An Experimental Study of the Initiation and Development of Subaqueous Dunes in 5mm Gravel.

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Abstract

In flume runs, incipient gravel dunes developed from lower-stage plane gravel beds during long-periods of marginal bedload transport rates. Incipient dunes also appeared on the stoss sides of low amplitude two-dimensional dunes as the wavelengths of the latter increased. The incipient bedforms were almost imperceptible positive bed features with heights of one or two grain diameters, and lengths and spans of a few centimetres. The spans were only slightly greater than the lengths making them distinctly ovoid in planform. These bedforms occurred for near-threshold conditions of motion (θ/θ_{crit} ratios = 1.0 to 1.016) and, after 16 hours of flow, typically had developed into the low amplitude two-dimensional bedforms with heights ranging between 0.029m and 0.055m, wavelengths of around 1 to 1.5m and spans of 0.6 to 0.9m. Lee side angles could be a degree or two but ranged up to angle-of-repose. Continued development (θ/θ_{crit} ratios of around 1.3) resulted in wavelengths ranging between 0.6m to 6m, averaging between 2.6m and 3.5m. The development of an additional crest often caused the downstream crestline to decay in height but not to stall in forward progression. Initial crest spacings are too large and bedform heights too small to generate coherent turbulent flow structures capable of initiating a further downstream bedform. Rather, as several, 'uniformly-spaced' low-amplitude incipient dunes appeared ‘spontaneously’, it isdeduced that an inherent resonance between the fluid and the plane mobile bed material dictates the initial spacing of bedforms. This is not consistent with near-bed sweeps at the grain scale being responsible for initial defects, but rather larger-scale flow structures develop, including those associated with surface waves. This observation, when leeside flow separation is absent, explains the application of potential flow instability mechanisms to the spontaneous development of bedforms.

1. Introduction

The development of incipient gravel dunes from a mobile lower-stage plane bed (LSPB) is poorly researched (Carling, 1999). In similar vein, the planform development of steeper, near-equilibrium dunes is not well known. Broad flumes are required to negate side-wall distortions of dune height and planform (*e.g.* Menduni and Paris, 1986). Consequently this investigation was designed to develop dunes from planar gravel beds with a D_{50} of 5mm in broad flows. Particular attention was given to the bulk hydraulic and morphological conditions associated with the first appearance of incipient dunes upon a mobile LSPB. In addition, both description and quantitative data detail the development of the flow-parallel vertical form and the planform of steep, near-equilibrium and non-equilibrium dunes. For brevity, bedforms developed with long, straight, or slightly sinuous crestlines that are approximately transverse to the flow are termed two-dimensional (2-D) dunes. Similarly, dunes with long, highly-sinuous crestlines, or short, recurved crestlines and are termed three-dimensional (3-D) dunes (after Allen, 1968: Costello and Southard, 1980). Here all data cannot be reported, but a detailed paper is in preparation.

2. Experimental Facility

The experiments were conducted in the 160m long flume within the Water Resources Centre of Tsukuba University, Japan. The flume width is 4m. Water is recirculated and there is an option to recirculate sediment. In these experiments the sediment recirculation was only used in runs 7 and 8. At the end of each run the flume was slowly back-flooded by closing an undershot tailgate whilst first maintaining, and then progressively reducing, the inflow until ponded water filled the flume. The flume was then drained slowly by slightly raising the tailgate. In this manner bedform development could be arrested, and the bedforms exposed, without rapid draw-down modifying the dune shape. Subsequently bedform migration could be reinitiated, without any disturbance, by slowly backflooding the flume with the tailgate closed, and then incrementally increasing the inflow whilst slowly opening the tailgate. The slope of the steel channel is fixed at 0.01 but the slope of bed sediments is adjusted by altering the height of an exit weir that retains the sediment filament within the flume. The water depth was controlled, by adjusting discharge, weir height and bed sediment gradient. The latter is controlled through the bed sediment transport process and thus uniform flow above a mobile bed readily cannot be obtained within several days. Yet, in practice, over shorter time-spans, near-uniform flow can be developed over distances of 20m to 30m. The time available for this study was limited. Thus it was decided to develop experiments to take advantage of the adjustment through time of the bed elevation. Consequently the development of bedforms occurred in steady, non-uniform flow throughout the length of the flume. In practice the incipient bedforms, reported below, developed within near-uniform flow that pertained for short lengths of the flume. The steeper 2-D and 3-D dunes developed in a flow-field that deepened and decelerated in a downstream direction. However by the end of the full series of experiments near uniform flow pertained throughout the flume.

3. Method

The flume was filled with 5mm gravel (Table 1) from 50m downstream of the entry section (0m) as far as the tailgate (160m) providing a bed sediment filament varying from zero thickness upstream to 1m thick downstream. Initially, the surface was screeded flat, but bed gradient was allowed to develop through the sediment transport process. This procedure resulted in a low-amplitude bar front developing between 95m and 110m which prograded up to 7m downstream during any single run, during which it diminished in height. As a result two distinct reaches developed. During initial runs a reach upstream of the bar front was characterised by a gentle bed gradient, shallow flow ($h = c.$ 0.35m) and the presence of incipient low-aspect dunes. A downstream reach was characterised by a steeper bed gradient, deeper flow (h = 0.35m to 0.75m) and steep 2-D dunes. During the course of eight runs the flow became increasingly uniform throughout, such that water depths were around 0.24m during the final two runs during which strongly 3-D dunes were recorded. Following runs 1 and 2, the bed surface was again screeded flat. For runs 3 through 5 the bedforms were preserved and the bed was again screeded flat before runs 6 through 8. Consequently the total duration for runs 1 to 2, 3 to 5 and 6 to 8 may be regarded as cumulative. The carriageway was equipped with a sediment bed surface indicator, a water surface point gauge and an acoustic doppler velocimeter (ADV). The height and lateral position of these instruments could be selected to within 10mm using digital position monitoring. Sediment and water surface elevations were recorded at 5m downstream intervals (from 70m to 160m) at 0.5m intervals across the flume width. These data provided water and bed surface slope information. For completeness, manometer readings were recorded at 69, 89, 122 and 154m along the length of the flume. Unrotated average downstream ADV flow speeds at 0.6 of the depth below the water surface were filtered and integrated over 120 seconds. Vertical photographs of the full 4m width of the flume, including bedforms, were obtained using a digital camera mounted 3.92m above the gravel surface on a mobile gantry. At the end of run 4 an ERC bedload sampler (with mouth width of 100mm; Ikeda, 1983) was installed in the incipient dune region at 105m. With flowing water in the large flume, it was not possible to observe the bed as the water was discoloured. Nevertheless, it was observed (when draining the flume) that, for conditions of initial motion (see Run 1 below) of just a few grains per second from an 1m^2 flat bed area, incipient dunes had developed after several hours. Using Duboys equation, the critical shear stress (τ_{crit}) was determined to be 3.1 Pa (u_{*crit} = 0.0559ms^{-1}; non-dimensional critical shear stress, θ_{crit} = 0.0386) for stable bed:LSPB transition. Higher, but still marginal, transport rates were observed more closely in uniform clear-water flow within a 0.3m wide flume with a working section of 4m. This latter condition was associated with a critical shear stress of 4.69 Pa (u_{*crit} = 0.068 ms^{-1}; θ_{crit} = 0.057) for general motion developed within a few seconds; thus the LSPB:dune transition occurred within the θ_{crit} – range: 0.0386-0.057. The settling velocities of three discrete size fractions (Table 1) were measured in still clear water at 12^{o}, for a 3m drop within a 10m high setting tube of 0.3m diameter. In all runs flow was fully turbulent (Re ~ 10^5).

Table 1

Grain size fraction (phi)	Density (gm cm^{-3})	Settling velocity (m s^{-1})
-3.0 to – 2.5	2.57	0.3758
-2.5 to – 2.0	2.57	0.3264
-2.0 to – 1.5	2.58	0.2889
Bulk sample	2.53	-

4. Summary Bedform Development

4.1 Incipient dunes

Run 1 established threshold sediment transport conditions for the stable bed:LSPB:incipient dune transitions within a short 'uniform' flow reach and runs 2 to 5 also consider this reach. The non-dimensional shear stress during run 1 was 0.0386 throughout the run section, such that incipient motion on a plane bed occurred (Fr = 0.52; h = 0.375m). Nevertheless, a few short wavelength (1m to 1.5m) low-amplitude dunes were evident, after the 17 hour run. These were of limited span (typically 1 to 2m) with straight, flow-normal or slightly skewed crestlines. During the 16.5 hour run 2, the non-dimensional shear stress increased in a downstream direction from 0.0386 to 0.055, whilst during the 3.75 hour run 4 the non-dimensional shear stress was sustained at 0.055. For both of these latter runs, the Froude number was 0.5 and the water depth was 0.365 and 0.382m respectively. In both cases, long wavelength incipient straight-crested transverse dunes with distinctive spacing developed (Fig. 1). These bedforms had lengths of between 0.95m and 5.67m whilst heights averaged 0.022m (range: 0.011m to 0.047m). Stoss slopes remained slight, averaging 0.63° (range: 0.1° to 1.3°) but leesides rapidly became steep 20° (range:15° and 32°) (see run 2 Fig.3). The bed was screeded flat after run 2 and by the end of run 5 (a total of 9.2 hours duration) the non-dimensional shear stress increased further ($\theta = 0.067$ to 0.074). For $\theta = 0.067$, a single bedload sample provided a transport rate of 0.052kg ms^{-1}. For these latter conditions, incipient dunes were of similar wavelength (3-4m) as noted during previous runs, but the heights of the dunes degraded (Fig. 4). Many of these dunes had gentle lee sides, but others had steep lee sides, such that flow separation should have

Fig.1: Incipient dunes, with light crests and dark troughs in run 1. The scale bars are 3m and 0.5m long. Arrows point to incipient transverse crests of limited span. Flow top to bottom.

occurred at each crestline (Dyer, 1986). However, in each case there was no evident erosion of the bed at a distance downstream where flow reattachment might be anticipated (*e.g.* 4 to 8 *H*; Allen, 1984; Best, 1996). Instead the bed downstream of each dune crest was planar and perceptibly 'horizontal'. The stoss toe of each dune was not defined by a break-of-slope, rather, the stoss-sides gradually increased in gradient to a maximum of 1^o degree, or so. The mechanism for initial defect development upon a LSPB, giving rise to incipient dunes, was not evident. Close inspection of the dry bed showed that slight positive bed features could develop, seemingly spontaneously, with heights of only a couple of grains, negligible stoss and lee slopes, wavelengths of up to 1m, or greater, and crest lengths of some decimetres. In these cases no initial small-scale (*e.g* tens of mm^2) distinct defect seemed to associated with bedform development, but rather bedform development appeared to occur owing to vertical accretion over a relatively large bed area (*e.g* tens of cm^2 see Fig. 1 and 2). However, once incipient dunes with distinctive crestlines were present, additional distinct bed defects (a couple of grains high with crestlines lengths and flow-parallel lengths measuring a few centimetres) could readily be discerned, usually high on the stoss sides of existing dunes (Fig. 2) and rarely near the stoss toes. These distinct bed defects, which eventually developed into new bedforms, formed on the stoss slope of existing bedforms of any length. For example, the crestline of one short-wavelength incipient dune (L = 0.95m) began to degrade, in height and lee side angle, as a new bedform began to develop immediately upstream of the crestline of the parent dune. More usually, bedform wavelengths exceeded c. 4m before minor topographic defects appeared formed new bedforms in intermediate positions.

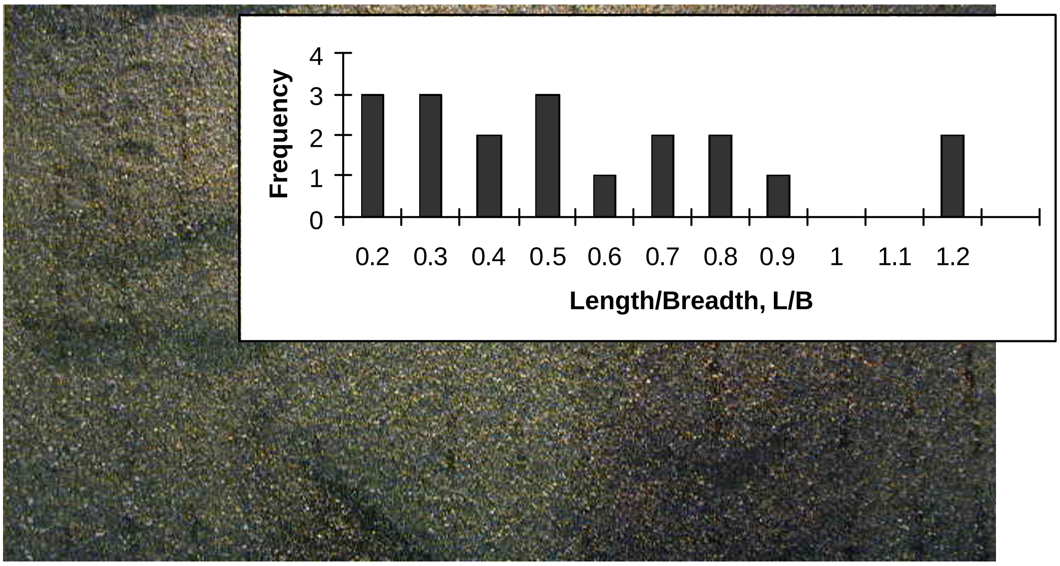


Fig.2: Incipient dunes. Scale bar in decimetres. Flow top to bottom.

4.2 Two-dimensional dunes

During runs 1 through 5 defined 2-D bedforms, with steep lee sides, developed downstream of the bar front. These had fairly regular, straight or slightly sinuous crestlines that were essentially flow-normal or slightly skewed, exhibiting spans of 2m to 4m which thus often extended across the full width of the flume. The 2-D dunes of run 1 lengthened from 0.70m to 0.85m and grew in height from 0.039m to 0.1m during run 2 as θ increased in a downstream direction from 0.056 to 0.077 (Fig. 4) As a result, average stoss slopes increased from 5.2^{o} to 6.7^{o} and lee slopes from 27^{o} to 37.5^{o}. However during runs 4 and 5 the non-dimensional shear stress fell to 0.05 or less, and the 2-D dunes were prograding downstream into water of increasing depth (0.42 to 0.74m), concomitantly the Froude number fell to less than 0.44. Despite the downstream reduction in shear stress and flow speed, the dunes continued to grow in height. Throughout these runs it was observed that as dunes migrated into deeper, slower-flowing water very steep dunes ($H:L$ ~ 0.12 to 0.14) with steep leeslopes could develop. The steepest lee slope measured was 49^{o}, well in excess of the measured angle of repose: 32^{o} to 34^{o}. Usually steep lee sides angles are associated with angular material and widely-graded sediments (Julien, 1995), which is not the case here. It appears that over-steepening occurs as bedforms

Fig.3: Plan aspect ratios of incipient dunes.

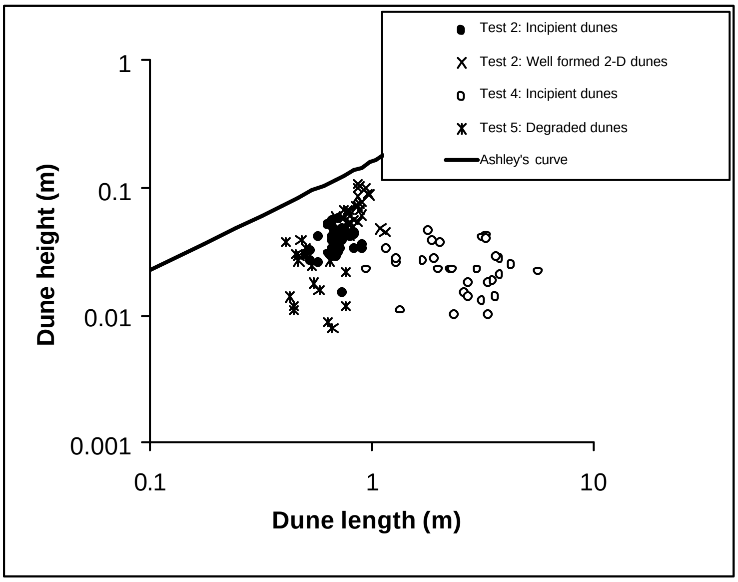


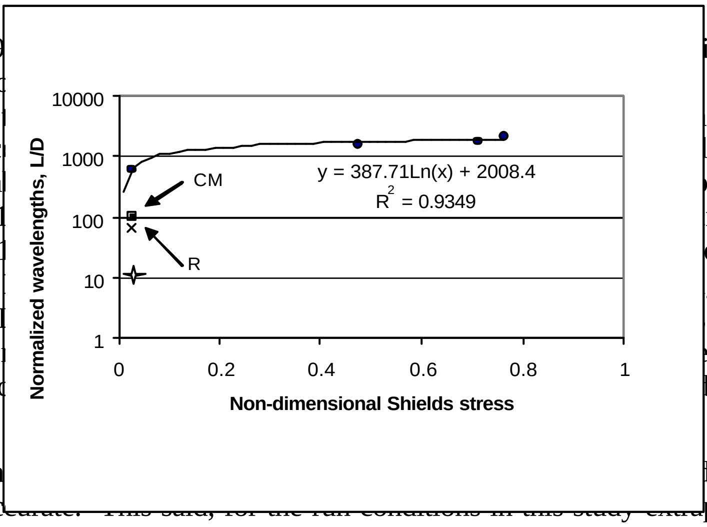
Fig. 4: *H:L* data in relation to the limit curve for 3-D dunes (Ashley, 1990).

migrated slowly into relatively quiescent water. Presumably, the absence of highly-turbulent separated flow in the leeside of these latter dunes precluded the avalanching of sediments that usually reduce leeside slopes to angle- of-repose. However these dunes tended to degrade, as they slowly migrated still further downstream (beyond 130m) into deeper waters ($Fr < 0.19$; $\theta < 0.05$) where the dune:LSPB transition pertained.

4.*3 Three-dimensional dunes*

Prior to run 6 the bed was screeded flat. On starting the flume, standing waves were observed at 112m to 130m but these reduced in height and spread upstream and downstream, flowing which Fr was 0.69. Non-breaking (and a few breaking) standing waves were locally persistent throughout the run. On draining the channel, dunes extend the full length of the flume to 155m, but locally (where the standing waves had been observed) graded into bedforms which appeared to be symmetrical to slightly asymmetrical transitional bedforms; the latter steepest on the down-flume side. During run 7 ($Fr = 0.74$) a strongly 3-D, wavy regular planform was evident in the bedform crestlines where rooster-tail standing waves had been observed breaking gently upstream. By the end of run 6 the difference between the slopes within the upstream and downstream sections was much reduced compared to run 5. However a clear change in bedform character was evident. In the upstream reach, incipient dunes had been replaced by steep 2-D dunes but unlike the 2-D dunes in earlier runs there were broad smooth, longitudinal ridges associated with the dunes but with a height less that that of the dunes. At the downstream end of this section, crests begin to bifurcate and trend diagonally across the flume. This change in planform may represent a transition to more 3-D dunes. Dune crestlines here were more sinuous, and tended to run diagonally across the flume, with relatively sharp changes in direction, producing distinct lobes and embayments. Dune crestlines also bifurcated, at which point each crestline bearing was altered. The 3-D dune crests had shorter spans compared with the more 2-D dunes in the upstream section. They had smaller mean wavelength, but mean height and slope angles were essentially the same. Variation in measured wavelengths were owing to appearance of 3-D bedforms of shorter spans and particularly an increase in crest bifurcations. Locally, short span, low dunes with parabolic or lobate forms also developed initially with negligible amplitude. These poorly developed, feint bedforms indicate that new dune crests sometimes were initiated in a highly 3-D state. Those 2-D dunes with longitudinal low-amplitude broad ridges may be transitional between 2-D and 3-D, the ridges being forerunners of the lobate forms of 3-D crestlines. At the end of run 7 the low amplitude dunes in run (transport rate of 0.046kg m^{-1} s^{-1}) increased in height as the bedslope in the upper flume section increased.

5. Discussion



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is indicative rather than accurate. This said, for the run conditions in this study extrapolation of Equation 1 predicts initial wavelengths of around 0.3m. Each of the present runs in cloudy water lasted several hours and thus the wavelengths at actual bedform inception were not always observed directly. Nevertheless, the wavelengths of incipient dunes, when observed for conditions of incipient motion, were rarely less than 1.0m and further, as shear stress increased (to induce marginal transport conditions) the bedform spacings increased (Fig. 6). Consequently these data permit an estimate of the minimum wavelength at inception.

Fig.5: Incipient dune development. CM = minimum data of Colman and Melville; R = minimum data of Raudkivi; star is minimum from this study.

An extrapolated ln-linear function relating the non-dimensional excess shear stress with the non-dimensional wavelength (Fig. 5) indicates that for incipient motion wavelengths would be not less than 0.6m. Although the (averaged) data in Fig. 5 are few, the scarcity of individual measures of incipient wavelengths less than 1.0m might indicate that, in fine gravel as opposed to sand, wavelengths at inception are relatively long. Further, for conditions of low excess shear stress, it was evident that one solitary dune did not first appear and then, by its presence induce the development of a train of additional dunes. Indeed initial crest spacings are too large and bedform heights to small to generate downstream evolving turbulent flow structures capable of remaining coherent and initiating a further downstream bedform. Rather, as several, 'uniformly-spaced' low-amplitude incipient dunes, latterly 2-D dunes, appeared 'spontaneously' it may be deduced that an inherent resonance between the fluid and the plane mobile bed material dictates the initial average spacing of bedforms. This method of initiation is not consistent with local turbulence (near-bed sweeps) at the grain-scale being responsible for engendering initial defects, but rather larger-scale flow structures develop, including those associated with surface waves (Gyr and Müller, 1996). This observation, when leeside flow separation is absent, explains the application of potential flow instability mechanisms to the spontaneous development of bedforms (Coleman and Melville, 1994; Coleman and Fenton, 1996). The incipient and low amplitude 2-D dunes were not depth-limited. Allen (1984) for example demonstrates that fully-developed dunes usually exhibit H:h ratios of 0.12 before flow blocking and accelerated flow speed above the crest induces a depth limitation, causing crestal flattening. In contrast, the incipient, well-developed and degrading 2-D dunes (for runs 2, 4 and 5) had relative heights ranging between 0.025 and 0.12, averaging 0.06. Thus these dunes, without toe scour, appear to have been equilibrium responses to the imposed flows, the bedform morphology being maintained over several hours in each run. Costello (1974) and Costello and Southard (1980) describe similar long wavelength, low-amplitude, 2-D dunes in coarse sand. Best (1996) has argued that this class of bedform is distinct from fully-developed 2-D and 3-D dunes, in-as-much as erosion at the point of flow reattachment (downstream of steep lee sides) plays no effective role in the dune-building process. This supposition appears to be confirmed in the majority of the present examples of incipient dunes. Specifically, the increase in the stoss slope scour that drives sediment transport must be large relative to the value in the vicinity of flow reattachment. This conclusion can be inferred because the incipient and low amplitude 2-D dunes clearly migrated downstream. Thus gravel particles must be entrained from the stoss sides, and deposited on the leesides, facilitating downstream migration. However, no scour hollows could be detected in the expected region of flow reattachment, rather the bed remained plane. Thus it must be inferred that either scour was present but is not measurable (i.e $<$ c.1D_{50}), or sediment for dune building is sourced from upstream of the dunefield. Any slight irregularities, developing in the lee of these dunes (which could form the bed defects leading to further dune development) would rapidly be over-run by the advancing lee side of existing dunes. It should be noted that a few steeper and higher dunes developed within the field of incipient dunes at the end of run 5 as the shear stress ($\theta >$ 0.074) and flow speed were increased. Additionally steep flow-transverse 2-D and 3-D dunes developed in the same bedstock when the shear stress was further increased and these exhibited leeside angles commensurate with the presence of flow separation (e.g. 10-15^{o}; Best and Kostachuk, 2002). Thus, although it was not possible to discern the presence or absence of flow-separation in any of the runs, it would seem that the development of separated flow is instrumental in controlling the phase transition from incipient 2-D dunes to well-developed 2-D dunes exhibiting increased crestline sinuosity and bifurcation, leading to the development of 3-D dunes. Note that Anderson and MacDonald (1990) suggest that bifurcations are transitory. The downstream limb rapidly detaches and the resultant termination rapidly moves downstream to reattach to the next downstream bedform. In the present case when a defect develops upstream of an existing crestline, the latter decays in height but must migrate more rapidly than before to allow the new defect to develop as an independent bedform. What is the mechanism which allows this accelerated migration? Is it simply the inverse relationship between bedform size and migration rate (Bagnold, 1954), or is it turbulence in the lee of the upstream incipient bedform which suppresses the height of the primary bedform through inducing accelerated migration of the latter's crest?

6. Conclusions

For conditions of marginal transport rates on LSPBs, incipient dunes developed in 5mm gravel after several hours. Thus in some situations time is the controlling factor dictating whether a bed is viewed as LSPB or dune-phase. Dunes developed for shear stress conditions only marginally above the θ-value for incipient motion on LSPBs. Incipient bedforms were strongly 3-D and lacked distinctive crestlines or lee slopes but rapidly developed into 2-D straight-crested transverse dunes with negligible amplitude, and distinctive leeslopes marked by the absence of flow separation in the leesides. Increase in shear stress and/or development into deeper water resulted in 2-D transverse dunes developing into firstly sinuous long-crested transverse bedforms with flow-parallel spurs emanating from the crests and latterly these sinuous forms were replaced by short-crested lunate 3-D dunes. More detailed studies than were possible herein are required at fine spatial and temporal resolutions to delineate near-bed flow structure including reach-scale instabilities as well as local separation, where present. Nevertheless, the spontaneous appearance of well-spaced bedforms over large areas of the bed tends to indicate that local coherent turbulence structures associated with flow separation at individual grains are not responsible for bedform initiation.

Acknowledgements

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