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Identification of particle-laden flow features from wavelet decomposition

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ABSTRACT

A wavelet decomposition based technique is applied to air pressure data obtained from laboratory-scale powder snow avalanches. This technique is shown to be a powerful tool for identifying both repeatable and chaotic features at any frequency within the signal. Additionally, this technique is demonstrated to be a robust method for the removal of noise from the signal as well as being capable of removing other contaminants from the signal. Whilst powder snow avalanches are the focus of the experiments analysed here, the features identified can provide insight to other particle-laden gravity currents and the technique described is applicable to a wide variety of experimental signals.

1. Introduction

Particle-laden gravity currents exist in many different forms throughout nature, examples include powder snow avalanches, turbidity currents and pyroclastic flows. These geophysical phenomena typically exhibit a dense, more granular flow, however here we are concerned with the suspended material, where the interplay between particle and interstitial fluid flow is paramount. These currents can be extremely destructive, due to the large changes in pressure over very short time periods, capable of subjecting structures to high stresses. The forces exerted by these pressure changes can be up to four times that exerted through hydrostatic pressure variation within the flows [1]. It is therefore of interest to study fluid pressure signals obtained from particle-laden gravity currents in order to gain a better insight into their internal structure and dynamics.

Here we are primarily motivated by powder snow avalanches (PSAs), but the techniques discussed are equally applicable to other forms of particle-laden gravity current.

Due to their dangerous nature and unpredictability, obtaining air pressure data from natural PSAs is extremely difficult. Laboratory-scale physical models are therefore a useful tool for collecting repeatable and controlled data.

1.0.1. Similarity criteria

PSAs are non-Boussinesq, since the particulate material (snow) is relatively dense compared with the ambient fluid (air) and the particles thus carry a significant proportion of the current's momentum.

Three different particulate materials have been used in order to create particle-laden gravity currents that have density ratios that fall within the non-Boussinesq regime—a sawdust and aluminium mixture [2], expanded polystyrene (EPS) [3,4] and powder snow [4].

The particle Reynolds number

$$\mathrm{Re}_\mathrm{p} = \frac{\rho_a u d_p}{\mu}, \tag{1}$$

is the ratio of the viscous and form drag forces (per unit volume) of a particle with diameter d_p and velocity u in ambient fluid of viscosity μ and density ρ_a (Fig. 1). The particle Reynolds number determines whether the drag is dominated by viscous or pressure forces. PSAs typically have a $\mathrm{Re}_\mathrm{p} \approx 3000$ meaning viscous drag forces play a minor role compared with the form drag of the particle. For values $500 < \mathrm{Re}_\mathrm{p} < 10^5$ the drag coefficient for a spherical particle is essentially independent of Re_p [5] and so within this range of Re_p drag forces in PSAs will be well modelled. It should be noted that both the natural and model powder snow particles are henceforth assumed to be spherical. While it is unlikely that the particles are perfectly spherical, a particle's eccentricity will only have an effect on its drag coefficient when $\mathrm{Re}_\mathrm{p} >\approx 10^5$ [5], which is well above the typical values of Re_p observed in natural PSAs.

Laboratory-scale snow-air and polystyrene-air models have a $\mathrm{Re}_\mathrm{p} \approx 150$ due to the currents reaching much lower speeds than PSAs. Therefore viscous forces between the air and snow/polystyrene particles will have a greater effect on these flows than in a PSA. However, for these models Re_p is still sufficiently large so that form drag will be dominant and viscous drag forces

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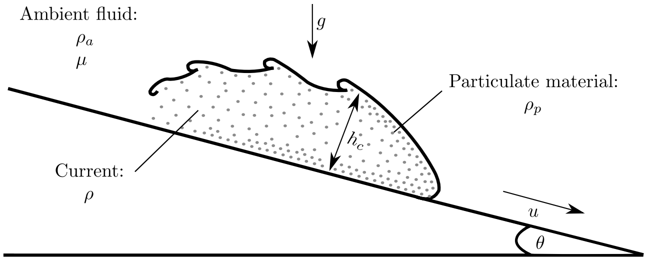

Fig. 1. Schematic diagram of a particulate gravity current of height h_c, density ρ and velocity u travelling down a plane inclined at an angle θ to the horizontal. Ambient fluid has density ρ_a and viscosity μ, and individual particles have density ρ_p.

can be considered small, especially compared with Bozhinskiy and Sukhanov's experiments ($\mathrm{Re}_p \approx 0.1$), where the particles are considered so fine that drag forces are dominated by viscous forces.

The Richardson number (Ri) is the ratio of potential energy to kinetic energy of particles at the sheared interface between two fluids. The Richardson number for a layer of height h_c and velocity u on a slope at angle θ to the horizontal is

$$\mathrm{Ri} = \frac{g' h_c \cos\theta}{u^2}. \tag{2}$$

The reduced gravity is $g' = g\Delta\rho/\rho_a$, where $\Delta\rho = \rho - \rho_a$ with ρ and ρ_a the densities of the current and the ambient fluid, respectively (Fig. 1). The Richardson number provides an indication of the stability of the flow [6]. If the Ri value is low, a dense flow will entrain air on the upper surface and become suspended. If the Ri value remains low the current will maintain the particles in suspension and further entrain air. The value of Ri for natural PSAs is typically ≈1, meaning that the powder snow particles become, and remain suspended. Due to the lower velocities of laboratory-scale snow-air and polystyrene-air flows, very high slope angles have to be used in order to achieve values of Ri identical to those observed in PSAs.

Polystyrene-air currents offer a significant advantage over snow-air currents in that they allow much more control over initial conditions. Dry snow metamorphoses and sinters into clumps within seconds, and therefore has to be broken up with a sieve shortly before or during release, greatly restricting control over initial conditions of the flow.

1.1. Flow features

It has been demonstrated both theoretically [7] and experimentally [4] that a gravity current head consists of a large rotating, vortex-like structure. The driving component of gravity accelerates the EPS beads and air downslope towards the front of the flow. At the front of the flow this acceleration is countered by drag from the ambient air. Turbulent eddies forming along the top surface of the flow entrain air and slow the flow at the top of the current. Moving back from the front the turbulence decreases and the denser EPS beads begin to settle and fall towards the chute. This forms a denser layer close to the chute surface which then accelerates towards the front due to its greater driving buoyancy force. The process then repeats creating a recirculating flow inside the head (Fig. 2). This recirculating flow causes a large positive peak in basal pore pressure quickly followed by a negative peak of approximately equal magnitude as the gravity current passes over a sensor (Fig. 3). After reaching the negative peak, the air behind the head becomes turbulent and the pressure returns to zero after the flow has passed.

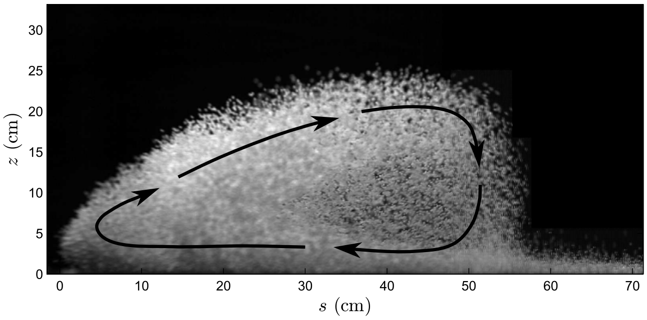

Fig. 2. Side-on image of an EPS bead gravity current. s is the distance into the current from the nose, where at the foremost point of the nose, $s = 0$. z is the perpendicular distance from the chute surface, where at the chute surface, $z = 0$. Black arrows indicate the relative motion of EPS beads within the gravity current head.

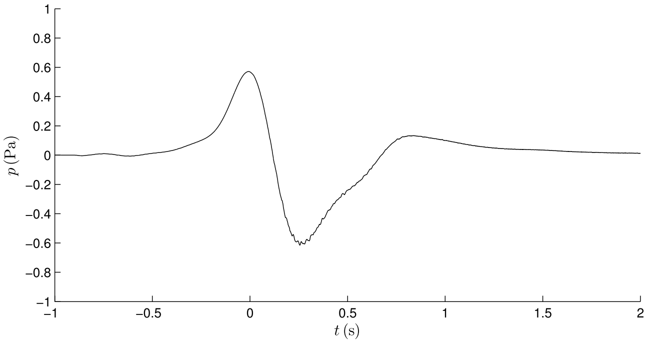

Fig. 3. A typical air pressure signal obtained from the chute surface of a laboratory scale avalanche. The time origin, $t = 0$, corresponds to the time of maximum pressure when the flow front reaches the sensor.

1.2. Wavelet decomposition methods

This work makes use of a wavelet decomposition technique, to first de-noise and filter air pressure signals obtained from laboratory-scale PSAs, and then to visualize data and identify flow features. This technique was developed to be applied to air pressure data signals, but is applicable to any other data time-series or one dimensional signal. Wavelet decomposition is a powerful technique that can be applied to many situations. Similar to Fourier-transform based techniques, time series data is transformed into the frequency domain. However, the advantage that a wavelet-based technique has over Fourier-transform based techniques is that time-domain information is retained during the transformation. This makes it particularly useful in our context for filtering, de-noising and also identifying flow features. Wavelet-based techniques have also been shown to be a robust tool for surrogate data generation [8], which is a powerful technique in testing for nonlinearity in time series [9].

Where Fourier analysis consists of breaking up a signal into sine waves of various frequencies, wavelet analysis is the breaking up of a signal into shifted and scaled versions of a mother wavelet. A wavelet is a waveform of limited duration that has an average value of zero. Unlike smooth and predictable sinusoids, they tend to be irregular and asymmetric. Examples of various different types of wavelet function are shown in Fig. 4.

Wavelets that have 'sharp edges' in the time domain (e.g. Haar (Fig. 4(a)) or Daubechies type 2 (Fig. 4(b))) have excellent temporal localization. This means that the properties of the signal at a point in time will correspond closely to the values for the wavelet coefficients at that point in time, with little smearing of the coefficients across neighbouring time positions. However,