The Effect of Bedform-induced Spatial Acceleration on Turbulence and Sediment Transport

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Abstract
Bedforms such as ripples and dunes represent bottom features that exist at in least quasi-equilibrium with the overlying flow. Because of flow separation that is typically associated with these features, the flow over them is highly complex. Sediment transport is highly dependent on the nature of the overlying turbulence field. The turbulence is characteristic of neither wakes nor of classic boundary layers and its structure is spatially variable. Topography-induced acceleration plays a critical role in the nature of the turbulence field. Measurements of mean flow and turbulence are presented here for separated flow over a range of bed slopes simulating bedforms of different steepness ratios. Steep slopes are found to significantly reduce the overlying turbulence. Future experiments to assess the effects of slope on sediment flux are described.

1. Introduction
For uni-directional flows where the threshold of sediment motion is exceeded, ripples and dunes are the rule rather than the exception. Generally these bedforms are asymmetrical with fairly sharp crests that trigger flow separation. On the basis of extensive measurements over a dune-shaped fixed bed, Nelson, et al., (1993) and McLean, et al., (1994) point out that the separation process produces a region of very high turbulence intensity above the trough and anomalous turbulence statistics over much of the backslope. Very near the bed (~2mm), downstream of the reattachment zone, the correlation coefficient is typically only about 0.2 to 0.3, significantly lower than the 0.35-0.4 found in classical boundary layers. The lower correlation coefficient is indicative of more frequent occurrences of Quadrant 1 "events" in a joint probability distribution of the horizontal and vertical fluctuating velocity components (u' and w' respectively). Nelson, et al., (1995) shows that these events, which are characterized by high streamwise velocity and upward vertical velocity, are highly efficient in transporting sediment even though they contribute negatively to the Reynolds shear stress. As a consequence downstream of reattachment where the mean velocity is quite small, but turbulent fluctuations are quite large, transport rates are higher than would otherwise be expected.

Most bedload transport equations (eg. Meyer-Peter and Mueller, 1948, Einstein, 1950, Yalin, 1963, Bagnold, 1973, van Rijn, 1984) are based on the assumption that sediment flux is proportional to the mean boundary shear stress in excess of the critical shear stress to some power. However, in the vicinity of the reattachment zone, these assumptions are questionable. Because of the large turbulent fluctuations, threshold conditions are frequently exceeded even though the mean stress is negligible. The measurements of McLean, et al., 1994, indicate that it is first of all difficult to even measure (or deduce indirectly) the boundary shear stress over a dune, and secondly the observations of Nelson, et al., 1995 suggest that Quadrant 1 events play a more active role in transport over dunes than in flows for which the transport equations alluded to above were developed. Given the negative contribution that these events make to the Reynolds stress, it is likely that additional factors, not parameterized by the shear velocity ($u_* = \sqrt{t_b / r}$, where τ_b is the boundary shear stress) come into play, hence these well-known relations likely will not be useful in modeling the transport within a dune or ripple field.

Downstream of reattachment the mean flow near the bed increases with streamwise distance, thus the mean drag force on a sediment particle will increase as well. However, the turbulence intensity even near the bed is quite high. The high levels of turbulence decrease with distance downstream. Therefore two counteracting processes are acting over the stoss side of a ripple or dune. The transport capacity due to the mean flow increases, whereas the transport capacity due to the energetic events from Quadrant 1 decreases. The amplitude of the events is reduced as the turbulence decays and they become less frequent as the correlation coefficient increases toward the classical value of approximately 0.4. It is arguable that these two competing processes might tend to produce a maximum in the local transport rate at a distance downstream of the reattachment zone that depends on the rates at which the mean flow accelerates and the turbulence decays.

2. Experimental setup

As Nelson, et al., (1993) point out, turbulence downstream of separation is strongly affected by the degree of acceleration that the flow experiences after reattachment. In a field of bedforms this is controlled by the steepness of the bedforms themselves. In order to investigate this process, a series of experimental runs were conducted in the recirculating flume in the Ocean Engineering Laboratory at the University of California, Santa Barbara. This facility is 23m long and 0.9m by 0.9m in cross-section. The common element in each run was an inclined ramp of length 0.8m and downstream height *H*=0.037m. This ramp induced flow separation and mean flow and turbulence profile measurements, ranging from 7-100 mm above the bed, were made at different distances downstream using a SonTek acoustic Doppler velocimeter. A second ramp, the steepness of which was varied for different runs, was placed downstream of the initial ramp. (See Figure 1) Five ramp steepnesses, having vertical rise to horizontal run ratios of 1:∞, 1:40, 1:20, 1:15, and 1:10 respectively, were investigated.

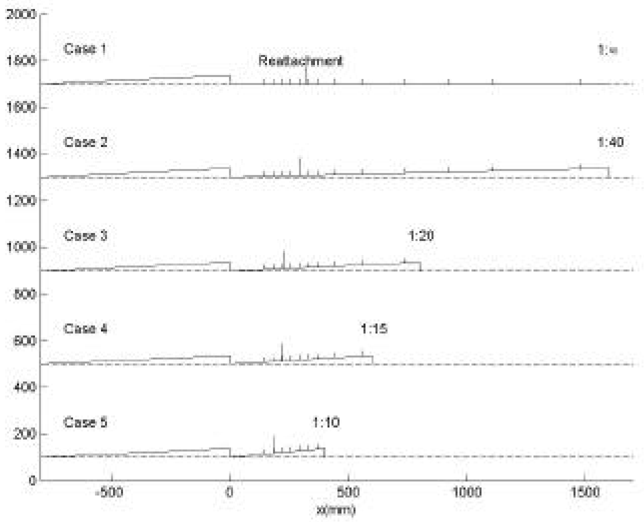

Figure 1: Experimental design: small tick marks on the downstream ramps indicate location of measurement profiles of mean flow and turbulence. Larger tick marks indicate reattachment.
One of the most obvious effects of increasing the degree of acceleration (slope steepness) is to reduce the size of the separation region. This was also observed by Kuehn (1980) and Engel

(1981). Nevertheless, this presents a challenge when it comes to making valid comparisons. For example reattachment was nearly 9*H* downstream of the ramp crest for the flat bed (1:∞) case and only about 4*H* downstream for the 1:10 acceleration case. Therefore should profiles at equal distance from the point of separation be compared, or should profiles at equal distance from reattachment (where an internal boundary layer begins to grow) be compared? It also should be noted that there is no such thing as a *point* of reattachment in highly turbulent flows such as these. Eddy shedding from the upstream ramp crest is highly variable and reattachment can only be defined in a mean sense. The SonTek ADV could only measure to within about 7mm of the bed, so determination of where the near-bed mean velocity went to zero was not possible, therefore, for this work the location of the center of the reattachment zone was estimated by dye insertion and also placement of a thin layer of fine sand in the vicinity of reattachment. The latter was done to locate the zone of maximum divergence.

Figure 2 shows the velocity within 10 ramp-heights downstream of the upstream ramp for the flat bed case (1:∞) and the steepest case (1:10). Profiles taken at the same distance from the end of the upstream ramp are plotted together. In the upper plot, which plots the data with respect to the local bed, the effect of the topographically-induced acceleration is clearly seen in the significantly larger near-bed velocity over the steep ramp. The separation zone and the momentum deficit associated with the wake that it creates is apparent in the flat bed profiles, but is much less apparent in the steep case. In the lower plot one sees that the two sets of velocity profiles track each other amazingly well, though the acceleration in the steep case (circles) is still evident. Here the momentum deficit is similar for the two cases; the steep profiles seem to simply be truncated by the presence of the bed.

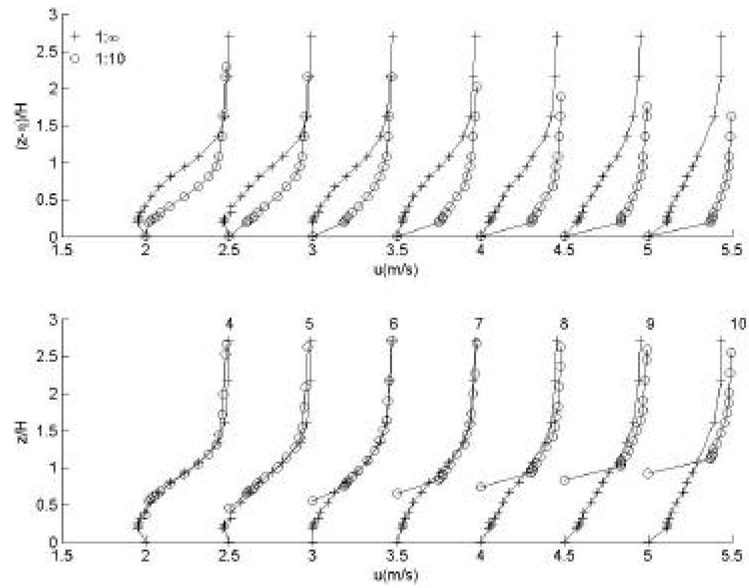

Figure 2. Comparison of profiles of mean streamwise velocity downstream of the ramp for a flat bed (Case 1) and a ramp with 1:10 slope (Case 5). In the top plot the profiles are plotted with respect to the distance from the local bed; in the bottom the profiles are plotted relative to the trough elevation. Numbers above the lower profiles indicate number of ramp heights downstream from point of separation.

In the upper plot of Figure 2 most of the profiles from the steep case are downstream of reattachment, whereas most of the flat bed profiles are within the separation zone, therefore it is perhaps better to compare profiles that are approximately the same distance from the reattachment zone. This can be seen in Figure 3. In the upper plot the larger velocities near the bed for the steep ramp case are still evident, but less than in Figure 2. It is apparent that the steep slope forces the wake to decay much more quickly yielding significantly greater near-bed velocity. In the lower plot of Figure 3 there is greater shear in the steep case near the bed in the reattachment region.

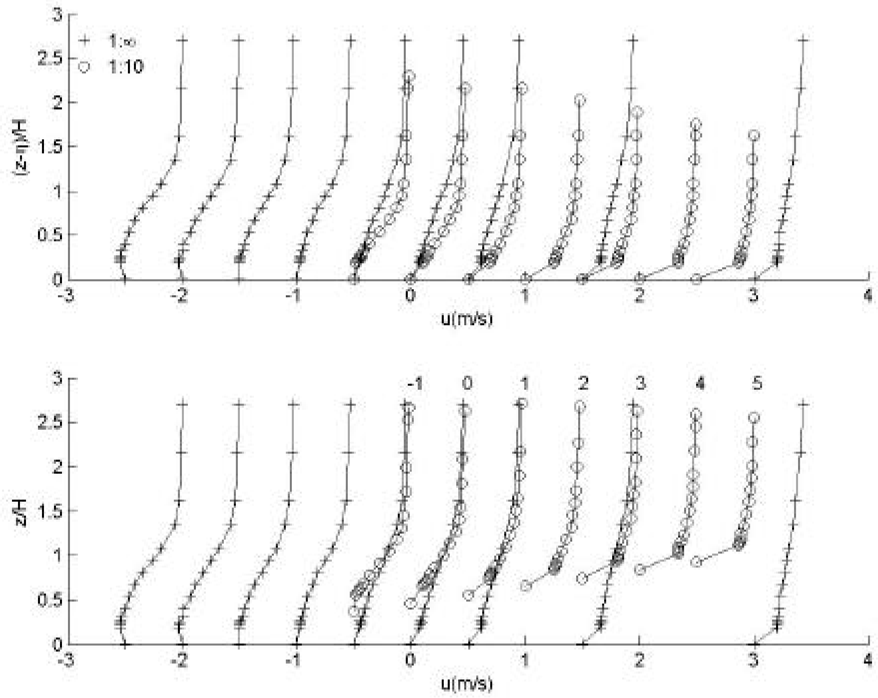

Figure 3. Comparison of vertical profiles of mean streamwise velocity downstream of the ramp for a flat bed (Case 1) and a ramp with 1:10 slope (Case 5). Profiles that are at approximately the same distance from the reattachment zone are plotted together. In the top plot the profiles are plotted with respect to the distance from the local bed; in the bottom the profiles are plotted relative to the trough elevation. Numbers above lower profiles indicate number of ramp heights downstream of reattachment.

As can be seen in Figure 4 the larger shear for the steep case leads to greater turbulence production near the bed. Even though the production is higher near reattachment for the steep case, it drops off quickly with distance downstream. Also larger production near the bed is offset by lower production rates away from the bed where shear is reduced by acceleration of the near-bed velocity. Indeed, when the production is integrated over the depth (Figure 5) we see that overall the higher topographic acceleration reduces the production of turbulent energy. The effects of the production are seen in Figure 6 where the streamwise velocity variance is shown. The flat bed case is seen to have significantly more turbulence, especially within the wake region away from the bed. This is graphically depicted in Figure 7 where the integral of the streamwise velocity variance is plotted versus distance from reattachment.

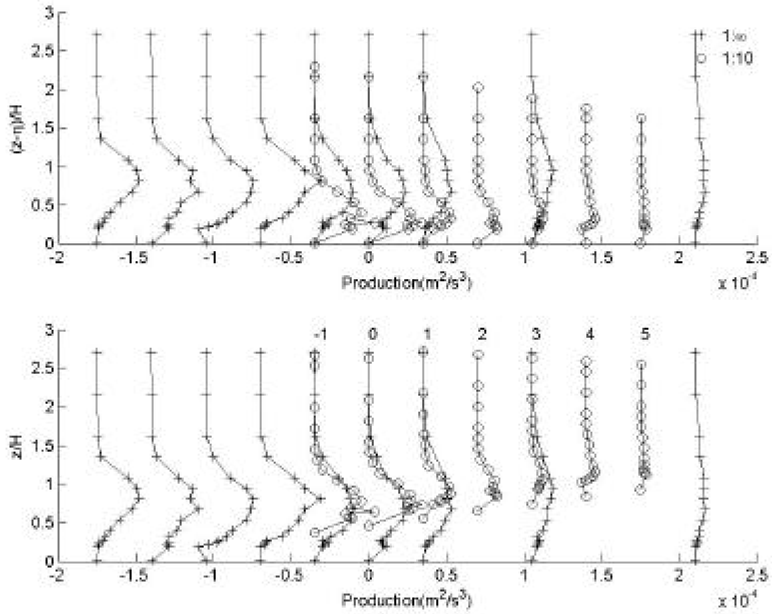

Figure 4. Comparison of turbulence production for profiles that are at approximately the same distance from reattachment.

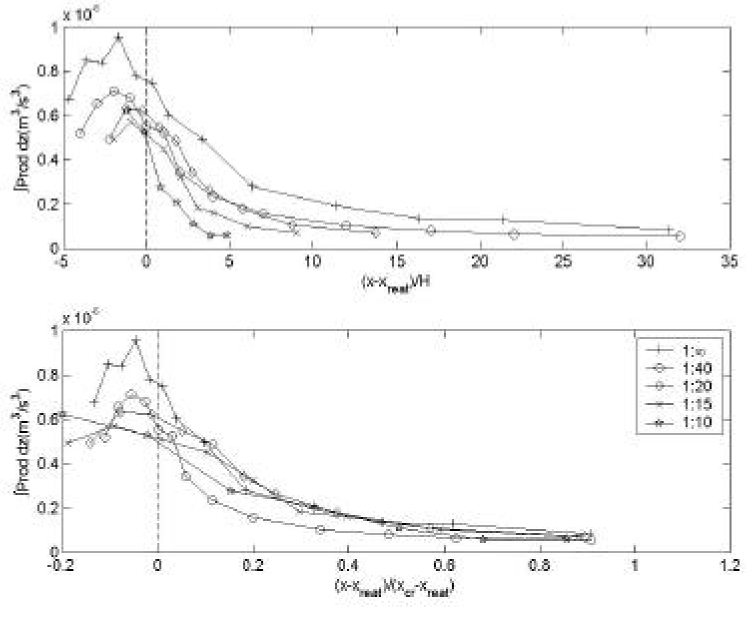

Figure 5. Vertically integrated turbulent energy production rate $(-\overline{u'w}\partial u/\partial z)$ as a function of distance from reattachment, normalized by ramp height H (upper) and by the distance from reattachment to the crest of the downstream ramp (lower).

For the two cases in Figure 6, there is little difference in the near-bed turbulence (see upper plot). From a sediment transport perspective, for real flows over ripples and dunes, this would suggest that, at least for conditions dominated by bedload, any difference in the sediment flux between these two cases would likely be produced by the difference in mean velocity of the near-bed flow. However, if there were significant suspended sediment, much of which will be carried into suspension near the crest, the flat bed case should provide much more turbulent mixing than the steep slope case would. The higher mixing could delay any settling of the sediment toward the bed.

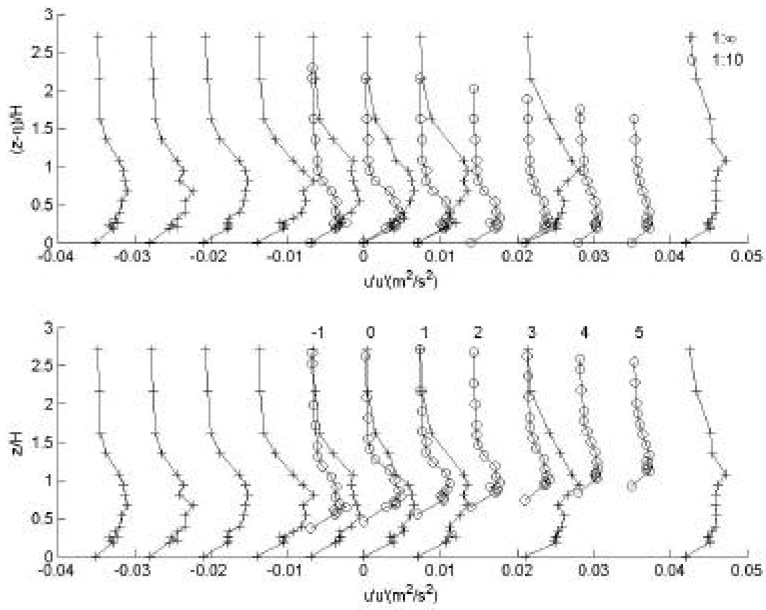

Figure 6. Comparison of the streamwise velocity variance, which dominates the total turbulence intensity, for profiles at similar distances from reattachment.

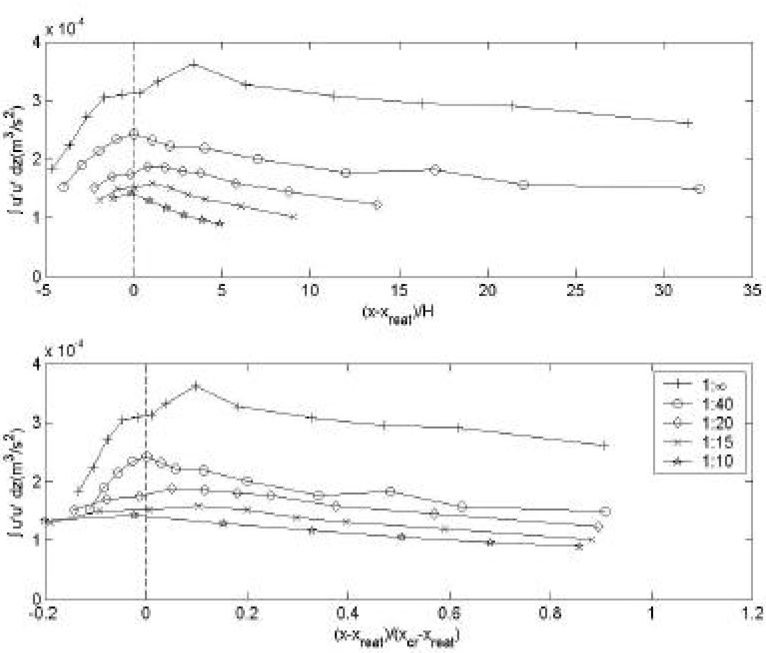

Figure 7. Streamwise variation of the integral of the velocity variance over the flow depth plotted versus distance from reattachment normalized by *H* (upper) and by the distance from reattachment to the crest of the downstream ramp (lower).

2. Future sediment flux measurements

The measurements presented here clearly indicate that the steepness of the topography downstream of separation has a dramatic effect on the mean flow and turbulence fields. This is analogous to the situation in developing ripples and dunes. As such bedforms grow their steepness changes. Therefore their evolution must be affected by the interaction of the topographically-induced acceleration effects and the sediment bed. However, there is virtually no information on sediment flux measurements under such non-equilibrium conditions. With this in mind we have begun a series of measurements aimed at measuring the local sediment flux rates over erodible beds similar to those shown in Figure 1.

The same fixed ramp shown in Figure 1 is emplaced over a sand bed. Downstream, ramps of sand initially having the same slopes as in Figure 1 are put in place. An array of 5 MHz acoustic transducers (32 in number) are deployed in a line along the center of the flume. These transducers measure the elevation of the bed directly below them to an accuracy of a fraction of a millimeter. The flume is very slowly filled to a depth 2-3 times the desired flow depth and the bed is carefully smoothed to begin with a uniform bottom slope. When all is prepared, the flume gate is opened to a predetermined height and the pump is turned on just before the desired water depth is achieved. This procedure allows us to accelerate the flow optimally (not too fast and not too slow) to the desired conditions. This usually requires a minute to a minute and a half. During this time there is negligible change in the initial topography (what change that does occur is recorded by the multiple transducer array (MTA)).

The erosion equation tells us that as long as the flow is two-dimensional and in at least quasi-steady state, the rate of change in the bed elevation is:

$$\frac{\partial h}{\partial t} = -\frac{1}{C_b}\frac{\partial q_s}{\partial x}$$

where C_b is the volume concentration of sediment in the bed, q_s is the sediment flux and x is the streamwise distance. By measuring the bed elevation h in a number of streamwise locations (as the MTA does) we can calculate the mean sediment flux over any time interval $Dt = t_2 - t_1$ as:

$$\overline{q_s}(x) = \overline{q_s}(x_0) - \frac{1}{(t_2 - t_1)C_b}\int_{x_0}^{x}[h(x', t_2) - h(x', t_1)]dx'$$

where x_0 is any location where the sediment flux is known. Taking $q_s(x_0) = 0$ at the end of the upstream ramp is reasonable. We have just begun to make such measurements and do not have enough results to include here. Nevertheless the technique is able to measure mean rates of a fraction of a mm^2/s.

In addition to the MTA system, we also deploy a 4 MHz acoustic Doppler profiling system that includes two pairs of transducers. In each pair one sensor is aligned so that in looks vertically down at the bed while the other is mounted downstream and tilted upstream at 30^o to the vertical so that its beam crosses that of the vertical transducer near the sediment bed. One pair is mounted at a stationary location, the other is mounted on a cart that moves slowly over the downstream sand ramp, providing not only velocity, but also sediment concentration and bed elevation information.

This experimental technique will produce measurements of sediment flux and flow statistics simultaneously so that correlations between them can be calculated. It is expected that the relationships will be a function of the acceleration rate, but it is hoped that this dependence will manifest itself systematically either by direct correlation of through the statistics of the near-bed velocity. With such information we hope to be able to accurately predict the sediment flux (and hence its spatial derivatives) within a ripple or dune field given the characteristics of the overlying flow. The latter can be derived from detail flow measurements such as the ones presented here, but our hope is to apply three-dimensional large eddy simulation models for arbitrary topography to predict the mean flow and turbulence characteristics. With such an approach we can predict the evolution of the bedforms.

Acknowledgements

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