UPDATED "GRAB AND DUMP" MODEL FOR SEDIMENT TRANSPORT UNDER ACCELERATION SKEWED WAVES

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Abstract

This study focuses on the grab and dump model, a simple sediment transport model first developed by Nielsen (1988). Despite showing overall good model performance for fine sediment, there were some improvements required for the coarse sediment cases. Analysis of acceleration skewness from the original dataset showed a positive correlation with the sediment flux, and this relation was subsequently applied to model development. A model based on shear stress with an acceleration component significantly improved the model performance for the coarse sediment. Additional enhancements of the model include applying a critical shear stress term and differentiating between suspended sediment transport and ripple migration. The model was also compared to an existing semi-unsteady model (van der A et al., 2010b) which showed that it was able to predict sediment flux to an similar accuracy.

Key words: Ripples, sediment transport, ripple migration, shear stress, acceleration skewness,

1. Introduction

With expected changes in intensity, frequency, and duration of extreme weather events (IPCC, 2012), understanding coastal sediment transport becomes more crucial. An area of sediment transport which is still not well understood is onshore sediment transport, which is a vital part of predicting beach recovery. Models for beach recovery require a good sediment transport model over ripples. The ripples which are focused upon in this paper are vortex ripples, which have significant effects on boundary layer structure and hence sediment transport (Nielsen, 1992). Unlike sediment transport with no bed forms, movement of sediment over ripples is dominated by the vortices which form on each side of the ripple and their subsequent ejection at flow reversal. It has been suggested that the sediment transport over ripples is a combination of suspended sediment and ripple migration. The nature of sediment suspension over ripples seems also counter-intuitive, as the sediment is transported in the opposite direction to the velocity which caused the sediment entrainment. The processes of sediment suspension and ripple migration occur concurrently, which pose significant challenges for model formulation.

There are a number of sediment transport models for shore normal transport over rippled beds, some of which take into account wave shape, such as acceleration skewness (van der A et al., 2010b). There is also an increasing number of models employing shear stress as the driver of sediment transport in lieu of velocity, which has traditionally been more prevalent. In unsteady models, the phase shifts between velocity and shear stress becomes important. The half-cycle concept of Dibajnia & Watanabe (1992) has been incrementally upgraded over the years (e.g. da Silva, et al., 2006; van der A, et al., 2010b; Watanabe & Sato, 2004) amongst existing semi-unsteady models. Another semi-unsteady model is Nielsen's (1988) grab and dump model, which performed well compared to the more traditional gradient diffusion and convective sediment transport models. The biggest advantage of this model is its simplicity, and being able to predict sediment transport rates while bypassing the diffusion/convection process. While the grab and dump model largely succeeded in predicting sediment flux magnitude, it did not always predict the transport direction correctly under conditions tested by Nielsen (1988). The main objective of this paper is to upgrade the grab and dump model, making use of all the data that now exists.

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2. Background

2.1. *The grab and dump model*

The grab and dump model is a model which was developed to predict shore normal sediment flux over horizontal rippled beds. The model is based on parameters which represent parcels of sediment which become entrained ("grabbed") at times of free stream reversal (Nielsen, 1988). One parcel moves a distance A onshore and the other moves distance A offshore, where A is the semi-excursion length. The sediment flux is calculated using equation (1).

$$q_s = C_{0s} w_s \left(A_b - A_f\right) A \tag{1}$$

Where A_b and A_f are backwards (offshore) and forwards (onshore) entrainment coefficients respectively, w_s is the settling velocity, and C_{0s} is the reference concentration for a sine wave of velocity amplitude of the first harmonic, U_1 (Nielsen, 1988). The sediment transport is directed in the opposite direction to the velocity that entrained it. The entrainment coefficients, as described by Nielsen (1988) are the velocity amplitude to the sixth power, as the reference concentration was believed to be proportional to the cube of the Shields parameter. U_{max} is the maximum velocity, U_{min} is the minimum, and these are scaled by U_1.

$$\left(A_f, A_b\right) = \left[0.5\left(\frac{U_{max}}{U_1}\right)^6, 0.5\left(\frac{U_{min}}{U_1}\right)^6\right] \tag{2}$$

The reference concentration is a function of the Shields parameter modified for flow over ripples, θ_r, (Nielsen, 1986) shown in equation (3). The Shields parameter needs to be adjusted for the presence of ripples, as the flow is enhanced at the crest of the ripple; this is shown in equation (4). η/λ is the ratio of ripple height to ripple length and $\theta_{2.5}$ is the grain roughness Shields parameter

$$C_0 = 0.005\, \theta_r^{\,3} \tag{3}$$

$$\theta_r = \frac{\theta_{2.5}}{(1-\pi\eta/\lambda)^2} \tag{4}$$

The model was applied to Schepers (1978) data, from a small scale wave flume, which measured the sediment flux for three different median sediment sizes (d_{50}) – 0.125mm, 0.25mm and 0.465mm. The velocity used in the wave flume was in the form of waves with two harmonics and a phase shift angle between the harmonics. Nielsen (1988) found that while the model was able to predict both the magnitude and cross-shore variation of the sediment flux accurately for the finest sediment (d_{50}=0.125mm), it was only able to predict the magnitude for the coarsest sediment (d_{50}=0.465mm). This is shown in Figure 1 below.

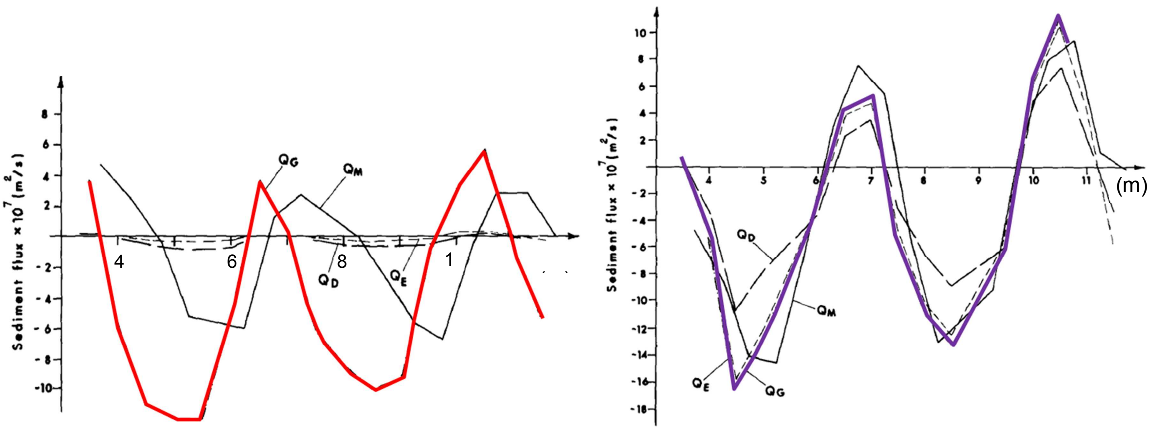

Figure 1. Predicted sediment flux from grab and dump model (bolded) for d_{50}=0.465mm (left) and d_{50}=0.125mm (right) from Nielsen (1988). Q_M is the measured sediment flux and the x-axis is the measurement from the wave maker (in metres).

2.2. *Analysis of results from coarse sediment*

The discrepancy in model performance between the two sediment sizes suggests that there may be differences in sediment transport behaviour. Schepers (1978) had even noted the sediment transport behaviour between the finer sediment and coarse sediment was markedly different. Additionally, Bijker et al. (1976) found that coarser sediment was influenced by the asymmetry in the orbital velocity. Hence sediment flux data was analysed by comparing their relationship with velocity skewness and acceleration skewness. The skewness used in this instance refers to the Fisher skewness, shown in equation (5).

$$skewness = \overline{u^3}/\left(\overline{u^2}\right)^{1.5} \tag{5}$$

The data points are coloured with respect to the magnitude of q_s in Figure 2. While q_s for the finer sediment (test 6) shows a negative correlation to velocity skewness, q_s from the coarser sediment case (test 30) shows a positive correlation with acceleration skewness. This explains the better q_s prediction for the fine sediment, as the grab and dump model (Nielsen, 1988) is based on velocity only. The positive correlation of the sediment flux with acceleration skewness for the coarse sediment suggests an acceleration term may be more suitable than velocity for relatively coarse sediments. This requires a revision of the original model.

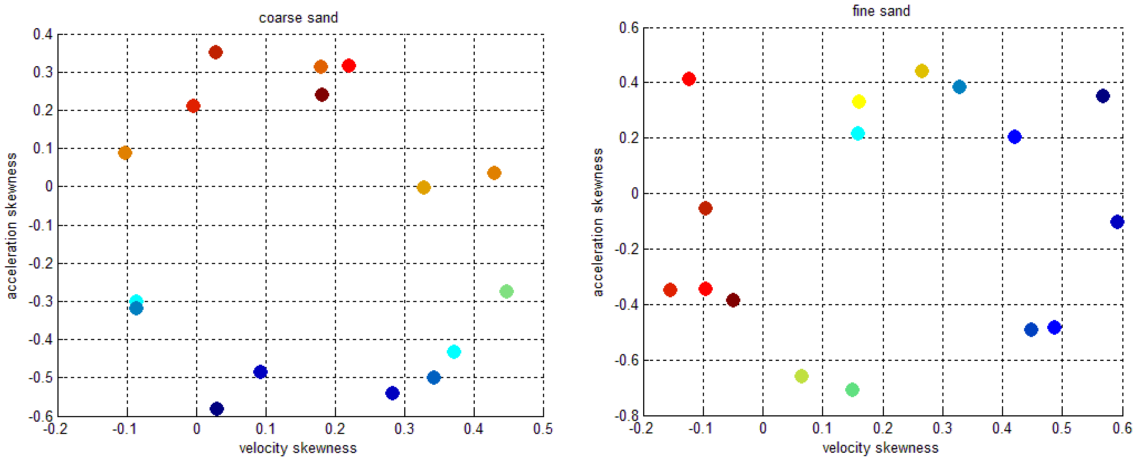

Figure 2. Velocity skewness and acceleration skewness for tests 30 and 6 with d_{50}=0.465mm and d_{50}=0.125mm respectively; q_s ranges from most positive (dark red) to most negative (dark blue). Data from Schepers (1978).

The incorporation of an acceleration term in wave sediment transport models is not a novel concept. Waves tend to exhibit sawtooth type shapes (steep front face, gently sloping rear face) prior to breaking in the surf zone, and these wave shapes have been found to affect the sediment transport direction (King, 1991). The positive correlation of the acceleration skewness with sediment flux has also been observed by Drake & Calantoni (2001) and has led to a range of acceleration-based sediment transport models (e.g. Nielsen, 2006; Calantoni & Puleo, 2006). The significance of the acceleration term has been related to the horizontal pressure gradient caused by the passage of a wave, which leads to momentum transfer to the near-bed layer (Calantoni & Puleo, 2006). Whether the acceleration is a suitable proxy for the horizontal pressure gradient, or contributes directly to the shear stress (Nielsen, 2006), it is clear that the fluid acceleration has a significant impact on the sediment transport rate.

There have been more updates to include acceleration skewness in existing sediment transport models in the last decade such as Watanabe & Sato (2004) extending the half-cycle model that was developed by Dibajnia & Watanabe (1992) to accommodate acceleration skewness. More recently van der A et al. (2010b) extended the model further and have succeeded in calibrating the model to a range of experiments in the SANTOSS dataset (van der Werf, et al., 2009). This has led to the present update of the grab and dump model in keeping with other updated models, and investigation of their comparative performance.

2.3. *Model development*

In order to incorporate the acceleration effects into q_s for the coarse sediment, the model formulation was revised. Instead of q_s being a function of the velocity, it was written as a function of the shear stress. Calculating the sediment flux based on shear stress was done through approximating the shear stress with an equation from Nielsen (1992), which is a function of both the free stream velocity u_∞ and du_∞/dt.

$$\tau(o,t) = \frac{1}{2}\rho f_{2.5} A(\cos\varphi_\tau\ \omega\ u_\infty(t) + \sin\varphi_\tau \frac{du_\infty}{dt}) \tag{6}$$

The $f_{2.5}$ refers to the wave friction factor with roughness equal to $2.5d_{50}$ and φ_τ is the phase shift, which is $\frac{\pi}{4}$ for laminar flows (Nielsen, 1992). For the coarser sediment cases, a phase shift of $\frac{\pi}{2}$ was used, which occurs when the shear stress term is dominated by the acceleration. The free stream velocity term in equation (6) was derived using $u(t) = Ae^{i\omega t}$, and not a Stokes wave which is commonly used in laboratory experiments. However this was considered to be a reasonable simplification for preliminary model formulation purposes.

The entrainment coefficients in the revised model were calculated with maximum and minimum shear stresses, scaled by the average shear stress to the 3rd power, similarly to equation (2).

$$\left(A_f, A_b\right) = \left[0.5\left(\frac{\tau_{max}}{\tau_{av}}\right)^3, 0.5\left(\frac{\tau_{min}}{\tau_{av}}\right)^3\right] \tag{7}$$

The q_s calculation was changed to equation (8) to reflect the positive correlation of the q_s to the acceleration, by adding the entrainment coefficients to maintain their respective directions.

$$q_s = C_{0s} w_s \left(A_b + A_f\right) A \tag{8}$$

2.3.1. *Applying threshold of sediment motion*

Similarly to traditional bed load formulas such as Meyer-Peter & Müller (1948), a critical Shields parameter at which sediment commences movement was specified in the revised grab and dump model in the hope that this may improve the sediment flux prediction. The critical Shields number was calculated using the non-dimensional sediment grain size as suggested by Soulsby (1997). When the Shields parameter is below the critical value, there was no sediment flux calculated. The proportion of the time that the threshold value was exceeded was calculated and applied as a multiplier to the entrainment coefficients in (7). The results from this modification to the model will be discussed in Section 3.

2.3.2. *Mixture of sediment sizes*

Depending on the sediment size distribution, sediment flux from both suspended sediment and ripple migration could occur. Calantoni & Puleo (2001) have suggested that one formula is insufficient to capture coastal sediment transport. Therefore some studies have calculated the sediment flux from each sediment transport mechanism separately (e.g. van der Werf, 2008; Traykovski, 1999). They are then combined to calculate the net sediment flux. In the case for the grab and dump model, the proportion of the suspended sediment flux, q_{ss}, can be calculated using the velocity-based original model, while the sediment flux due to ripple migration, q_r, can be calculated using the revised, shear stress-based model. Determining the percentage of the sediment, which gets transported by suspension or ripple migration, poses some challenges. Van der Werf et al. (2008) suggested the use of shear velocity to differentiate between the different sediment transport mechanisms.

In order to calculate the percentage of the sediment that is able to be suspended, the maximum sediment size that will be able to be entrained was calculated by the criterion for maximum settling velocity based on maximum skin friction (Fredsøe & Deigaard, 1992). Maximum skin friction was calculated using:

$$u_* = \sqrt{1/2\, f_{2.5}} A\omega \tag{9}$$

The maximum settling velocity can be estimated from:

$$w_{s,max} = 0.8u_* \tag{10}$$

The critical grain diameter d_{crit} can be calculated from formulas from Hallermeier (1981), as well as Migniot's (cited in Hallermeier, 1981) simple equation:

$$w_{s,max} = 125d_{crit} \qquad \text{(cgs units)} \tag{11}$$

As there is a range of skin friction factors and semi-excursion lengths for each test case in Schepers (1978), there is a range of d_{crit} values. For test 30, d_{crit} was found to be between 0.14mm and 0.37mm for both methods. According to the sediment size distribution curve from Schepers (1978), all of the sediment is larger than this d_{crit}, which suggests minimal contribution from q_{ss} to the total sediment flux.

q_r was also compared with the measured sediment flux from test 18 with a smaller sediment size, with d_{50} = 0.25mm. d_{crit} was calculated to be between 0.13 mm and 0.36mm. This represents quite a spread with the two different methods, with Hallermeier's (1981) equations suggesting a majority of q_{ss} (90 to 100%) and Migniot's (cited in Hallermeier, 1981) method suggesting a majority of q_r (95 to 100%). q_{ss} and q_r were weighted by the respective percentages and compared in Figure 3. The measured sediment flux shows a better fit with Mignot's method, which suggests there is a higher percentage of q_r for this test case.

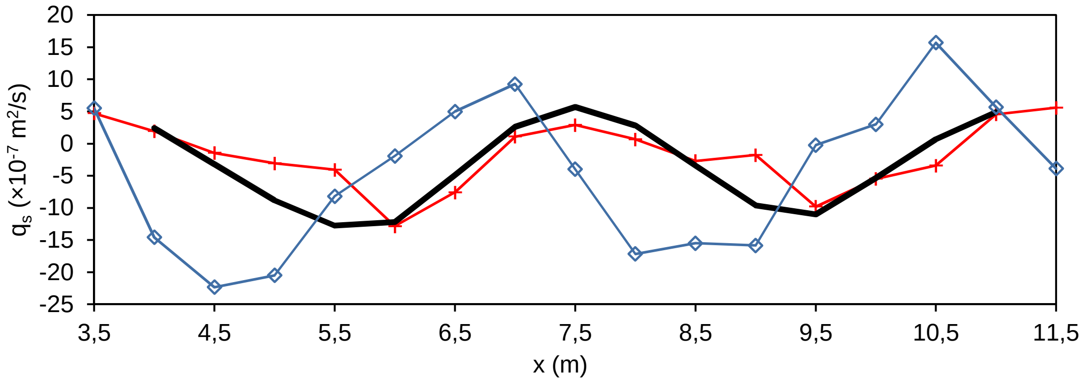

Figure 3. Measured data (thick black line), predicted sediment flux using percentages from Hallermeier (squares) and Migniot (crosses).

The percentage of suspended sediment was also calculated for the experiments of Hurther & Thorne (2011), as it was directly measured in their experiments. From their observations, q_{ss} is approximately 40% and q_r is approximately 60%. Using Migniot's equation (11), 36% is predicted to be q_{ss}, while Hallermeier's equations suggest 100% is q_{ss}. Migniot's equation (11) although simple, appears to achieve more sensible results.

The settling velocity used in calculating q_{ss} from the GD model will most likely have to be modified to reflect the median suspended sediment size, rather than the total median sediment size. This would decrease the settling velocity and hence the total sediment flux. The contribution from the suspended sediment flux will however have only a minor impact on the overall sediment flux in test 18 in Schepers (1978) due to the very small percentage of q_{ss}. The significance of altering the settling velocity will have to be estimated by applying the model to a case which has more equal split of sediment transport mechanisms, such as in Hurther &Thorne (2011).

2.3.3. *Traditional bed load models*

Having established that there are two separate sediment transport processes present for finer and coarser sediments over ripples, an alternative method of predicting the coarser sediment transport was investigated. A number of researchers have suggested that the sediment transport for coarser sediment is ripple migration and that this is related to bed load transport (e.g. Traykovski et al., 1999, van der Werf et al., 2007, Hurther & Thorne, 2011). As used in Traykovski et al. (1999), a traditional bed load model from Meyer-Peter & Müller (1948) was tested, using the shear stress calculated in equation (6).

$$\Phi_B = C(\theta' - \theta_c)^n \qquad (12)$$

Φ_B is the non-dimensional bed load transport rate. The critical Shields parameter θ_c of 0.05 was used and 8 and 1.5 were used for C and n respectively. Traykovski et al. (1999) required the use of the modified Shields parameter θ_r in order to predict the sediment flux from this equation. This process was not required for Schepers' (1978) test case as this enhancement factor should only be used for anorbital ripples (Wiberg & Harris, 1994), and these ripples are classified as orbital ripples. The resulting sediment flux from bed load calculations is shown in the following section.

3. Results and Discussion

3.1 Model results comparison

The results of the revised grab and dump model can be seen in Figure 4. The revised grab and dump model (circles) show very good agreement with the measured data, apart from the most negative sediment flux values. This was resolved by incorporating a critical shear stress term (discussed in 2.3.1) which governs when the sediment transport formula is applicable (squares). Interestingly, the traditional bed load formula from Meyer-Peter & Müller (1948) also produces a good prediction of the sediment flux when the shear stress term incorporating acceleration (equation 6) is used (crosses). This is thought to be due to the high proportion of q_r that is contributing to the total sediment flux, which was also established in 2.3.2.

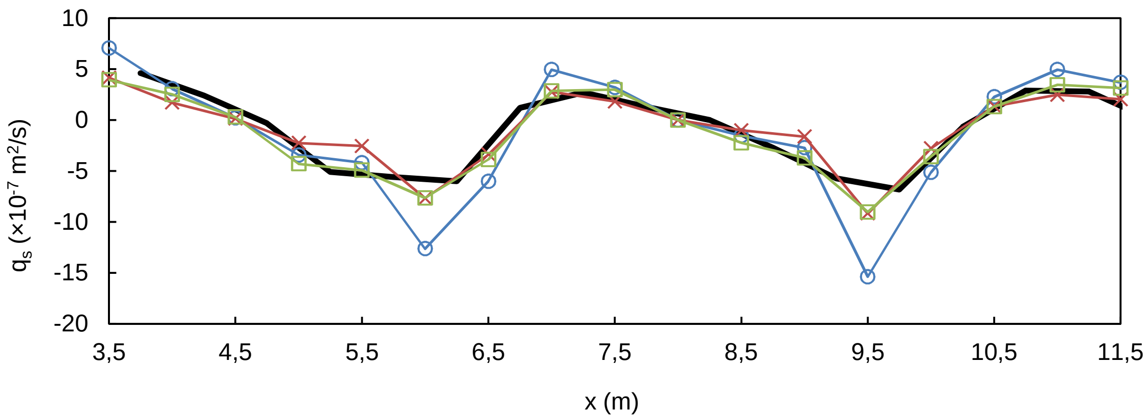

Figure 4. Measured data (thick black line) for d_{50}=0.465mm, test 30 (Schepers, 1978), revised grab and dump model (circles), with critical shear stress (squares) and traditional Meyer-Peter & Müller model (crosses)

3.2 Boundary layer streaming

Boundary layer streaming induces a net velocity in the shoreward direction (Longuet-Higgins, 1958). This suggests that the distance over which the parcel of sediment moves shoreward should have a contribution from the streaming velocity. The streaming velocity used was the Lagrangian time-averaged velocity $5(A\omega)^2/4c$ (Longuet-Higgins, 1958), where c is the wave celerity. The influence of including a streaming term was therefore also tested. The streaming velocity multiplied by half the wave period was added to distance A for the shoreward motion, and subtracted from distance A for the offshore motion. The streaming velocity was also multiplied by a multiplication factor in order to modify the contribution from the streaming velocity to the calculated sediment flux to best fit the measured sediment flux.

The modification in sediment flux calculations suggest that boundary layer streaming does not affect the cross-shore variation of the sediment flux, but has the effect of vertically shifting the calculated sediment flux. This result suggests that the discrepancy between the measured and the predicted sediment flux by the grab and dump model found by Nielsen (1988) was unlikely to be due to the lack of streaming velocity in the model. Additionally, Davies & Villaret (1999) found that vortex ripples make boundary layer streaming weaker, and Bijker et al. (1974) observed that bottom drift velocities for rippled beds are considerably reduced compared to flat beds.

3.3 Comparison to existing semi-unsteady sediment transport models

The revised grab and dump model was compared to another semi-unsteady model by van der A et al. (2010b). Van der A et al. (2010b) developed a half-wave cycle type model to account for acceleration skewness similarly to Watanabe & Sato (2004). They calibrated their new model against the large SANTOSS dataset. We use the sediment flux measurements from test 30 in Schepers (1978) to compare the performance of the van der A et al. (2010b) model to the revised grab and dump model. As the calibration parameters from the van der A et al. (2010b) model were specific to the SANTOSS data set, they were changed for use with data from Schepers (1978). The new calibration parameters used were α_r=8, m=6.8 and n=1. The predicted sediment flux against the measured sediment flux can be seen in Figure 5.

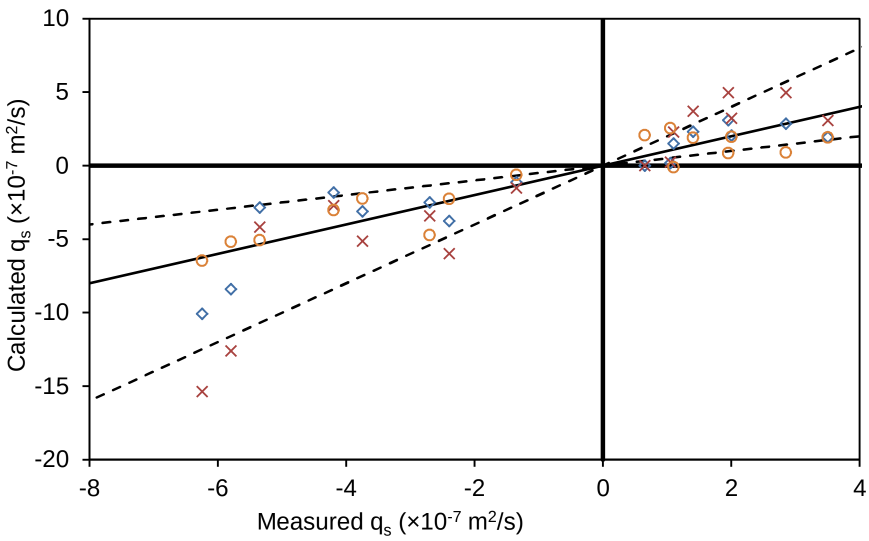

Figure 5. Model performance for revised grab and dump model (crosses), revised grab and dump model with critical shear stress (diamonds), and van der A et al.'s (2010b) model (circles) for test 30 from Schepers (1978). The solid line indicates 1:1 line, and the dotted lines show the lines for a factor 2 difference.

The predicted q_s from the revised grab and dump model showed a significant improvement from the predictions from Nielsen (1988) for the coarser sediment. Comparing the q_s from test 30, while the original model predicted the direction of q_s poorly, the revised model with critical shear stress was able to accurately predict the direction for 15 out of 16 measured points and for all but two points, the predicted q_s magnitude was within a difference of factor of two (see Figure 5). The van der A et al. (2010b) model on the other hand, had 12 out of 16 points within a factor of 2, and also 15 out of 16 points predicted in the right direction. The model performance for these two models is similar. The one point predicted in the wrong direction for the grab and dump had a relatively small measured sediment flux (6.5×10^{-8} m^2/s) and the predicted sediment flux was very close to zero (-5×10^{-10} m^2/s). Therefore the margin of error was insignificant despite the error in sediment transport direction. The root mean square errors for the van der A et al. (2010b) model and the grab and dump model with critical shear stress are 1.18×10^{-7} and 1.61×10^{-7} respectively. Considering the significantly simpler nature of the revised grab and dump model, the comparable performance to the model from van der A et al. (2010b) is surprising.

3.4 Future improvements to the model

Although the grab and dump model has successfully addressed the discrepancy of the sediment flux direction from the original model and data, there are several components in the model formulation that could be improved with the additional data that has been collected since the model was first presented.

3.4.1 *Reference concentration*

The reference concentration relationship with the Shields parameter adjusted for ripples (equation 3) has a considerable amount of scatter (Figure 3 in Nielsen, 1986), and there is more than 20 years of data available since it was established. As this relation determines the magnitude of the sediment flux, it is a significant part of the grab and dump model. As a rough estimate of the magnitude, equation (3) performs quite well, as seen from the accuracy of calculated sediment flux magnitude in Figure 4. However, with increased complexities in the model, a more accurate prediction of sediment transport magnitude is required. With increased availability of sediment concentration time series, it is thought that utilising C_1, the amplitude of the first harmonic of the sediment concentration, may be more suitable for the grab and dump model than the previously analysed $\overline{c}$, the time averaged sediment concentration . Currently, alternative methods for predicting the reference concentration are being sought.

3.4.2. *Phase shift*

One of the only free parameters in the grab and dump model is the phase shift angle in equation (6). It is well established that in laminar flow over a flat plane, the angle is 45°. For turbulent flows over flat planes, it is generally agreed to be less but for mobile beds, the value is not easily decided (e.g. Nielsen & Guard, 2010 Fig 6). Both van der Werf et al. (2007) and Hurther & Thorne (2011) measured sediment transport over ripples with velocity skewness but zero acceleration skewness; both have noted large phase lags between the free stream velocity and the near-bed velocity. The velocity phase shift between the free stream velocity and the near-bed velocity under the vortex ripple regime is strongly driven by the vortex formation on either side of the ripple (van der Werf et al., 2007), which would also relate to the phase shift in the shear stress.

In the case of rough, flat beds, the phase lead of the near-bed velocity relative to the free stream velocity is considered to be in the order of 15 to 30 degrees, where bed friction becomes significant (Hurther & Thorne, 2011). Van der A et al. (2010a) undertook measurements for sediment transport under acceleration skewed flows in the sheet flow regime. As the main contributing parameters to the phase shift in the grab and dump model is yet to be determined, the process of fitting the best phase angle to each of van der A‘s (2010a) test cases were carried out, and then subsequently analysed for any existing patterns. The values of phase shift for these cases could be simply the phase between the free stream velocity and the bed shear stress, but measurements of shear stress are difficult and not commonly measured in sediment transport experiments. Preliminary analysis shows that the phase shift is very dependent on the Reynolds number and shows some variation with velocity skewness, as well as contributions from the sediment concentration phase lag. Sediment concentration phase lag has been suggested to have a significant impact on sediment transport. (e.g. Ribberink et al., 2008; Grasso et al. 2011). There are difficulties in determining how much the various parameters affect the magnitude of the phase shift. A clearer definition of the phase shift is required in order to extend the grab and dump model to the sheet flow regime.

3.4.3. *Expansion to sheet flow scenarios*

The revised grab and dump model could also be extended to predict sheet flow under acceleration skewed flows. As described above, a different phase shift angle would be required. Results from applying the model to data from van der A et al. (2010a) shows good model performance with phase angle values of between 12° and 33°. The results are shown in Figure 6. This suggests that the model may prove suitable for swash zone sediment transport modelling.

The phase angle applied to the T=5s case was 30°, 20° for T=6 and T=7s, and 25° for T=9s. All of the points tested predict the sediment flux within a factor of 2, with the phase shift angles used in the correct range as suggested in the literature. The favourable performance of the model, despite a spread in the phase angles applied, is a good indication that the magnitude of the sediment flux is correct even under sheet flow scenarios.

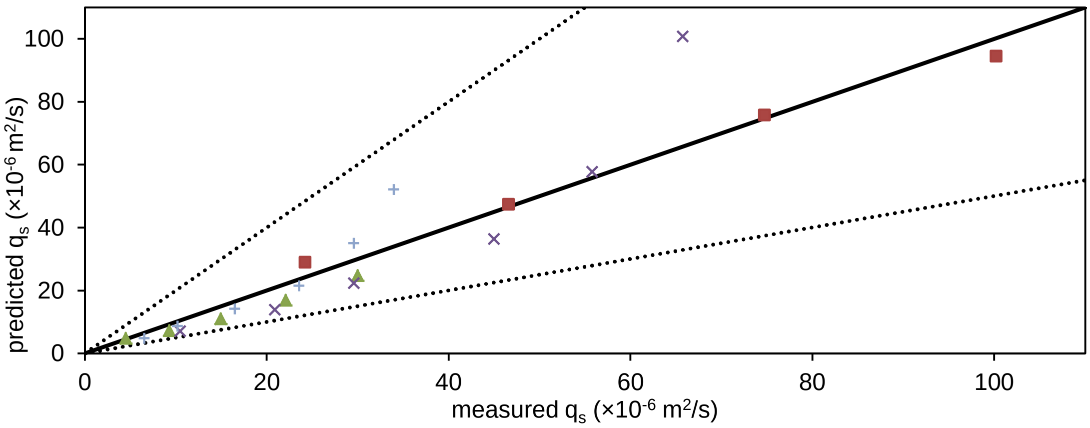

Figure 6. Model performance for revised grab and dump model under sheet flow conditions from van der A et al. (2010a) for d_{50}=0.15mm, T= 5s (triangles), 6s (squares), 7s(×s), and 9 s(+s). Solid line denotes 1:1 line, dotted lines are for a factor of 2 difference.

4. Conclusions

The grab and dump model, first developed by Nielsen (1988) has been updated to accommodate a larger range of conditions. Through the use of shear stress from Nielsen (1992) instead of velocity as the main component in the model, it was able to predict the sediment flux from experiments with coarser sediment. Addition of a critical shear stress term also improved the prediction further. A traditional bed load model was also found to predict the sediment flux well when limited to conditions of transport by ripple migration, when using a shear stress calculated by equation (6) (i.e. including an acceleration term). Although still under development, the revised model shows promise and is a potential alternative to existing semi-unsteady models, most of which have been built upon the half-wave cycle concept devised by Dibajnia & Watanabe (1992).

There are still remaining challenges, with the most significant issues being the reference concentration calculation and choosing a suitable phase angle. The model is also not capable of predicting sediment transport when there is zero acceleration skewness and the φ_τ used is close to 90°, as the entrainment coefficients from equation (7) would almost be equal and therefore produce minimal sediment transport. Unfortunately, many large-scale experiments undertaken over rippled beds have zero acceleration skewness; the model will need to be developed further in order to predict sediment transport for these conditions. There are also opportunities to extend the grab and dump to sheet flow scenarios, with promising results obtained from applying the model to data from van der A et al. (2010a).

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