Experimental Thermal and Fluid Science 71 (2016) 95–102

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

The formation and migration of sand ripples in closed conduits: Experiments with turbulent water flows

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ARTICLE INFO

Article history:
Received 3 March 2015
Received in revised form 18 October 2015
Accepted 19 October 2015
Available online 26 October 2015

Keywords:
Bed load
Turbulent water flow
Instabilities
Ripples

ABSTRACT

The transport of solid particles by a fluid flow is frequently found in nature and industry. Some examples are the transport of sand in rivers and hydrocarbon pipelines. When the shear stresses exerted by a fluid flow on a granular bed remain moderate, some grains are set in motion without fluidizing the bed; the moving grains form a layer, known as bed load, that moves while maintaining contact with the fixed part of the bed. Under bed load conditions, the granular bed may become unstable, generating ripples and dunes. Sand ripples are commonly observed in closed conduits and pipes such as in petroleum pipelines, sewer systems, and dredging lines. Although of importance for many scientific domains and industrial applications, the formation of ripples in closed conduits is not well understood, and the problem is still open. This paper presents an experimental study on the formation and migration of sand ripples under a turbulent closed-conduit flow and bed-load conditions. In our experiments, fully-developed turbulent water flows were imposed over a granular bed of known granulometry in a transparent channel, and bed load took place. For different water flow rates and grain diameters, the growth and migration of bedforms were filmed by a high-definition camera, and a numerical code was developed to determine the wavelength and celerity of the bedforms from the acquired images. The obtained results are compared with published stability analyses.

1. Introduction

When a fluid flows over a granular bed, grains can be entrained owing to momentum transfer from the fluid to the grains. If the shear stresses exerted by the fluid on the granular bed remain moderate, some grains are set in motion without fluidizing the bed; the moving grains form a layer, known as a bed load, that moves while maintaining contact with the fixed part of the bed. Bed load is frequently found in nature and industry. In nature it is present, for example, in the erosion of riverbanks and the formation and migration of dunes in deserts. In industry, it is present in petroleum pipelines, pharmaceutical processes, dredging lines, and sewer systems. Under bed load conditions, the granular bed may become unstable, generating ripples and dunes. In the specific case of oil industry, it is common to observe the formation and migration of ripples inside offshore pipelines conveying oil and sand. These ripples increase pressure losses, raising production costs for petroleum extraction. In addition, their migration along the pipeline causes flow transients. Still concerning offshore activities of the oil industry, the pipelines are subject to movements of sand dunes over the sea bed, which interfere with production activities [1]. Therefore, better knowledge of bed load and associated instabilities is of importance to understand erosion and deposition in nature, and to control various industrial processes.

The formation and migration of ripples and dunes have been the subject of many studies in previous decades. In the aeolian case, the work of Bagnold [2] was followed by many others that contributed to our understanding of aeolian dunes. Some more recent examples are [3–8]. In the aquatic case, numerous studies were concerned specifically with the stability of a granular bed sheared by a fluid flow [9–17]. The stability of a granular bed is given by the balance between local erosion and deposition; therefore, the mechanisms creating a phase lag between the shape of the granular bed and the bed-load transport rate must be known. Engelund and Fredsoe [13] summarize the stability analyses of most of these papers and show that the fluid flow perturbation, the gravitational field, and the inertia of the grains are directly related to the stability of the bed. Owing to its negative phase lag with respect to the bedform, the fluid flow perturbation caused by the shape of the bed is a destabilizing mechanism [18–20], whereas the local slope of the bed (gravity effects) and the grain inertia (relaxation effects)

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http://dx.doi.org/10.1016/j.expthermflusci.2015.10.017
0894-1777/

due to their positive phase lag with respect to the fluid flow perturbation are the stabilizing mechanisms [21,15,22].

Some stability analyses and experimental studies were carried out for the specific case of turbulent flows of liquids in closed conduits. Kuru et al. [23] presented a theoretical and experimental study of the initial instabilities of granular beds in pipes. Their experimental test section was a 31.1 mm-diameter pipe, with a length of 7 m, and they employed mixtures of water and glycerin as the fluid media and glass beads as the granular medium. The authors presented a linear stability analysis of a clear-layer and suspension-layer cocurrent two-phase flow. They did not consider the bed load in their model, although the grains used and the fluid flow conditions were clearly in the bed-load range. They found that instabilities appear because the shear stresses caused by the clear layer on the interface with the suspension layer are shifted upstream with respect to the undulations of this interface. The wavelength they found overpredicts the experimental measurements, probably because they neglected the bed-load layer and the corresponding effects of relaxation. Their experimental results (performed mainly in the turbulent regime) showed that the initial wavelength scales with the flow rate of the fluid; however, their linear stability analysis was not able to explain the experimental results.

Coleman et al. [24] experimentally studied the instabilities of granular beds in a closed conduit. The experimental test section was a 6-m-long horizontal closed conduit with a rectangular cross section (300 mm wide by 100 mm high), and they employed water as the fluid medium and glass beads as the granular medium. The fluid flow was in the turbulent regime. They found that the initial instabilities have a well-defined wavelength, which scales with the grain diameter but not with the fluid flow. They also found that the formation of ripples in closed-conduit flows and in subcritical open-channel flows are similar, with roughly the same wavelength for the initial ripples.

Franklin [25] experimentally studied the initial instabilities of different granular beds under turbulent water flows. The experimental test section was a 6-m-long horizontal closed conduit with a rectangular cross section (120 mm wide by 60 mm high) made of a transparent material. He employed water as the fluid medium and glass and zirconium beads as the granular media. The fluid flow was measured by PIV (Particle Image Velocimetry), and the granular bed evolution was measured by using a high-definition camera. Franklin [25] found that the initial instabilities have a well-defined wavelength, which scales with both the diameters of the grains and the fluid flow.

Franklin (2010) [22] presented a linear stability analysis for the specific case of granular beds sheared by the turbulent boundary layers of liquids. The analysis considered the fluid flow perturbation, local slope, and relaxation effects; however, it neglected the presence of free surfaces. Therefore, the analysis is suitable for bedforms scaling with the low regions of the boundary layer or to closed-conduit flows. Franklin [22] showed that the length scale of the initial bedforms varies with the fluid flow conditions.

Franklin [26] proposed a weakly nonlinear analysis for the stability of granular beds in pipes and closed conduits for the specific case of the turbulent flows of liquids. The author demonstrated that, after the linear growth phase, the bed instabilities saturate in amplitude while maintaining the same wavelength of the linear phase.

This paper presents an experimental study on the formation and migration of ripples in closed conduits under turbulent flow conditions. In our experiments, pressure-driven turbulent water flows were imposed over a granular bed of known granulometry in a transparent channel. For different flow rates and grain diameters, the growth and migration of bedforms were filmed by a high-definition camera. The wavelength and celerity of the bedforms were determined by post-processing the images with a numerical code of our own. The results are compared with published stability analyses.

2. Experimental device

2.1. Experimental setup

The experimental device consisted of a water reservoir, progressive pump, flow straightener, 5-m-long channel, settling tank, and return line. The flow straightener was a divergent–convergent nozzle filled with $d = 3$ mm glass spheres, the function of which was to homogenize the flow profile at the channel inlet. The channel had a rectangular cross section (160 mm wide by 50 mm high) and was made of a transparent material. Fig. 1 shows a schematic of the experimental loop. The channel test section was 1 m long and started 40 hydraulic diameters (3 m) downstream from the channel inlet. A fixed granular bed consisting of glass spheres glued onto the surfaces of PVC plates was inserted into the channel section in which the flow is developed, assuring that the turbulent flow was completely developed in the test section. In the test section, the grains were deposed and formed a loose granular bed having the same thickness (7 mm) as the fixed bed. Glass spheres with a specific mass of $\rho_s = 2500\ \mathrm{kg/m^3}$ were employed to form both the fixed and loose granular beds. The grains were classified into three populations, each having their minimum and maximum sizes limited by the use of sieves with distinct meshes: the first had its size ranging from $d = 212\ \mu\mathrm{m}$ to $d = 300\ \mu\mathrm{m}$, and it is assumed that the mean diameter was $d_{50} = 256\ \mu\mathrm{m}$; the second had its size ranging from $d = 300\ \mu\mathrm{m}$ to $d = 425\ \mu\mathrm{m}$, and it is assumed that $d_{50} = 363\ \mu\mathrm{m}$; the third had its size ranging from $d = 500\ \mu\mathrm{m}$ to $d = 600\ \mu\mathrm{m}$, and it is assumed that $d_{50} = 550\ \mu\mathrm{m}$. Prior to each test, the loose granular bed was smoothed and leveled.

The tests were performed at ambient conditions, i.e., an atmospheric pressure of 1 atm and a room temperature of approximately 25 °C. The water flowed in a closed loop driven by the pump from the reservoir through the channel and grain separator and back to the reservoir. The water flow rate was controlled by changing the excitation frequency of the pump and was measured with an electromagnetic flow meter. The nominal test flow rates were in the range of $6.6\ \mathrm{m^3/h} \leqslant Q \leqslant 10.3\ \mathrm{m^3/h}$, the cross-section mean velocities were in the range of $0.27\ \mathrm{m/s} \leqslant U \leqslant 0.42\ \mathrm{m/s}$, and the Reynolds number $Re = U2H_{gap}/\nu$ was in the range of $2.3 \cdot 10^4 \leqslant Re \leqslant 3.6 \cdot 10^4$, where H_{gap} is the distance from the granular bed to the top wall. Franklin et al. [27] measured water flow fields for the same experimental device over similar moving beds. The water flow profiles presented in Franklin et al. [27] were assumed to be valid for the present experiments and are used in this study.

Preset water flows were imposed by the pump, generating a turbulent flow of water over the granular bed to obtain the transport by bed load. Under the effect of the flow, there was the formation and migration of ripples, which were filmed by a high-definition camera. The obtained images were sent to a computer, where they were stored for further processing and analysis.

A high-definition CCD camera with a resolution of 2048 px × 2048 px and a 14-bit digital output was employed to film the bed evolution. A computer was used to control the frequencies and exposure times of the high-definition camera and to store the acquired images. In order to provide the necessary light, approximately 200 LED (Light-Emitting Diode) lamps were attached to plates and branched to a continuous current source. The plates were positioned in order to provide oblique light so that the crests were highlighted. A Makro-Planar lens with a 50-mm focal distance was used, and the calibration process was performed