A SIMPLE EMPIRICAL MODEL FOR SHIELDS PARAMETER ESTIMATION IN THE SWASH ZONE

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Abstract

A new approach for estimating Shields parameter in the swash zone is proposed. Effects of in-exfiltration on the effective weight of surficial sands caused by the vertical pressure gradient-induced seepage force were proved to be insignificant on sediment movement in the swash zone. The new model is based on the altered bed shear stress and the effect of beach slope. The enhanced bed shear stress (boundary layer thinning) acts as an onshore mobilizing force and the beach slope-related particle gravity plays a role as a resisting force in the uprush process, whereas an opposite scenario with a reduced bed shear stress (boundary layer thickening) occurs in the downwash when the particle gravity supports sands moving offshore.

Key words: Swash zone, Shields parameter, in-exfiltration, effective weight, bed shear stress, beach slope

1. Introduction

The swash zone, as a part of beachface intermittently covered and exposed by uprush and backwash, is one of the most challenging fields in coastal engineering. This is ascribed to the highly dynamic feature of the swash zone, including the complicated hydrodynamics and morphodynamics in this particular region. The uprush is driven by the strong roller that develops on wave breaking, whereas backwash is essentially gravity driven (Petti and Longo, 2001). Waves and currents coexist here with plenty of turbulence generated mainly by breaking waves and partially by the bottom friction. Accordingly, investigation on the sediment transport and beach topography evolution in the swash zone becomes difficult. Recently, a large amount of laboratory experiments (Foote and Horn, 1999; Steenhauer et al., 2011; Cáceres and Alsina, 2012) and field measurements (Masselink and Hughes, 1998; Larson et al., 2004; Blenkinsopp et al., 2011; Power et al., 2011) were conducted using various updated measuring facilities, approaches, and data processing techniques. In parallel, different numerical models were also developed for simulating various specific phenomena in the swash zone (Brocchini, 2006; Calantoni et al., 2006; Barnes and Baldock, 2010). The corresponding results were discussed in several review papers by focusing on different aspects, e.g., turbulence effects by Longo et al., (2002), beach groundwater flow by Horn (2006) and swash zone morphodynamics by Masselink and Puleo (2006). General reviews on the swash zone processes can also be found in Butt and Russell (2000), Elfrink and Baldock (2002) and Puleo and Butt (2006).

The present study pays attention to the sediment transport in the swash zone. Sediment movement under the swash of uprush and backwash includes various transport modes (Masselink and Puleo, 2006), i.e., suspended load (at the beginning of uprush caused by the external turbulence induced from the broken bore), bedload (in the middle of uprush and backwash) and sheetflow (at the beginning of uprush and the end of backwash due to large bottom velocities). Interactions between hydro- and morpho-dynamics impede our understanding on the physical essence of the phenomenon. According to the degree of detail at which different processes are resolved and in the computational requirements, three different modeling concepts were categorized: empirical model, simplified deterministic model and detailed deterministic model (Elfrink and Baldock, 2002). The flow field in the swash zone is non-stationary with the presence of a mean oscillatory flow and several effects such as macro turbulence induced oscillations (Petti and Longo, 2001). In the field, swash zone fluid motion is often a three-phase fluid flow, i.e., air, water and sediment.

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To reveal all potentially important details of the flow and sediment transport in the swash zone, a Reynolds Averaged Navier–Stokes (RANS) type model (Christensen et al., 2000; Christensen and Deigaard, 2001), or a sophisticated multi-phase flow model (Liu and Sato, 2005a, 2006; Longo, 2005), is needed, especially for the sheetflow regime.

In this study, however considering the purpose for engineering practice, we investigated the swash zone sediment movement mechanism on the basis of the simple empirical model and presented a newly modified Shields parameter in the swash zone, which is on the basis of the altered bed shear stress and the effect of beach slope (sand gravity). Section 2 revisits two existing works by scrutinizing their empirical models. Section 3 proposes a modified Shields parameter for the sand transport estimation in the swash zone. Discussions and further perspectives on the modified Shields parameter are carried out in Section 4, followed by final conclusions.

2. Existing Models

2.1. *Nielsen model and Turner-Masselink model*

It has been suggested by a number of researchers that influence of infiltration during uprush and exfiltration during backwash on sediment transport in the swash zone may be significant owing to the following two effects: increase or decrease of the effective weight of surficial sediment particles corresponding to the stabilization and destabilization phases, respectively, and increase or decrease of the shear stress exerted on sediment particles corresponding to the boundary layer thinning and thickening phases, respectively (Nielsen, 1997; Turner and Masselink, 1998; Nielsen et al., 2001; Butt, et al., 2001). To account for such combined effects on the sediment transport, various empirical models were proposed on the basis of the modified Shields parameter, in which the Nielsen model (Nielsen, 1997, hereafter referred to as N97) and the Turner and Masselink model (Turner and Masselink, 1998, hereafter referred to as TM98) are two typical ones.

N97 model suggested the use of the modified Shields parameter θ in a form,

$$\theta = \frac{u_{*0}^2 \left(1 - \alpha \frac{w}{u_{*0}}\right)}{gd\left(s - 1 - \beta \frac{w}{K}\right)} \tag{1}$$

in which u_{*0} is the bottom shear velocity without seepage, w denotes vertical seepage velocity with positive values corresponding to the exfiltration process, g represents the acceleration due to gravity, d is the median sand size, K is the sediment hydraulic conductivity or the permeability coefficient in soil mechanics, and $s = \rho_s / \rho$ is the specific gravity of the sediment, where ρ_s and ρ are the sand and fluid densities, respectively. In Eq. (1), α and β are two dimensionless coefficients giving the strength of the shear stress increase and the downward drag, respectively. Nielsen et al. (2001) proposed the following values for these two parameters, $\alpha = 16, \beta = 0.4$ according to the previous experimental studies. Comparing with the original Shields parameter θ_0 without ventilation,

$$\theta_0 = \frac{u_{*0}^2}{gd\left(s-1\right)} \tag{2}$$

the modified Shields parameter shows, in a linearized form, the increase with negative w related to infiltration and decrease with positive w related to exfiltration of the bottom shear stress in the numerator. The extra term in the denominator represents the effects of w on the effective weight of surficial grains, with negative w (infiltration) corresponding to an increase on the effective weight, and vice versa.

TM98 model considered these two aspects independently. As for the effect from the vertical seepage force which may change the effective weight of surficial grains, based on Martin and Aral (1971), they proposed the following expression,

$$\frac{W}{W_0}=1-\frac{1}{2(s-1)}\frac{w}{K} \tag{3}$$

to account the relative weight of surficial sediments, where W is the weight of surficial sediment in the presence of vertical through-bed flow and W_0 represents the corresponding value without the seepage flow. When estimating the effect of the altered bed stress, they followed the relative bed stress formula of Conley and Inman (1994),

$$\frac{\tau}{\tau_0}=\frac{bV/f_w}{\exp(bV/f_w)-1} \tag{4}$$

in which τ and τ_0 are bed stresses with and without vertical seepage flows. Coefficient b was found to be equal to 0.9 according to Conley and Inman (1994). Nevertheless, TM98 utilized a value of 2 according to Mickley et al., (1954) after a rough analysis for the steady flow. The flow ventilation parameter V is defined as the ratio between the seepage velocity w and the near bed velocity u, $V=w/u$. The sign of V indicates whether exfiltration ($V>0$) or infiltration ($V<0$) occurs concurrently with the near bed flow. Conley and Inman also claimed the flow ventilation parameter $|V|$ will not exceed the value of 10^{-3} for geophysically reasonable permeability. In Eq. (4), symbol f_w represents the wave friction factor, which is difficult to determine accurately (Hughes, 1995) and even varies over the swash cycle (Puleo and Holland, 2001).

In TM98, combined effects on the relative Shields parameter from seepage flow are determined by the simple summation of Eqs. (3) and (4) as,

$$\frac{\theta}{\theta_0}=\left(1-\frac{1}{2(s-1)}\frac{w}{K}\right)+\left(\frac{bV/f_w}{\exp(bV/f_w)-1}\right) \tag{5}$$

2.2. *Discussions on N97 and TM98 models*

Regarding Eq. (5), two points have to be figured out for this expression. One is that when taking into account the combined effects of seepage flow on the relative Shields parameter, authors just simply added Eqs. (3) and (4) to yield Eq. (5). This is weird considering that Eq. (5) presents a value of 2 even in case that there is no swash infiltration-exfiltration influence. Under such condition, the vertical seepage velocity w (thus the flow ventilation parameter V) is equal to zero and $\exp(bV/f_w)-1\rightarrow bV/f_w$ when $bV/f_w\rightarrow 0$. This results in a relative Shields parameter $\theta/\theta_0=2$, which is inconsistent with the concept that θ/θ_0 should be equal to unity under such non-percolation condition. Another point is that Eq. (3) induces a large weight of surficial sediments in case of infiltration ($w<0$), which should cause decrease in Shields parameter with respect to the inverse relationship between the Shields parameter and the immersed sediment weight in Eq. (2). Opposite scenario should be regarded for the exfiltration case. However, the first term in the right hand side of Eq. (5) does not present such tendency (opposite in fact). Considering these two points in TM98 model and analogue to N97 model, Eq. (5) could be modified as,

$$\frac{\theta}{\theta_0}=\frac{bV/f_w}{\left(\exp\left(bV/f_w\right)-1\right)\left(1-\frac{1}{2\left(s-1\right)}\frac{w}{K}\right)} \tag{6}$$

to avoid the aforementioned two discrepancies.

As for N97 and TM98 models, whether the effect of in-exfiltration on sediment movement is really significant in the swash zone is still far from complete understanding. Many previous experimental studies (Martin, 1970; Carstens et al., 1976) suggested that for practical situations, apart from an upward gradient near the critical value for fluidization or liquefaction, the effect of vertical pressure gradients into or out the bed leading to the seepage force acting on the surficial bed particles, may be insignificant for sediment movement. Nielsen et al. (2001) found that the infiltration effect is likely to be very weak and hardly measurable. In case of exfiltration, seepage out of a bed does not affect incipient motion measurably because the seepage force is lost once the sediment particle rocks (Martin, 1970).

A remaining question is whether the upward vertical hydraulic gradient can be so large to fluidize bed materials in the swash zone. According to Sumer and Fredsøe (2002), there are two kinds of liquefactions: the residual liquefaction caused by the buildup of pore pressure and the momentary liquefaction caused by the upward vertical pressure gradient in the soil during the passage of a wave trough. Residual liquefaction commonly occurs during earthquakes (Zen and Yamazaki, 1990). To build up the pore pressure, the frequency of the cyclic loading should be high, and the pore-pressure accumulation occurs generally in undrained soils with a low permeability, such as mud with grain size being smaller than 0.63 μm. Another requirement is the sand skeleton or matrix should be initially loosely packed to allow the rearrangement of the soil grains at the expense of the pore volume of the soil. However, in a field situation, residual liquefaction will not occur under the wind wave or swell action because of seabed sand long time history of wave experience, which makes sand grains become much more densely packed. As for the momentary liquefaction, it is a local and instantaneous phenomenon caused by the relatively extreme wave conditions, e.g., storm surge or tsunamis (Yeh et al., 2013), which normally will not occur in a completely saturated soil with a large permeability. From the numerical calculation of Okusa (1985) and Zen et al., (1998), under certain wave and soil conditions, the maximum momentary liquefaction depth can be so large up to several meters, which is quite different from normal measurements in the swash zone. According to the writer's knowledge, up to now, there is no obvious evidence from field observations to show that the liquefaction do occur in the swash zone under normal wave conditions. From their field investigations of the swash-induced pressure gradient, Baldock et al. (2001) found the near-surface (~ 10 mm) hydraulic gradients can be so large to overpass the threshold liquefaction value proposed by Packwood and Peregrine (1980) based on Madsen (1974), and may fluidize a sediment bed. Nevertheless, instead of liquefaction, Baldock et al. contributed this to the nonhydrostatic pressures developing within the sheetflow layer that occurs during the backwash since the sheetflow layer thickness is also in the order of 10 mm (Horikawa et al., 1982; Liu and Sato, 2005b). Hence, we argue that the liquefaction phenomenon, neither the residual one nor the momentary one, will occur in the swash zone under natural wind wave or swell conditions.

Further considering the vertical seepage flow-related infiltration and exfiltration in the swash zone, these two processes are prevailed in the shoreward of the swash zone, where the sand beach is relatively 'dry' compared to the position located at the seaward limit of the swash zone. In the seaward swash zone, the beach sediments are expected to be nearly close to full saturation (Baldock et al., 2001), which is ascribed to the situation that this part of beachface is under the ground water table. At the seaward limit, the measured vertical hydraulic gradients are small, typically in the range of 0-0.2 (Baldock et al., 2001). Consequently, the vertical seepage flow in this part plays a minor role on sediment movement. On the other hand, in the shoreward swash zone, the sand beach saturation decreases, i.e., partially saturated, since the beachface is above the ground water table or capillary fringe level. As a result, more significant in-exfiltration flows are expected. However, in this region, the water is rather clear with almost no sand particles in movement (Masselink and Puleo, 2006). Therefore, effects from in-exfiltration on sediment movement are also neglectable in this part although the measured vertical hydraulic gradient is relatively large here. With respect to the numerical simulation, Packwood (1983) developed a model to simulate the bore hydrodynamics over a rigid, but permeable bed, and found that comparing to the impermeable bed result, the porous bed has very little effect in the uprush phase, whereas certain differences can be observed during backwash due to a significant loss of water mass in the uprush. However, Packwood's model analyzed the percolation of the run-up on an initial dry beach, which artificially exaggerates the water loss in the uprush and is quite different from the real situation in the swash zone where certain pore water always stays inside the sand bed. Hence, the general bore hydrodynamics in the swash zone may not significantly 'feel' the influence from infiltration or exfiltration.

On the basis of these descriptions, we conclude that regarding the increase or decrease of the effective weight of surficial sand particles caused by the vertical seepage forces, effects of in-exfiltration on sediment movement are insignificant in the swash zone. Therefore, the extra term in the denominator of N97, Eq. (1), and in TM98, Eq. (3), should be neglected with respect to the swash zone sand movement.

3. Modification on the swash zone Shields parameter

Following above discussions, change on the effective surficial particle weight from in-exfiltration can be ignored. The effect with respect to the boundary layer thinning and thickening (corresponding to the altered bottom shear stress) is still remained. Conley and Inman (1994) conducted detailed measurements on the bottom boundary layer velocity, near-bed turbulence and bed stress over a rigid permeable bed under oscillatory flows. They found infiltration with flow into the bed enhances the near-bed velocities and bed stress while exfiltration with flow out of the bed leads to a reduction in these quantities. Consequently, this ventilated boundary layer induces a net velocity in the direction of the oscillatory flow which is subject to infiltration, i.e., a landward directional net velocity for a swash movement. Following Mickley et al. (1954), Conley and Inman proposed the ratio of mean bed stress between permeable and impermeable bed as Eq. (4), the one used in TM98 model.

Both N97 and TM98 models take into account the increase or decrease of bed shear stress during the uprush or backwash phases. This mechanism causes sand particles move in the onshore direction, which induces beach accretion. Because effects of in-exfiltration on the effective weight of surficial grains are insignificant, the remaining question is how the beachface counteracts such landward sand transport tendency caused by the altered bed shear stress. This is attributed to the beachface morphology, i.e., beach slope. One of the most characteristic features of the beachface in the swash zone is its steep gradient compared to the rest of the beach profile, e.g., surf zone. This is due to swash motion tending to favor onshore, rather than offshore sediment transport (Masselink and Puleo, 2006). For such a steep beach slope, the gravity force plays a role as a resisting force in the uprush and a mobilizing force in the downwash. Overall, the sand gravity is trying to drag sediment particles seaward. An effective Shields parameter can be formulated to account for the sloping bed effect (Fredsøe and Deigaard, 1992),

$$\frac{\theta}{\theta_0} = \cos\gamma\left(1 \mp \frac{\tan\gamma}{\tan\phi}\right) \tag{7}$$

where γ represents the beach slope angle, ϕ denotes the friction angle of the sediment. Inside the bracket of Eq. (7), a negative sign presents the case for uprush and a positive sign is for downwash. In this expression, the steeper the beach face, the more onshore sediment transport is impeded and the more offshore sand movement is supported.

Therefore, a dynamic balance between the altered bed shear stress (Eq. 4) and the beach slope effect (Eq. 7) could be expected, which leads to the equilibrium beachface in the swash zone. As a result, a modified Shields parameter for the swash zone sediment transport is proposed as,

$$\theta = \theta_0 \cos\gamma\left(1 + \frac{\tan\gamma}{\tan\phi} sign(V)\right)\frac{bV/f_w}{\exp\left[bV/f_w\right]-1} \tag{8}$$

where in case of $V > 0$ corresponding to the downwash phase, increase or decrease on the effective Shields parameter is implemented through the term inside the bracket (for the beach slope effect) or the last ratio term (for the altered bed shear stress effect). An opposite scenario occurs when $V < 0$ corresponding to the uprush process. Shields parameter on a flat and impermeable bed θ_0 can be estimated using Eq. (2).

4. Discussions and Perspectives

4.1. *Discussions*

In a preliminary analysis, we assume that the flow ventilation parameter V is varying between -0.001 and +0.001, which is a reasonable range for the geophysical permeability (Conley and Inman, 1994), and the beach slope angle is varying from a flat bed of 0 degree to a steep reflective beach of 10 degree. In calculation, we further assumed the friction angle of the sediment particle is $\tan\phi = 0.6$, coefficient b in Eq. (4) is chosen as 2.0 after Mickley et al., (1954), and the wave friction factor is simply kept as a constant $f_w = 0.01$ following Turner and Masselink (1998).

Figure 1 illustrates the relative Shields parameter θ/θ_0 distribution after considering the effect from the altered bed shear stress and the beach slope. Same as previous descriptions, Figure 1 highlights the influence from these two factors. That is, considering the altered bed stress, θ/θ_0 is larger than unity during the uprush process in which the boundary layer thinning phenomenon enhances the bed stress; whereas, θ/θ_0 is smaller than unity during the downwash process in which the boundary layer thickening inhibits the development of bed stress. The larger the absolute value of the flow ventilation parameter $|V|$, the more sufficient influence on the Shields parameter is observed. As for the beach slope effect, the result is just opposite with relative Shields parameter being smaller than unity in the uprush and larger than unity in downwash owing to the effect from sand particle gravity. The beach slope effect on the relative Shields parameter becomes significant with the increase of beach slope angle.

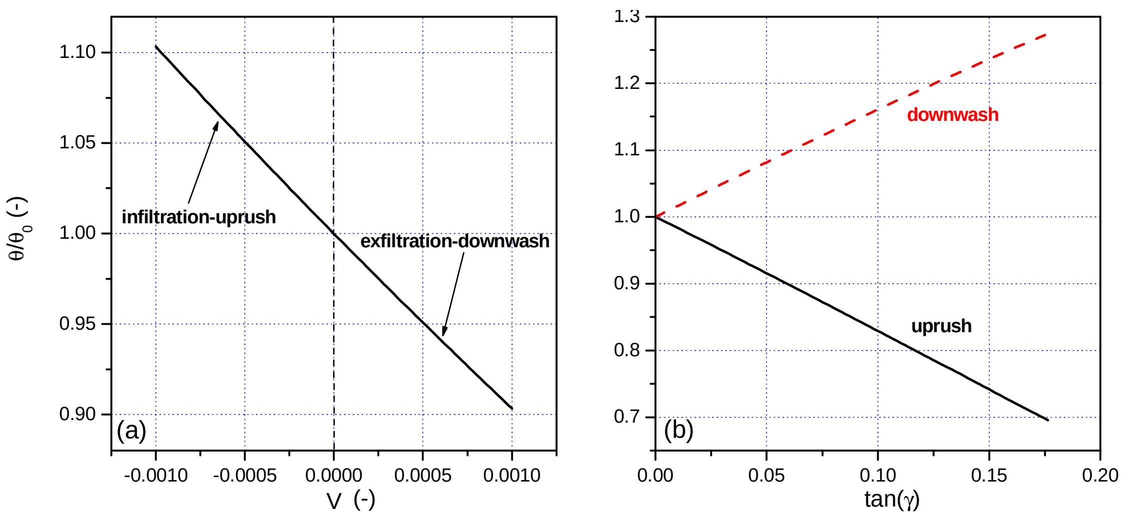

Figure 1. Relative Shields parameter distribution after the altered bed shear stress (a) and the beach slope effect (b).

Figure 2 demonstrates the contour line distribution of the relative Shields parameter during the uprush and downwash processes, respectively. In Fig. 2a (uprush phase), for the same beach slope $\tan(\gamma)$, the larger the absolute ventilation parameter $|V|$, the larger θ/θ_0, whereas for the same value of $|V|$, a larger the value of $\tan(\gamma)$ leads to a smaller θ/θ_0. Along the contour line of '1.0', effects from the altered bed shear stress and the beach slope appropriately counteract with each other resulting no change on the Shields parameter (same as the Shields parameter on a flat and impermeable bed, Eq. 2). Below this contour line at the lower left corner of Fig. 2a (refer to as part I), θ/θ_0 is larger than unity which means the effect from the altered bed stress caused by the boundary layer thinning phenomenon is more significant than that from the beach slope effect; whereas above the '1.0' contour line at the upper right region of Fig. 2a (refer to as part II), θ/θ_0 is smaller than unity indicating the effect of beach slope is more significant. This is straightforward because in part I, the beach slope is relatively mild (a dissipative beach), and the Shields parameter is predominated by the enhanced bed stress which moves sand particles onshore and results in a steep beachface during the uprush process, whereas in part II, the beach slope is relatively steep (a reflective beach), and the Shields parameter is more controlled by the beach slope effect (the sediment self-gravity), which tends to transport sands offshore and flats the beachface during the uprush process.

Figure 2b shows the relative Shields parameter distribution during the downwash process. At the lower right corner, the relative Shields parameter is smaller than unity indicating that bed stress reduction plays a more significant role than that from the beach slope influence, and sand particles remain onshore. At the upper left region of Fig. 2b, an opposite scenario occurs with sands tending to move offshore. This is in agreement with the understanding that the steeper the beach slope, the more offshore sediment movement prevails due to the gravity effect, which finally results in a mild beachface. A dynamic balance on the effective Shields parameter in the swash zone will be achieved in case that the relationship between the beach slope and the ventilation parameter is located on the '1.0' contour line in Fig. 2b, where the traditional Shields parameter, i.e., Eq. (2), can be directly applied.

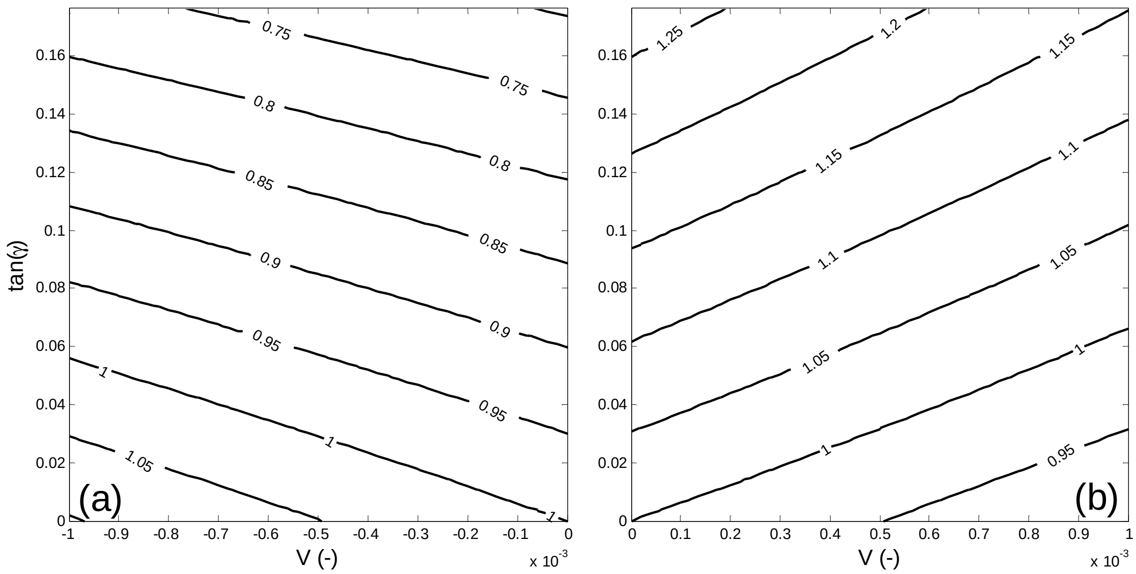

Figure 2. Relative Shields parameter contour lines in the uprush (a) and downwash phases (b).

4.2. *Perspectives*

A comparison with experimental data is needed for validating the proposed model. However, evaluation of sediment transport models in the swash zone against measured data is rather difficult (Elfrink and Baldock, 2002). Field measurements usually only cover a small range of hydrodynamic and sediment transport conditions. Laboratory experiments have other restrictions such as scale effects. Taking into account the newly developed Shields parameter in the swash zone, Eq. (8), the beach slope γ can be easily measured in the field. However, it is rather difficult to determine the magnitude of the vertical seepage velocity w, thus the flow ventilation parameter V, even under laboratory conditions. For natural sand beaches and assuming a laminar movement of groundwater, w can be determined using Darcy's law for an unconfined, homogeneous and hydraulically isotropic aquifer,

$$w = -K\frac{\partial h}{\partial z} \tag{9}$$

where h represents the hydraulic head, which can be measured through various piezometers (Turner and Masselink, 1998; Baldock et al., 2001). The remaining question is how to determine the value of sediment hydraulic conductivity or soil permeability coefficient K. Lambe and Whitman (1969) argued that the value of K varies from the order of 10^{-9} cm/s of practically impermeable soil, e.g., clay, up to the order of 1 cm/s of highly permeable soil, e.g., gravel. Puleo and Butt (2006) pointed out that field estimation of parameter K spans three orders of magnitude and there are presently no means to determine its spatial variability. Many factors affect the value of K, mainly including the sand size and grading, void ratio, soil skeleton structure, degree of soil saturation and soil mineral ingredients. Turner and Nielsen (1997) applied the empirical formula of Krumbein and Monk (1942) to calculate the value of K for well-sorted sands. Later, Butt et al., (2001) applied the empirical formula of Bear (1972), which is regarded as the most up-to-date formula and shows the superiority over the old method of Krumbein and Monk (1942). Applying Krumbein and Monk (1942), values were an order of magnitude smaller than those from experimental measurements (Baird et al., 1998). However, all these empirical formulae have their limitations by considering this very complex phenomenon in an oversimple way. These formulae also do not take into account the spatial variability of K (heterogeneous feature of sand structure). Determining the value of K through such a rough and uncertain approach, then directly applying it to the swash zone sediment movement, is rather unsuitable and may result in an unrealistic conclusion.

Most of the previous experiments were only for the direct pore pressure measurement within the sand bed at a few vertical locations (Turner and Nielsen, 1997; Turner and Masselink, 1998; Baldock et al., 2001; Butt et al., 2001). The vertical pressure gradient was obtained through the pore pressure time series of several measured points. Subsequently, investigations were conducted by applying some empirical formulae, such as the one for hydraulic conductivity. There was no direct and firm connection between the experimental data (pore pressure) and various modifications on the Shields parameter. On the other hand, all field or laboratory facilities were intrusive for the existing experimental measurements. Effects from instruments can also be significant, especially for the pore-pressure measurement in the surface layer of a sand beach, e.g., Baldock et al., (2001) performed the measurement within an upper 40 mm of the bed with the uppermost measuring point at z=-5 mm. Within such a surface layer, influence from the existence of facilities is inevitable, and the local flow field is modified in the vicinity of facilities resulting in some unwished phenomena, such as scouring. Experimental validation on the modified Shields parameter in the swash zone is definitely needed, which would be anyway difficult due to the nature of the phenomenon. Therefore, it is highly recommended to conduct reliable measurements on relevant parameters, such as the hydraulic conductivity, before the measured data being applied to the model's validation.

5. Conclusions

Revisiting two existing empirical models on the swash zone Shields parameter, the Nielsen (1997) model and the Turner and Masselink (1998) model, were conducted. These two models are based on the concepts that uprush-related infiltration increases the effective surficial sand particle weight, and simultaneously increases the bed shear stress due to the boundary layer thinning, whereas the opposite scenario occurs in the downwash-related exfiltration process. However, effects of in-exfiltration on the effective weight of surficial sands caused by the vertical pressure gradient-induced seepage force were proved to be insignificant on sediment movement in the swash zone. Taking into account the liquefaction mechanism, it is shown that this phenomenon is hard to occur in swash zone sand beaches under natural wind wave or swell conditions on the basis of various field observations.

Following the aforementioned insights, a new approach for estimating Shields parameter in the swash zone is proposed, which is based on the co-action of the altered bed shear stress and the beach slope effect. In the uprush, the enhanced bed shear stress acts as a mobilizing force to move sand particles to the onshore direction whereas the beach slope (sand self-gravity) plays a role as a resisting force to maintain sands offshore. The opposite scenario occurs during the downwash phase. A dynamic function between these two effects determines the sediment movement direction and shapes the beachface profile in the swash zone. Along the '1.0' contour lines in Fig. 2, these two mechanisms receive a balance between each other and the modified Shields parameter becomes equal to the traditional one (the flat and impermeable bed case).

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