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On the role of fluid infiltration into gravel dunes — Using a 3D numerical model

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ABSTRACT

Both the hydrodynamic conditions as well as the related sediment transport processes of sandy bedforms are understood fairly well. However, little is known about the genetic processes of bedforms involved in environments dominated by gravel. In the coastal environment storm waves, spring tides, bore waves and to a lower frequency tsunamis are common phenomena that can provide the required energy to form gravel bedforms. Given the high energy of such wave events and the formidable practical difficulties of fixed instrumentation and in-situ measurements, knowledge on the hydrodynamic processes in the direct vicinity and in the interior of gravel bedforms is still limited.

A 3D numerical flume tank model using Smoothed Particle Hydrodynamics (SPH) was generated to study the nature of flows for an extreme wave above and in the interior of gravel bedforms as a complementary method to in-situ measurements. With typical flume tank dimensions ($X = 2.68$ [m], $Y = 0.25$ [m], $Z = 0.8$ [m]), three experiments were undertaken to test a range of simplified bedform geometries (stoss side slopes = 42°, 23°, 13°) using a unimodal grain fraction. The water column was represented by 11 million fluid particles and the bedforms by 480 immobile solid particles. A single numerical wave was introduced using a vertical paddle that moved to $X = 0.3$ [m] perpendicular to the bottom of the tank. Fluid velocities, extracted at each timestep, at each point of the tank, were used to determine free stream, pore water flow velocities, and residence times from all experiments. Results showed that when the wave crest was positioned before the bedform crests pore water flows appeared predominantly in the downstream direction. However, when the position of wave crest was located after the bedform crests, a vortex developed at the leeside of all bedforms, causing a change of the pore water flow towards the upstream direction. Regions of inflow, outflow and pore water flow through the pore spaces were evident in all experiments, but changed as the stoss side slope angles were decreased. It is concluded that variations in the stoss side steepness appear to control the locations, and the position of the wave crest the directions of pore water flow, which was illustrated in a conceptual model.

1. Introduction

Bedforms are sedimentary structures that develop through the forcing of fluid flow along a sediment surface. In the aquatic environment, a great variety of bedform geometries occur on a large number of spatio-temporal scales due to textural variability of sediments and prevailing hydrodynamic drivers. Prior researchers have investigated the highly dynamic nature of bedforms (e.g. Allen, 1966; Venditti, 2013), since these (I) allow reconstruction of sedimentary environments as well as past flow conditions and (II) influence flow resistance and sediment transport rate (Allen, 1993; Julien, 2010). According to Allen (1982, 1993), bedforms are typically divided into three genetic groups: microforms (e.g., ripples), mesoforms (e.g., dunes) and macroforms (e.g., bars). For a better understanding of the genetic processes of such bedforms, research is focused predominantly on their morphologies, the hydrodynamic conditions in the water column and the related sediment transport dynamics (Gath, 2011). Due to a wide global abundance of sandy sediments, the majority of bedform studies investigate their generation and evolution in sandy sediments under both unidirectional flows and wave motion (e.g. Bennett and Best, 1995; Kwoll et al., 2014; Nielsen, 1981; Venditti et al., 2005). Consequently, both hydrodynamic conditions above sandy bedforms as well as related sediment transport processes are understood fairly well. Hydrodynamic conditions typically feature an accelerating flow over the bedform crest on the stoss side and a flow separation zone on the lee side, below which a turbulent vortex develops (Bennett and Best, 1995). Related sediment transport involves erosion over the length of the stoss side and subsequent deposition in the form of cross-bedded layers on the lee side (Kleinhans, 2004; Mazumder, 2003; Venditti, 2013). Conceptual models summarizing these findings can be found e.g. in Best (1992); Coleman and Nikora (2011); Gyr and Kinzelbach (2004); Kleinhans (2004) and Mazumder (2003).

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Despite the intensive research on bedform formation, little is known about the genetic processes involved in meso- and macroform environments dominated by gravel (see Carling, 1999; Carling et al., 2006; Williams et al., 2006; for an overview). Carling (1999) and Carling et al. (2006) highlighted the existence of subaqueous fine gravel dunes in an intertidal environment, i.e. the Severn Estuary in the UK, where gravel was deposited upon bedrock benches and was reported to migrate across a bedrock platform. Similarly, Williams et al. (2006) reported on the remobilization of gravel dunes through strong tidal current, i.e. during spring tides. Occurrences of fine gravel dunes in subcritical flows have been documented by means of echo sounding during river floods (Carling, 1999; Dinehart, 1992a, 1992b). The development of such gravel dunes could be demonstrated in flume studies under controlled conditions (Carling et al., 2006; Carling, 1999; Hubbell, 1987). Despite these investigations there are still few studies of gravel dunes, a fact predominantly relating to the sparse occurrence of gravel bedforms compared to their sandy counterparts (see Carling, 1999; Carling et al., 2006; Williams et al., 2006). Since gravel is defined as larger than 2 mm in grain size and thus higher in mass than sand, it is less supertitle to erosion. It has been shown in various studies that gravel is moved almost exclusively by wave action (asymmetric wave motion), as tidal or other currents simply lack the energy to move gravel (van Rijn, 1984). As a result high energetic events or extreme wave events are required to initiate erosion and sediment transport of gravel. In the coastal environment storm waves, spring tides, bore waves and to a lower frequency tsunamis are common phenomena that can provide the required energy to form gravel bedforms. Especially the propagation of bore waves is known to play a major role in terms of sedimentary motion of gravel (e.g. Carling, 1999; Chanson and Tan, 2010; Chanson Miahr, 2005; Khezri and Chanson, 2012a, 2012b). Given the low frequency of such high energy wave events and the formidable practical difficulties of fixed instrumentation and in-situ measurements (Hall, 2011), knowledge on the genetic processes of gravel bedforms is still limited (see Carling, 1999). The hydrodynamic conditions in the water column, at the fluid-porous interface and in the interior of the pore spaces of such structures – especially in relation to their sandy counterparts – require further investigation.

Numerical models provide a supplementary tool to the difficult task of in-situ measurements and large flume tank experiments of gravel bedforms that helps to both visualize and quantify the physical conditions associated with these structures. SPH (Smoothed Particle Hydrodynamics) as a numerical simulation technique can help to overcome these limitations, because of the Lagrangian approach therein. Unlike other numerical methods such as, the Finite Volume Method or the Finite Difference Method which are mesh based Eulerian approaches, SPH does not require a mesh or grid to discretize the domain (study area) or to calculate the spatial derivatives of the dynamic fluid laws (Dalrymple and Rogers, 2006; Monaghan, 2005a). In any SPH model, the physical domain is discretized by a finite number of numerical particles that interact with each other following the fluid conservation laws (Monaghan, 2005b, 1994). Accelerated using a graphics processing unit (GPU), 3-D simulations of millions of particles can be run quickly. This allows numerical investigations of unprecedented detail and speed. In the past, SPH has been widely used to study free surface flows (Crespo et al., 2008; Dalrymple and Rogers, 2006; Gomez-Gesteira et al., 2012). Moreover, SPH is ideally suited to simulating flows in complex geometries as shown by Bui and Fukagawa (2013) or Bartzke et al. (2016). Consequently, it is anticipated that the method provides an effective means to simulate different hydrodynamic features (i.e., extreme wave events in the present case) as well as the flow through a granular bedforms composed of individual particles in three dimensions, which is extremely computational intensive, even impossible with Eulerian approaches (Bartzke and Huhn, 2015; Schmeeckle, 2014).

Our main goals were therefore to simulate and quantify the hydrodynamic processes within a wave-forced water column as a representative for an extreme wave event generated in a three-dimensional numerical wave tank, while simultaneously capturing the physical processes in the interior of underlying granular bedforms in the size of gravel dunes. Particular attention was payed to the flow around individual spherical particles that were generated to mimic a granular assembly of gravel bedforms in the size of dunes overlying impermeable bedrock, with varying stoss side slopes of 42°, 23° and 13°. Notably, this work aims at producing physical insights into the processes that occur at the surface and in the pore spaces of gravel dunes interior in high resolution under a high energy wave event such as a bore wave or a tsunami, as opposed to reproducing a predictive model. This approach could ultimately improve contemporary understandings of the nature of flow into the pore spaces of a gravel bedform, via gaining an improved understanding of the flow pattern, velocities and residence times.

2. Materials and methods

The numerical simulation technique Smoothed Particle Hydrodynamics (SPH) was used to generate the 3D numerical flume tank model. The physical domain of the SPH model was discretized by a finite number of numerical particles that interact with each other following fluid conservation laws (Monaghan, 2005a). Thereby, each particle is assigned with its own physical properties such as mass or density. In the case of a fluid, the physical integration between individual fluid particles is solved following meshless and Lagrangian approach solving the Navier–Stokes equations through convolution-based discretization (Dalrymple and Rogers, 2006). Derivatives are found by analytical differentiation of interpolation formulae. By this calculation architecture, SPH is capable of stimulating various flow features in a three dimensional water body such as laminar streaming and turbulence (Barreiro et al., 2013). In the Appendix we provide a brief overview of the governing SPH equations used in the models.

SPH models are highly dependent on the amounts of particles available in each simulation. If the number of particles increases, the resolution and quality of the results simultaneously increase. Acceleration of the calculation of fluid in dynamical processes can be achieved by using the memory capacities of a computer's graphics processing unit (GPU), which allows running 3-D simulations of millions of particles quickly as compared to computations carried out on a Central Processing Unit (CPU). For example, at present, it is possible to simulate more than 10 million fluid particles on a GPU in a reasonable timeframe compared to simulations performed on a CPU (www.dualsphysics.org). In the present study, the open-source solver chosen is DualSPHysics, version 3.1, since this is validated for a range of flow conditions (Barreiro et al., 2013; Dalrymple and Rogers, 2006; Gomez-Gesteira et al., 2012) being suitable to simulate bedforms and the hydrodynamic conditions in a 3D numerical wave tank. Furthermore, the mathematical "correctness", validity, and applicability of the SPH method to investigate various problems have been demonstrated by many prior studies (Altomare et al., 2015; Barreiro et al., 2013; Gomez-Gesteira et al., 2012; Monaghan, 2005a, 2005b).

2.1. Model configuration

Our 3D numerical flume tank was generated in typical flume tank dimensions ($X = 2.68$ [m], $Y = 0.25$ [m], and $Z = 0.8$ [m]). The entire model was generated with $np = 11.745.606$ million particles. A schematic of the 3D numerical flume tank is presented in Fig. 1. Initially, a box opened to the top was generated using five solid, un-deformable walls (Fig. 1). The entire length of each sidewall was 2.65 [m]. The front and back walls were created at the right and left ends of the flume tank and were 0.25 [m] wide, ranging from $Y = 0.0$ [m] to $Y = 0.25$ [m]. Both, back and sidewalls were 0.8 [m] high. At the base of the flume tank, a bottom wall was generated with a size that ranged from $X = 0.0$ [m] to $X = 2.68$ [m] and from $Y = 0.0$ [m] to $Y = 0.25$