Understanding mountain stream culvert blocking using experimental models and the jamming theory of granular flows (Ref IAP2-18-45)

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Key Words
- Mountain streams, road culverts, jamming theory

Overview

Flooding in upland and mountain environments can cause major geomorphological change which impacts on both the natural landscape and human infrastructure. Road networks in such areas are particularly vulnerable to erosion and chronic sedimentation problems where streams intersect the road network. Under normal flow conditions streams can be easily diverted under roads through culverts. However, during extreme events these culverts may become blocked by coarse debris (both sediments and organic material) resulting in sediment-laden flow over the road network resulting severe erosion or blockage.

Figure 1 shows an excellent example of this problem in the immediate aftermath of the December 2015 floods in central Cumbria along the main A591 trunk road. The storm was the largest in a 150 year local rainfall series and set a new UK 48-hour rainfall record of 405 mm (falling in 38 hours, 4-6 December). The flood had major impacts on catchment infrastructure resulting in the closure of a main arterial highway (A591), extensive culvert damage, loss of commercial forestry, disruption to reservoir operation and loss of archaeological remains. Erosion of the A591 adjacent to Raise Beck and damage and blockage along the A591 by Thirlmere resulted in the road being closed for 5 months, with an estimated it cost to the Cumbria economy of up to £1 million per day.

Figure 1. Blocked road culverts on the A591 leading to chronic sedimentation on the road infrastructure (December 2015).

This example demonstrates that culverts are not designed to cope with extreme events, which are predicted to become more frequent in the UK uplands. In addition there are no theoretically based design criteria for mountain stream culverts and 'normal' practice is to replace damaged culverts with the same designs. Therefore there needs to be an overall rethink of this problem which is based on a sound understanding of the mechanics of the mountain stream sediment transport which results in the blockage of culverts.

In this PhD we propose to use a novel combination of small scale model experiments coupled with an understating of granular flow jamming theory to predict critical conditions of culvert blockage (Chevoir et al., 2007).

Granular systems exhibit jamming and exhibit pattern-forming behaviours that influence the flow which
enhances the potential for culvert blockages. A number of algorithms and simple models are available to predict the critical conditions under which such behaviours occur. These will be developed and parameterised as part of this research. This will provide new insights into the mechanism of culvert blocking by sediment transport in mountain streams.

The overall aim of this work is to develop a better understanding of the mechanisms leading to culvert blockage in mountain streams using a combination of field measurements, small-scale laboratory flume experiments and the jamming theory of granular flows. The specific objectives are:

1) Use an existing database of the impact of the Storm Desmond Floods of 2015 on the A591 in Cumbria to develop a conceptual model of processes leading to road culvert blockage.

2) Using the conceptual model developed in (1), design a series of small-scale flume experiments to investigate the processes of culvert blockage and the particular scenarios (channel configuration and culvert design) leading to critical blockage conditions.

3) Use the experimental model to evaluate the importance of sediment and large woody debris in culvert blockage.

4) Apply the theory of jamming of granular flows to predict the critical conditions resulting in the jamming of debris in stream culverts.

5) Synthesise the experimental and theoretical results to provide improved design criteria for mountain stream road culverts, and slope management above roads from which sediments and vegetation are sourced.

Methodology

The methodology will involve:

1. A synthesis of the existing database of culvert blocking during the December floods of 2015 on culverts of the A591 in Cumbria. This will involve an empirical analysis of the results, simple sediment transport modelling and comparison to existing design criteria for road culverts. Additional field data will be collected to determine stream channel slopes and dimensions; the grainsize of the stream sediment and the potential for recruitment of large woody debris.

2. Flume experiments will be used to simulate sediment transport in a steep stream system through an experimental culvert. This will be carried out in the reduced-scale debris flow modelling facility at Durham University. The model will be reconfigured to test a combination of debris supply rates and different culvert geometries to determine critical blocking conditions.

Timeline

Year 1
Development of a conceptual model of culvert blockage in mountain streams and a review of literature of culvert design. Field work in Cumbria to provide additional background data for development of the flume modelling simulation. Initial consultation with stakeholders over desired deliverables from the project.

Year 2
Flume modelling of culvert blockage scenarios and testing of the jamming theory using simple 'marble' models. Refinement and testing of the jamming theory of granular flows for realistic culvert simulations. Workshop with stakeholders to demonstrate and discuss the value and benefits of the modelling approach.
Modelling of culvert blockage scenarios and the development of guidelines for (i) the improved design of mountain stream culverts and (ii) strategies for the management of debris in mountain streams (debris supply control). Final consultation with stakeholders to agree management guidelines.

Training & Skills

Training is fundamental to the development of postgraduate research students and, together with the DTP, University and Department we provide a substantial training programme. Priorities for training are determined from the ‘Training Needs Analysis’ carried out in the initial supervisory meeting with the student.

Departmental training in (a) research skills and techniques and (b) research environment are provided through four mechanisms: (i) a programme of taught modules; (ii) internal training ‘workshops’ that focus on key geographical research skills and techniques; (iii) input from supervisors; and (iv) departmental seminars by visiting speakers and presentations by postgraduate students themselves. Physical geography research postgraduates normally take the taught departmental module ‘Implementing Research Design’ during their first year. The aim of this module is to help students put University training in research design into practice specifically in relation to physical geography research both generally and with regard to the student’s own project work. Students receive instruction in data collection and the scientific method, contextualizing and problematizing research in physical geography, planning for field- and laboratory work, and team and group working in physical geography. Assessment of students in this module is formative. In addition to generic training offered by the University, the Department also provides training through a series of in-house ‘workshops’. These workshops offer the opportunity to gain both experience and knowledge with a number of tools in a specifically geographical disciplinary context and to gain an understanding of some of the wider structures and practices which make up academic life. This programme has been developed in response to postgraduate requests and is open to ALL postgraduate students irrespective of degree or year of study.

Research training continues through the second and third years, and is based around a number of themes: Recognition and validation of problems; Demonstration of the original, independent and critical thinking, and the ability to develop theoretical concepts; Knowledge of recent advances within research field and in related areas; Understanding relevant research methodologies and techniques and their appropriate application within research field; Ability to analyse and critically evaluate findings and those of others; and Summarising, documenting, reporting and reflecting on progress.

References & Further Reading


Further Information

Further information can be obtained by contacting Jeff Warburton.