CHAPTER 160

Oscillatory Bedload Transport Studies by Imaging of Tracers

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Abstract

Full scale laboratory flows producing vigorous bed load transport are conducted at varying periods but constant maximum velocities. The time-varying sediment transport in the first half cycle is measured using video imaging of dyed natural sand. The acceleration of the fluid (proportional to the frequency of the oscillation in these experiments) is found to significantly affect the velocity of the sediment response (bedload transport), and the phase and the absolute magnitude of fluid velocity associated with the initiation of sediment motion.

Introduction

Bedload has long been recognized as an important element in surfzone sediment transport because, over a great portion of the nearshore, and excepting those areas of greatest near bottom fluid energy, bedload is recognized as the only means for moving sediment. Observing and quantifying bedload is inherently more difficult than for suspended sediment because the density of the carpet flow precludes the conventional acoustical and optical scattering measurements that have been developed for the relatively sparse suspensions above the bed. Further, the assumption that the suspended material moves at the velocity of the adjacent fluid cannot be made for bedload, requiring that both the fluid and the sediment velocities be measured independently to understand the response of the sediment to fluid forcing.

As a result of these difficulties, few observations are available of bedload under oscillatory flows under either field or laboratory conditions and little is known about the character of these important flows. Recognizing this, we began a program of full scale laboratory investigations in an oscillatory tunnel employing traps several years ago (King et al., 1984, King, 1991). More recently, the present authors developed an improved technique for observing bedload remotely in this same tunnel without the problems associated with integrating sediment response over time that is inherent with traps. This method is described in general in the following section and in detail in Gallagher et al. (1991).

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As first suggested by King (1991), our work strongly indicated that accelerations played an important role in bedload transport, affecting significantly the magnitude of the sediment velocity with a fixed fluid velocity amplitude, as well as affecting the phase of the response and the initiation of the sediment motion. Given that present predictive models for bedload transport depend only upon the magnitude of the velocity and ignore its time rate of change (see King and Seymour, 1989 for a review of models), we felt that these findings were significant and should be brought to the attention of other researchers concerned with quantifying bedload transport. It should be noted that Hallermeier (1982) discussed the dependence of bedload transport and concluded that fluid accelerations played a "direct role" in sand transport and suggested laboratory work to clarify the effects. The present paper describes our initial work and suggests that these results are of sufficient importance to justify further research in this area, particularly utilizing other means (such as acoustical bedload sensors) to verify and to further quantify these effects.

Measurement Techniques

The oscillatory flow tunnel (OFT) at the Scripps hydraulic laboratory is a flat U-tube with a long rectangular center section and cylindrical risers on either end (see Figures 1 and 2). It is driven by a hydraulic cylinder powering a ram in one of the risers. The test section is 39.4 cm wide, 40 cm high, and 600 cm in length. The maximum water particle excursion in the test section is 214 cm. There is no free surface and the water is forced in solid body motion of arbitrary waveform by computer control. Additional details are contained in King et al. (1984) and King (1991). As described in Gallagher et al. (1991) and Gallagher and Seymour (1991), a smooth bed of natural sand is prepared in which there is a section of the same sand dyed a contrasting color. The general arrangement is shown in Figure 3. In these experiments, a half cycle of sinusoidal water motion was then commanded with a maximum free stream velocity of 80 cm/s. Holding this maximum velocity constant, the period of the oscillatory motion was varied in each experiment over a range from 3 to 6 seconds. That is, the maximum acceleration varied by a factor of two while the maximum velocity remained constant.

As the fluid accelerates from rest, it reaches a condition at which the sand in the bed begins to move and during the deceleration portion of the half cycle, the sand eventually all comes to rest. The motion is detected in these experiments by video imaging. A video camera with a wide angle lens is mounted just above the transparent top of the OFT and images are recorded at approximately 30 hz. These video records are recorded on super VHS format and can be output as steady single frames from a high quality medical-imaging-type tape player. In the color image, the dyed sand is readily recognizable from the natural sand. Therefore, each image shows the accumulated motion in a single direction, to that time, of the dyed sand, since the flow does not reverse. The single frame images are readily stored in a PC computer using a standard commercial framegrabber board and its related software.

The sediment does not move as a monolithic block. Rather, there is a large dispersion in the response that increases with time and distance downflow, in spite of the well sorted character of the sand (median and mean diameter = 1.1 mm, sorting factor = 0.29, skewness = 0.02, kurtosis = 0.66).. This response dispersion is shown conceptually in Figure 4. Because a particle-by-particle tracking strategy seemed too cumbersome, the method used in Gallagher et al., 1991 was employed. Simply stated, the image in the computer is converted to grey scale and the numbers

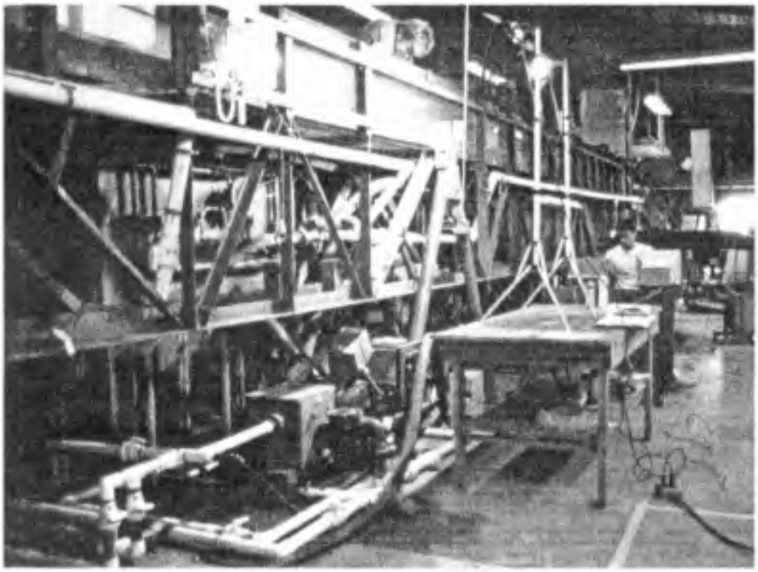

Figure 1. General view of the oscillatory flow tunnel in the SIO hydraulic laboratory.

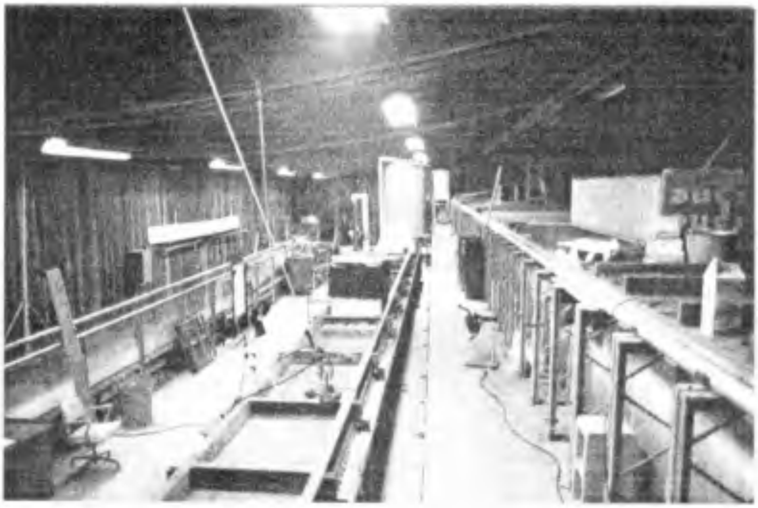

Figure 2. View of the top of the oscillatory flow tunnel with the lid closed.

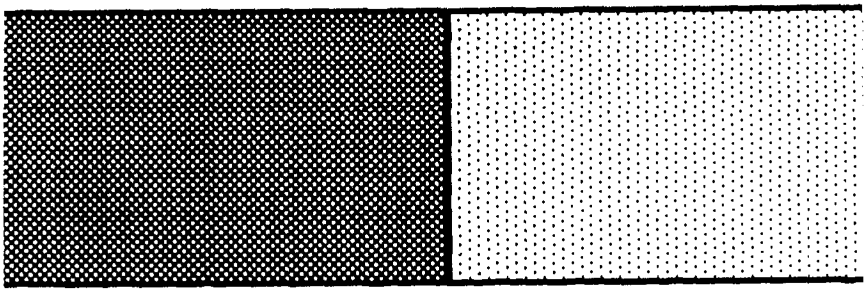

Figure 3. Schematic arrangement of upper surface of the bed prior to the experiment, showing dyed sand section. Motion will be from left to right.

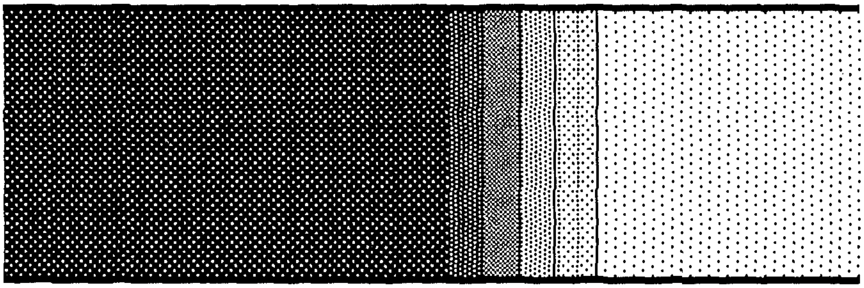

Figure 4. Schematic view of upper surface of the bed following the experiment. Water and sediment motions have been from left to right.

representing the intensity (darkness) of each pixel in the image are averaged over a column extending across the tunnel, orthogonal to the flow. This average color intensity is then a measure of the amount of dyed sand in the upper layer or two that has moved into that column of pixels. In general, this number should increase with time until the sediment motion stops and then remain steady. In practice, that is what is observed. The dyed sand section has sufficient length, relative to the sediment motion, that no undyed sand is imported into the image.

Figure 5 shows a representative plot of these intensities along the flow axis from a single image. Some low level noise of the type shown here is always present, but the data also always show a clear underlying curve representing the distribution of distances travelled by the dyed sand grains. A smooth curve is passed through the data using a high order polynomial fit and this smooth curve then represents the results of a single image from an experiment. To define a representative distance traveled for each of these distributions (images), the intersection of the smooth curve with an arbitrary intensity level was chosen (see dashed line on Figure 5.)

Prior work (King, 1991) had shown that the free stream velocity could be accurately determined from a linear position transducer on the ram and this position was recorded on a PC during the experiment. The computer periodically actuated a light visible in the video image in approximately one out of each 15 images, which allowed time synchronization within about 0.015 seconds. In this manner, the free stream velocity could be obtained by differentiating the ram position and the position of the representative dyed sand intensity contour could be time correlated with it. The sediment velocity and acceleration were obtained by successive differentiation of the positions obtained from the images.

Results

Experiments were conducted at periods of 3,4,5 and 6 second periods, all with amplitudes resulting in a maximum velocity of 80 cm/s. The response of the sediment is shown in Figure 6. Note that time has been nondimensionalized by the period so that a single curve represents the fluid velocity in each case. It can be clearly seen that the higher accelerations (lower periods) result in an initiation of motion at a later phase than for the lower accelerations. The phases are plotted as angles against peak accelerations in Figure 7. The results are shown in dimensional form in Table I and it is clear that the absolute initiation velocities are higher when the rate of change of fluid velocity is higher, which might be considered counter-intuitive.

The resulting sediment velocities are shown in Figure 8. Smooth curves have been fitted to the calculated velocity values. Note that the maximum sediment velocity increases monotonically with the maximum fluid acceleration and it occurs at a later phase. The shortest period oscillation (3 seconds) results in a maximum sand velocity of almost 60 cm/s - about 75% of the maximum free stream fluid velocity.

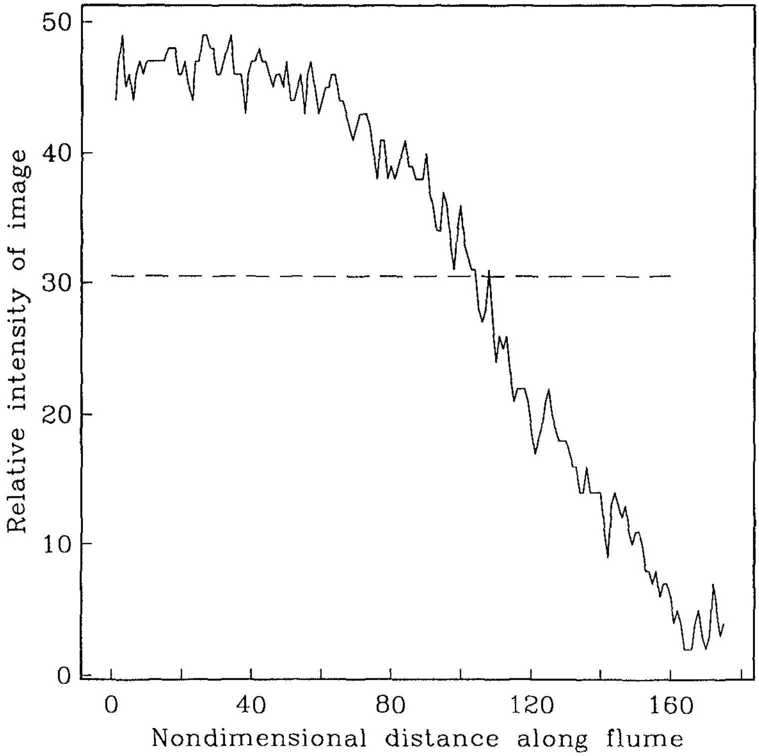

Figure 5. A non-dimensional plot of the intensities of the image (higher intensity signifies greater fraction of dyed versus natural sand) against distance down the flume. The origin of the abscissa is the initial boundary between the dyed and the natural sand.

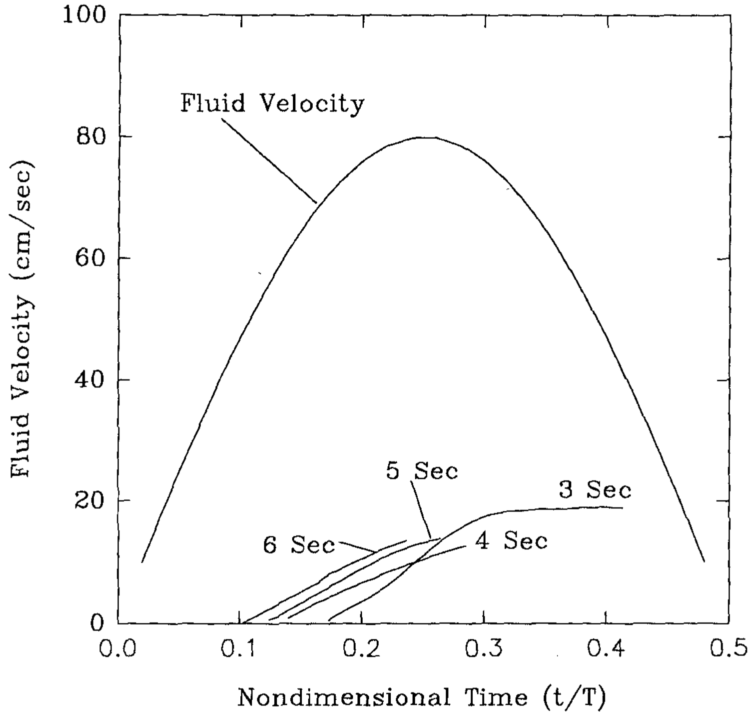

Figure 6. Sediment movement and fluid velocity plotted against nondimensionalized time (fraction of oscillatory period). The periods of the water motions are plotted adjacent to the sediment responses. The effects of acceleration can be clearly recognized.

Table 1.
Free stream velocity and acceleration calculated for the phase at which bedload transport is initiated.

Exp No.	Period (sec)	Phase (deg)	Velocity (cm/s)	Acceleration (cm/s^2)
6	3	46.8	58.3	114.7
9	4	41.4	52.9	94.3
12	5	34	44.7	83.3
15	6	31	41.2	71.8

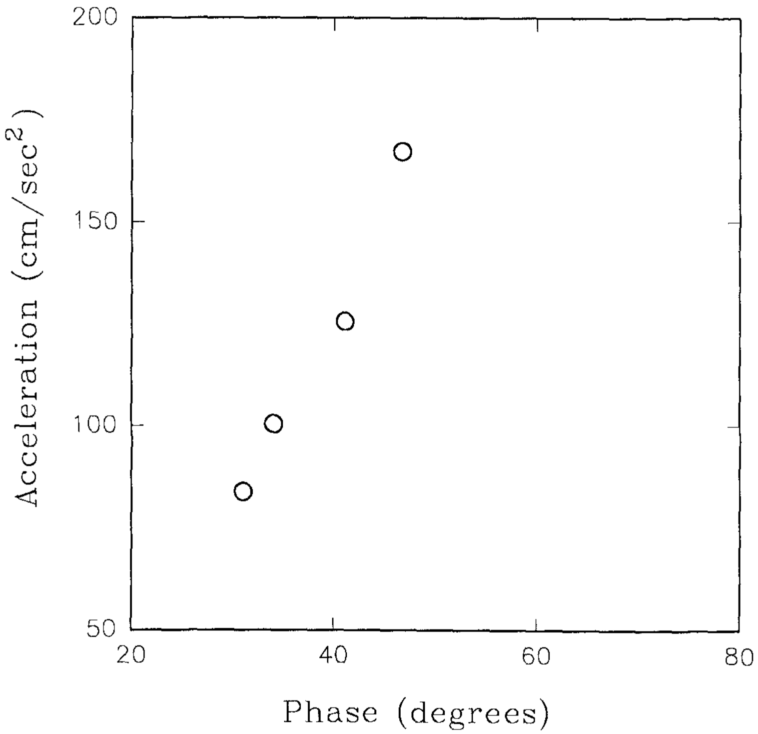

Figure 7. The phase of the initiation of motion (in degrees) plotted against the magnitude of the peak acceleration for each run.

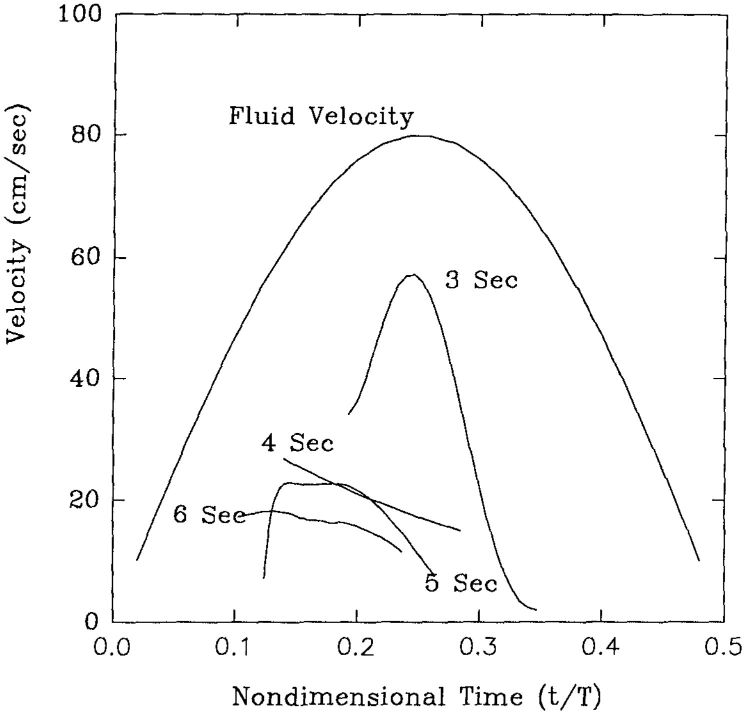

Figure 8. The velocity of the fluid and the resulting velocities of the sediment at various periods of oscillatory flow are plotted against nondimensional time.

Discussion and Conclusions

These experiments were begun from rest after long stilling periods such that laminar flow conditions existed at least at the initiation of fluid flow. Because the flow was stopped as it decreased to zero (no flow reversal) there was little or no opportunity to develop a boundary layer typical of continuing oscillatory flows - in which the bottom stress is theoretically expected to lead the free stream by $\pi/4$. Therefore, there was unlikely to be any substantial phase differences between the free stream and the nearbed flows. In fact, careful observation of suspended particle velocities in King (1991) indicate no discernible phase shift right down to the bed in the half cycle flows.

The significance of this is that any phase shifts between sand and the fluid observed would be a function only of the response of the sediment to the bottom stress. We observed substantial velocity phase leads for the sediment in the longer period experiments, but these reduced to near zero for the shortest period. In fact, in all of the experiments the sediment came to rest either before the maximum free stream velocity had been reached or before it had dropped to 75% of its maximum value. This very surprising result would indicate a response mechanism that is highly sensitive to acceleration - as the positively directed acceleration approaches zero, the bedload ceases, even though the free stream velocity is at or near its maximum value. Sleath (1978) observed a phase lead of the sediment of roughly $\pi/8$ in continuously oscillating flows and discounted inertial effects because the acceleration leads the velocity by $\pi/2$. However, the present evidence - which removes any effects of phase shifts in the boundary layer - seems to indicate that acceleration is indeed a first order factor in bedload transport.

Because the experiments do not replicate the turbulence and the fully developed boundary layer under waves, we do not believe that the absolute numbers measured here for sediment response are useful values. However, we believe we have succeeded in isolating a very important and largely overlooked factor in the forcing of bedload that must be accounted for in realistic predictive models.

Acknowledgements

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