Simulating the tsunami hazard: Quantitative predictions

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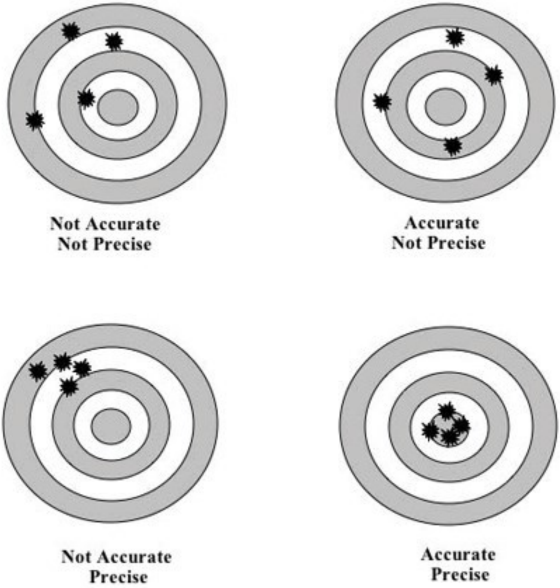
Outline:

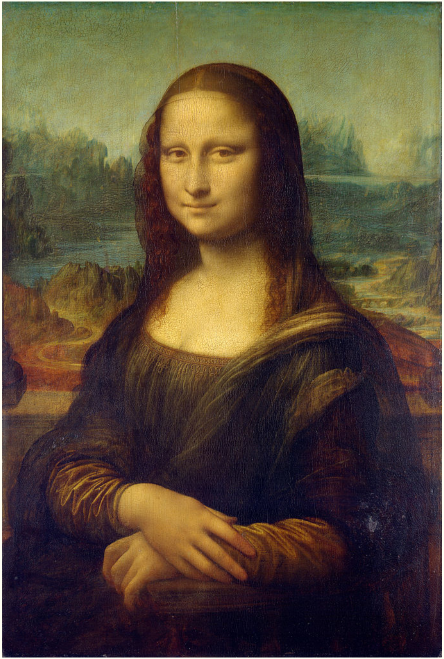
- Thoughts and concerns about hazard modeling
- Tsunami hazard from deposits
- Tsunami and Storm Boulders
  - Three-Dimensional Modeling
  - Simplified modeling
- Sand

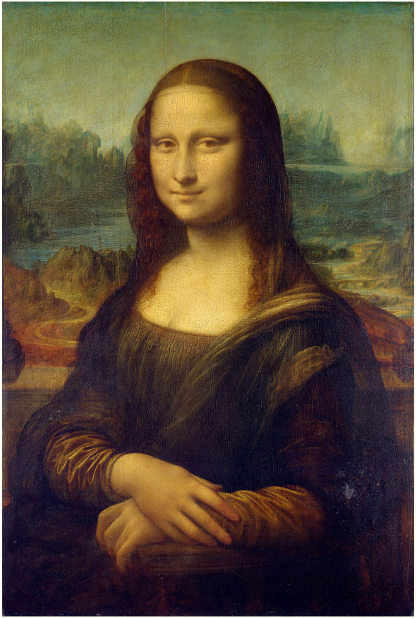
Thoughts and concerns about hazard modeling

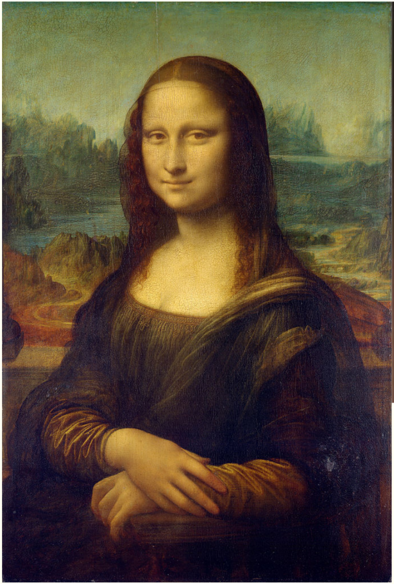
George E. P. Box

All models are wrong; some models are useful.


Not Accurate
Not Precise
Accurate
Not Precise
Not Accurate
Precise
Accurate
Precise

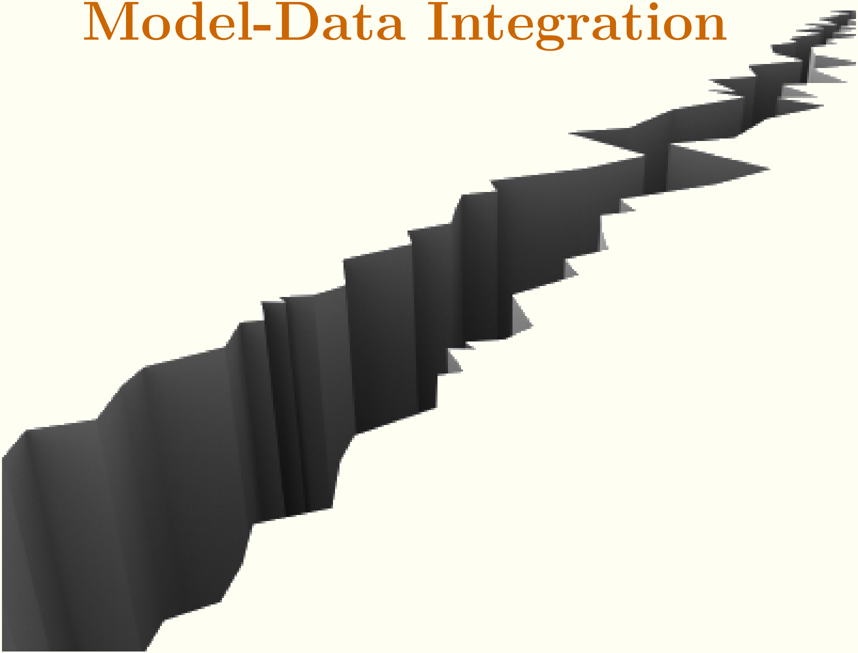






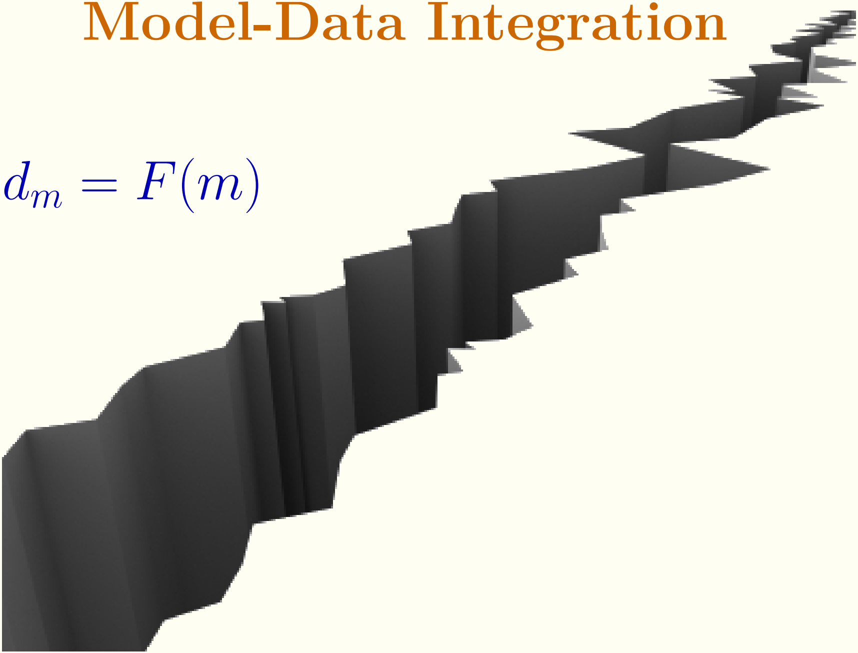
Model Coupling

Model-Data Integration



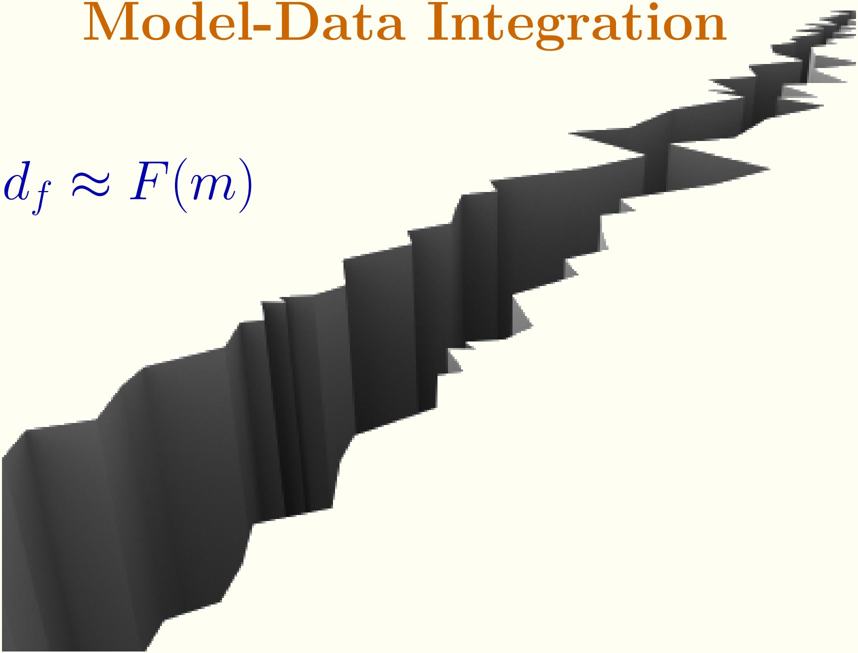
Model-Data Integration

$$d_m = F(m)$$



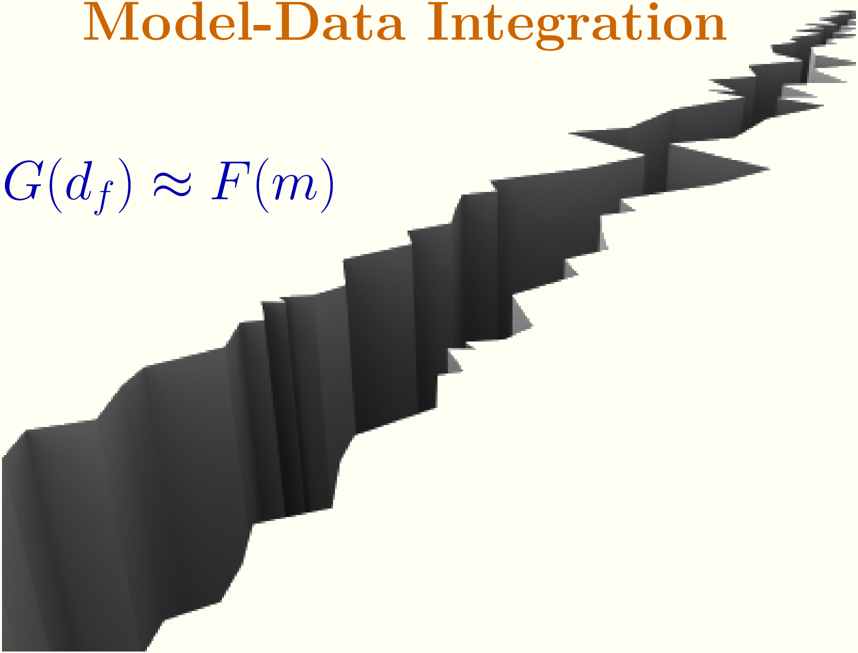
Model-Data Integration

$$d_f \approx F(m)$$



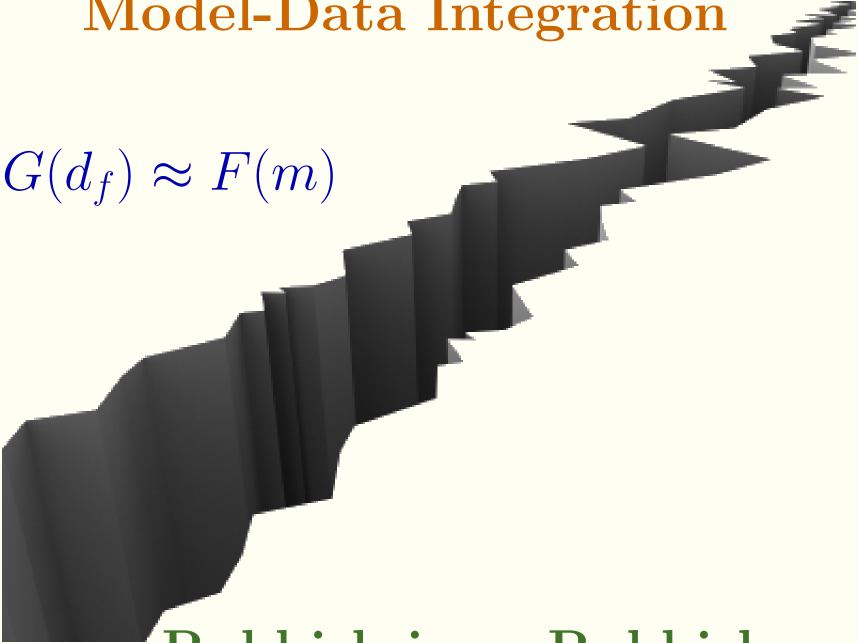
Model-Data Integration

$$G(d_f) \approx F(m)$$



Model-Data Integration

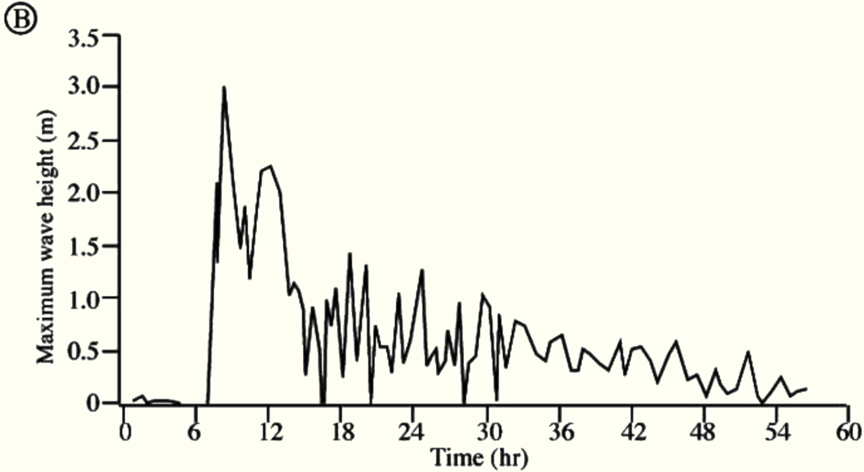
$$G(d_f) \approx F(m)$$



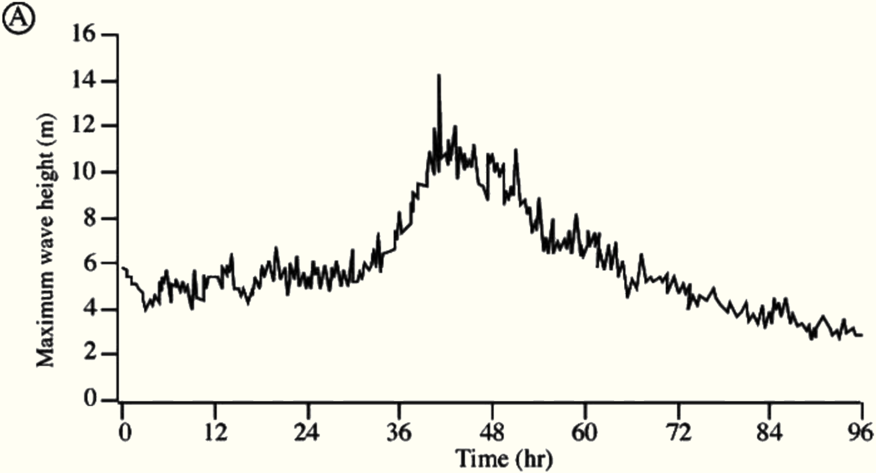
Rubbish in = Rubbish out

Tsunami Hazard from Deposits

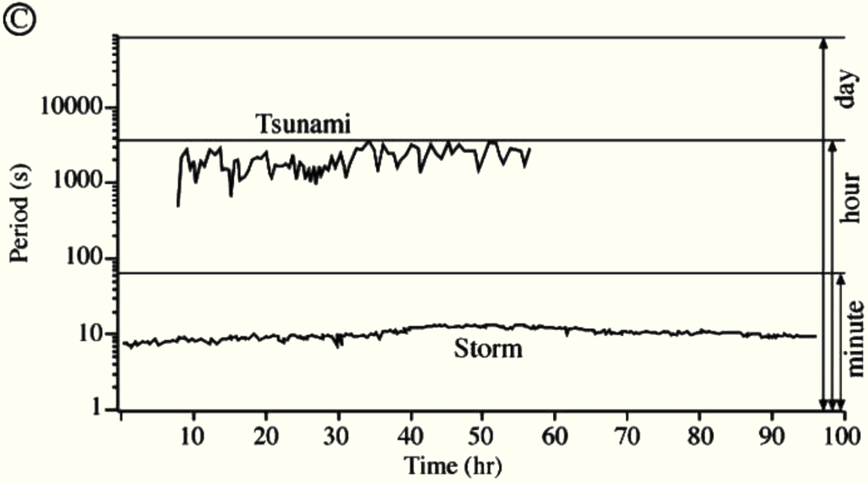
Tsunami


Ⓑ
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0
Maximum wave height (m)
0
6
12
18
24
30
36
42
48
54
60
Time (hr)

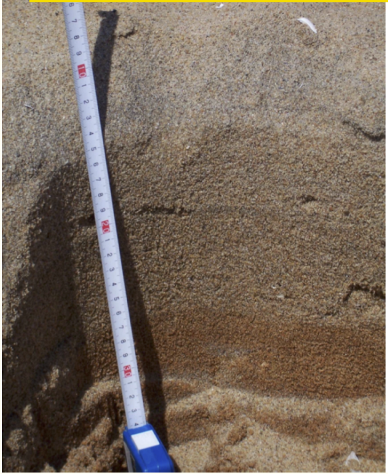
Storm

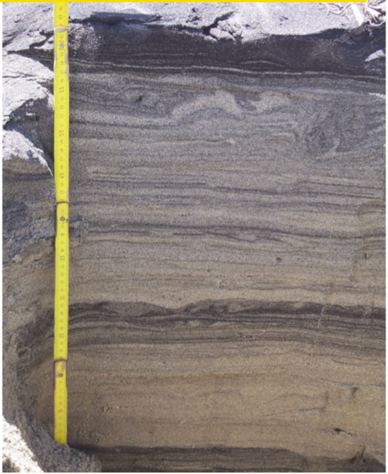

A
Maximum wave height (m)
0
2
4
6
8
10
12
14
16
0
12
24
36
48
60
72
84
96
Time (hr)

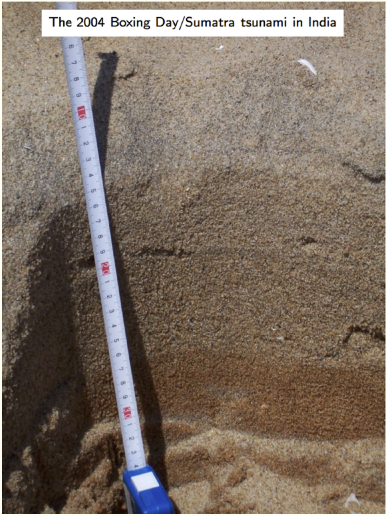
Period Comparison



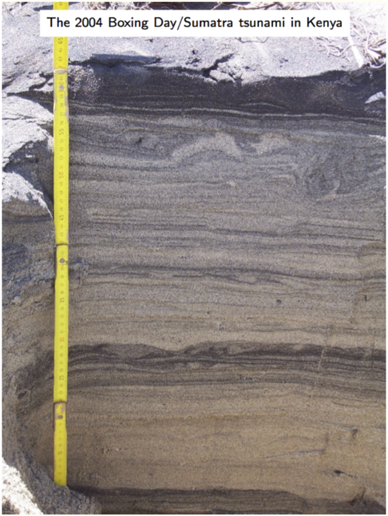
Which one is the tsunami deposit?



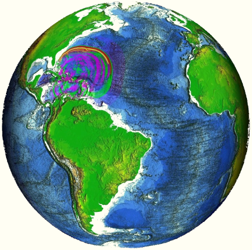




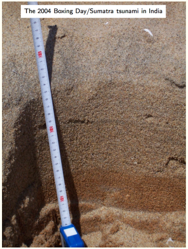
The 2004 Boxing Day/Sumatra tsunami in India



The 2004 Boxing Day/Sumatra tsunami in Kenya



$\Longrightarrow$



$\Longrightarrow$

Tsunami and Storm Boulders

ϕ-Scale	Size range [mm]	Aggregate name
$-8 <$	> 256	Boulder
-6 to -8	64 - 256	Cobble
-5 to -6	32 - 64	Very coarse gravel
-4 to -5	16 - 32	Course gravel
-3 to -4	8 - 16	Medium gravel
-2 to -3	4 - 8	Fine gravel
-1 to -2	2 - 4	Very fine gravel
0 to -1	1 - 2	Very coarse sand
1 to 0	0.5000 - 1	Coarse sand
2 to 1	0.2500 - 0.5000	Medium sand
3 to 2	0.0125 - 0.2500	Fine dand
4 to 3	0.0062 - 0.0125	Very fine sand
> 4	< 0.0062	Silt, Mud

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Geophysical Research Letters

RESEARCH LETTER

10.1002/2015GL063712

Key Points:

- Better approach is needed to distinguish boulders moved by storms from tsunamis
- Three-dimensional simulations are more accurate than simplified approaches
- Boulder dislodgement is complex and nonlinear. More work is needed

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Boulder dislodgement and transport by solitary waves: Insights from three-dimensional numerical simulations

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Abstract The analysis of boulder motion and dislodgement provides important insights into the physics of the causative processes, i.e., whether or not a boulder was moved during a storm or tsunami and the magnitude of the respective event. Previous studies were mainly based on simplified models and threshold considerations. We employ three-dimensional numerical simulation of the hydrodynamics coupled with rigid body dynamics to study boulder dislodgement and transport by solitary waves. We explore the effects of three important nondimensional parameters on the boulder transport problem, the Froude number *Fr*, the aspect ratio in logarithmic scale α, and the submergence factor, β. Our results indicate that boulder motion is complex, and small changes in one of the nondimensional parameters result in significantly different behavior during the transport process and the final resting place of boulders. More studies are needed to determine the role of boulders in tsunami and storm hazard assessments.

1. Introduction

Scaling Analysis

$$
\begin{aligned}
(h)_t + (uh)_x &= 0 \\
(hu)_t + (hu^2)_x + \frac{1}{2}(gh^2)_x &= -ghb_x
\end{aligned}
$$

$$\Downarrow$$

$$
\begin{aligned}
\mathrm{St}(h^*)_{t^*} + (u^*h^*)_{x^*} &= 0 \\
\mathrm{St}(h^*u^*)_{t^*} + (h * u^{*2})_{x^*} + \frac{1}{2\mathrm{Fr}^2}(h^{*2})_{x^*} &= -\frac{\beta}{\mathrm{Fr}^2}h^*b^*_{x^*}
\end{aligned}
$$

Strouhal number: $\mathrm{St} = \frac{x_{\mathrm{ref}}}{t_{\mathrm{ref}}u_{\mathrm{ref}}}$; Froude number: $\mathrm{Fr} = \frac{u_{\mathrm{ref}}}{\sqrt{gh_{\mathrm{ref}}}}$; Submergence: $\beta = \frac{b_{\mathrm{ref}}}{h_{\mathrm{ref}}}$. With $x_{\mathrm{ref}} = \kappa^{-1}$, $t_{\mathrm{ref}} = (c\kappa)^{-1}$, $h_{\mathrm{ref}} = h_w$, $u_{\mathrm{ref}} = c$, and $b_{\mathrm{ref}} = lb_y$, where lb_y is boulder height, c denotes wave speed, and κ represents the wave number.

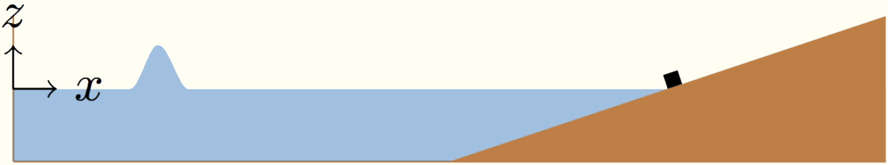
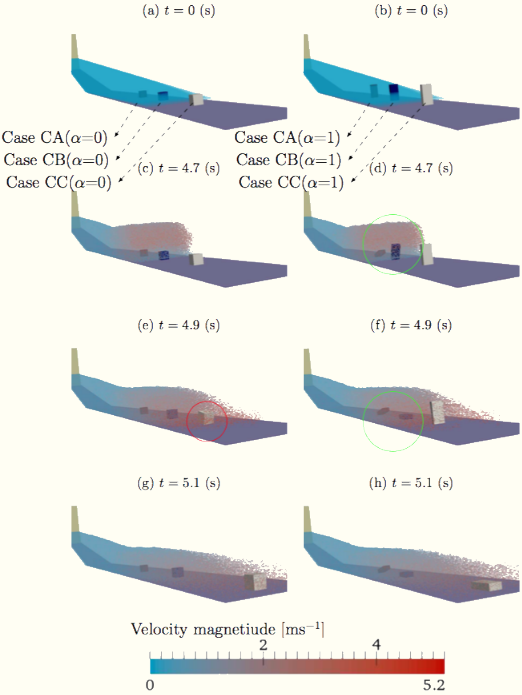
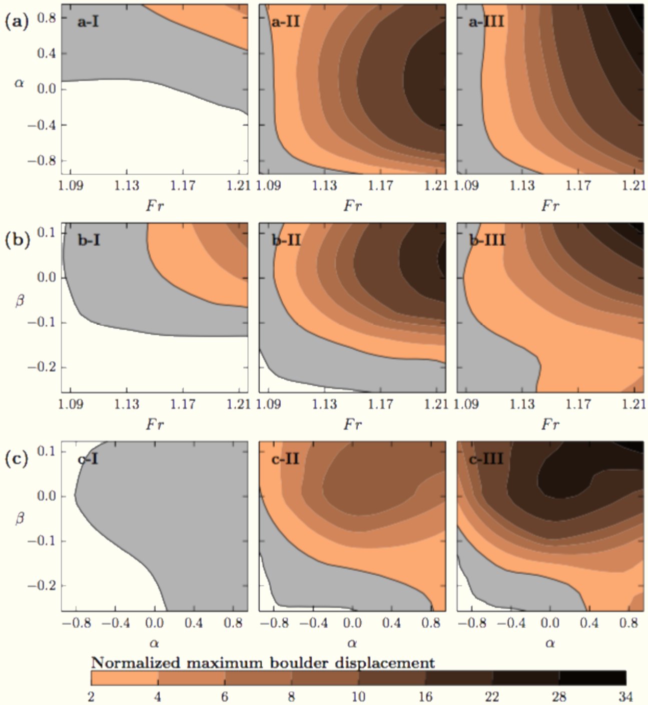

z
x

Table 2.1: Physical and numerical simulation parameters ($h_w = 0.3$ m. h_b represents the depth of the water at the location of boulder. c is the solitary wave celerity). Submergence factor: $\beta = \frac{h_b}{h_w}$ (y axis); Froude number: $Fr = c(\sqrt{gh_w})^{-1}$; boulder aspect ratio in logarithmic scale: $\alpha = \log_2(lb_y lb_x^{-1})$ [$x - y$ plane; boulder normalized width: $W_b = lb_y h_w^{-1}$; boulder normalized volume: $V_b = lb_x lb_y lb_z h_w^{-3}$; density ratio: $\rho_b \rho_w^{-1}$; friction coefficient: μ;

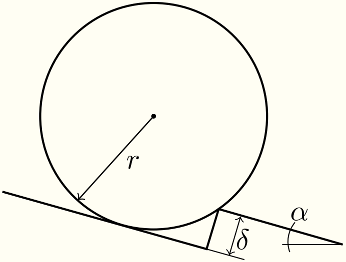
Scenario:	CA	CB	CC	CD
Submergence factor:	−8/30	−4/30	0	4/30
Froude number:	1.08, 1.15, 1.22	1.08, 1.15, 1.22	1.08, 1.15, 1.22	1.08, 1.15, 1.22
boulder aspect ratio:	−1, 0, 1	−1, 0, 1	−1, 0, 1	−1, 0, 1
boulder normalized width:	4/30	4/30	4/30	4/30
boulder normalized volume:	$4^3/30^3$	$4^3/30^3$	$4^3/30^3$	$4^3/30^3$
density ratio:	2	2	2	2
friction coefficient:	0.6	0.6	0.6	0.6


(a) $t = 0$ (s)
(b) $t = 0$ (s)
Case CA(α=0)
Case CB(α=0)
Case CC(α=0)
Case CA(α=1)
Case CB(α=1)
Case CC(α=1)
(c) $t = 4.7$ (s)
(d) $t = 4.7$ (s)
(e) $t = 4.9$ (s)
(f) $t = 4.9$ (s)
(g) $t = 5.1$ (s)
(h) $t = 5.1$ (s)
Velocity magnetiude [ms^{-1}]
0
2
4
5.2



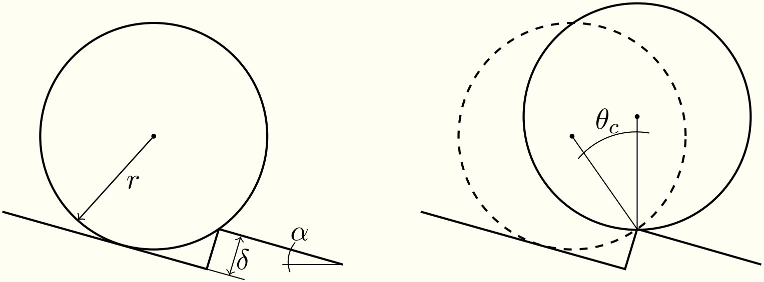
(a)
a-I
a-II
a-III
α
0.8
0.4
0.0
−0.4
−0.8
1.09
1.13
1.17
1.21
Fr
(b)
b-I
b-II
b-III
β
0.1
0.0
−0.1
−0.2
(c)
c-I
c-II
c-III
−0.8
−0.4
0.0
0.4
0.8
Normalized maximum boulder displacement
2
4
6
8
10
16
22
28
34

Initial position



α – Slope, δ – Roughness

Initial position Dislodgement position



α – Slope, δ – Roughness

$$\theta_c(\delta, \alpha) = \left[\tfrac{\pi}{2}\delta - \alpha\right] \geq 0$$

$$\Sigma \mathbf{F} = \mathrm{m}\mathbf{a}$$

$$\rightsquigarrow$$

$$(x, y) \to (\theta, r)$$

$$\rightsquigarrow$$

$$\Sigma \mathbf{F} = \mathrm{m}\frac{\mathrm{d}\theta^2}{\mathrm{d}t^2} = \mathrm{m}\theta_{tt}$$

with the assumption that $r = \text{const.}$

This Equation of Motion can be rewritten [Schmeeckle and Nelson, 2003]:

$$V\,L\ \left(\frac{7}{5}\rho_s + \rho_f C_m\right)\theta_{tt} = \mathbf{\Sigma F}$$

$$\mathbf{\Sigma F} = \mathbf{D}\sin(\theta - \alpha) + (\mathbf{L} + \mathbf{B})\cos(\theta - \alpha) - \mathbf{W}\cos(\theta)$$

With

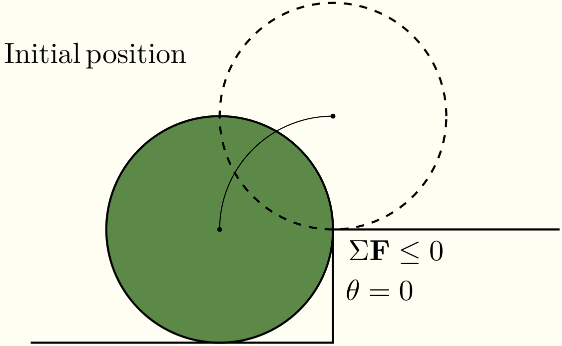
V – particle volume, ρ_s – particle density, ρ_f – fluid density,

L – distance between the center of gravity and point of rotation (r),

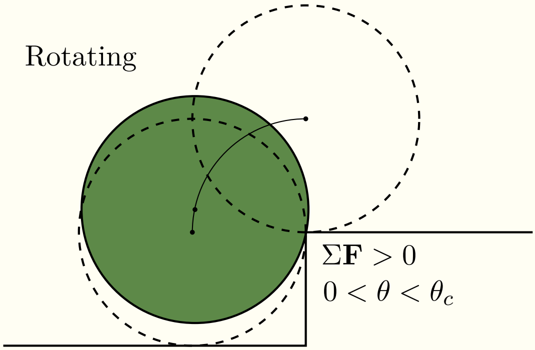
C_m – added mass coefficient (0.5 for spheres in water),

$\mathbf{D}$ – drag, $\mathbf{L}$ – lift, $\mathbf{B}$ – buoyancy, $\mathbf{W}$ – weight

Example: $\alpha = 0$ and $\delta = 1 \rightsquigarrow \theta_c = 0.5\pi$



Example: $\alpha = 0$ and $\delta = 1 \rightsquigarrow \theta_c = 0.5\pi$



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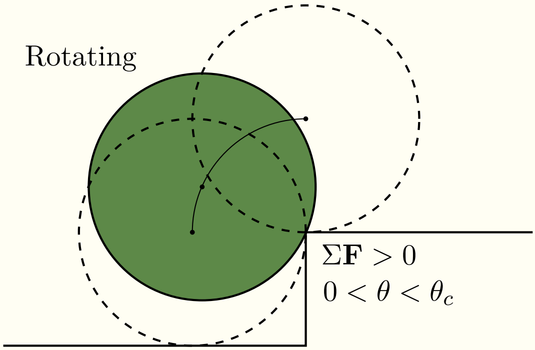

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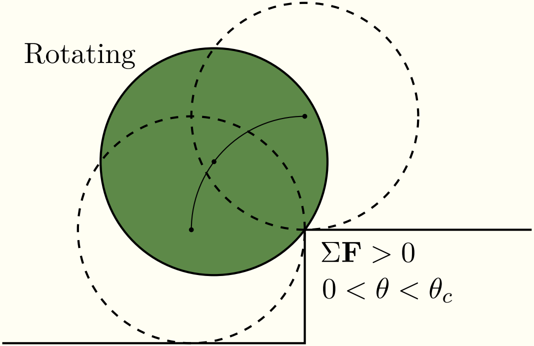
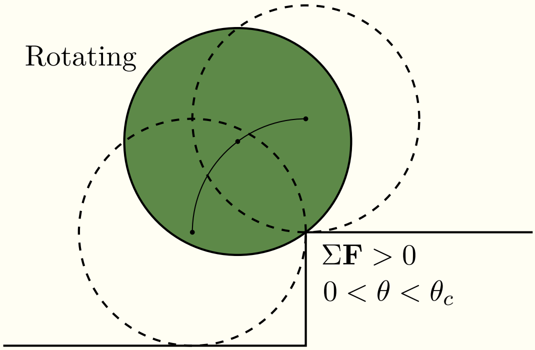
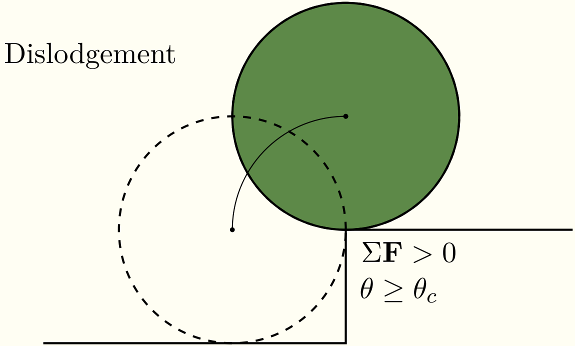


Example: $\alpha = 0$ and $\delta = 1 \rightsquigarrow \theta_c = 0.5\pi$



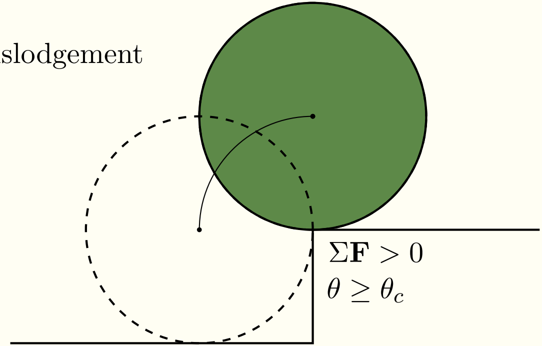
Example: $\alpha = 0$ and $\delta = 1 \rightsquigarrow \theta_c = 0.5\pi$



Duration of rotation: $T_r = t(\text{for}\,\theta = \theta_c) - t(\text{for}\,\Sigma\text{F} = 0)$

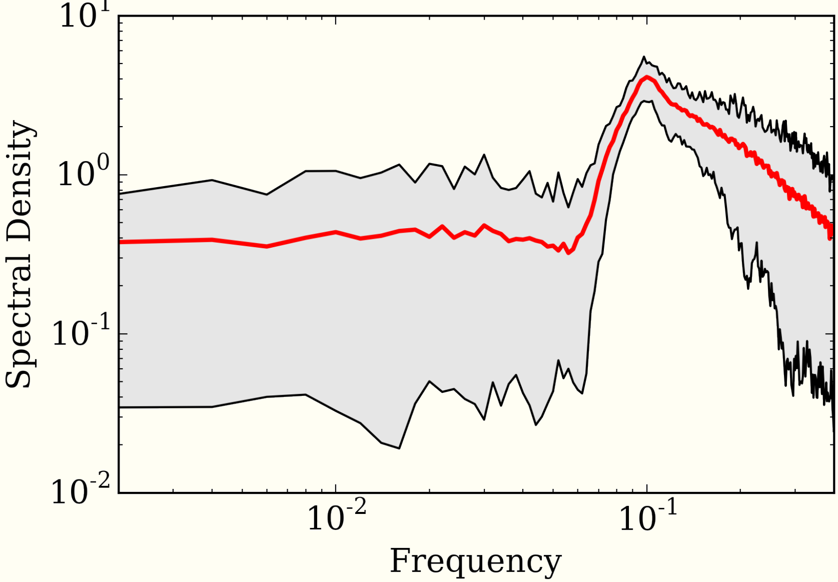
Example: $\alpha = 0$ and $\delta = 1 \rightsquigarrow \theta_c = 0.5\pi$

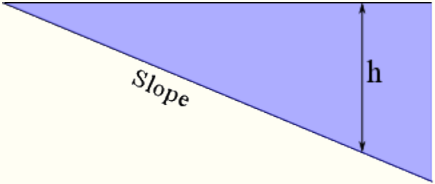
Dislodgement

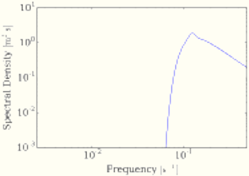


Duration of rotation: $T_r = t(\text{for}\,\theta = \theta_c) - t(\text{for}\,\Sigma\mathrm{F} = 0)$

$$I = \int_{t_o}^{t_o+T_r} \Sigma \mathbf{F} \mathbf{d}\mathrm{t} \geq I_c$$

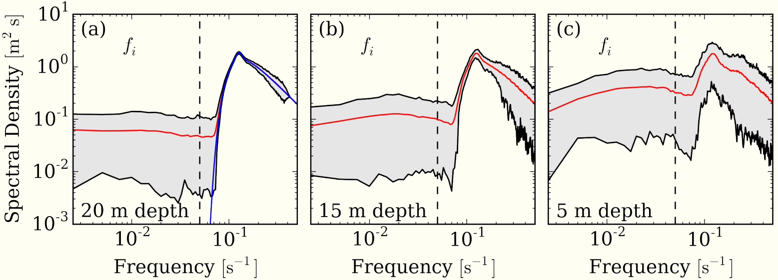

10^1
10^0
10^{-1}
10^{-2}
Spectral Density
10^{-2}
10^{-1}
Frequency





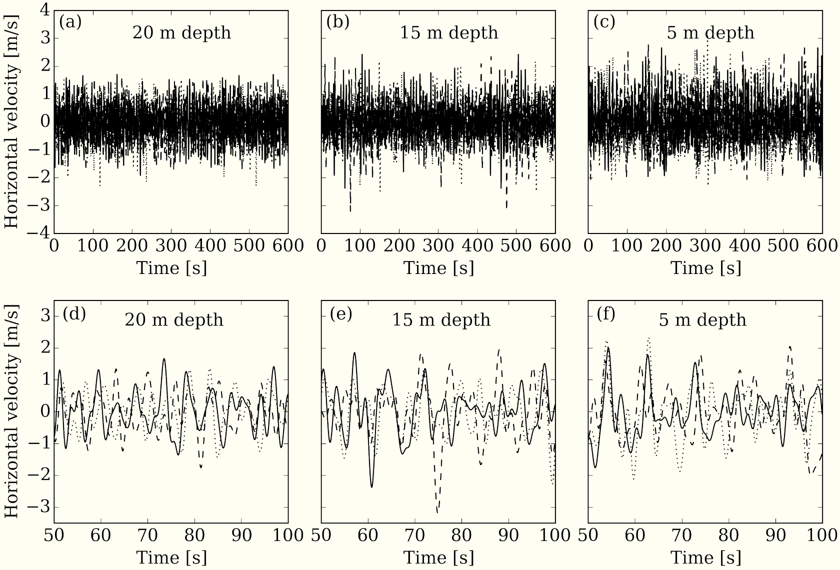
$$\frac{db_J}{dx} = -i \sum_{P,Q} W_{J,\pm P,Q} b_P b_Q e^{-i\Delta_{J,P,Q}\theta} \delta_{J,Q+P}$$

$$+ 2i \sum_{P,Q} W_{J,\pm P,Q} b_{-P} b_Q e^{-i\Delta_{J,-P,Q}\theta} \delta_{J,Q-P}. \quad (1)$$

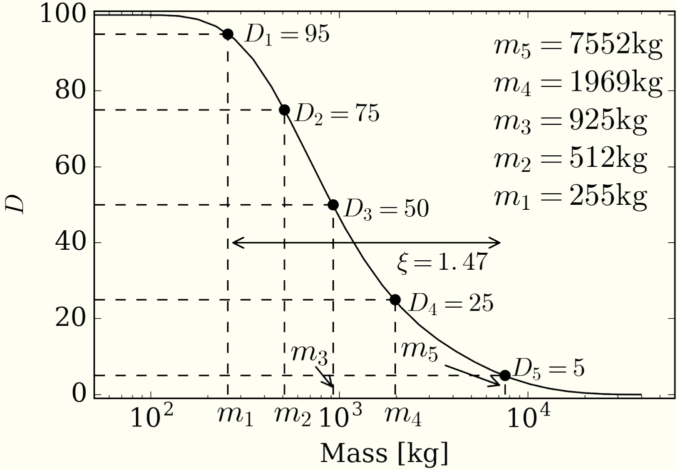


$$\tilde{E} = \frac{\int_{f>0.05}(\text{Spectral Density})}{\int_f(\text{Spectral Density})}$$

$$\tilde{E}_{(a)} = 5.6 \times 10^{-4},\ \tilde{E}_{(b)} = 2.3 \times 10^{-3},\ \tilde{E}_{(c)} = 2.6 \times 10^{-2}$$

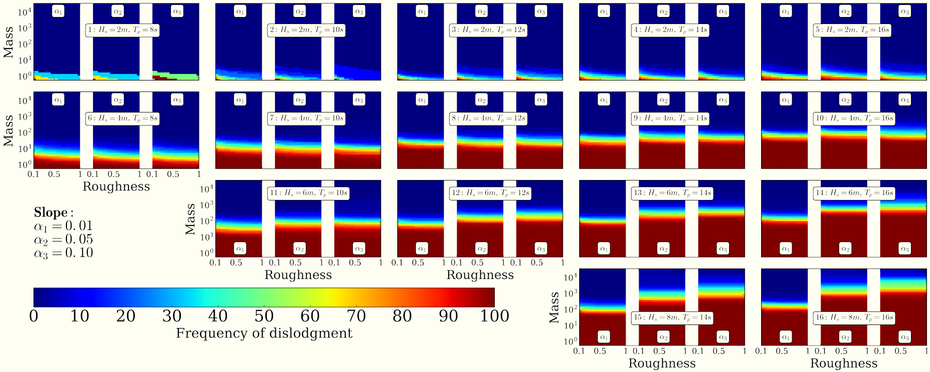


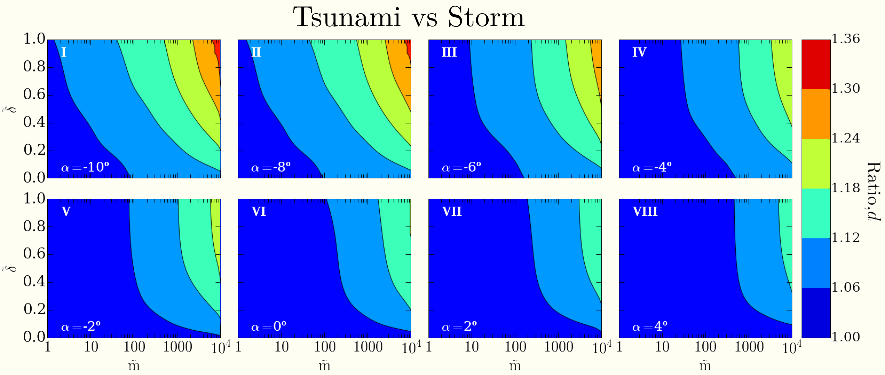
(a) 20 m depth
(b) 15 m depth
(c) 5 m depth
(d) 20 m depth
(e) 15 m depth
(f) 5 m depth
Horizontal velocity [m/s]
Time [s]



$$D = \frac{N_D}{N} \tag{2}$$

N is the total number of realizations ($N = 100$), and N_D is the number of realizations for which boulder dislodgement occurred.


1: $H_s = 2m$, $T_p = 8s$
2: $H_s = 2m$, $T_p = 10s$
3: $H_s = 2m$, $T_p = 12s$
4: $H_s = 2m$, $T_p = 14s$
5: $H_s = 2m$, $T_p = 16s$
6: $H_s = 4m$, $T_p = 8s$
7: $H_s = 4m$, $T_p = 10s$
8: $H_s = 4m$, $T_p = 12s$
9: $H_s = 4m$, $T_p = 14s$
10: $H_s = 4m$, $T_p = 16s$
11: $H_s = 6m$, $T_p = 10s$
12: $H_s = 6m$, $T_p = 12s$
13: $H_s = 6m$, $T_p = 14s$
14: $H_s = 6m$, $T_p = 16s$
15: $H_s = 8m$, $T_p = 14s$
16: $H_s = 8m$, $T_p = 16s$
α_1
α_2
α_3
Mass
Roughness
Slope:
$\alpha_1 = 0.01$
$\alpha_2 = 0.05$
$\alpha_3 = 0.10$
0 10 20 30 40 50 60 70 80 90 100
Frequency of dislodgment


Tsunami vs Storm
I
II
III
IV
V
VI
VII
VIII
α = -10º
α = -8º
α = -6º
α = -4º
α = -2º
α = 0º
α = 2º
α = 4º
δ̃
m̃
1.0
0.8
0.6
0.4
0.2
0.0
1
10
100
1000
10^4
Ratio, d
1.36
1.30
1.24
1.18
1.12
1.06
1.00

Sand

Suspend-load domain: The sediment in this domain is thought to be much smaller than the expected fluid structures, which results in a continuum model for particles in suspension and for the fluid. Theoretically there are N different grain-size classes in the domain. The different classes have a volume fraction of $\chi_s(t, \boldsymbol{x})$ with $s = 1, \ldots, N$. Hence, the volume fraction for the fluid is $\chi_0 = 1 - \sum \chi_k$. Furthermore, parameters with over-lines, such as $\overline{\chi}$, are averaged by the Favre method ($\chi' = \chi - \overline{\chi}$). The velocity of each grain-size class is denoted by $u_i^s(t, \boldsymbol{x})$; where a constant grain density is assumed for simplicity. The velocity of the fluid is denoted with $u^f(t, \boldsymbol{x})$. The velocity of the solid phase is $\widetilde{u}_i^s = (\overline{\chi u_i^s}) / (\overline{\chi_s})$ and of the fluid phase, $\widetilde{u}_i^f = (\overline{\chi_0 u_i^f}) / (\overline{\chi_0})$. The velocity fluctuations then become $\Delta u^f = u^f \widetilde{u}_i^f$ and $\Delta u_i^s = u_i^s - \widetilde{u}_i^s$. Using these definitions, the continuity and momentum equations for the fluid and solid phase can be derived. The continuity equation for the fluid phase is:

$$\frac{\partial \rho_f \overline{\chi_0}}{\partial t} + \partial \frac{\rho_f \overline{\chi_0} \widetilde{u}_i^f}{\partial x_i} = 0 \tag{1}$$

The momentum equation for the fluid phase is:

$$\frac{\partial \rho_f \overline{\chi_0} \widetilde{u}_i^f}{\partial t} + \frac{\rho_f \overline{\chi_0} \widetilde{u}_i^f \widetilde{u}_j^f}{\partial x_j} = -\overline{\chi_0} \frac{\partial \overline{P^f}}{\partial x_i} + \frac{\partial T_{ij}^{fT}}{\partial x_j} + \rho_f \overline{\chi_0} g_i + \sum_s \left(\beta \overline{\chi_s} \left(\tilde{u}_i^f - \tilde{u}_i^s \right) + \beta \nu_T \frac{\partial \overline{\chi_s}}{\partial x_i} \right) \tag{2}$$

The momentum equation for the solid phase is:

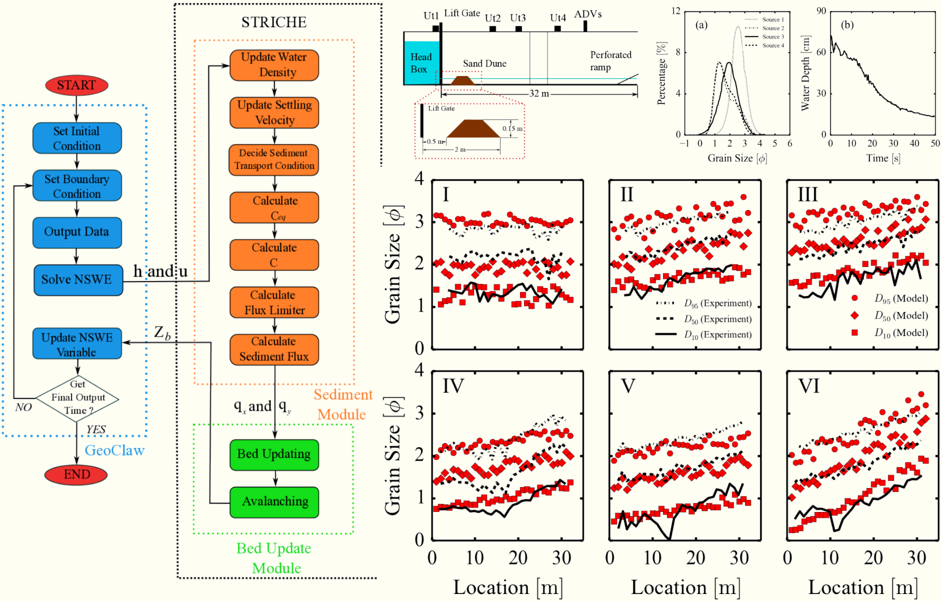
$$\frac{\partial \rho_s \overline{\chi_s} \widetilde{u}_i^s}{\partial t} + \frac{\rho_s \overline{\chi_s} \widetilde{u}_i^s \widetilde{u}_j^s}{\partial x_j} = -\overline{\chi_s} \frac{\partial \overline{P^f}}{\partial x_i} + \rho_s \overline{\chi_s} g_i - \beta \overline{\chi_s} \left(\tilde{u}_i^f - \tilde{u}_i^s \right) + \beta \nu_T \frac{\partial \overline{\chi_s}}{\partial x_i} \tag{3}$$

with T_{ij}^{fT} representing fluid stresses and P^f, the fluid pressure. For the fluid stresses, a respective turbulence-closure model, such as $k - \epsilon$, needs to be applied. Finally, the continuity equation for the solid phase is:

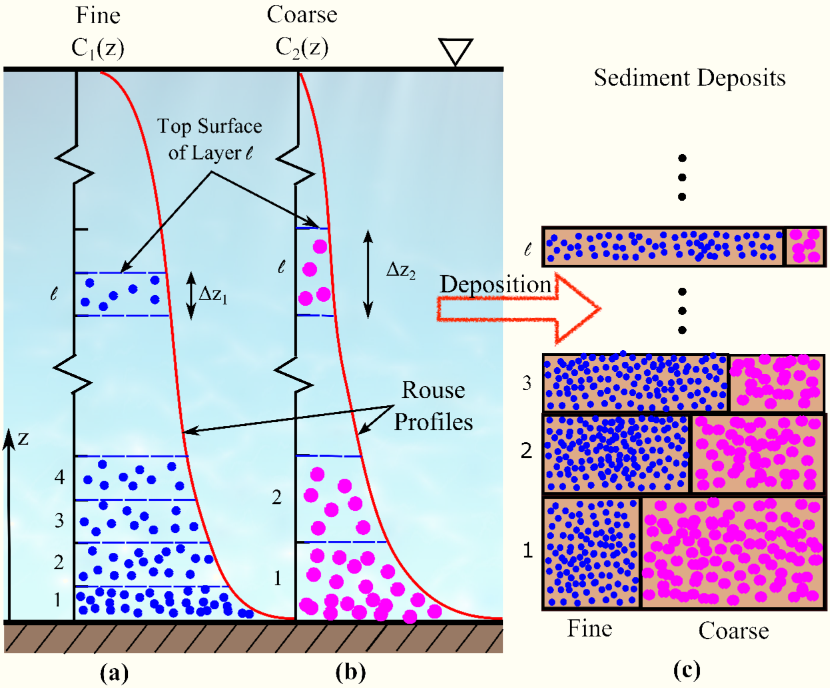
$$\frac{\partial \rho_s \overline{\chi}}{\partial t} + \partial \frac{\rho_s \overline{\chi} \widetilde{u}_i^s}{\partial x_i} = 0 \tag{4}$$

With the presented framework, the advection-diffusion equation becomes:

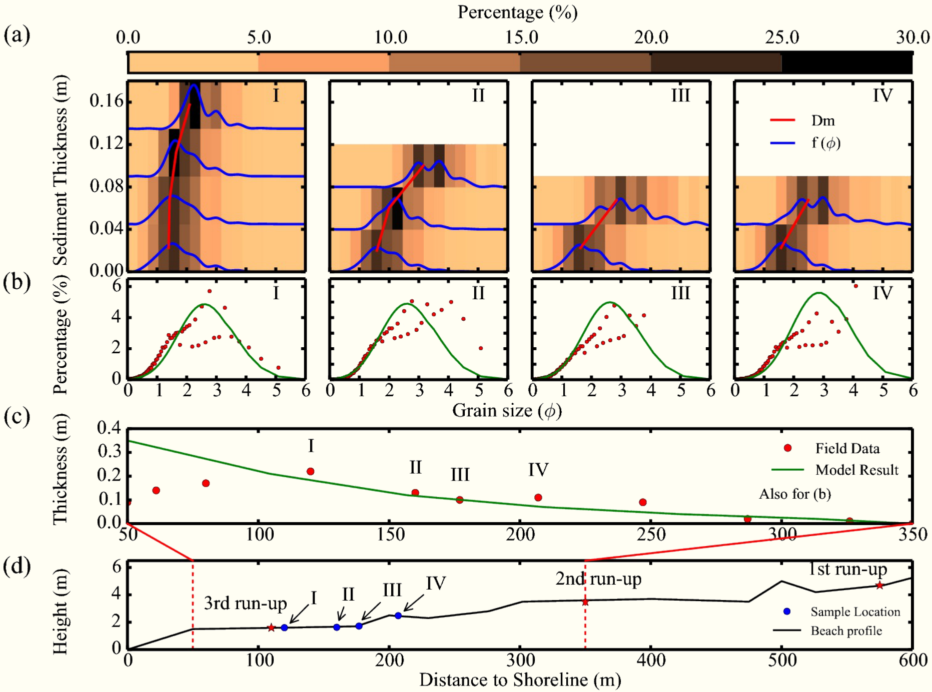
$$\frac{\partial \rho_s \overline{\chi_s}}{\partial t} + \frac{\partial}{\partial x_i} [(\tilde{u}_i - w_s \delta_{j3}) \rho_s \overline{\chi_s}] = \frac{\partial}{\partial x_i} \left(\frac{\nu_T}{\sigma_k} \frac{\partial \rho_s \overline{\chi_s}}{\partial x_i} \right) \tag{5}$$



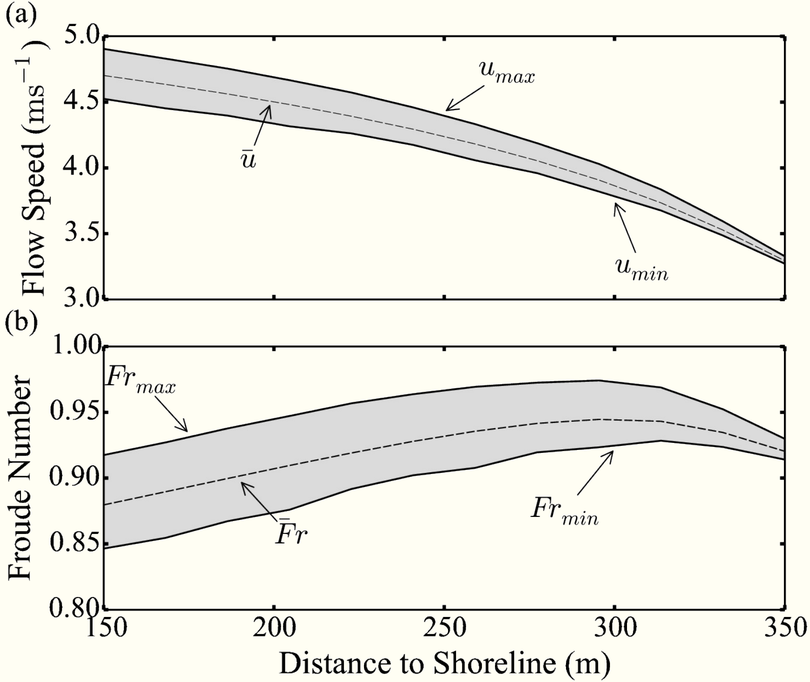
STRICHE
START
Set Initial Condition
Set Boundary Condition
Output Data
Solve NSWE
Update NSWE Variable
Get Final Output Time ?
NO
YES
END
GeoClaw
h and u
Z_b
Update Water Density
Update Settling Velocity
Decide Sediment Transport Condition
Calculate C_{eq}
Calculate C
Calculate Flux Limiter
Calculate Sediment Flux
Sediment Module
q_x and q_y
Bed Updating
Avalanching
Bed Update Module
Ut1
Lift Gate
Ut2
Ut3
Ut4
ADVs
Head Box
Sand Dune
Perforated ramp
32 m
Lift Gate
0.15 m
0.5 m
2 m
(a)
Source 1
Source 2
Source 3
Source 4
Percentage [%]
Grain Size [ϕ]
(b)
Water Depth [cm]
Time [s]
I
II
III
IV
V
VI
Grain Size [ϕ]
Location [m]
D_{95} (Experiment)
D_{50} (Experiment)
D_{10} (Experiment)
D_{95} (Model)
D_{50} (Model)
D_{10} (Model)



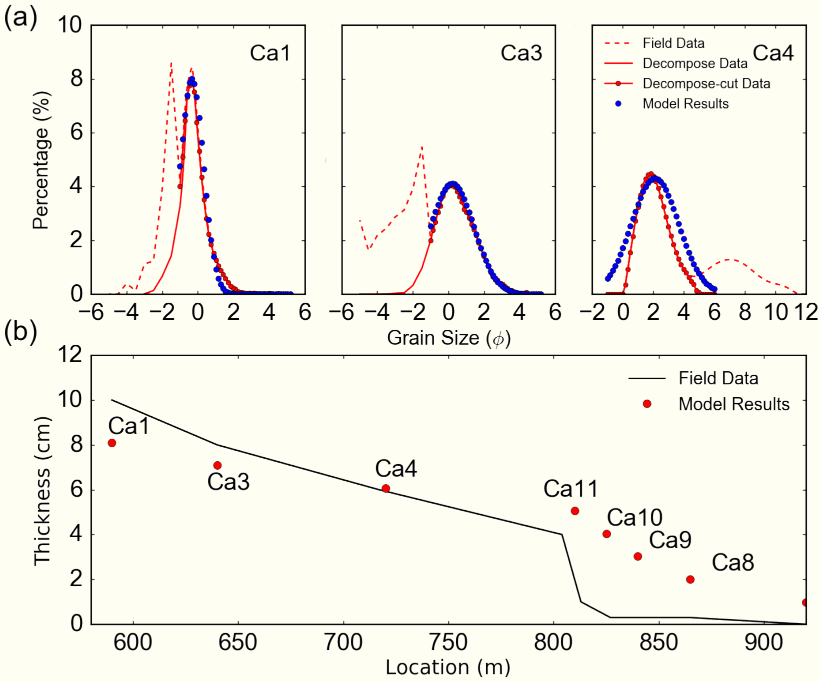
Fine
$C_1(z)$
Coarse
$C_2(z)$
Sediment Deposits
Top Surface
of Layer ℓ
ℓ
Δz_1
Δz_2
Deposition
Rouse
Profiles
z
4
3
2
1
(a)
(b)
(c)
Fine
Coarse

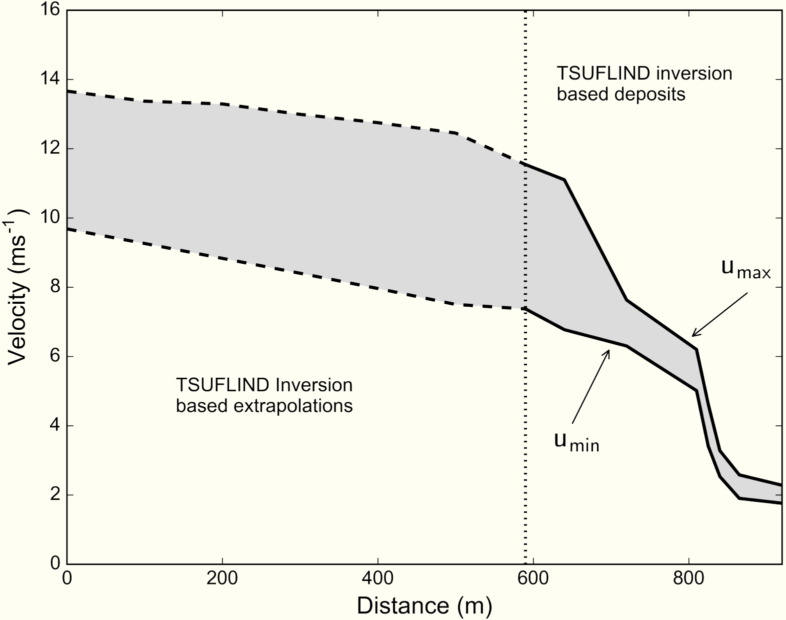


(a)
Percentage (%)
0.0
5.0
10.0
15.0
20.0
25.0
30.0
Sediment Thickness (m)
I
II
III
IV
Dm
f (ϕ)
(b)
Percentage (%)
Grain size (ϕ)
(c)
Thickness (m)
Field Data
Model Result
Also for (b)
(d)
Height (m)
3rd run-up
2nd run-up
1st run-up
Sample Location
Beach profile
Distance to Shoreline (m)

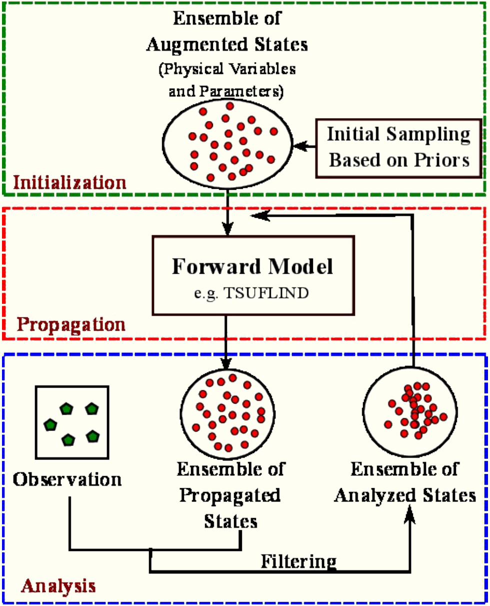


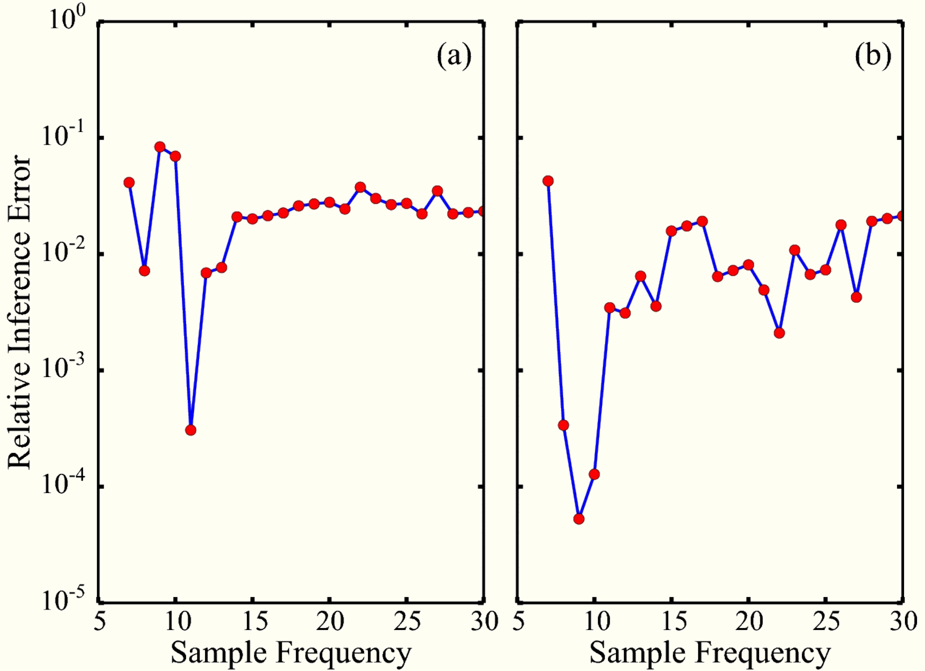
(a)
Flow Speed (ms^{-1})
5.0
4.5
4.0
3.5
3.0
u_{max}
$\bar{u}$
u_{min}
(b)
Froude Number
1.00
0.95
0.90
0.85
0.80
Fr_{max}
$\bar{F}r$
Fr_{min}
150
200
250
300
350
Distance to Shoreline (m)


(a)
Ca1
Ca3
Ca4
Field Data
Decompose Data
Decompose-cut Data
Model Results
Percentage (%)
Grain Size (ϕ)
(b)
Field Data
Model Results
Ca1
Ca3
Ca4
Ca11
Ca10
Ca9
Ca8
Thickness (cm)
Location (m)



TSUFLIND inversion
based deposits
TSUFLIND Inversion
based extrapolations
u_{max}
u_{min}
Velocity (ms⁻¹)
Distance (m)
0
2
4
6
8
10
12
14
16
0
200
400
600
800


Ensemble of
Augmented States
(Physical Variables
and Parameters)
Initial Sampling
Based on Priors
Initialization
Forward Model
e.g. TSUFLIND
Propagation
Observation
Ensemble of
Propagated
States
Ensemble of
Analyzed States
Filtering
Analysis



Relative Inference Error
Sample Frequency
Sample Frequency
(a)
(b)

Some Final Thoughts:

- It is difficult to separate storms from the tsunamis in the geologic record!
  - We need better models
  - We need better field data
  - We need better integration between field and Modeling
- Inferences of flow characteristcs carries uncertainties!
  - Move towards statistical physics
  - Machine Learning