FLOW OVER A MOVABLE SEDIMENT BED: LABORATORY EXPERIMENT

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Abstract

The dynamics of erodible bed due to flow is of great importance for sediment transport in irrigation canals, rivers and coastal zone. The problem is one of the most complex, and its practical solution has not yet been fully reached. The goals of this research are to study the development of different bed forms in unidirectional flow. Experimental results are compared with the theoretical models of the two-dimensional potential flow over a wavy stream bed. The flow over bed forms is investigated with experiments with artificial bottom roughness, and a laser Doppler anemometer is used to measure the local velocity.

1. Introduction

The interaction between a fluid flow and bottom sediments is a topic of considerable interest for coastal and hydraulic engineers. Bed forms, such as ripples, dunes and antidunes, play a significant role in the makeup of resistance to flow in alluvial channels, and many engineering problems associated with the coastal environment are often determined by sediment transport due to current and wave action. An understanding of the generation and properties of bed forms can be expected from a detailed analysis of the kinematics and dynamics of the interaction between flow and the bed.

In the present article we give results pertaining to a kinematical stability analysis of the bed forms generated by steady open-channel flows. The potential-flow model presented below incorporates approaches developed by Sretenskii[1], Kennedy[2], Reynolds[3] and Davis[4].

2. Model

Flow over undulated rigid bottom. Using the method [1,4], let us determine the velocity field perturbations caused by bedforms in the case of unidirectional steady-state flow.

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We assume that the fluid is of constant depth h and has flow velocity U in the positive x-direction, as shown in Fig. 1. The bed is impermeable and undulated infinitely, and the flow is nonseparating. Let the function $y = -h + \eta(x)$describe the bedform, and let us consider the case of $\eta(x) = a \cos kx$, where a is small.

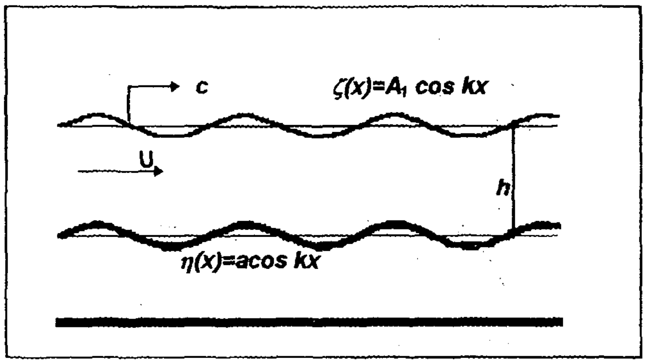


Fig. 1.

Considering the classical potential flow satisfying appropriate conditions at a free surface and a kinematic restriction at a sinosoidally perturbed bed, we find the velocity potential

$$\phi = -Ux + (U^3 a/2k \cosh kh)[(g/U^2 + k)\, e^{ky} + (g/U^2 - k)\, e^{-ky}][\sin kx/(U^2 - c^2)] \quad (1)$$

where c is the speed of waves of length $2\pi/k$ in water of depth h.
The equation of free surface is

$$\zeta = (U^2 a/\cosh kh)[\cos kx/(U^2 - c^2)] \quad (2)$$

Thus the crests and troughs of the free surface and the bottom correspond or are opposite according as $U^2 > c^2$ or $U^2 < c^2$. The horizontal velocities at the crest and trough positions on the bed surface, u_{cr} and u_{tr} are given by

$$u_{cr/tr} = U\,(1 \pm ak) \quad (3)$$

and so depend directly on the undulated bottom steepness ak.
The stream function $\psi(x,y)$ is determined by

$$\psi = Uy + (U^3 a/2k \cosh kh)[(g/U^2 + k)\, e^{ky} - (g/U^2 - k)\, e^{-ky}][\cos kx/(U^2 - c^2)] \quad (4)$$

Flow over a movable sediment bed. The analytical model [2,3] predicts bed forms, their characteristics, and their stability for a free surface flow over an erodible bed. The dominant wavelength of the bed form can be determined from

$$F^2 = U^2/(gh) = (1 + kh \tanh kh + k\delta \cot k\delta)/[(kh)^2 + (2 + k\delta \cot k\delta)\, kh \tanh kh] \quad (5)$$

where F is the Froude number, h is the fluid depth, k is the wavenumber, and δ is the distance by which the local sediment transport lags the local velocity ($\delta/h=j$). Note, that in the case of antidunes the wavelength is expressed by

$$L_{min} = 2\pi\, U^2/g \quad (6)$$

Antidunes are seen to occur at F^2 lying between (1/kh) tanh kh, 1/kh and the curve for Eq.(5) with $\delta=0$. The transition occurs between F=1.0 and F=0.844. The upper limit of F for ripples and dunes is described by

$$F^2 = (1/kh) \tanh kh \quad (7)$$

The amplitude a of the bed profile is related to the amplitude A of the surface waves by

$$a = A\,[1 - g/(k\,U^2) \tanh kh)] \cosh kh \quad (8)$$

The last equation shows that the bed and water surface profiles are in phase (antidunes) or out of phase (dunes) according to $U^2 \gtrless g/(k) \tanh kh$.

3. Experimental Procedures

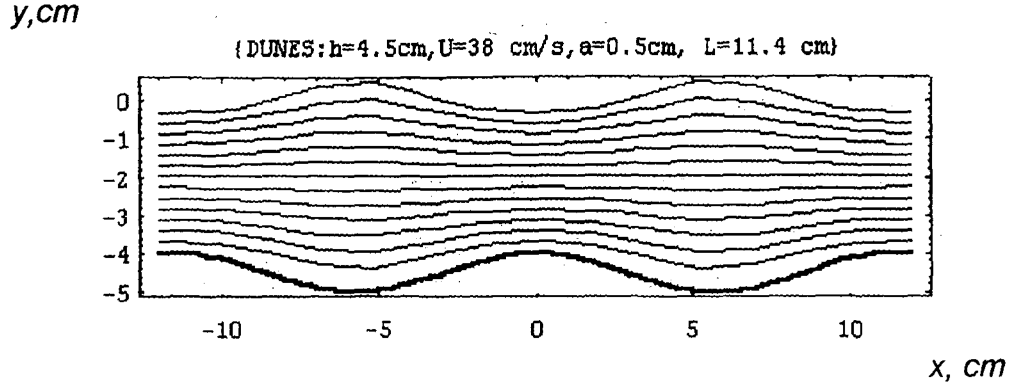
The flume has a total length of 160 cm, a width of 8 cm, and a depth of 14 cm. The current was generated by a constant head system. The current was generated by constant head system. The water was recirculated through a settling basin where most of the sediment load was trapped. By adjusting the height of the weir at the end of the flume, the desired water depth was obtained. Two types of sediment material were used: a) 0.35 mm sand and b) 0.60 mm sand. The slope of the flume was changed in the range of (0^0, $1^0 25'$). To produce the undulated rigid bottom forms, the modeling clay was used. The initially horizontal layer of plasticine has the depth of 25 mm.

The procedure in the experiments was to measure the velocity in the free stream flow using LDA or volumetric method, and to estimate simultaneously the response of the sand bed by a photometric method. Estimates showed that displacement of the fluid-sand interface from the equilibrium position on the photopictures was measured within an accuracy of 0.5 mm.

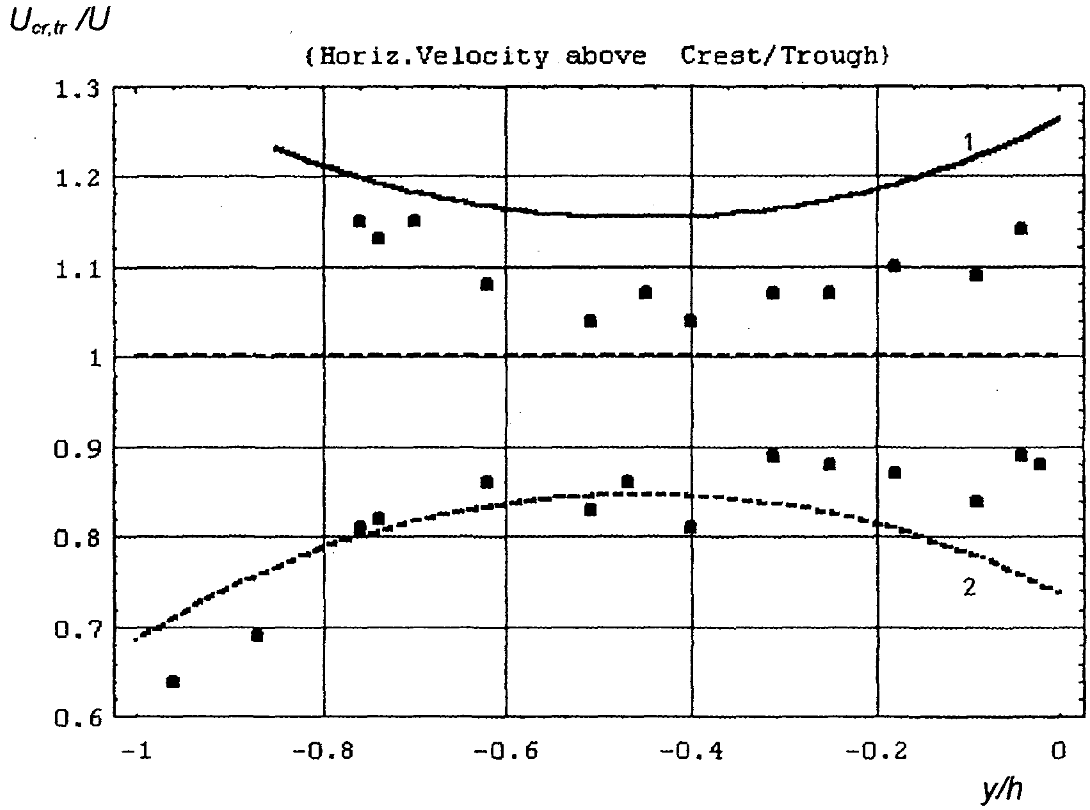
The flow kinematic parameters were measured using a laser Doppler anemometer (LDA DANTEC). A LDA-system consisted of two beams, one component modular optics operating in the directscatter mode. The kinematic data were recorded and processed using a data acquisition and signal processor system and a personal computer with special software [4].The measured velocity of the water particle is known to be directly related to the Doppler frequency measured by the LDA, the angle of beams intersection and the wave length of light [5]. For these experiments the signal processor was set for a Doppler frequency range of 0.12 MHz or 0.40 MHz. A frequency shift of 40 MHz was used for the Doppler frequency ranges. These settings for the red light (λ = 632.8 nm) covered the expected velocity range of -0.4 to 1.1 m/s, respectively. The vertical velocity profiles were obtained by displacing the modular optics by means of a traverse mechanism. The combined relative error of the velocity measurement did not exceed 3%.

4. Results and Discussion

Flow over undulated rigid bottom. We considered a set of laboratory results which would enable the near-bottom velocity field to a set of observations of sediment transport on a wavy sand bed. A prerequisite for understanding of the response of the bed to the uniform flow in the fluid area.



a)



b)

Fig. 2. a) Streamlines for nonseparating potential flow over the undulated rigid bottom; b) Vertical profiles of the normalized horizontal velocity above crest and trough positions: U=38.0 cm/s, h=4.5 cm, a=0.5 cm, $L=2\pi/k$=11.4 cm: 1 - crest, 2 - trough

The original bed profile is shown in detail as the full line in the lower part of Fig. 2a. The bed wavelength was L=11.4 cm , so its steepness was ak=0.25. The flow above the zero streamline ψ=0 displays the expected features, namely that the streamlines converge over the crests and diverge over the troughs (Fig. 2a). The consequence of this may be seen in Fig. 2b, where vertical profiles of horizontal velocity are shown. At the crest the surface velocity is 1.27U, where U is the undisturbed free-stream velocity, and at the trough the surface velocity is 0.68U. The velocity perturbation due to the bed form extends throughout the area of the flow up to free surface because water is relative shallow compared with the bed wavelength (h/L=0.39). The presence of free surface caused relative increases in velocity over crests, and relative decreases in the troughs. Results of velocity measurement by LDA are presented in Fig. 2b. The theory is in good agreement with the experimental data.

Flow over a movable sediment bed. Experiments showed that for certain intervals of the Froude number, the surface of a mobile bed had periodic irregularities - sand waves. The following classification can be used: 1) ripples and dunes ($F<1$), and antidunes ($F>1$). Figure 3 shows theoretical curves derived from Eq.(5), and the experimental data. Note that models [2,3] is not totally realistic because they ignore the separation zone associated with bed forms. No generally accepted theory of the origin of sand waves has been produced.

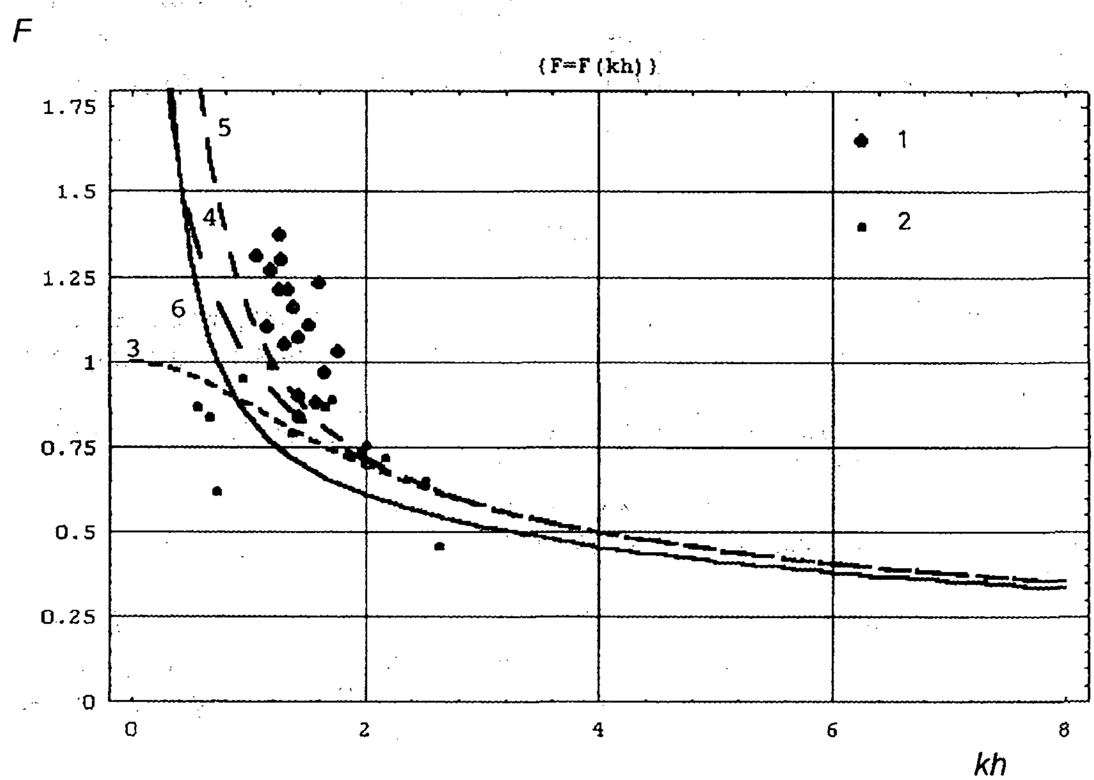


Fig. 3. Comparison of predicted and observed bed forms: 1 - antidunes; 2 - dunes; 3 - $F^2=(1/kh)\tanh kh$; 4 - $F^2=1/kh$; 5 - $F^2=1/(kh\tanh kh)$; 6 - Eq. (5) with $\delta=0$

The Froude number is high for antidunes, but if so, the Reynolds number should also be high. For large Re the relative length of dunes is given by $L\approx 2\pi h$ (See [7]), while the relative length of antidunes is determined by Eq. (5). The relative lengths of dunes and antidunes do not differ more than twice in the range of Froude numbers corresponding to practically possible flows. Hence simultaneous occurrence of dunes and antidunes is impossible.

5. Conclusions

It has been shown how the velocity field over the sinusoidal bed may be determined in relation to the given uniform flow. Since the model used is linear, the principle of superposition is true and so, for more complex bottom topography, the final result for the velocity may be obtained by superimposing solutions for each component of the bed profile.

An analysis of mechanics of sand waves formed by a flowing fluid with a free surface has been presented. Kennedy-Reynolds' model was used to discribe the parameters of the bed forms and their behaviour. The surface waves, the turbulence and the stability of bed can be considered as possible reasons for occurrence of sand waves: dunes and antidunes are more related to the flow, and only ripples may be the features of the mobile bed.

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