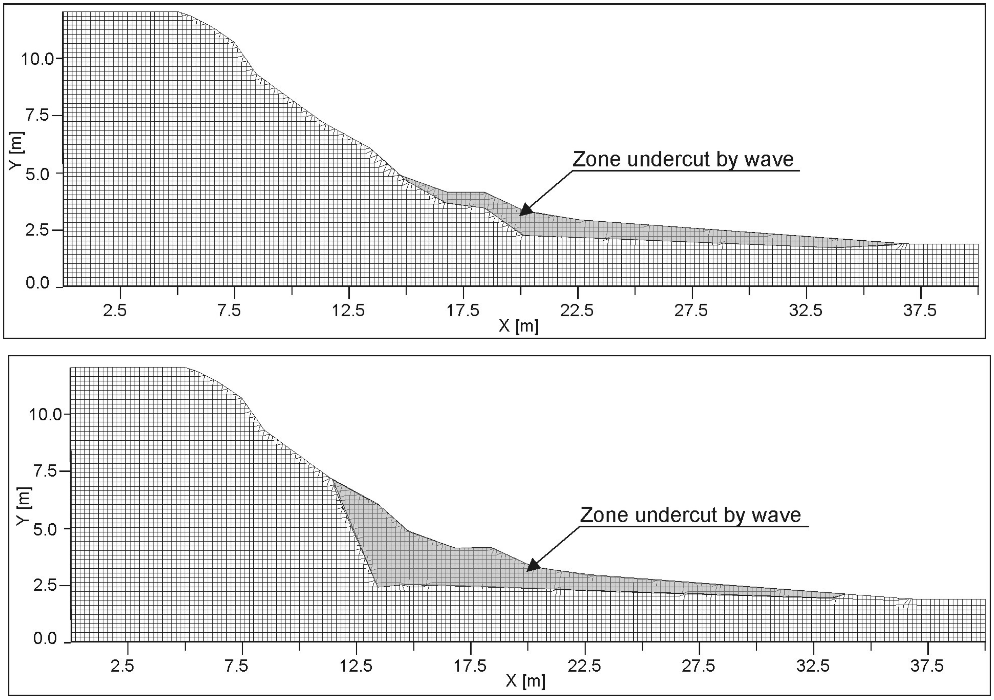

Fig. 5. Division of the dune model into finite difference zones:
(a) trial 2, (b) trial 6

7. Results of Calculations

The results prove that the original dune is stable. Relatively small undercutting in trial 2 does not cause any instability. In contrast, the undercutting in trial 6 produces an extensive failure of the dune. Figures 6–8 illustrate the landslide process in this trial. Deformed finite-difference mesh imposed on the original one is shown in Fig. 6. Figure 7 presents the location of the slide zone, and the horizontal displacement curve in the vertical profile at $X = 10$ m is shown in Fig. 8.

It should be noted that the numerical simulation was stopped arbitrarily. In reality, the deformation process would lead to a complete slide of the dune, and a new dune profile would be created.

8. Summary and Conclusions

Waves attacking the beach and dunes under stormy hydraulic and hydrodynamic conditions cause a lowering of the beach coordinate and undercut the dune toe, thus leading to dune erosion. The calculation results in trial 6 with properly chosen wave parameters prove that the undercutting also triggers a landslide within the dune mass, with a maximum depth of about 5 m. It causes a lowering of the dune crest by about $0.6 \div 0.7$ m.

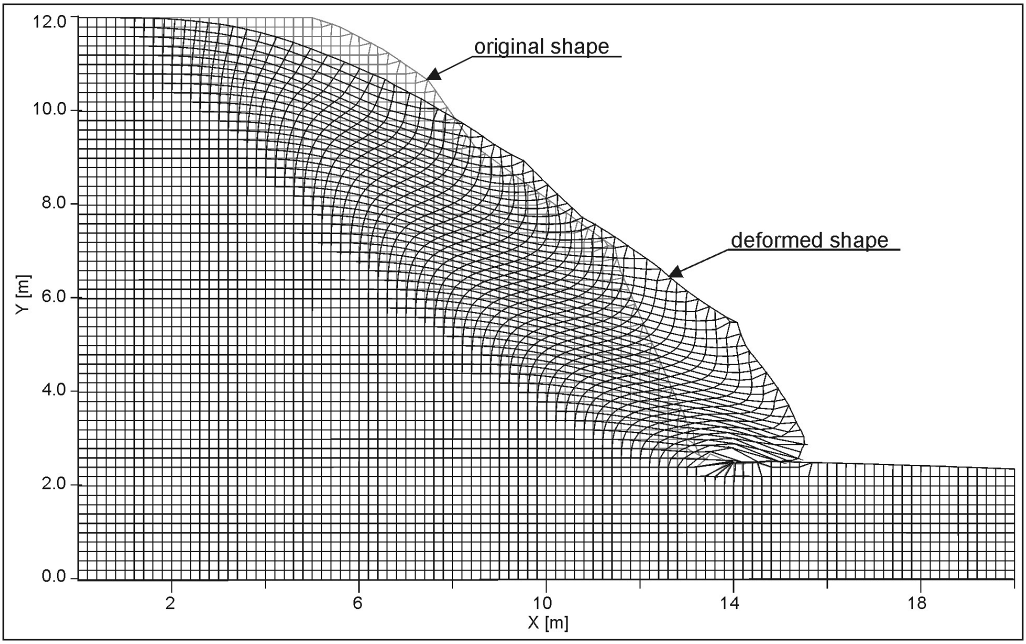

Fig. 6. Finite difference meshes – original and deformed by the landslide

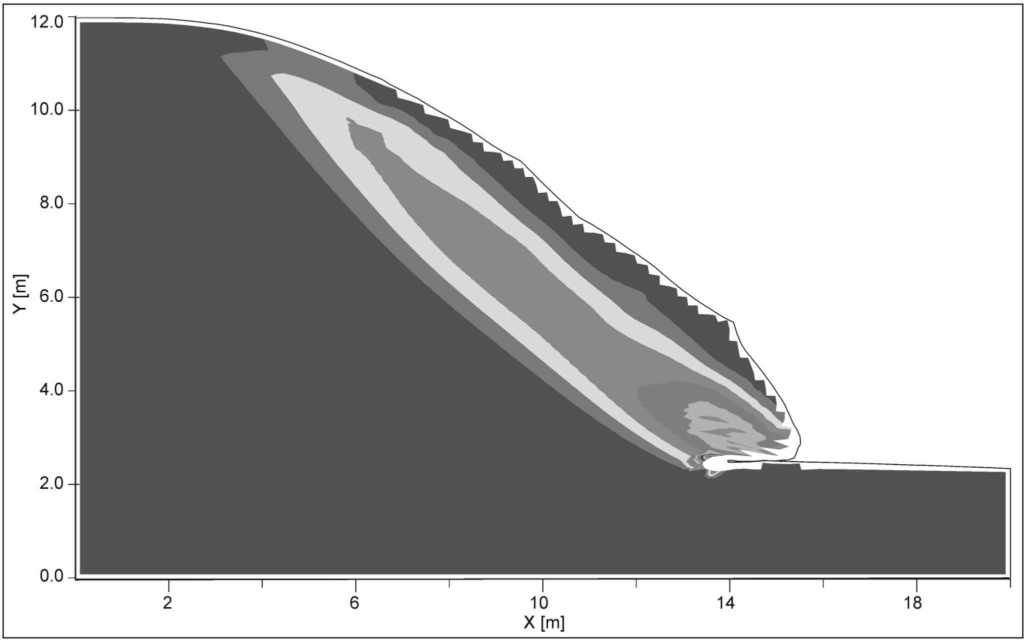

Fig. 7. Slide zone in the undercut dune

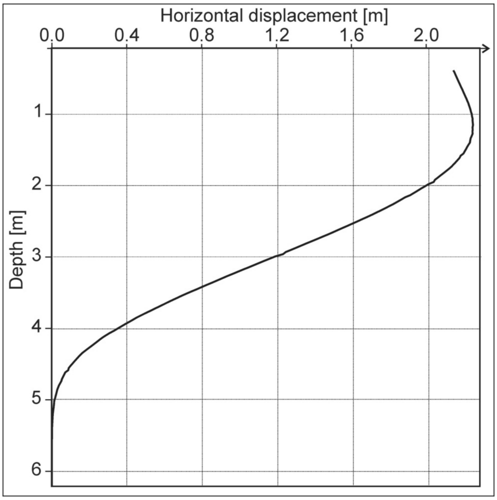

Fig. 8. Calculated curve of horizontal displacement at $X = 10$ m

Numerical models such as XBEACH, SBEACH or CSHORE do not take into account landslide occurrence, and thus underestimate dune erosion. The results of the analysis suggest that landslide processes should be considered, so as to enhance the accuracy of erosion calculations.

The above conclusion, although well documented by the present results, has to be verified experimentally. Such verification is possible through, for example, field measurements carried out in a coastal section prone to erosion and accumulation for high and low dunes and for wide and narrow beaches. The investigations could encompass

- hydrologic and hydrodynamic background to a depth of about 15 m,
- free-surface elevation at a depth of about 0.5 m,
- range and height of wave run-up onto the beach/dune,
- seabed and coastline rebuilding (bathymetric and tachymetric measurements from the dune crown to a depth of about 8 m),
- landslide displacements of the dune measured by an inclinometric method,
- a digital 3D-representations of the terrain to map the entire coastal zone by, for example, LIDAR and multibeam echosounder devices,
- defining the sedimentary structure of sand dunes (study of the differentiation in sediment grains and layers).

Landslide processes have to be taken into account by physical and numerical models describing seabed and shore rebuilding. Landslide movement should be identified by means of systematic in situ measurements. Experimental verification of the hypothesis concerning the possibility of dunes being modelled and reshaped not only by superficial soil avalanching, but also by deeper movement can provide valuable insights for coastal dynamics.

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