LCR203 Final Report.
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Summary

The major goal of the Marsden Fund supported project “Stochastic Mechanics of Soil Erosion” is to achieve a new fundamental understanding of soil erosion. Commonly used models of soil erosion explain some, but not all, erosion phenomena. In particular, random effects are not well defined by these models. To better understand the interactions between flowing water and soil surfaces, this study used the superposition of hydrodynamic and soil resistance forces in their stochastic representation.

The main achievement of this study was the development of a new third-generation erosion model to calculate the rate of soil loss for all varieties of the controlling factors. Two supplemental models – hydrodynamic and soil structure – were investigated both theoretically and through the use of experimental technique. These models show the probability distribution function of soil resistance and driving forces in the flow. These probability distribution functions were used in the final soil erosion model.

Some of our key findings were:

1. The fundamentals of erosion stochastic mechanics are well founded (see Sidorchuk, Smith, & Nikora, 2004; Sidorchuk, 2005)

2. A third-generation theoretical erosion model was built and coded (see Sidorchuk & Nikora, 2005)

3. Experimental methods to verify the theory were founded and approved.

4. A series of numerical experiments, as well as laboratory and field experiments were run that showed a general validity of the proposed theory.

Introduction

The water erosion theory for cohesive soils is still largely undeveloped, in spite of its significance for many aspects of human activity at both national and international scales. For many years, efforts have focused mainly on the development of empirical predictive relationships based on data collected in areas with differing climatic and land-use conditions. We will call these empirical erosion models the first-generation models. Development of these first-generation models required significant resources, was time-consuming, and did not provide satisfactory progress. As a result, a new generation of erosion models, known as physically based erosion models, were developed. However, these ‘second generation’ models were still semi-theoretical or semi-empirical and relied on simplified stream power (or bed shear stress) relationships to describe the rate of erosion. In these models, the complexity of soil resistance to erosion was expressed by simple erodibility coefficients. These simplifications were a significant weakness of these second generation models and reflect a fundamental lack of understanding of the erosion processes.

A new, third generation of erosion models was urgently needed to account for the stochastic nature of soil erosion. The complex interactions between flowing water and soil surface was known to cause stochastic detachment and deposition of soil particles (or aggregates), and this stochasticity now appears to be the key factor in soil erosion mechanics. Stochasticity, largely overlooked in previous considerations, was one of the key points of this study. The main goal of the project was to advance the fundamental understanding of both deterministic and stochastic components of soil erosion mechanics and, using this improved understanding, to develop a new methodology and models of soil erosion based on the fundamental principles of turbulent flow hydrodynamics and cohesive soil geo-mechanics.

Progress

The project team combined two groups: Dr Aleksey Sidorchuk (Principal Investigator) and Ted Pinkney (field and laboratory studies) from Landcare; and Dr Vladimir Nikora (AI, hydrodynamics), Dr Alistair Smith (mathematical/computer modelling), Dr Stephane Popinet (numerical hydrodynamics), Dr Jochen Schmidt (field experiments), and Glenn Cooper (instrumentation, data analysis, field and laboratory studies) from NIWA. To better achieve several experimental tasks, and to strengthen collaborative links, Dr Roger Nokes (Particle Tracking Velocimetry, hydrodynamics) and William Veale (post-graduate student) from the University of Canterbury were added to the team. Two students, Holm Voigt and Sonja Szymczak from Bonn University, Germany, were also involved in the field experiments.

The project objectives and related achievements were:

1. Develop a structural model of cohesive soil.

Soil structure is defined as the distribution of physical soil characteristics in space, time and probability space (i.e. statistical distribution). The size of soil particles and aggregates, which can be expressed using various measures such as length, area, volume and weight, was the characteristic of primary interest. From a theoretical point of view, the expected size distribution should be logarithmically normal, as suggested by Kolmogorov (1941), who studied the process of the random destruction of soil particles using scale-invariant probability of particle fragmentation.

Using a wide range of initial and boundary conditions, we simulated numerically, the Kolmogorov-type algorithm of soil particle fragmentation. The distinct feature of these numerical experiments was fragmentation scale dependence. We carried out experiments on the different relationships between failure probability and particle size, and for an extensive range of fragmentation scenarios. All led to the same result: the logarithmically normal distribution of soil particles. Each type of fragmentation process was characterised by specific rates of mean size decrease and particle size variability increase.

We also completed experimental investigations of the distribution of resistance within a soil sample. The measuring device (Fig. 1), constructed by Ted Pinkney, was based on the principle that the resistance to movement of a solid body through plastic media is controlled mainly by dry friction. Therefore, resistance distribution in a soil sample can be obtained by cutting saturated plastic soil with a narrow blade. Samples of loess soil from Ballantrea station (near Palmerston North), ash soil from Kai Iwi area (near Wanganui), and clay soil from Tiramoana station (near Christchurch) were used for the experiments. With these experimental soil cuts (Fig. 2), we were able to measure the distribution of soil resistance within the soil sample. The numerous experiments produced stable results. The probability distribution of resistance within a soil sample followed a logarithmically normal function (Fig. 3), and we were able to use Kolmogorov-type theory to calculate soil resistance distribution and for soil erosion modelling.

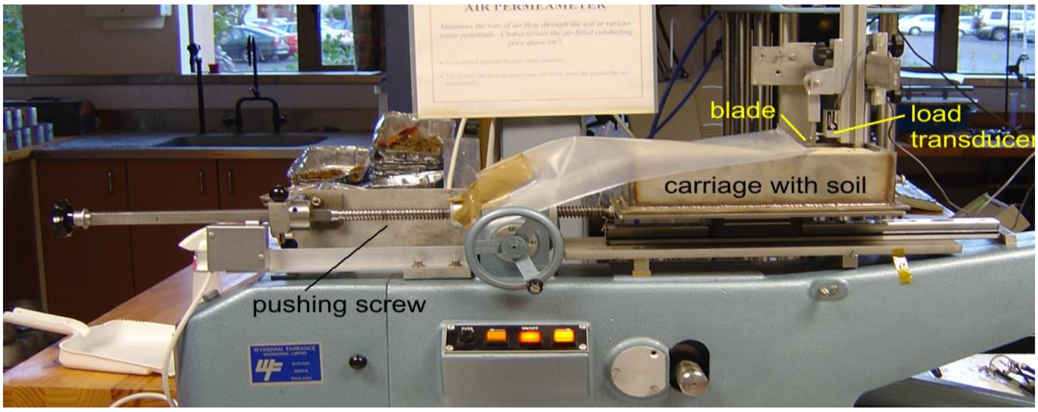


Fig. 1. The device to measure resistance distribution in a soil sample.

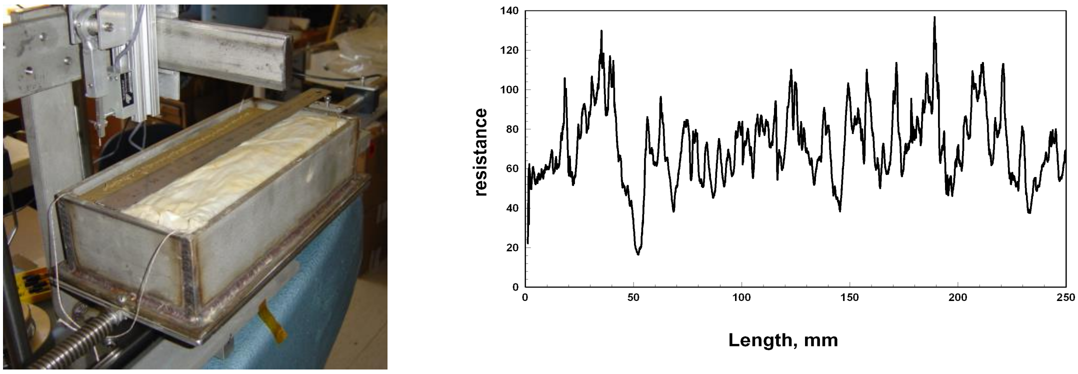


Fig. 2. An example of an experimental cut of saturated plastic soil.

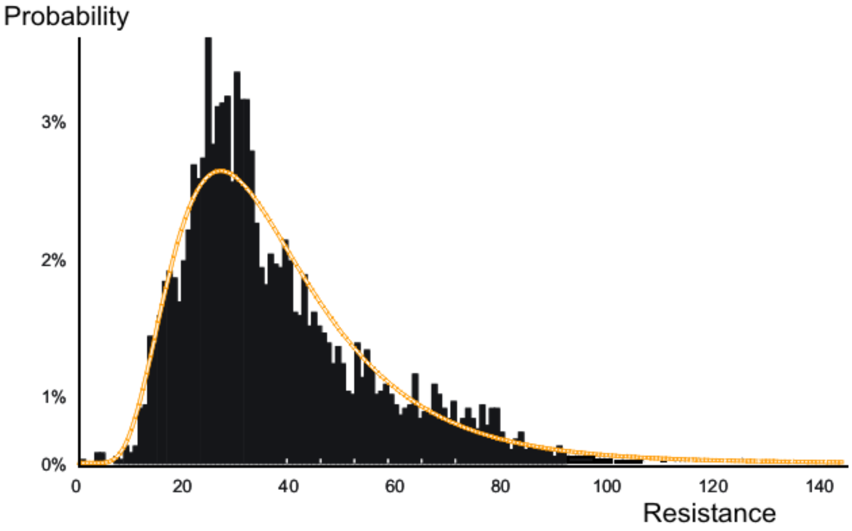


Fig. 3. Logarithmically normal distribution of resistance in a soil sample.

2. Develop a hydrodynamic model of flows with small and/or partial relative submergence.

Most natural overland flows belong to the class of hydraulically rough-bed flows. They have been studied using the time-averaged Navier-Stokes equations for fluid, and advection-diffusion equations for passive substances and suspended sediments. These equations have been used as tools for both modelling and interpreting numerical and experimental results. However, in most situations these equations are not practicable due to the highly three-dimensional structure of mean flow and turbulence, especially in the near-bed and near-water-surface regions. To resolve the problem conceptually, the time (or ensemble) averaging of the Navier-Stokes and advection-diffusion equations should be supplemented by volume or area averaging in the plane parallel to the average bed. This double-averaging procedure provides new momentum and continuity equations for fluid, averaged in both time (ensemble) and space domains, and which explicitly contain important additional terms such as form-induced stresses and form and viscous drag terms. Similarly, the double-averaged advection-diffusion equations for passive substances and suspended sediments explicitly contain form-induced fluxes as well as source/sink terms describing interface fluxes (e.g., sediment erosion/deposition processes in the region below the roughness tops).

To develop this methodology, we reviewed and refined the averaging theorems, and derived the double-averaged (in time and in space) momentum equation for fluid, and the advection-diffusion equations for a passive substance and suspended sediments. These new equations differ from those considered in previous studies, by accounting for the change in roughness density with the vertical coordinate and with time, and for the particle-settling effects in the case of suspended sediments. We also revised flow classification in relation to flows with small relative submergence or to partially inundated flows. We used these theoretical equations for deriving and testing relationships for vertical distribution of double-averaged velocities in the roughness layer, i.e. between the roughness tops and troughs. These relationships were then used in modelling the effects of soil heterogeneity on erosion processes.

3. Computer simulations for a range of physically sound scenarios.

First, we reviewed a wide range of approaches in modelling overland flows and associated erosion processes. From these we selected Large Eddy Simulation and Cellular-Automata Simulation methods as the main tools to study stochastic effects in soil erosion. Several additional modelling approaches, such as 2d/3d Euler-based models and 2d/3d Navier-Stokes-based models, were also considered and developed.

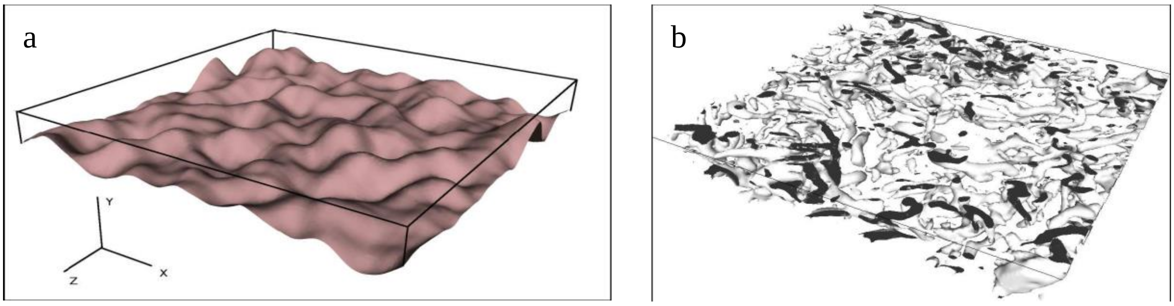
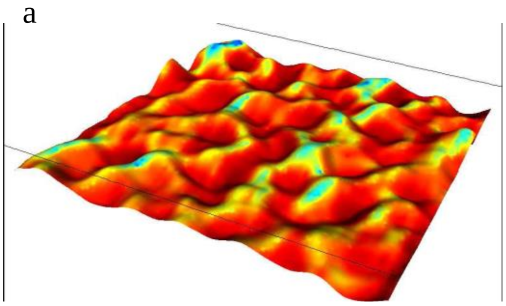


Figure 4a (left), geometry of the simulation domain; and 4b (right), core vortices in the overland flow.



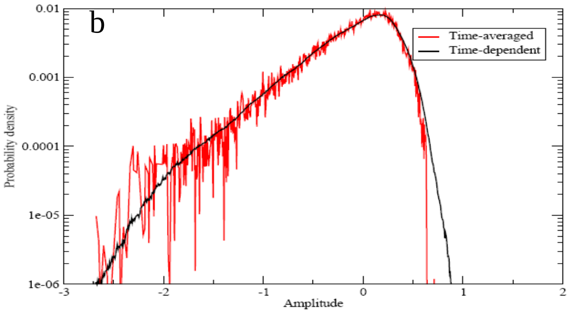


Figure 5a (left), time-averaged pressure field on the rough surface; and 5b (right), probability density functions for the time-dependent and time-averaged surface pressure.

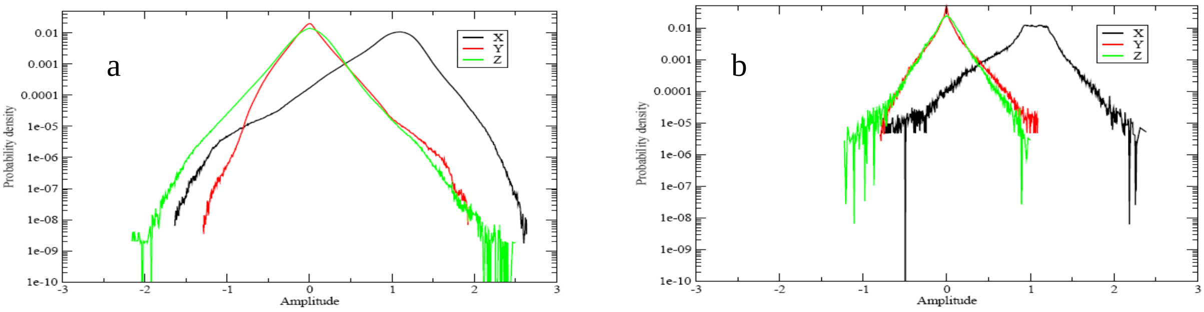


Figure 6a (left), probability density functions for the time-dependent; and 6b (right), time-averaged velocity components.

We also developed a cellular-automata-based computational model to study the heterogeneity effects of soil material on erosion parameters. The model exposes the effect of spatial heterogeneity on erosion pattern by the use of non-dimensional variables and a simplified erosion formulation. Many simulations were run, encompassing a wide range of physical scenarios. The most important results, from our perspective were: 1) the key heterogeneity parameter influencing the erosion rate and soil surface roughness is the correlation length-scale in soil properties; 2) the spectral structure persists from the soil resistance force to the soil surface profile; and 3) soil erosion behavior is significantly different for low and high heterogeneity of flow and soil.

4. Laboratory and field experiments on flow structure and erosion rate.

The structures of overland flows and raindrop effects were addressed in a number of experimental studies, in which measurement procedures and instruments provided information on bulk characteristics, averaged in time, in space or in both. However, the instantaneous variables required for this study could not be measured, so a new experimental approach was developed to achieve the necessary level of temporal and spatial resolution. A special experimental device, an overland flow flume, was designed and built (Fig. 7), and has been used to study a wide range of hydrodynamic scenarios, including those over flat beds and beds covered with single and multiple obstacles. Experiments with erodible beds and with rain were not completed due to technical problems. Velocity measurements have been made with the Particle

Tracking Velocimetry technique developed at the University of Canterbury. This laboratory work was carried out in close cooperation with Dr R. Nokes and W. Veale (a master student) from Canterbury University (Civil Engineering Department), who developed and tested unique measurement techniques for measuring quasi-instantaneous velocities of experimental overland flows.

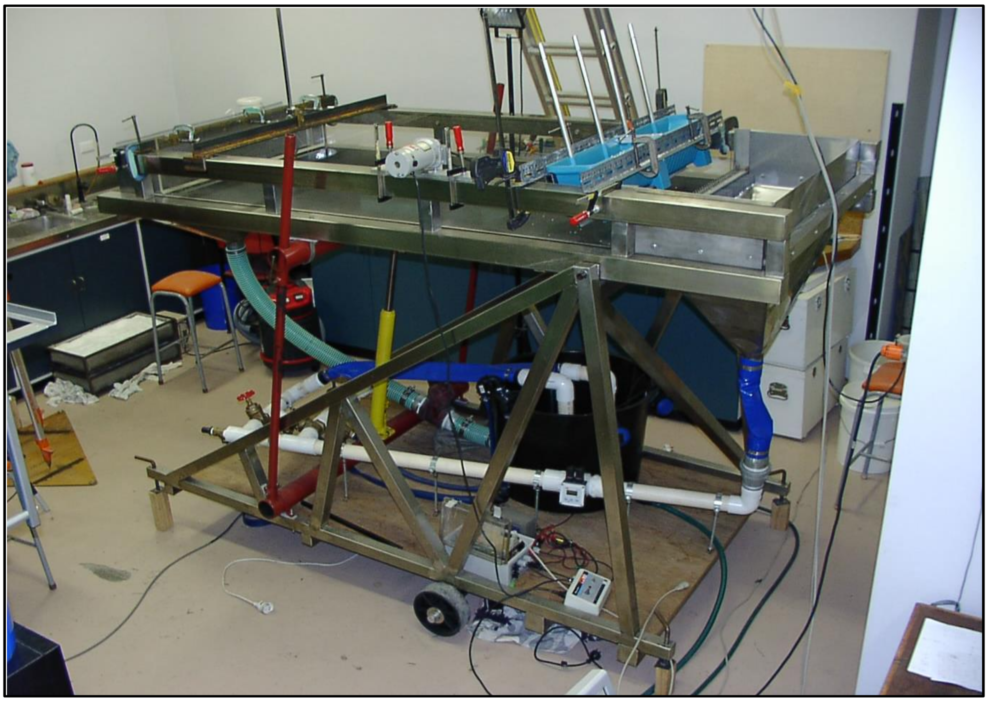


Figure 7. NIWA's flume for studying overland flows.

The experiments provided data on instantaneous velocity fields and showed that overland flows exhibit properties of both 2d and 3d turbulence. In particular, we obtained information on probability distributions of horizontal velocity components (Fig. 8), their correlation functions (Fig. 9), velocity spectra, and structure functions.

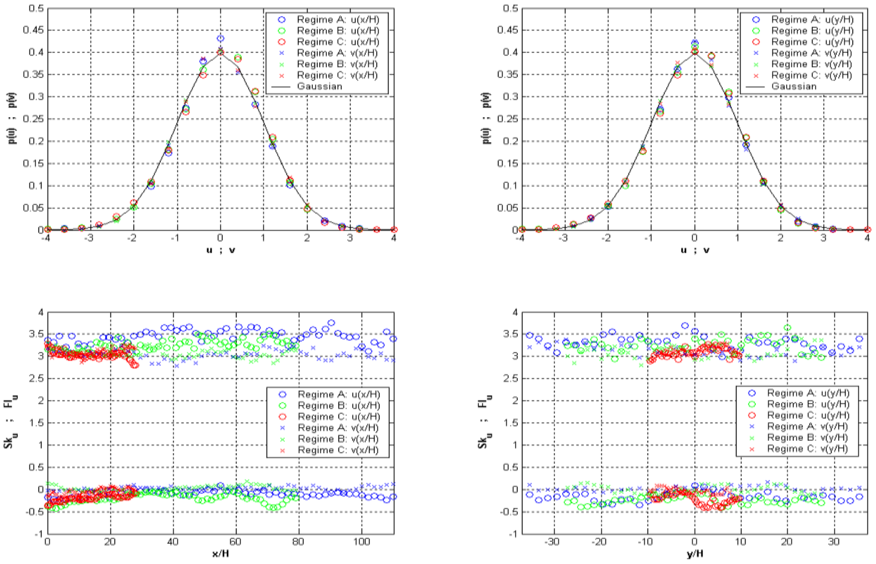


Figure 8. Probability distribution functions and longitudinal and transverse distributions of skewness and kurtosis coefficients for longitudinal (*u*) and transverse (*v*) velocity components.

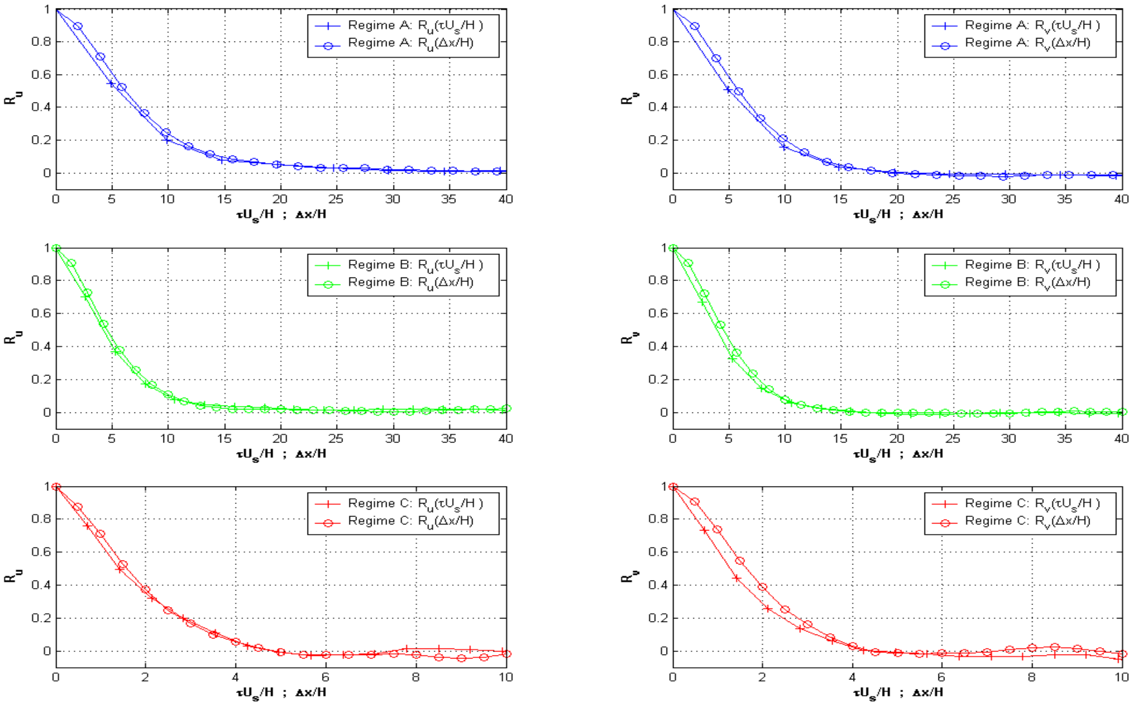


Figure 9. Normalised autocorrelation functions for longitudinal (left) and transverse (right) velocities.

The data show that the flow structure for super-critical flows resembles that of a two-dimensional turbulence with inverse energy cascade. In contrast, although large-scale structures were also present in the sub-critical flow, this flow energy spectrum was different, with direct energy cascade. Based on our results and the published data of different authors we suggest a physical explanation for the observed behaviour. The experiments strongly support Jirka's (2001) hypothesis that secondary instabilities of base flow may generate large-scale two-dimensional eddies, even in the absence of transverse gradients in time-averaged flow properties.

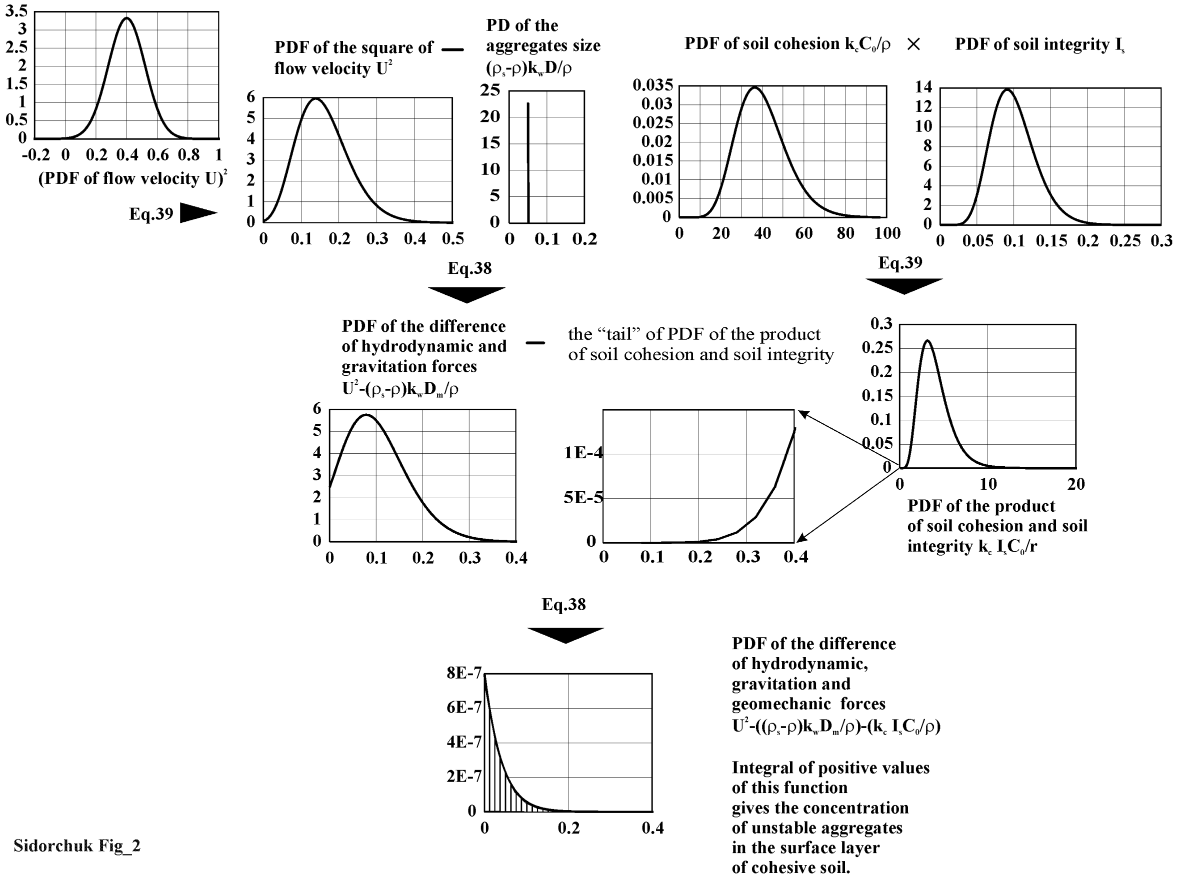
Fig.10a (left), rainfall simulator; and 10b (right), high-speed camera during field experiments

We supplemented our laboratory experiments with field tests using a flow-meter, a specially designed field-scale rainmaking facility, and a digital high-speed video (Figs 10a and 10b). Experiments in the field gave an opportunity to work with real soil, and the equipment used made it possible to measure flow and sediment yield variability.

5. Development of soil erosion model.

Theoretical investigations on stochastic soil erosion show two main methods of calculating soil detachment: (1) as the product of unstable soil aggregates concentration and the mean velocity of these aggregates; and (2) as the average of velocities of all aggregates in the soil surface layer. Both calculation methods are described mathematically with the equivalent expressions. The second method, being simpler for codification, was used to develop a third-generation computer soil erosion model.

This third-generation model includes a sequence of the recalculation of probability density functions (PDF) for the main driving and resistance forces that control the erosion rate (Fig. 11). The calculations provide the rate of soil aggregate detachment, which is obtained only from clear theoretical consideration, without "black-box"-type empirical information. PDFs for hydrodynamic and soil structure factors, obtained from the hydrodynamic and soil structure models described, are the main inputs.



Integral of positive values of this function gives the concentration of unstable aggregates in the surface layer of cohesive soil.

Sidorchuk Fig_2

Fig. 11. Calculation matrix of soil aggregate detachment rate with third-generation stochastic model.

Additional work

The preliminary results in soil erosion modelling (based on the new fundamental ideas) were used for climate and land-use reconstructions from information contained in stratified sediment sequences. The methodology of such reconstruction was presented at the Gordon Research Conference "Past Ecosystem Processes and Human-environment interactions" in Santa Inez, California, USA, in February 2005, and will also be discussed at the LUCIFS (Land Use and Climate Influence on Fluvial System, PAGES, IGBP) meeting in Frankfurt, Germany, in May 2006. These methodological investigations show that erosion modelling may be a powerful tool in proxy data interpretation. Stratified sequences can be modelled at different erosion landscapes for different climate and land-use scenarios. With additional information on vegetation cover change (for example, from pollen analysis), the erosion model makes it possible to calculate climatic characteristics (mainly precipitation) from proxy records.

Future research

We now have both a new fundamental understanding of erosion mechanics, and a method of calculating erosion rates theoretically without using empirical relationships and coefficients. The results of this Marsden project demonstrate that the direction of studies in soil erosion processes needs to change. The proposed theory shows what additional variables need to be measured in the laboratory and in the field; and the experiments show the main measurement methods. As this measuring technique is still not fully developed, future research must concentrate on the development of experimental equipment and methods to measure flow and soil structure. Once the equipment and methods have been developed and tested, the model created during this project has the potential to be of great value in predicting soil loss in different environments and for various types of land use.

Signature of contact Principal Investigator

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