EXPERIMENTAL INVESTIGATIONS OF COMBINED FLOW SEDIMENT TRANSPORT

EVERETT SMITH,1 MAX S. DANILLER-VARGHESE,2 PAUL M. MYROW,1 AND DAVID MOHRIG2
1Department of Geology, Colorado College, Colorado Springs, Colorado 80903 U.S.A.
2Department of Geological Science, University of Texas, Austin, Texas 78712, U.S.A.
e-mail: maxdv@utexas.edu

ABSTRACT: In shallow marine environments gravity-driven currents (e.g., hyperpycnal flows) often traverse surface wave fields, and the resulting complex flows are key mechanisms for offshore sediment transport. Our laboratory experiments illustrate how surface waves alter sediment transport in gravity-driven density currents. The addition of a wave field to a gravity-driven current resulted in a 7–8.5% increase in the downslope transport of the deposit volume. Additionally, oscillatory velocities recorded at downslope locations in surface-wave-altered turbidity currents were larger than wave-field velocities measured at the same location without a turbidity current. These observations indicate that surface waves alter turbidity currents in a longitudinally complex manner whereby the influence of oscillatory currents is transported downslope within the body of the turbidity current. These effects were observed in a conservative case: the maximum orbital velocities of the wave field were an order of magnitude less than the maximum unidirectional velocities of the current. We predict that if the velocities of the wave field and the current were sub-equal, a plausible scenario for hyperpycnal flows in near-shore, deltaic, and proximal shelf environments, these effects would be substantially more effective. This work has significant implications for modeling offshore sediment transport in shallow marine environments and for interpreting the deposits of such flows, most notably that the presence or absence of combined-flow ripples might not indicate whether the current was deposited above or beneath wave base.

INTRODUCTION

Longstanding debates exist about the mechanisms of sediment transport in shallow marine environments, particularly the seaward transport of sediment during storms (Myrow and Southard 1996; Lamb et al. 2008). Marine, gravity-driven, sediment-laden density currents (turbidity currents) were invoked early on as one such mechanism (Hamblin and Walker 1979; Dott and Bourgeois 1982; Leckie and Walker 1982). Subsequent oceanographic data cast doubt on this idea because modern storms on continental shelves develop shore-parallel geostrophic flows (Swift et al. 1986; Duke et al. 1991). One possible mechanism for triggering turbidity currents in such a setting is failure of nearshore sandy shorelines, through cyclic wave loading (Walker 1984; Piper and Normark 2009; Falcini et al. 2012). An argument against such a mechanism for significant turbidity-current transport in shoreline to inner-shelf settings is that such flows cannot be maintained on the low slopes (less than 1 degree) typical of these settings (Myrow and Southard 1996).

More recently, numerous studies have suggested that offshore transport could be accommodated by hyperpycnal flows: continuous density currents generated by high-discharge fluvial flows with high sediment concentrations that enter a standing body of water and plunge below the surface (Mulder and Syvitski 1995; Parsons et al. 2001; Myrow et al. 2002; Mulder et al. 2003; Lamb et al. 2008; Piper and Normark 2009). Modern examples of depositional systems characterized by hyperpycnal flows include the Eel River, California (Mulder and Syvitski 1995), wadi Al Batha, Oman (Bourget et al. 2010b), and fluvial inputs along the Makran margin (Bourget et al. 2010a), among many others (Katz et al. 2015). Hyperpycnal flow deposits from such systems are well known from the ancient (Dott and Bird 1979; Myrow et al. 2002; Plink-Bjorklund and Steel 2004; Pattison 2005; Lamb et al. 2008). Hyperpycnal flows are especially common in steep and small to mid-sized coastal drainages, and in exceptionally turbid rivers during peak flows (Mulder and Syvitski 1995). River floods, and the resulting hyperpycnal flows, generally form in response to large atmospheric storms, and thus the flows may traverse a zone of large storm waves that affect flow dynamics and potentially aid in sediment suspension (Lamb et al. 2008; Myrow et al. 2002; Myrow et al. 2008). It has been proposed that superposition of surface waves on a turbidity current could enhance the ability of the current to transport sediment and thus increase flow duration and downstream flux of sediment (Wright et al. 1991; Myrow and Southard 1996; Myrow et al. 2002). This proposition is strongly supported by observations of enhanced sediment transport by naturally occurring wave-supported fluidized mud flows (Ma et al. 2010). Although there has been some experimental investigation of the general dynamics of hyperpycnal flows and their deposits (Lamb et al. 2010), there has been little experimental work to investigate this hypothesis concerning the effects of waves on turbidity currents. Field studies have been conducted on wave-supported gravity flows produced in the ocean by ambient waves and currents (Wright et al. 2001; Wright and Friedrichs 2006), and a number of theoretical and numerical modeling studies have addressed such flows (Traykovski et al. 2007; White and Helfrich 2008; Kämpf and Myrow 2014, 2018). However, these studies have been done on wave-modified fluid mud suspensions, not flows with granular sediment, such as the silt grade sediment used in this study. Granular flows do not have many of the...
complications that arise from flocculation of cohesive mud and hindered settling, and, at high concentrations, gelling to form sediment-supported dispersion that is dominated by non-Newtonian effects (Kämpf and Myrow 2014, 2018).

Given the likelihood that surface gravity waves affect hypopycnal flows in many instances, and the geologic evidence to support it (Mulder et al. 2003; Myrow et al. 2002; Zavala et al. 2006; Lamb et al. 2008; Myrow et al. 2008), experimental work on combined wave and turbidity-current flows is essential in order to more generally understand the links between the terrestrial and marine realms, including accurate modeling of sediment budgets (Walsh and Nittroer 2009). This paper presents the results of novel experiments that investigate the role of surface waves in the sediment transport of low-concentration turbidity currents. The continuous combined flows created in these experiments pulsed (as opposed to reversing) because the maximum orbital velocity of the oscillatory flow was several times less than the unidirectional flow velocity generated by density-driven gravity currents (see Lamb et al. 2008). Herein, we demonstrate that under such conditions, surface waves influence the velocity structure of these combined flows and the quantity of sediment transported downslope by such currents.

Laboratory experiments appropriately scaled to provide dynamic similarity have proven to be useful for studying natural mechanisms of sediment transport and bedform dynamics, despite lingering problems of capturing complex flow dynamics (Dorrell et al. 2014; Abd El Gawad et al. 2012). Specifically, both laboratory experiments (Sequiro et al. 2012, Table 1) and mathematical modeling (see Liapidesviki et al. 2018) have been highly successful tools for investigating many aspects of turbidity currents, and as a result much is known about these flows (e.g., Kneller and Buckee 2010; Parsons et al. 2007). Additionally, extensive laboratory experiments and mathematical models have explored the fluid dynamics, sediment transport, and bedforms of oscillatory flows (Wiberg and Harris 1994; Pedocchi and García 2009; Falcini et al. 2012; Nienhuis et al. 2015; Perron et al. 2018). Finally, combined flows of clear-water currents and oscillatory flows, and resulting bedforms, have been explored from a variety of standpoints. Davies and Li (1996) developed a 1D model for predicting sediment transport under sheet-flow conditions with wave influence. Early attempts at construction of a combined-flow phase diagram (Myrow and Southard 1991) were supplanted by extensive experimental studies by Perillo et al. (2014a, 2014b) who produced phase diagrams for bedforms created in a wide range of combinations of magnitudes of oscillatory-flow and unidirectional-flow components. In terms of combined flows with oscillatory-flow and turbidity-current flow components, Falcini et al. (2012) developed a mathematical model for predicting conditions of sediment bypass by wave-supported sediment gravity flows. They corroborated the accuracy of this model with field observations of wave-supported, high-density, mud-rich flows (Jaramillo et al. 2009). A small number of other field-based studies investigating the roles of wave-supported fluid-mud flows on shallow continental shelves provide some quantification of the parameters governing gravity-current and wave combined flows. However, there are almost no published data on the experimental investigation of wave-modified granular turbidity currents, other than an early, obscure study published in an Australian government publication on the oceanic dispersal of fly ash (Foster and Stone 1963). Thus, our experimental work on the dynamics of combined flows that have turbidity-current and wave components is a significant advance in our understanding of sediment transport under such poorly understood combined flows, which likely play a major role in sediment transport on modern shelves and played a similar role in the past. In addition, given that much of the field and theoretical work has been done on fluid mud and related deposits, our study of granular sediment is of great significance to the interpretation of silt-grade to sand-grade tempestites in the rock record.

**METHODS**

**Experimental Setup**

Experimental flows were modeled in an open-channel flume in the Experimental Sedimentology Laboratory at the Jackson School of Geosciences, The University of Texas at Austin (Fig. 1). The flume is 11.00 m long, 0.61 m wide, and 1.22 m deep and contains a ramp within it. Starting at the flume’s upstream end (0 m), the ramp is a horizontal surface from 0 to 1.24 m with the top of the ramp 1.01 m above the base of the flume. Beginning at 1.24 m, there is a 5-m-long ramp at a slope of 9°, levelling out to a 2.35 m horizontal plane that sits 0.06 m above the flume base. Whereas the overall slope of the ramp is constructed at 9°, one of the plates has an unintended, slightly lower slope (7°) from 4.88 to 6.00 m. The ramp is constructed of 0.02 m thick acrylic plastic plates, overlaid with a lightly textured, 3-mm-thick, rubber mat creating bed roughness. Beyond the experimental domain there is a sump from 10.00 m to 11.00 m, with an added depth of 0.73 m beneath the flume bottom that has a drain. In this box there is a standpipe to maintain a constant water depth of 1.15 m above the true flume bed during experimental flows.

The wave field in the tank is generated with a 2’ × 4’ (0.61 m × 1.22 m) acrylic plastic paddle fixed on a horizontal metal bar attached to a...
motorized wheel. A foam mat in the upstream end of the flume reduces reflections off the back wall. The wave maker produces waves with a 0.013 m amplitude, an approximate 3 m wavelength, and a period of 1.4 s.

For each flow, 900 l of water is mixed with 113.4 kg of 200 mesh quartz silt ($D_{50} = 30$ micrometers) in a 1000 l reservoir creating a 942 l mixture of 4.2% percent quartz silt concentration by volume. This mixture is pumped to a constant-head tank feeding the flume through a 2-inch (51 mm) diameter PVC pipe flush with the ramp. For the duration of each flow, augurs continuously mix the sediment and water in both the reservoir and the head tank. These inputs allow for turbulent suspension and transport of sediment in our experimental scale, with a particle Reynolds number ($Re_p = \frac{ud}{v}$) of 1.6 and a Shields Number ($\theta = \frac{u^2}{gD}$) of 6.2. These parameters place our experiments above the threshold to initiate full sediment suspension (van Rijn 1984; Niño et al. 2003). Given these parameters, we are confident that our experiments scale with other experiments, including the sediment transport processes (Luthi 1981; Straub et al. 2008; Alexander et al. 2008; these are compiled in Figure 1 in de Leeuw et al. 2016).

A Nortek Vectrino Profiling Velocimeter (ADV) measures flow velocity at the centerline of the flume at 8.31 m from the inlet. The ADV measures the flow in 2 mm bins between 3 mm and 73 mm above the bed, at a frequency of 10 Hz (Fig. 1). A Keyence laser topography scanner (LTS) on a moveable carriage measures centerline elevation from 8.03 m to 4.73 m. A Nortek Aquadopp Acoustic Doppler Profiler (ADP) mounted to the front of the carriage collects velocity measurements at 4 or 8 Hz, depending on the experiment, over the entire water column, excluding a blanking distance of 10 cm. The ADP data is collected in 2.5 and 3 cm vertical bins.

The primary variables are the presence or absence of a wave field, the inlet discharge of the current (either $1.25 \times 10^{-3}$ m$^3$/s or $0.6 \times 10^{-3}$ m$^3$/s), and the position of the inlet in the tank (Table 1). All of these are used to test the relative effects of a wave field on a current.

With the exception of the inlet location, flows 5–8 were the same as flows 1–4. Flow 9 has an additional, identical profiling ADV mounted in the center of the flume at 3.18 m in the center of the flume (Fig. 1), which was used to take velocity measurements from 7 cm above the water column, with the purpose of creating simultaneous time-series data for both upslope and downslope locations.

The Imposed Wave Field

The velocities of gravity waves decay exponentially with depth (Fig. 2).

\[ u(z) = ce^{kz} \]  

(1)

where $c$ is a near-surface wave orbital velocity (0.015 m/s for the RMS field), $z$ is depth beneath surface, and $k$ equals 2 times $\pi$ divided by the wavelength at the surface, 3 m. The surface waves have the same velocity at all positions across the tank but decay with depth. Rate of decay is different from upstream to downstream. Upstream (e.g., 5 and 5.5 m) there is only minimal decrease in velocity with depth, but much more in the more distal positions. Overall, the root-mean-squares of these velocity profiles correspond roughly with the predicted decay ($R^2 = 0.84$). Reflections at the upslope region of the tank, which diminished with increasing water depth, may have altered the oscillatory field but only to a minor degree. By producing a 0.1-m-deep current through waves of 0.01 m amplitude in 1 m of water, our experiments model flows that are approximately equivalent to a 10-m-deep current in a wave field with surface amplitudes of 1 m in 100-m-deep water, which are realistic conditions for storms on modern shelves.

RESULTS

Sediment Transport with and without Waves

Following each flow, we recorded centerline elevation scans and took sediment samples, recording sediment thickness and grain-size distributions (Figs. 3, 4). The primary difference between deposits from flows with and without waves is the spatial distribution of sediment. The combined flows produced a 7–8.5% downslope shift of the median of the mass of the deposit relative to the flows without waves. Changes in sediment discharge also affect the degree of downslope shift, e.g., combined flow 1 with a release rate of $1.25 \times 10^{-3}$ m$^3$/s, versus combined flow 3, with a release rate of $0.6 \times 10^{-3}$ m$^3$/s (Fig. 3). Because the wave fields were identical, the ratio of orbital wave velocities to unidirectional-current velocities was greater in the case of flow 3 than in flow 1, and as expected there was an increase in the downslope shift of sediment relative to flow 1 (7% shift) to flow 3 (8.5% shift).

The grain-size data (Fig. 4) indicate very little difference between deposits with or without waves. No meaningful change in grain size (settling velocity) yet thicker deposits farther out into the basin (Fig. 3).
suggest higher suspended-sediment concentrations being advected out into the basin, a signal of enhanced flow capacity for the currents with waves.

**Combined-Flow Velocity Data, Upslope and Downslope**

During one experiment (#9), we installed a second stationary ADV probe near the inlet (Fig. 1). To isolate the oscillatory velocities of the wave field from the turbulence of the combined flow, we extracted a wave signal using a fifth-order Butterworth bandpass filter with a frequency range of 0.60 Hz to 0.86 Hz (Figs. 5, 6). The oscillatory velocities of the resulting wave signal in the combined flow are greater than those measured in the wave field alone. A two-sample Kolmogorov-Smirnov (K-S) nonparametric test determines the degree to which two samples of data are likely to have been derived from the same distribution. A K-S test examines the difference between the samples, and applies a level, \( \alpha \), beyond which the samples cannot be distinguished as coming from separate populations. We applied this test to our data and found that it rejects the null hypothesis that the wave signal in the combined flow and that of the wave field alone are from the same distribution with a strict significance level of \( \alpha = 0.01 \) and a high degree of certainty, \( p << 0.01 \) (95% confidence for \( p \) values < 0.05).

The wave signal measured in the flow by the upslope ADV (Fig. 7) illustrates an even wider distribution of velocities, indicating that upslope oscillation could be a potential source for the deviation downslope, implying wave signal connectivity from upslope to downslope.

**DISCUSSION**

**Enhanced Sediment Transport**

The respective 7% and 8.5% downslope shifts in the volume of flow-deposition (Fig. 3) indicate that surface-wave modification enhances the overall transport capacity of turbidity currents. Although the downslope shift in deposition due the addition of waves was small, the wave-field velocities were an order of magnitude smaller than the current velocity. Flow 3 had a lesser sediment discharge rate than flow 1, giving flow 3 a lesser unidirectional current velocity. Given that both flows had identical wave fields, flow 3 had a greater ratio of wave to current velocity. The overall volume of deposit of flow 3 shifted 8.5% farther downslope than the same turbidity current without waves, whereas the overall volume of deposit of flow 1 shifted only 7% farther downstream than the same

**FIG. 3.—**The cumulative fraction deposited within the topographic scanner domain for flows 1–4. The upslope end of the flow deposits is located on the right at position, 4.3 m, and the downslope end of the flow, 8 m. In cases of both high and low discharge, wave input increases net downslope transport.

**FIG. 4.—**A violin plot of the probability density functions and \( D_{50} \) measurements for samples collected from the deposits of flows 5–8 (Table 1) at the same eight locations along the flow deposit. Location numbers indicated on the horizontal axis match locations given in Figure 1 along the flume bed. Upslope is to the left and downslope locations are to the right.
turbidity current without waves. While this result is not conclusive, it suggests that as the ratio of orbital wave velocities to unidirectional current velocities increases, the enhancement of downslope sediment transport would increase as well.

This finding is consistent with the proposal by Myrow and Southard (1996) that the addition of surface waves to a turbidity current could increase the turbulence in the flow without decreasing the density contrast at the boundary between the flow and the overlying water column, the effect being an overall increase in the flow capacity (cf. Velikanov 1954; Bagnold 1966). Baas et al. (2005) found that the bodies of turbidity currents are vertically grain-size and density stratified with more turbulent upper and lower zones, produced by shear along the bed and upper surface of the turbidity current, and a weakly turbulent zone of maximum flow velocity in the center. We propose that the repetitively added shear due to waves at the top of the turbidity current acts to increase turbulence, break down the stratification of the current, and in particular destroy the central low-turbulence zone. As a result, the turbidity current becomes fully mixed and more turbulent, which allow greater sediment suspension. Additionally, we propose that the surface waves prevent the largest-scale Kelvin-Helmholtz convection cells above the turbidity current from fully developing. By disrupting such macroturbulence, the surface waves effectively reduce the diffusivity of the turbidity current across its upper boundary and therefore reduce mixing of finer-grained sediment into the water column. One result of this would be that the currents maintain more sediment, which, combined with greater turbulence to suspend sediment, would better maintain flow velocity and increase flow capacity. Our findings of increased sediment transport are in agreement with observations of natural wave-supported fluid-mud flows (Ma et al. 2010) and modeling experiments (Kämpf and Myrow 2014, 2018).

**Downslope Propagation of Wave Effects**

Combined-flow data from experiment 9 (Fig. 7) show oscillatory velocities at the downslope location that are both greater than, and statistically distinct from, those of the wave field at the same location measured in the absence of a current (Fig. 2). We interpret these higher oscillatory velocities as the result of downslope propagation of wave momentum from upslope areas where maximum orbital velocities are higher. This is a new finding that clearly demonstrates a transmission of a wave signal from shallow water to deeper water, which is carried by the current itself, although the mechanism for this transmission is not apparent. We propose that this propagation results from surface waves that develop at the interface between the turbidity current and overlying ambient fluid (similar to a liquid pendulum), which are transported downslope and continue to resonate in the body of the current in positions where waves are weak or even absent.
Given that density-driven gravity currents occur in a wide variety of shallow environments where surface waves are present, this phenomenon of downslope-propagating wave motion is potentially a previously unrecognized and significant mechanism. In our experimental flows the maximum orbital velocities are nearly an order of magnitude smaller than the unidirectional current velocities. However, in modern environments with much more powerful waves, and potentially higher ratios of oscillatory to current velocity; this effect of downslope-propagating wave motion could be greater than that observed in our study. If so, this phenomenon could be recorded in ancient rocks, and have significant implications when identifying paleo-environmental conditions from deposits of wave-modified turbidity currents in the rock record. For instance, our finding suggests that it is possible to transmit flow oscillations to positions beyond wave base, and for any water depths above storm wave base, wave-related shear stresses could be greater than those associated with the ambient wave field in the absence of this effect.

CONCLUSIONS

An understanding of the modification of turbidity currents by surface waves and the resulting spatial evolution of such combined flows is paramount for studying tempestites and modeling sediment budgets across continental shelves. This study reveals several novel aspects of the dynamics of wave-modified turbidity currents, specifically, enhanced sediment transport and the downslope propagation of wave influence.

1. Comparisons of sediment deposition between turbidity currents with and without an imposed wave field (Fig. 3) indicate greater downslope sediment transport by the latter. Our study suggests that increases in the ratio of oscillatory velocities to unidirectional flow velocities results in an increase in this effect. In the case of our experiments, the orbital wave velocities were an order of magnitude smaller than unidirectional current velocities, and were thus in a minimal pulsating regime. We speculate that stronger pulsating flows and reversing flows could result in a profound increase in downstream sediment transport, which has important consequences for shallow-marine storm deposition.

2. A comparison of velocity data during flow 9 (Fig. 7) to the orbital velocities of the wave field in the absence of the flow (Fig. 2), reveals greater oscillatory velocities in the combined flow than could result from the influence of surface waves at that point alone. This increase in oscillatory velocities must result from a transfer of momentum from shallow depths where surface-wave influence is higher. This transfer may result from oscillations at the interface of the turbidity current and the overlying flow.

3. Our experiments show that wave-modified turbidity currents should be considered an important process for offshore sediment transport that can help explain discrepancies between processes and deposits in shallow-marine systems. Enhanced flow capacity and altered flow competency with surface-wave modification of turbidity currents needs systematic study across different ratios of oscillatory to unidirectional velocities and over varying slopes, grain sizes, sediment concentrations, and flow rates.

SUPPLEMENTAL MATERIAL

Two figures are available from the SEPM Data Archive: https://www.sepm.org/supplemental-materials.

ACKNOWLEDGMENTS

The authors would like to thank Junwoo Kim, James Buttles, and Eric Prokoki for their assistance in the laboratory and for fruitful discussions. We would like to acknowledge Bill McCaffrey, Matthieu Cartigny, an anonymous reviewer, and the journal editors and staff whose thoughtful, thorough suggestions improved the paper. Support was provided by the National Science Foundation (EAR-1225879) and the UF-CSM RioMAR Consortium.

REFERENCES


Received 22 October 2018; accepted 9 April 2019.