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多元淺水波理論數值模擬河相及土石流之研究(1/3)

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Computational modelling of geomorphic mountain flows based on multi-component shallow water theory

Summary

The three-year research programme pursues the development of novel modelling tools for the description and prediction of geomorphic mountain flows. The approach is based on a multi-component, shallow layer description of horizontal two-dimensional flow. The overall programme aims to: 1) establish governing equations accounting for the coupled motion of water, liquefied soil, and transported sediment; 2) develop and implement suitable computational techniques; 3) test the equations and computations against theoretical, experimental and field information.

As planned in the original proposal, work in the first year has concentrated on the development of the theoretical framework and computational solver. The main theoretical result is a set of general geomorphic flow equations which account for: 1) separate sub-layers having their own density, velocity and rheology; 2) mass and momentum exchanges across sub-layers as well as along and transverse to the flow; 3) modes of support of the granular phase which include contact-load, pore-pressure support, and turbulent suspension. From a computational point of view, the main achievement has been the completion of a second-order accurate, two-dimensional solver for two-layer flows, and its successful application to various geomorphic test cases. The most interesting computation performed to date with the new solver has been the simulation of an evolving field of antidune bedforms.

Further revisions to both the theoretical and computational methods will no doubt prove necessary as we proceed. Nonetheless, the basic tools are ready for the next steps planned for the second and third year of the programme. A key part of these efforts will be to carry out detailed comparisons of model results with available laboratory and field data.

1. Theoretical framework

The starting point of the present research programme is a shallow layer, sharp interface description of geomorphic flows developed in our earlier work. This description proved successful in describing idealised dam-break transients observed in the laboratory. However it had important limitations: 1) no relative velocity was allowed between the water and sediment transport layer; 2) lateral flow boundaries had to be specified as rigid walls rather than erodible banks; 3) the granular phase could only be supported as contact-load. These three limitations made the original description unrealistic for field flows of practical interest.

The theoretical work undertaken in this first year addressed the above limitations through the following advances:

1. Derivation of a general framework allowing different sub-layers of the flow to have independent velocities. Instead of a single momentum equation for the entire flowing layer, different sub-layers are now governed by their own continuity and momentum equations.

2. Development of a criterion distinguishing between reflection and overflow along the loose shoreline of an evolving geomorphic flow. This makes it possible to incorporate erodible banks within the evolving flow domain rather than restrict attention to fully-reflecting rigid walls placed at the domain boundaries.

3. Probably the main result of this year's theoretical efforts was to work out descriptions for alternative modes of transport of the granular phase. Three modes can now be described:
    a) Contact-load of a dense granular phase composed of coarse sediment. This is rather simple to model and was worked out earlier;
    b) Pore pressure support of a liquefied granular phase. This mode of support involves contraction of the granular phase, permeability-controlled pore pressure equilibration, and lowering of the effective granular stress. It was found possible to incorporate these complicated effects in a surprisingly simple way, using shock relations across a sharp consolidation interface.
    c) Turbulent suspension of a dilute dispersion of fine sediment. This was not originally one of our goals, since it was felt to be too complicated. However it turns out that turbulent interactions can also be described in a surprisingly compact way using a sharp interface description. To do so however, it is necessary to budget not only mass and momentum, but also turbulent kinetic

energy.

2. Computational solver

A horizontal two-dimensional code for geomorphic two-layer flows was successfully implemented. The computational algorithms are based on the Godunov scheme of Harten, Lax and Van Leer (HLL), extended to second order accuracy using MUSCL extrapolation. To obtain good results, it was found that the following aspects had to be treated with extra care:

1) Topography: the effet of pressure thrust along the lower boundary of each layer.
2) Shorelines: the evolving internal boundary between zones of flow and no-flow.
3) Source terms: fluxes of mass and momentum across the horizontal interfaces.

These three computational issues are significant already for shallow flows over rigid boundaries. Their significance is even greater in the context of geomorphic flows, since the loose bed boundary itself evolves with the flow. Problems due to improper treatment of the interaction between the flow and its boundary can thus be amplified due to the boundary response.

The new code was tested on a variety of problems. Over steep rigid beds, the code is able to simulate the emergence and coarsening of roll waves, in agreement with experiments and the results of previous investigators. The most interesting novel result was the successful computation of antidunes for flows over steep loose slopes. The fact that the water and sediment transport layers have independently varying velocities appears to be a crucial feature in this regard. A second important aspect is that second-order accuracy of the scheme is necessary for the physical instability not to be overcome by numerical diffusion. Sample antidune computations are shown on Figures 1 and 2. Although a quantitative comparison remains to be made, the results are in rather close qualitative agreement with experimental observations. To the best of our knowledge, these are the first successful computations of an evolving field of antidunes.

The code is currently restricted to contact-load sediment transport, however work is in progress to incorporate the other two mechanisms for which a theoretical description is now available: pore-pressure support and turbulent suspension. The results obtained so far are thus quite encouraging, and allow us to look forward to the next steps of the programme's second and third year. Year 2 will focus on detailed comparisons of the model predictions with available laboratory experiments, while year 3 will be devoted to comparisons with documented field events.

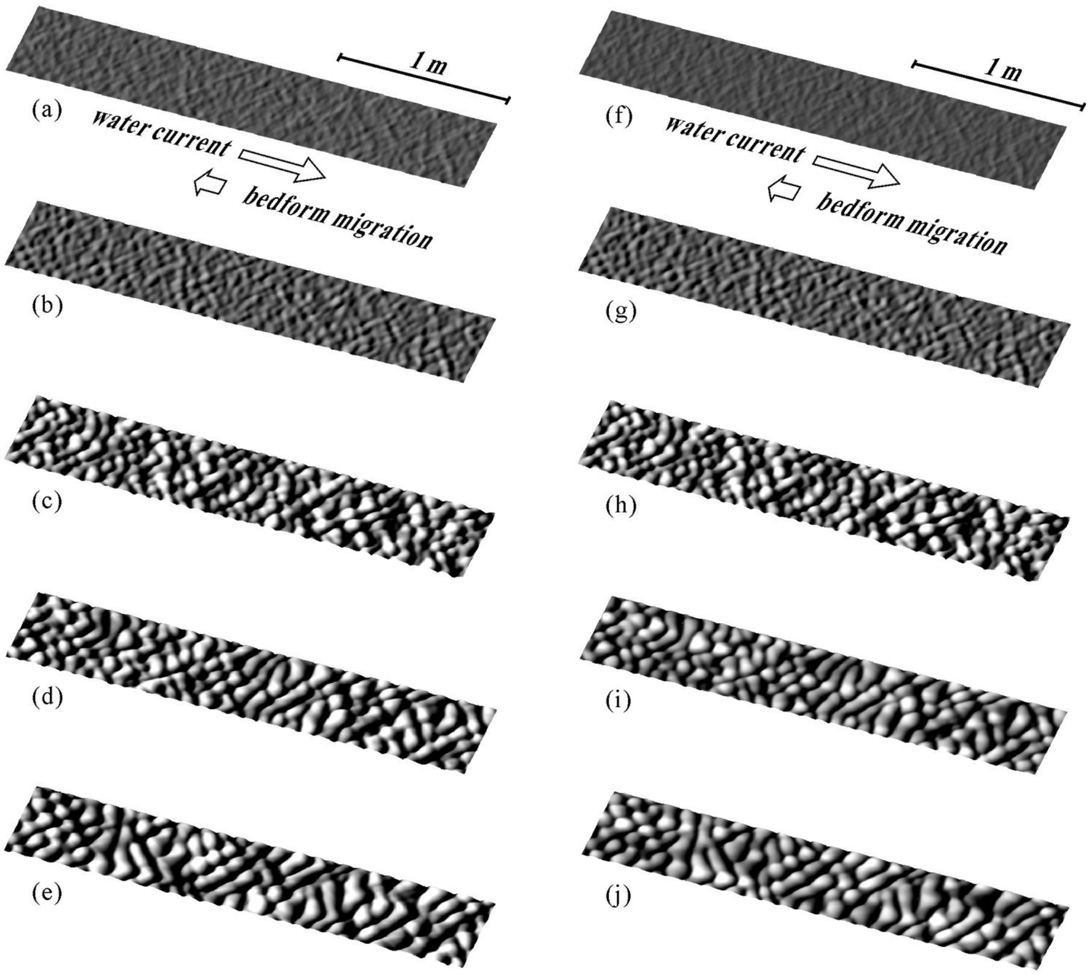

Figure 1. Simulated train of antidunes: (a)-(e) water surface at times $t = 1, 2, 5, 10, 20$ s; (f)-(j) sand bed surface at the same instants. The gray scale codes surface elevation with respect to mean surface level.

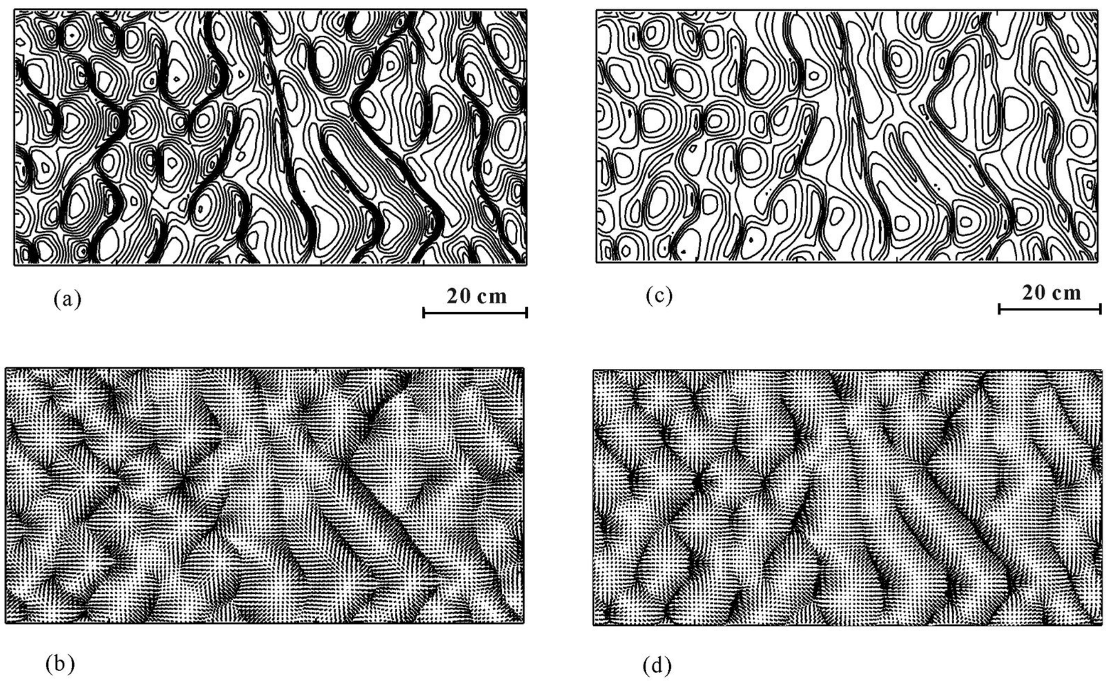

Figure 2. Antidunes detail at time $t = 20$ s: (a) water surface; (b) water velocity field; (c) sediment interface; (d)

sediment layer velocity field. Contours at 1 mm intervals and mean velocity subtracted from vector fields.