Landslide Tsunami Hazard Assessment Approaches

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While not yet widely employed for tsunami impact studies, the Probabilistic Tsunami Hazard Assessment (PTHA) approach appears to be the inevitable future methodology for quantifying tsunami hazard. With PTHA, the user would be provided a probabilistic set of some characteristic quantity, such as runup or momentum flux, which would then be used to determine design loadings or used as the hazard index variable within a risk analysis (Geist and Parsons, 2005). The foundation for PTHA comes from Probabilistic Seismic Hazard Assessment (PSHA), a widely used method that provides, for example, a ground shaking or acceleration that has a 2% chance of exceedence over 50 years. There is not yet a widely accepted equivalent quantity for tsunami, although there have recently been a handful of studies demonstrating the approach for tsunamis generated by subduction zone earthquakes (e.g. Gonzalez et al., 2009).

A probabilistic assessment of earthquake-generated tsunami hazard is currently feasible due to available seismic information and a “simple” generation mechanism; however this is likely not the case for landslide-generated tsunami hazard. A lack of both geophysical data and fundamental understanding of the generation mechanism make probabilistic input distribution functions and logic trees highly subjective, and arguably so poorly constrained that any result is meaningless. It is the purpose of this study to better describe, in a probabilistic manner, one of the main inputs required of a PTHA. Here we attempt to develop a method to generate wave height exceedence curves for a given landslide by incorporating uncertainties on the slide motion description.

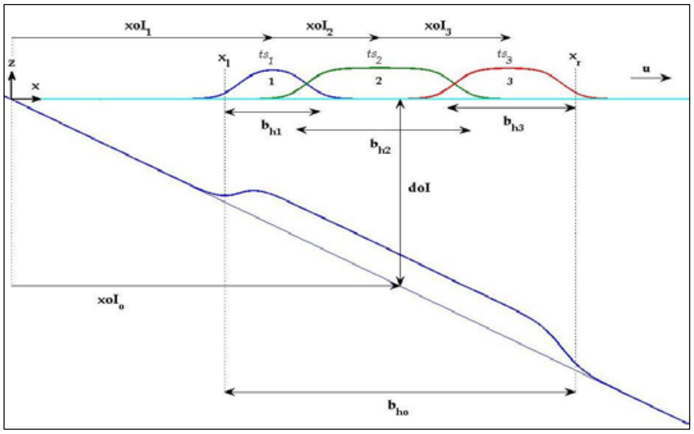
A numerical study aimed at probabilistically assessing the coastal hazard posed by tsunamis induced by one-dimensional submarine rigid landslides that experience translational failure is presented. The model utilized is a linear, fully dispersive mild-slope equation model for wave generation and propagation. This model has the capability of simulating submarine landslides that detach into multiple rigid pieces as failure occurs. Monte Carlo simulations are employed, with an emphasis on the shoreward-traveling waves, to construct probability of exceedance curves for the maximum dimensionless wave height, from which wave statistics can be extracted. As inputs to the model, eight dimensionless parameters are specified both deterministically in the form of parameter spaces and probabilistically with normal distributions. Figure 1 provides the basic setup and result of the approach. In the top subplot, we see that a single “specified” landslide is allowed to break up into three different slide pieces; Nc=3 for this example. In the lower subplot are exceedence curves for a landslide allowed to break into various pieces (Nc’s). Immediately obvious is that slide masses that break into fewer pieces have the potential, on average, to generate larger wave heights. On the other hand, for certain unlikely scenarios, it is possible for a slide that disintegrates into 2 or 3 pieces to in fact generate a larger landward traveling wave than the single coherent (Nc=1) slide. The reason for this is that the waves generated by the individually moving pieces can superimpose if the timing is “right,” generating a concentration of wave energy larger than that possible with the single slide. Such events, albeit unlikely, are very important for PTHA type studies, particularly when the facility of interest requires very low risk and recurrence, such as a Nuclear Power Plant.

References:

Geist, E. L., and T. Parsons (2005): ***Probabilistic Analysis of Tsunami Hazards***, *Nat. Hazards, 37 (3), 277-314.*

González, F.I., E.L. Geist, B. Jaffe, U. Kânoğlu, H. Mofjeld, C.E. Synolakis, V.V. Titov, D. Arcas, D. Bellomo, D. Carlton, T. Horning, J. Johnson, J. Newman, T. Parsons, R. Peters, C. Peterson, G. Priest, A. Venturato, J. Weber, F. Wong, and A. Yalciner (2009): ***Probabilistic tsunami hazard assessment at Seaside, Oregon for near- and farfield sources***. *J. Geophys. Res., 114, C11023.*

- Deterministic Inputs:
- *Nc* – Number of detached pieces (Nc=3 in figure)
- *b* – slide width along slope to thickness ratio
- *doI* – depth above slide center to thickness ratio
- *slope* – bottom slope
- *delay*–dimensionless factor scaling failure duration



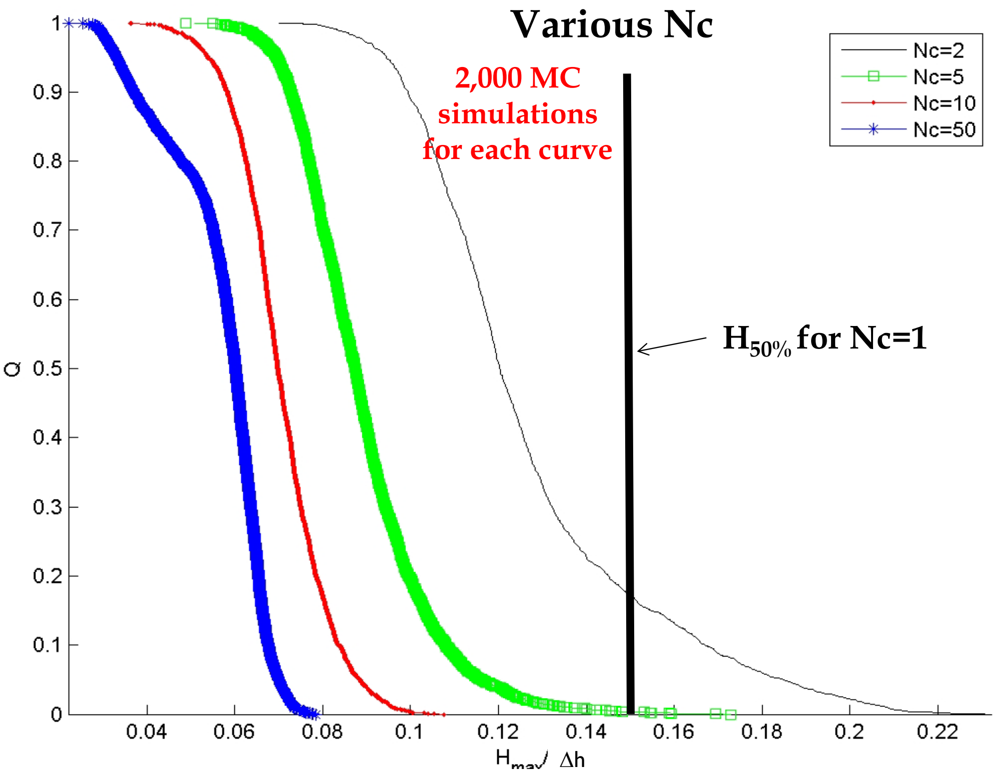


Figure 1. Setup and example results for wave height generation by landslide assessment. In the lower plot are probability of exceedence (Q) curves for different Nc values, with the horizontal axis showing the generated wave height (H_{max}) scaled by the initial slide thickness (Δh).

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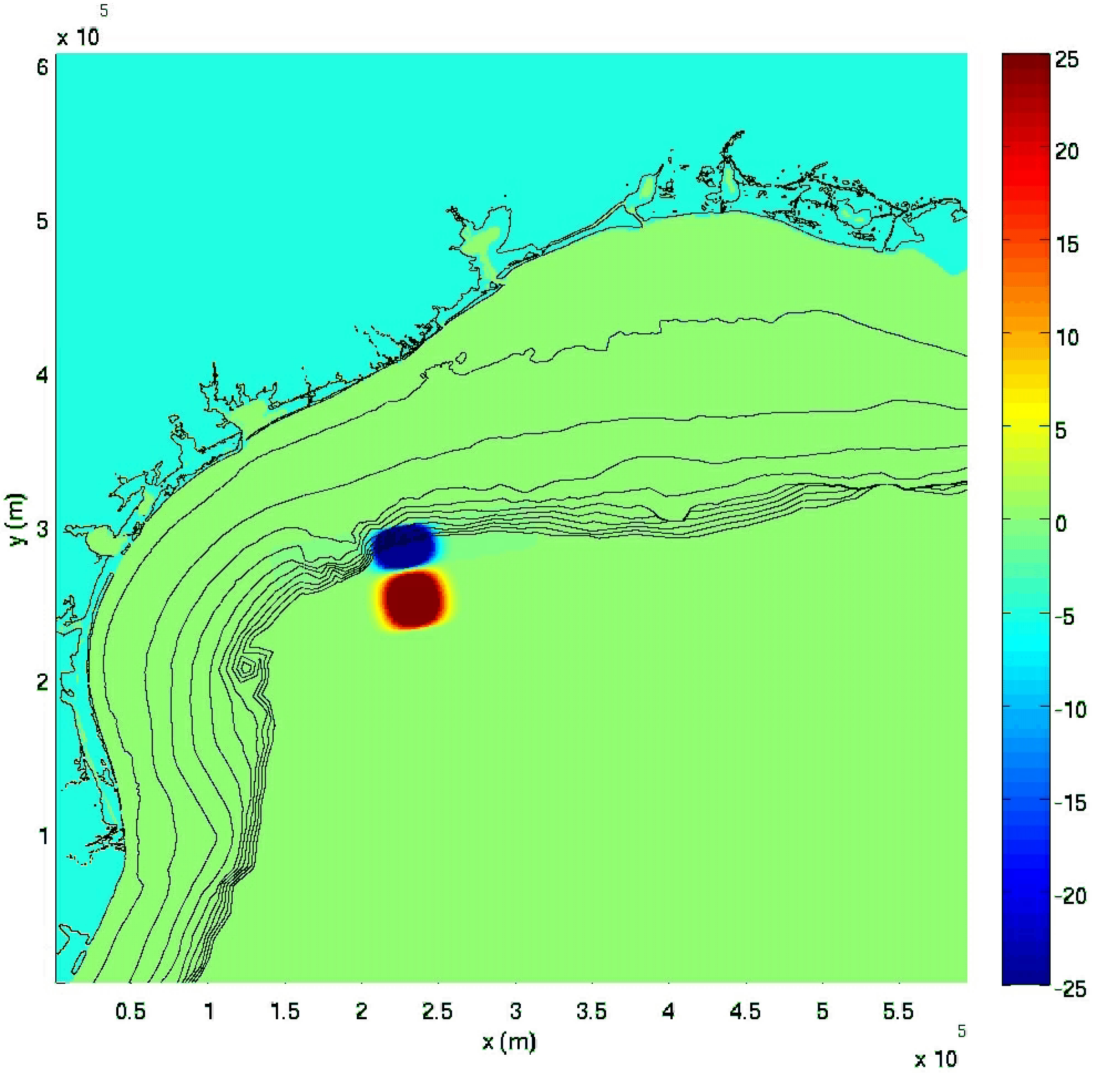

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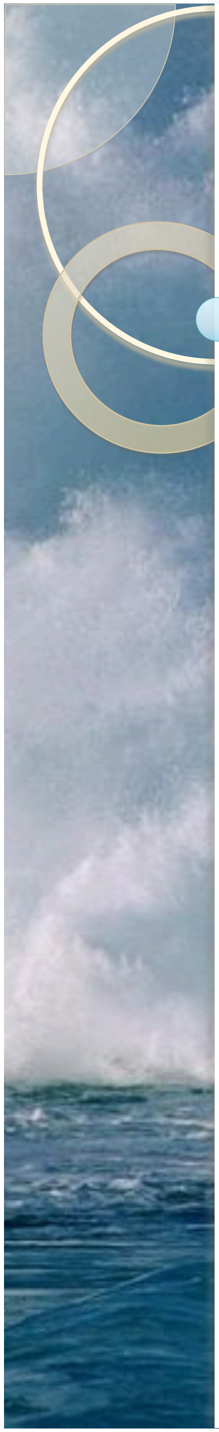


Outline

General Approach for Site Safety Assessment for New Nuclear Reactor Applications

- Work done with Nuclear Regulatory Commission (NRC) & USGS over past 4 years
- Highly conservative, Probable Maximum Tsunami (PMT)

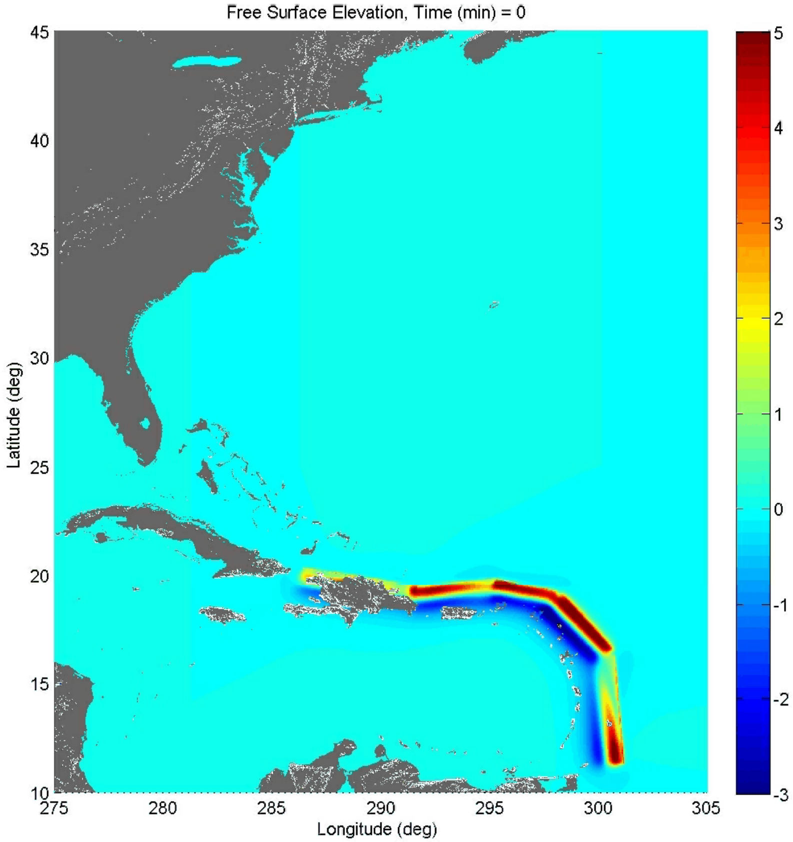
Probabilistic Approach for the Waves Generated by a Specified Landslide

- Not looking at return periods
- Specify some parameter distribution / uncertainty (e.g slide speed, slide “coherency”, etc)
- Quantify how the generated wave height reacts to this uncertainty -> probability of exceedence curve for H

Determining the PMT – NRC Approach

Develop a hierarchal approach

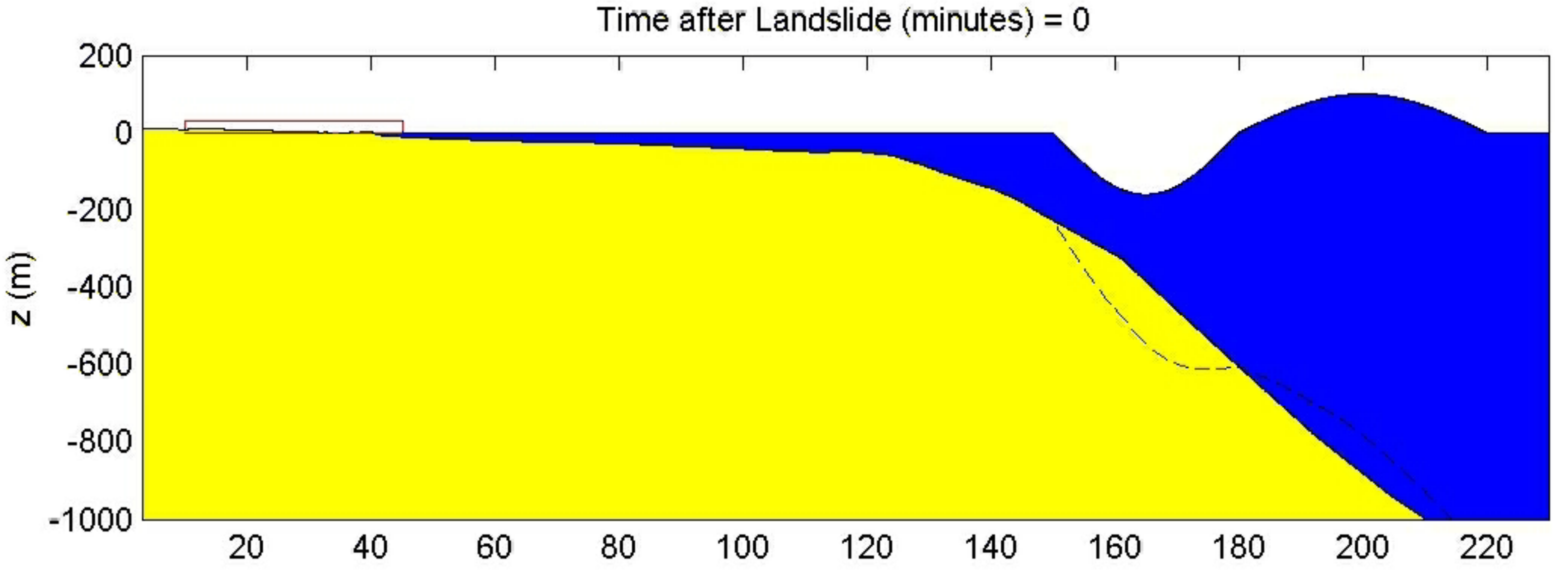
- Identify any earthquake or landslide source that could conceivably impact the site
- For earthquakes, use the maximum earthquake that the fault could produce (not based on local historical precedent)



Determining the PMT – NRC Approach

Develop a hierarchal approach

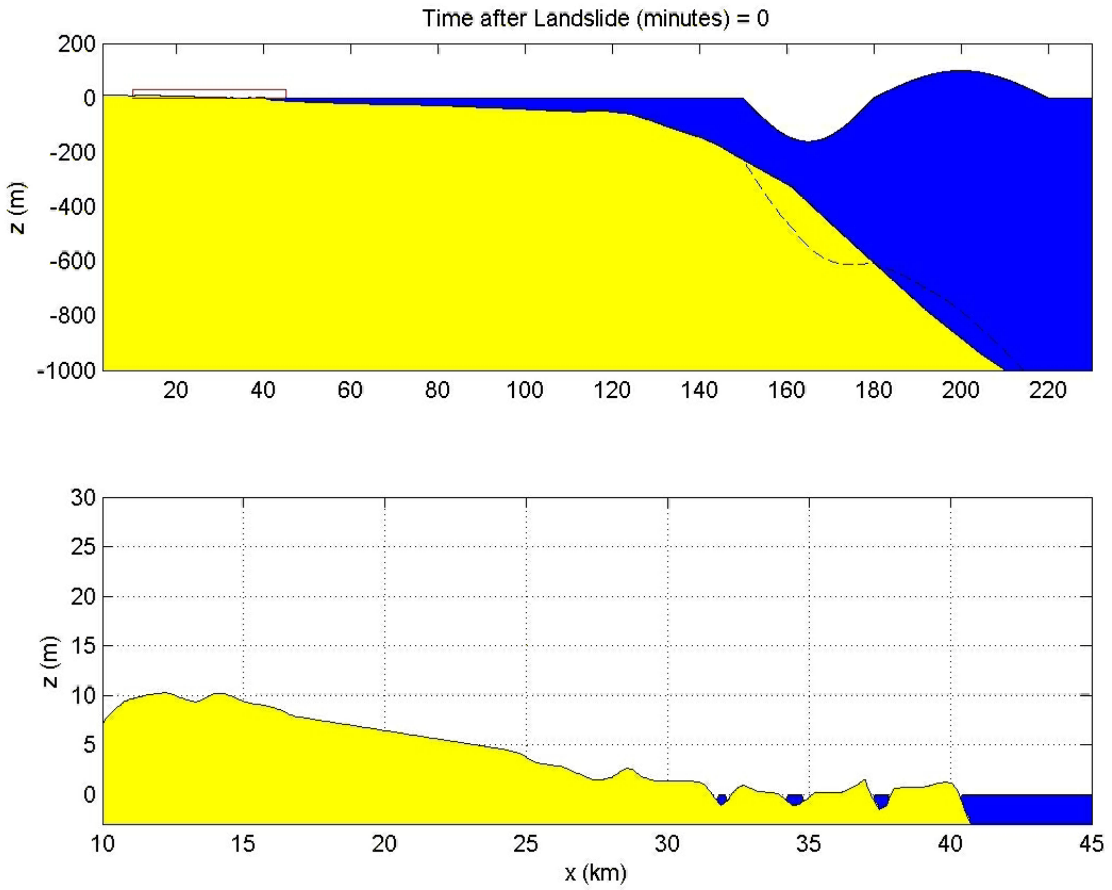
- Identify any earthquake or landslide source that could conceivably impact the site
- For landslides, use existing bathymetry data to map the dimensions of the failure
- Assume the slide failed all at once and quickly, such that the generated tsunami has an initial amplitude equal to the slide scarp depth (slide thickness)
- For local slides, start with 1HD simulations (equivalent to the entire offshore shelf failing simultaneously



Determining the PMT – NRC Approach

Develop a hierarchal approach

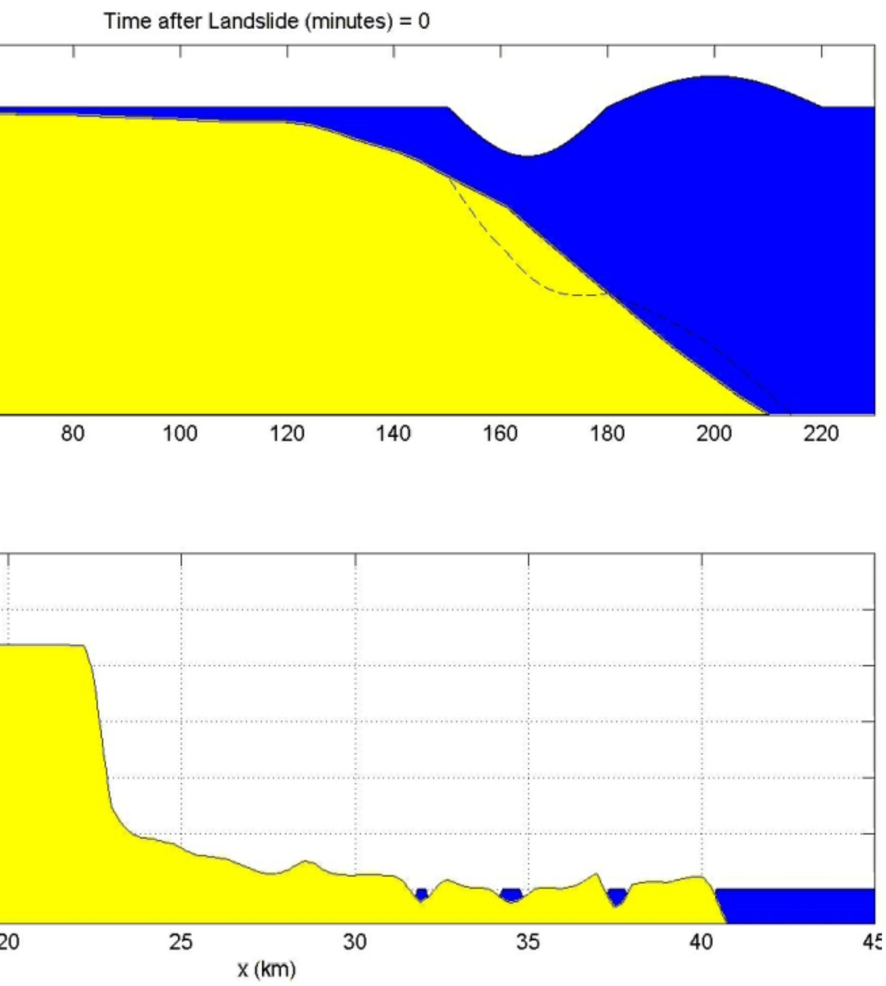
- For runup & inundation, start with assuming the entire land area is hydraulically smooth

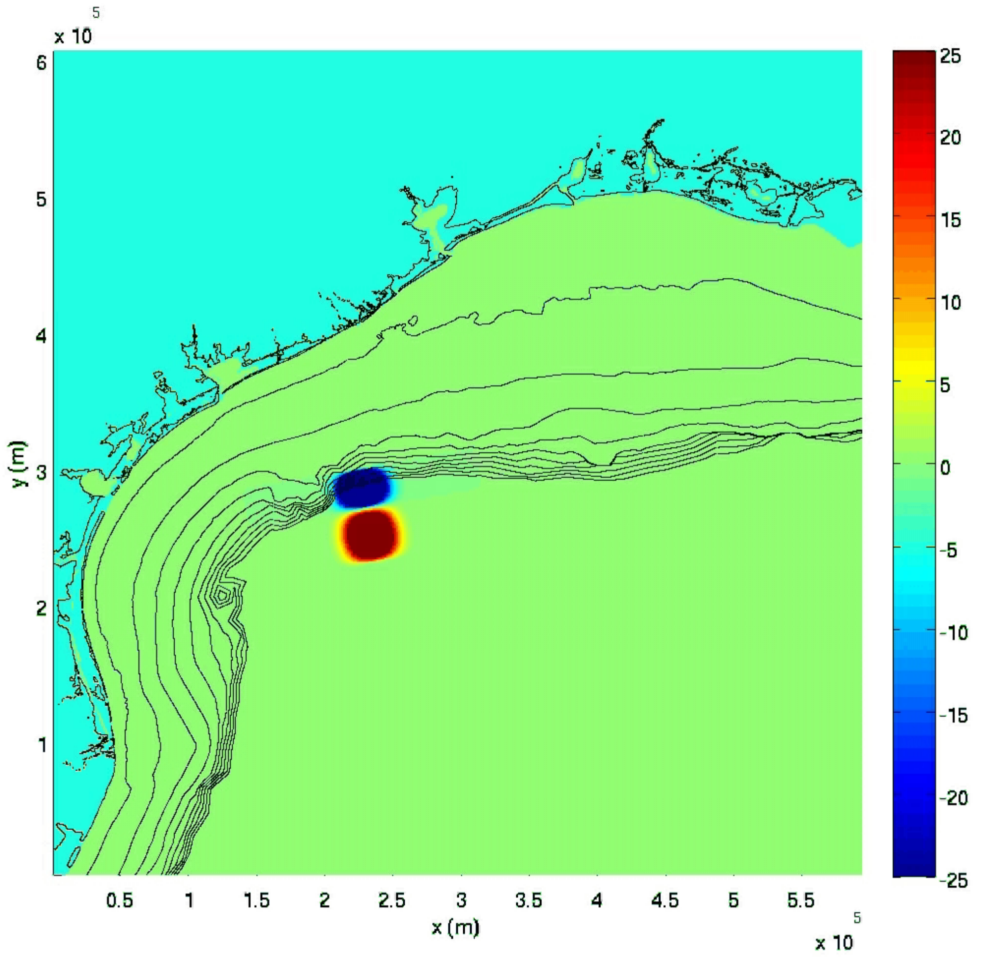


Determining the PMT – NRC Approach

Develop a hierarchal approach

- If this condition floods the inland location of interest, then perform a 1HD simulation with "realistic" friction, and perform a 2HD simulation to quantify radial spreading effects





Determining the PMT – NRC Approach

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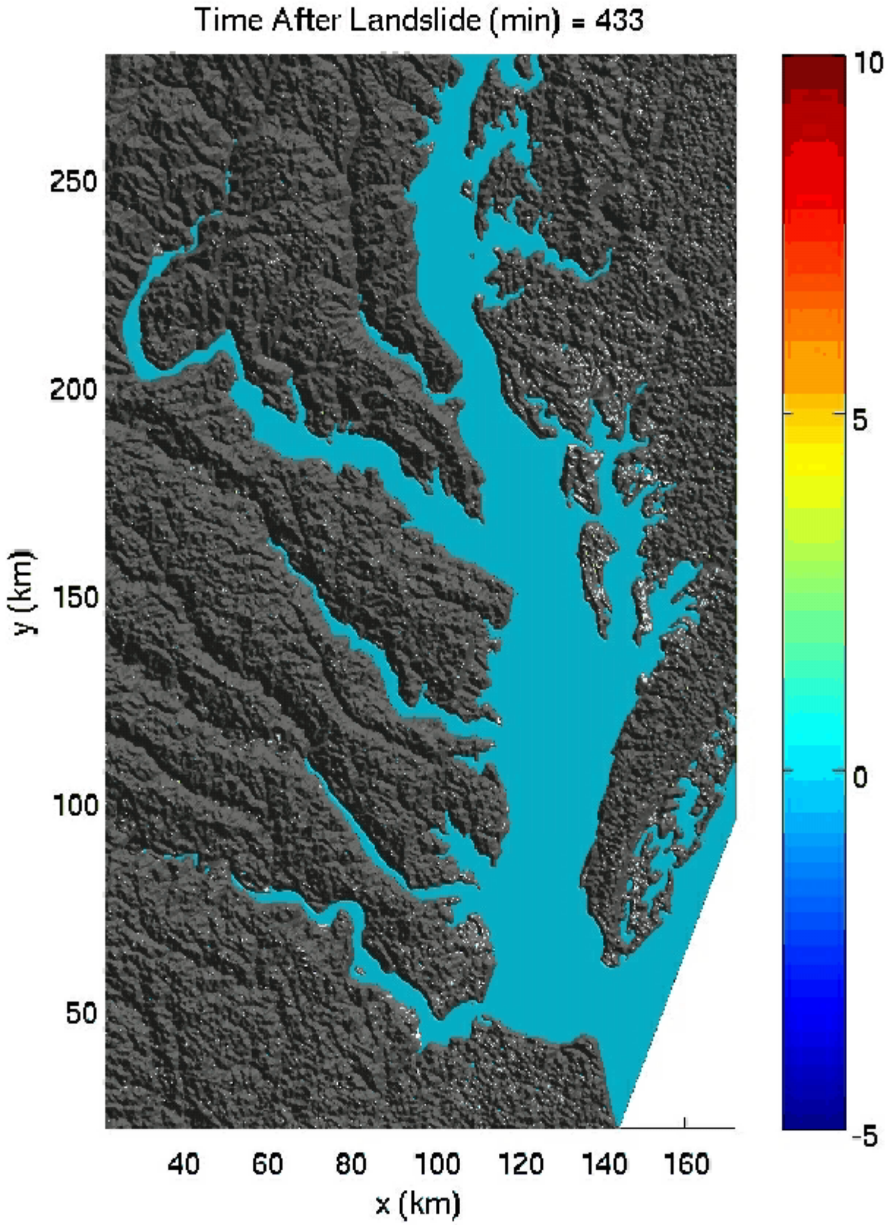
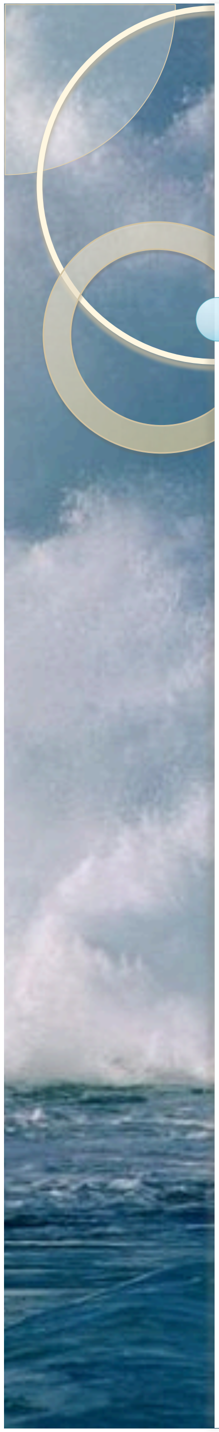


Also perform a 2HD simulation for any source with 1HD-modeled inundation near the site, to quantify possible refractive focusing

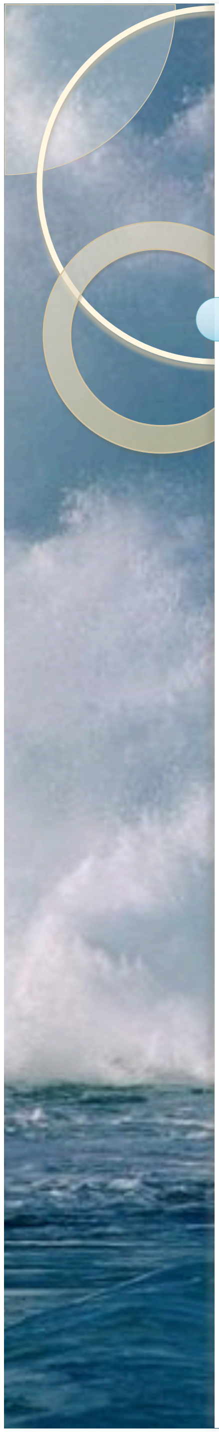


Determining the PMT – NRC Approach

- Develop a hierarchal approach
  - If either of these conditions impact the inland site, then the time-history of the landslide motion should be modeled, using conservative and realistic slide motions
  - If these impact the site, then that particular tsunami source is a candidate for the PMF (probably maximum flood – the constraining design condition)

Approach is very useful for tsunami hazard assessment of nuclear facilities

- Start with the most conservative approach, and remove levels of conservatism **if needed**
- Not very useful for anything else… where a less extreme approach is justified.



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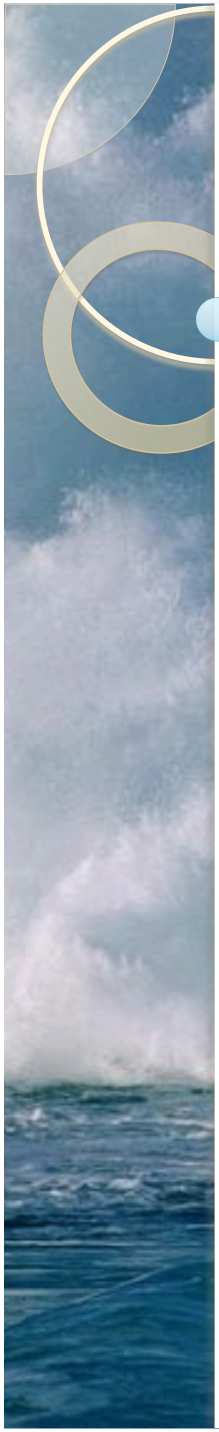
- **Specify some parameter distribution / uncertainty (e.g slide speed, slide "coherency, etc)**
- **Quantify how the generated wave height reacts to this uncertainty -> probability of exceedence curve for H**

-> develop a "simple" model to predict the free surface response to an arbitrary slide time history, then Monte-Carlo it to provide some statistical measure of height



Linear Mild-Slope Equation

(Dingemans, 1997; Bellotti *et al*., 2008; Cecioni & Bellotti, 2010)

Free surface evolution equations (z=0):

$$\eta_t = G\varphi - \nabla\cdot(F\nabla\varphi)\boxed{-h_t}$$

$$\left(\quad F = \frac{ccg}{g} \; ; \; G = \frac{w^2 - k^2 ccg}{g} \quad \right)$$

$$\varphi_t = -g\eta$$

Mild-Slope Equation:

$$\eta_{tt} - \nabla\cdot(gF\nabla\eta) + gG\eta = h_{tt}$$

Time-dependent

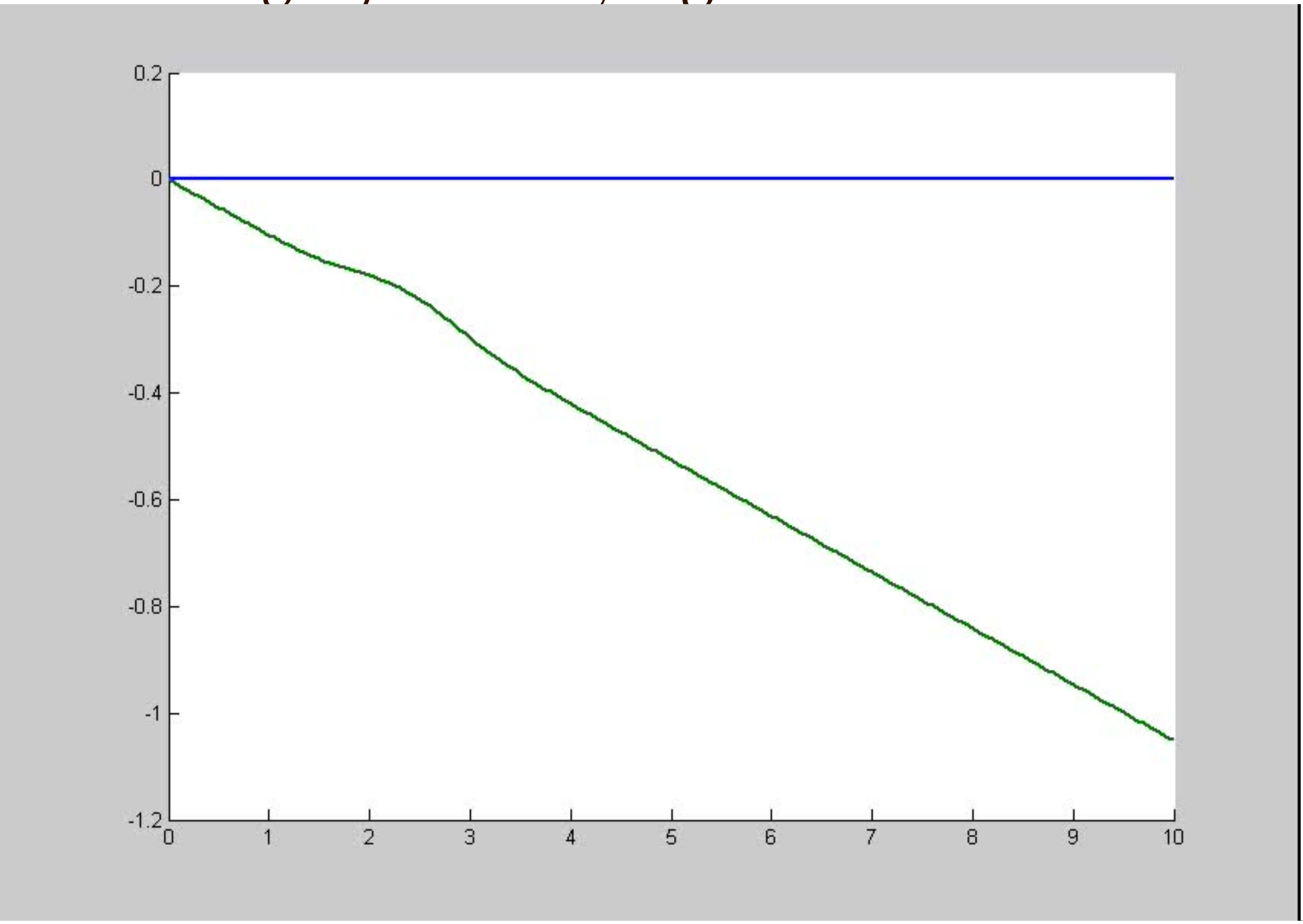
$\Big\downarrow$ FFT in time

$$\nabla\cdot(ccg\nabla N) + w^2\frac{cg}{c}N = \frac{1}{\underbrace{\cosh(kh)}}H$$

Frequency-dependent

1-D Model Validation

Slide of Lynett & Liu (2002): 0.05-m thick, 1-m long moving w/ a decaying acceleration on 6°-slope

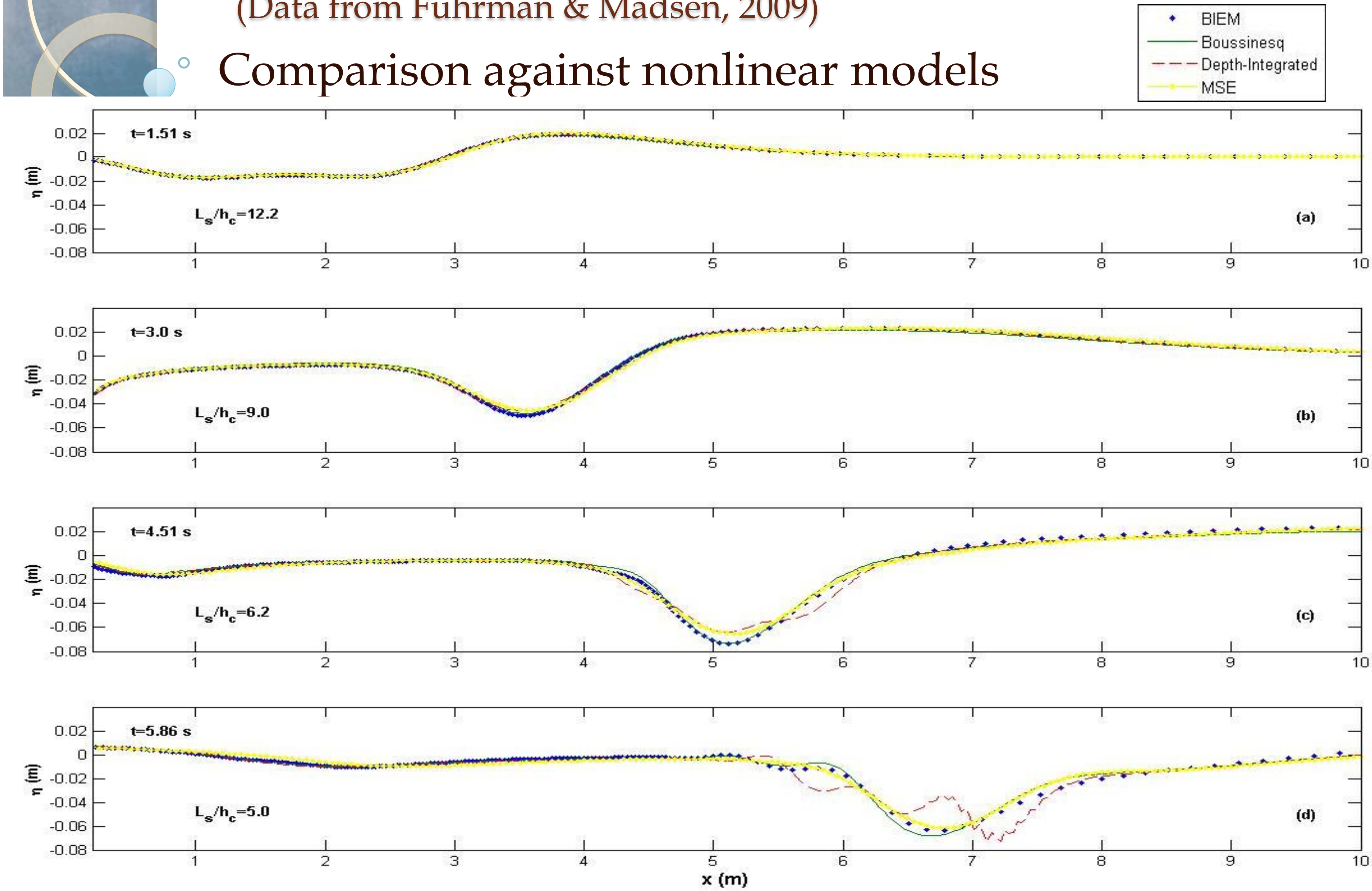


dx=5 cm
dt=0.1 s

1-D Model Validation

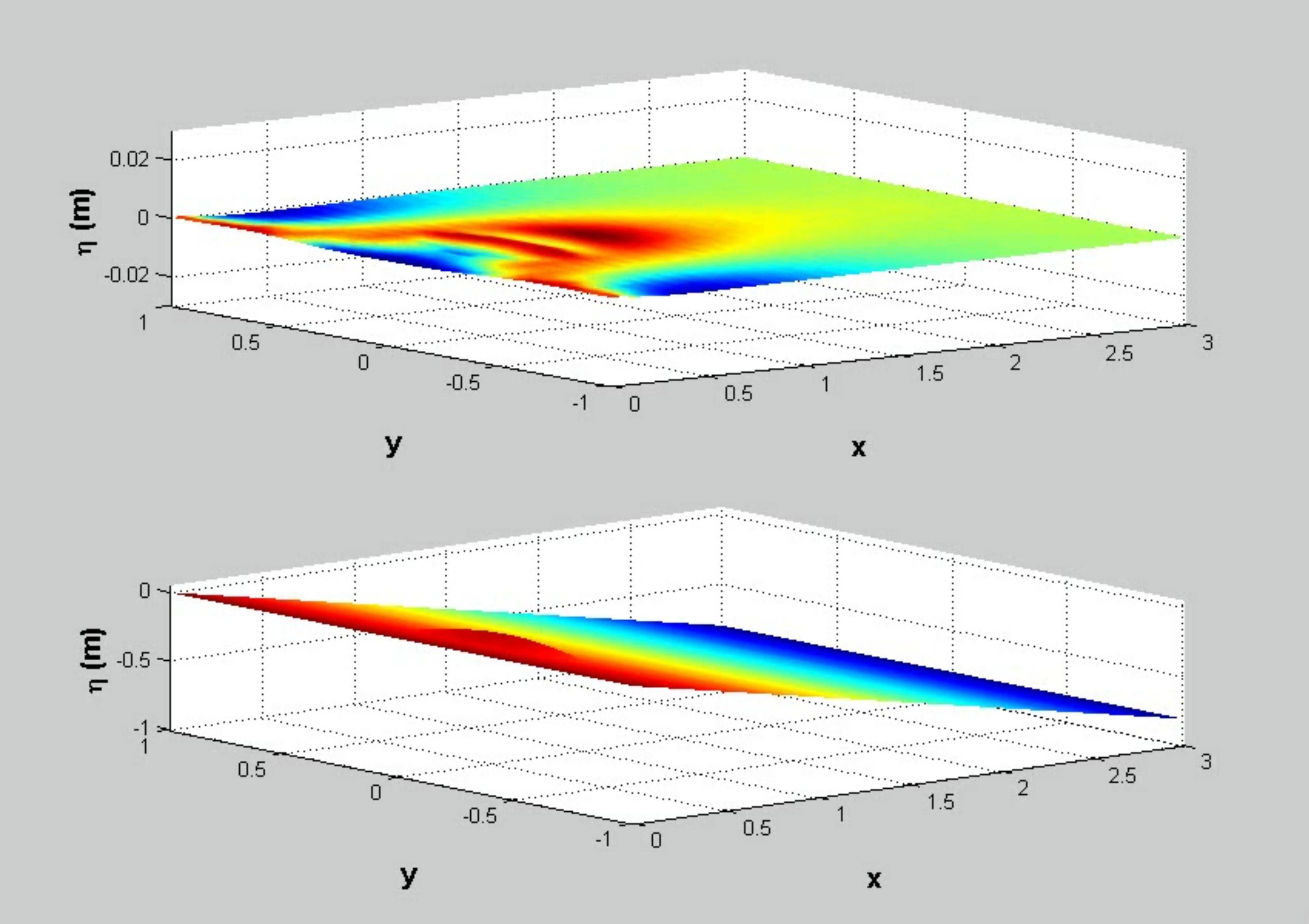
(Data from Fuhrman & Madsen, 2009)

- Comparison against nonlinear models



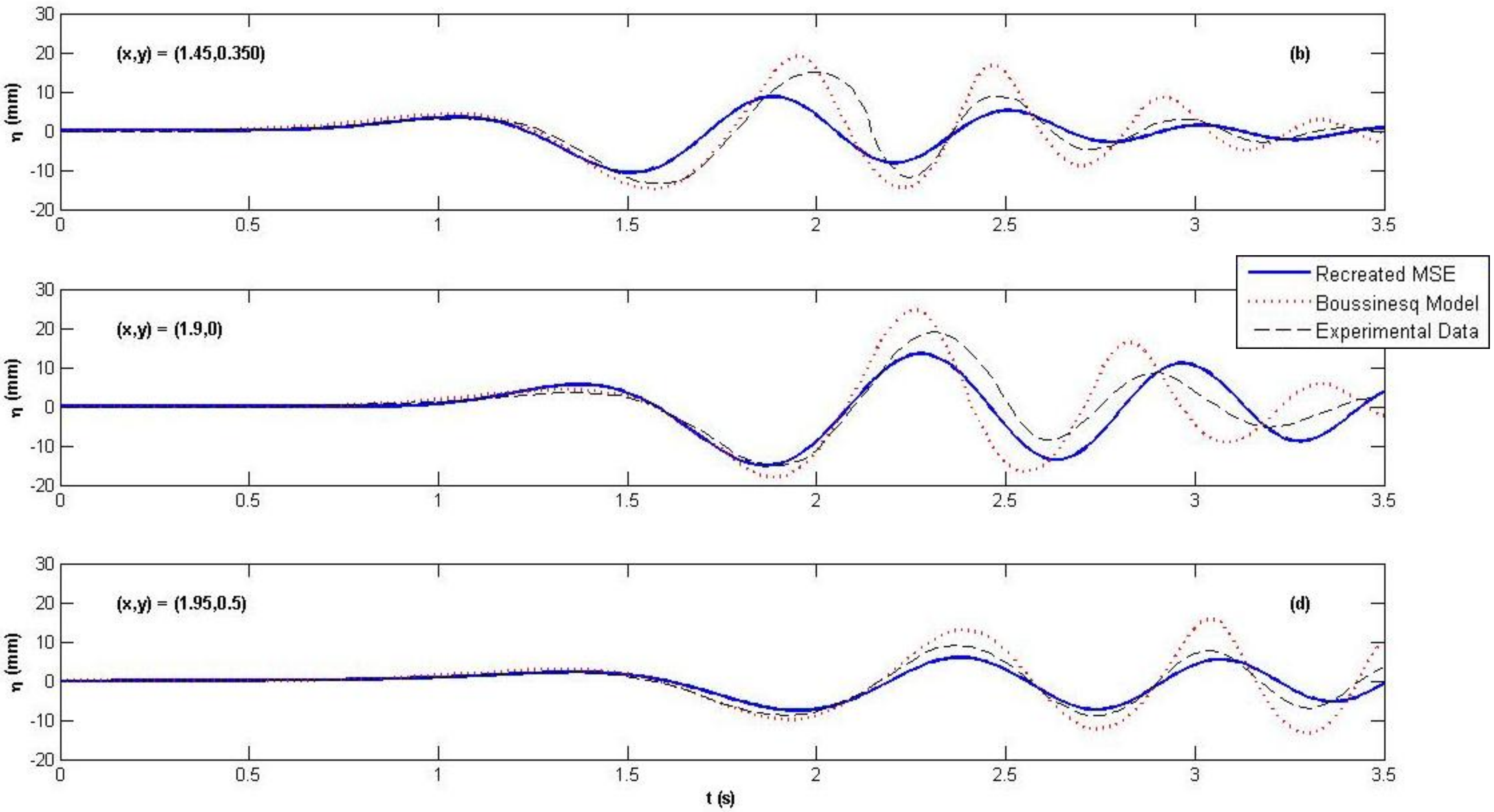
2-D Model Validation

Slide of Enet & Grilli (2007): 0.082-m thick, 0.395-m long, 0.680-m wide traveling w/ a decaying acceleration on a 15°-slope



2-D Model Validation

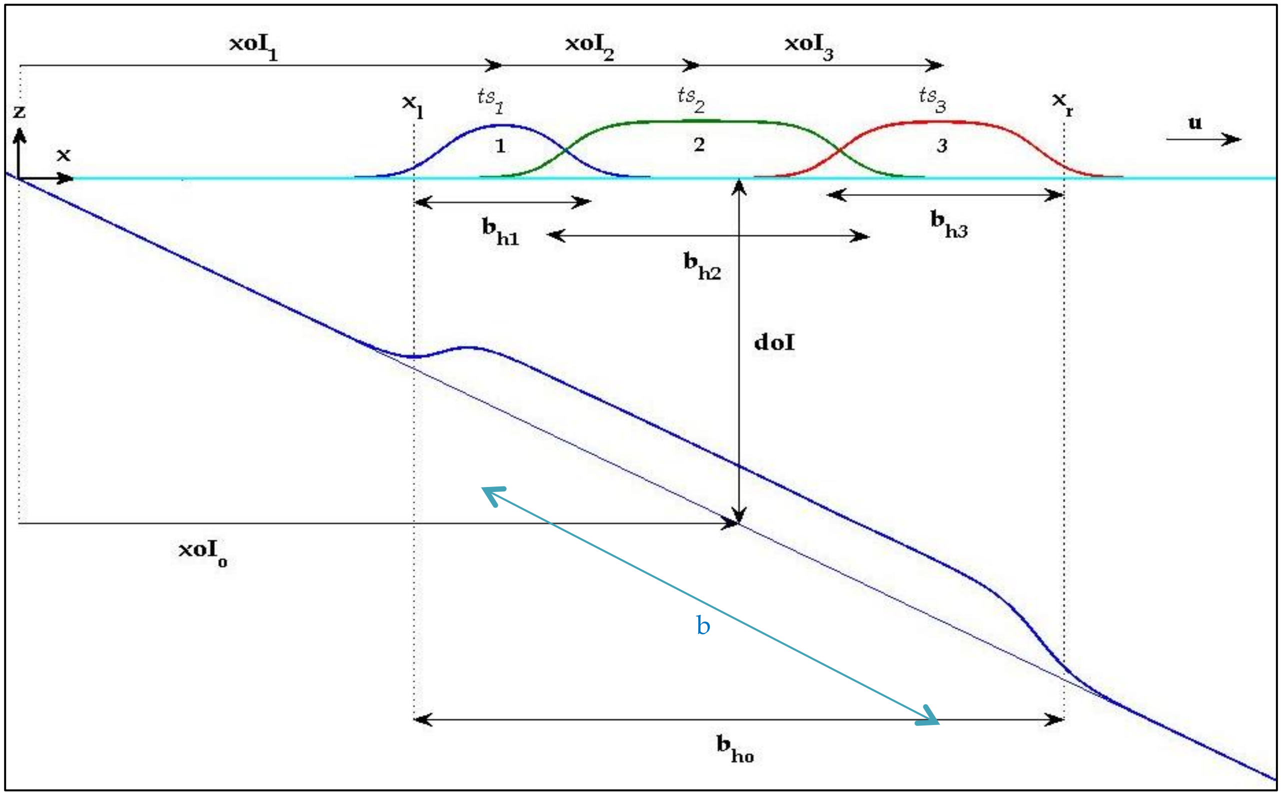
Digitized time series from Fuhrman & Madsen (2009)



Probabilistic Approach: 1HD Inputs

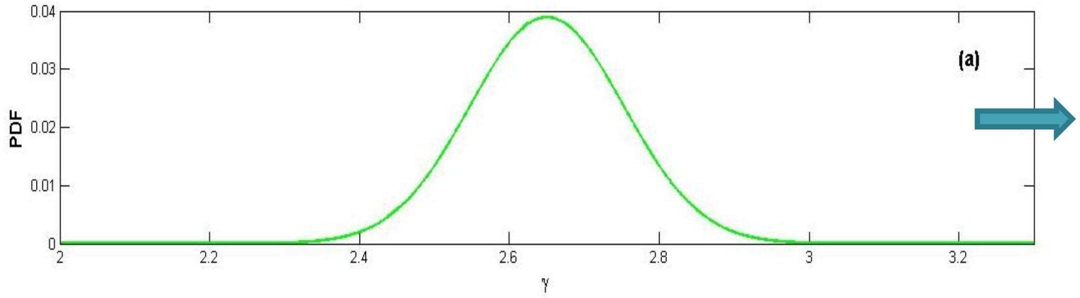
Deterministic Inputs:

- *Nc* – Number of detached pieces (Nc=3 in figure)
- *b* – slide width along slope to thickness ratio
- *doI* – depth above slide center to thickness ratio
- *slope* – bottom slope
- *delay*–dimensionless factor scaling failure duration



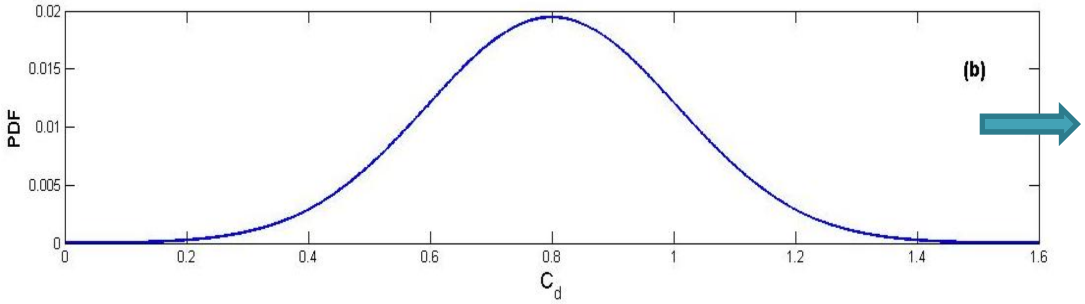
Probabilistic Approach: Inputs

Parameters randomized with normal distributions:



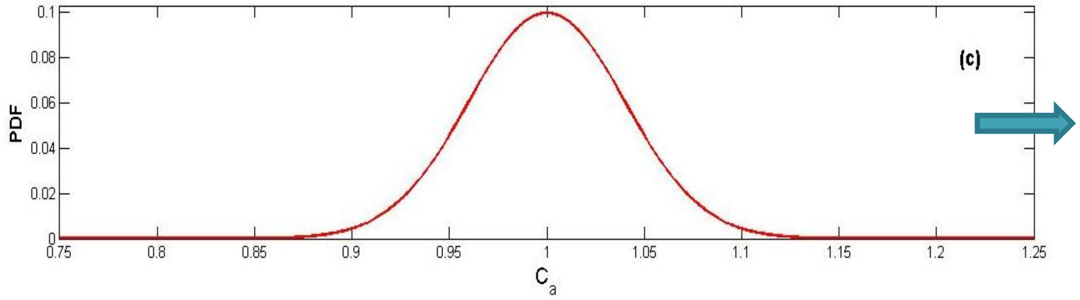
Specific weight
(γ)

μ =2.65, σ =12%



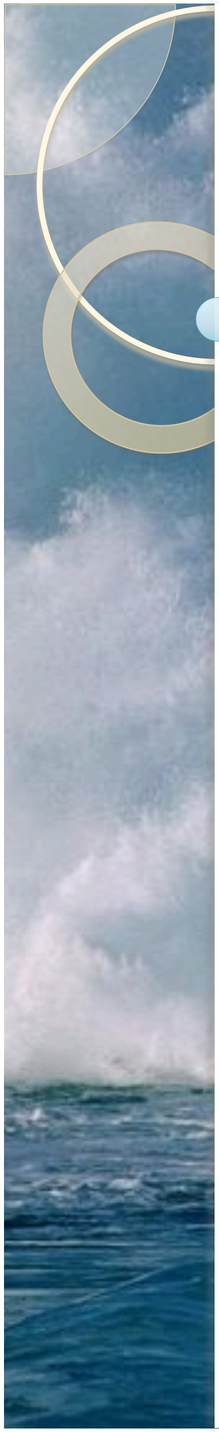
Drag Coefficient (C_d)

μ =0.8, σ =56%



Added-mass
Coefficient (C_a)

μ =1.0, σ =20%



Probabilistic Approach: Slide Motion

The relative width of each slide “piece” is randomized

The time interval between motion initialization of each “piece” is randomized

Velocity evolution and displacement for each piece are

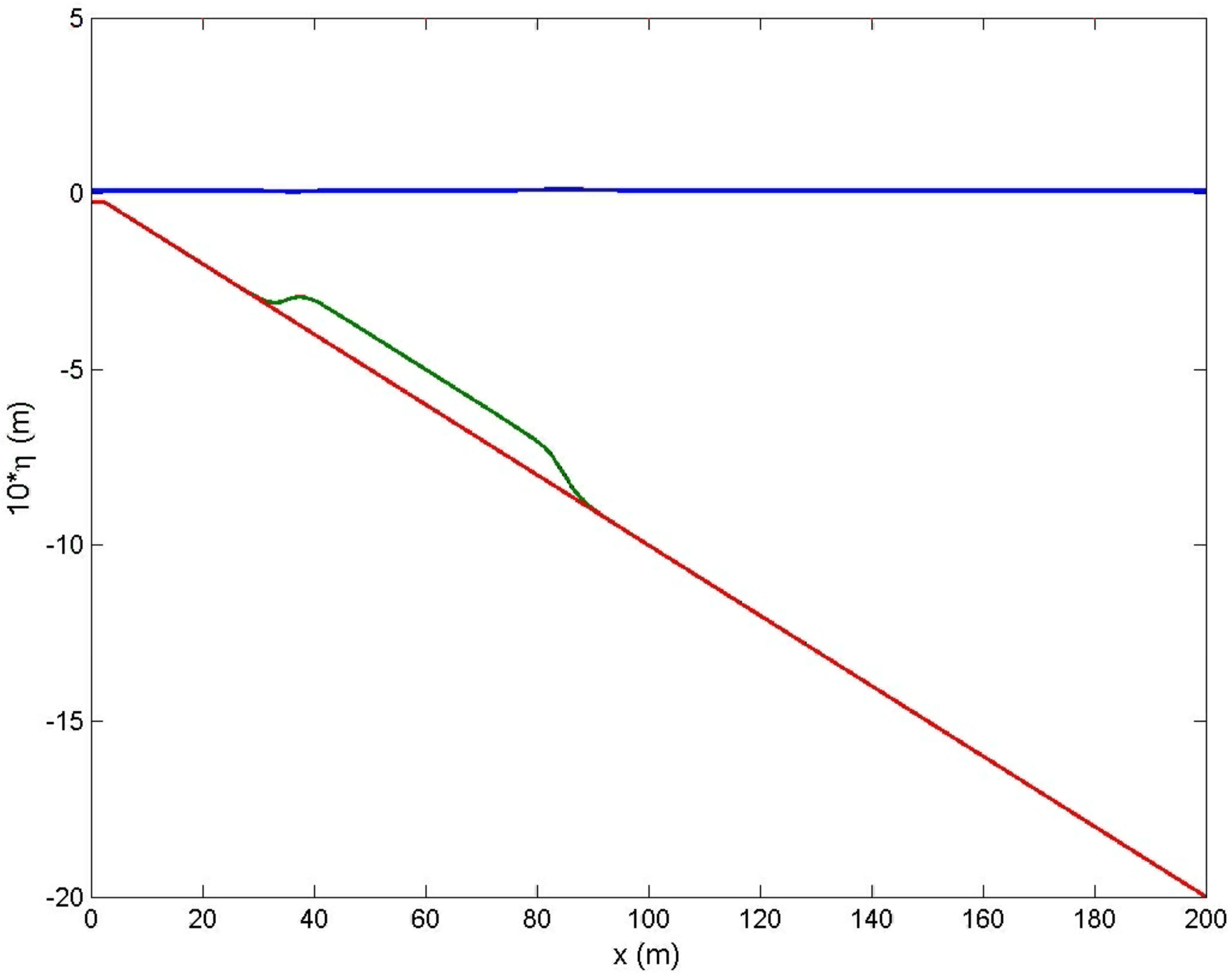
$$u_c = u_t \tanh\left(\frac{t - ts}{t_o}\right) \qquad ds = ds + u_c * dt$$

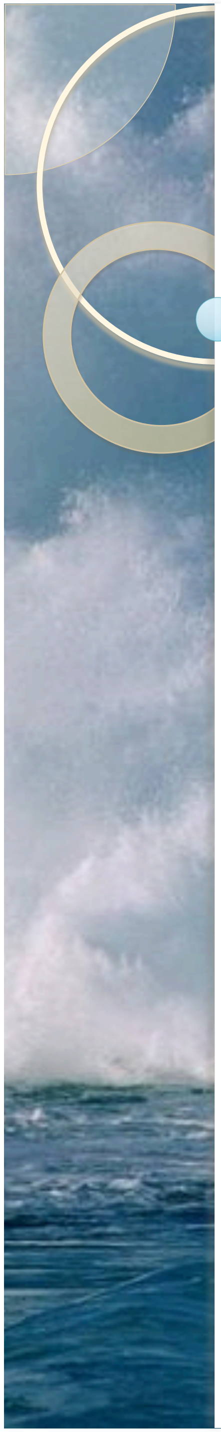
Water depth function for each piece is

$$h(x,t) = h_o(x) - \frac{1}{4} m_R \Delta h \left[1 + \tanh\left(\frac{x - x_l(t)}{S}\right)\right]\left[1 - \tanh\left(\frac{x - x_r(t)}{S}\right)\right]$$

Probabilistic Approach: Slide Motion

Nc=1 – doI=6 – b=50 – 1/10 slope – delay= UnDefined





Probabilistic Approach: Slide Motion

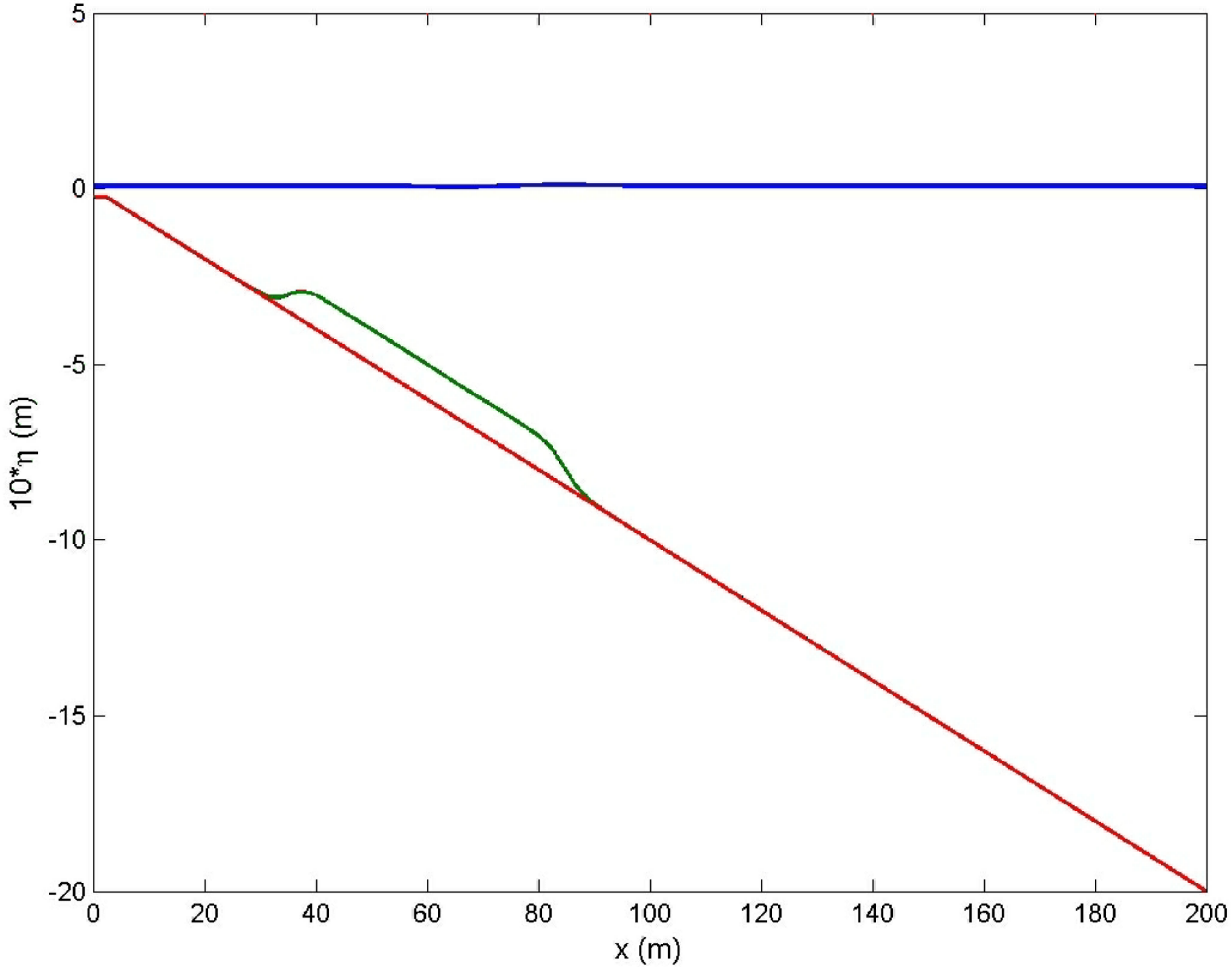
Nc=3

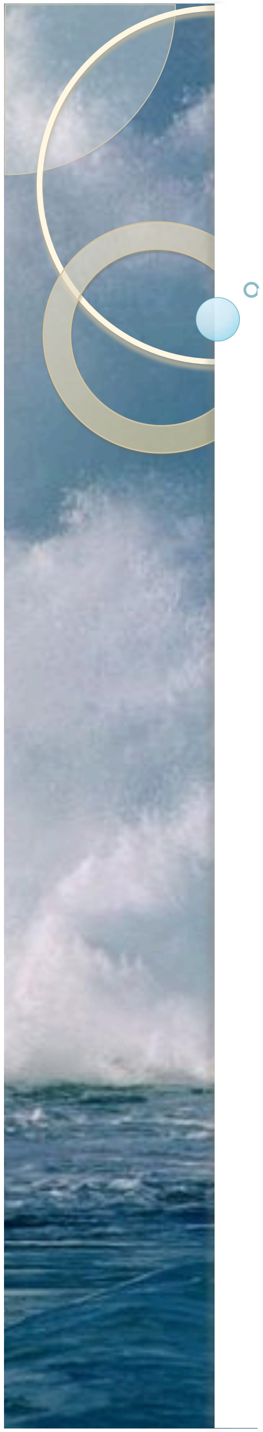
doI=6

b=50

1/10 slope

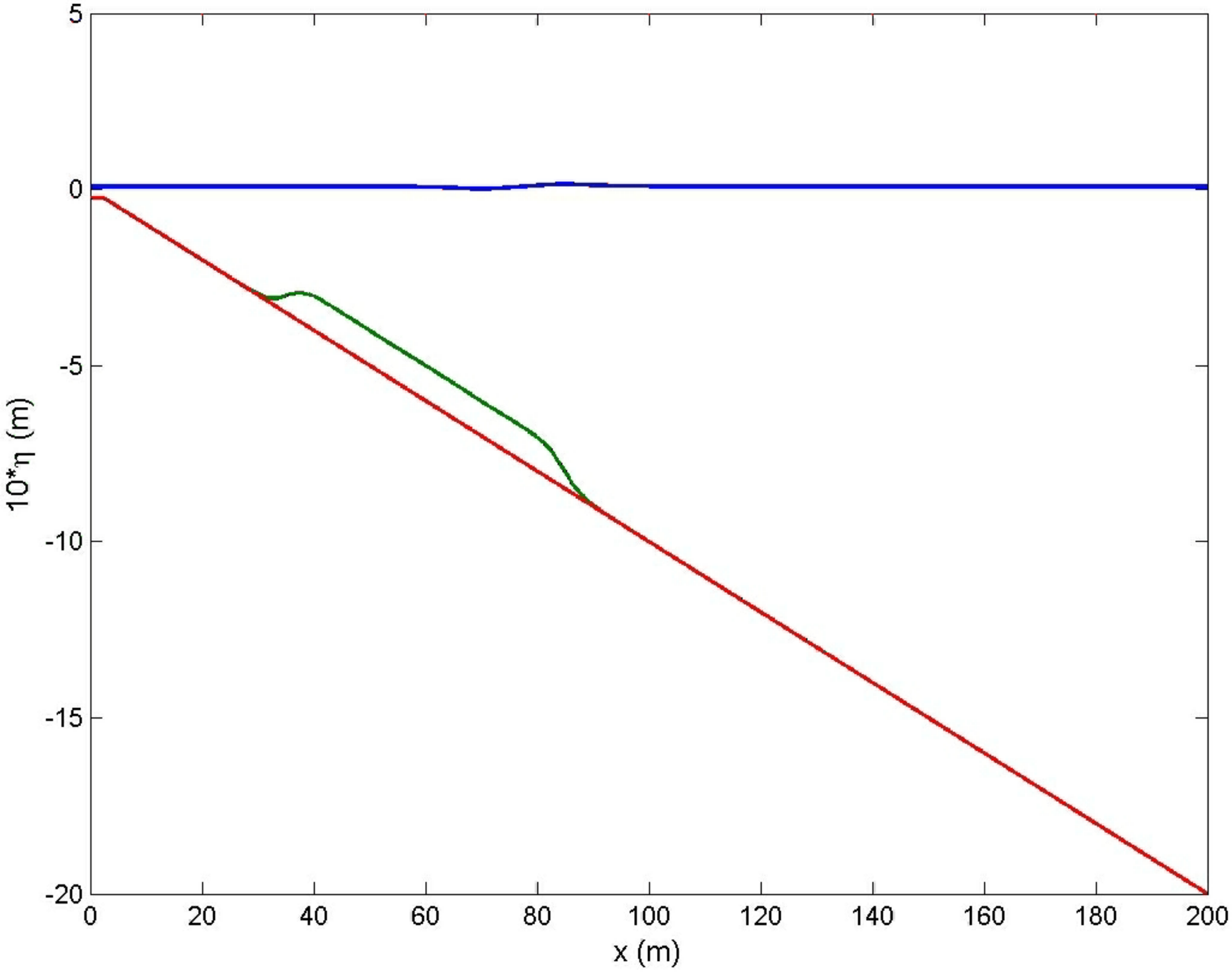
delay=10





Probabilistic Approach: Slide Motion

Nc=3 – doI=6 – b=50 – 1/10 slope – delay=20



Probabilistic Approach: Slide Motion

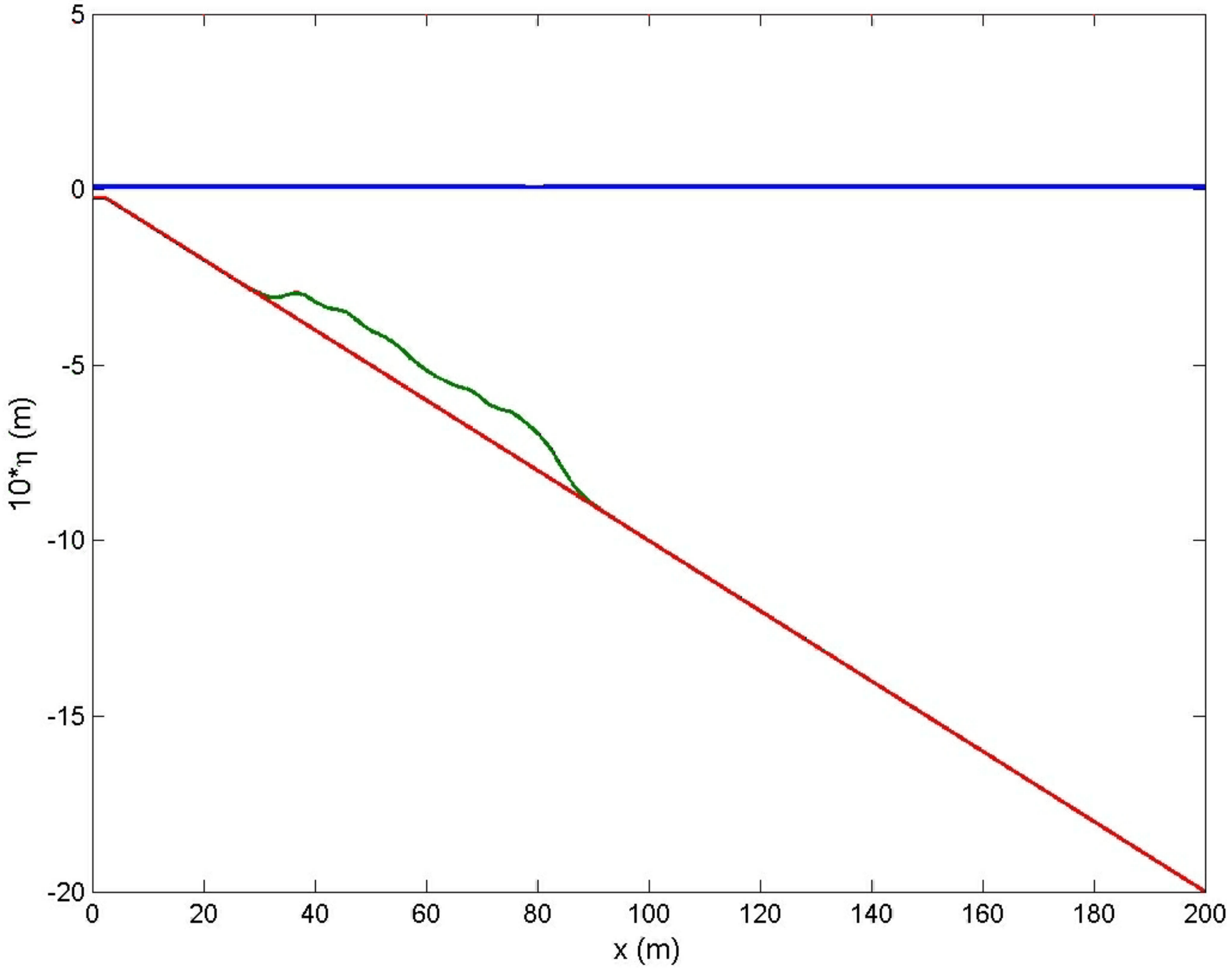
Nc=50

doI=6

b=50

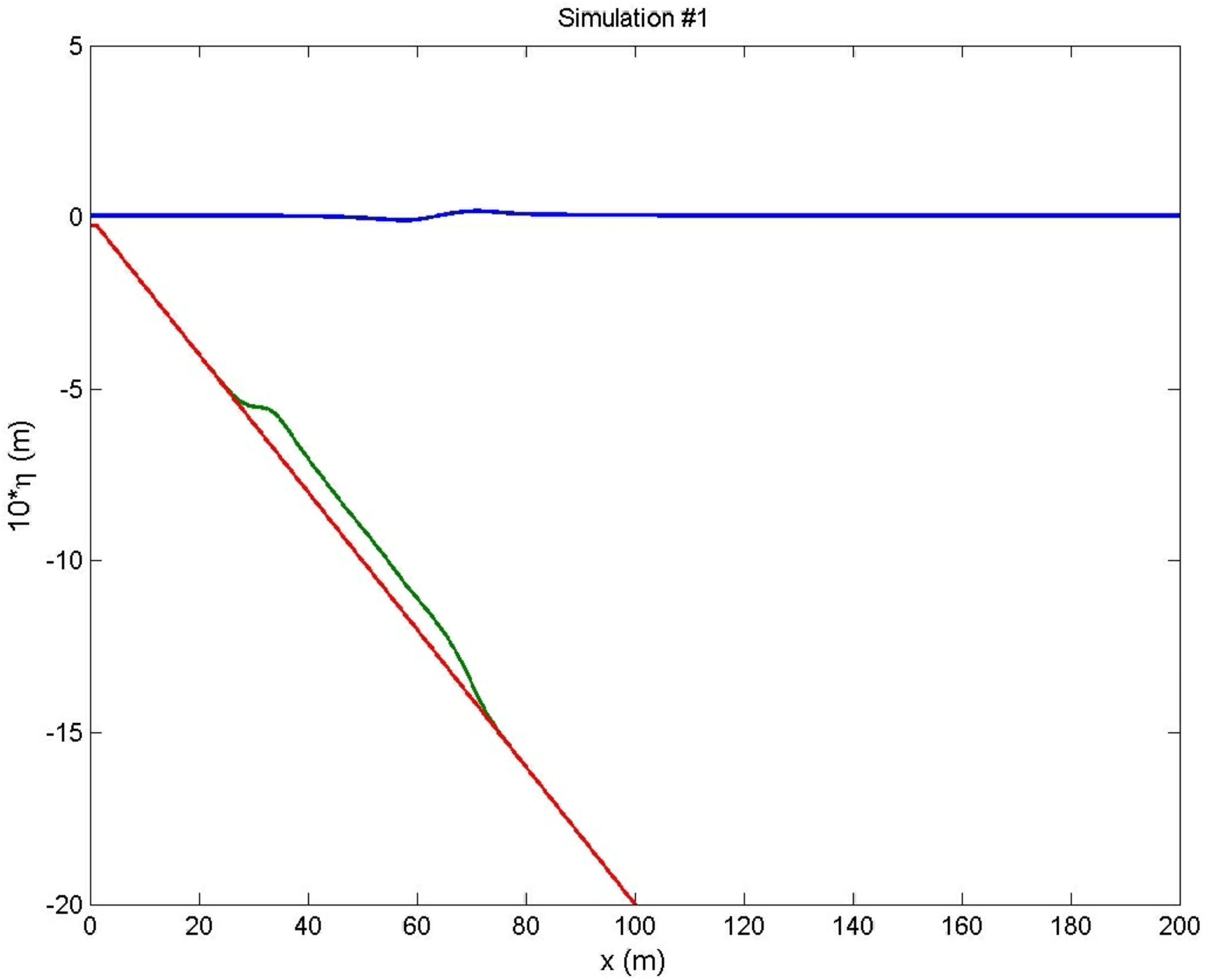
1/10
slope

delay=10



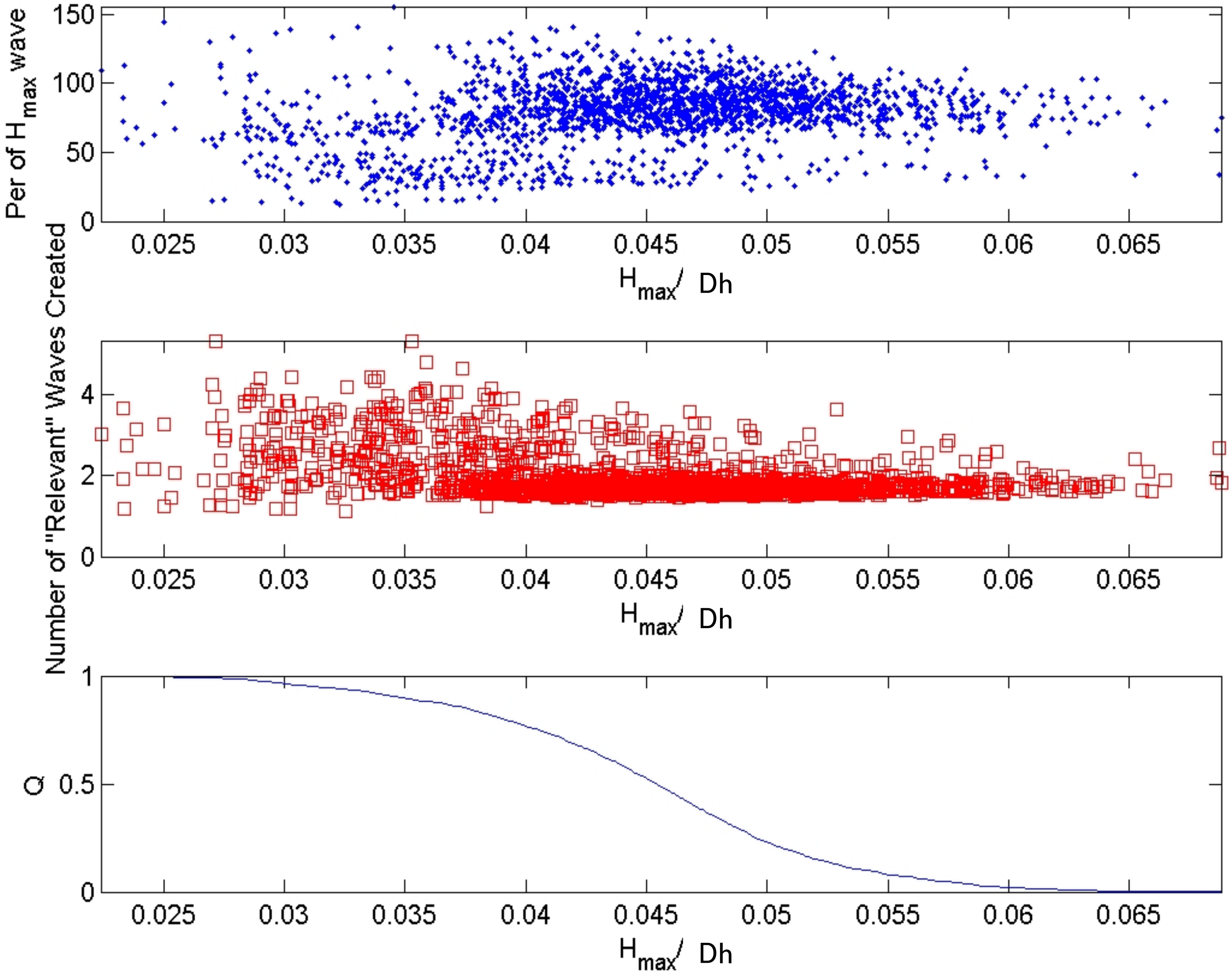
Probabilistic Approach: Slide Motion

Nc=5 – doI=10 – b=40 – 1/5 slope – delay=3



Probabilistic Approach: Results

(Landward Limit)



Nc=10

slope=1/5

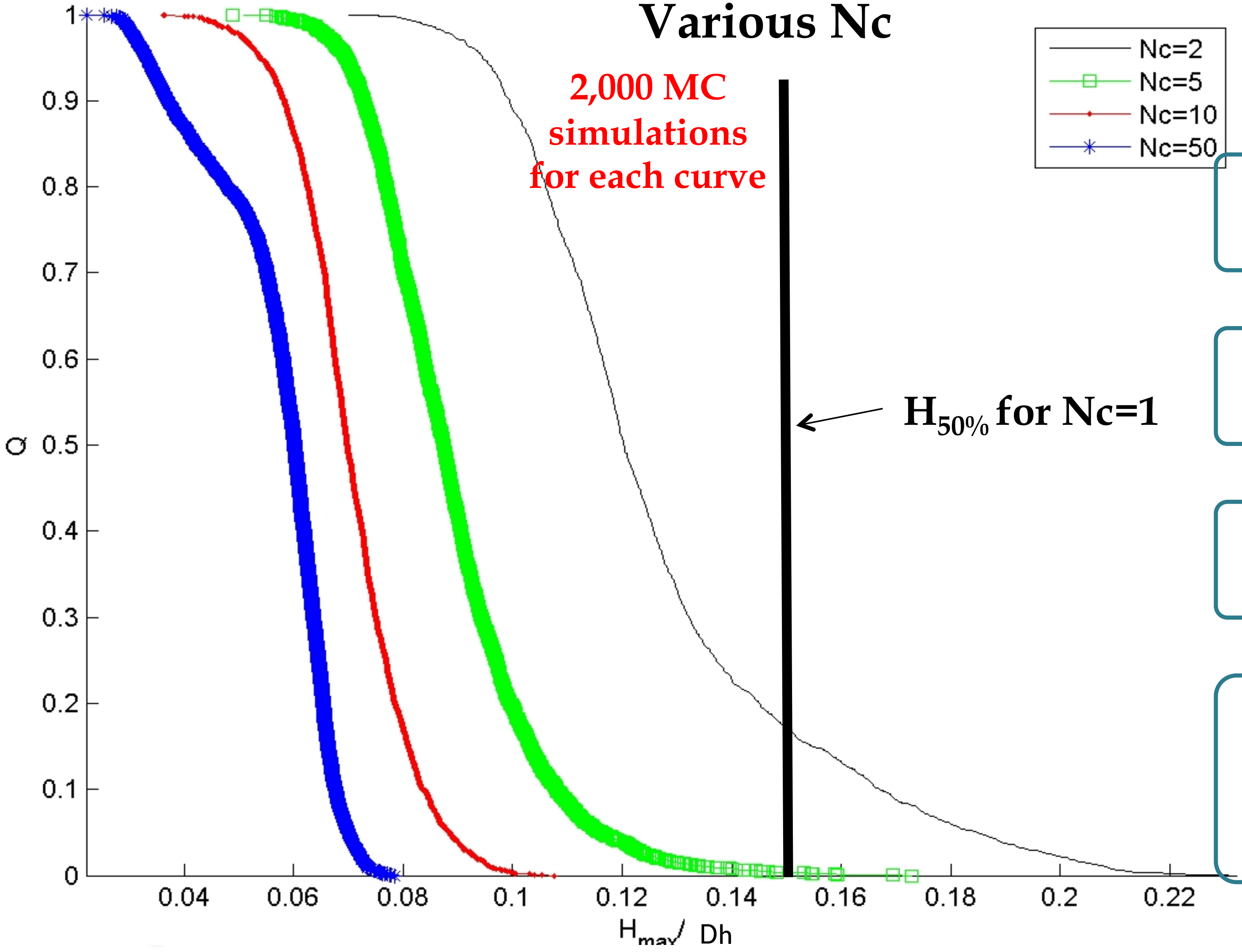
b/Dh=25

doI/Dh =10

Delay/(doI/g)$^{0.5}$ =10

Probabilistic Approach: Results

(Wave Height at Landward Limit of Initial Slide)



Various Nc

2,000 MC simulations for each curve

$H_{50\%}$ for Nc=1

slope=1/5

b/Dh=40

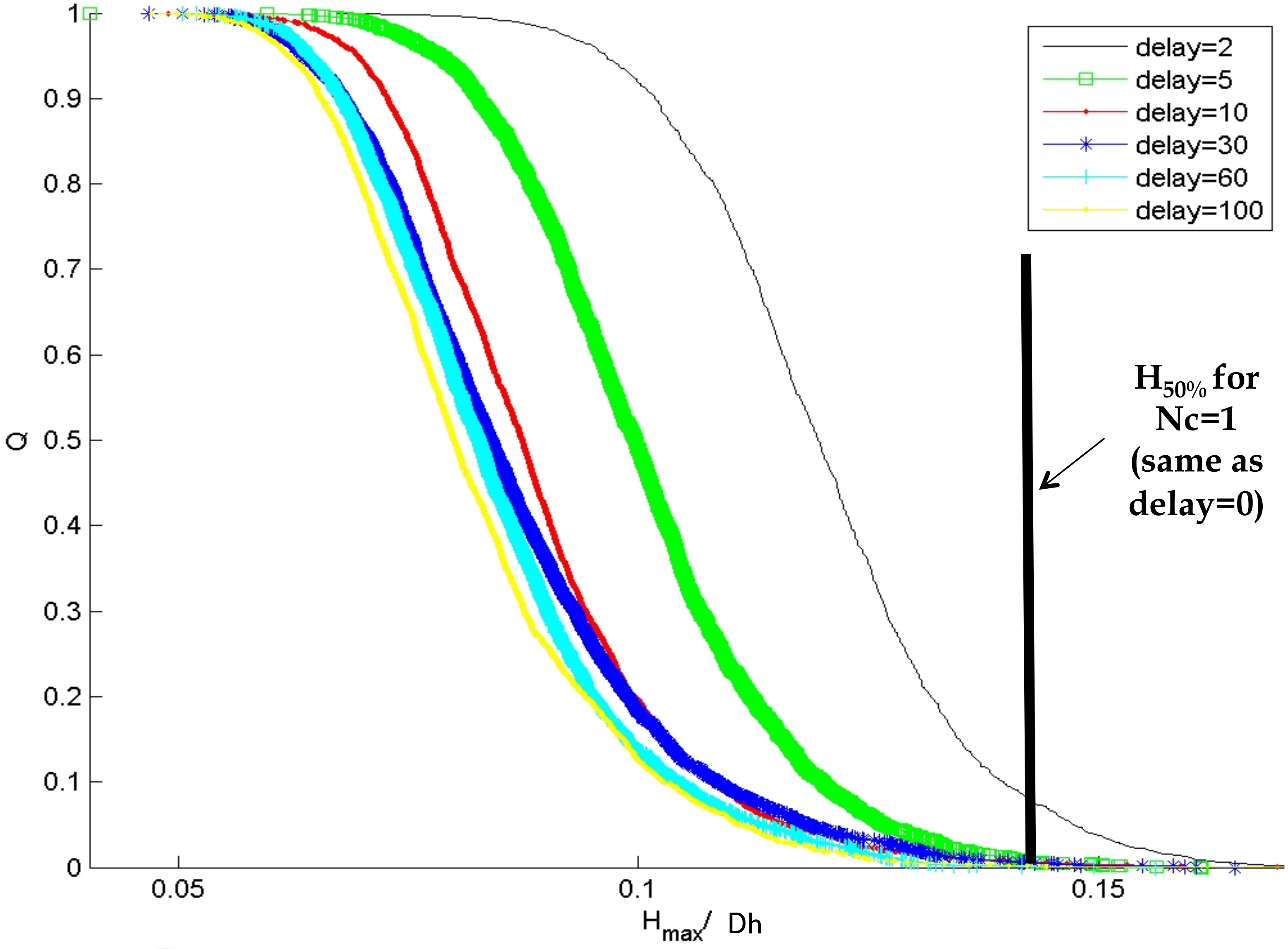
doI/Dh =10

Delay/(doI/g)$^{0.5}$ =10

Probabilistic Approach: Results

(Wave Height at Landward Limit of Initial Slide)

Various Delays



$H_{50\%}$ for Nc=1 (same as delay=0)

Nc=5

slope=1/5

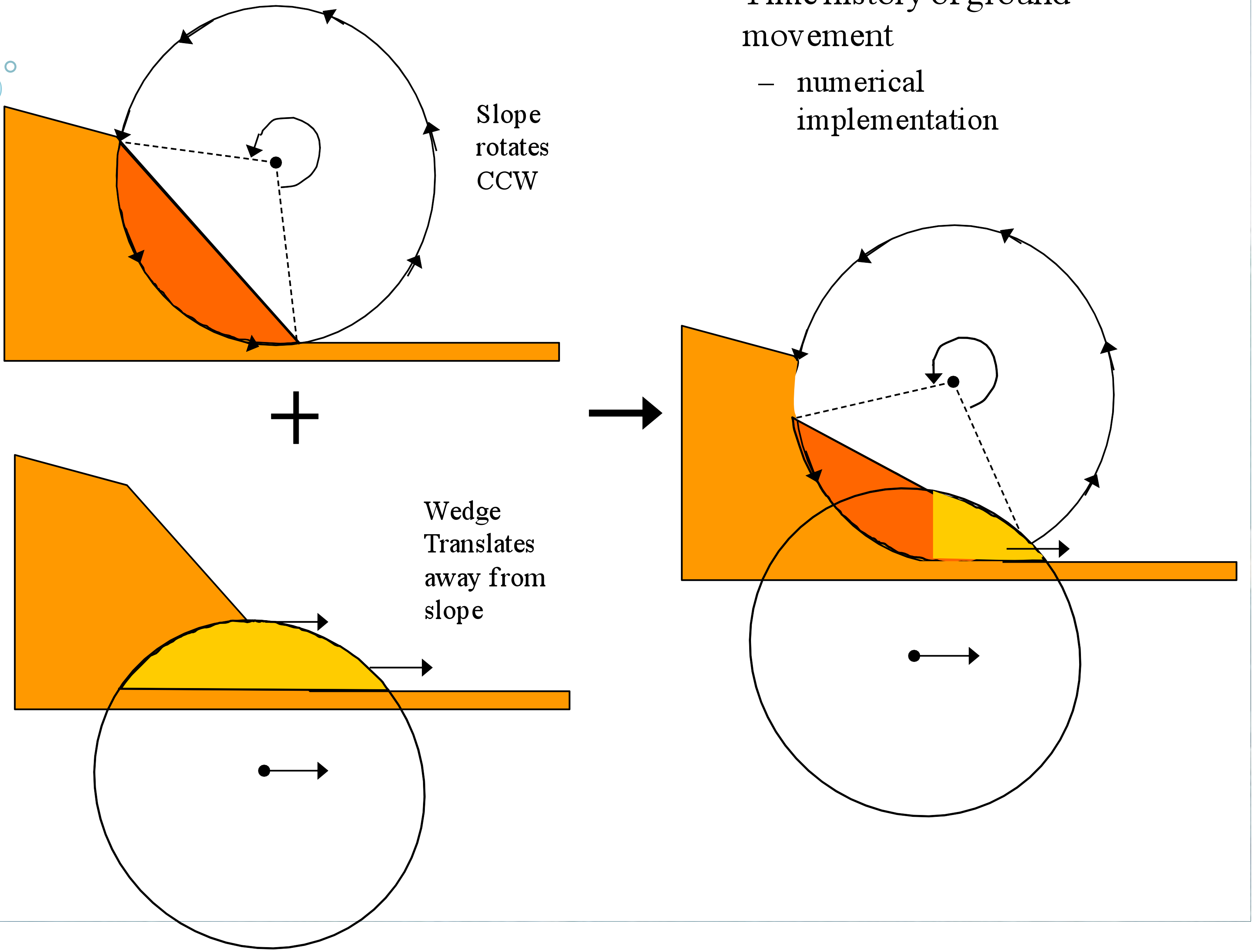
b/Dh=40

doI/Dh

=10

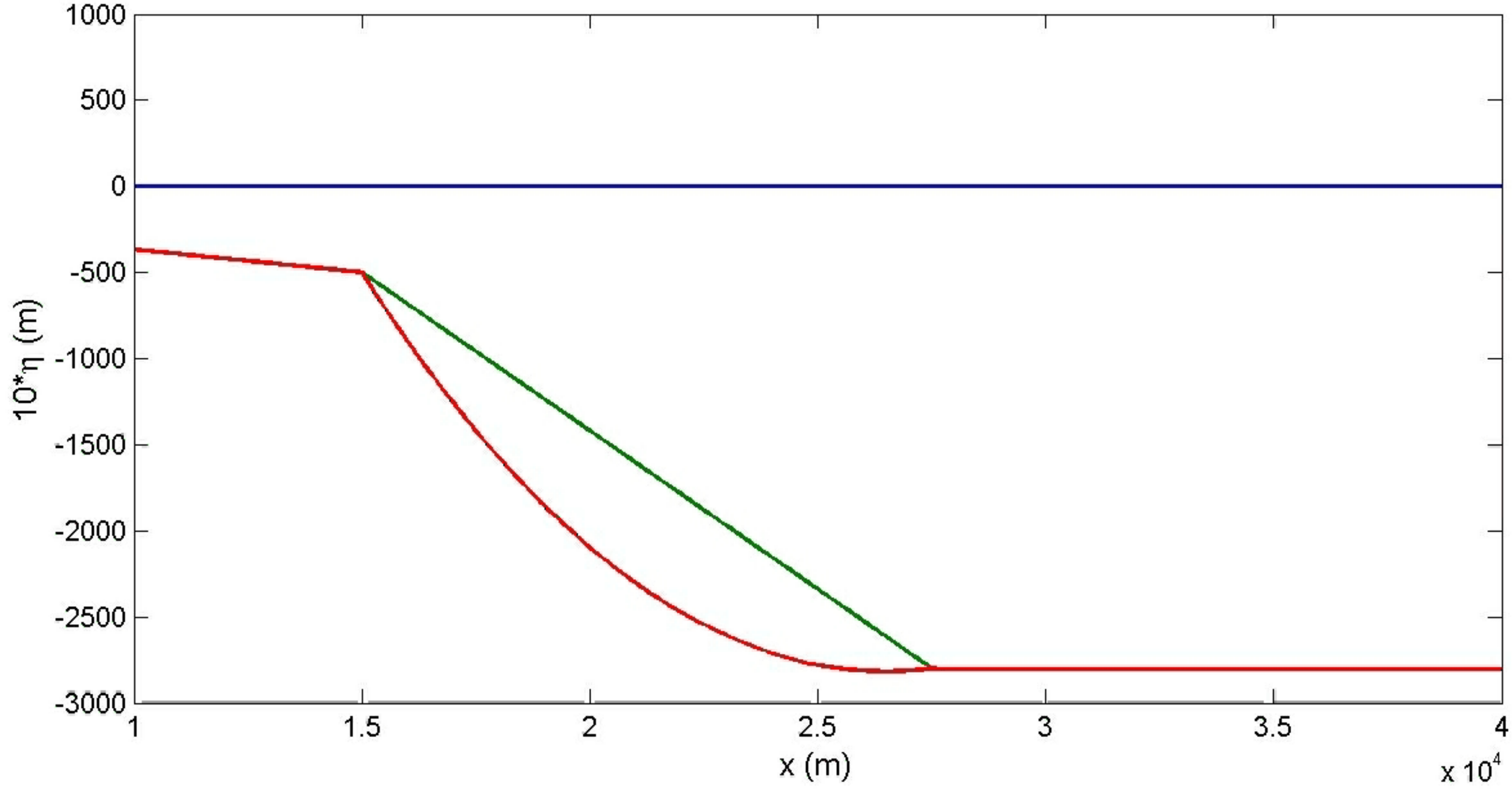
Probabilistic Approach: Rotational Motion

- Time history of ground movement
  - numerical implementation



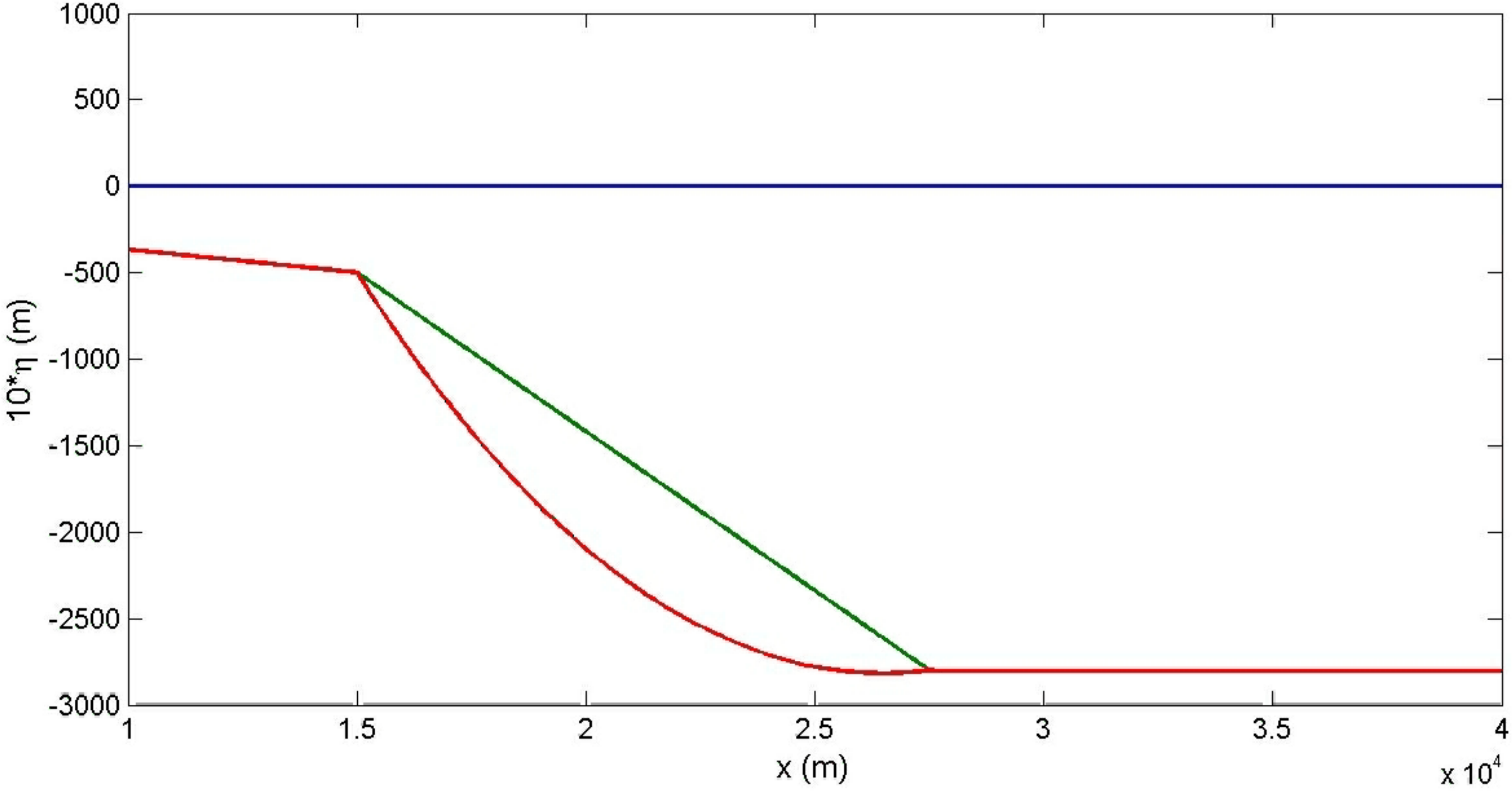
Probabilistic Approach: Rotational Motion

Time scale of motion = 15 min

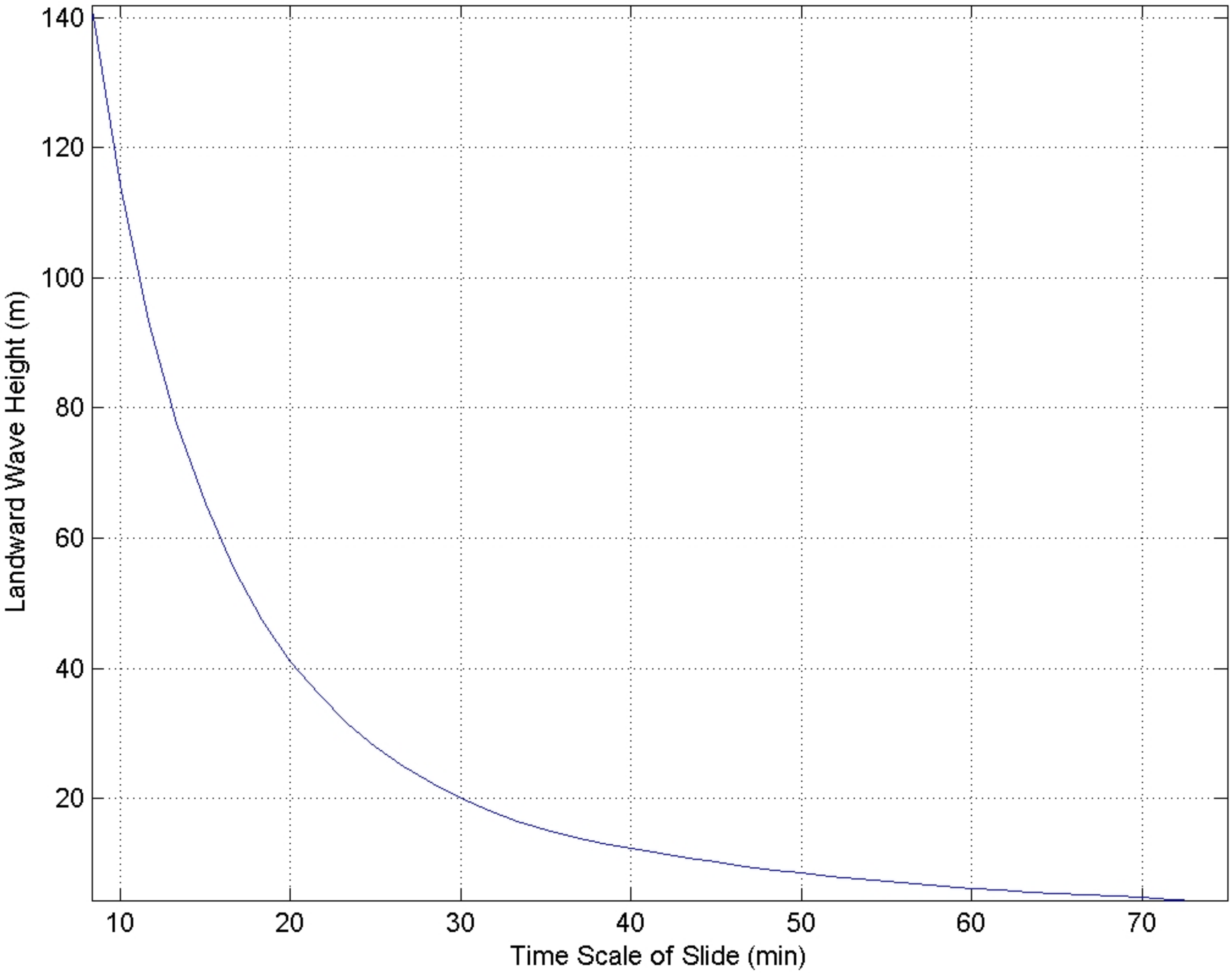


Probabilistic Approach: Rotational Motion

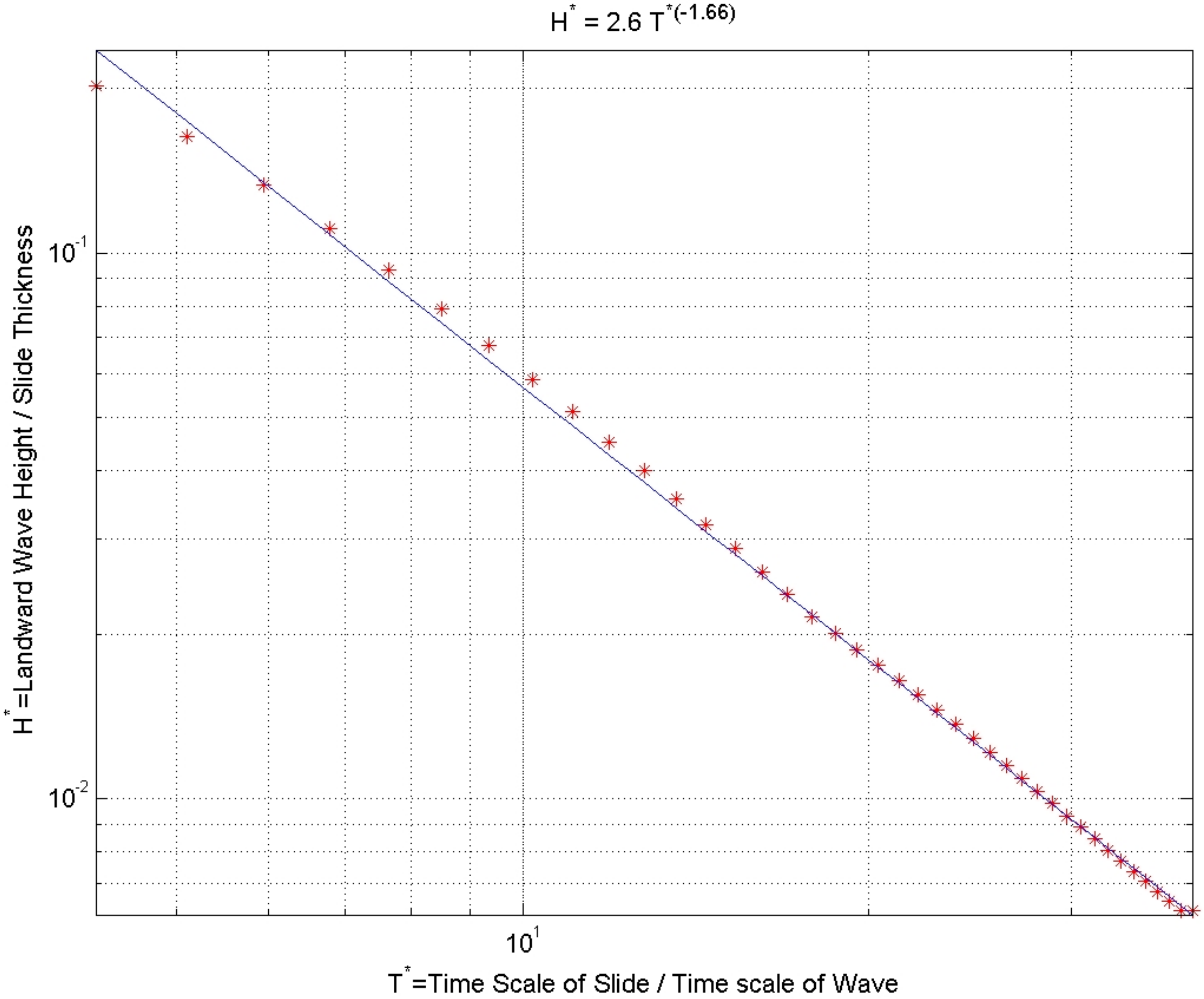
Time scale of motion = 45 min



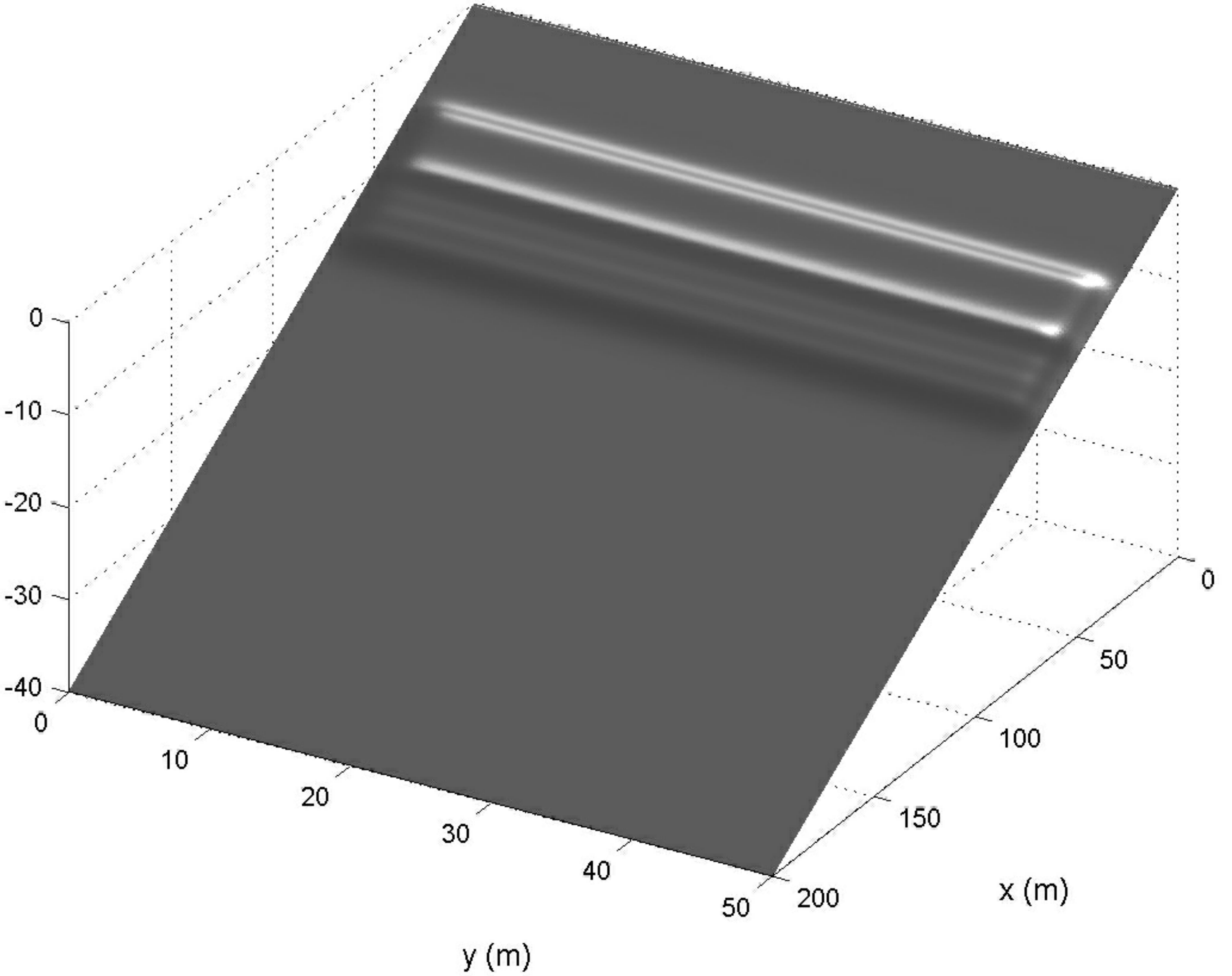
Probabilistic Approach: Rotational Motion



Probabilistic Approach: Rotational Motion



Probabilistic Approach: 3D Options



Conclusions

"Worst Conceivable Tsunami" approach used for safety assessment at nuclear sites

- Provides an upper-bound on tsunami impact, singularly useful for this particular application

Monte-Carlo Approach

- Linear waves, but completely arbitrary slide time-history
- Allows for the estimation of:
    - Statistical Wave Height (e.g. $H_{50\%}$,$H_{2\%}$)
    - Associated wave period & number of waves
- Can compare with single-body, deterministic runs, to provide a measure of the conservatism
- Need much more geophysical information about existing slides
    - Can a distribution for Nc be created?
    - Info will tend to be very local, site-specific

Conclusions

Need much more geophysical information about existing slides

- Can a distribution for Nc be created?
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Example use – What would be needed as inputs for a given location:

- Deterministic/Probabilistic Inputs:
  - Slide Slope
  - Slide Thickness
  - Time scales
    - Duration of failure initiation: downslope (translational)
    - Duration of failure initiation: lateral (translational)
    - Duration of slumping (rotational)
  - Measure of slide mass cohesion (Nc distribution)
  - Failure “patchiness”, a fraction of failure in the lateral direction

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    - Duration of slumping (rotational)
  - Measure of slide mass cohesion (Nc distribution)
  - Failure "patchiness", a fraction of failure in the lateral direction
- Outputs:
  - Probabilistic distribution of Height, Period, # of Waves