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ABSTRACT

Morphological predictions on the basis of uniform (non-graded) sediment revealed an unrealistically strong development of scour hole in the area directly to west of Maasvlakte 2. Additional computations with a state-of-the-art graded sediment transport model have shown that armouring effects do indeed reduce the depth and extent of the scour hole. By means of sensitivity calculations the impact of armouring on the scour development has been examined. The sensitivity tests confirm that the incorporation of armouring processes strongly reduces the development of the scour hole, suggesting an approximately 30% decrease in terms of the area below the -20m depth contour.

I. INTRODUCTION

Rotterdam is creating a prime new European location for port activities and industries which will be reclaimed from the sea, linking directly to the current port and industrial zone. The total land reclamation known as Maasvlakte 2 will consist of 1,000 hectares of commercial sites for deep sea container handling, chemical industry and distribution (figure 1).

The most obvious spot for the new port is situated in an area known as Natura 2000 site Voordelta, a Special Area of Conservation (SAC) (figure 2). Safeguarding the natural values of the Voordelta was one of the leading principles on which the design of Maasvlakte 2 is based.

Figure 1. Design of Maasvlakte 2

The effects of the construction, presence and uses of Maasvlakte 2 have been determined by means of an Environmental Impact Assessment (EIA) and an Appropriate Assessment (AP) of the effects on the SAC. The Maasvlakte 2 project includes compensation projects for the natural values which will or may be lost. Compensation will be found in the realization of a 25.000 ha marine reserve and 35 ha new dunes. In this way the foundation is laid for the construction of a functional and optimal accessible port area, while impact on the natural features and the environment is limited and compensated to the greatest possible extent.

Within the framework of the Maasvlakte 2 project extensive studies have been executed to determine the impact of Maasvlakte 2 on the existing current pattern and the transport of sand and silt, and the resulting morphological changes.

Figure 2. Natura 2000 site Voordelta

In this paper specific attention is given on the issue of large scale scour of the surrounding seafloor, which is important from various perspectives, viz.:

- environmental affects: erosion of the seafloor below NAP -20m needs to be compensated in view of loss of habitat and loss of potential feeding area, for protected birds that tend to feed not deeper than -20m.
- maintenance need of the sandy sea defence of Maasvlakte 2: extent and location of the scour hole may cause additional erosion of the beach and dunes.
- dredging requirements: sand originating from the scour hole may cause additional accretion of the existing access channel to the port of Rotterdam (Maasgeul)

II. Scour development present situation

The present port entrance dates from the period 1968-1976. Regular bathymetrical surveys have been carried out during construction and after completion of the works. Surveys were executed both in the immediate vicinity of the works in progress (Zuiderdam and Noorderdam) and in a larger sea area to the west of the Maasvlakte (figure 3).

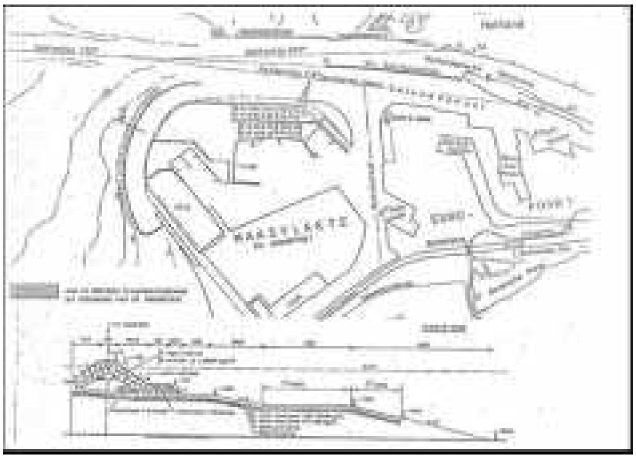


Figure 3. Original situation

During construction local erosion was observed along the Zuiderdam moving along with the temporary head of the structure. At two locations the erosion remained present during a longer period: along the southern bend of the Zuiderdam, at the transition from the rock protection to the sandy beach, and 2 km northward of it, approximately along the middle part of the Zuiderdam (figure 3).

During construction only limited erosion was observed at a larger scale: erosion rates between 1970 and 1976 were approximately 0.1 to 0.2m per year in the sea area to the west of Maasvlakte. Locally, also areas with some accretion were found: accretion rates were less than 0.1m per year.

After completion of the port entrance erosion in the sea area to the west of the Maasvlakte has continued. However, successive bathymetrical surveys indicate that the erosion process gradually slowed down over the years. Presently, the scour hole has reached more or less an equilibrium state (figure 4). The scour hole exists nearly along the whole outer contour of the Zuiderdam covering an area of approximately 160 hectares. The maximum bottom depth is approximately NAP -18m. This implies that since 1970 a maximum erosion of approximately 6 m has occurred (based on the initial depth of NAP -12m).

The design of Maasvlakte 2 shows much agreement with the present situation. Computations for Maasvlakte 2 indicate that the main flow characteristics in the future situation will undergo only little changes as compared to the present situation. Therefore, it is reasonable to expect that the development of scour in the new situation with Maasvlakte 2 will show much resemblance with the scour hole in the present situation.

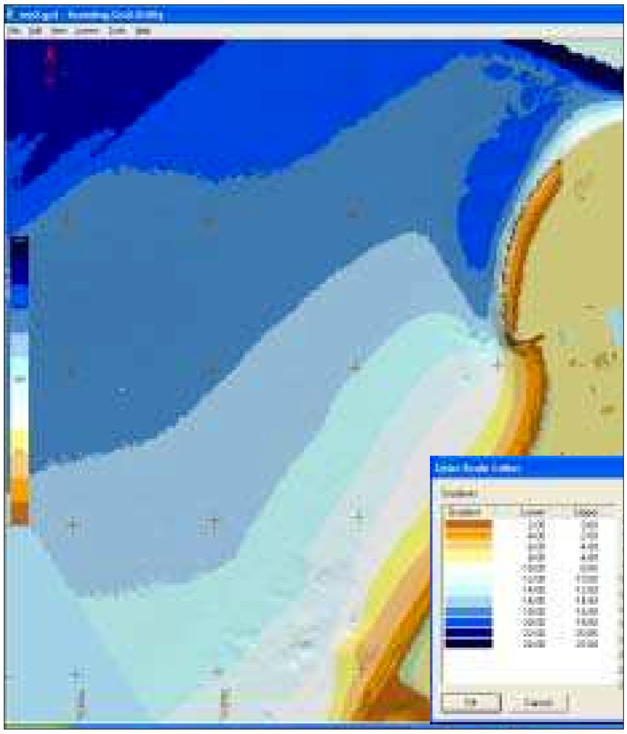


Figure 4. Bathymetrical survey (2006)

III. Morphodynamic computations

The morphological impact of Maasvlakte 2, including the issue of large scale scour of the surrounding seafloor, has been determined on the basis of morphodynamic computations. Thereby use has been made of the integrated modelling system Delft3D developed by WL|Delft Hydraulics, including the modules Delft2D-RAM, Delft2D-MOR and Delft3D-ONLINE (Table I).

For the various investigations, which were carried out in the course of time, always modules with latest functionalities and improved usability have been used.

TABLE I.
APPROACHES MORPHODYNAMIC MODELS

DELFT2D-MOR: this process based module which is a subset of DELFT3D system is designed to simulate sediment transports and morphological developments in coastal, river and estuarine areas (Roelvink and Van Banning, 1994). The 'standard' morphodynamic method involves a coupled simulation of waves, currents, transport and bottom changes. A morphological process is built up from morphological time steps, which consist of a simulation of wave-current interaction over a tidal cycle, followed by a number of intermediate steps where transport is computed and averaged over a tidal cycle, and the bottom is updated. The transport and bottom computations are repeated a number of times using "continuity correction" (= constant discharge trough cells), until bottom changes are so large that a full hydrodynamics computation is required. The method requires full transport computations through tidal cycle, which can be time-consuming especially when suspended-load transport induced by waves and currents in shallow areas is to be accounted for.
DELFT2D-RAM: this hybrid module which is also a subset of DELFT3D system can be applied for Rapid Assessment of Morphology (Roelvink et al., 2001). The RAM module can be characterized as a 'quick-and-dirty' bottom updating scheme (based on the "continuity correction') in combination with repeated detailed computations of hydrodynamics and sediment transport using DELFT2D-MOR.
DELFT3D-ONLINE: this module which is the latest refinement of Delft3D system can operate in 2DH and in 3D mode. The module is characterized by online coupling between hydrodynamic and transport/bottom modules which enables simultaneous computation of flows and transports and simultaneous feedback to bottom changes. Therefore, hydrodynamic flow calculations are always carried out using the correct bathymetry. Only the wave model is executed separately. Acceleration of the morphological developments is achieved by up-scaling the bottom developments during each time step by means of a so-called morphological scaling factor. In this project the Delft3D-ONLINE module was used in 2DH mode. The Maasvlakte 2 computations have been carried using a recently developed calculation scheme in which the simulation is split into a number of parallel processes, which all represent different conditions; at a given frequency all processes provide bottom changes to the merging process, which returns a weighted average bottom change to all processes which then continue the simulation (Roelvink, 2006).

In this paper only results will be presented derived from the most recent studies which were carried out in 2005 and 2006 for the current lay-out of Maasvlakte 2 (figure 1).

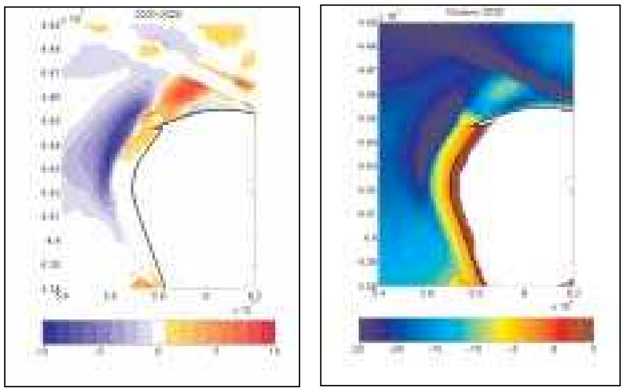
A. Study 2005 (Roelvink and Aarninkhof, 2005)

The set-up and execution of this study elaborated as much as possible on earlier investigations in order to be able to compare the results (e.g. wave- and current conditions, bed material characteristics, roughness size). However, the most important shortcomings of the previously used Delft2D-RAM/MOR module were overcome by:

- use of the wave propagation model SWAN and the DELFT3D-ONLINE approach which was required for a realistic reproduction of bottom changes in the shallow areas of the Voordelta site.
- incorporation of wave effects which was considered to be important for the development of the scour hole and the maintenance of the sandy beach and dunes.

In figure 5 a typical example of the morphological development is given after 20 years. Both (a) the erosion-sedimentation pattern and (b) the final bottom geometry are shown. It appears that a scour hole will develop almost along the entire north-westerly coastline of Maasvlakte 2. A depth of NAP-25m is exceeded in a rather large area. Sand originating from the scour hole is mainly deposited in the access channel but also in the area to the north of Maasvlakte 2 some accretion can be observed.

The location of the scour hole agrees very well with the area with maximum tidal current velocities during flood phase (figure 6).



(a) bottom changes (b) bottom geometry

Figure 5. Computation DELFT3D-Online (2005)

In Figure 7 the time development of the scouring is shown in terms of (a) the area subjected to erosion with a depth larger than 1 m, (b) the area which is eroded below NAP-20m and (c) the maximum erosion depth. The applied model and the associated input parameters result in a scour hole with a size of 1420 hectare after 20 years. The area below NAP -20m which is calculated is about 760 ha and the maximum depth is about NAP-27m.

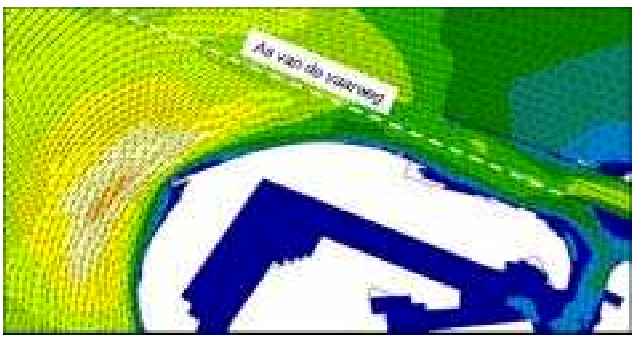
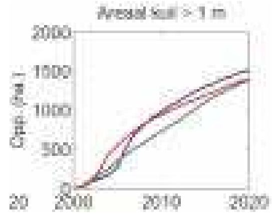
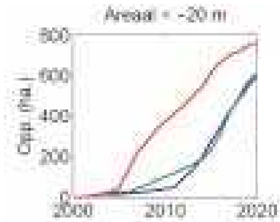


Figure 6. Flow pattern during maximum flood

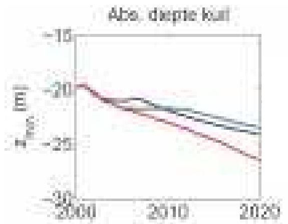
From these figures it can be seen that the process of scour continues after 20 years and that equilibrium is not yet reached. A similar calculation for the existing situation (autonomous situation) also showed a persistent scour for the next 20 years. These unrealistically strong developments do not correspond with the experiences from the existing Maasvlakte. The observer scour is much smaller that the calculated scour. The calculated size and depth of the scour hole are therefore considered as rather conservative estimates.



(a) extent of erosion area with depth > 1m



(b) extent of erosion area below NAP-20m



(c) maximum erosion depth

Figure 7. Computation DELFT3D-Online (2005)

t25 = autonomous situation
t26 = intermediate lay-out (850 hectare)
t27 = final lay-out (1000 hectare)

B. Study 2006 (Elias et al., 2006)

Further analysis revealed that the overestimation could be related to the schematization of the seafloor by means of uniform non-graded sediment with a mean particle size of 160 micron.

From literature it is known that sorting of graded bed material and natural armouring of the surface layer may result in a strong reduction of the scouring process. Also a heterogeneous composition of the sub-seafloor may have a strong impact. Until recently experience with the modelling of graded material was mainly restricted to river applications; for coastal areas such applications were still rare. However, with the latest version of DELFT3D this process can be simulated in a schematized way by distinguishing several sediment fractions and bottom layers.

Within the framework of the Maasvlakte 2 project the graded sediment model has been applied to carry out sensitivity computations. The computations are of a comparative nature not aiming at providing an accurate prediction of the location and extent of the scour hole. The latter can only be achieved by extensive calibration and verification of the model and the incorporation of the effect of both wave-induced and flow- induced sediment transports.

1) IJmuiden case

Because only little experience with the model existed, a concise investigation for the scour hole near the harbour moles of IJmuiden has been conducted firstly. The underlying reasoning is that this scour hole is well measured and documented. Also some studies with DELFT3D for the area have been carried out in the past (Roelvink et al., 1994; Lesser et al., 2004).

From these computations the correct functioning of the model was demonstrated. The sorting process of bed material in the scour hole by erosion of finer fractions and lagging behind coarser fractions could be reproduced in a satisfactory manner (figure 8). Also a lot of experience was obtained about the best way of schematisation, viz.: number of layers, layer thickness and fractional partition of bed material.

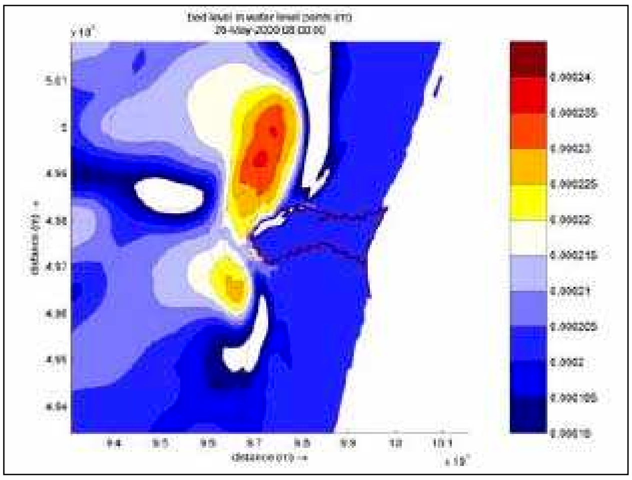


Figure 8. IJmuiden case, spatial distribution of mean grainsize (after 20 years)

2) Maasvlakte 2 case

Subsequently, computations have been performed for the situation of Maasvlakte 2 using the graded sediment model. The set-up of the model was, wherever possible, chosen in accordance with the study of 2005.

Computations were carried out for uniform and graded bed material. For the computations with uniform sediment a number of mean particle sizes have been distinguished, viz: 160 and 200 micron (overall values entire area) and

160/285 micron (with a distinction between the characteristics of seabed and cross-shore profile of Maasvlakte 2). The characteristics of the graded material have been derived from grading curves determined from soil drilling samples wich were collected in the area during a survey in 2005 (figure 9).

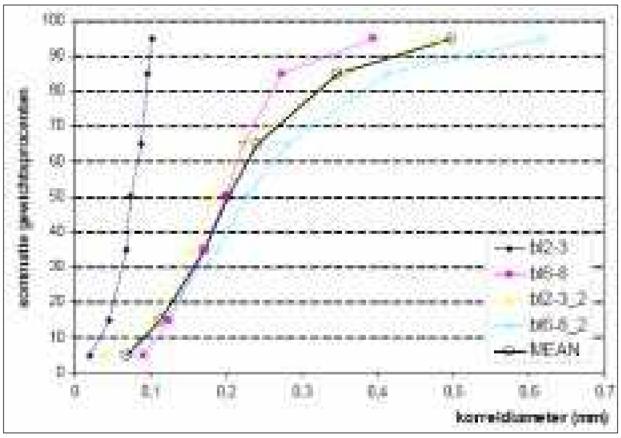


Figure 9. Grading curves from soil drilling samples collected in the area

The bed material is schematized using the average grading curve represented by 5 sediment fractions (table II).

TABLE II.
SEDIMENT FRACTIONS

Fraction	D50 (micron)	relative distribution (%)
1	91	20
2	171	30
3	242	30
4	347	10
5	487	10

It appears that the average D50 of the bed material is 200 micron. This is considerably larger than the value of 160 micron which was used in all previous computations of Maasvlakte 2 (as a representative mean value of the whole study area). Further on it is shown that this difference in particle size will already have some impact on the development of the scour hole.

In the original computations several schematizations for the sub-seafloor were used. The results presented in this paper only refer to the schematization with 15 bottom layers each having a thickness of 1 m.

In figure 10 the calculated bottom geometry after 20 years is shown for the various simulations with uniform and graded bed material. From this figure the difference between graded and uniform material can be seen very clearly. With graded material the maximum erosion depth and the extent of the erosion area are strongly reduced. The results of the cases with uniform material are very similar to the results of previous studies. Some differences in extent and depth of the scouring hole can be observed, depending on the particle size. However, the general shape of the scouring hole remains the same in these cases.

In figure 11 a comparison is made between the computational results with graded bed material and uniform bed material (with a D50 of 200 micron). The differences between these two cases are both related to the maximum scour depth and the extent of the erosion area. With uniform bed material a maximum depth of more than 10m below the original bottom level is reached after 20 years (NAP -26.5m). With graded material this is reduced to 4m (NAP-20.5m). With the effect of graded material incorporated the development of the scour hole is strongly reduced; an approximately 30% reduction in terms of the area below the NAP-20m depth contour is suggested.

IV. CONCLUSIONS

Morphological predictions on the basis of uniform (non-graded) sediment revealed an unrealistically strong development of a scour hole in the area directly west of Maasvlakte 2. Additional computations with a state-of-the-art graded sediment transport model have shown that armouring effects do indeed reduce the depth and extent of the scour hole. By means of sensitivity calculations the impact of armouring on the scour development has been examined. For that purpose the existing Maasvlakte 2 model was extended with a graded sediment schematisation based on the composition of the sub seafloor. The sensitivity tests confirm that the incorporation of armouring processes strongly reduces the development of the scour hole, suggesting an approximately 30% decrease in terms of the area below the NAP-20m depth contour.

In summary, the use of an innovative, graded sediment transport model has shown the potential for improved prediction of the morphological evolution of scour holes. These techniques enable the Port of Rotterdam to anticipate well on the expected scour hole development, the resulting access channel maintenance and additional compensation for the scour below NAP-20m in the planned marine reserve. Additionally the model can contribute importantly to future EIA's for large-scale coastal interventions.

ACKNOWLEDGMENT

We thank the Port of Rotterdam Authority giving this opportunity to publish and to present the results of the research in question at the ICSE 2006.

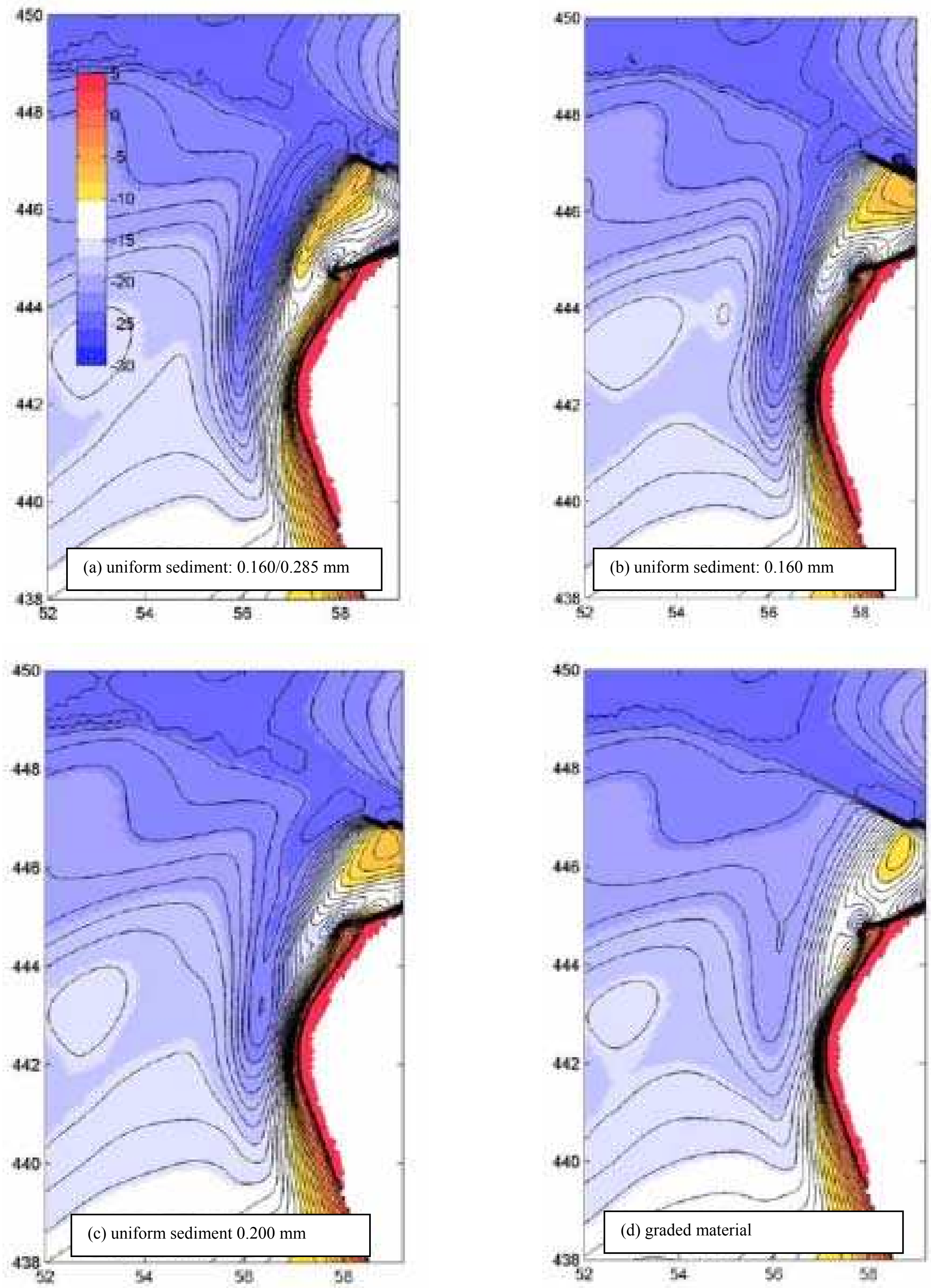
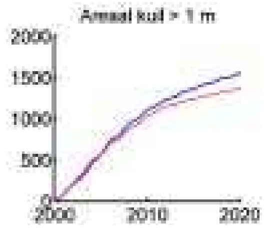
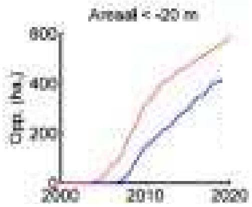


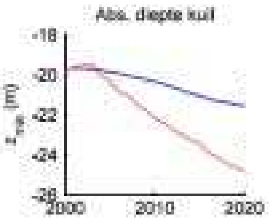
Figure 10. Example DELFT3D-Online (2006)



(a) extent of erosion area with depth > 1m



(b) extent of erosion area below NAP-20m



(c) maximum erosion depth

Figure 11. Example DELFT3D-Online (2006)
(red: uniform; blue: graded)

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