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河流影响下的沙丘地貌演化模拟研究

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河流影响下的风沙地貌演化模拟研究

Computational Simulation of Landform Change in a Fluvial-Aeolian Interacting Field

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摘要

传统上对干旱地区地表环境的研究是以风蚀动力为主，然而地球地貌的演化是各种自然过程及环境因子相互作用的结果，风蚀地貌亦然。自20世纪60年代以来，不断有研究人员注意到地球甚至火星地表风蚀沙丘与河流相互影响的现象或痕迹，发现地球地层记录中广泛存在干旱环境的风水交互沉积，从而认识到风水交互作用对地貌的发展与环境变化的联系。但由于风蚀、水蚀地貌的驱动机制不同，风沙地貌与流水地貌的研究是相对独立发展的。因此，研究不同时空尺度下风水交互作用的动力机制、风水交互作用对土壤侵蚀、地貌发展的影响以及地貌与气候变化的关系显得愈发重要和迫切。

为了系统研究风沙-水文交互作用及其对地貌的影响，本项研究首次将风蚀与水蚀动力模型进行耦合，其中风蚀沙丘地貌模拟是基于DECAL模型和Werner的计算机算法进行修改和完善，流域地貌模拟则基于CAESAR-Lisflood模型，从而实现动态模拟不同时空尺度范围内（小至中尺度，时间长至千年）风水交互作用中的地貌演化及沉积物迁移过程。在简化的环境情景模拟中，风与水（包括常年性和短暂性河流）交互作用地貌的长期发展过程和规律可得到最直观的观察，并可以对比流域输沙量对地貌变化的响应；前期全球调查中总结的河流-风蚀沙丘交互地貌类型可涵盖所有可观测到的模拟地貌，这进一步证实和完善了风水交互地貌类型分类的有效性。情景模拟进一步发现一些地貌类型在某些环境条件下（定量的河流水流量和风输沙率）可以轮回转化，这些环境条件由此可为地貌发展转化的临界条件及临界值研究提供参考。

关键词：沙丘，河流，地貌演化，计算机模拟

Abstract

The interaction between fluvial and aeolian processes can significantly change Earth surface morphology. When rivers and sand dunes meet, the interaction of sediment transport between the two systems can lead to change in either or both systems. However, these two systems are usually studied independently which leaves many questions unresolved in terms of how they interact. This study investigated the interactions between fluvial and aeolian processes (specifically between rivers and dunes) - in particular the triggers that may switch the dominance between one process and the other, and the consequent changes in geomorphology that may occur.

To observe the dynamic interaction process between the aeolian and fluvial systems and the impact on geomorphology, a highly novel cellular fluvial and aeolian/dune model was integrated to simulate the interacting process. The global investigation results provide the basic information to set up the simulation domain where different flow regimes, perennial and ephemeral/intermittent, have been simulated interacting with different level of aeolian power. Various interaction types observed from modelling were coincided well with the classification categorised from the field observation. The modelling not only proved that the six interaction categories are comprehensive and applicable, but also further improved the understanding towards them from dynamic perspective.

Keywords: dunes, rivers, geomorphology, modelling

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1 Introduction

1.1 Background

Nearly 40% of the global human population live in drylands and, as a consequence, they are susceptible to geomorphological hazards such as floods and sand storms which can result in catastrophic landscape changes. Central to our management of these hazards, and for predicting their impact on human populations, is the urgent need for data on the complex interaction processes between fluvial (river) and aeolian (wind) environments. The impact of catastrophic landscape change on humans can be significant. Vermeersch and Van Neer (2015) found that river-sand dune interactions contributed both to colonisation (through the creation of water sources by natural sand dune damming of water courses) and the cessation of occupation (due to dam breaching caused by increased river flow) by Palaeolithic hunter-fisher-gatherer groups in the Nile valley in Upper Egypt, *ca*. 20,000 years ago. Similar impacts have occurred throughout human history. With increasing populations and growing desert margins due to climatic variation the impacts on humans from complex interaction processes in deserts will become more frequent.

Recently, Liu and Coulthard (2014) compiled a global inventory of 230 sites where there was evidence of both fluvial and aeolian processes operating using satellite imagery, indicating that in arid and semi-arid environments across the Earth such interactions were widespread. However, their research was limited by their use of imagery that only represent single, static moments in time, whereas both sand dunes and rivers are highly dynamic systems. This leaves a set of unanswered questions concerning the dynamic interaction of aeolian dunes and rivers. How do sand dunes alter rivers over time? How do rivers in turn alter sand dunes? How can each disrupt or interact with the other? How do sand dunes cross over a river system? Are there distinctive landforms or patterns left by these interactions – and how well does the static interpretation (Liu and Coulthard, 2015) reflect the dynamic?

Such questions can only be partly answered by using field data as the rates of change (i.e. dune movement) in aeolian and fluvial systems are often too slow to generate a meaningful record within our limited range of observations. In addition, the periodic nature of observation (e.g. remote sensed imagery) will likely miss events that are important in the system evolution, such as changes associated with floods or storms. An alternative approach would be to use numerical modelling to allow us to simulate the dynamic interactions between dune and river processes and examine how landforms evolve and what can control them.

1.2 Research aim

The aims of this work report are to:

1. Developing an aeolian-fluvial combined computational model;
2. Observe and analysis the dynamic interaction processes between the aeolian and fluvial systems, and the impact on geomorphology.

1.3 Research Approach

The approach adopted in this study would address the research aims by applying a combination of numerical simulation. The dune model will be developed based on Werner's (1995) algorithm, whereas the fluvial model will be based on Coulthard et al.'s (2013).

2 Modelling sand dunes

2.1 Background

There is a long history of numerical modelling for aeolian dunes (Bishop et al., 2002; Howard et al., 1978; Hugenholtz et al., 2012; Kroy et al., 2002; Livingstone et al., 2007; Nishimori et al., 1998; Ouichi and Nishimori, 1995; Parteli and Herrmann, 2003; Wippermann and Gross, 1986). Notable approaches include the use of simple cellular automata type models by Werner (1995), Nishimori et al., (1998) and Ouichi and Nishimori (1995) that have been used to show the development and dynamics of sand dunes. These cellular models assumed that a dune field can be represented by the moving 'slabs' of sand in a down wind direction over a mesh of square grid cells. These slabs can pile up and lead to a 'shadow zone' in the downwind direction where slabs cannot be moved. Additionally, when the slabs pile up to a height leading to slopes that exceed a threshold angle they can landslide down. When iterated this leads to accumulation on the upwind side and landslides on the downwind, enabling dunes to form and migrate downwind (Werner, 1995). By varying the sediment supply and wind direction this model can be made to replicate the development of barchan, transverse ridge, linear and star dunes (Barchyn and Hugenholtz, 2012; Bishop et al., 2002; Werner, 1995). Werner and Nishimori's work has since been extensively built upon and used by a number of researchers (e.g. Baas and Nield, 2007; Bishop et al., 2002; Eastwood et al., 2011; Momiji and Warren, 2000; Narteau et al., 2009; Pelletier, 2009; Zhang et al., 2012).

More complex methods for simulating sand dune development have been developed (e.g. Zhang et al., 2012) but the attraction of the simple cellular models described above is that their parsimony and numerical efficiency allows their application to larger spatial areas and over longer time scales. Both of which are important considerations if such models were to be combined with fluvial simulations.

2.2 Method

2.2.1 Model description

The dune model used in this study is based on Werner's (1995) non-dimensional algorithm as implemented by Baas (2002). There are some operational modifications to merge the code with the fluvial CAESAR-Lisflood model but the principal algorithms are the same as DECAL (Nield and Baas, 2008), Baas, 2002). A description of the dune models operation is provided below.

2.2.1.1 Model algorithm

In the combined model, slabs were used to simulate a pack of sand grains, rather than a single grain, movement on a map grid of cells as the model space. Shear stress from the wind was abstracted with a simple shadow zone rule. At each cell a certain angle θ was imposed in upwind direction and any cell that was below the height of this wind shadow was deemed as shadow zone (Figure 2-1). The sand slab transportation was classified into three conditions. Firstly, a grid cell is randomly selected from the modelled domain and if it can be entrained (i.e. does not lie within a shadow zone) it is then moved downwind a constant transport length l which is set to 1 grid cell. At the new location, the slab is deposited or eroded again according to the deposition probability (P_d). This sand slab transportation process is repeated until it is deposited. A slab must be deposited if it falls in the shadow zone which is defined on the leeward side of a dune ($P_d = 1$). In the meantime, the angle of repose (30°) is enforced through avalanches in the direction of steepest descent with slab that fall into this area being forced to erode ($P_d = 0$).

For each time step of the model operation, the total number of random grid cell selections equals the size of the model domain. This means that on average every cell is polled – but it is possible for cells to be looked at more than once ever model iteration. Previous workers have noted a sensitivity of the DECAL model to input conditions (i.e. the input of sand) (Eastwood et al., 2011).

Additionally, a non-periodic boundary condition was adapted. A feature of Werner's original (1995) and subsequent studies is the adaption of periodic boundaries where sand leaving the domain at (for example the bottom edge) is re-introduced or re-cycled at the top of the domain. This enables a conservation of sand within the modelled domain. However, this approach was not used in this study as we aim to mix fluvial and aeolian transport. Therefore sand may be moved by a river over a different boundary (e.g. the right hand edge) disrupting the continuity afforded by a periodic boundary. Therefore, the model was set to have fresh sand entering the model space along the upwind border throughout the simulation and bedforms that migrate off the downwind edge of the model space are not re-introduced along the upwind edge. However, the amount of sand leaving the downwind edge of the simulated field is recorded as the sand output by aeolian process – and sand leaving from other boundaries as fluvially transported sand.

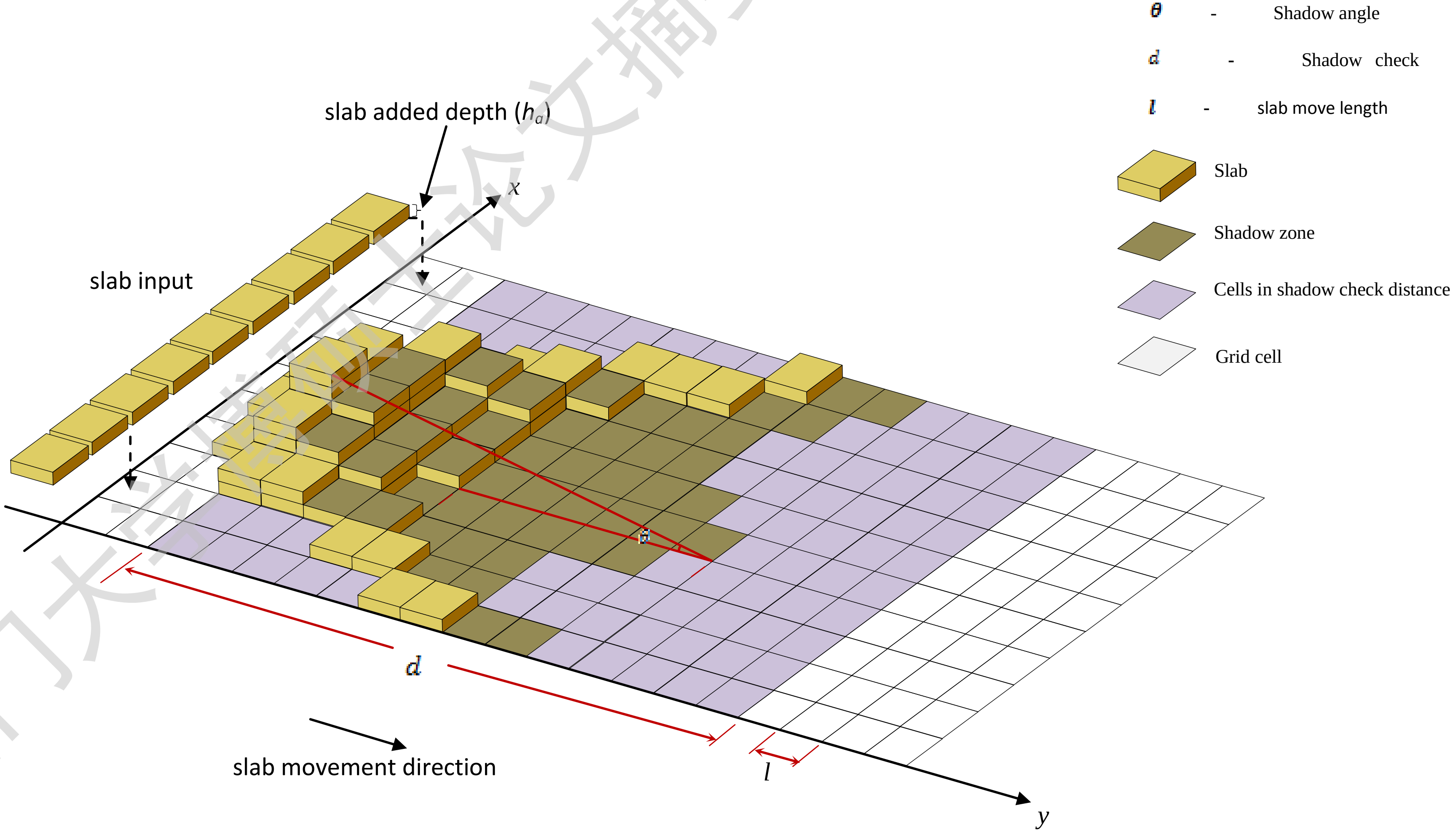

Figure 2-1 Schematic diagram of cellular dune model.

2.2.1.2 Model parameters

There are nine input parameters used in the dune simulations. The value of each parameter has to be set at the beginning of each run and remains constant throughout the simulation. Some parameters have no impact on the dune field boundary conditions but are related to computational operation and efficiency, thus were taken as *Fixed parameters* and were set to the same value for all simulations in this study; whilst some other parameters are based on physical properties associated with the dune field characteristics and thus were categorized as *Controlling Parameters*.

I. Fixed parameters

1) Downstream offset (travel distance automatically added)

The downstream offset parameter defines the slab transport length l for each iteration. Although this transport length can be any value, previous researchers found that an increase in effective slab transport distance does not contribute anything additional to the development of dune patterns (Nield and Baas, 2008). Therefore, to ensure that moving slabs interact with all the model space, the downstream offset parameter in this study was set to 1 grid cell.

2) Grid size of dunes (g)

The grid cell size of dune model space can be set independently of the fluvial model grid cell size. This allows the easier scaling of dunes to rivers. The smaller the value, the longer it takes the model run time. Therefore, in this study, this value was set to 10 metres (the same size as the fluvial model) to optimise model run times.

II. Controlling parameters

1) Dune landslip angle

In real field, dune landslip angle is between 30° and 33°. Typically, in Werner’s and subsequent implementation works, this value was set as 30° (Werner, 1995), Baas, 2002), Eastwood et al., 2011), Barchyn and Hugenholtz, 2012). In this study, the dune landslip angle was set to 30° in all simulation tests.

2) Slab added depth (h_a)

This is a value which describes the height of sand volume (h_a) added into the dune simulation per iteration of the dune model. The length of each iteration was determined by the time step (min) between dune calls box. This value should not exceed the slab thickness (h_s – below) otherwise sand is added at a faster rate than it can be removed.

3) *Maximum slab thickness (h_s)*

The maximum slab thickness is the height of each sand cell which is moved to next cell in metres.

4) *Shadow angle (θ)*

From each cell of topography, a line is traced down at an angle of θ ($\theta \le 15°$) to the horizontal surface (**Error! Reference source not found.**). Any slabs that are below the height of this line are deemed to be in a shadow zone. The shadow zone represent the air flow separation area where the slabs will be forced to deposit (P_d=1). Barchyn and Hugenholtz (2012) found that this parameter can affect the maximum height that dunes form, however, most researchers fix this value at $15°$ (Eastwood et al., 2011).

5) *Shadow check distance (d)*

Shadow check distance is the distance up wind that the model will check to identify whether a slab is moved into the shadow zone. Slabs in shadow zones are not eroded, otherwise it can be entrained depend on the deposition probability. The parameter unit is grid cells.

6) *Deposition probability (P_d)*

This parameter determines whether or not a slab of sand is dropped out or can be moved on to the next cell. The value ranges from 0 to 1. Eastwood et al. (2011) found that a low P_d can result in higher and more variable transport rates but most researchers set this value at 0.6 as this is meant to simulate preferential deposition that occurs on sandy substrates due to momentum absorption.

7) *Time step between dune calls (t)*

The value of this parameter controls how often the dune model is called to move the slabs. This parameter can therefore exert a strong control over sand transport rates – as it effectively controls when sand is moved within the model. This parameter is also important for the integration of the two models and will be discussed in later.

2.2.2 Sensitivity analysis set up and configuration

Sensitivity analysis can help to explore how highly correlated the model result is to the value of given input parameters and thus identify the parameters which exert the most influence on the dune formation. Furthermore, once a full understanding of the model performance is gained – parameter values can then be assigned to allow the model to predict realistic rates of sand movement and dune migration – that can be used in the fluvial/aeolian model integration.

To understand the input parameters influence on model results, a range of simulations were carried out to test the sensitivity of each parameter. Although there are nine model parameters listed above, only the controlling parameters affect the simulation results and were therefore considered for this analysis. Even so, seven parameters each with different range of values still constitutes a large combination of parameters that would take a significant amount of run time and generate a great deal of output information. Therefore, *Screening* and *Sampling-based* approaches were applied to determining which input parameters were examined and the experimental design (Muleta and Nicklow, 2005), Helton et al., 2006).

2.2.2.1Simulation domain

The sensitivity tests were carried out over a model domain with a smooth gently sloping but non-erodible surface arbitrarily sized 3000m length in *x* direction (flow direction) and 1000m length in *y* direction (downwind direction). There is a small elevation difference between the top and bottom border of 1m which forming a slope of gradient of 0.0033 (Figure 2-2). This slope is introduced for these tests as is the same gradient used in the combined fluvial and aeolian simulations.

For sensitivity analysis the model run duration was 100 years which was enough for a dynamically stable pattern to form. In each simulation, the first few years represent a “warm-up” period as sand starts to accumulate and form dunes with a relatively stable morphology. The length of this “warm-up” period depends on the sand transport rate. The