Sediment transport and bedform morphodynamics in sand-gravel mixtures.

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ABSTRACT: Bedform morphodynamics and sediment transport have been widely investigated in alluvial environments where grain size distributions and current flows are assumed to be uniform. This is not reflective of shelf sea environments characterized by oscillatory currents and sediment mixtures. The presence of sand-gravel mixtures causes a reduction of sediment mobility and additionally incorporates an effect known as the 'hiding-exposure' effect resulting in complex morphodynamics. In this research, the complexity of this problem is highlighted through recent flume tank experiments, inspired by offshore analyses, in which an attempt was made to quantify 'hiding-exposure' effects and the effect of sediment mixtures on the development and migration of ripples. Initial results indicate the presence of the 'hiding-exposure' effect and the dependence of bedform dynamics on the composition of sediment mixtures with smaller more uniform ripples formed in the presence of gravel and sediment transport rates decreased by more than 66% in mixtures containing 15% gravel compared to that in pure sand.

1. INTRODUCTION

Bedform morphodynamics are controlled primarily by sediment transport processes that have been widely investigated resulting in a vast number of predictive bedload transport formulae. The most commonly reported of which are those of Meyer-Peter and Müller (1948), Einstein (1950), Yalin (1963), Bagnold (1956; 1966), Engelund and Hansen (1967), Ashida and Michiue (1971), van Rijn (1984) and Nielsen (1992), and the widely used formula of Engelund and Fredsøe (1976). These formulae were originally developed for application in open channel flows with quasi-steady current velocities; however, they are not entirely reflective of shelf sea environments due to inherent assumptions such as unidirectional current flows and uniform grain size distributions.

Shelf seas are typically characterized by bi-directional currents and/or waves, and the presence of sediment mixtures as a result of paleo-glacial or -fluvial processes during the quaternary period between the last glacial maximum. In a sand-gravel mixture, less sediments will typically be available to form bedforms, which influences the dynamics of the bed. The presence of these mixtures also incorporates an effect known as the 'hiding-exposure' effect where small grains are 'hidden' by larger, more 'exposed' grains changing the efficiency of the flow to mobilize different grain size fractions. As the flow further entrains and redistributes sediments, the mixture will change, as will the 'hiding-exposure' effect, depending on the strength and asymmetry of the flow. This could potentially lead to varying depths of the active layer, from armoured gravels to mobile sands, and is thought may significantly affect bedload transport processes and seabed morphodynamics.

The presence of sediment mixtures and their interaction has been accounted for through the development of fractional transport formulae in recent years. This has been accomplished through adaptation of formulae such as that of Meyer-Peter and Müller (1948), van Rijn (1984), van Rijn *et al.* (2007) and Ribberink (1998) for the transport of both uniform and non-uniform sediments. Similarly, the formulae of Parker *et al.* (1982), Wu *et al.* (2000) and Wilcock and Crowe (2003) have been developed directly for the fractional transport of mixed-sized sediments. The 'hiding-exposure' effect has also been quantified for steady flows and incorporated into bedload transport formulae through the application of corrective formulae such as that developed by Ashida and Michiue (1972), Egiazaroff (1965), Parker et al. (1982) and Wilcock and Crowe (2003). This has led to advances in the prediction of mixed sediment transport; however, the focus so far has been on alluvial environments.

This ongoing research aims to investigate the 'hiding-exposure' effect under conditions similar to that observed in offshore environments (i.e. with oscillatory currents and non-uniform sediment mixtures). Both offshore data analyses and flume experiments are discussed to highlight the complexity of this problem.

2. METHODOLOGY

2.1. Offshore Data Analysis

Llanelli Sand Dredging Ltd (LSDL) provided acoustic data (MBES, backscatter & side-scan sonar) and sediment sample data, both inside and outside a dredged area of seabed, for the purposes of this research. These results and other studies across the Irish Sea (e.g. Van Landeghem et al., 2009, 2015) indicated that where sand and gravel were present in a mixture, the ratio of gravel to sand on average was approximately 15:85. This informed trial flume tank experiments to extend the offshore analysis into environments with different forcing factors (i.e. current strengths, sediment distributions, etc.).

2.2. Flume Tank Experiments

An attempt was made to quantify the threshold of motion for pure sand, gravel and sediment mixtures. Fractional transport rates, quantified through collection and PSA of transported sediment from each run, were used to calculate the threshold of motion of each mixture at a dimensionless reference transport rate of 0.002 using the method of Parker *et al.* (1982). Comparison of the threshold of motion for each mixture allowed the identification of 'hiding-exposure' effects where observable.

The effect of different sediment mixtures on the development and migration of ripples was investigated using a 10 m long by 0.3 m wide recirculating flume. Bedform development during reversing current flows, as well as changes to the bed at the end of each experiment was monitored using an array of 16 *SeaTek* 5MHz transducers.

3. PRELIMINARY RESULTS

3.1. Offshore Data Analysis

A series of asymmetric, flow-transverse, progressive sand waves were identified with a complex pattern of migration direction and speed. Surficial sediments grade across the area from gravelly (or gravelly-muddy) sand in the southeast corner of the study area to sand in the north-west (Figure 1). The link between the properties of the sediment mixture and the sediment wave dynamics is subject to further analyses.

3.2. Flume Tank Experiments

During shear flume experiments, the mobility of gravel fractions increased in a mixture with sand, whose mobility decreased. A relationship was derived between the grain size (D_i) and the calculated dimensionless critical shear stress of each grain size fraction ($\tau_{cr,i}{}^*$) (Figure 2). As the sediment becomes less uniform, from pure sand to a mixture of 15% gravel to 85% sand, the critical shear stress at incipient motion increases for the smallest fractions ($D_i = 0.15\ mm$) by up to 33% and decreases for the largest fractions ($D_i = 6.82\ mm$) by up to 20%. The quantification was complicated by the shape of the gravel grains, as irregularly shaped grains would be more mobile, yet caught by other grains more easily. 'Hiding-exposure' corrections ideally allow for variable grain shape (e.g. Bridge and Bennett, 1992), as indeed the shape of grains influenced sediment transport in a marine setting considerably (Le Roux, 2005; Durafour et al. 2014).

The sedimentary bedform dynamics in the larger, horizontal flume tank were noticeably dependent on the properties of the sediment mixture, as with increased gravel percentage more uniform and smaller ripples formed, taking longer to form a stable set of bedforms and migrating slower. A sediment mixture containing 15% gravel displayed a decrease in transport rate by more than 66% compared to pure sands. The 'hiding-exposure' effect was difficult to quantify in this experimental setting, as sediment mobility was the dominant factor, and temporary armouring effects behind sporadically mobile gravel grains rendered the dynamics more complex.

4. TENTATIVE CONCLUSIONS

Sediment mixtures influence sedimentary bedforms in various ways:

- The critical shear stress at incipient motion increases for the smallest fractions ($D_i = 0.15\ mm$) by up to 33% and decreases for the largest fractions ($D_i = 6.82\ mm$) by up to 20% in a mixture of 15% gravel, 85% sand compared to that in 100% sand.
- Bedform dynamics are dependent on the properties of sediment mixtures: an increased presence of the gravel fraction caused the formation of smaller, more uniform ripples with slower migration rates.
- Although gravel in a mixture with sand exhibited increased mobility, this was not reflected in bedform migration rates.
- Bedforms formed in sediment mixtures containing 15% gravel were found to have decreased transport rates by more than 66% compared with those formed in pure sands.

5. FUTURE WORK

Data from different environments across the Irish Sea will be analysed to investigate the link between sediment mixtures and sediment wave dynamics. Results will then be used to further constrain flume tank experiments in which the effect of different sediment mixtures on sediment transport processes and bedform morphodynamics will be explored.

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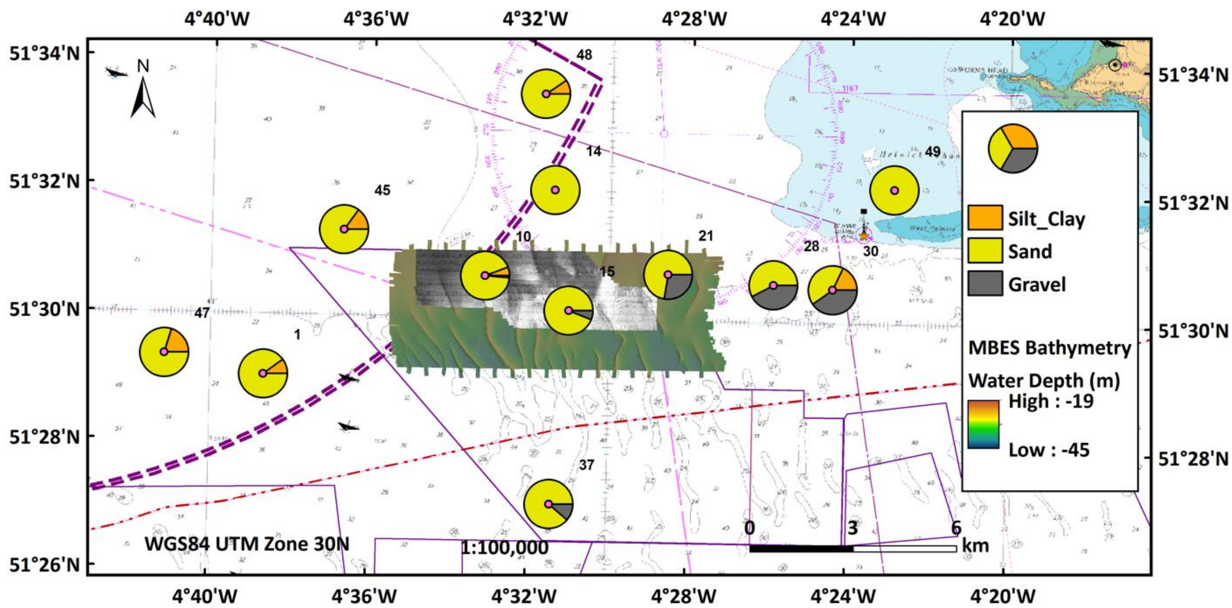

Figure 1. Distribution and average percentage composition of surficial sediments fractions (silt/clay, sand and gravel) across the study area.

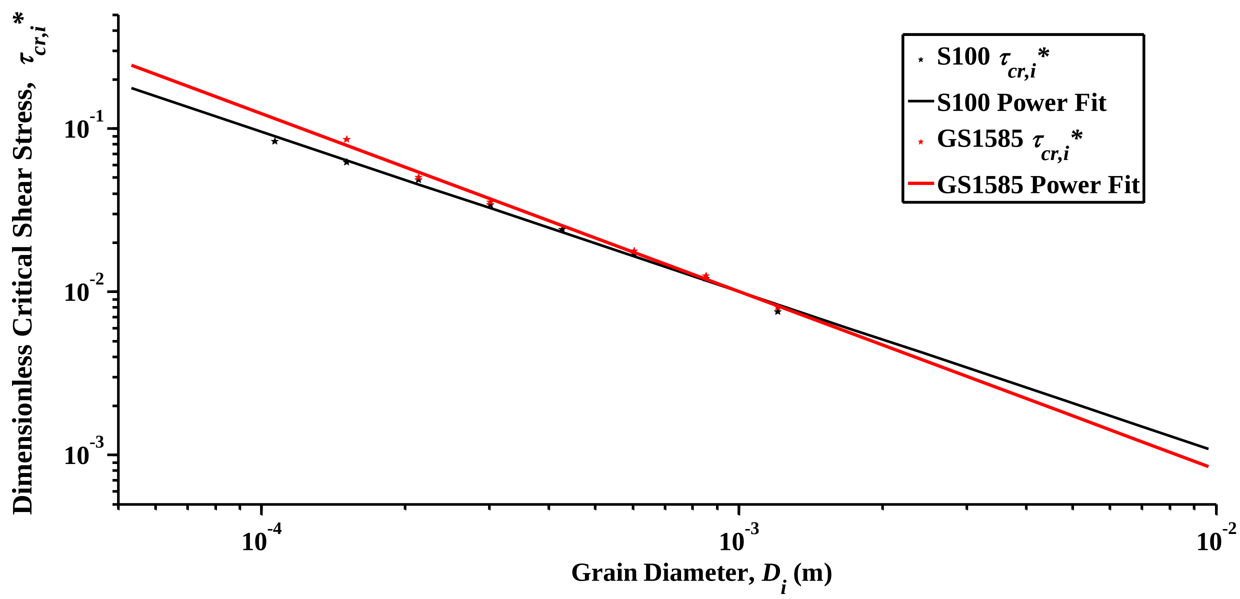

Figure 2. Dimensionless critical shear stress ($\tau_{cr,i}{}^*$) vs. mean grain diameter (D_i) of the i^{th} grain size for 100% sand (S100) and a mixture of 15% gravel, 85% sand (GS1585).