Hoffmans, Gijs; Verheij, Henk; Van Hoven, Andre
Instability of Grass caused by Wave Overtopping

Verfügbar unter / Available at:

<https://hdl.handle.net/20.500.11970/100233>

Vorgeschlagene Zitierweise / Suggested citation:

Hoffmans, Gijs; Verheij, Henk; Van Hoven, Andre (2010): Instability of Grass caused by Wave Overtopping. In: Burns, Susan E.; Bhatia, Shobha K.; Avila, Catherine M. C.; Hunt, Beatrice E. (Hg.): Proceedings 5th International Conference on Scour and Erosion (ICSE-5), November 7-10, 2010, San Francisco, USA. Reston, Va.: American Society of Civil Engineers. S. 1023-1032.

Instability of Grass caused by Wave Overtopping

Gijs Hoffmans¹, Andre van Hoven², Henk Verheij³

^{1,2,3} Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands
email: gijs.hoffmans@deltares.nl

ABSTRACT

This paper presents a method to deal with the instability of turf in a grass cover that could be considered as an engineering approach, in which both turbulence and two strength models (root model and turf-element model) are discussed in a heuristic way. Turbulence is discussed because of its essential role in erosion. The root model determines the shear strength of rooted soil in the vertical direction. The turf-element model based on a force balance predicts not only the instability of the grass cover but also the initiation of motion of grass. The results of the turf-element model are compared with experimental data of some prototype experiments at Dutch sea dikes.

Introduction

Grass prevents erosion and is an effective control measure. This form of protection has long been used for agricultural drainage channels and on slopes of dikes. In addition, grass-lined emergency spillways are being used as an alternative to costly concrete lining. Following Samani and Kouwen (2002), five methods to evaluate the stability of grass-lined channels have been proposed: maximum permissible velocity, maximum depth, equivalent stone size, permissible tractive force and permissible deflection. All these methods are based on hydraulics, and are probably good enough for steady, uniform flow for the evaluation of roughness coefficients (e.g. Temple 1999). De Baets et al. (2005) investigated the impact of root density and root length density of grass on the erodibility of root-permeated saturated top soils and added this aspect to the available methods based on hydraulics. As hydraulics (load) and geotechnical and vegetation (strength) aspects of the grass cover interact, this requires more insight.

Dutch river dikes usually have clay layers covered with grass on the crest and on both the inner and outer slopes. Sea dikes with hard revetments in the wave impact zone of the seaward slope also have a grass cover on the crest and the inner slope. The grass cover includes grassland vegetation rooted in soil with two layers: the topsoil and the subsoil (Fig. 1, Muijs 1999). The porous turf layer consists of organic matter and sandy clay with a high root density and is elastic in moist conditions. The root structure connects the small clay aggregates and prevents them from being washed out, whereas the underlying clay substrate is stiffer or plastic and less permeable. On the inner slope, the sward contributes to the strength of the grass cover by covering the clay aggregates during overtopping flows, although its contribution to the actual grass strength may be modest. Near the surface, the grass strength is dominated by the root reinforcement, whereas deeper below the surface, where the number of roots decreases rapidly, the soil cohesion and the submerged weight of the soil dominate its strength.

Turbulence

For a grass-clay aggregate, relatively large forces are required to break up the aggregates within the bed, while relatively small forces may suffice to transport pure sand and small clay aggregates. Therefore, at the onset of dislocation, a grass cover or other types of vegetation on dike slopes will experience considerable turbulence, especially at

Figure 1. Definition sketch of grass cover (Muijs 1999)

steep slopes. Usually the bed roughness is characterised by the Chézy coefficient (C) as in

$$U_0 = C \sqrt{R_h S_b} \quad (1)$$

in which R_h is the hydraulic radius that may be taken equal to the flow depth (h) for overtopping flow at dikes, S_b is the dike slope and U_0 is the depth-averaged flow velocity. The depth-averaged relative turbulence intensity (r_0) is defined as (Hoffmans 2010)

$$r_0 = \frac{\sqrt{k_0}}{U_0} \quad \text{where} \quad k_0 = \frac{1}{h} \int_0^h \left(\sigma_u^2(z') + \sigma_v^2(z') + \sigma_w^2(z') \right) dz' \quad (2)$$

in which k_0 is the depth-averaged turbulence energy and σ_u , σ_v and σ_w are standard deviations of the fluctuating velocities in the streamwise, transverse and normal (z') directions. For uniform flow and hydraulic smooth conditions, Nezu (1977) found $\sigma_u(z') = \alpha_u u_* \exp(-z'/h)$, $\sigma_v(z') = \gamma_v \sigma_u(z')$ and $\sigma_w(z') = \gamma_w \sigma_u(z')$ where u_* is the bed shear velocity, $\alpha_u = 1.92$, $\gamma_v = 0.71$ and $\gamma_w = 0.55$. For channels with smooth and rough bed, the turbulence distributions are reasonable the same (Graf 1998). Substituting these empirical relations in Eq. 2 yields $k_0 = (\alpha_0 u_*^2)$ with $\alpha_0 = [\frac{1}{2} \{1 - \exp(-2)\} \cdot \frac{1}{2} \alpha_u^2 \{1 + \gamma_v^2 + \gamma_w^2\}]^{0.5} = 1.2$.

Usually in k - ε models the near bed turbulent energy is defined as $k_b = (u_*^2)/(c_\mu)^{0.5}$ in which $c_\mu = 0.09$ (e.g. Launder and Spalding 1972). Assuming that $k(z')$ is linear distributed $k_0 = 1.65(u_*^2)$. Since $k(z')$ is an exponential distribution the value of 1.65 is less, so an appropriate value of α_0 for all types of uniform flow is $\alpha_0 = 1.2$. Using the Chézy equation, r_0 is for uniform flow

$$r_0 = \alpha_0 \frac{u_*}{U_0} = \alpha_0 \frac{\sqrt{g}}{C} \quad (3)$$

where g is the acceleration due to gravity. Prototype experiments on different sea dikes using a wave-overtopping simulator [typical wave characteristics are $H_s = 2$ m (significant wave height) and $T_w = 5.7$ s (peak wave period) for a varying dike crest

freeboard] showed that at the inner slope of sea dikes, the steepness of which is about 1V:3H, the maximum depth-averaged flow velocities (U_m) per overtopping event reach values up to 8 m/s (corresponding wave volume per unit width is 5,500 ℓ/m) (Fig. 2). The flow depths vary from 2 cm to 40 cm resulting in high turbulence intensities ($0.1 < r_0 < 0.3$).

Figure 2. Relation between maximum depth-averaged velocity and wave volume

Emmerling (1973) investigated the instantaneous structure of the pressure near the bed under uniform turbulent flow conditions in air. The frequency (f) of the turbulent wall pressure fluctuations varied from 20 Hz to 2000 Hz and the mean flow velocity in the boundary layer measured 8.5 m/s. Hence, the largest eddies at macro (wave number ($k_w = 2\pi f/U_0$) is 0.15 cm^{-1}) and micro ($k_w = 1.5 \text{ cm}^{-1}$) scale which contribute most to the lift force are considered. The standard deviation of the instantaneous pressure ($\sigma_{p,b}$) on the bed was found to be $3\tau_0$ where τ_0 is the mean bed shear stress and that the maximum pressure fluctuation (p_m) could be up to $6\sigma_{p,b}$. With estimates of $p_m/\sigma_{p,b} = 6$ and $\sigma_{p,b} = 3\tau_0$, p_m can be written as

$$p_m = \alpha_\tau \tau_0 \quad \text{with} \quad \alpha_\tau = 18 \quad (4)$$

When grass-clay aggregates are uplifted, p_m represents the maximum lowering of the local pressure caused by eddies. According to Nezu (1977) $\sigma_{p,b}/\tau_0$ depends on the Froude number (Fr). If the turbulent structure is dominated by the Reynolds shear stresses, $\sigma_{p,b}/\tau_0$ is about 3 for $\text{Fr} < 0.5$ and $\text{Fr} > 2$. At the transition from sub to supercritical flow, $\sigma_{p,b}/\tau_0$ reaches an evident maximum, thus α_τ has no universal value. The mean bed shear stress, defined as $\tau_0 = \rho(u^*)^2$, using Eq. 3 reads

$$\tau_0 = \alpha_0^{-2} \rho (r_0 U_0)^2 = 0.7 \rho (r_0 U_0)^2 \quad (5)$$

resulting in $p_m = \alpha_0^{-2} \alpha_\tau \rho (r_0 U_0)^2 = 12.5 \rho (r_0 U_0)^2$. Based on the above, pressures of about 50 kN/m^2 can be determined for the conditions with overflowing waves. In the next sections the influence of both the dike slope and the slope roughness is included by r_0 [$= \alpha_0 (gh_m S_b)^{0.5} / U_m$ where the maximum flow depth (h_m), U_m and S_b are obtained from measurements per wave volume].

Root model

The Mohr-Coulomb equation describes the shear failure of soil in terms of shear stresses as well as normal stresses and can be written as (e.g. Lambe and Whitman 1969)

$$\tau_s = c_e \cos \phi_e + (\sigma - p_w) \sin \phi_e \quad (6)$$

where c_e is the effective soil cohesion, p_w is the soil pore water pressure, σ is the soil normal stress, τ_s is the soil shear strength and ϕ_e is the effective internal friction angle. The soil cohesion (c) is the result of cementation, weak electrical bonding of clays and organic colloids and capillary tension, whereas ϕ_e represents the frictional interaction of individual particles and the interlocking of particles. The magnitude of σ depends on the weight of the soil and the soil moisture, whereas the buoyancy generated by p_w reduces the normal stress. For dry soil when $p_w = 0$ both $c_e = c$ and ϕ_e equals the internal friction angle (ϕ).

Typically the strength of roots is modelled by an artificial additional cohesion (c_r). In a root permeated soil Eq. 6 can be modified to include c_r

$$\tau_s = c_e \cos \phi_e + c_r + (\sigma - p_w) \sin \phi_e \quad (7)$$

Most attempts to determine the effects of root reinforcement by grassland vegetation have used root-cohesion estimates according to the root equation of Wu et al. (1979), which requires the root tensile strength (σ_r) and the mean root diameter (d_r). Where a root crosses a shear zone, σ_r can be resolved into components parallel (H_r) and perpendicular (V_r) to the shear zone (Fig. 3). Thus, c_r is

$$c_r = \frac{A_r}{A_1} (V_r \tan \phi + H_r) = \sigma_r \frac{A_r}{A_1} (\cos \theta \tan \phi + \sin \theta) \quad (8)$$

where A_r/A_1 is the root area ratio also known as RAR and θ is the angle of shear rotation. Though little is known about θ from field observations of conifers, Wu et al. (1979) suggested a range of 45° to 70° . Since Eq. 8 is insensitive to changes in θ (it is close to 1.2 for a large range of θ), c_r may be rewritten as $c_r \approx 1.2 \sigma_r A_r/A_1$.

Although horizontal roots may have some impacts on the threshold condition for vertical motion, here the vertical grass strength (V_{grass}) and the critical vertical grass strength ($V_{grass,c}$) are approximated by

$$V_{grass} = \sigma_{grass} \cos \theta = \sigma_r \frac{A_r}{A_1} \cos \theta \quad \text{and} \quad V_{grass,c} = \sigma_{grass,c} \cos \theta = \sigma_{r,c} \frac{A_r}{A_1} \cos \theta \quad (9)$$

where σ_{grass} and $\sigma_{grass,c}$ represent the normal grass strength and the critical normal grass strength. Hence, $V_{grass,c}$ does not include the critical friction strength of roots on clay ($c_{grass,c}$). If $c_{grass,c} \ll V_{grass,c}$ all roots are well-anchored and they will all break simultaneously, so they will not be pulled out before breaking owing to a lack of anchoring. However, prototype and laboratory experiments have demonstrated that the roots do not all break simultaneously (e.g. Pollen and Simon 2003) so if deformations are not included Eqs. 8 and 9 overestimate the critical values of c_r and V_{grass} .

The critical tensile strength depends strongly on the type and the quality of the grass. Sprangers (1999) measured grass parameters such as the root length and the dry

root mass densities from 24 Dutch dike sites. He found that A_r/A_1 of dike grassland decreases exponentially with depth and that about 50% of the roots can be found in the top 6 cm of the turf, while about 75% of the roots were located within the top 20 cm. Above λ_{ref} ($= 10$ cm) about $\frac{2}{3}$ of all roots are to be found. The critical vertical grass strength, which is at maximum near the surface and decreases with depth, is here estimated by

$$V_{\text{grass},c}(z) = \sigma_{0,\text{grass},c} \exp\left(\frac{z}{\lambda_{\text{ref}}}\right) \cos \theta \quad \text{with} \quad \sigma_{0,\text{grass},c} = \sigma_{r,c} \left(\frac{A_r}{A_1}\right)_0 \quad (10)$$

in which $\sigma_{0,\text{grass},c}$ is the critical normal grass strength near the surface and $(A_r/A_1)_0$ represents the root area ratio close to the surface. For Dutch grasses, the number of roots near the surface lies in the range of 20 to 50 per standard area according to VTV-2006 (or 15,000 per m^2 to 60,000 per m^2). Using $d_r = 0.113$ mm it follows that $0.0002 < (A_r/A_1)_0 < 0.0008$.

Based on Spranger's work, the Dutch guidelines for assessing primary dikes (VTV 2006) distinguish 4 different qualities for the grass cover in which the quality of the grass is strongly correlated to the number (No) of roots. The mean root diameter of Dutch grasses is 0.113 mm (Paulissen 2009), which is significantly finer than the range of d_r tested by the Chinese researchers Chengh et al. (2003). If the following assumptions are made: $d_r = 0.113$ mm, $\sigma_{r,c} = 20 \cdot 10^6$ N/m 2 , $\theta = 45^\circ$, $\phi = 30^\circ$ and $c_{\text{grass},c}$ is neglected with respect to $V_{\text{grass},c}$ then the root properties can be determined (Table 1).

Table 1 Root properties of Dutch dike grassland (near the surface)

Grass quality VTV-2006	⁽¹⁾ (No) $_0$ per VTV area	⁽²⁾ $(A_r/A_1)_0$ (-)	⁽³⁾ $(A_r/\text{No})_0$ (mm 2)	⁽⁴⁾ $(A_1/\text{No})_0$ $^{\text{b}}$ (mm)	⁽⁵⁾ $c_{0,r,c}$ (kN/m 2)	⁽⁵⁾ $\sigma_{0,\text{grass},c}$ kN/m 2
very poor	18	0.0003	39	6	5.7	5.1
poor	26	0.0004	27	5	8.2	7.4
average	53	0.0008	13	4	16.8	15.0
good						

⁽¹⁾ (No) $_0$ is number of roots per VTV area near the surface;

(No) $_0 = (A_{r,\text{VTV}}/A_{1,\text{root}})_0$ where $A_{r,\text{VTV}}$ = number of roots near the surface per VTV area which is defined as $\frac{1}{2}\pi d_r^2$ with $d_b = 0.03$ m and $A_{1,\text{root}} = \frac{1}{2}\pi d_r^2$ with $d_r = 0.113$ mm;

⁽²⁾ $(A_r/A_1)_0$ is root area ratio near the surface with $A_1 = 1$ m 2 ;

⁽³⁾ $(A_r/\text{No})_0$ is turf area per root near the surface;

⁽⁴⁾ $(A_1/\text{No})_0$ $^{\text{b}}$ is root spacing near the surface;

⁽⁵⁾ see Eq. 8 using $\theta = 45^\circ$, $\phi = 30^\circ$, $\sigma_{r,c} = 20 \cdot 10^6$ N/m 2 ;

⁽⁶⁾ see Eq. 9 using $\sigma_{r,c} = 20 \cdot 10^6$ N/m 2 .

Turf-element model

If a grass-clay aggregate with the dimensions of a cube is considered, the following forces acting on this cube can be distinguished: the load due to the lift force caused by pressure fluctuations perpendicular to the grass cover, and the strength, i.e., the submerged weight of the soil, and the forces caused by shear, cohesion and the roots. Figure 4 shows a cube $\ell_x \ell_y \ell_z = \ell^3$ at a horizontal plane where ℓ_x , ℓ_y and ℓ_z are length scales in the x , y and z direction respectively and ℓ is the representative aggregate scale. A grass-clay aggregate is unstable if the load is larger than the strength, thus

$$F_p \geq F_w + F_s + F_c + F_g \quad (11)$$

Figure 3. Forces acting upon a turf element

where $F_p [= p_m \ell_x \ell_y]$ is the maximum lift force. The force $F_w [= (1-n)(\rho_s - \rho) g \ell_x \ell_y \ell_z]$ is the submerged weight of the soil [n (≈ 0.4) is the porosity, ρ is the fluid density and ρ_s is the bulk density of soil]. The sum of the shear forces acting on the four sidewalls reads $F_s = \tan \phi (1-n)(\rho_s - \rho) g (\ell_x + \ell_y) (\ell_z)^2$. The sum of the artificial cohesion forces (F_c), which act on the four sidewalls, depends on the critical rupture strength of clay ($C_{clay,c}$) and the critical friction strength of roots ($C_{grass,c}$) averaged over ℓ_z . The sum of the cohesion forces (F_c) is approximated by $F_c = (1-n)(C_{clay,c} + C_{grass,c}) 2(\ell_x + \ell_y) \ell_z$ and the total force at the bottom-element is $F_g = (1-n)(C_{clay,c} + V_{grass,c}(z = -\ell_z)) \ell_x \ell_y$.

The assumption of Eq. 11 is applicable if p_m at the top of the grass-clay aggregate significantly decreases with depth or if the penetration length (ℓ_p) is $\ell_p/\ell \ll 1$. According to De Groot et al. (1996) $\ell_p = (c_v T_p / \pi)^{0.5}$ where c_v is the consolidation coefficient and T_p is the pressure period of the vortices in the turbulent flow at the inner slope of the dike. If the order of magnitude of c_v is $O(c_v) = 10^{-2} \text{ m}^2/\text{s}$ and $O(T_p) = 0.1 \text{ s}$, then $O(\ell_p) = 0.01 \text{ m}$, thus the pore pressure variation equals the total stress variation at a depth larger than one or two times ℓ_p . Based on measured flow fluctuations in open pores of granular filters under uniform and sub critical flow conditions, Klar (2005) found that the turbulence energy at 2 cm below the bed level is about 10% of k_b . Using $\ell_x = \ell_y = \ell_z = -z$, Eq. 11 can be rewritten as

$$p_m \geq V_{soil}(z) = -(1-n) \left[(\rho_s - \rho)(1 + 2 \tan \phi) g z - 4(C_{clay,c} + C_{grass,c}) - (C_{clay,c} + V_{grass,c}(z)) \right] \quad (12)$$

where $V_{soil}(z)$ is the vertical soil strength as function of z . When describing incipient motion, horizontal forces are usually considered. The critical condition for moving grass-clay aggregates is reached if τ_0 equals the critical mean bed shear stress (τ_c). If there is neither clay nor grass and neglecting the shear forces, τ_c of loosely packed materials is ($z = -d$)

$$\tau_0 \geq \tau_c = \Psi_c (\rho_s - \rho) g d \quad \text{with} \quad \Psi_c = \alpha_r^{-1} (1-n) = 1/18 (1-0.4) = 0.033 \quad (13)$$

In turbulent flow, the critical Shields parameter (Ψ_c) varies from 0.03 to 0.06 for coarse sand and gravel, whereas for small Reynolds numbers up to fully laminar flow Ψ_c increases from 0.03 to 0.2. Hence, the first term in Eq. 12 confirms the earlier research of Shields. Substituting $z = -\lambda_{ref}$, Eq. 12 can be rewritten as

$$\tau_0 \geq \tau_c = \Psi_c \left[(\rho_s - \rho)(1 + 2 \tan \phi) g \lambda_{ref} + 4(C_{clay,c} + C_{grass,c}) + (C_{clay,c} + V_{grass,c}(-\lambda_{ref})) \right] \quad (14)$$

Compacted clay has a high resistance against erosion and a low hydraulic conductivity (k) provided the clay is kept in sufficiently moist condition. However, k of a grass-clay aggregate is significantly higher owing to atmosphere, flora and fauna and varies from 10^{-5} m/s to 10^{-4} m/s owing to cracks and other disturbances (Kruse 1998). Hence, near the surface the submerged weight and the rupture strength of clay are negligible with respect to the friction strength of the roots. If $(\rho_s - \rho)(1 + 2 \tan \phi) g \lambda_{ref} \ll C_{clay,c} \ll C_{grass,c}$ then Eq. 14 reduces to

$$\tau_0 \geq \tau_c = \Psi_c (4C_{grass,c} + V_{grass,c}(-\lambda_{ref})) \quad (15)$$

Per sidewall the strength of roots averaged over λ_{ref} is

$$C_{grass,c} = \frac{1}{\lambda_{ref}} \int_{-\lambda_{ref}}^0 V_{grass,c}(z) dz = \alpha_{grass} \sigma_{0,grass,c} \cos \theta \quad (16)$$

where $\alpha_{grass} = 1 - \exp(-1) = 0.64$. Combining Eqs. 10, 15 and 16 yields

$$\tau_0 \geq \tau_c = (1 + 3\alpha_{grass}) \Psi_c \sigma_{0,grass,c} \cos \theta = 2.9 \Psi_c \sigma_{0,grass,c} \cos \theta \quad (17)$$

Assuming that the flow is hydraulically rough, thus $r_0 > 0.05$ and for the condition of incipient motion $r_0 U_0 = r_{0,c} U_c$, the critical depth-averaged flow velocity is

$$U_c = (r_{0,c})^{-1} \alpha_0 \sqrt{(1 + 3\alpha_{grass}) \Psi_c \sigma_{0,grass,c} \cos \theta / \rho} = 2.0 (r_{0,c})^{-1} \sqrt{\Psi_c \sigma_{0,grass,c} \cos \theta / \rho} \quad (18)$$

where $r_{0,c}$ is the critical depth-averaged relative turbulence intensity. When the slope steepness increases or the bed becomes rougher the bed turbulence increases.

Examples of some prototype experiments

At several test locations in the Netherlands (Delfzijl, Boonweg, St. Philipsland, Kattendijke and Afsluitdijk) both the grass and dike core were inspected to determine the grass cover stability and the resistance of the grass to erosion. Different strength parameters were measured, such as the number of roots, soil cohesion, internal friction angle and liquidity index (Van Hoven et al. 2010). The wave-overtopping simulator (Van der Meer, 2007) was used to test the erosion resistance of the inner slope. Experiments were carried out by simulating a six hour storm for every overtopping condition at a constant q . These conditions started with a q of 0.1 ℓ/s per m and increased to 1 ℓ/s per m, 10 ℓ/s per m, 20 ℓ/s per m, 30 ℓ/s per m, 50 ℓ/s per m and 75 ℓ/s per m after testing no significant damage to the grass cover was observed.

The number of roots near the surface varied from 20 to 50 according to the Dutch standard area (VTV 2006). For turbulent flow the boundaries between occasional particle movement at some locations and general transport are $0.03 < \Psi_c < 0.06$. Assuming that $r_{0,c} = 0.17$, $d_r = 0.113$ mm, $\sigma_r = 20 \cdot 10^6$ N/m², $\lambda_{ref} = 0.10$ m and $\theta = 45^\circ$ Eq. 18 gives for poor grass: $4 \text{ m/s} < U_c < 7 \text{ m/s}$, for average grass: $5 \text{ m/s} < U_c < 9 \text{ m/s}$ and for good grass: $U_c > 6.5 \text{ m/s}$ (Table 2). Consequently, all experiments lie in the broad belt originally given by Shields (Fig. 4).

Conclusions and recommendations

The critical normal grass strength as given in Table 1 is predicted to vary from 5 kN/m² to 15 kN/m² and represents the range of different qualities of grass. The critical vertical grass strength is influenced by No, d_r ($= 0.113$ mm), $\sigma_{r,c}$ ($= 20 \cdot 10^6$ N/m²), λ_{ref} ($= 10$ cm) and θ ($= 45^\circ$). Since these parameters can easily be determined to a reasonable degree of precision, the computed value of $V_{grass,c}$ should also be accurate in this respect. However, $V_{grass,c}$ does not include the heterogeneity of the grass cover, e.g., the decrease of d_r with depth and the standard deviations of No, d_r , $\sigma_{r,c}$, λ_{ref} and θ respectively.

Although the modelling is based on physical considerations and should be representative for the strength of the grass cover, the model is based on static equilibrium conditions ($c_{grass,c} \ll V_{grass,c}$). Therefore, it is necessary to examine the deformation of grass as function of the dynamic load, i.e. the relation between $c_{grass,c}$, $V_{grass,c}$ and the elastic modulus for grass, in greater detail and to validate the incipient motion of grass by carrying out sufficient experiments. Moreover, it is recommended to analyse the penetration of the pressure fluctuations close to bed.

The turf-element model should be considered as a conceptual approach, which incorporates a good description of the physics. The model predicts the initiation of motion of turf as an element with a length scale of 10 cm. To update the VTV in 2011 it is necessary to examine the deformation of grass as function of the load and to understand the physical significance of the parameters used in the turf model for different types of grass and clay.

Table 2 Observations and calculations of prototype experiments on Dutch sea dikes

Test location	Experimental programme (discharge in ℓ/s per m)	Observations at inner dike slope	U_m (m/s) (Fig. 2)	Grass quality VTV-2006	U_c (m/s) $\Psi_c = 0.03$	U_c (m/s) $\Psi_c = 0.06$
Delfzijl 1	0,1-1-10-20-30-50	no damage	7	poor	4.0	7.0
Boonweg 1	0,1-1-10-30-50-75	no damage	8	good	6.5	> 10
Boonweg 2	0,1-1-10-30-50-75	no damage	8	good	6.5	> 10
Boonweg 3	0,1-1-10-30-50-75	damage at 75	8	good	6.5	> 10
Boonweg 4	0,1-1-10-30-50-75	damage at 50	7	good	6.5	> 10
St. Philipsland	0,1-1-10-30-50-75	damage at 50	7	good	6.5	> 10
Kattendijke 1	0,1-1-10-30-50-75	no damage	8	good	6.5	> 10
Afsluitdijk 1	1-10-30-50-75	damage at 50	7	average	5.0	9.0

Figure 4. Critical depth-averaged flow velocity as function of the grass strength

References

- Akkerman, G.J., Van Gerven, K.A.J., Schaap, H.A., Van der Meer, J.W., 2007. Workpackage 3: Development of alternative overtopping-resistant sea defences, Phase 3: wave overtopping erosion tests at Groningen sea dyke, Rijkswaterstaat, Delft.
- Cheng, H., Yang, X., Liu, A., Fu, H., Wan, M., 2003. A study on the performance and mechanism of soil-reinforcement by herb root system. *Proc. of the 3rd Int. Conf. on Vetiver and Exhibition*, Guangzhou, China.
- De Baets, S., Poesen, J., Gyssels, G., Knapen, A., 2006. Effects of grass roots on the erodibility of top soils during concentrated flows, *Geomorphology*, 76, 54-67.
- De Groot, M.B., Andersen, K.H., Burcharth, H.F., Ibsen, L.B., Kortenhaus, A., Lundgren, H., Magda, W., Oumeraci, H., Richwien, W., 1996. Foundation design of caisson breakwaters, Publication 198. Norwegian Geotechnical Institute, Oslo, Norway.

- Emmerling, A., 1973. Die momentane Struktur des Wanddruckes einer turbulenten Grenzschicht-strömung, Max-Planck-Institut für Strömungsforschung, Bericht 9.
- Graf, W.H., 1998. *Fluvial Hydraulics*, Flow and transport processes in channels of simple geometry, Wiley & Sons, New York.
- Hoffmans, G.J.C.M., 2010. Stability of Stones Under Uniform Flow, *J. of Hydr. Engrg., ASCE*, 136(2), 129-136.
- Klar, M., 2005. Design of an endoscopic 3-D particle-tracking velocimetry system and its application in flow measurements within a grave layer, *Doctoral Thesis*, University of Heidelberg, Germany.
- Kruse, G., 1998. Impact of weathering on resistance of soils, in *Dikes and revetments, Design, Maintenance and Safety Assessment* (edt. K.W. Pilarczyk), Balkema, Rotterdam,.
- Lambe, T.W., Whitman, R.V., 1969. *Soil Mechanics*. John Wiley, New York.
- Lauder, B. E., Spalding D.P., 1972. *Mathematical models of turbulence*, Academic Press, London.
- Muijs, J.A., 1999. Grass cover as a dike revetment, Translation of TAW-brochure "Grasmat als Dijkbekleding" 9, Ministry of Public Works and Water Management, Rijkswaterstaat, Delft.
- Nezu, I., 1977. Turbulent structure in open-channel flows, (Translation of Doctoral Dissertation in Japanese), Kyoto University, Kyoto, Japan.
- Paulissen, M.P.C.P., 2009. Personal Communications. Alterra, Wageningen University and Research Centre, The Netherlands.
- Pollen, N.L., Simon, A., 2003. A new Approach for Quantifying Root-Reinforcement of Streambanks: the RipRoot, American Geophysical Union, Fall Meeting 2003, abstract #H52A-1174.
- Samani, J.M.V., Kouwen, N., (2002), Stability and erosion in grassed channels, *J. Hydr. Engrg., ASCE*, 128(1), 40-45.
- Shields, A., 1936. Anwendung der Aehnlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung, Mitteilungen der Preussischen Versuchsanstalt für Wasserbau und Schiffbau, Heft 26, Berlin NW 87.
- Sprangers, J.T.C.M., 1999. Vegetation dynamics and erosion resistance of sea dyke grassland, *Doctoral Thesis*, Wageningen Agriculture University, Wageningen, The Netherlands.
- Temple, D.M., 1999. Flow resistance of grass-lined channel banks. *Applied Engineering in Agriculture*, 15(2), 129-133.
- Van der Meer, J.W., 2007. Workpackage 3: Development of alternative overtopping-resistant sea defences, Phase 3: Design, construction, calibration and use of the wave overtopping simulator, Rijkswaterstaat, Delft.
- Van der Meer, J.W. Verheij, H.J., Lindenberg, J., Van Hoven, A., 2007. Wave overtopping and strength of the inner dike slopes; Predictions, [in Dutch], INFRAM, Marknesse, The Netherlands.
- VTV, 2006. Safety assessment of the primary flood defences [in Dutch], Ministry of Transport, Public Works and Water Management, Rijkswaterstaat, Delft.
- Winterwerp, J.C., Van Kesteren, W.G.M., 2004. *Introduction to the physics of cohesive sediment in the marine environment*, Elsevier, Amsterdam.
- Wu, T.H., McKinnell, W.P. III, Swanston, D.N., 1979. Strength of tree roots and landslides on Prince of Wales Island, Alaska. *Canadian J. of Geotechnical Res.* 16(1), 19-33.