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Hydrodynamics on seedlings of halophytic plants around a salt marsh cliff

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ABSTRACT

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In this paper, the hydrodynamics on seedlings of halophytic plants around a salt marsh cliff are discussed focusing on vortices in front of the cliff based on PTV measurement and a numerical model. A PTV method is developed in a unique way in this study. The result of the PTV experiment reveals the internal water particle movement around the salt marsh cliff and shows the existence of a vortex in front of the cliff. The vortex occurs because of the flow separation on the stepped bottom. The vortex might give negative impact to the seedlings of salt marsh plants, therefore the strength and the position of the vortex is investigated by a numerical model. By comparing with the result of PTV it is found that the numerical model is capable of showing the internal movement and is also successful in showing the vortex in front of the cliff. In the case studies, the influences of different topography and wave conditions on vertices in front of the cliff were investigated. From this study it is found that high waves and long period waves produce vortices which can be dangerous to the seedlings.

ADITIONAL INDEX WORDS: *PTV, CADMAS-SURF, separation vortex, ecosystem*

INTRODUCTION

Salt marshes in estuaries, characterized by mudflats and cliffs with halophytic vegetation, have come to attract more attention from coastal engineers and decision makers with the increasing concern regarding climate change. This is because these areas have disaster prevention functions against sea level rise by dissipating wave energy (Brampton, 1992; Möller *et al.*, 1999; Möller, 2006) and also by increasing sediment deposition via ecosystem engineering (Jones *et al.*, 1997; Bouma *et al.*, 2005). Not only such protection but other important features and functions have also been recognized such as (1) valuable eco-system functions which can promote species diversity and (2) usability as a recreational area for human beings (Constanza *et al.*). However, at the same time, these ecosystems are vulnerable and sensitive to environmental changes and have potential for resulting catastrophic shifts (Scheffer *et al.*, 2001). It has been reported that many salt marsh vegetations and cliffs recently are retreating due to anthropogenic effects such as dredging the waterways near the salt marsh area or increasing extreme events caused by recent climate change. For instance, cliff erosion was observed in the Westerschelde estuary in the southwest of the Netherlands between 1982 and 1998 (Van de Koppel *et al.*, 2005) and is still ongoing (Figure 1). To deal with such a situation, it would be important to investigate local hydrodynamics around a salt marsh cliff to understand the impact of this mechanism that can drive seedlings establishment, plant survival and expansion of surviving vegetation patches. Plant survival and expansion can subsequently create positive feedback loops with sediment accretion and can thereby ultimately stop salt-marsh-cliff erosion and salt-marsh regeneration. For understanding of the local hydrodynamics is also important to study erosion around the salt marsh cliff. To this end, a wave flume experiment and a series of numerical simulations are conducted in this study.

METHODS

It would be difficult to understand all hydraulic phenomena around the stepped bottom (salt-marsh-cliff) by existing analytical models since wave breaking and vortices (e.g. Bleck and Oumeraci, 2002) can both occur in such strongly varying topography. Therefore, wave flume experiments and numerical simulation are possible effective ways to investigate the hydraulic characteristics around the salt-marsh-cliff. However, a normal attempt of the traditional flume experiment, where velocity is measured point by point, is not a very efficient way of capturing an overview of the movement of water particles under waves because measurements have to be done for all the interest areas by repeating the flume experiment. For this reason, a new approach based on the PTV (Particle Tracking Velocimetry) technique (e.g. Adrian, 1991; De Vries, 2007) to capture the hydrodynamics around the cliff was developed. The measurement results are used to validate a numerical model, CADMAS-SURF (Isobe *et al.*, 1999; Coastal Development Institute of Technology, 2001) and the model is used in case studies to investigate hydrodynamics around a salt marsh cliff.

Experimental set-up

The physical model experiments for a salt marsh cliff have been conducted at the Environmental Fluid Mechanics Laboratory of

Delft University of Technology. The wave flume used for the experiments was 40 m long, 0.80 m wide and 1.0 m high. A piston type wave generator, which has a function to compensate reflected waves, was installed at one side. The model structures shown in Figure 2 were placed at 8.3 m from the central position of wave paddle. Behind a gentle slope (i=1/30) and flat bottom, which represents a mud flat in the field, an impermeable cliff with a height of 15 cm was installed resembling a salt marsh cliff. At the end of the flume, a wave absober was installed to reduce the influence of the edge of the flume. Regular waves are used in this PTV experiment to understand the basic hydraulic characteristics around the cliff.

PTV method

Particle Image Velocimetry and Particle Tracking Velocimetry (PIV and PTV) have their roots in flow visualization techniques (Van Dyke, 1982) and these methods have been popular for analyzing flow around a structure for decades. The differences between PIV and PTV is the number of tracer particles. In case of PTV, a sparse seeding is used and each tracer particle can be analysed individually. In this analysis, PTV technique is applied to flow analysis around cliff under wave condition because flow separation is observed at each step. By analyzing the consecutive pictures of the particle, the instantaneous velocities are obtained step by step. Figure 3 shows an example of the captured consecutive pictures from a video camera used to analyze the motion of the water. The upper part shows the first picture and the lower the second, and the velocity is calculated based on the different spatial positions, analyzed based on correlation and divided by the time difference of two pictures.

The selection of the particle is one of the most challenging tasks. If the size of one particle is smaller than one picture cell of a video camera, it is not suitable for PTV analysis. In this study, an off-the-shelf home video camera with a resolution of 576×720 is used. The interest area is about 50 cm in vertical and 70 cm in horizontal, thus the size of the particle will have to be, at least, more than 1 mm. The selected material is Ball Bullets for an airsoft gun, whose density is almost same (980 kg/m^3) as water (1000 kg/m^3). The diameter of the Ball Bullet is 6 mm. To fill the density gap between the Ball Bullets and water, candle wax was used. Firstly candle wax was melted in a cup and a Ball Bullet was soaked in it to cover the Ball Bullet with wax. Thus the density of the Ball Bullet becomes less due to the wax's lower density. The waxed Ball Bullet still maintained its isotropy for direction since the wax was almost uniform. After the waxing, the density of the Ball Bullets was checked by putting them in water one by one. Only those waxed Ball Bullet, which could float for more than 5 seconds in the same position in the water, were chosen and this procedure was repeated until enough numbers of particles were ready for use in this experiment. The total number of particles used in the experiment was about 250.

Numerical model

In the analysis of the results a VOF (Volume of Fluid) model CADMAS-SURF has been applied. The VOF method is a computationally intensive model that can deal with the effects of free surface and wave breaking, and provide information of water surface elevation, wave velocity, wave acceleration and wave pressure for each cell. This model seems to be suitable to study hydraulic characteristics of a salt marsh including a separation flow since other wave models such as energy balance equation models and Boussinesq equation models are not capable to reproduce hydrodynamics on the strongly varying topography. The basic equations of this model are shown below.

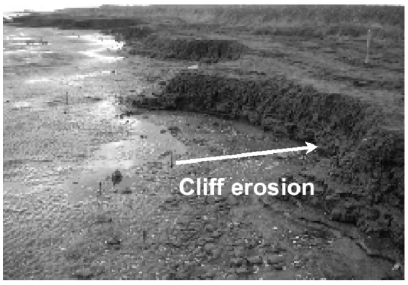

Figure 1. An example of cliff erosion at the edge of a salt marsh in the Westerschelde estuary, The Netherlands.

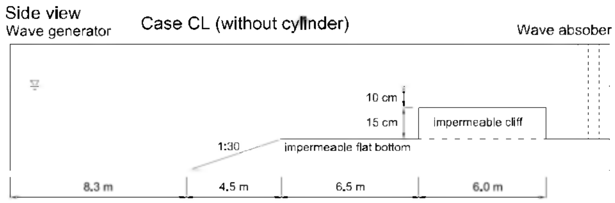

Figure 2. Experimental set-up for PTV measurement. The measurement is conducted around the salt marsh cliff.

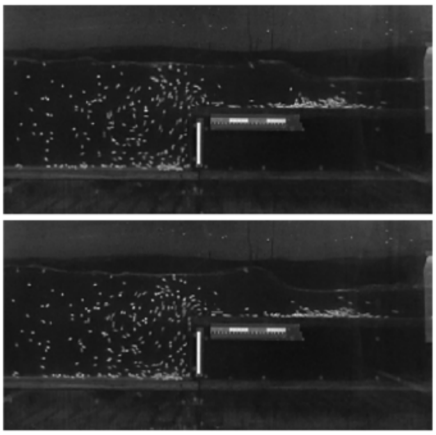

Figure 3. Captured consecutive pictures by PTV technique.

The continuity equation:

$$\frac{\partial \gamma_x u}{\partial x} + \frac{\partial \gamma_z w}{\partial z} = S_\rho \qquad (1)$$

The momentum equations:

$$\lambda_v \frac{\partial u}{\partial t} + \frac{\partial \lambda_x uu}{\partial x} + \frac{\partial \lambda_z wu}{\partial z}$$
$$= -\frac{\gamma_v}{\rho}\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left\{\gamma_x \nu_e \left(2\frac{\partial u}{\partial x}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_z \nu_e \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)\right\} + S_u - R_x$$
$$\lambda_v \frac{\partial w}{\partial t} + \frac{\partial \lambda_x uw}{\partial x} + \frac{\partial \lambda_z ww}{\partial z} \qquad (2)$$
$$= -\frac{\gamma_v}{\rho}\frac{\partial p}{\partial z} + \frac{\partial}{\partial x}\left\{\gamma_x \nu_e \left(\frac{\partial w}{\partial x} + \frac{\partial u}{\partial z}\right)\right\} + \frac{\partial}{\partial z}\left\{\gamma_z \nu_e \left(2\frac{\partial w}{\partial z}\right)\right\} + S_w - R_z - \gamma_v g$$

where t is time, x and z are the horizontal and vertical coordinates, u and w the horizontal and vertical velocities, ρ is the water density, p pressure, ν_e the kinematic viscosity (summation of the molecular viscosity ν and eddy viscosity ν_t), g is the gravitational acceleration, γ_v is the porosity, γ_x and γ_z are the horizontal and vertical permeability and S_p, S_u, S_w are source terms for wave generation. λ_v, λ_x, λ_z are expressed by using the inertia coefficient C_M and R_x, R_z are resistance terms for a porous structure as shown below:

$$\begin{aligned} \lambda_v &= \gamma_v + (1-\gamma_v)C_M \\ \lambda_x &= \gamma_x + (1-\gamma_x)C_M \\ \lambda_z &= \gamma_z + (1-\gamma_z)C_M \end{aligned} \qquad (3)$$

$$\begin{aligned} R_x &= \frac{1}{2}\frac{C_D}{\Delta x}(1-\gamma_x)u\sqrt{u^2+w^2} \\ R_z &= \frac{1}{2}\frac{C_D}{\Delta z}(1-\gamma_z)w\sqrt{u^2+w^2} \end{aligned} \qquad (4)$$

where Δx and Δz are the size of the calculation grid, and C_D is the drag coefficient.

The basic equation of VOF method used in the model is shown as follows.

$$\gamma_v \frac{\partial F}{\partial t} + \frac{\partial \gamma_x u F}{\partial x} + \frac{\partial \gamma_z w F}{\partial z} = \gamma_v S_F \qquad (5)$$

where F is a function of VOF method to show the volume of water in each cell and S_F is source terms for wave generation.

As a turbulence model, k-ε model was used in this calculation.

The total number of the grid for the calculations is 68250, 1365 grids in x-axis (27.3 m in total, Δx=2.0 cm) and 50 girds in z-axis (0.75 m in total, Δz=1.5 cm).

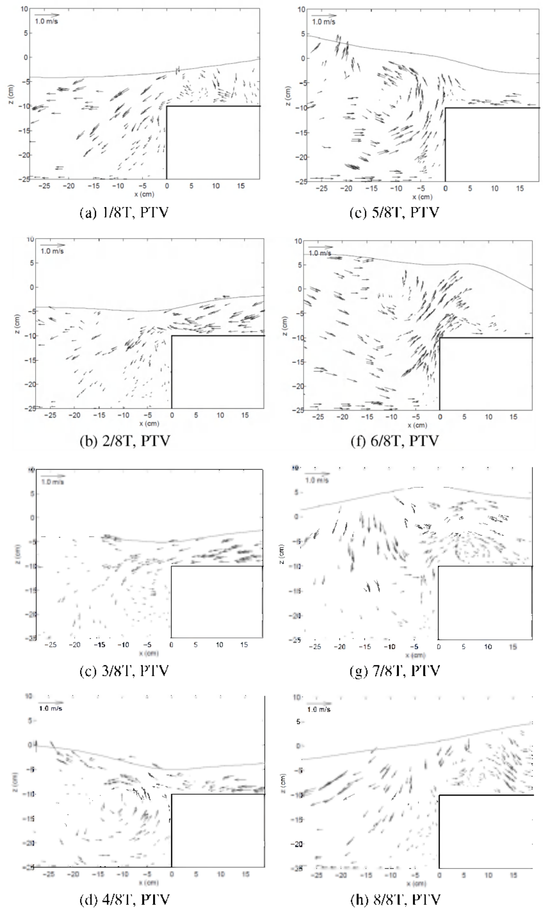

Figure 4. Velocity vectors around a salt marsh cliff at each time step within one wave period obtained by PTV method.

RESULTS

PTV results

Figure 4 shows the velocity vectors around a salt marsh cliff at each time step within one wave period obtained by PTV method. The water surface was traced from the captured picture for each step. 1/8T shows a moment after a wave crest has passed and water particles start to move backward. At 2/8T, the backwash on the cliff accelerates and becomes stronger than the flow at 1/8T. When it reaches 3/8T, a separation vortex in front of the cliff starts forming since the strong horizontal backwash flow on the cliff plunges into an area in front of the cliff in which the horizontal velocity is very small at the moment. At 4/8T and 5/8T, the vortex becomes more obvious and goes upward since the entire vortex starts being lifted due to the next wave crest. The vortex in front of the cliff disappears after 6/8T, and a new vortex starts forming just behind the cliff edge. At 7/8T, wave crest has reached to the cliff edge and the vortex on the cliff becomes very strong, which can be seen in an instantaneous video image in Figure 5. However, the present PTV result shows weak vectors in that area. The reason the PTV method can not show the correct vectors is presumably due to the insufficient time resolution of the video camera. The time resolution of this camera was 25 Hz. The picture of the shape of each Ball Bullet becomes a line rather than a round shape and it implies that the resolution of the video is not high enough to capture the vortex behind the cliff. Another possibility for the discrepancy might be due to the rather big size of the Ball Bullet compared to the size of the vortex. After 8/8T, the water particles in front of the cliff start to move backward again.

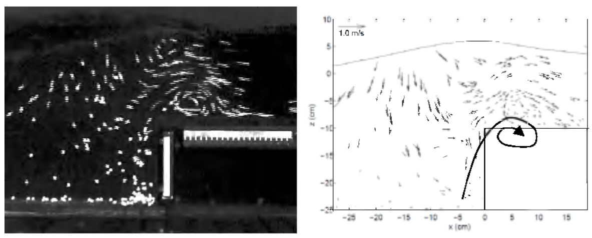

Figure 5. An instantaneous video image (left) and the schematic image of vortex on the cliff (right) at the moment of 7/8T.

All the results other than the vortex on the cliff in Figure 4 are confirmed to be the same as video image, therefore, it can be concluded that the overall tendency is well represented by this method. Though the very strong vortex on the cliff could not be captured, this method could be improved by using a hi-speed video camera.

Numerical results

One of the advantages of the VOF method is to be able to describe the velocity for each cell. Figure 6 shows the velocity vectors around a salt marsh cliff at each time step within one wave period obtained by CADMAS-SURF. The water surface was

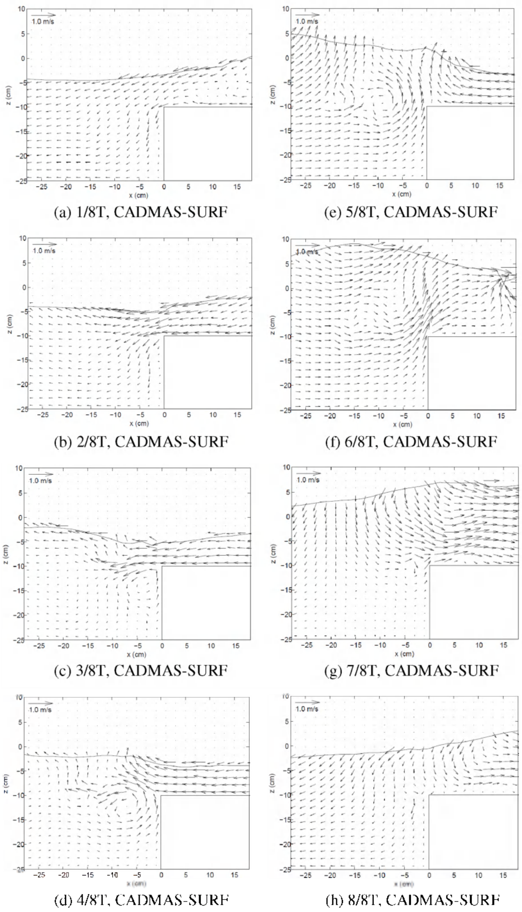

Figure 6. Velocity vectors around a salt marsh cliff at each time step within one wave period obtained by the model.

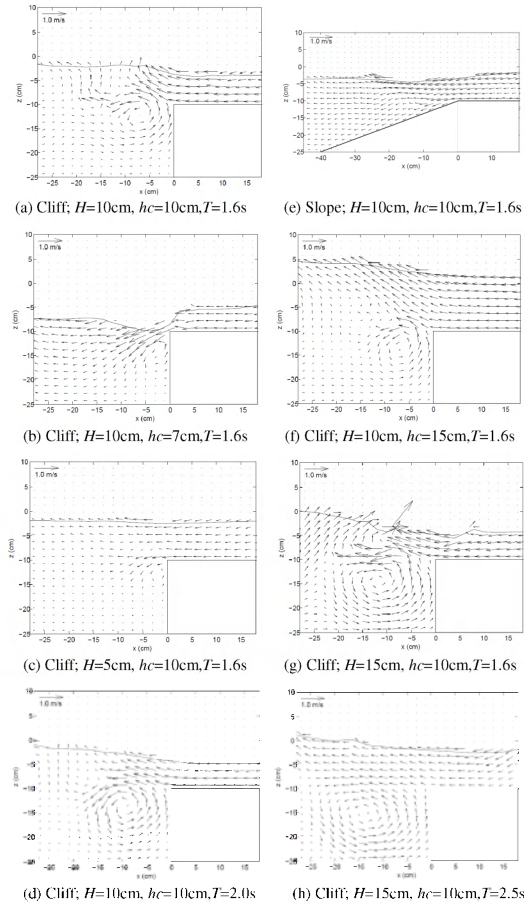

Figure 7. Velocity vectors around a salt marsh cliff in different hydraulic and bottom conditions obtained by the model.

calculated by VOF method as shown before. Even though the input wave is not exactly the same as in the flume experiment (a piston type wave generator is used in the flume experiment, and a stokes wave is used in the numerical model as an input), the shape of the water surfaces are almost same as the PTV results. The tendency of the velocities is also nicely represented by this numerical model. However, the vortex on the cliff is not shown well in the numerical model neither. The reason would be due to the spatial resolution of this numerical calculation. The size of the vortex is about 6 cm in horizontal and 4-5 cm in vertical, while the calculation grid was 2.0 cm in horizontal and 1.5 cm in vertical. The spatial resolution is only about 3 cells for the vortex in each direction, which have to be improved for such an intensive vortex. But from the fact that the vortex in front of the cliff is nicely represented in this model, in which the size of the vortex in front of the cliff was 12 cm in horizontal and 10 cm in vertical, it is possible to calculate the vortex on the cliff as well when the spatial resolution is about 6 cells for the vortex in each direction. Therefore, it would be possible to calculate the small vortex on the cliff by doubling the grid resolution.

From the results obtained here, though the vortex on the cliff is not shown well, it can be concluded that this numerical model is applicable to the study of vortex in front of the cliff.

CASE STUDIES

It can be assumed that such vortices in front of the cliff would cause negative effects on salt marsh seedlings. In this section, the vortices in front of the cliff are investigated in different hydraulic conditions and it is discussed which hydraulics and topographic condition have stronger vortex.

Figure 7 shows instantaneous velocity distribution in different hydraulic conditions, in each of which the backwash becomes strongest in one cycle of wave period, calculated by the numerical model. (a) Cliff and (e) Slope is the comparison between stepped bottom and sloped bottom (slope angle is 20°). It is noted that both bottom shapes can be seen in salt marsh in nature. In the case of a sloped bottom, the separation vortex was not observed while a strong vortex can be seen with a stepped bottom. Therefore, it can be said that the shape of the topography is an important factor in the formation of the vortex. In general, steeper the slope the greater the chances to produce a vortex. Next, (a) h_c=10 cm, (b) h_c=7 cm and (f) h_c=15 cm is the comparison of the effect of the water depth on the cliff, h_c. In the case of (b) h_c=7 cm, the backwash around the cliff corner becomes very strong because water surface gradient becomes steep around the cliff. However, the vortex of (b) is weaker than ones in (a) and (f) because the thickness of the backwash is thin. In the case of (f) h_c=15 cm, the strength of the vortex is almost same as in (a). It seems that the sensitivity of the depth to the formation of vortex is not very obvious. (a), (c) and (g) is the comparison of the incoming wave height. From these results it can be clearly seen that the more the wave height is the stronger the vortex becomes. Not only the strength of the vortex, the position changes, to downward and backward. This may have a greater influence on the seedlings. (a), (d) and (h) show the comparison of wave period. It can be seen that the position of the vortex moves downward and backward similar to case (g) when the wave period become longer.

From these results, it can be concluded the wave height and wave period of the incoming wave would be very important factors in determining the strength and position of the vortex in front of the cliff.

DISCUSSIONS

It is felt that the strength of vortices maybe related to the stroke of the motion of a water particle. In the small amplitude theory, stroke of the motion of a water particle can be shown as in Equation (6). From the equation, if there is a direct relationship between stroke of the motion of a water particle ($2a$) and vortex strength, incoming wave height H, water depth h, and wave number k from the equation is a function of strength of vortex. Here, k is represented by $2\pi/L$, and $2\pi/L$ is a function of T, therefore wave period T is also an important factor for the strength of vortices in front of the cliff.

$$2a = H\frac{\cosh k(h+y)}{\sinh kh} \qquad (6)$$

From the case studies, it is found that the area in front of the cliff would be a severe environment for seedlings. The vortices can be made stronger by wave conditions and bottom shape as shown. When the wave height is big and period become long, the vortices might have a negative influence on the seedlings. In general, hydraulic conditions become severe during a storm. In case of a storm the wave period tends to be very long by the effect of the swell from the offshore and wave height can be high. The relationship between the vortex in front of the cliff and survival of the plant is not yet clear but seedlings do not often occur in front of the cliff in fields in the netherlands.

Not only in front of the cliff but also the area just behind the cliff edge would be very severe condition for plants to survive. For instance, the strong backwash as can be seen Figure 7, strong vortices and wave breakings. These make the water velocity high and makes a lot of turbulences may result in high mortality for plants and less seedlings in this area. This is also can be seen in Figure 1, in which there are no plants just behind the cliff.

CONCLUSIONS

The hydrodynamics on seedlings of halophytic plants around a salt marsh cliff are investigated by flume experiment and a numerical model. PTV measurements reveal the existence of a vortex in front of a salt marsh cliff. The vortex occurs because of the flow separation on the stepped bottom. The vortex might give negative impact to the seedlings of salt marsh plants, therefore the strength and the position of the vortex is investigated by a numerical model. From this study it is found that high waves and long periods wave produce vortices which can be lethal to the seedlings. With regard to sea level rise and increasing storm frequencies due to climate change, higher waves and long period waves can be expected to occur near marsh cliffs. This could have profound effects on salt marsh ecosystem stability and potential for recovery worldwide.

In future it might be important to investigate the relationship between the strength of the vortex and resulting survival of seedlings quantitatively.

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