Mechanistic Determination of Bedload Ensemble Statistics

KEVIN PIERCE
UNIVERSITY OF BRITISH COLUMBIA

ABSTRACT:

A three year computational and experimental research program of ten specific projects is proposed to investigate the kinematic and exchange statistics at the foundation of contemporary stochastic bedload transport theory. Computations will drive the Lagrangian transport of a discrete granular phase with a synthetic turbulent flow. Entrainment, motion, and deposition will result. The flow and granular characteristics will be prescribed to measureable channel properties. Virtual trajectories will be concatenated into ensembles, simulating kinematic and exchange statistics. This is an investigation of the deterministic mechanics underlying stochastic transport. Experiments will develop three dimensional Lagrangian transport ensembles with binocular computer vision. Mean and turbulent flow properties will be measured with particle image velociometry. Steady and unsteady flow conditions will be considered. The exchange and kinematic statistics obtained will be the first ever reported in 3D and unsteady flows, with promise to influence the developing stochastic theory of bedload transport, and they will test the computational model. The directive is to develop understanding of the mechanistic underpinnings of stochastic theories, to work toward rendering them applicable to engineering and ecological problems.

1 INTRODUCTION:

Bedload transport has strong feedback with stream morphology [Church & Ferguson, 2015; Recking et al., 2016], so its prediction is crucial to a wide range of problems, from aquatic habitat restoration to energy production [McDonald & Nelson, 2010; Kondolf et al., 2014; Wohl et al., 2015]. Unfortunately, existing capabilities are inadequate. Predictions can deviate by 1 or 2 orders of magnitude from measured values [Gomez & Church, 1989; Martin, 2003; Recking et al., 2012]. The lack of reliable bedload transport models is a critical research problem.

Modelling is challenging because movement is driven by turbulent forces [Schmeeckle et al., 2007; Celik et al., 2010; Dwivedi et al., 2010, 2011; Amir et al., 2014; Celik et al., 2014; Vowinckel et al., 2016; Shih et al., 2017] and is resisted by a network of variable factors, including granular geometry [Miller & Byrne, 1966; Paintal & Anderson, 1969; Paintal, 1971], sorting [Parker & Klingeman, 1982; Lisle & Madej, 1992], hiding [Egiazaroff, 1965; Fenton & Abbott, 1977], variations in upstream sediment supply [Madej et al., 2009; Elgueta, 2018], hydraulic history [Reid et al., 1985; Mao, 2012], sediment storage [Hoey, 1992], channel slope [Prancevic & Lamb, 2015; Maurin et al., 2018], channel width [Zimmermann et al., 2010], fine sediment concentration [Wilcock & Mcardell, 1997], and collective granular arrangements across a range of spatial scales [Brayshaw, 1984; Church et al., 1998; Hassan et al., 2007; Venditti et al., 2017].

As a result, sediment fluxes fluctuate widely in time and space, even under apparently steady conditions [Drake et al., 1988; Hoey, 1992; Böhm et al., 2004; Radice et al., 2009; Singh et al., 2009; Turowski, 2010; Houssais & Lajeunesse, 2012; Roseberry et al., 2012; Ancey et al., 2014; Heyman et al., 2016]. Practically, the factors driving and resisting sediment motion appear to be statistical distributions, rather than fixed values, as do the bedload fluxes themeslves. Bedload transport reveals a probability problem [Einstein, 1937]. In small and medium streams, bedload transport is especially of this character. Large grain sizes relative to channel dimensions, episodic supplies of sediment, and noisy hydrographs all contribute to wide distributions of driving factors, resisting factors, and resultant sediment fluxes [Hassan et al., 2005; Church, 2006; Comiti & Mao, 2012; Church & Ferguson, 2015].

Since stochastic approaches accomodate distributions, they may be well suited to predicting the flux in these streams. One only needs to specify the statistics of particle exchange and kinematics. Exchange statistics include the areal entrainment rate, areal deposition rate, and the particle diffusivity. Kinematic statistics include probability distributions of velocity, travel time, and hop distance [Ancey et al., 2014; Furbish et al., 2016; Heyman et al., 2016]. If exchange and kinematic statistics are specified, then the statistically expected bedload flux is too, complete with temporal and spatial variations. This prediction would provide ecology and engineering practitioners with a crucially needed foundation.

Unfortunately, a practical method to obtain the kinematic and exchange statistics is lacking, so that stochastic models are not useful to applications. The development of a mechanistic linkage to these statistics from measureable channel properties is exposed as a critical research problem. This mechanical linkage can be called closure for the analogous problem in turbulence theory [Heyman et al., 2016]. The development of closure is the directive of this research program. The chosen approaches are computational physics and flume experiments. The targets are: (1) a computational model of kinematic and exchange statistics which uses measureable fluid and granular characteristics as input; and (2) 3D observations of kinematic and exchange statistics in steady and unsteady flows, in conjunction with measurements of underlying fluid and granular characteristics.

The computational model will include grain-scale resolution and turbulent forcing, permitting exploration of kinematic and exchange statistics over the parameter space of turbulent fluid and granular characteristics. Experiments will develop a progressive dataset of Lagrangian bedload transport of crucial significance to subsequent studies of stochastic transport theory, and experiments will validate the computational model. In the following, the research problem of determining mechanistic closure is given context in 2, and proposed computational and experimental methods are discussed in §3.1 and §3.2 respectively. The ten specific projects composing the research program are introduced in §4, before a summary and some discussion of the greater scope of the research program in §5.

2 BACKGROUND:

In order to frame the proposed research problem as a missing link between Newtonian mechanics and the ensemble statistics required for stochastic bedload flux calculations, two necessary preliminaries are to describe the existing stochastic theory of bedload flux, and to review earlier attempts to calculate 3D Lagrangian bedload trajectories with Newtonian mechanics. These preliminaries will support the proposed computational and experimental methods revealed in §3.1 and §3.2 respectively.

2.1 STOCHASTIC BEDLOAD FLUX:

The modern stochastic formulation of the bedload flux involves the number of active particles per unit area γ and the downstream particle velocity u. These quantities vary through space and time, which has motivated a Reynolds-like decomposition into ensemble average and fluctuating components: $\gamma = \langle\gamma\rangle + \gamma'$ and $u = \langle u\rangle + u'$. From this decomposition, different physical arguments have arrived at the same ensemble flux [Furbish et al., 2012c; Ancey et al., 2014; Ballio et al., 2014]:

$$\langle q\rangle = \langle u\rangle\langle\gamma\rangle - \partial_x D_u \langle\gamma\rangle. \tag{1}$$

Here $\partial_x = \partial/\partial x$ is the downstream spatial derivative (similarly ∂_t for time) and D_u is a particle diffusivity describing the scaling of the ensemble mean squared particle displacement with time [Furbish et al., 2012c]. This flux has advective (first term) and diffusive (second term) components. Notably, the advective component was effectively derived by Einstein [1950].

Bedload diffusion has a delicate interpretation, exhibiting three ranges of behavior: local, intermediate, and global. Its characteristics are far more elaborate than a classical random walk diffusion [Einstein, 1905; Zhang et al., 2012]. The diffusive scaling in each range is $\langle x^2\rangle \propto D_u t^{\alpha}$. These ranges are distinguished by the length and time scales of observation, and they emerge due to the predominance of different processes within each range [Nikora et al., 2001b; Nikora, 2002]. The local range is super-diffusive ($\alpha > 1$) due to the predominance of fluid forcing over bed collisions, trapping, or burial. The intermediate range is normal diffusive ($\alpha = 1$) due to the joint predominance of fluid forcing and bed collisions relative to trapping and burial. The global range is likely sub-diffusive ($\alpha < 1$) due to the predominance of trapping and burial over other processes [Zhang et al., 2012; Martin et al., 2012; Hassan et al., 2013; Hassan & Bradley, 2015; Furbish et al., 2017b], however, the specifics of this picture are contradictory in the literature and require further research. If D_u, $\langle u\rangle$, and $\langle\gamma\rangle$ are specified at the scale of interest, bedload flux is predicted by equation 1.

Imposing particle conservation through exchange and motion specifies $\langle\gamma\rangle$ in terms of entrainment, deposition, and transport [Charru et al., 2004; Lajeunesse et al., 2010; Furbish et al., 2012c; Ancey et al., 2014, 2015; Furbish et al., 2017b]:

$$\partial_t\langle\gamma\rangle + \partial_x\langle q\rangle = E - D. \tag{2}$$

E and D are the exchange statistics. They are the rates of particle entrainment and deposition per unit area of Einstein [1950].

Additionally, D links to E through the kinematic statistics. Deposition is entrainment upstream at previous moments:

$$D(x,t) = \int_0^\infty dl_p \int_0^\infty dt_p E(x-l_p, t-t_p) P_{L_p,T_p}(l_p, t_p). \tag{3}$$

$P_{L_p,T_p}(l_p, t_p)$ is the joint probability distribution of particle hop length and travel time. The integrals accumulate entrainment from all upstream positions $x - l_p$ at earlier times $t - t_p$, $E(x-l_p, t-t_p)$, with the probability of moving distance l_p in time t_p, $P_{L_p,T_p}(l_p, t_p)dl_p dt_p$, over all possibilities of l_p and t_p [Furbish et al., 2012b; Fathel et al., 2015; Furbish et al., 2017b,a]. The marginal distributions of P_{L_p,T_p} are the particle hop length and travel time, originally introduced by Einstein [1937]: $P_{L_p}(l_p) = \int_0^\infty dt_p P_{L_p,T_p}(l_p, t_p)$ and $P_{T_p}(t_p) = \int_0^\infty dl_p P_{L_p,T_p}(l_p, t_p)$.

From this stochastic formalism, the statistically expected flux $\langle q \rangle$ is determined from exchange and kinematic statistics. The exchange statistics are the areal entrainment rate E, areal deposition rate D, and diffusivity D_u. The kinematic statistics are the joint distribution of downstream particle displacement and travel time $P_{L_p,T_p}(l_p, t_p)$ and the downstream particle velocity distribution $P_U(u)$. This formulation is elegant, and shows promise for capturing the variability of real streams, but it has a major issue which prevents its application. Theory provides no specification of its required input statistics in terms of practically measurable channel parameters, nor does it constrain the diffusive scaling region boundaries. This proposal concerns these specifications.

2.2 STOCHASTIC LAGRANGIAN MECHANICS:

The required statistics and diffusive range boundaries result from underlying Newtonian mechanics. Lagrangian particle trajectories emerge from the integration of

$$m\frac{d\mathbf{v}}{dt} = \mathbf{F}(\mathbf{x}, t, \ldots), \tag{4}$$

where **F** describes all interactions of the particle with the fluid and all other particles. For the reasons discussed in §1, **F** is very difficult to characterize, so this approach offers considerable resistance. If **F** is properly described, equation 4 will describe entrainment, motion, and deposition of particles. When many trajectories are accumulated from integrations of 4 from a wide variety of possible initial and boundary conditions, the resulting ensemble will define the kinematic and exchange statistics, and the diffusive range boundaries required to apply equation 1 at the scale of interest.

Of course, **F** is intricate, with contributions from a turbulent fluid phase and dynamic granular phase, interlinked through the fluid response to the dynamic granular boundary it induces: this linkage is not well understood. Many studies of bedload transport have integrated 4 with some approximation of **F**. Adequate approximations are difficult to construct: either approaches are too simple to capture essential features, or too computationally expensive to be practically useful. The approximation chosen should depend on the phenomena of interest, noted by Murray [2003] as a "regrettable necessity" due to the complexity of these phenomena.

The proposed methods in §3 are the result of a careful literature review, borrowing and elaborating aspects of earlier approaches to strike a balance between complexity and computational cost, in line with the appropriate complexity model selection framework developed by Larsen et al. [2016], while tailoring the approach to produce the quantities of interest [Murray, 2003], which in this case are large Lagrangian ensembles expressing entrainment, motion, and deposition. In order to motivate the selected methods, the strengths and weaknesses of a set reviewed approaches will now be evaluated against these metrics, starting from the simplest approximations of **F** and moving to the most complex.

The simplest category of efforts to form ensembles from integrating equation 4 has represented **F** by a fluctuating bulk streamwise force without an explicit process linkage to turbulence or bed collisions [Zhang et al., 2012; Ancey et al., 2014; Fan et al., 2014, 2016]. These modified random walk models derive ensembles with probability distributions of streamwise particle velocity which agree in form with those obtained in experiments, and some have revealed ranges of diffusion [Zhang et al., 2012; Fan et al., 2016], although the range boundaries seem unrealistic.

These approaches reveal equation 4 as the foundation of ensemble statistics, and they are computationally inexpensive, allowing the simulation of large ensembles (10^5) on a typical personal computer in minutes. However, their simplicity prevents their application to the problem of mechanical closure, since they are unable to produce travel time, hop length, entrainment, or deposition statistics. These quantities require a vertical motion component with a granular forces upon bed contact.

The next level of complexity has considered **F** as 2D or 3D turbulent driving forces, while bed impacts are incorporated with a simplistic hard sphere impulse approach (from [Crowe et al., 1998]), capturing their basic features. These models are reviewed in Bialik [2015]. Bed geometry is considered a uniform arrangement of immobile spheres, either close packed [Bialik, 2010; Bombardelli et al., 2010; Bialik et al., 2012; Moreno & Bombardelli, 2012; Bialik, 2013; Bialik et al., 2015], or with vacancies [Kharlamova & Vlasak, 2015]. Some approaches generated turbulence with spectral methods [e.g. Bialik et al., 2012].

Among the spectral turbulence models, there is clear resolution of the three ranges of bedload diffusion. Spectral turbulence is attractive because it provides a computationally inexpensive way to develop turbulent velocity fields with prescribed statistics, including mean profiles and turbulent intensities. However, in these models, boundaries of the diffusive zones seem unrealistically large, probably in part because of the simplicity of bed geometry and collisions, and because moving particles do not have feedback with the flow, since it is only characterized statistically.

A more complex set of studies has considered a fully resolved mobile granular phase, including grain-grain interactions into **F** using the discrete element method (DEM) of Cundall & Strack [1979]. In DEM, each pair of contacting grains interacts with repulsive, frictional, and viscous forces [Džiugys & Peters, 2001]. Early examples of this approach represented the fluid contribution to **F** as constant or steadily varying, possibly modified by particle exposure [Jiang & Haff, 1993; Jefcoate, 1995; Jefcoate & McEwan, 1997; McEwan & Heald, 2001; McEwan et al., 2004]. These studies strongly support the conclusion that bedload transport is poorly characterized by mean properties of the flow and sediment bed.

Later DEM studies modeled the fluid contribution to **F** as an idealized turbulent forcing generated by measured [Schmeeckle & Nelson, 2003] or spectral synthetic time series [Nikora et al., 2001b]. The study of Nikora et al. [2001b], applying spectral synthetic turbulence generation in conjunction with DEM, revealed local and intermediate diffusion regimes separated by a realistic scaling boundary. The discrete element method is attractive since it allows for incorporation of realistic particle-particle interactions, although admittedly it has a relatively high computational cost.

The most complex (and realistic) approximations of **F** have emerged in the last five years. Large eddy simulations (LES) of the fluid phase have been performed in conjunction with granular dynamics simulations with DEM [Schmeeckle, 2014, 2015; Sun & Xiao, 2016; Liu et al., 2016; Elghannay & Tafti, 2017a,b]. These LES-DEM computations provide a wealth of information about sediment transport characteristics. However, they are computationally expensive, and their recent emergence is coupled to the development of computing technology.

State of the art LES-DEM computations are expressed in Elghannay & Tafti [2017a]. They computed 10 trials across a range of flow conditions, from bedload to washload. Each considers at most 330,000 identical spheres, simulated alongside turbulent flow for 10s. They find $q_s \propto \tau^{3/2}$ (i.e. Meyer-Peter & Müller [1948]) with departures near threshold conditions. The simulations indicate unequivocally that coherent turbulent structures drive entrainment events, and that underlying Newtonian mechanics govern sediment transport processes. However, it's clear that computational cost limits the application of LES-DEM to the current problem, since the study of kinematic and exchange distributions on intermediate or global ranges requires much longer than 10s, and many controls on sediment exchange are known to require multiple grain sizes for their expression [e.g. Parker & Klingeman, 1982; Brayshaw, 1984].

Therefore, keeping with the model selection criteria presented in Larsen et al. [2016] and Murray [2003], remaining in clear sight of the computational objective, which is to calculate large ensembles of (~10^5) Lagrangian trajectories given measurable flow and granular characteristics, the chosen computational model for the proposed research program will couple spectral synthetic turbulence (SST) generation to the discrete element method (DEM). SST provides a computationally inexpensive method to generate turbulent time series with prescribed statistics and correlations. DEM is the best available method to account for the granular phase contributions to bedload dynamics.

Since turbulence statistics can be prescribed to SST, rather than determined after computation, as in LES, the SST approach has additional advantages over LES for the research program, even if the computational expense criterion were discarded. SST is the simplest way to turn statistical measurements from real streams, such as mean velocity profiles, Reynolds stress profiles, and energy spectra, into realistic turbulent flow fields. The specifics of the coupled SST-DEM model are described in §3.1. The proposed experimental methods are presented in §3.2, and the ten specific research projects which to be developed from these are revealed in §4.

3 METHODS:

3.1 COMPUTATIONAL METHODS:

The proposed SST-DEM model will express sediment entrainment, motion, and disentrainment with resolution of individual grains. This model will contain grain-grain and fluid-grain interactions. Its inputs will be the prescribed mean velocity profile, turbulent spectrum, Reynolds stress tensor, channel geometry, and the particle size distribution. Its outputs will be large ensembles of Lagrangian trajectories. The model will calculate ensemble kinematic and exchange distributions required by stochastic transport theories in terms of measurable input fluid and granular characteristics. Only one coupled SST-DEM model exists in the literature [Nikora et al., 2001b], although DEM has been employed in many studies, and simple spectral turbulence generators have also featured in some [e.g. Bialik et al., 2012]. The SST and DEM methods will now be introduced and their strengths and weaknesses discussed.

SST generation was first developed by [Kraichnan, 1970] to study particle diffusion through a turbulent velocity field. SST has been researched intensely since its development because it generates inflow boundary conditions for numerical simulations required by aerodynamics and heat transfer applications [Shur et al., 2014; Dhamankar et al., 2015; Wu, 2017]. The Kraichnan generator develops time independent velocity fields with a prescribed spectral energy density. The generated field is isotropic and homogeneous; its turbulent characteristics are the same in every direction and within any chosen control volume [Wu, 2017].

Notably, channel flow is anisotropic and inhomogeneous; turbulent intensities vary with distance from the channel wall, and are different in longitudinal, vertical, and transverse directions [Nikora & Goring, 2000]. The SST generators applied in sediment transport literature rescaled isotropic/homogenous velocity fields with empirical turbulent intensities and mean velocity profiles, and resampled the spectral fields repeatedly, until realistically correlated velocity fields were obtained by trial and error [Nikora et al., 2001b; Bialik, 2010]. There is no reason to expect velocity fields generated in this way will exhibit the coherent turbulence associated with channel flows [Kline et al., 1967; Ninto & Garcia, 1996; Adrian, 2007] and considered crucially linked to bedload motion [Vowinckel et al., 2016; Shih et al., 2017]. In light of the considerable research performed in SST generation, improving upon these earlier approaches to generate SST with these coherent structures should be a matter of borrowing from the extensive literature.

Refinements of the Kraichnan method have provided anisotropic inhomogenous SST, permitting the generation of legitimate channel flow with coherent structures and appropriate correlations, provided Reynold stresses are prescribed in addition to energy spectra [Clark & Vassilicos, 2011; Dhamankar et al., 2015; Smirnov et al., 2001; Yu & Bai, 2014; Shur et al., 2014; Adler et al., 2018]. The proposed SST-DEM model will incorporate one of these refined generators. In all Kraichnan-like methods, the spectral energy density $E(k)$ is prescribed to a random velocity field $\mathbf{u}(\mathbf{x}, t)$ by developing it as a Fourier series with random phases [Bechara et al., 1994; Bailly & Juve, 1999]:

$$\mathbf{u}(\mathbf{x}, t) = \sum_{\mathbf{k}} \sqrt{2E(k)\Delta k}\big[\hat{\mathbf{A}}_{\mathbf{k}} \cos(\mathbf{k}\cdot\mathbf{x} - \omega_{\mathbf{k}} t) + \hat{\mathbf{B}}_{\mathbf{k}} \sin(\mathbf{k}\cdot\mathbf{x} - \omega_{\mathbf{k}} t)\big]. \tag{5}$$

The magnitude $|\mathbf{k}|$ is distributed across a range related to the minimum and maximum size of eddies in the flow: $k_{min} \le |\mathbf{k}| \le k_{max}$, $k_{min} \propto 1/l_{max}$, and $k_{max} \propto 1/l_{min}$. The directions of $\mathbf{k}$ are randomly selected from a unit sphere. The frequencies $\omega_{\mathbf{k}}$ reflect the time correlations in the field. The unit vectors $\hat{\mathbf{A}}_{\mathbf{k}}$ and $\hat{\mathbf{B}}_{\mathbf{k}}$ have random directions satisfying $\hat{\mathbf{A}}_{\mathbf{k}} \cdot \mathbf{k} = 0$ and $\hat{\mathbf{B}}_{\mathbf{k}} \cdot \mathbf{k} = 0$ so that the field is incompressible. Δk is the spacing between adjacent modes. Careful discussion of these topics is available in Dhamankar et al. [2015] and Wu [2017]; to this point, there is little deviation from the original formulation of Kraichnan [1970].

In some generalized Kraichnan generators, the Reynolds stresses are incorporated into the velocity field through a Cholesky decomposition, originally introduced by Kaiser & Dickman [1962] to study population correlations in social sciences. The stress tensor $\mathbf{R}(\mathbf{x})$ is decomposed into a product of lower triangular matrices as $\mathbf{R} = \mathbf{L}\mathbf{L}^{\mathrm{T}}$. The product of $\mathbf{L}$ with $\mathbf{u}$ provides a turbulent velocity field with prescribed mean velocity profile, turbulent intensities, and spectral energy content [Shur et al., 2014; Dhamankar et al., 2015; Wu, 2017]:

$$\mathbf{u}'(\mathbf{x}, t) = \mathbf{L}(\mathbf{x})\mathbf{u}(\mathbf{x}, t). \tag{6}$$

The prescribed flow statistics are well represented by $\mathbf{u}'$ when several thousand modes $\mathbf{k}$ are included in equation 5. In the proposed model, this velocity field will be coupled to individual grains using the classic results for fluid-grain forces [e.g. Maxey & Riley, 1983]. Grains will respond to these synthetic turbulent fluid forces, in addition to grain-grain forces, through a DEM framework.

Within DEM, every two grains in contact interact with repulsive, viscous, and frictional forces in tangential and normal directions [Cundall & Strack, 1979; Džiugys & Peters, 2001]. The granular dynamics are governed by the numerical integration of the joint equations of motion with a small timestep. There are powerful codes available which perform these computations with uniform spheres [Plimpton, 1995] or arbitrary convex polyhedra [Wachs et al., 2012]. The computational model in this proposal is just a matter of modifying one of these to include turbulent forcing from the synthetic turbulence. Notably, Dr. Wachs is at UBC and has offered the Grains3D codes, able to handle particles of arbitrary shape, for this simulation [Wachs et al., 2012]. Additionally, the author has the ability to generate randomly shaped grains from prescribed statistical shape descriptors, having copied the limited literature on this topic [Mollon & Zhao, 2013]; studying the effects of particle shape on entrainment is considered as a tertiary investigation.

Admittedly, DEM has a somewhat high computational cost. However, the bedload transport regime exists under flow conditions that do not deviate too far from threshold, and under these flow conditions, there is a well-defined dynamic active layer near the bed surface below which particles do not move [Church, 2017]. Therefore, grains below this active layer can be locked out of the simulation, providing an appreciable reduction in computational cost.

Admittedly, an unavoidable shortcoming of the proposed SST-DEM model is that moving grains influence flow characteristics in their locality [Ferreira et al., 2009; Singh et al., 2010; Santos et al., 2014; Liu et al., 2016], since they provide an additional energy and momentum sink. The SST-DEM model neglects this coupling as the turbulent flow is only described by its statistics. As a result, the validity of spectral turbulent forcing is undermined when particle activities are large. This is not a major issue, since relatively small bedload activities will be sufficient for all of the specific computational investigations outlined in §4, however it is a limitation to keep in mind. In all, the computational model will be, by design, a progressive and appropriate tool to study mechanical closure between measureable channel properties and the ensemble statistics required by stochastic transport models with new depth.

3.2 EXPERIMENTAL METHODS:

A set of Lagrangian tracking experiments has already been conducted, and the analysis and publication of the data is an important portion of this proposal. Bedload transport of 5mm glass beads was recorded for 20 to 30 minutes across 4 different steady flow conditions, and unsteady dam break flow conditions, including over 1200 repeats, using two high speed (190fps) cameras arranged to achieve 3D binocular vision [Wohler, 2009]. In a parallel set of experiments, particle image velociometry (PIV) [Raffel et al., 1998] was employed to obtain two-dimensional (2D) mean velocity profiles and turbulent statistics for the 4 steady flow conditions.

Experiments were designed to yield large Gibbs ensembles characterizing the 3D exchange and kinematic statistics of bedload transport, in conjunction with the statistical properties of the fluid flow. In all, the experiments are a fundamental and progressive contribution to the existing database on Lagrangian transport; they will be the first 3D Lagrangian tracking measurements reported, and the first unsteady flow Lagrangian particle tracking measurements, to the authors knowledge. Additionally, they provide the outputs and inputs of the SST-DEM model, so it can be tested. However, obtaining the experimental ensembles will require delicate particle tracking and stereo reconstruction analyses.

Particle tracking and stereo reconstruction approaches are now proposed. First, the particle tracking process is divided into object detection and linking stages. Object detection is the identification of particles within each video frame. Linking is the process of connecting particle identities between frames– a mathematical assignment problem. For object detection, the method of median background subtraction and connected region identification was successfully utilized in previous studies [Radice et al., 2006; Heyman et al., 2016], so this will be considered first.

If median background subtraction provides insufficient resolution, the second approach will apply a convolutional neural network over individual frames to learn a compressed representation of particle positions. This representation can then be inverted for high fidelity particle positions. This approach has been recently applied very successfully to detect biological cells in microscope images [Xue et al., 2017]. Linking detected particles between frames will then follow the Jonker-Volgenant algorithm [Jonker & Volgenant, 1987], successfully applied by Heyman et al. [2016] to obtain 2D trajectories. After these steps are complete, collections of 2D trajectories will be obtained, one collection from each camera.

Stereo reconstruction proceeds from these stereopairs of 2D trajectories, using disparity relations developed from complementary calibration images [Wohler, 2009]. These images were obtained with a specially constructed black and white PVC grid in many different orientations within the experimental domain. With these disparity relations, image coordinates of an object taken by one camera can then be mapped to a prediction of its coordinates in the other camera. Additionally, the stereo pair of image coordinates of an object defines its 3D position.

To reconstruct 3D trajectories from the stereopairs of 2D trajectories, the set of coordinates of one frame will be mapped onto a prediction of its coordinates in the other frame with the disparity map, and vice versa. Then, linking across cameras is a second assignment problem to be solved with the Jonker-Volgenant algorithm [Jonker & Volgenant, 1987]. From this analysis, large ensembles of 3D Lagrangian trajectories will result, providing exchange and kinematic statistics across a range of steady and unsteady flow conditions. The number of individual trajectories observed at each flow condition is estimated to be between 15,000 and 100,000: the upper end of this estimated range is much larger than all other studies of this type [e.g. Roseberry et al., 2012; Heyman et al., 2016].

4 RESEARCH PROGRAM:

The specific research program and its three year timelime are now outlined. Each project builds progressively toward the desired outcomes, which are (1) a validated computational physics model of exchange and kinematic statistics using measurable channel parameters, and (2) 3D observations of kinematic and exchange statistics in steady and unsteady flows, in conjunction with the underlying fluid and granular properties. Ten specific projects are now introduced. Each project is outlined with a problem statement, proposed solution, and anticipated production. Solutions employ the methods from §3.

4.1 SPECTRAL SYNTHETIC TURBULENCE FOR SEDIMENT TRANSPORT:

Problem:
There is scope for an adaption of the spectral synthetic turbulence literature, mostly developed for aerodynamics and heat transfer applications, into a form useful for channel flow and geomorphic applications. In particular, this is required for the proposed SST-DEM model. Flow over a rough bed is anisotropic and heterogeneous, and exhibits coherent turbulent structures [Adrian, 2007]. Therefore, the spectral turbulence generator employed by previous authors in the sediment transport literature [Bialik et al., 2012; Nikora et al., 2001a] cannot express the coherent structures of wall-bounded turbulence.

Solution:
More sophisticated spectral methods have been developed to generate inhomogeneous and anisotropic turbulence [Smirnov et al., 2001; Clark & Vassilicos, 2011; Shur et al., 2014; Adler et al., 2018], but these have not been adopted by sediment transport researchers. After a careful literature review, one of these approaches will be adopted for the development of synthetic channel flow turbulence.

Production:
There is scope for a short article comparing the synthetic generators previously utilized in sediment transport with the improved generators available in the literature. In particular, the quadrant analysis scheme presented in Ferreira et al. [2009] can be employed to compare the coherent structures manifested by the Nikora et al. [2001b] and [Bialik, 2013] work with those generated by the Shur et al. [2014] generator, for example. This will motivate these generators as useful and computationally efficient alternatives to large eddy simulation in computational sediment transport studies, and contribute to the development of the SST-DEM model.

4.2 BOUNDARIES OF DIFFUSIVE SCALING REGIONS:

Problem:
Nikora et al. [2001b] proposed three distinct diffusive ranges: local, intermediate, and global. This idea has been elaborated extensively [Hassan & Bradley, 2015; Furbish et al., 2017b], and these ranges have been simulated [Martin et al., 2012; Zhang et al., 2012; Bialik et al., 2015; Fan et al., 2016] and extracted through meta-analysis of experiments conducted at different scales [Zhang et al., 2012]. However, the boundaries (time and space) of the three scaling regions have not been directly connected to the mechanics of particle transport. All simulations in the literature compute these ranges with modified random walk models having no reference to specific bed collision and resting and burial processes. Meanwhile, theoretical explanations of the diffusion ranges have explained them in terms of the preeminence of specific processes within each range [Hassan & Bradley, 2015; Furbish et al., 2017b]. There is a disconnect between simulation and theory.

Solution:
An early version of the SST-DEM model will be developed to study the diffusion of tracer particles through the virtual coupled fluid-granular system. The mean squared displacement $\langle x^2 \rangle \propto D_u t^\alpha$ of the tracer population will be tracked across a long timescale of near-threshold transport. If the simulation can be run long enough, tracer diffusion should show an evolution of the scale parameter α through all three diffusion regimes. All tracers will have positions, exposures, and velocities tracked through the simulation. Therefore the evolution of α can be related to movement and resting phases, and the relative importance of fluid-induced acceleration, collision-induced deceleration, resting, and burial can be quantified in relation to each diffusive range.

Production:
An article will be written relating the evolution of α through its three ranges to the predominance of specific transport and residence processes within each of the three sets of scales. The scaling boundaries will be discriminated in time and space, and this will be related to the corresponding length and time scales on which processes predominate.

4.3 3D LAGRANGIAN BEDLOAD STATISTICS IN STEADY FLOW (1): KINEMATICS

Problem:
Lagrangian ensemble exchange and kinematic statistics are the foundation of stochastic sediment transport models. Unfortunately, there are very few measurements of these statistics in the literature [Ancey et al., 2006; Lajeunesse et al., 2010; Roseberry et al., 2012; Heyman et al., 2013; Fathel et al., 2015; Heyman et al., 2016], and none of these measurements have resolved all three dimensions of motion simultaenously. The first 3D phenomenon to be investigated is the well documented lateral variation of exchange characteristics [Nelson, 2010; Hodge et al., 2013; Venditti et al., 2017]. This has not been resolved in Lagrangian experiments. The second 3D phenomenon of interest is the covariance of each velocity component with travel time. These covariances set the form of the velocity distribution expected from entropy analysis [Furbish & Schmeeckle, 2013; Furbish et al., 2016]. One one component of this covariance has been investigated so far, and in only one set of experiments [Fathel et al., 2015].

Solution: This project will add to the database and rectify the 3D deficiency. This study will be unique because lateral variation of entrainment and deposition rates will be resolved. , so an additional contribution will be

4.4 A TURBLENT GRANULAR MODEL OF BEDLOAD ENSEMBLES:

Problem:
As outlined in §1, a practical link from measurable channel parameters to the ensemble statistics required by stochastic transport models is sorely needed for applications in ecology and engineering. Existing approaches with realistic treatment of a turbulent fluid phase coupled to a mobile granular phase are too computationally demanding for ready deployment [e.g. Schmeeckle, 2014; Elghannay & Tafti, 2017a].

Solution: Therefore, the a coupled SST-DEM model treating realistic turbulence and grain-grain interactions will be developed. The reduced computational complexity of SST relative to other approaches, in addition to locking out of the degrees of freedom of particles below the active layer, will facilitate the computation of long transport time-series, generating large ensembles of trajectories through entrainment, motion, and deposition.

Production:
The first presentation of the model will be an article exhibiting its general capabilities by studying the ensemble kinematics of bedload transport. For uniform 5mm glass beads under flow conditions just above threshold, the forms of hop length, velocity, acceleration, and travel time distributions will be presented, along with the covariance of hop length and travel time. These will be compared to recent theoretical [Furbish et al., 2012a, 2016] and experimental [Lajeunesse et al., 2010; Roseberry et al., 2012; Ancey et al., 2014; Fathel et al., 2015; Heyman et al., 2016] reports of these quantities, motivating the SST-DEM model as a useful tool for subsequent studies of mechanical closure.

4.5 COMPUTATION OF THE ENSEMBLE KINEMATICS OF BEDLOAD TRANSPORT:

The model developed in project 4 will be employed to study kinematic statistics for uniform spherical particles over the parameter space of turbulent properties. This work will elaborate on previous efforts [e.g. Bialik, 2010; Ancey et al., 2014; Fan et al., 2014] in this category, with much more realism in the turbulent and granular forces.

One quantity of interest is the form of the kinematic distributions: velocity distributions are probably exponential-like [Roseberry et al., 2012; Furbish & Schmeeckle, 2013; Fan et al., 2014; Fathel et al., 2015; Furbish et al., 2016], but they may be Gaussian [Lajeunesse et al., 2010; Ancey et al., 2014], and they may even transition between these two possibilities depending on location in the water column [Heyman et al., 2016]. As few experiments have been performed, exploring a restricted range of conditions, the wide variation in mean and turbulent flow statistics accessible by the model may lend some closure to this discussion of the form of kinematic distributions.

4.6 GRANULAR JAMMING AND PARTICLE MOBILITY:

Zimmermann et al. [2010] proposed that forces between grains are a neglected component of particle mobility considerations, and hypothesized that their incorporation into mobility analysis may explain the anomalously high particle entrainment thresholds often observed in small and steep mountain streams [Prancevic & Lamb, 2015]. They considered that particles in steep mountain streams jam across the channel width, so that force chains between the grains stabilize them to entrainment. This hypothesis has received some support from reduced complexity modeling [Saletti, 2016; Saletti et al., 2016], but this approach did not actually resolve force chains, nor have they ever been observed. Notably, the model developed in project 4 accounts for all inter-granular forces, so that jamming can be considered.

Therefore, this project proposes artificially increasing the transverse forces imparted by the wall onto the granular bed at a locality, and recording the resultant transverse distribution of forces through the bed across the channel, in concert with the areal entrainment rate of surface particles at this locality. This is expected to confer fundamental support for the jamming hypothesis, and shape subsequent research on bedload transport in mountain streams. Jamming is fully expected to emerge: the only questions concern its effect on entrainment thresholds. Jamming is very well documented in granular matter which is not subjected to shear flow [Corwin et al., 2005; Liu & Nagel, 2010], and there is no obvious physical argument as to why shear flow would remove this possibility.

4.7 SEDIMENT ENTRAINMENT BY IMPACT EJECTION:

As discussed, one aspect expressed by bedload transport is wide fluctuations in its rate, even under apparently steady conditions. This aspect is attributed, in one set of studies, to the phenomenon of collective entrainment, whereby the presence of moving particles in a locality is correlated to an increased entrainment rate in that locality [Ancey et al., 2006, 2008; Heyman et al., 2014; Ancey et al., 2014; Heyman et al., 2016]. Determining the specific processes behind collective entrainment is important. For instance, the entrainment of multiple grains may occur because one grain entrained in a conventional way, and the other grains in contact with it were contingent on it for stability, so they too were entrained. Alternatively, the entrainment of multiple grains could occur because a particle in motion collided with the bed, imparting momentum to a group of otherwise immobile particles, leading to their collective entrainment. According to McEwan and Willets (1991) who investigated aeolian saltation, the moving grains may be considered as made up from two components: aerody- namically entrained grains and impact generated grains. Further, McEwan et al. (1999) developed this approach, adapting it to the fluvial conditions, suggesting that the number of uniform grains Ne entrained per unit area per unit time is equal to

This study will decompose entrainment events into individual and collective categories. Each category will then be partitioned into processes. Did the particle(s) entrain in a conventional way (that is, through a loss of force balance as considered by Wiberg et al. [1987], or did it entrain due to impact ejection? This partition would be difficult and subjective in an experiment, but it is straightforward in a Lagrangian simulation. This project will extract the relative importance of the impact ejection process and conventional flow-based entrainment for presentation.

4.8 DEPOSITION STATISTICS, BED ROUGHNESS, AND TURBULENCE:

Bed roughness is hypothesized to increase the probability of deposition upon the collision of moving grains with the bed. Since the frequency of bed contant is encapsulated in kinematic statistics of bed particles, which themselves are linked to mean and turbulent flow characteristics Bialik et al. [2012], a complex dependence of areal deposition rates on flow statistics and bed roughness is expected. These will be presented.

4.9 BEDLOAD ENSEMBLE STATISTICS, A COMPARISON OF EXPERIMENT AND MODELING:

This project will synthesize the experimental and computational results of projects 3 and 4, in order to explore the validity of the turbulent granular model of bedload ensembles. Fundamentally, this project will check that the mean velocity profiles, energy spectra, and Reynolds stresses obtained in the steady flow PIV experiments can be used to reproduce the ensemble exchange and kinematic ditsributions observed in the steady flow particle tracking experiment using the computational model. Differences between expected and measured results will be highlighted and explained.

4.10 3D LAGRANGIAN BEDLOAD STATISTICS IN UNSTEADY DAM BREAK FLOW:

There are apparently no studies of ensemble statistics within unsteady flow experiments. This project concerns the analysis of the set of repeated dam break flow experiments already performed. The particle tracking and stereo analysis techniques developed in project 3 will be refined for application to the unsteady flow case. Upon analysis of the 1200 experimental repetitions, ensemble statistics will be developed across the set of realizations. This will lead to time and space varying entrainment, deposition, velocity, and activity distributions, fundamentally expanding the database on statistical characterizations of particle transport in turbulent shear flows.

4.11 GRAIN SHAPE AND THE TRANSITION BETWEEN BEDLOAD AND GRANULAR CREEP:

5 CONCLUSION:

Stochastic transport models are a significant theoretical advancement, since they can incorporate variability in flow characteristics, channel geometry, and granular arrangement as fundamental characteristics, and this variability appears intrinsic to small and medium sized natural streams. However, in order to be practically viable for ecological and engineering applications, stochastic models require an additional linkage between their statistical input parameters and practically measurable channel parameters. The proposed research program is a set of computational and experimental projects which frame this linkage as a problem in Newtonian mechanics.

The targets of the research program are (1) a computational physics scheme to explicitly calculate large ensembles of Lagrangian trajectories from integrating the sediment equations of motion, and (2) an unprecedented high resolution dataset of large ensembles of 3D Lagrangian bedload trajectories, in steady and unsteady flows. The computational projects will rely on coupling spectral synthetic turbulence to a discrete granular phase. Model selection is guided by the problems considered, and especially with regard to computational cost. The experimental projects will rely on 3D binocular vision and particle image velociometry.

These experimental and computational developments will contribute to theoretical and practical aspects of stochastic bedload transport theory. The directive is to clarify the mechanical connections between turbulent and granular properties and kinematic and exchange statistics of bedload transport. The wider scope of this research is to work toward a practically applicable framework for stochastic bedload sediment transport predictions which substantiates channel morphology, river ecology, and engineering approaches; this is a small and integral program within a greater mechanistic-stochastic movement in the earth sciences.

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