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Experimental tsunami deposits: Linking hydrodynamics to sediment entrainment, advection lengths and downstream fining

Joel P.L. Johnson [a],*, Katie Delbecq [b], Wonsuck Kim [a], David Mohrig [a]

[a] Department of Geological Sciences, The University of Texas at Austin, Austin, Texas 78712, USA
[b] Texas Commission on Environmental Quality, Austin, Texas 78753, USA

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ABSTRACT

A goal of paleotsunami research is to quantitatively reconstruct wave hydraulics from sediment deposits in order to better understand coastal hazards. Simple models have been proposed to predict wave heights and velocities, based largely on deposit grain size distributions (GSDs). Although seemingly consistent with some recent tsunamis, little independent data exist to test these equations. We conducted laboratory experiments to evaluate inversion assumptions and uncertainties. A computer-controlled lift gate instantaneously released ~6.5 m^3 of water into a 32 m flume with shallow ponded water, creating a hydraulic bore that transported sand from an upstream source dune. Differences in initial GSDs and ponded water depths influenced entrainment, transport, and deposition. While the source dune sand was fully suspendable based on size alone, experimental tsunamis produced deposits dominated by bed load sand transport in the upstream ~1/3 of the flume and suspension-dominated transport downstream. The suspension deposits exhibited downstream fining and thinning. At 95% confidence, a published advection-settling model predicts time-averaged flow depths to approximately a factor of two, and time-averaged downstream flow velocities to within a factor of 1.5. Finally, reasonable scaling is found between flume and field cases by comparing flow depths, inundation distances, Froude numbers, Rouse numbers and grain size trends in suspension-dominated tsunami deposits, justifying laboratory study of sediment transport and deposition by tsunamis.

1. Introduction

Following recent tsunamis including the December 2004 Indian Ocean event and the March 2011 Tohoku Japan event, scientists conducted rapid response surveys to establish flow depths and velocities, inundation extent, tsunami deposit thickness, GSDs, sedimentary structures, and geochemical and biological signals (e.g., Abe et al., 2012; Chague-Goff et al., 2012; Fujino et al., 2010; Jaffe et al., 2012; Moore et al., 2006; Nakamura et al., 2012; Richmond et al., 2012). Even with eyewitness videos and interviews, it is challenging to reconstruct flow properties with sufficient accuracy to validate hydrodynamic model predictions.

Because these extreme events occur rarely in particular locations, magnitudes and frequencies of prehistoric tsunamis and storm surges must be inferred from their sedimentary deposits in order to quantify local coastal risks. Measuring recurrence intervals relies on ^{14}C and other dating techniques. Reconstructing event magnitudes relies on hydrodynamic inverse models. Stratigraphic data, such as grain size distributions (GSDs) and deposit thicknesses, can be used in quantitative sediment transport relations to infer flow depths and velocities (Jaffe and Gelfenbuam, 2007; Moore et al., 2007; Woodruff et al., 2008). Because deposits inherently under-constrain variables associated with wave hydrodynamics, inversions require many simplifying assumptions. For example, the Tsunami Sedimentation Model (TsuSedMod) solves for flow velocity, based on the assumption that the amount and GSD of deposited sediment at a given location represents the maximum amount the flow could carry in suspension (Jaffe and Gelfenbuam, 2007). Soulsby et al. (2007) developed an inverse model for calculating water depth and inundation distance, based on the duration of time that topography is flooded during tsunami uprush and backflow, combined with the settling velocity of different size classes within the suspended grain size distribution. In the analysis below, we apply a related but even simpler advection-settling model described by Woodruff et al. (2008), based in part on Moore et al. (2007). The advection-settling model assumes that the time it takes for coarse grains to settle out of the flow while also being advected inland constrains flow depth and velocity.

These and other models have been applied to deposit GSDs from historical and modern tsunamis and hurricane storm surges (Brandon et al., 2014; Jaffe et al., 2011; Spiske et al., 2010; Wallace et al., 2014; Witter et al., 2012), but inversion uncertainties are poorly constrained. Deposit GSD is likely influenced by a range of interrelated factors: the magnitude of the tsunami, the source area GSD, sorting processes

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* Corresponding author.
E-mail address: joelj@jsg.utexas.edu (J.P.L. Johnson).

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during transport, and the coastal topography. When waves reach a coastline, water depths become shallow and wave amplitudes increase, leading to migrating hydraulic jumps (bores) in many cases. Tsunami wave heights, velocities and inundation distances are greatly influenced by characteristics of the coastal environment including near-shore topographic slope and surface roughness due to vegetation, human development, and ponded water where present (e.g. tidal marshes, lagoon complexes, mangrove swamps). Tsunamis entrain sediment from beaches, barrier dunes or other near-shore (proximal) accumulations, and transport it inland (distal). Near-shore GSDs vary widely in different coastal environments, and *pre-event* source GSDs for modern and ancient events are generally unknown.

Potential sources of inverse model uncertainty include a lack of understanding how source GSDs and entrainment processes influence deposit GSDs, and the extent to which grains transported as bed load rather than only in suspension influence model predictions. Because of model assumptions, both the advection-settling model and TsuSedMod should only apply to sediment deposited from suspension. However, even for suspendable sizes, some near-bed grains will always be transported as bedload. Following the terminology of García (2008), bed-material load transport (the transport of the grain sizes found on the bed) can be divided into sediment that is mixed into the interior of the flow by turbulence (suspended load), and grains that travel very close to the bed (bed load). Near-bed transport can occur by various processes including rolling, saltation, and granular shearing within layers multiple grains thick. Exchange of suspendable grains always occurs between suspension higher in the flow and the near-bed region in which bed load transport dominates. When the bed material is sand there need not be a grain size difference between bed load and suspended load, although both transport processes are capable of sorting grains.

Our laboratory study was motivated by a need for data quantifying relationships among source GSD, wave hydrodynamics, and resultant sediment deposits, in order to explore the following questions: How is the GSD of the sediment source area expressed in tsunami deposits? Do distinct grain size and thickness signatures develop from bed-load or suspended-load transport and deposition? How accurately can a simple hydrodynamic inverse model predict tsunami height and flow velocity based on deposit grain sizes? After addressing these questions, we compare the geometric scaling of experimental wave heights, inundation distances, and grain-size fining trends with data from modern tsunamis.

2. Experimental design

Six experiments were conducted in a 32 m long, 0.5 m wide, and 0.8 m high flume at The University of Texas at Austin (Fig. 1). The smoothly troweled concrete flume bed was flat with no overall slope. The flume head box has a unique computer-controlled lift gate that can impound ~6.5 m^3 of water pumped from a retaining pond. The gate was raised from the bed to above the flume in a fraction of a second to create a bore that simulates tsunami flow (Fig. 1).

The experiments were designed to test the sensitivity of deposit grain size and thickness to (a) the depth of ponded water within the flume before the bore was released, and (b) the initial GSD of the sediment supply (Tables 1 and 2; Fig. 2). Five of the six runs started with ponded water, mimicking an environment such as a lagoon with reasonable deposit preservation potential. Experiments 1 through 3 (Ts1_Dry_Fine, Ts2_10_Fine and Ts3_19_Fine) used initial ponded water depths of 0 cm (a dry flume bed), 10 cm and 19 cm respectively, and a single source GSD ("Fine"). Experiments 4 through 6 (Ts4_8_FinerBi, Ts5_8_MedUni and Ts6_8_MedBi) used three coarser source GSDs, and a constant initial ponded water depth of 8 cm (Tables 1 and 2; Fig. 2). Sediment was introduced just in front of the lift gate as a trapezoidal dune approximately 1.5 m long and 15 cm high, located 0.5–2 m in front of the lift gate (Fig. 1). 180 kg of dry sediment was used in each experiment. When the bore was released, flow over the sand dune rapidly entrained sediment as could occur for a tsunami engulfing a proximal coastal dune complex or barrier island.

Water velocities were measured at 100 Hz using two side-looking Nortek Vectrino ADVs, mounted 19.3 m downstream of the lift gate, along the flume centerline 9 cm and 15 cm above the flume bed. Measurements became accurate roughly 0.5 s after arrival of the aerated bore. Flow depths were measured using four ultrasonic transducers (MassaSonic M-5000) mounted 0.8 m above the bed that measured the distance down to water or concrete at 200 Hz. These were located in the head box and at 7.25, 17.70 and 19.10 m downstream of the lift gate. In experiment 3 the transducer data logger malfunctioned, and depth was instead estimated from video recorded through a Plexiglas sidewall window located 18.7 m downstream from the lift gate.

The record of flow depths for Ts1_Dry_Fine illustrates the main experimental steps and flow characteristics (Fig. 3). After filling the head box and lifting the gate, the pump was left on for 10 additional seconds (the approximate time it took most bores to reach the end of the flume). The pump was then turned off and inlet discharge dropped from ~0.27 m^3/s to zero. When the bore reached the end of the flume some water and sediment surged out past the 20 cm high perforated ramp at the downstream end, but most sediment remained within the flume and settled to the bed both during and immediately after flow. The perforated ramp reduced wave reflection when the bore reached the end of the flume, but a return wave nonetheless propagated upstream (Fig. 3). The passage of this wave greatly reduced local downstream flow velocities but caused minimal net transport of sediment upstream or downstream, based on observations and sidewall video. The return wave may crudely correspond to tsunami backflow in a natural setting.

Following tsunami deposition and slow subsequent water drainage, deposit thickness was measured manually at 25 cm intervals along the length of the flume. Sediment samples were collected at one-meter intervals and analyzed for grain-size distribution at 1/8th ϕ resolution using an image-based Retsch Camsizer. The sediment samples included the entire thickness of the deposit to avoid bias from possible vertical grain-size variations, and because mm-scale deposits could not be easily subsampled into meaningful horizontal layers.

3. Experimental results

3.1. Flow depths and velocities

The depth of initially ponded water influenced velocity, flow depth and *Fr* (Fig. 4). Froude number is defined as:

$$Fr = \frac{U}{\sqrt{gh}} \tag{1}$$

where U is depth-averaged downstream velocity, h is water depth, and g is gravitational acceleration. Velocities measured at 9 cm and 15 cm above the bed (i.e., roughly 0.4 h) were essentially the same (comparisons not shown) and are assumed in subsequent calculations to represent depth-averaged velocities. We highlight several observations. First, the fastest velocities and shallowest depths occurred over the dry concrete bed (Ts1_Dry_Fine), while the slowest velocities and deepest flow occurred for the deepest initial ponded depth (19 cm; Ts3_19_Fine). Second, flow velocities were highest just after the bore and then decreased gradually. For the five experiments with ponded water, flow depths were highest ~0.5–1 s after bore front arrival, and then decreased only slightly through time. Third, in all cases *Fr* decreased with time following passage of the bore. As *Fr* is most sensitive to velocity (Eq. (1)), it was highest for Ts1_Dry_Fine ($Fr \geq 1$) and lowest for Ts3_19_Fine ($Fr \approx 1$ at the bore, then decreasing to $Fr \approx 0.75$). For ponded depths of 8–10 cm (experiments 2, 4, 5 and 6), flow was initially