A two-layer granular landslide model for tsunami wave generation: Theory and computation

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Abstract

We develop and test a new two-layer model for granular landslide motion and tsunami wave generation. The landslide is described as a saturated granular flow, accounting for intergranular stresses governed by Coulomb friction. Tsunami wave generation is simulated by the three-dimensional non-hydrostatic wave model NHWAVE, which is capable of capturing wave dispersion efficiently using a small number of discretized vertical levels. Depth-averaged governing equations for the granular landslide are derived in a slope-oriented coordinate system, taking into account the dynamic interaction between the lower-layer granular landslide and upper-layer water motion. The model is tested against an analytical solution for granular dam-break flow and 2D and 3D laboratory experiments on impulsive wave generation by subaerial granular landslides. Model results illustrate a complex interplay between the granular landslide and tsunami waves, and they reasonably predict not only the tsunami wave generation but also the granular landslide

Preprint submitted to Ocean Modelling

July 29, 2015

motion from initiation to deposition.

Keywords:

landslide, granular flow, tsunami, non-hydrostatic model, NHWAVE

1. Introduction

Tsunamis can be generated by subaerial or submarine landslides in reservoirs, lakes, fjords, bays and oceans. Examples include tsunamis generated by subaerial landslides in Lituya Bay, Alaska in 1958 (Fritz et al., 2001, 2009; Weiss et al., 2009), Puerto Aysen, Chile in 2007 (Sepulveda and Serey, 2009; Naranjo et al., 2009), Tafjord, Norway in 1934 (Harbitz et al., 1993; Braathen et al., 2004), and by submarine landslides at Grand Banks, Newfoundland in 1929 (Fine et al., 2005), Papua New Guinea in 1998 (Synolakis et al., 2002; Tappin et al., 2001, 2002), Haiti in 2010 (Fritz et al., 2012) and Japan in 2011 (Tappin et al., 2014). The potential role played by large scale SMF's in tsunami climatology has been reviewed recently by Masson et al. (2006) and Harbitz et al. (2014). Compared to seismogenic tsunamis, landslide or submarine mass failure (SMF) tsunamis are normally characterized by relatively shorter wave lengths and stronger wave dispersion, and potentially may generate large wave amplitudes locally and high run-up along adjacent coastlines. Due to a complex interplay between the landslide and tsunami waves, accurate simulation of landslide motion as well as tsunami generation is a challenging task.

The development of models for landslide tsunami generation centers around

20 two main focuses: choice of a physical model for landslide rheology, and
 21 choice of a level of approximation of the flow field and pressure field in the
 22 hydrodynamic model used to simulate the generation and propagation of re-
 23 sulting waves. The developer must also decide on the details of interaction
 24 between kinematics and dynamics of the landslide material and overlying
 25 water column. The hydrodynamics of landslide-induced tsunamis has been
 26 extensively studied using numerical models based on different levels of sim-
 27 plification. Examples, in increasing order of completeness in the underlying
 28 theory, include shallow water equations (Harbitz, 1992; Jiang and LeBlond,
 29 1992, 1993; Fine et al., 2005), Boussinesq equations (Lynett and Liu, 2003;
 30 Watts et al., 2003; Fuhrman and Madsen, 2009; Zhou and Teng, 2010), 3D
 31 non-hydrostatic models (Ma et al., 2012, 2013), fully nonlinear potential flow
 32 theory (Grilli and Watts, 1999, 2005; Grilli et al., 2002) and Navier-Stokes
 33 equations (Heinrich, 1992; Quecedo et al., 2004; Mader, 2004; Liu et al.,
 34 2005; Yuk et al., 2006; Lovholt et al., 2008; Ataie-Ashtiani and Shobeyri,
 35 2008; Abadie et al., 2010; Montagna et al., 2011; Horrillo et al., 2013). Each
 36 of these approaches can provide useful information in suitable parameter
 37 ranges; however, full Navier-Stokes solvers are still numerically demanding.
 38 In the development below, we concentrate on further extensions to the non-
 39 hydrostatic modeling approach.

40 Most models of landslide or SMF tsunami generation consider the land-
 41 slides as rigid blocks with prescribed landslide shape and behavior. Landslide
 42 motion is specified based on laboratory measurements or on an equation of

43 motion based on the balance of forces acting on the sliding mass, includ-
44 ing weight, buoyancy, friction, hydrodynamic drag and inertia forces (Enet
45 and Grilli, 2007). This approach has been widely employed for estimating
46 tsunami hazard (Grilli et al., 2014; Tappin et al. 2014). As discussed by
47 Abadie et al. (2010, 2012), however, this methodology has severe limitations
48 in application to real cases, where landslides may be deformable and have
49 time-varying 3D geometry.

50 Another approach to simulating landslide-induced tsunamis is to consider
51 both the landslide and the water as two different fluids. This approach allows
52 the landslide to deform, and is capable of describing the two-way coupling
53 between the landslide and surrounding water. Tremendous effort has been
54 devoted to developing this type of model. For example, Jiang and Leblond
55 (1992, 1993) developed a two-layer model in which the lower-layer landslide
56 was treated as either a laminar incompressible viscous fluid or a Bingham
57 visco-plastic fluid, with the deformable underwater landslide and associated
58 tsunami waves dynamically coupled. This approach has been further devel-
59 oped by Fine et al. (2005) and Skvortsov and Bornhold (2007). Abadie et al.
60 (2012) employed a 3D multi-fluid Navier-Stokes model THETIS to simulate
61 tsunami waves generated by the potential collapse of the west flank of the
62 Cumbre Vieja Volcano (CVV), Canary Islands, Spain. The landslide and
63 water were considered as two immiscible fluids with different densities. The
64 free surface as well as the landslide-water interface were captured using a
65 volume of fluid (VOF) algorithm. A similar approach is employed by Hor-

66 rillo et al. (2013). Assier-Rzadkiewicz et al. (1997) modeled the underwater
 67 landslide as sediment-water mixture, with rheology varying from linear fluid
 68 viscosity at low sediment concentration to Bingham visco-plastic rheology at
 69 high concentration. The model was applied to simulate a laboratory land-
 70 slide and could reproduce the water waves generated by the landslide with
 71 reasonable accuracy. Heinrich et al. (1998) implemented the same approach
 72 in a 3D Navier-Stokes solver, and applied the model to study water waves
 73 generated by a potential debris avalanche in Montserrat, Lesser Antilles.
 74 This approach was also adopted and implemented by Ma et al. (2013) in the
 75 non-hydrostatic wave model NHWAVE, without inclusion of the Bingham
 76 visco-plastic behavior at high concentration. Their model was not able to
 77 capture landslide deposition.

78 The two-fluid models described above can be reasonably successful in
 79 predicting tsunami wave generation. However, they often fail to correctly
 80 simulate landslide motion from initiation to deposition. Underwater land-
 81 slides are gravity-driven flows of dense grain-fluid mixture. Fluid or visco-
 82 plastic continuum rheologies typically are not sufficient to explain details of
 83 landslide behavior, from initiation of motion from a quasi-equilibrium initial
 84 static state, through dynamics of the evolving slide, to final arrest of mo-
 85 tion and landslide deposition (Iverson and George, 2014). It is necessary to
 86 consider the intergranular stresses and pore fluid pressure in the landslide
 87 model. Initial steps towards development of granular flow-based models for
 88 landslide behavior have usually been based on depth-integrated models pi-

89 oneered by Savage and Hutter (1989), Iverson (1997) and others. These
90 models were initially developed for application to shallow subaerial debris
91 flows. Pioneering work to implement these formulations as models for sub-
92 marine landslides were carried out by Kelfoun et al. (2010) and Giachetti et
93 al. (2011), among others. In their model, the landslide was simulated by a
94 depth-averaged granular flow model, in which the intergranular stresses were
95 modeled by Coulomb friction. Tsunami wave generation was simulated using
96 a shallow-water equation model based on the assumption that the landslide-
97 induced tsunamis are long waves, as in the previous two-fluid models of Jiang
98 and LeBlond (1992, 1993), Fine et al. (2005) and Skvortsov and Bornhold
99 (2007). The model was used to examine the consistency of run-up predic-
100 tions with patterns of sediment deposition which are hypothesized to be the
101 result of tsunami inundation. Their model, however, contains several critical
102 limitations. The Coulomb frictional retarding stress was assumed to be con-
103 stant over the whole domain. Wave dispersion was not captured due to the
104 shallow-water assumption.

105 In this paper, we establish a numerical model for the generation and
106 propagation of tsunami waves by granular landslides. A discrete two-layer
107 landslide-induced tsunami generation model is developed and validated us-
108 ing analytical solutions and laboratory measurements. The landslide is de-
109 scribed as a granular flow accounting for intergranular stresses governed by
110 Coulomb friction, following the theoretical framework described by Savage
111 and Hutter (1989) and Iverson (1997). Tsunami wave generation is simu-

lated using the 3D non-hydrostatic wave model NHWAVE, which is fully nonlinear and is capable of efficiently capturing wave dispersion using 3-5 discretized vertical levels and simulating wave breaking and associated wave energy dissipation by a shock-capturing scheme. The governing equations for the granular landslide and tsunami waves are coupled dynamically and solved using a Godunov-type finite volume TVD scheme.

The remainder of the paper is organized as follows. Section 2 presents the theoretical basis for the two-layer granular landslide and tsunami wave model. The formulation for the lower-layer granular landslide is derived. The interactions between the landslide and surrounding water as well as the numerical schemes employed to solve the granular flow equations are also discussed. The granular landslide model is first validated in section 3 using an analytical solution for dam-break flow developed by Mangeney et al. (2000). The model is then applied to study waves generated by a 2D granular landslide in section 4 and a 3D granular landslide in section 5. Conclusions and avenues of future model improvement are presented in section 6.

2. Two-layer Granular Landslide and Tsunami Model

In this section, we derive the formulations for the two-layer granular landslide and tsunami model. In this model, the landslide motion and tsunami wave generation are simulated by separate model components. The lower-layer landslide movement is simulated by a granular flow model, while the upper-layer tsunami wave motion is simulated by the three-dimensional Non-

134 Hydrostatic WAVE model NHWAVE (Ma et al., 2012). The lower layer
 135 landslide and upper layer water interact at each time step, maintaining a
 136 fully-coupled kinematic and dynamic connection between the layers.

137 *2.1. Lower-Layer Granular Landslide*

138 In this study, we simulate the landslide as a saturated granular debris
 139 flow. The details of the derivation follow from Iverson and Denlinger (2001)
 140 unless otherwise noted. Following Iverson (1997) and Iverson and Denlinger
 141 (2001), we adopt a slope-oriented coordinate system as shown in figure 1,
 142 with x' oriented down-slope, y' along slope and z' oriented upwards and
 143 perpendicular to the slope. Mass and momentum conservation equations
 144 from continuum mixture theory are given by

$$\nabla' \cdot \mathbf{v} = 0 \quad (1)$$

145

$$\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla' \mathbf{v} \right) = -\nabla' \cdot \mathbf{T} + \rho \mathbf{g} \quad (2)$$

146 Here, $\rho = \rho_s \gamma_s + \rho_f \gamma_f$ is mixture density, ρ_s and ρ_f are the densities of
 147 solid and fluid, respectively, and γ_s and γ_f are volume fractions of solid
 148 and fluid, respectively. $\mathbf{v} = (v_{x'}, v_{y'}, v_{z'})$ is the mixture velocity, given by
 149 $\mathbf{v} = (\rho_s \gamma_s \mathbf{v}_s + \rho_f \gamma_f \mathbf{v}_f) / \rho$, with $\mathbf{v}_s$ and $\mathbf{v}_f$ being the velocities for solid and
 150 fluid phases. $\mathbf{T} = \mathbf{T}_s + \mathbf{T}_f$ is the total stress tensor for the mixture and
 151 consists of contributions from the fluid and solid phases, with $\mathbf{T}$ defined as
 152 positive in compression. $\mathbf{g} = (g_{x'}, g_{y'}, g_{z'})$ is the gravitational acceleration

153 vector.

154 Further simplifications of the governing equations can be achieved by
 155 assuming the characteristic horizontal length scale l of the landslide is much
 156 greater than the characteristic vertical length scale h (i.e. $h/l \ll 1$), which
 157 is usually true in landslides. Based on scaling analysis, the acceleration and
 158 horizontal diffusion terms in the vertical momentum equation are at least an
 159 order of magnitude smaller than the gravitational acceleration and vertical
 160 diffusion terms, thus the equation can be reduced to

$$\rho g_{z'} = -\frac{\partial T_{z'z'}^s}{\partial z'} - \frac{\partial T_{z'z'}^f}{\partial z'} = -\frac{\partial T_{z'z'}^s}{\partial z'} - \frac{\partial P^f}{\partial z'} \quad (3)$$

161 where $T_{z'z'}^s$ and $T_{z'z'}^f$ are normal stresses in the solid and fluid phase, respec-
 162 tively. P^f is the pressure in the fluid phase. At the landslide-water interface,
 163 we have $P^f|_{z'=h_a} = P_h^f$, with $h_a(x', y', t)$ being the local time-varying thick-
 164 ness of the landslide. The solid stress should vanish at the landslide-water
 165 interface, so that $T_{z'z'}^s|_{z'=h_a} = 0$.

166 Integrating equation (3) from 0 to h_a and using the boundary condition
 167 for $T_{z'z'}^s$ at the interface $z' = h_a$, we get

$$T_{z'z'b}^s = T_{z'z'}^s(x', y', 0) = \rho g_{z'} h_a + P_h^f - P_b^f \quad (4)$$

168 where subscript b refers to the bed. We assume that fluid pressure inside the
 169 landslide varies linearly with depth. Thus, the pore pressure at the bed is

170 given by

$$P_b^f = P_h^f + \lambda \rho g_{z'} h_a \quad (5)$$

171 where λ is a parameter to be determined. In granular flow, the pore pres-
 172 sure varies temporally and spatially, and has to be obtained by solving an
 173 additional equation. Here, we simply assume λ is a constant which will be
 174 calibrated using laboratory measurements.

175 Substituting equation (5) into (4), we obtain the z' direction normal stress
 176 $T_{z'z'}^s$ at the bed,

$$T_{z'z'}^s = (1 - \lambda) \rho g_{z'} h_a \quad (6)$$

177 and the depth-averaged z' direction normal stress,

$$\bar{T}_{z'z'}^s = \frac{1}{2} (1 - \lambda) \rho g_{z'} h_a \quad (7)$$

178 A depth-integrated model for landslide motion is next obtained by in-
 179 tegrating equations (1) and (2) over the landslide thickness. The depth-
 180 averaged mass and momentum equations in the x' and y' directions are given
 181 by

$$\frac{\partial h_a}{\partial t} + \frac{\partial(h_a u_a)}{\partial x'} + \frac{\partial(h_a v_a)}{\partial y'} = 0 \quad (8)$$

$$\begin{aligned} 182 \quad \rho \left[\frac{\partial(h_a u_a)}{\partial t} + \frac{\partial(h_a u_a^2)}{\partial x'} + \frac{\partial(h_a u_a v_a)}{\partial y'} \right] = \rho g_{x'} h_a - \int_0^{h_a} \left[\frac{\partial T_{x'x'}^s}{\partial x'} + \frac{\partial T_{x'x'}^f}{\partial x'} + \right. \\ \left. \frac{\partial T_{y'x'}^s}{\partial y'} + \frac{\partial T_{y'x'}^f}{\partial y'} + \frac{\partial T_{z'x'}^s}{\partial z'} + \frac{\partial T_{z'x'}^f}{\partial z'} \right] dz' \end{aligned} \quad (9)$$

183

$$\rho \left[\frac{\partial(h_a v_a)}{\partial t} + \frac{\partial(h_a u_a v_a)}{\partial x'} + \frac{\partial(h_a v_a^2)}{\partial y'} \right] = \rho g_{y'} h_a - \int_0^{h_a} \left[\frac{\partial T_{x'y'}^s}{\partial x'} + \frac{\partial T_{x'y'}^f}{\partial x'} + \frac{\partial T_{y'y'}^s}{\partial y'} + \frac{\partial T_{y'y'}^f}{\partial y'} + \frac{\partial T_{z'y'}^s}{\partial z'} + \frac{\partial T_{z'y'}^f}{\partial z'} \right] dz' \quad (10)$$

184 where u_a and v_a are depth-averaged velocities in x' and y' directions, respec-
185 tively.

186 2.1.1. Evaluation of Solid Stresses

187 The depth-averaged solid stresses in the x' direction momentum equation
188 may be approximated by

$$- \int_0^{h_a} \left[\frac{\partial T_{x'x'}^s}{\partial x'} + \frac{\partial T_{y'x'}^s}{\partial y'} + \frac{\partial T_{z'x'}^s}{\partial z'} \right] dz' = - \left[\frac{\partial(h_a \bar{T}_{x'x'}^s)}{\partial x'} + \frac{\partial(h_a \bar{T}_{y'x'}^s)}{\partial y'} \right] + T_{z'x'b}^s \quad (11)$$

189 Following Savage and Hutter (1989), we can relate the depth-averaged normal
190 stresses $\bar{T}_{x'x'}^s$ and $\bar{T}_{y'y'}^s$ to the depth-averaged z' direction normal stress $\bar{T}_{z'z'}^s$
191 by using a lateral stress coefficient $k_{act/pass}$ derived from Coulomb theory

$$\bar{T}_{x'x'}^s = \bar{T}_{y'y'}^s = k_{act/pass} \bar{T}_{z'z'}^s \quad (12)$$

192 where $k_{act/pass}$ is also called the Earth pressure coefficient. If the internal be-
193 havior of the granular material is frictional, $k_{act/pass}$ can be given by (Iverson
194 1997; Savage and Hutter, 1989)

$$k_{act/pass} = 2 \frac{1 \mp [1 - \cos^2 \phi_{int} (1 + \tan^2 \phi_{bed})]^{1/2}}{\cos^2 \phi_{int}} - 1 \quad (13)$$

195 where ϕ_{int} is the internal friction angle of the granular solid and ϕ_{bed} is the
 196 friction angle of grains contacting the bed. The sign $\mp$ is negative (and
 197 $k_{act/pass}$ active) for diverging flow (indicated by $\frac{\partial u_a}{\partial x'} + \frac{\partial v_a}{\partial y'} > 0$) and positive
 198 (and $k_{act/pass}$ passive) for converging flow (indicated by $\frac{\partial u_a}{\partial x'} + \frac{\partial v_a}{\partial y'} < 0$). This
 199 expression is valid if $\phi_{bed} < \phi_{int}$. If, on the other hand, $\phi_{bed} > \phi_{int}$, $k_{act/pass}$
 200 is given by

$$k_{act/pass} = \frac{1 + \sin^2 \phi_{int}}{1 - \sin^2 \phi_{int}} \quad (14)$$

201 The transverse solid shear stresses $\bar{T}_{y'x'}^s$ and $\bar{T}_{x'y'}^s$ are related to the normal
 202 stresses and can be written as

$$\bar{T}_{y'x'}^s = \bar{T}_{x'y'}^s = -\text{sgn}(S_{x'y'}) \left[\frac{1}{2} k_{act/pass} (1 - \lambda) \rho g_{z'} h_a \right] \sin \phi_{int} \quad (15)$$

203 where $S_{x'y'}$ is the rate of strain in the $x' - y'$ plane. The basal shear stress
 204 $T_{z'x'b}^s$ is obtained by using the well-known Coulomb-type friction law

$$T_{z'x'b}^s = -T_{z'z'b}^s \tan \phi_{bed} = -[(1 - \lambda) \rho g_{z'} h_a] \tan \phi_{bed} \frac{u_a}{\sqrt{u_a^2 + v_a^2}} \quad (16)$$

205 with a corresponding expression for $T_{z'y'b}^s$.

206 *2.1.2. Evaluation of Fluid Stresses*

207 The depth-averaged fluid stresses in the x' direction momentum equation
208 are formulated as

$$-\int_0^{h_a} \left[\frac{\partial T_{x'x'}^f}{\partial x'} + \frac{\partial T_{y'y'}^f}{\partial y'} + \frac{\partial T_{z'x'}^f}{\partial z'} \right] dz' = -\int_0^{h_a} \left[\frac{\partial P^f}{\partial x'} - \gamma_f \mu \left(\frac{\partial^2 v_{x'}}{\partial x'^2} + \frac{\partial^2 v_{x'}}{\partial y'^2} + \frac{\partial^2 v_{x'}}{\partial z'^2} \right) \right] dz' \quad (17)$$

209 where γ_f is the fluid volume fraction in the landslide and μ is Newtonian
210 dynamic viscosity. Using Leibniz' rule, we get

$$-\int_0^{h_a} \frac{\partial P^f}{\partial x'} dz' = -\left[\frac{\partial}{\partial x'} \left(\int_0^{h_a} P^f dz' \right) - \frac{\partial h_a}{\partial x'} P_h^f \right] = -\frac{\partial (h_a \bar{P}^f)}{\partial x'} + \frac{\partial h_a}{\partial x'} P_h^f \quad (18)$$

211 From equation (5), we obtain the depth-averaged fluid pressure as

$$\bar{P}^f = P_h^f + \frac{1}{2} \lambda \rho g_{z'} h_a \quad (19)$$

212 Plugging equation (19) into equation (18) gives

$$-\int_0^{h_a} \frac{\partial P^f}{\partial x'} dz' = -h_a \frac{\partial P_h^f}{\partial x'} - \frac{\partial}{\partial x'} \left(\frac{1}{2} \lambda \rho g_{z'} h_a^2 \right) \quad (20)$$

213 We further assume that the fluid shear stresses in equation 17 are negligi-
214 ble, considering that they are much smaller than the Coulomb friction. The
215 slope-parallel diffusion terms are also negligible, due to the relatively larger
216 horizontal length scale in the landslide. The depth averaged solid and fluid
217 stresses in the y' direction momentum equation can be obtained following

218 the same procedure as above.

219 2.1.3. Conservative Form of the Granular Flow Equations

220 The granular flow equations are solved by using a Harten-Lax-vanLeer
 221 (HLL) approximate Riemann solver. In order to apply the HLL shock-
 222 capturing scheme, we have write the governing equations in a conservative
 223 form given by

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x'} + \frac{\partial \mathbf{G}}{\partial y'} = \mathbf{S} \quad (21)$$

224 in which $\mathbf{U} = (h_a, h_a u_a, h_a v_a)^T$. The fluxes are

$$\mathbf{F} = \begin{pmatrix} h_a u_a \\ h_a u_a^2 + \frac{1}{2}[(1 - \lambda)k_{act/pass} + \lambda]g_{z'}h_a^2 \\ h_a u_a v_a \end{pmatrix} \quad (22)$$

225

$$\mathbf{G} = \begin{pmatrix} h_a v_a \\ h_a u_a v_a \\ h_a v_a^2 + \frac{1}{2}[(1 - \lambda)k_{act/pass} + \lambda]g_{z'}h_a^2 \end{pmatrix} \quad (23)$$

226 The source term is

$$\mathbf{S} = \begin{pmatrix} 0 \\ S_{x'} \\ S_{y'} \end{pmatrix} \quad (24)$$

227 where

$$\begin{aligned}
S_{x'} = & g_{x'} h_a - \frac{h_a}{\rho} \frac{\partial P_h^f}{\partial x'} - (1 - \lambda) g_{z'} h_a \tan \phi_{bed} \frac{u_a}{\sqrt{u_a^2 + v_a^2}} \\
& - \operatorname{sgn}(S_{x'y'}) h_a k_{act/pass} \frac{\partial}{\partial y'} [g_{z'} h_a (1 - \lambda)] \sin \phi_{int}
\end{aligned} \tag{25}$$

228

$$\begin{aligned}
S_{y'} = & g_{y'} h_a - \frac{h_a}{\rho} \frac{\partial P_h^f}{\partial y'} - (1 - \lambda) g_{z'} h_a \tan \phi_{bed} \frac{v_a}{\sqrt{u_a^2 + v_a^2}} \\
& - \operatorname{sgn}(S_{y'x'}) h_a k_{act/pass} \frac{\partial}{\partial x} [g_{z'} h_a (1 - \lambda)] \sin \phi_{int}
\end{aligned} \tag{26}$$

229 where λ is a parameter to be determined.

230 2.2. Tsunami Wave Generation

Tsunami wave generation and propagation is simulated using the 3D Non-Hydrostatic WAVE model NHWAVE (Ma et al., 2012). NHWAVE solves the incompressible Navier-Stokes equations in well-balanced conservative form, formulated in time-dependent surface and terrain-following σ coordinates defined by

$$t = t^* \quad x = x^* \quad y = y^* \quad \sigma = \frac{z^* + h}{D}$$

231 where (x^*, y^*, z^*) is the traditional Cartesian coordinate system with z^* ori-
232 ented upwards against gravity and the still water surface lying in the (x^*, y^*)
233 plane. Total water depth is given by $D(x, y, t) = h(x, y, t) + \eta(x, y, t)$, where
234 h is the water depth from the still water level to the landslide surface, which
235 is temporally varying during landslide motion, and η is water surface eleva-
236 tion relative to still water. In keeping with the σ coordinate approach, h and

237 η are assumed to remain single-valued functions of (x, y) at all times.

238 Following Ma et al. (2012), well-balanced mass and momentum conser-
 239 vation equations in σ coordinates are given by

$$\frac{\partial D}{\partial t} + \frac{\partial Du}{\partial x} + \frac{\partial Dv}{\partial y} + \frac{\partial \omega}{\partial \sigma} = 0 \quad (27)$$

240

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} + \frac{\partial \mathbf{G}}{\partial y} + \frac{\partial \mathbf{H}}{\partial \sigma} = \mathbf{S}_h + \mathbf{S}_p \quad (28)$$

241 where $\mathbf{U} = (Du, Dv, D\omega)^T$. (u, v, w) are velocity components in (x, y, z)
 242 directions. ω is the velocity normal to a level σ surface. The fluxes in the
 243 momentum equations are

$$\mathbf{F} = \begin{pmatrix} Duu + \frac{1}{2}g\eta^2 + gh\eta \\ Duv \\ Duw \end{pmatrix} \quad \mathbf{G} = \begin{pmatrix} Duv \\ Dvv + \frac{1}{2}g\eta^2 + gh\eta \\ Dvw \end{pmatrix} \quad \mathbf{H} = \begin{pmatrix} u\omega \\ v\omega \\ w\omega \end{pmatrix}$$

244 The source terms on the right hand side of equation (28) are contributions
 245 from hydrostatic pressure and dynamic pressure, respectively. The turbulent
 246 diffusion terms have been ignored. These terms can be formulated as

$$\mathbf{S}_h = \begin{pmatrix} g\eta \frac{\partial h}{\partial x} \\ g\eta \frac{\partial h}{\partial y} \\ 0 \end{pmatrix} \quad \mathbf{S}_p = \begin{pmatrix} -\frac{D}{\rho f} \left(\frac{\partial p}{\partial x} + \frac{\partial p}{\partial \sigma} \frac{\partial \sigma}{\partial x^*} \right) \\ -\frac{D}{\rho f} \left(\frac{\partial p}{\partial y} + \frac{\partial p}{\partial \sigma} \frac{\partial \sigma}{\partial y^*} \right) \\ -\frac{1}{\rho f} \frac{\partial p}{\partial \sigma} \end{pmatrix}$$

247 where p is the non-hydrostatic component of the pressure field. Further

248 details of the model may be found in Ma et al. (2012).

249 *2.3. Interaction Between Landslide and Water*

250 The governing equations describing the lower-layer landslide and upper-
251 layer water motion are derived in two different coordinate systems. The
252 granular landslide model is built in a slope-oriented coordinate system with
253 z' perpendicular to the bottom, while the upper-layer water motion is de-
254 scribed in a regular Cartesian coordinate system with z vertical. To calculate
255 the upper-layer thickness, it is necessary to find the landslide height in the
256 vertical z direction, indicated by h_s in figure 1. With the given bottom slope
257 α , h_s can be estimated as $0.5(h_{aA} + h_{aB})/\cos\alpha$, where h_{aA} and h_{aB} are the
258 predicted landslide heights in the z' direction at two neighboring grid points
259 as demonstrated in figure 1. In addition, the streamwise gradients in two
260 coordinate systems are related as $\partial/\partial x' = \cos\alpha\partial/\partial x$. The orientation of
261 bed slope in y direction can be treated in the same manner.

262 Interaction between the landslide and water are accounted for by impos-
263 ing continuity of normal stress (pressure P_h^f) at the interface, and by using
264 the kinematic interfacial constraints for each layer. The shear stresses at the
265 landslide-water interface are negligible for laboratory scale granular land-
266 slides. More studies on their effects on huge landslide motion have to be fur-
267 ther studied. Mixing at the landslide-water interface has also been ignored.
268 In test simulations, we find that the pressure P_h^f , which includes both the
269 hydrostatic and non-hydrostatic components, dominates the interactions be-

270 tween two-layer flows, and that contributions from lateral interfacial stresses
 271 are negligible. The pressure at the interface is given by

$$P_h^f = \rho^f g(h + \eta) + p(-h) \quad (29)$$

272 where $p(-h)$ represents the nonhydrostatic component of fluid pressure at
 273 the slide surface.

274 The boundary conditions at the landslide-water interface for the upper-
 275 layer equations have to take into account the temporal variation of water
 276 depth. Hence, the boundary condition for the vertical velocity is given by

$$w|_{z=-h} = -\frac{\partial h}{\partial t} - u\frac{\partial h}{\partial x} - v\frac{\partial h}{\partial y} \quad (30)$$

277 where the horizontal gradients of water depth h are also temporally varying
 278 and have to be updated at each time step. The boundary condition for
 279 dynamic pressure is derived from the momentum equation for w (Ma et al.,
 280 2012). The linearized boundary condition for dynamic pressure is written as

$$\frac{\partial p}{\partial \sigma}|_{\sigma=0} = \rho(h + \eta)\frac{\partial^2 h}{\partial t^2} \quad (31)$$

281 *2.4. Numerical Scheme*

282 The equations for the lower-layer landslide (eq. (23)) and upper-layer
 283 water motion (eqs. (30) and (31)) are solved using the same numerical
 284 framework for spatial differencing and time-stepping. For the upper-layer

285 water motion, the details of the numerical scheme can be found in Ma et al.
 286 (2012) and are not repeated here. For the lower-layer granular landslide, the
 287 governing equation (23) is also discretized by a second-order finite volume
 288 method. The HLL approximate Riemann solver is used to estimate the fluxes
 289 at cell faces. In order to apply the Riemann method, we need to compute
 290 the speeds and directions of elementary waves that determine fluxes of the
 291 conserved variables $\mathbf{U}$ by propagating information about $\mathbf{U}$ in space and time
 292 (Toro, 1997). To characterize these mathematical waves, we rewrite equation
 293 (23) using the chain rule as (Denlinger and Iverson, 2001)

$$\frac{\partial \mathbf{U}}{\partial t} + \mathbf{A} \cdot \frac{\partial \mathbf{U}}{\partial x'} + \mathbf{B} \cdot \frac{\partial \mathbf{U}}{\partial y'} = \mathbf{S} \quad (32)$$

294 where

$$\mathbf{A} = \frac{\partial \mathbf{F}}{\partial \mathbf{U}} = \begin{bmatrix} 0 & 1 & 0 \\ c^2 - u_a^2 & 2u_a & 0 \\ -u_a v_a & v_a & u_a \end{bmatrix} \quad (33)$$

295 and

$$\mathbf{B} = \frac{\partial \mathbf{G}}{\partial \mathbf{U}} = \begin{bmatrix} 0 & 0 & 1 \\ -u_a v_a & v_a & u_a \\ c^2 - v_a^2 & 0 & 2v_a \end{bmatrix} \quad (34)$$

296 and c is the speed of ideal gravity waves given by

$$c = \sqrt{[(1 - \lambda)k_{act/pass} + \lambda]g_z h_a} \quad (35)$$

297 The gravity wave speed c in the granular flow equations is fundamentally
 298 different from that in the standard shallow-water equations. It considers the
 299 effects of Coulomb friction and denotes the maximum rate of information
 300 propagation due to lateral stress transfer in the grain-fluid mixture. With
 301 the calculated gravity wave speed c , the flux at the cell interface is determined
 302 by

$$\mathbf{F}(\mathbf{U}^L, \mathbf{U}^R) = \begin{cases} \mathbf{F}(\mathbf{U}^L) & \text{if } s_L \geq 0 \\ \mathbf{F}^*(\mathbf{U}^L, \mathbf{U}^R) & \text{if } s_L < 0 < s_R \\ \mathbf{F}(\mathbf{U}^R) & \text{if } s_R \leq 0 \end{cases} \quad (36)$$

303 where

$$\mathbf{F}^*(\mathbf{U}^L, \mathbf{U}^R) = \frac{s_R \mathbf{F}(\mathbf{U}^L) - s_L \mathbf{F}(\mathbf{U}^R) + s_L s_R (\mathbf{U}^R - \mathbf{U}^L)}{s_R - s_L} \quad (37)$$

304 with wave speed s_L and s_R defined by

$$s_L = \min(u_L - c_L, u_s - c_s) \quad (38)$$

$$s_R = \max(u_R + c_R, u_s + c_s) \quad (39)$$

305 where u_s and c_s are estimated by

$$u_s = \frac{1}{2}(u_L + u_R) + c_L - c_R \quad (40)$$

$$c_s = \frac{c_L + c_R}{2} + \frac{u_L - u_R}{4} \quad (41)$$

306 where $\mathbf{U}^L$ and $\mathbf{U}^R$ are the left and right values of $\mathbf{U}$ at the cell face.

307 **3. Verification of the Granular Flow Model using an Analytical** 308 **Solution**

309 We first verify the granular flow model using the analytical solution of
310 Mangeney et al. (2000) for a frictional dam break debris flow onto a numerical
311 dry surface. The analytical solution for the fluid height is given by

$$h_a = \frac{1}{9g \cos \alpha} \left(\frac{x}{t} - 2c_0 + \frac{1}{2}mt \right)^2 \quad (42)$$

312 where g is gravitational acceleration, α is the angle of the bed slope, t is
313 time, x is the coordinate with $x = 0$ located at the front of the dam at t
314 $= 0$ s, $c_0 = \sqrt{gh_0 \cos \alpha}$ and $m = -g \sin \alpha + g \cos \alpha \tan \phi_{bed}$. This formula is
315 valid in the region defined by $x_L < x < x_R$, where $x_L = -c_0 t - \frac{1}{2}mt^2$ and
316 $x_R = 2c_0 t - \frac{1}{2}mt^2$.

317 To be consistent with the analytical solution, we set the pressure at the
318 landslide-water interface $P_h^f = 0$ Pa. The parameter λ is set to be 0, con-
319 sistent with the assumption of a dry granular flow. The Earth pressure
320 coefficient $k_{act/pass}$ is 1.0. The fluid stress given in equation (22) is also ne-
321 glected. The computational domain is 2 km long, with $x < 1$ km occupied
322 by the granular material. The initial height of the dam is $h_0=20$ m. Figure 2
323 shows the comparisons of numerical results and analytical solutions for three
324 scenarios. The first scenario represents the dam break debris on a plane bed.
325 The landslide material has no bed friction. The second and third scenarios
326 are the dam breaks on a slope bed with the slope angle of 20° . The bed

friction angles of the granular material are 0° and 20° , respectively. As we can see, the simulations match very well with the analytical solutions for all three scenarios. The mean relative errors for these three simulations in the dam-break front regions are 1.53%, 3.20% and 2.39%, respectively, where the relative error is defined as $|x_c - x_a|/x_a \times 100\%$ with x_c being the computed value and x_a being the analytical solution. These results indicate that the model can well capture the granular flow motion.

4. Impulsive Wave Generation by a Granular Landslide in a Two-dimensional Wave Flume

Impulsive wave generation by granular landslides have been extensively studied in laboratory experiments (for example, Fritz et al., 2004; Heller and Hager, 2010; Mohammed and Fritz, 2012). In this section, we employ the laboratory measurements of Heller and Hager (2010) to validate our two-layer granular landslide model. The experiments were conducted in a prismatic water wave channel of 11 m length, 0.5 m width and 1.0 m depth. The granular landslide material was contained in a slide box which was accelerated by a pneumatic landslide generator down a 3-m-long hill slope ramp. As the slide box reached the maximum velocity, its front flap opened. The landslide left the box, accelerated further down the hill slope ramp due to gravitational forcing, and entered the water column, generating impulse waves in the wave channel (Heller and Hager, 2010). In the selected test case, the slide box has a size of 0.6 m length and 0.118 m height as demonstrated in figure 3.

349 The granular landslide material has a grain diameter $d_g = 4$ mm, an internal
 350 friction angle $\phi_{int} = 34^\circ$, a grain density $\rho_g = 2,745$ kg/m³, and a bulk slide
 351 density $\rho_s = \rho_g(1 - n) = 1,678$ kg/m³ with a bulk slide porosity $n = 0.389$.
 352 The dynamic bed friction angle is $\phi_{bed} = 24^\circ$. The landslide had an initial
 353 velocity of 3.25 m/s when it was released. The properties of the landslide are
 354 listed in Table 1. The still water depth is 0.3 m. The landslide profiles were
 355 recorded by two laser distance sensors (LDS). Their locations are shown in
 356 figure 3. The impulse waves were measured at seven wave gauges which are
 357 also displayed in figure 3.

358 2D simulations are conducted using only one grid cell in the transverse
 359 direction of the wave channel. The length of the computational domain is the
 360 same as that of the channel in the experiment, which is 11 m. The horizontal
 361 extent of the domain is discretized by 550 grid cells with grid size of 0.02 m.
 362 Three vertical levels are used to simulate the upper-layer water motion. For
 363 the granular landslide, we choose the same landslide material parameters as
 364 those in the experiment. The Earth pressure coefficient $k_{act/pass}$ is calculated
 365 by equation (13). For portions of slides located above the water line and
 366 exposed to the atmosphere, the fluid pressure at the interface $P_h^f = 0$. We
 367 assume that the granular material is dry before water entry, and thus the
 368 parameter λ is set to be zero in the subaerial environment.

369 To accurately predict the tsunami wave generation by granular landslides,
 370 it is very important to capture the granular landslide motion and evolution
 371 of its profile. Therefore, we first compare the simulated granular landslide

372 profiles with the measurements, as shown in figure 4. Time $t = 0$ s is taken
373 to be when the front of the landslide reaches the water surface. Because
374 these two LDSs were installed above the water, the landslide profiles were
375 not affected by the landslide-water interactions. As we can see, the present
376 granular flow model can generally predict the landslide motion and its profile
377 evolution. The speed of the landslide front can be estimated from the time
378 lag between these two profiles. The model accurately captures the landslide
379 front location, indicating that the speed of the landslide front is also well
380 predicted by the model. The measured profiles have steep tails because of
381 large internal friction of the landslide material. In the simulation, however,
382 the tails are smoothed out. In addition, the height of the landslide is slightly
383 overpredicted by the model. This overprediction of the landslide height is
384 reduced when the landslide moves closer to the water surface.

385 Accurate simulation of underwater landslide motion is more difficult due
386 to the intense interactions between the landslide and water. Figures 5 and
387 6 show the measured and simulated impulse wave generation, underwater
388 landslide motion and granular deposit. During the landslide impact, the
389 landslide-water interactions are especially complicated with the entrainment
390 of large air cavities. In our two-layer model, we assume that the lower-layer
391 landslide and upper-layer water remain in contact, and thus the model cannot
392 represent this aspect of the event. In addition, the current model does not
393 account for the modification of Coulomb friction due to changes in bed slope.
394 Because of these two reasons, the landslide at the transition of the bed slope

395 (panel (a) and (b)) is not well simulated. The model slightly overpredicts
 396 the height of the slide front in the slope as seen in figure 4, which results in
 397 the overestimation of impulsively-generated wave heights. As the landslide
 398 moves onto the horizontal bed, the gravitational driving force vanishes. The
 399 basal sliding friction decreases the landslide velocity until the landslide comes
 400 to rest. After comparing the centroid locations of the simulated landslide,
 401 it was found that the landslide has almost come to rest at $t_r = 6.86$, where
 402 $t_r = t(g/h)^{1/2}$ is the normalized time after landslide impact. From figure
 403 5 and 6, we see that the model reasonably simulates the landslide motion,
 404 although the predicted centroid locations of the landslide are further offshore
 405 compared to the measurements. It is likely caused by the neglect of Coulomb
 406 friction increase at the transition of the slope.

407 Comparisons of simulated and measured waves are given in figure 7. Past
 408 studies (Fritz et al., 2004) have shown that the characteristics of landslide
 409 generated waves were related to the following two dimensionless parameters:
 410 the landslide Froude number $F = v_{si}/\sqrt{gh}$ and the dimensionless landslide
 411 thickness $S = s_i/h$, where v_{si} and s_i are the centroid impact velocity and
 412 landslide thickness at impact, respectively, and h is the still water depth. In
 413 the experiment considered here, these two non-dimensional parameters are
 414 $F = 2.72$ and $S = 0.32$, respectively. Based on the criteria suggested by Fritz
 415 et al. (2004), the impulsively-generated waves fall into the weakly nonlinear
 416 oscillatory wave regime $((4 - 7.5S) < F < (6.6 - 8S))$. In the simulation,
 417 the computed landslide centroid impact velocity is 4.10 m/s, which is slightly

418 smaller than the measured value (4.67 m/s). The computed landslide impact
 419 thickness is 0.10 m, which is slightly larger than the measured value (0.095
 420 m). The non-dimensional parameters from the simulation are $F = 2.39$ and
 421 $S = 0.33$, respectively, indicating that the predicted waves are still weakly
 422 nonlinear oscillatory waves. This is confirmed in figure 7, from which we
 423 see that the waves generated by the granular landslide are reasonably well
 424 captured by the model, although the model overpredicts the leading wave
 425 heights, especially at the gauges in the near field. The relative errors at
 426 gauges 2 and 3 are 42.7% and 23.7%, respectively. In the far field, the leading
 427 wave heights are more accurately predicted. For example, the relative errors
 428 at gauges 5 and 6 are 16.3% and 18.7%, respectively.

429 In figure 7, we also show the sensitivity of numerical results to the pa-
 430 rameter λ . In equation (5), we see that the parameter λ determines the pore
 431 pressure at the bed. If $\lambda = 0$, the pressure at the bed P_b^f equals that at
 432 the landslide-water interface P_h^f , indicating that the fluid pressure inside the
 433 granular landslide is constant. This would generate the maximum Coulomb
 434 friction for underwater landslide. If $\lambda=1.0$, the landslide is completely sus-
 435 pended in the water column, and the Coulomb friction at the bed vanishes.
 436 Therefore, the parameter λ determines the magnitude of Coulomb friction
 437 imposed on the landslide. In figure 7, the solid lines show the results with
 438 $\lambda = 0.5$, while the dash-dotted lines show the simulation results with $\lambda =$
 439 0.2. We see that the predicted impulse waves are generally similar. The
 440 leading wave height is slightly larger with a larger value of λ , which results

441 in a relatively smaller Coulomb friction. The effect of λ is more significant
 442 to the second wave. In the current simulations, we assume that the granular
 443 material is completely dry in the subaerial environment. Thus λ is set to be
 444 zero before the landslide enters the water column. Therefore, the λ effect
 445 on the leading wave is not significant. After the landslide enters the water
 446 column, the Coulomb friction is reduced. A larger value of λ will result in a
 447 smaller Coulomb friction, resulting in a larger second wave as seen in figure
 448 7. The effects of λ on the impulse waves are mostly in the near field. In
 449 the far field (panel (f)), the difference of the simulated impulse waves with
 450 different values of λ is insignificant.

451 The interactions between the landslide and surrounding water involve
 452 energy conversion. The increase in potential energy in the water layer induced
 453 by the landslide can be calculated by

$$E_{pt} = \int_{-(h-h_a)}^{\eta} \rho g z dz - \int_{-h}^0 \rho g z dz \quad (43)$$

454 where h is the initial water depth without landslide, h_a is the landslide thick-
 455 ness, E_{pt} is the total potential energy increase after the landslide impact. The
 456 first term on the right hand side evaluates the potential energy after land-
 457 slide impact, while the second term calculates the potential energy before
 458 landslide. The total potential energy increase is contributed by two parts.
 459 The first part is due to the static increase of water level with the presence
 460 of underwater landslide, which can be estimated as $E_{ps} = \rho g(\eta + h - h_a)h_a$.

461 The second part is due to the generation of impulse waves by the landslide
 462 motion, which can be calculated by

$$E_{pw} = E_{pt} - E_{ps} = \frac{1}{2}\rho g(\eta - h_a)^2 \quad (44)$$

463 Thus, the potential energy due to the presence of impulse waves for the whole
 464 computational domain can be evaluated as $E_{pot} = \int E_{pw} dx$. The kinetic
 465 energy of the impulse waves is $E_{ke} = \frac{1}{2}\rho D \int (u^2 + w^2) dx d\sigma$, where D is the
 466 total water depth. Figure 8 shows the calculated potential energy and kinetic
 467 energy of the impulse waves after the landslide impact for the simulation with
 468 $\lambda = 0.5$. After the impact, the energy of the landslide is converted to the
 469 water column, resulting in the increase of both kinetic energy and potential
 470 energy. At the early stage, the kinetic energy increases faster due to the high
 471 speed of the landslide. It reaches a peak (peak A) when the landslide hits
 472 the plane bed. The kinetic energy has the maximum value (peak B) when
 473 the leading wave crest propagates away from the landslide. The potential
 474 energy increases more slowly at the early stage of the subaqueous landslide
 475 with the continuous generation of impulse waves, possibly due to the fact
 476 that the model is not able to capture the separation of the water and the
 477 slide. It reaches the maximum value (peak C) slightly later than that of
 478 kinetic energy when the whole leading wave front passes the landslide. At
 479 this time, the landslide has almost stopped moving. The interactions between
 480 the landslide and surrounding water become weaker. When all the waves pass

481 by the landslide ($t(g/h)^{1/2} > 16.8$), the potential energy and kinetic energy
482 of the impulse waves are equal, which would be expected from linear theory.

483 The displacement of the landslide centroid and the velocity at the leading
484 edge after landslide impact are shown in figure 9. We can see that the
485 landslide finally stops moving at $t(g/h)^{1/2} = 8.45$ after the impact, when
486 the displacement of the landslide centroid has the maximum value of 2.94
487 m and the velocity at the leading edge is zero. At the impact, the velocity
488 at the leading edge of the landslide is about 4.12 m/s. This velocity keeps
489 increasing until $t(g/h)^{1/2} = 0.92$ when the landslide reaches the transition
490 of the slope. After then, the landslide front velocity decreases rapidly due
491 to the large resistance at the slope transition. At the plane bed, the leading
492 edge velocity almost decreases linearly because of the Coulomb friction.

493 **5. Tsunami Waves Generated by a Three-dimensional Granular** 494 **Landslide**

495 The model is next applied to study tsunami waves generated by a 3D
496 granular landslide. The three-dimensional laboratory experiments were con-
497 ducted by Mohammed (2010) and Mohammed and Fritz (2012) in the tsunami
498 wave basin at Oregon State University. The basin is 48.8 m in length and
499 26.5 m in width. The case we choose for this study has a still water depth of
500 0.6 m. The granular landslide was released on a hillslope, which was inclined
501 at 27.1° with a smooth 9.3 m long steel plate as the sliding surface. The
502 landslide had a volume of 0.378 m^3 , initially contained and accelerated in

503 a box with size of 1.05 m $\times$ 1.2 m $\times$ 0.3 m. The landslide was modeled
504 with naturally rounded river gravel with the following parameters: particle
505 size range from 6.35 to 19.05 mm, $d_{50} = 13.7$ mm, $\rho_g = 2,600$ kg/m³, land-
506 slide bulk density $\rho_s = 1,760$ kg/m³, porosity $n_{por} = 0.31$, effective internal
507 friction angle $\phi_{int} = 41^\circ$, and dynamic bed friction angle $\phi_{bed} = 23^\circ$. These
508 parameters are summarized in Table 2.

509 The computational domain and model setup are shown in figure 10. The
510 domain size is 48 m in length and 28 m in width, discretized by 960×560
511 grid cells. Three vertical levels are employed to simulate the upper-layer
512 water motion. Slightly different from the laboratory setup, the hillslope
513 covers the whole width of the computational domain with $x < 8.13$ m. The
514 landslide is released in the middle of the hillslope at $y = 14.0$ m. The granular
515 parameters are chosen to be the same as those in the experiment. Again,
516 the earth pressure coefficient $k_{act/pass}$ is calculated by equation (13). The
517 parameter λ is taken to be 0.0 above the water and 0.5 after the landslide
518 enters the water column. We validate the model by comparing the tsunami
519 waves at 9 wave gauges displayed in figure 11 as red dots.

520 We first compare the simulated landslide velocity and thickness at impact
521 with the measurements. In the experiment, the landslide impact velocity is
522 5.72 m/s, resulting in a Froude number $F = v_s/\sqrt{gh} = 1.87$. The landslide
523 thickness at impact is $s = 0.072$ m and the relative landslide thickness is
524 $S = s/h = 0.12$. According to the criteria given by Fritz et al. (2004),
525 the generated tsunamis fall into the category of nonlinear oscillatory waves.

526 The model captures the movement of the granular landslide on the hillslope
 527 reasonably well with the predicted landslide thickness at impact $s = 0.078$
 528 m, which is close to the measurement ($s = 0.072$ m). The landslide impact
 529 velocity is slightly underestimated with a value of 4.54 m/s. Apparently,
 530 the predicted tsunamis are still nonlinear oscillatory waves. This is con-
 531 firmed in figure 11, which shows the comparisons of simulated and measured
 532 tsunami waves at 9 wave gauges. Generally, the model simulates the tsunami
 533 waves well, although the wave heights are overestimated at some stations;
 534 for example, the station with $\theta=30^\circ$ and $r/h=7.7$, which is the closest to the
 535 shoreline. This indicates that the tsunami waves in the generating area are
 536 overpredicted. As discussed in section 4, three reasons may be used to explain
 537 this overprediction. (1) In the current model, the lower-layer landslide and
 538 upper-layer water remain in contact, thus the formation of air cavity during
 539 landslide impact is not captured; (2) The current model does not account for
 540 the increase of Coulomb friction due to the change of curvature at the tran-
 541 sition of the slope; (3) The model slightly overpredicts the landslide height
 542 at the impact. In the far field, the overestimation of wave height decreases
 543 and the simulated tsunami waves match well with the measurements. By
 544 the end of the time series at stations of $\theta=0^\circ$ and $r/h=9.0, 14.2$, the small
 545 free surface oscillations are not captured by the model partially due to the
 546 relatively coarse horizontal grids used in the simulation.

547 In figure 11, we also demonstrate the results from the simulation with
 548 $\lambda = 0.2$. The effects of λ on the impulse waves are similar to the 2D case.

549 The second and third waves are more significantly affected by this parameter
550 compared to the leading wave. The reason has been explained above. Again,
551 this parameter only affects the impulse waves in the generating zone. In the
552 far field, where the waves are not directly generated by the landslide, the
553 results are not sensitive to this parameter.

554 Figure 12 and 13 show the simulated landslide motion and tsunami wave
555 generation after the landslide impact. The general patterns of landslide mo-
556 tion and associated tsunami waves are very similar to the laboratory ob-
557 servations (Mohammed and Fritz, 2012). The impact and penetration of
558 the landslide produce an initial wave crest as seen in panel (d). The water
559 displacement develops into a radial wave front with the wave propagating
560 primarily in the direction of the landslide. As the wave front moves away
561 from the shoreline, a wave drawdown is observed on the hillslope in panel
562 (f) followed by a wave run-up. The periodic changes of wave run-up and
563 rundown at the shoreline generate the second wave with radial wave front
564 and the trailing wave train as seen from panel (j) and (l). The 3D landslide
565 motion is more complicated due to the lateral spreading of the granular ma-
566 terial compared to the 2D case. After the landslide impact, the landslide
567 width increases dramatically due to the retarding effect of the water. As
568 the landslide reaches the transition of the slope, the granular material piles
569 up. Over the plane bed, the granular material deposits quickly. The final
570 deposition is found to be located at the plane bed close to the transition of
571 the slope as shown in panel (k), which is more offshore than that observed

572 in the experiments (Mohammed, 2010) as shown in figure 14. The excessive
573 offshore runout of the slide is probably due to the present model’s neglect of
574 the additional friction due to the curvature change at the transition of the
575 slope. More accurate simulation of the landslide through the transition of
576 the slope requires a model that is capable of simulating granular flow over
577 3D irregular terrain.

578 To examine the effects of non-hydrostatic pressure on tsunami wave gen-
579 eration, we conducted another simulation with the non-hydrostatic pressure
580 correction turned off in NHWAVE. The comparisons of tsunami waves from
581 the non-hydrostatic and hydrostatic simulations are presented in figure 15.
582 As expected, wave dispersion is not well captured by the hydrostatic sim-
583 ulation, with wave energy being mostly concentrated in the leading wave.
584 As a result, the granular landslide produces a larger wave in the generating
585 zone with a steeper wave front. Wave height in the hydrostatic simulation
586 decays more rapidly in all directions than that in the non-hydrostatic simula-
587 tion. These results also confirm that the shallow-water assumption employed
588 by previous researches (i.e. Jiang and LeBlond (1992, 1993), Kelfoun et al.
589 (2010) and Giachetti et al. (2011), among others) is probably not valid for
590 tsunami waves generated by rapidly deforming landslides, even for waves be-
591 ing generated in regions with local water depth tending to zero. This was also
592 the conclusion of Ma et al. (2012) for rigid landslides. The non-hydrostatic
593 component of the flow field plays an $O(1)$ role in determining the correct
594 form of the resulting tsunami wave. The sensitivity of model results to com-

putational grids is also presented in figure 15, which clearly shows that the simulated impulse waves have negligible differences by increasing the vertical layers. Three vertical levels in NHWAVE are sufficient to capture the impulse wave processes. Figure 15 also demonstrates the convergence of model results with increasing grid refinement as the simulated impulse waves using coarser grids with $\Delta x = 0.06$ m and $\Delta y = 0.07$ m have negligible differences with those from a fine grid simulation.

6. Conclusions

In this paper, we have developed a model for tsunami generation by deformable granular landslides. The model utilizes a discrete, two-layer formulation to represent the landslide volume and overlying water layer. The landslide is modeled as a depth-integrated granular flow following Savage and Hutter (1989) and Iverson (1997). The landslide model is formulated in slope-oriented coordinates based on the following major assumptions: (1) The characteristic horizontal length scale of the landslide is much greater than the characteristic vertical length scale; (2) The fluid pressure inside the landslide varies linearly with depth; (3) The fluid frictional shear stresses at the landslide-water interface are relatively small compared to the Coulomb friction at the bed; (4) The water surface is a single value function of the horizontal coordinates, the effects of air cavity formation during landslide impact are negligible. The water layer is modeled using the existing non-hydrostatic surface wave model NHWAVE of Ma et al. (2012), with three vertical levels

617 used in the σ coordinate formulation. The two layers are coupled through
618 kinematic boundary conditions and through continuity of normal stresses,
619 and are solved using the same finite-volume approach.

620 The two-layer model was validated using analytical solutions for granu-
621 lar dam-break flow as well as measured tsunami waves generated by 2D and
622 3D laboratory granular landslides. The model simulations illustrate a com-
623 plex interplay between the granular landslide and associated tsunami waves.
624 Dam-break flow was accurately predicted by the granular flow model em-
625 ploying a shock-capturing numerical scheme. The granular landslide motion
626 as well as tsunami waves generation were all reproduced with reasonable
627 accuracy.

628 The results here demonstrate the potential usefulness of the granular flow
629 approach in modeling the generation of short, dispersive tsunami waves dur-
630 ing landslide events. The present model can be further improved in several
631 respects. First, our model results demonstrate that the predicted tsunami
632 waves are sensitive to the parameter λ (pore pressure at the bed) in the gen-
633 erating zone when the landslide runout distance is long. The determination
634 of this parameter needs to be studied further. Secondly, the Coulomb friction
635 may vary spatially due to changes in local bed slope, which is not completely
636 accounted for in our sample computations. Thirdly, model applications on
637 the submarine granular landslides will have to be validated by experimental
638 data.

639 Two avenues of further model improvement are being pursued. First,

640 the use of slope-oriented coordinates here facilitates a correct representation
 641 of downslope body forces and the resulting vertical acceleration component,
 642 but greatly complicates model extension to landslide motion over arbitrary
 643 three-dimensional bathymetry. An approach to this problem which retains
 644 the use of locally slope-oriented coordinates has been developed by Kelfoun
 645 and Druit (2005) for subaerial landslides, and has subsequently been applied
 646 to tsunami generation by Kelfoun et al. (2010) and Giachetti et al. (2011).
 647 The formulation requires great care in determining bed curvature effects.
 648 Alternately, Denlinger and Iverson (2004) have shown a formulation for the
 649 landslide layer in standard Cartesian coordinates with x, y horizontal. In this
 650 case, vertical acceleration and its effect on the pressure field becomes the
 651 difficult factor to describe accurately. Denlinger and Iverson (2004) develop
 652 a simple explicit estimate for the pressure correction to hydrostatic results
 653 using the vertical momentum balance and continuity; the result is analogous
 654 to the approach followed by Yamazaki et al. (2009) in their incorporation of
 655 non-hydrostatic, dispersive wave effects in a depth-integrated model for the
 656 water layer. Alternately, the pressure correction can be evaluated explicitly
 657 in terms of higher spatial derivatives of the horizontal motion; this approach
 658 leads to equations with forms analogous to Boussinesq equations for the water
 659 layer, which are well understood but which greatly complicate the numerical
 660 approach to solving the horizontal momentum equations. See, for example,
 661 Shi et al. (2012), where the equations for the water layer are solved using
 662 the same finite volume TVD scheme as employed here but with extensions to

663 deal with higher-order derivatives. Our preference at this stage in our work
664 is to pursue the approach of Denlinger and Iverson (2004).

665 The second avenue of future model improvement lies in improving the
666 model for landslide rheology. For the case of saturated or partially saturated
667 granular debris flows, Iverson and George (2014) have recently described
668 a model which maintains the separate identity of solid and fluid phases in
669 the landslide mass, and, in so doing, is able to account for dilatancy ef-
670 fects and rapid changes in rheological properties as landslide motion evolves.
671 The model is capable of maintaining a potential landslide mass in an initial
672 motionless state, with the landslide being initiated by perturbations to the
673 initial configuration. The application of such a model would be a great asset
674 to the process of coupling geotechnical stability analysis with landslide and
675 tsunami hazard assessment. The extension of the present model to incor-
676 porate this formulation is relatively straight forward and will be described
677 subsequently.

678 **Acknowledgments**

679 The authors are indebted to Dr. Carl Harbitz and two anonymous review-
680 ers for their constructive comments. We sincerely thank Dr. Heller for mak-
681 ing his experimental data available to us. J. T. Kirby and F. Shi acknowledge
682 support from the National Tsunami Hazard Mitigation Program (NTHMP),
683 National Weather Service Grants (NA10NWS4670010, NA13NWS4670014
684 and NA14NWS4670041). T. J. Hsu was supported by the Department of

685 Civil and Environmental Engineering, University of Delaware during the
686 early stages of this work.

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Table 1: Two-dimensional granular landslide parameters (Heller and Hager, 2010)

description	symbol	value
still water depth	h	0.3 m
slide length	l_s	0.6 m
slide thickness	s	0.118 m
slide impact thickness	s_i	0.095 m
slide initial velocity	v_s	3.25 m/s
slide centroid impact velocity	v_{si}	4.67 m/s
bulk slide density	ρ_s	1,678 kg/m ³
grain density	ρ_g	2,745 kg/m ³
grain diameter	d_g	4 mm
bulk slide porosity	n	0.389
hill slope angle	α	45°
dynamic bed friction angle	ϕ_{bed}	24°
internal friction angle	ϕ_{int}	34°
slide Froude number	F	2.72
relative slide thickness	S	0.32
relative slide mass	M	1.25

Table 2: Three-dimensional granular landslide parameters (Mohammed and Fritz, 2012)

description	symbol	value
still water depth	h	0.6 m
slide length	l_s	1.05 m
slide width	w_s	1.2 m
slide thickness	s	0.3 m
slide impact thickness	s_i	0.072 m
slide frontal impact velocity	v_{si}	5.72 m/s
bulk slide density	ρ_s	1,760 kg/m ³
grain density	ρ_g	2,600 kg/m ³
grain diameter	d_{50}	13.7 mm
bulk slide porosity	n	0.31
hill slope angle	α	27.1°
dynamic bed friction angle	ϕ_{bed}	23°
internal friction angle	ϕ_{int}	41°
slide Froude number	F	1.87
relative slide thickness	S	0.12
relative slide mass	M	1.56

Figure 1: Sketch of the landslide and the slope-oriented coordinate system. α is the bed slope angle. The slide height in the slope-oriented coordinate system h_a is correlated with the upper layer thickness. A and B are two neighboring grid points in the slope-oriented coordinate. The slide thickness in the (x, z) coordinate h_s can be estimated by $0.5(h_{aA} + h_{aB}) / \cos \alpha$.

Figure 2: Verification of the granular flow model using analytical solutions of Mangeney et al. (2000) for a frictional dam break debris flow onto a numerically dry surface. Panel (a): initial profile of the dam-break on the slope; (b): bed slope $\alpha = 0^\circ$ with no friction ($\phi_{bed} = 0^\circ$) at $t = 20$ s; (c): bed slope $\alpha = 20^\circ$ with no friction ($\phi_{bed} = 0^\circ$) at $t = 15$ s; (d): bed slope $\alpha = 20^\circ$ with friction ($\phi_{bed} = 10^\circ$) at $t = 20$ s. The initial height of the dam in all cases is $h_a = h_0 = 20$ m. Solid lines: simulations; dashed lines: analytical solutions.

Figure 3: Upper panel: The setup of wave flume and the positions of seven capacitance wave gages along channel axis. The angle of the slope is $\alpha = 45^\circ$. The still water depth $h=0.3$ m. Lower panel: The position of the landslide, which is 0.6 m long and 0.118 m high. The evolution of the landslide profile is recorded by two Laser Distance Sensors (LDSs) (from Heller (2007)).

Figure 4: The comparisons of simulated (solid lines) and measured (dashed lines) landslide profiles recorded at (a) LDS_{-1} and (b) LDS_0 .

Figure 5: PIV raw images recorded at $t_r = t(g/h)^{1/2} =$ (a) 1.14; (b) 2.29; (c) 3.43; (d) 4.57 and (e) 5.72 after slide impact (from Heller (2007)).

Figure 6: The simulated impulse wave generation and granular landslide motion at $t_r = t(g/h)^{1/2} =$ (a) 2.29; (b) 3.43; (c) 4.57; (d) 5.72 and (e) 6.86 after slide impact. The solid lines show the free surface elevations, while the dashed lines display the interfaces between the granular landslide and water.

Figure 7: The comparisons of simulated (solid and dash-dotted lines) and measured (dashed lines) impulse waves at 6 wave gauges (gauge 2 to 7) generated by a 2D laboratory granular landslide (Heller and Hager, 2010). The solid lines show the simulation results with $\lambda = 0.5$; the dash-dotted lines show the simulation results with $\lambda = 0.2$.

Figure 8: The upper panel shows the calculated potential energy (solid line) and kinetic energy (dashed line) per unit width for the simulation with $\lambda = 0.5$ after the impact ($t\sqrt{g/h} = 0$ at impact). The potential energy is calculated as $E_{pot} = \frac{1}{2}\rho g \int (\eta - h_a)^2 dx$. The kinetic energy is $E_{ke} = \frac{1}{2}\rho D \int (u^2 + w^2) dx d\sigma$. The lower three panels show the impulse waves (solid lines) as well as the granular landslide (dashed lines) at time A, B and C, corresponding to the peaks of kinetic energy and potential energy indicated in the upper panel.

Figure 9: The predicted landslide displacement and the velocity at the leading edge after slide impact. The break in the curve at $t_r = 2.3$ corresponds to the time when the landslide reaches the horizontal bed.

Figure 10: The computational domain and model setup for Mohammed and Fritz (2012). Upper panel: plan view of the domain. The red dots show the wave gauge array used to measure the water surface elevation. The granular slide collapses down the hillslope with the slope angle of 27.1° . The width of the hillslope is 8.13 m. The contours show the water depth. Lower panel: a transection at $y = 14.0$ m. The free surface is exaggerated for a better view. The still water depth is 0.6 m.

Figure 11: The comparisons of simulated (solid and dash-dotted lines) and measured (dashed lines) impulse waves at (a) $\theta=0^\circ$, $r/h=9.0, 14.2, 23.3, 40.2$; (b) $\theta=30^\circ$, $r/h=7.7, 10.3, 16.4$ and (c) $\theta=60^\circ$, $r/h=13.3, 17.3$, generated by a 3D laboratory granular landslide (Mohammed and Fritz, 2012). The solid lines show the simulation results with $\lambda = 0.5$; the dash-dotted lines show the simulation results with $\lambda = 0.2$.

Figure 12: The simulated granular landslide motion (left panels) and tsunami wave generation (right panels) at $t =$ (a) and (b) 0.0 s; (c) and (d) 0.5 s; (e) and (f) 1.0 s after slide impact.

Figure 13: (Continued) The simulated granular landslide motion (left panels) and tsunami wave generation (right panels) at $t =$ (g) and (h) 1.5 s; (i) and (j) 2.0 s; (k) and (l) 2.5 s after slide impact.

Figure 14: The comparisons of simulated (red line) and measured (blue dashed line) granular deposits.

Figure 15: The comparisons of impulse waves from a non-hydrostatic simulation (solid lines) and a hydrostatic simulation (dash-dotted lines) at $\theta=0^\circ$, $r/h=$ (a) 9.0, (b) 14.2, (c) 23.3 and (d) 40.2, generated by a 3D granular landslide. The dashed lines show the simulated impulse waves using 5 vertical layers. The dotted lines show the simulated impulse waves using coarser grids ($\Delta x = 0.06$ m, $\Delta y = 0.07$ m).