USC Viterbi
School of Engineering

Modeling Generation and Propagation of Landslide Tsunamis

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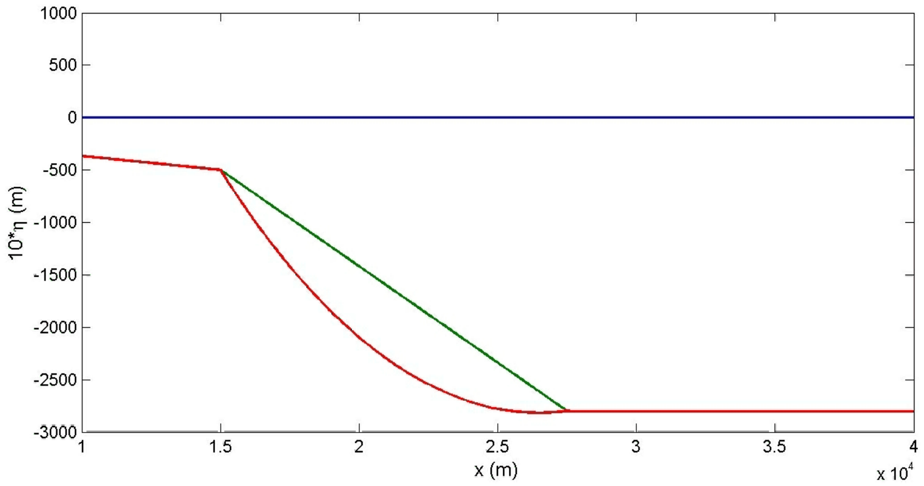

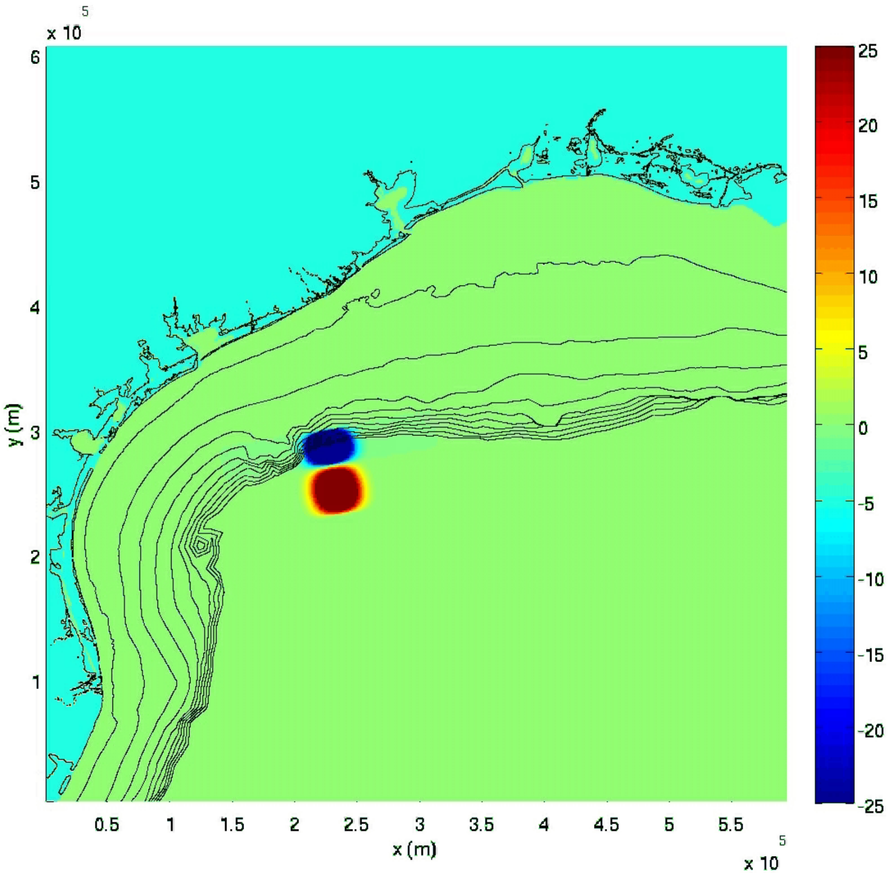

Modeling Generation and Propagation of Landslide Tsunamis - OUTLINE

Approaches for Generating Waves Directly from Landslide Motion

- Modeling the slide mass (types of failures, types of rheology)
- Modeling the waves generated (shallow water models, dispersive models, nonlinearity)
- Establish the (wide) range of slide dynamics, and the proper hydrodynamics to capture wave physics

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) – attempt to select the "worst" wave that might be generated from the wide range of slide dynamics

Probabilistic Approach for the Waves Generated by a Specified Landslide

- Given a specific slide geometry and slide failure mechanism, can we capture the distribution of possible generated wave heights?
- 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

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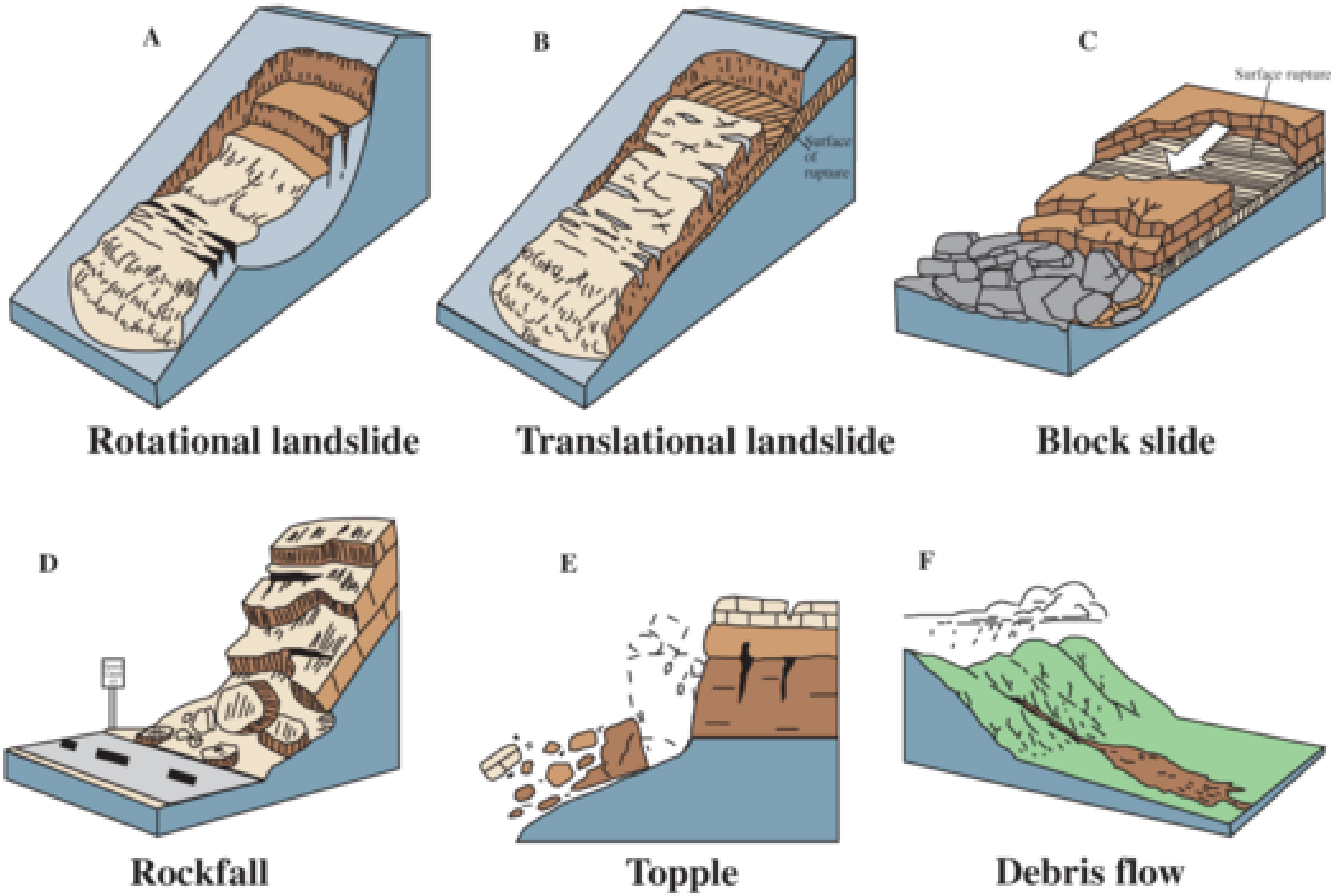
Approaches for Generating Waves Directly from Landslide Motion

<u>Types of Failures</u>

Mass movements can take a wide variety of forms, and each will have different tsunamigenic efficiency and potential



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Approaches for Generating Waves Directly from Landslide Motion

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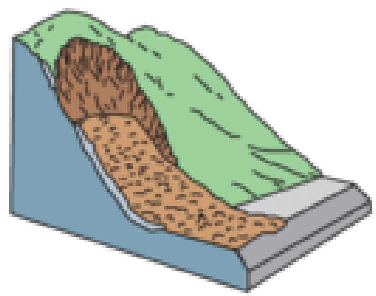
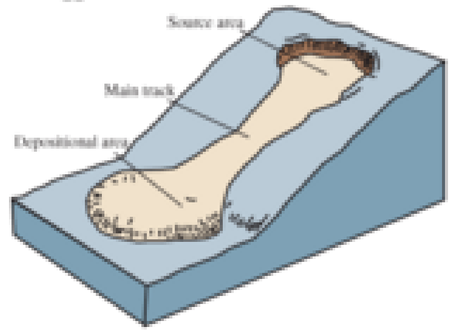
G



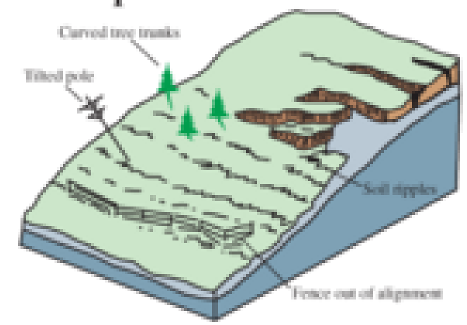
Debris avalanche

H



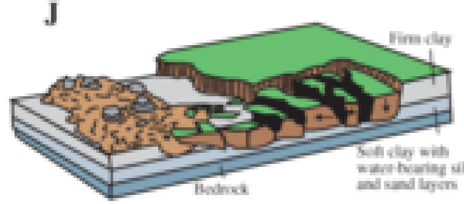
Earthflow

I



Creep

J



Lateral spread

Mass movements that are "shallow" (horizontal length scale much greater than local depth), "coherent" (fails as a single mass, not a group of smaller pieces), "fast" (time scale on the order of the generated wave period), and involve strong VERTICAL ACCELERATION will be the most tsunamigenic sources

Approaches for Generating Waves Directly from Landslide Motion

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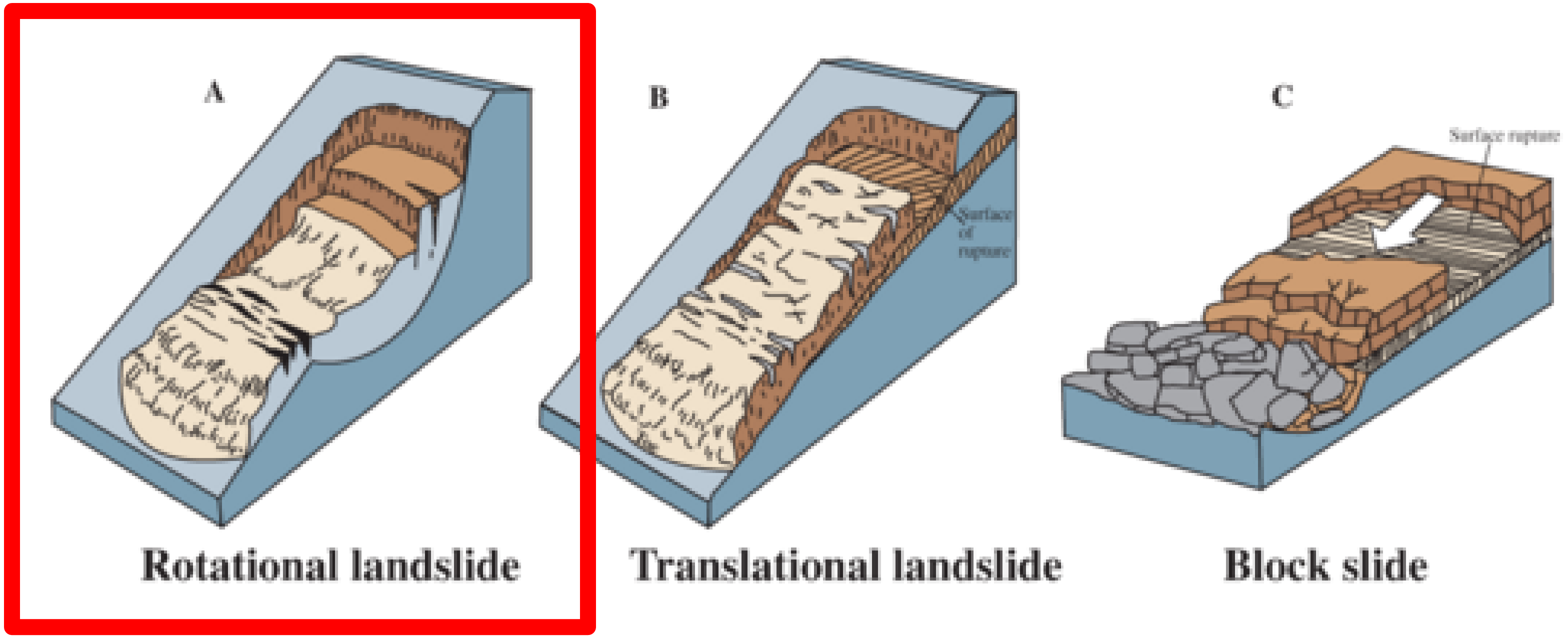

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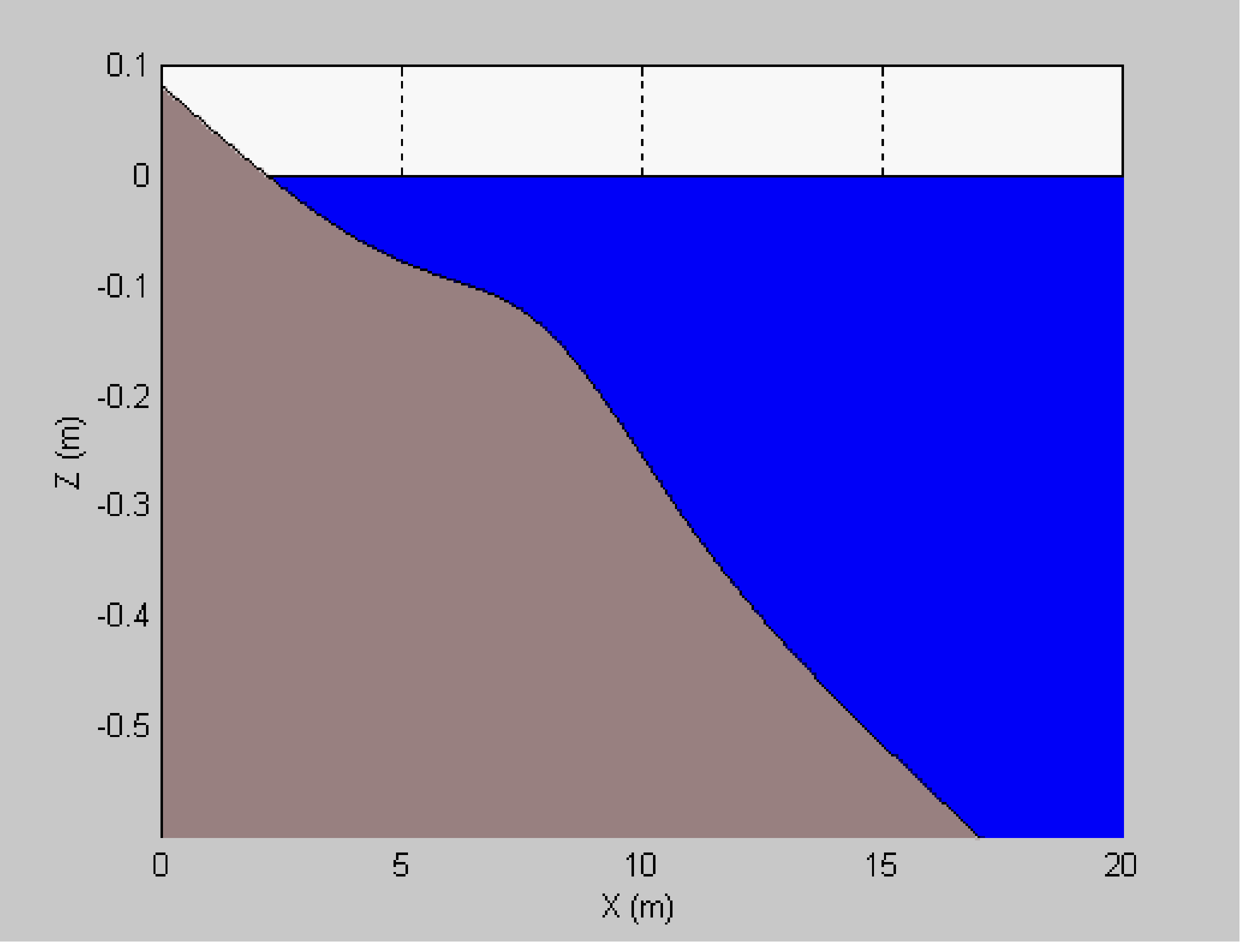
- **Rotational slides (slumps)**

Approaches for Generating Waves Directly from Landslide Motion

Types of slide motion & rheology

Most (or at least many) existing studies assume the slide translates down slope following **solid body motion**

- Slide speed is dependent on material density, drag coefficient, added mass coefficient, interface friction
- There is variation in these properties – can distributions be generated??
- Shape of slide controls the drag and added mass coefficient, but also the generated wave properties



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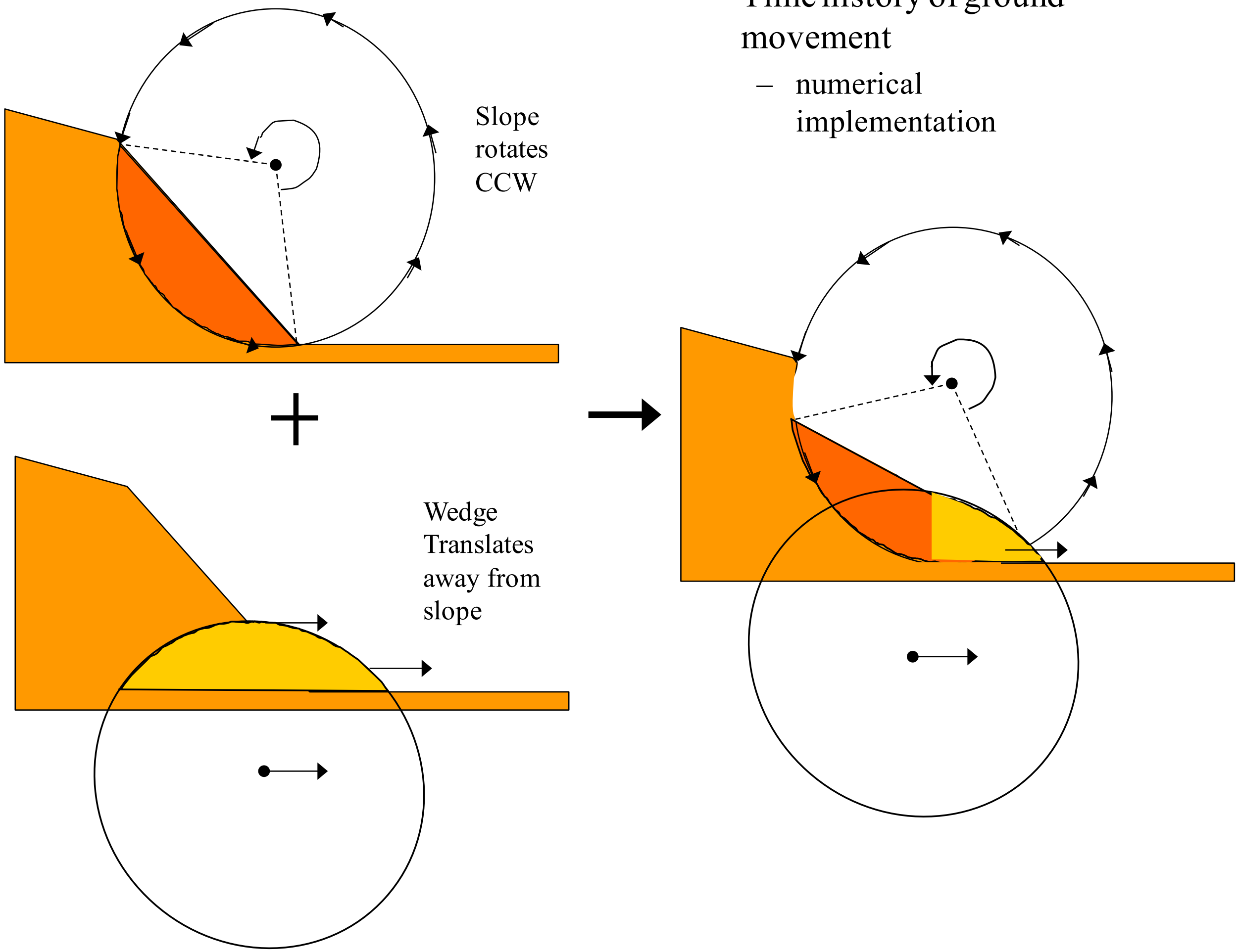
- Time history of ground movement
  - numerical implementation



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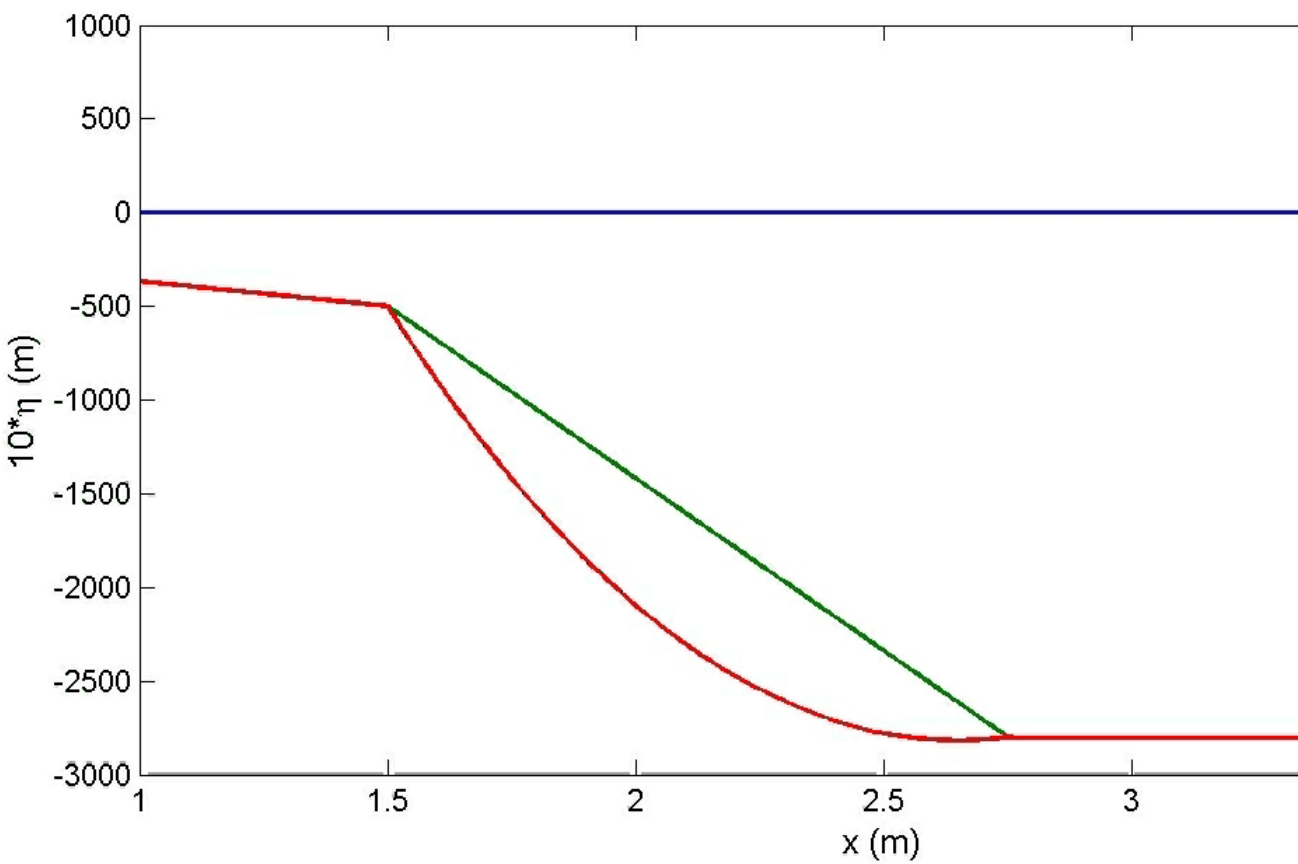

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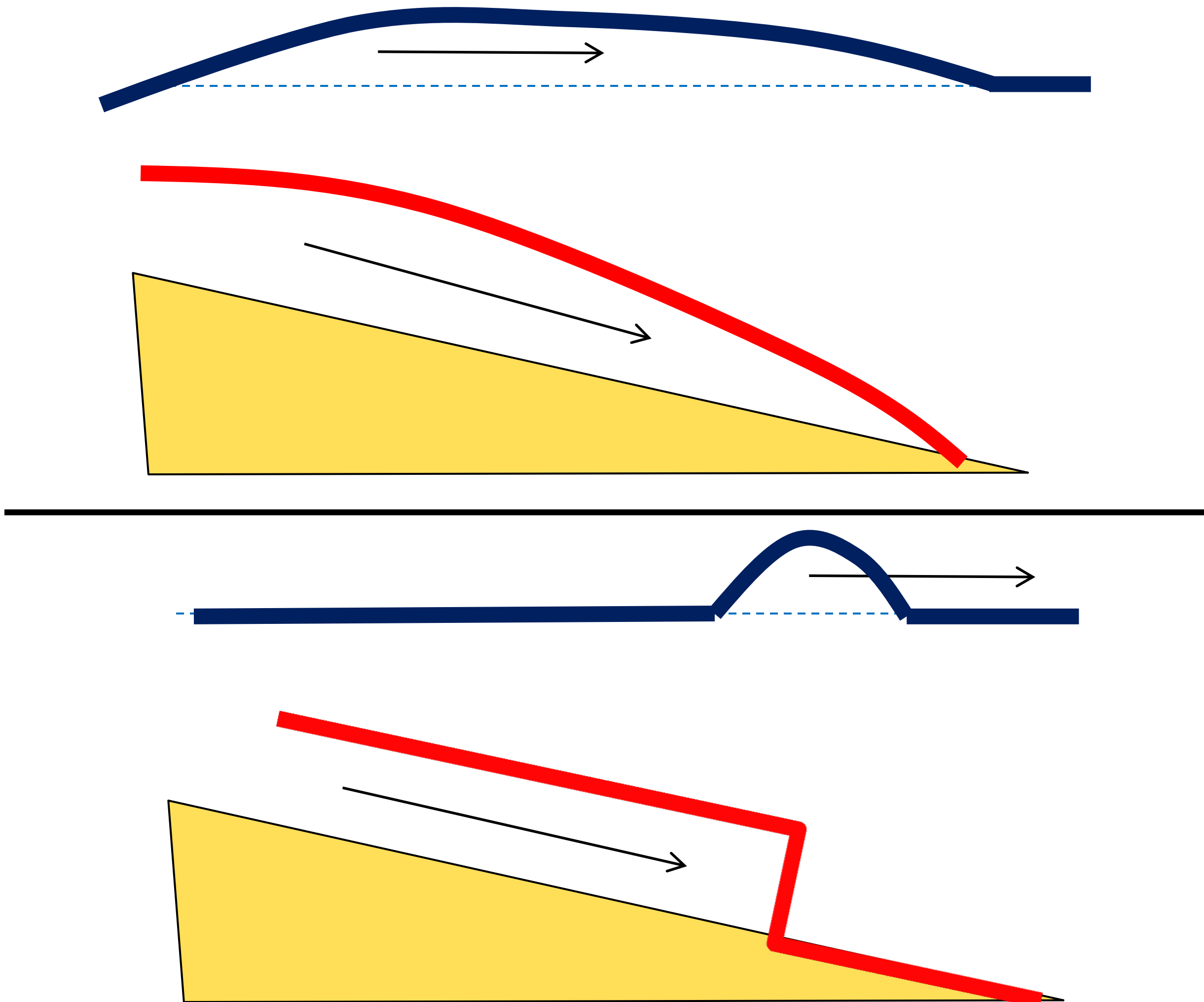

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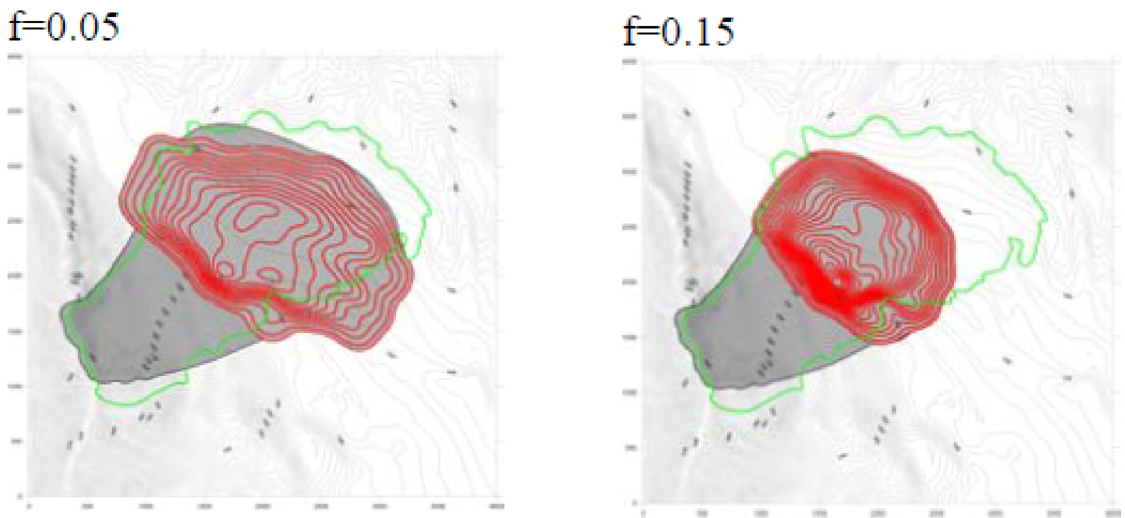
Approaches for Generating Waves Directly from Landslide Motion

Types of slide motion & rheology

A increasing number of studies attempt to model the slide mass as a viscous continuum, described by various stress laws

- Simplest is to model the slide as a highly viscous Newtonian fluid (honey slide)
  - ➢ Allows for deformation of the slide mass, have to tune viscosity
  - ➢ Initial wave generation often most important stage, is this a proper model at this time?
- A number of rheological models have been proposed, including Bingham, Herschel-Bulkley, and bilinear rheologies of viscoplastic fluids (muddy flows, silts & clays, debris flows)
  - Can the threshold shear strength be well defined? Can a distribution be developed?



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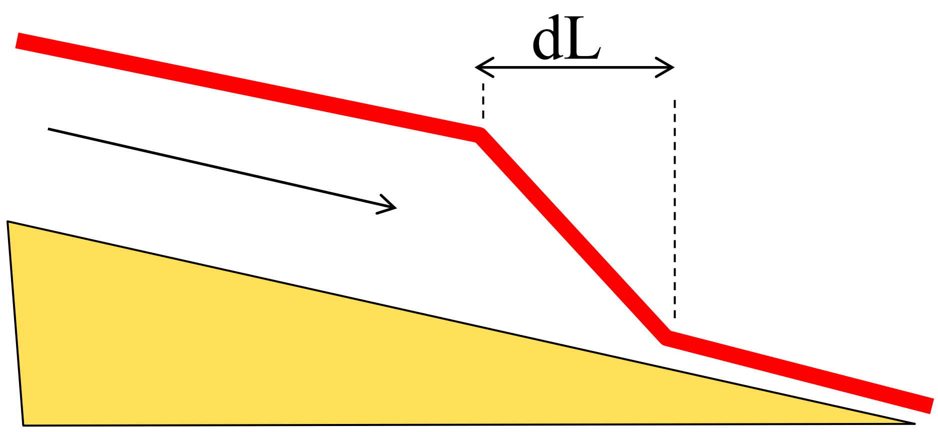
Approaches for Generating Waves Directly from Landslide Motion

Modeling the Generated Waves

- It is natural to try to model landslide waves with the "traditional" nonlinear shallow water wave equations.
  - However, both the slide-water column coupling and the generated wave propagation can be (and often is) characterized as a dispersive (short wave) problem



For the process to be properly described by the shallow water model:

dL>>local water depth

(practically speaking dL>~25*h)

*Note that the above dL represents a characteristic horizontal length scale, it does not necessary mean the front or slide half-length. There can be numerous important length scales for an irregular mass (think spectrally).

Difficult to satisfy for an arbitrarily deforming mass

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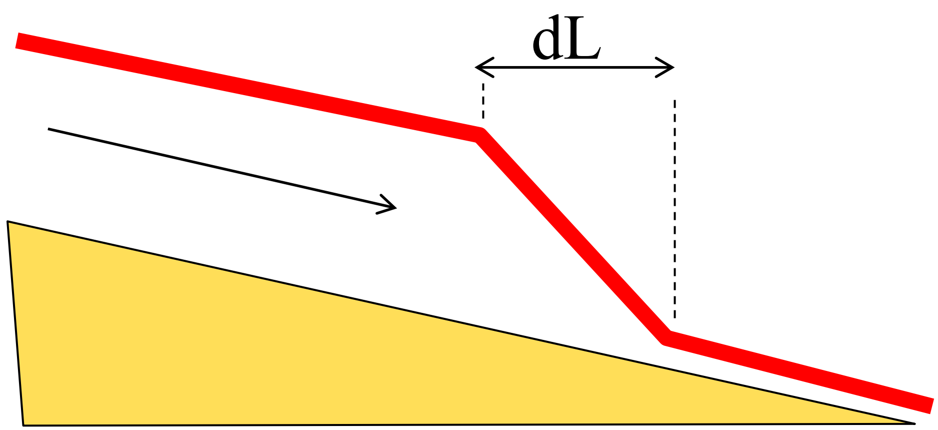

For the process to be properly described by the shallow water model:

dL>>local water depth

(practically speaking dL>~25*h)

Best to use a dispersive model (e.g. Boussinesq), or even better a fully 3D non-hydrostatic model. For near vertical fronts, the latter would be REQUIRED.

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Approaches for Generating Waves Directly from Landslide Motion

Modeling the Generated Waves

- For a DETERMINISTIC coupled slide+waves forecast, one would need to:
  1. Decide on the geometry of the mass movement – not just volume, but 2D slip surface as well
  2. Choose a mass movement failure mechanism (e.g. rotational, translational) and/or choose a slide material behavior model (e.g. solid body motion, Bingham)
  3. Choose the coefficients that govern the material behavior model (e.g. drag coefficient, threshold shear stress formulation coefficients)
  4. Based on geometric properties of slide (throughout its evolution) choose an appropriate hydrodynamic model to accurately model the "important" wave frequencies
  5. Develop a bathy / topo grid for propagation of the waves away from the source, and choose a still water level (high tide, sea level rise)
  6. Specific a bottom friction factor (probably spatially variable) to account for energy dissipation during shallow and overland tsunami flow
- For a PROBABILISITC forecast, a branching decision tree of the above steps is needed, with parameter distributions for all the "important" empirical factors involved in the simulation

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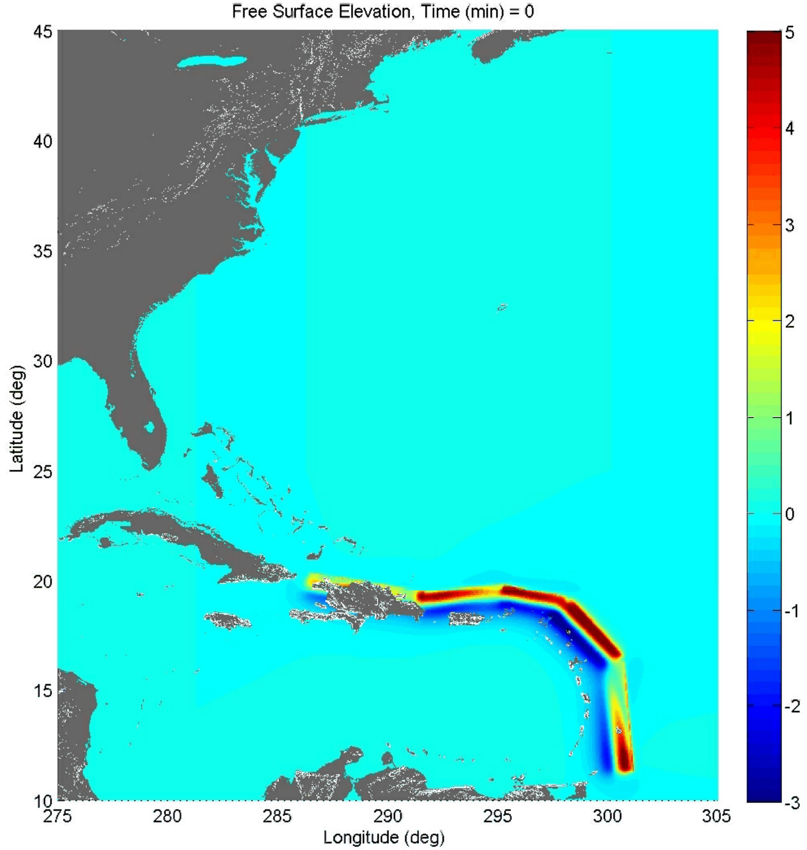
Approach for Site Safety Assessment for New Nuclear Reactor Applications

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)



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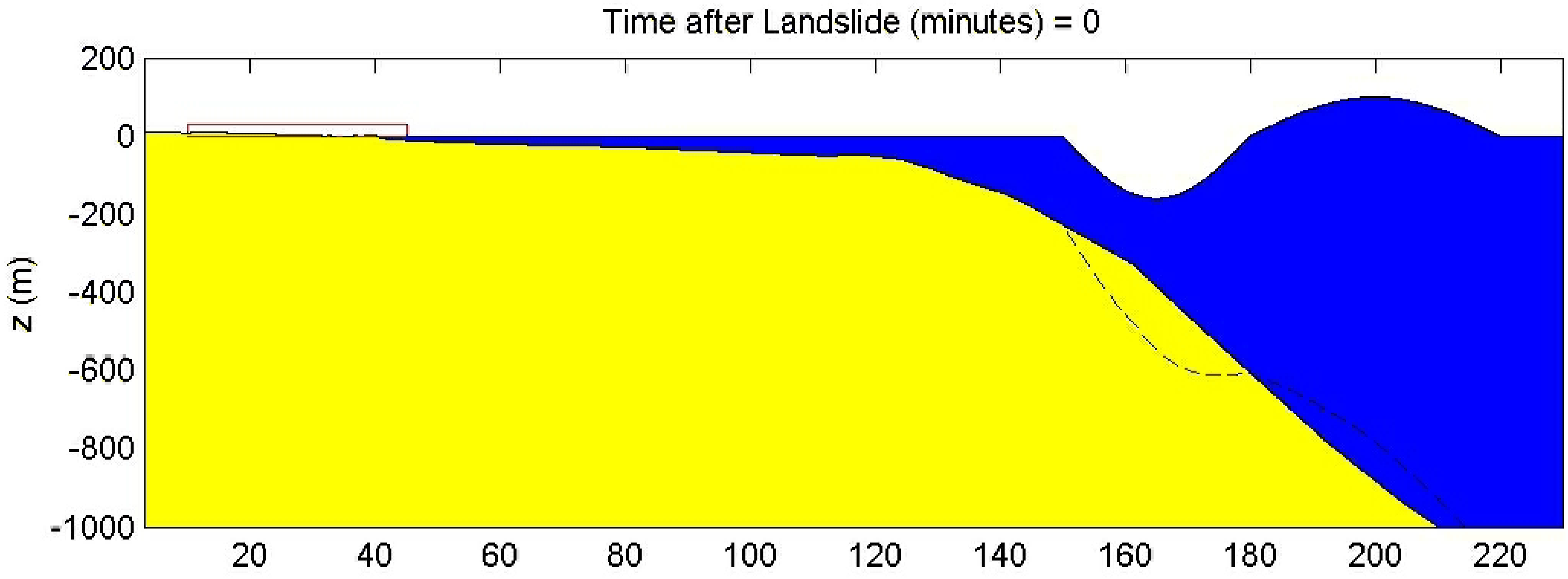
Approach for Site Safety Assessment for New Nuclear Reactor Applications

Develop a hierarchal approach

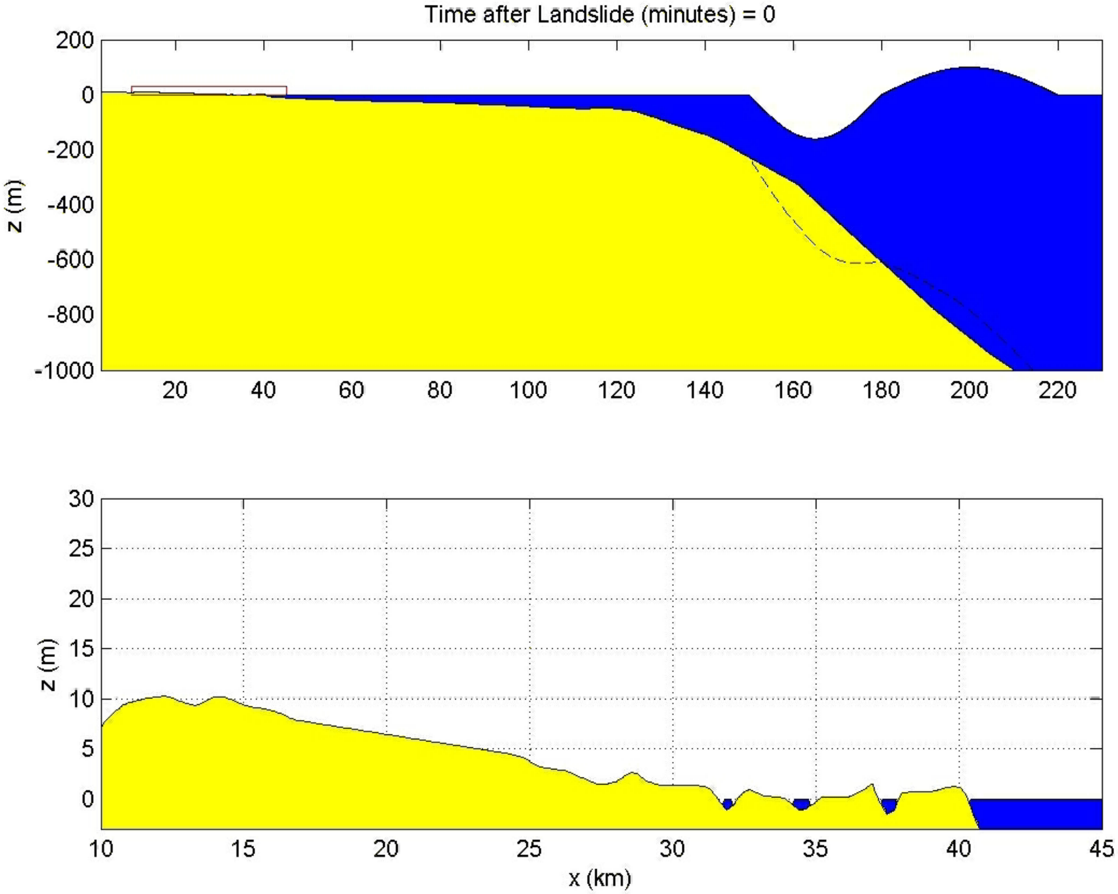
- Identify any earthquake or landslide source that could conceivably impact the site
- For landslides, use existing bathymetry data to map the dimensions of the failure
- Following the previous discussion, most of the uncertainty is in the landslide motion, so we conservatively assume the slide failed 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)



Approach for Site Safety Assessment for New Nuclear Reactor Applications

Develop a hierarchal approach

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



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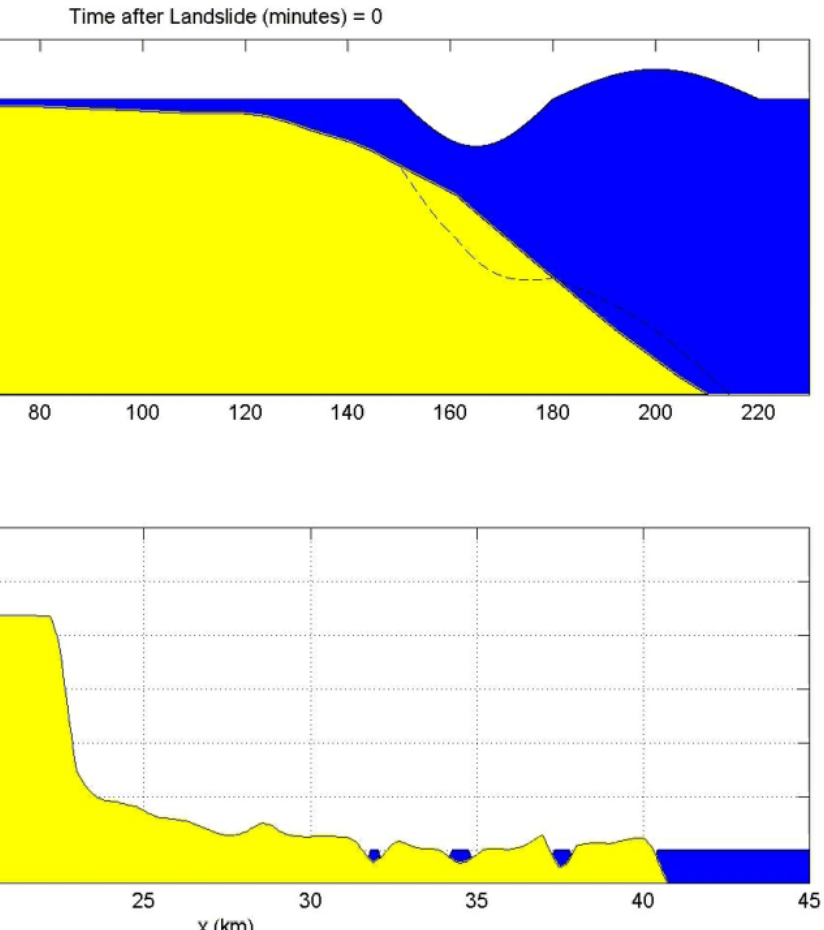
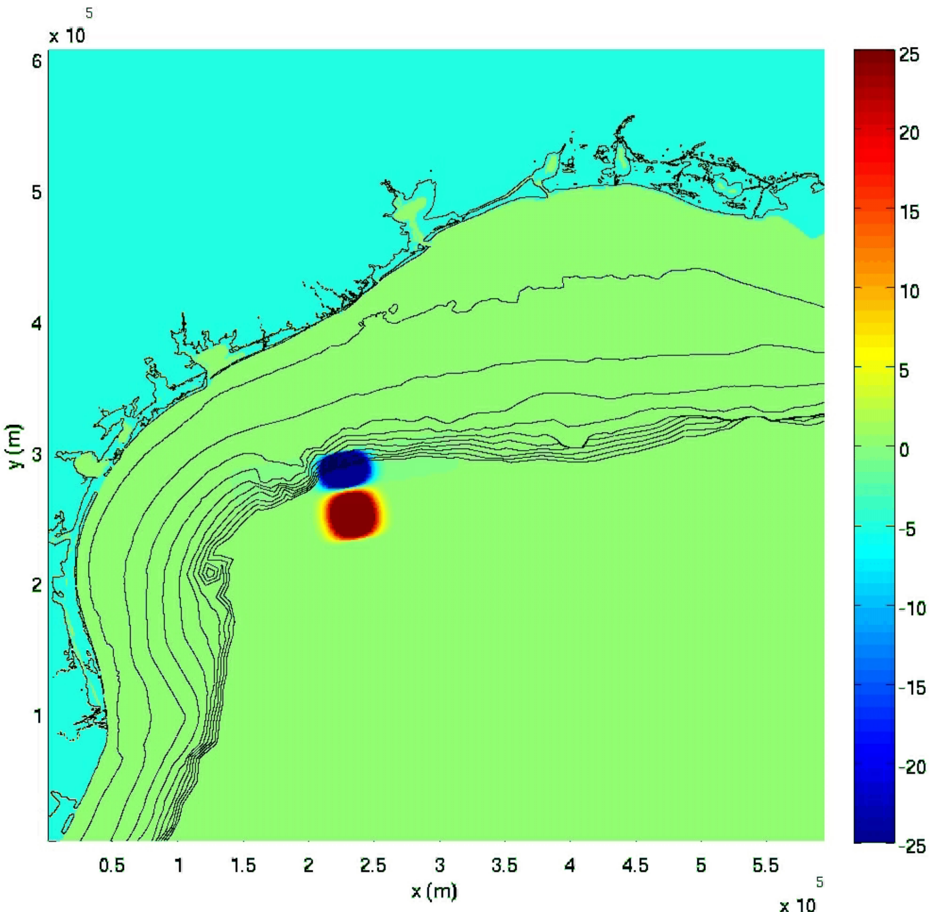
Approach for Site Safety Assessment for New Nuclear Reactor Applications

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

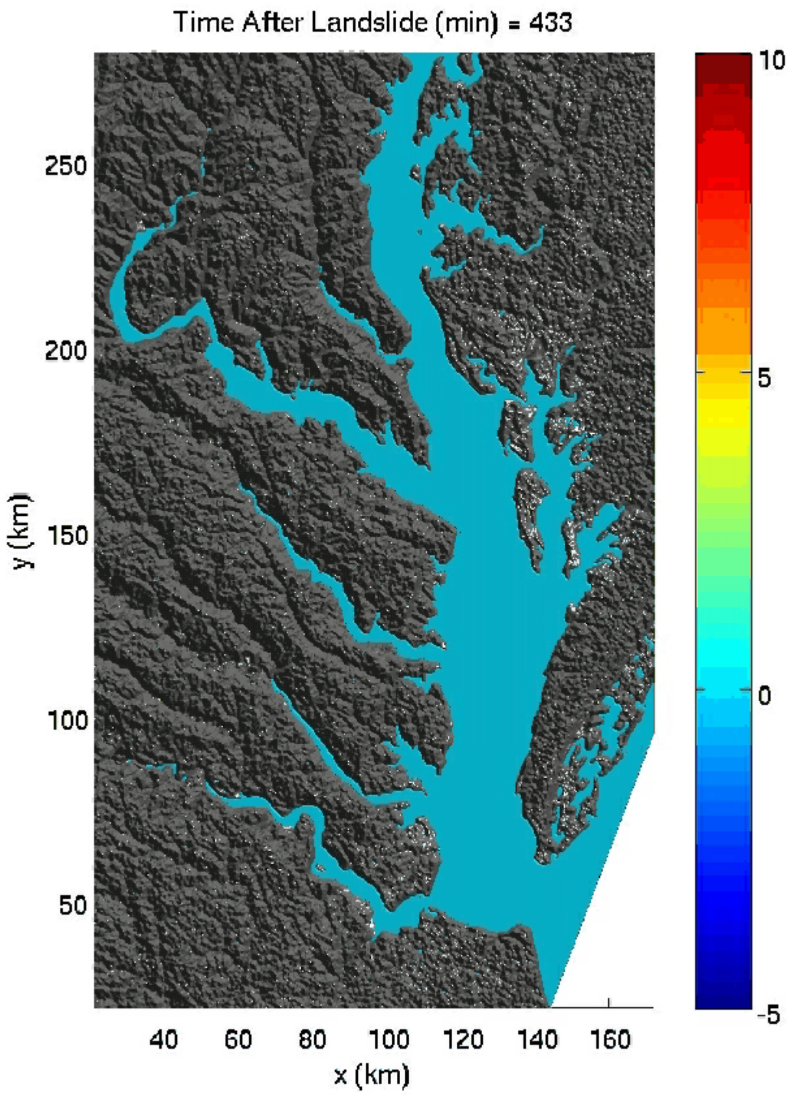




Approach for Site Safety Assessment for New Nuclear Reactor Applications

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, and local refraction/diffraction focusing effects



Approach for Site Safety Assessment for New Nuclear Reactor Applications

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**
- Measures of uncertainty or probability are not included in the analysis; using expert judgment to define a highly conservative result

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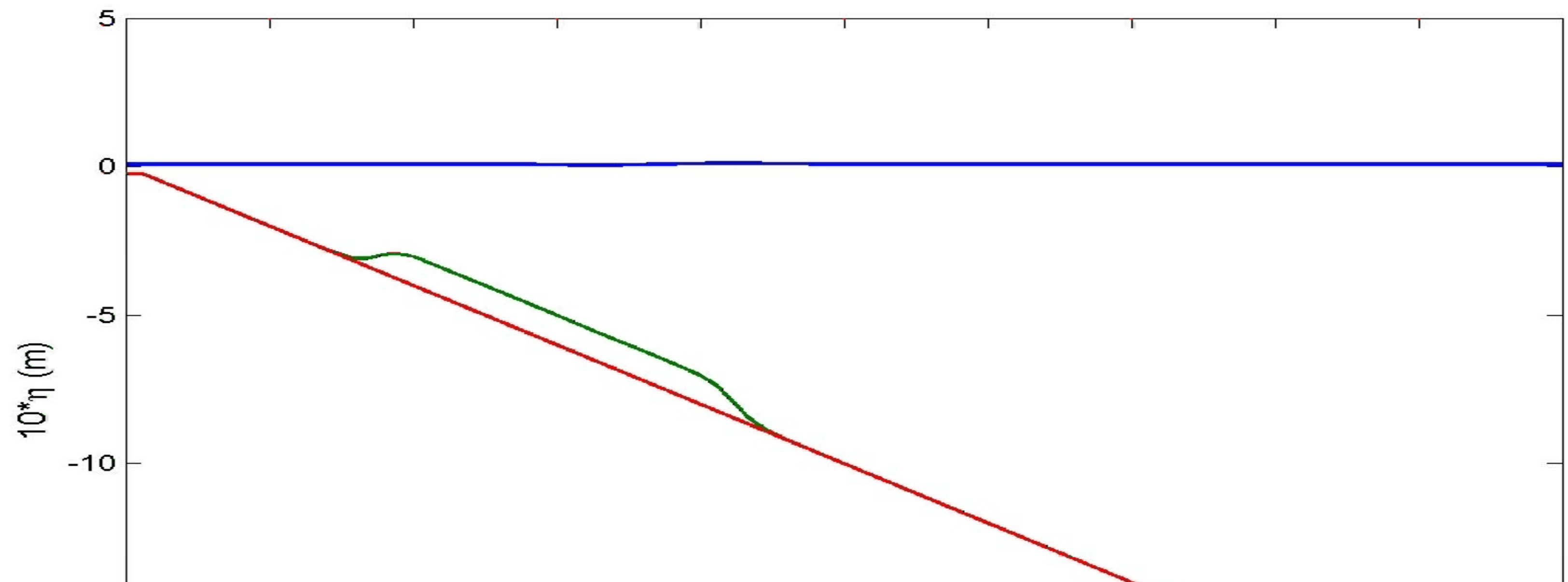
Probabilistic Approach for the Waves Generated by a Specified Landslide

Example approach to generate a probability distribution for the waves generated by a submarine

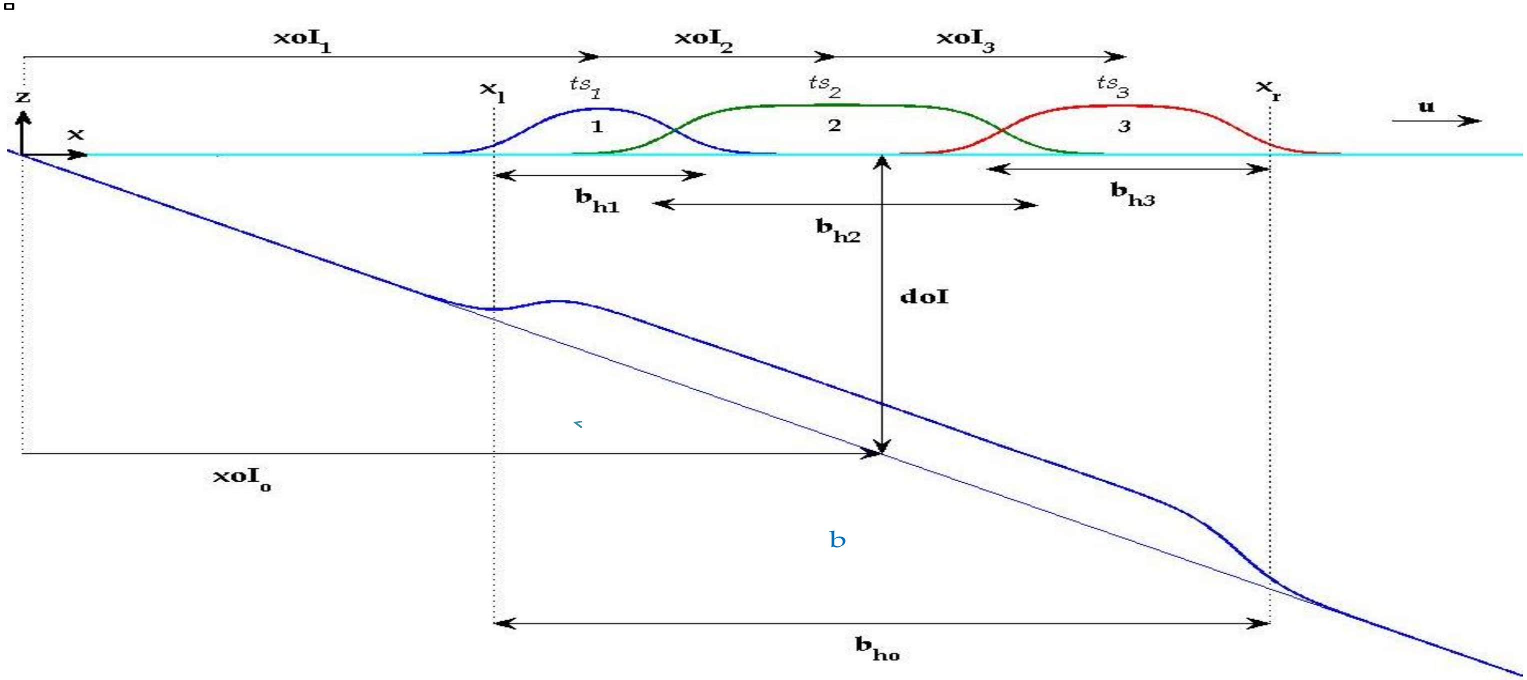
- Given a specific slide geometry and slide failure mechanism, can we capture the distribution of possible generated wave heights?
- Look at a simple case of a translational slide moving down a linear slope
- Allow the initial slide mass to failure in different segments, staggered in time. The motion of each slide is governed by solid body motion.



Probabilistic Approach for the Waves Generated by a Specified Landslide

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



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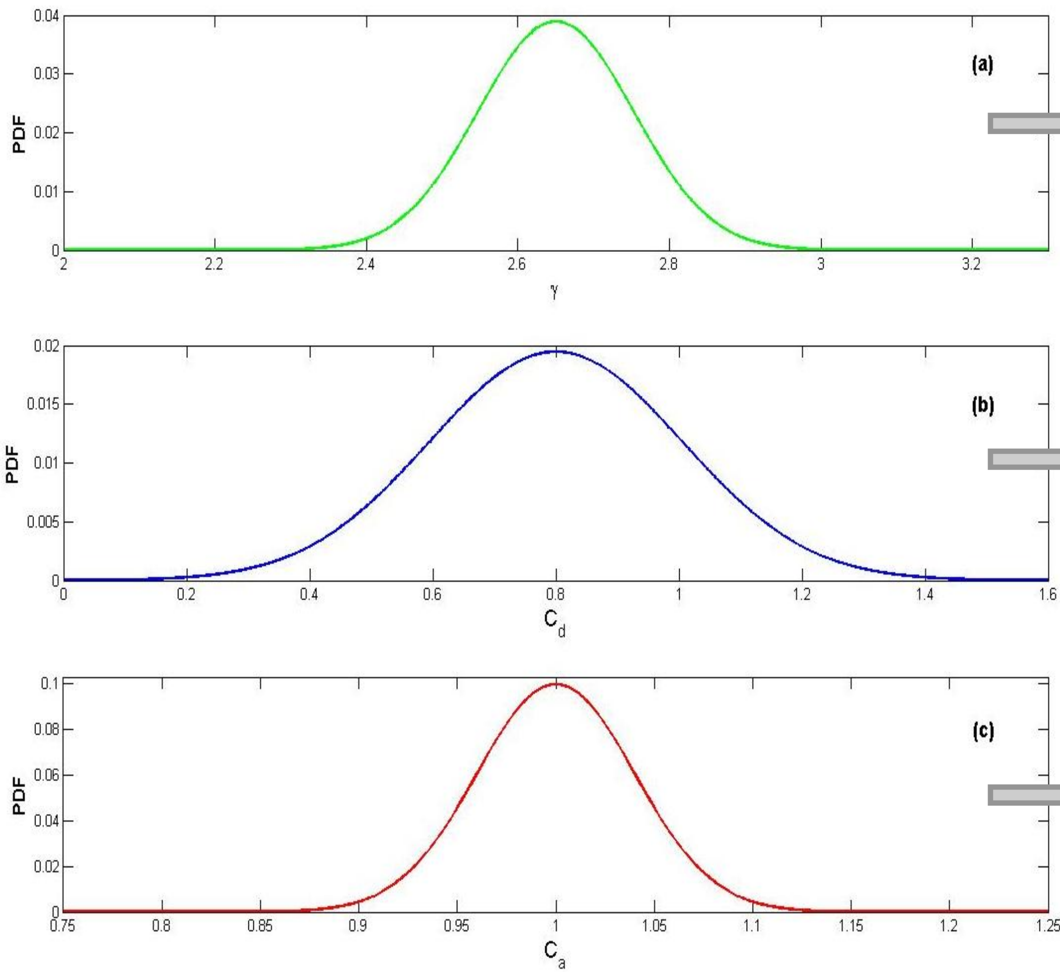
Probabilistic Approach for the Waves Generated by a Specified Landslide

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%

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Probabilistic Approach for the Waves Generated by a Specified Landslide

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

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

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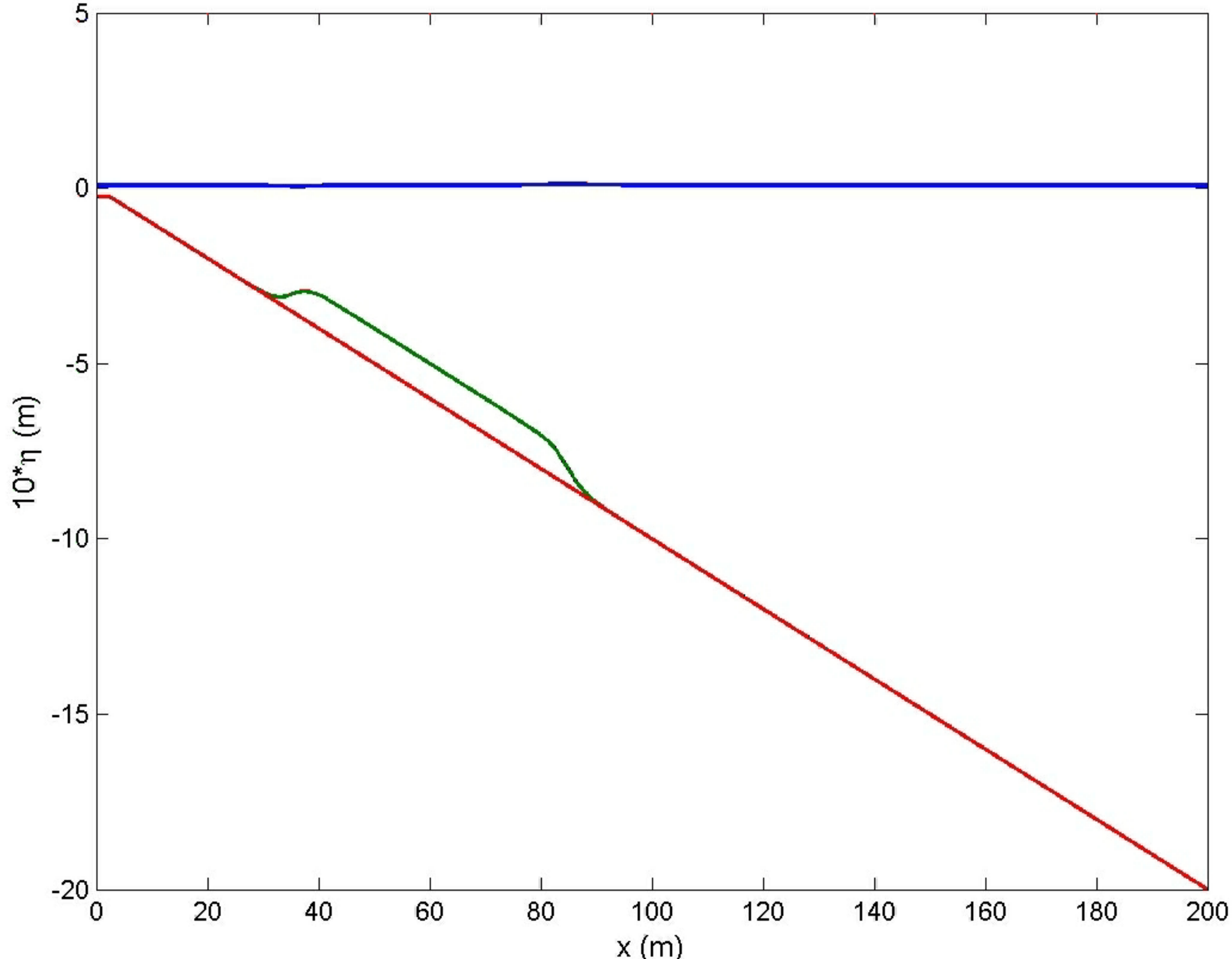
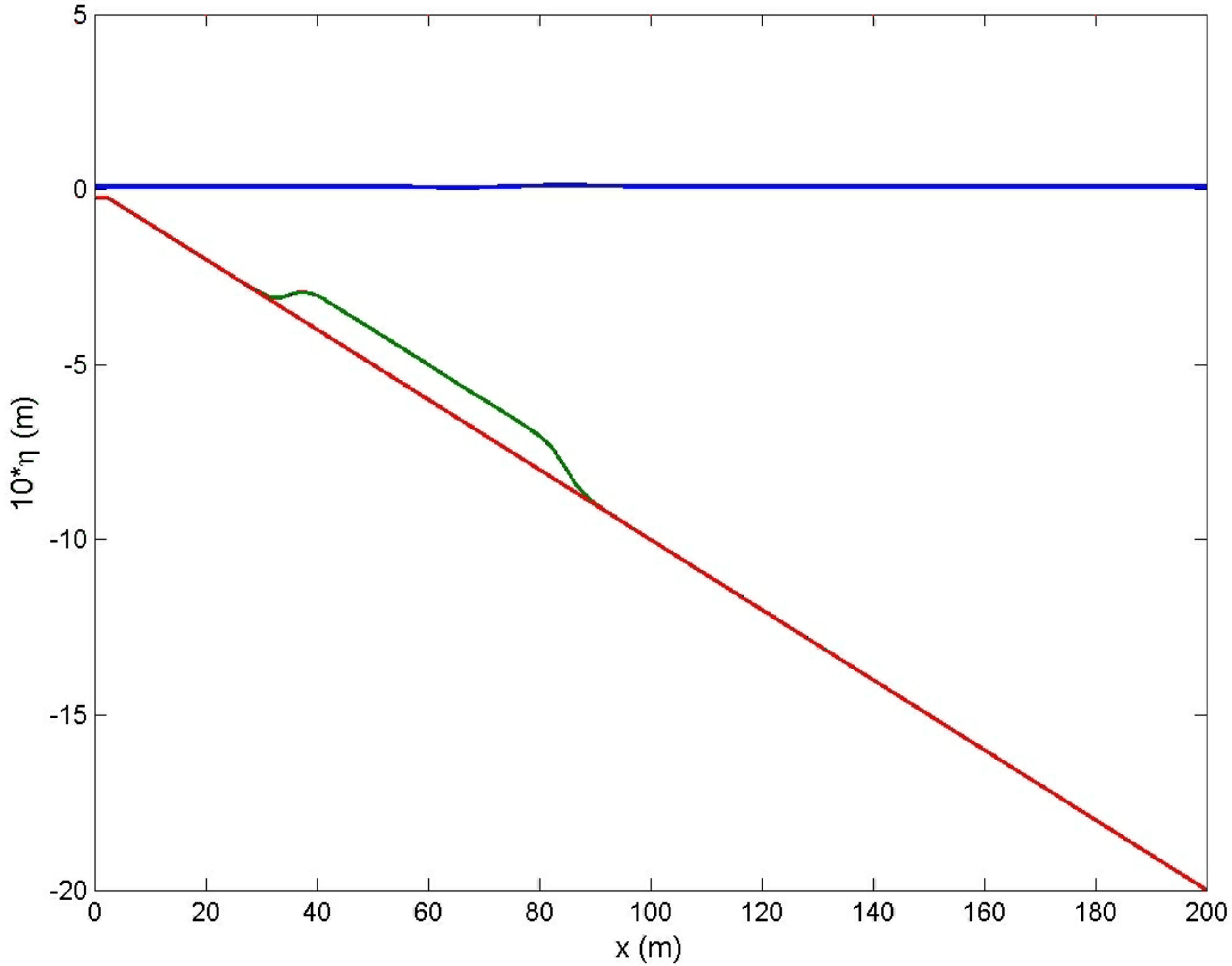
Probabilistic Approach for the Waves Generated by a Specified Landslide

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



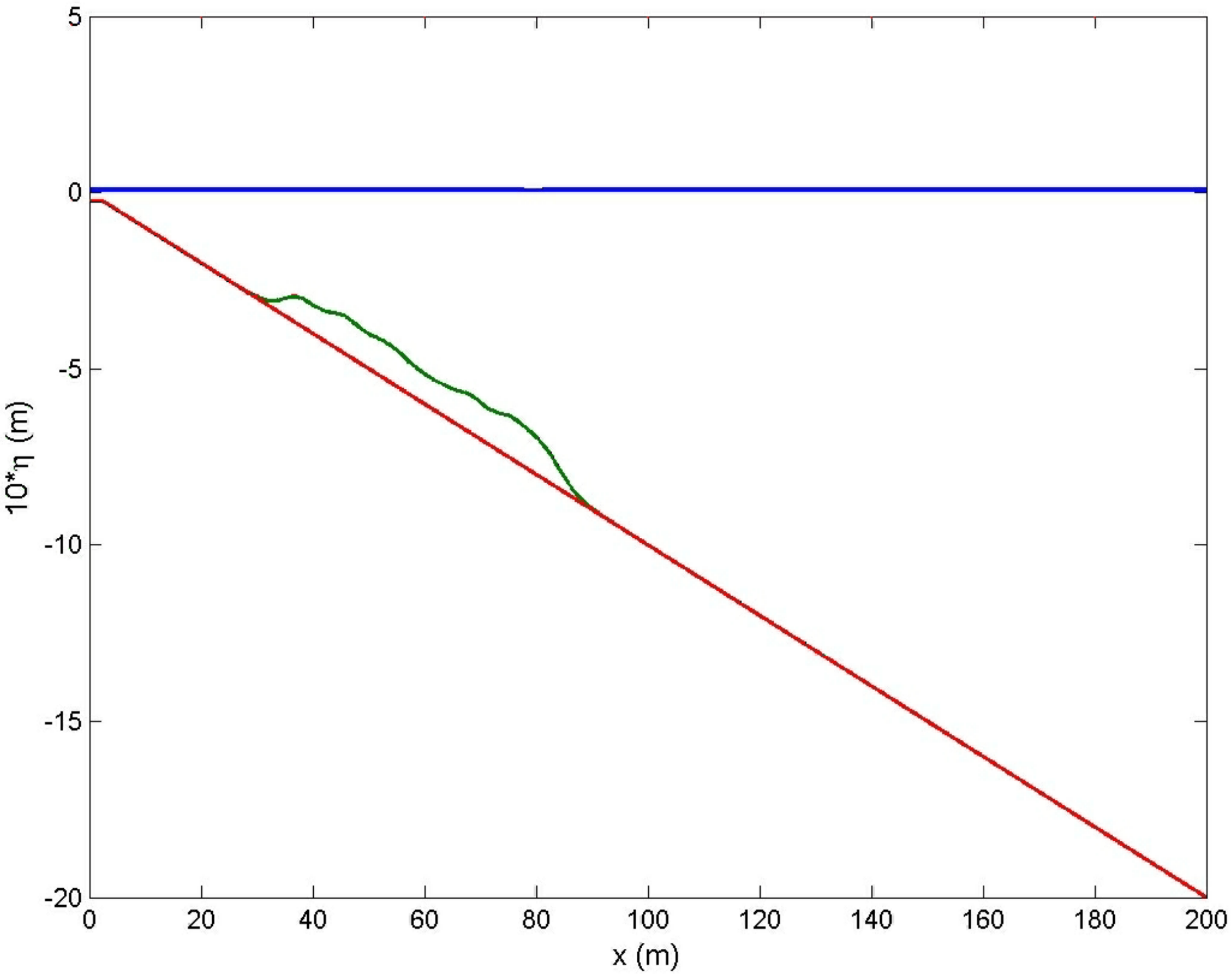
Probabilistic Approach for the Waves Generated by a Specified Landslide

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



Probabilistic Approach for the Waves Generated by a Specified Landslide

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



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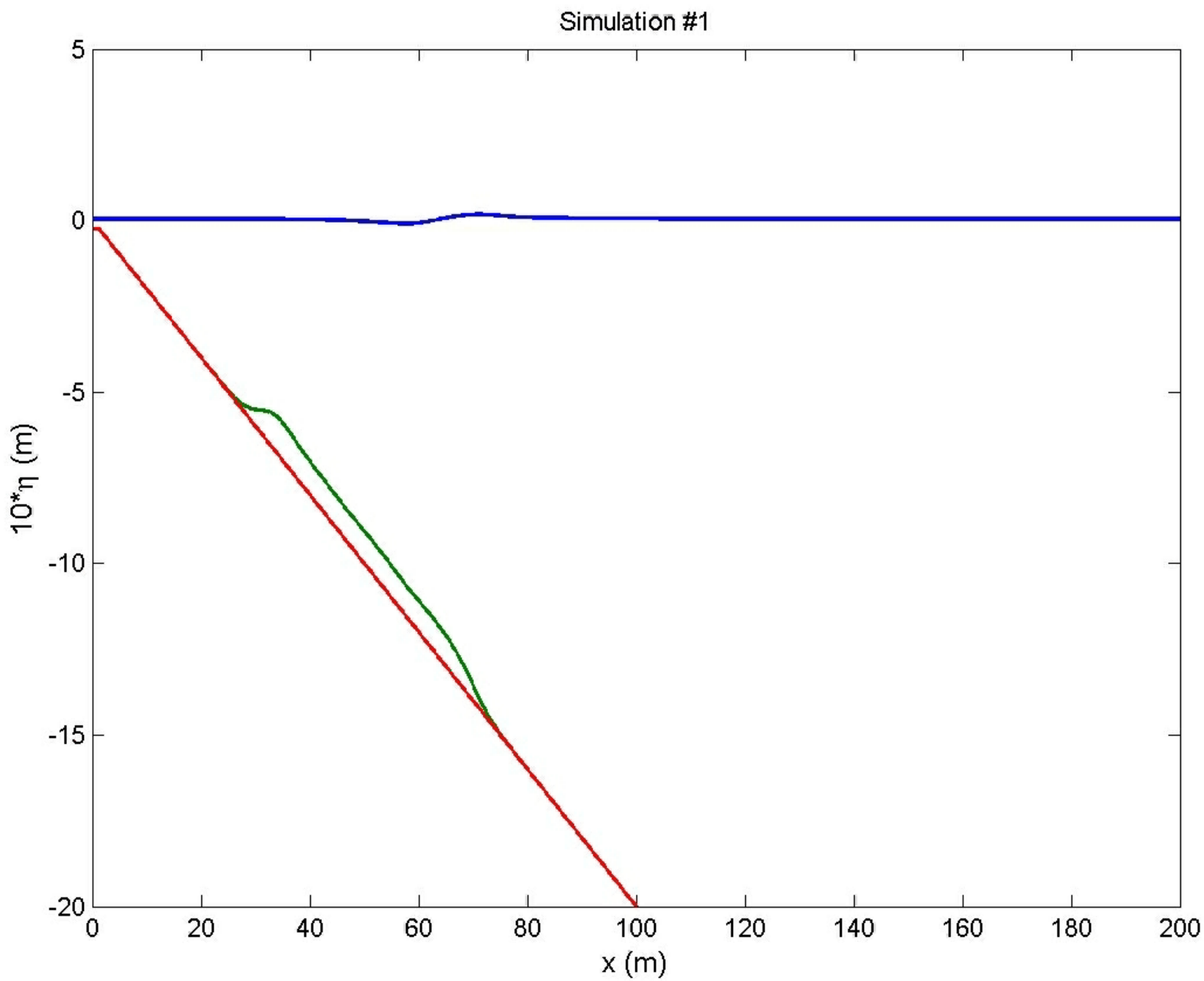
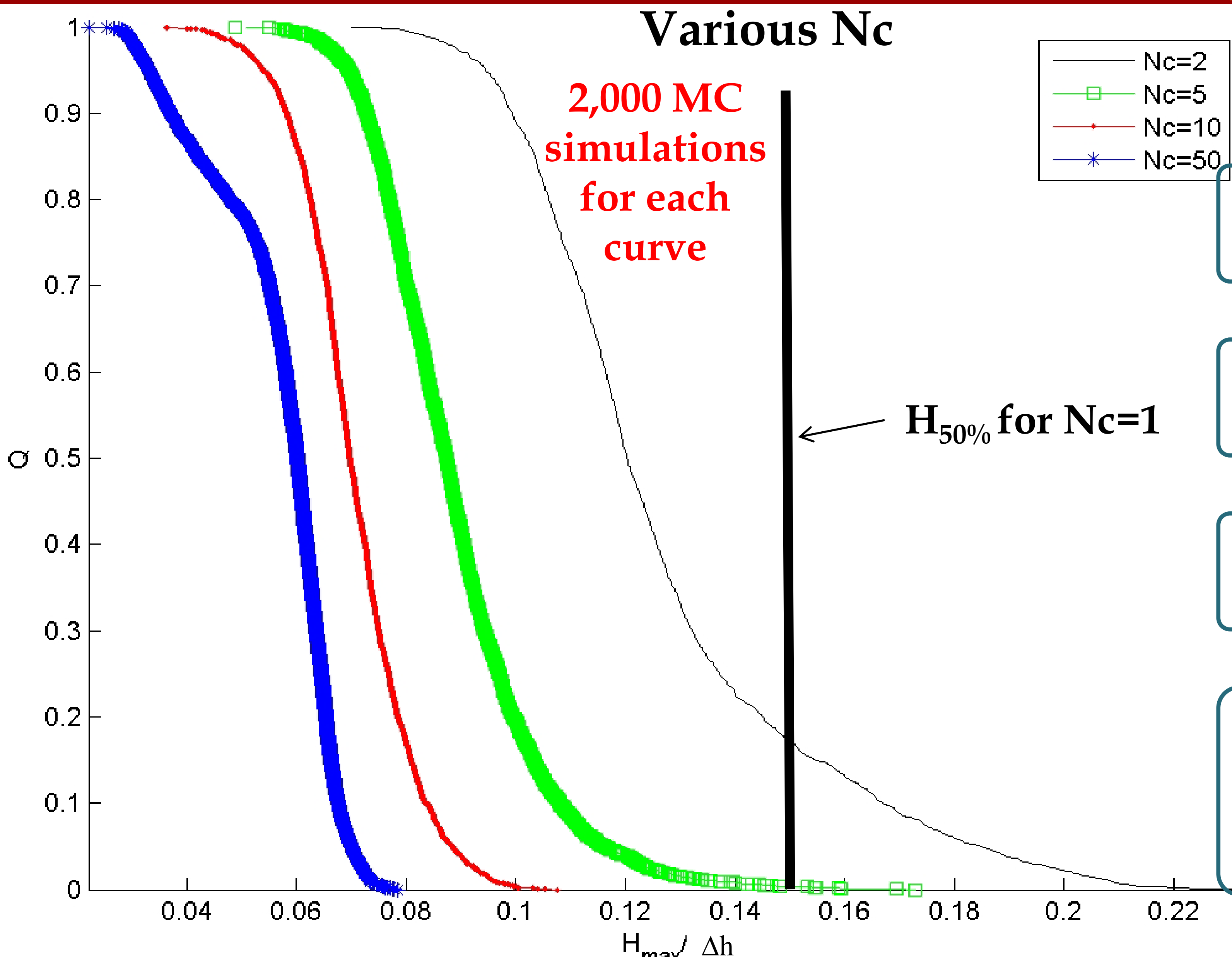
Probabilistic Approach for the Waves Generated by a Specified Landslide

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



Probabilistic Approach for the Waves Generated by a Specified Landslide



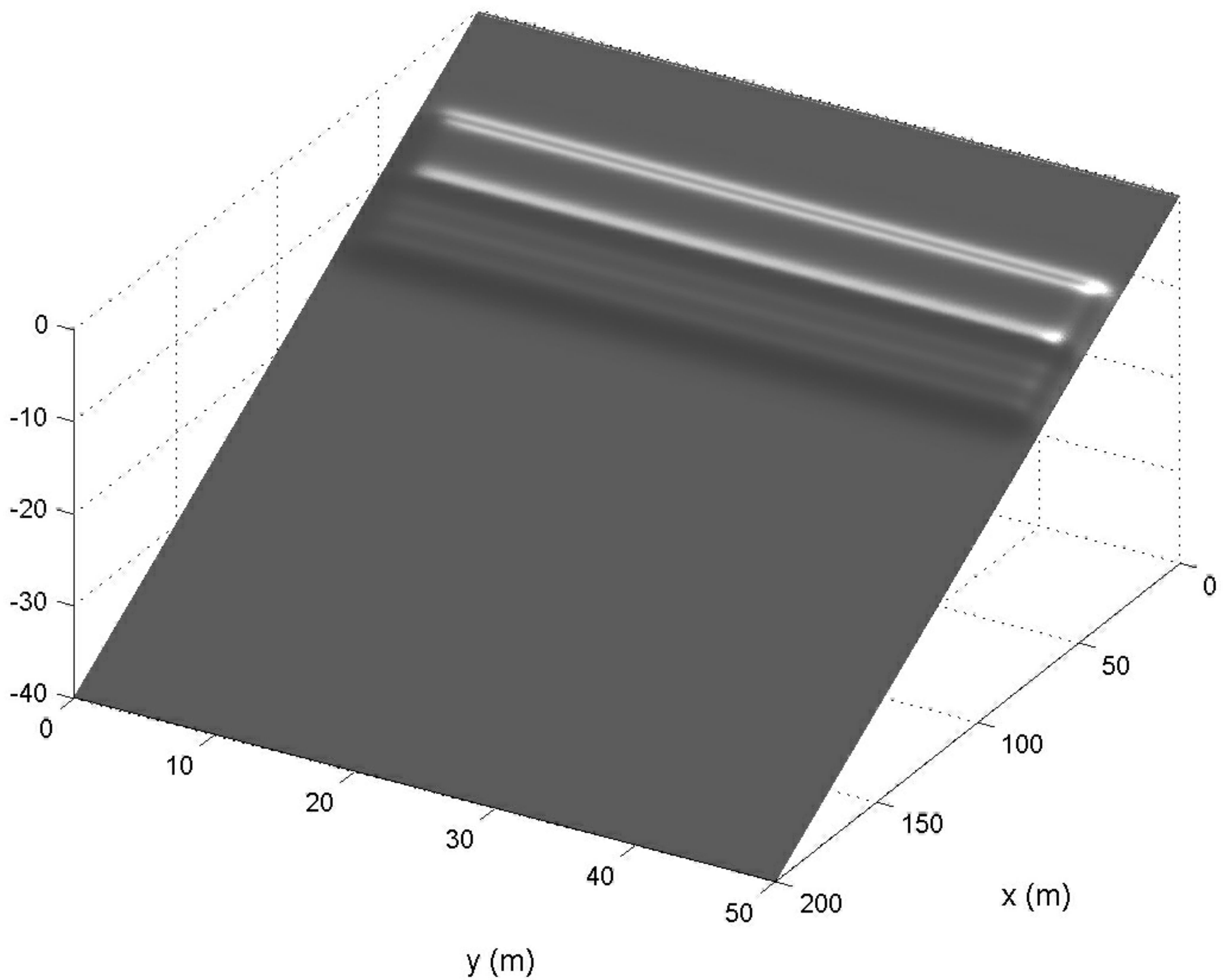
slope=1/5

b/Δh=40

doI/Δh =10

Delay/(doI/g)^0.5 =10

Probabilistic Approach for the Waves Generated by a Specified Landslide



Modeling Generation and Propagation of Landslide Tsunamis - 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

Landslide Tsunami Height Distribution

- 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

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Conclusions

Need much more geophysical information about existing slides

- Can a distribution for Nc be created?
- Info will tend to be very local, site-specific

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

Conclusions

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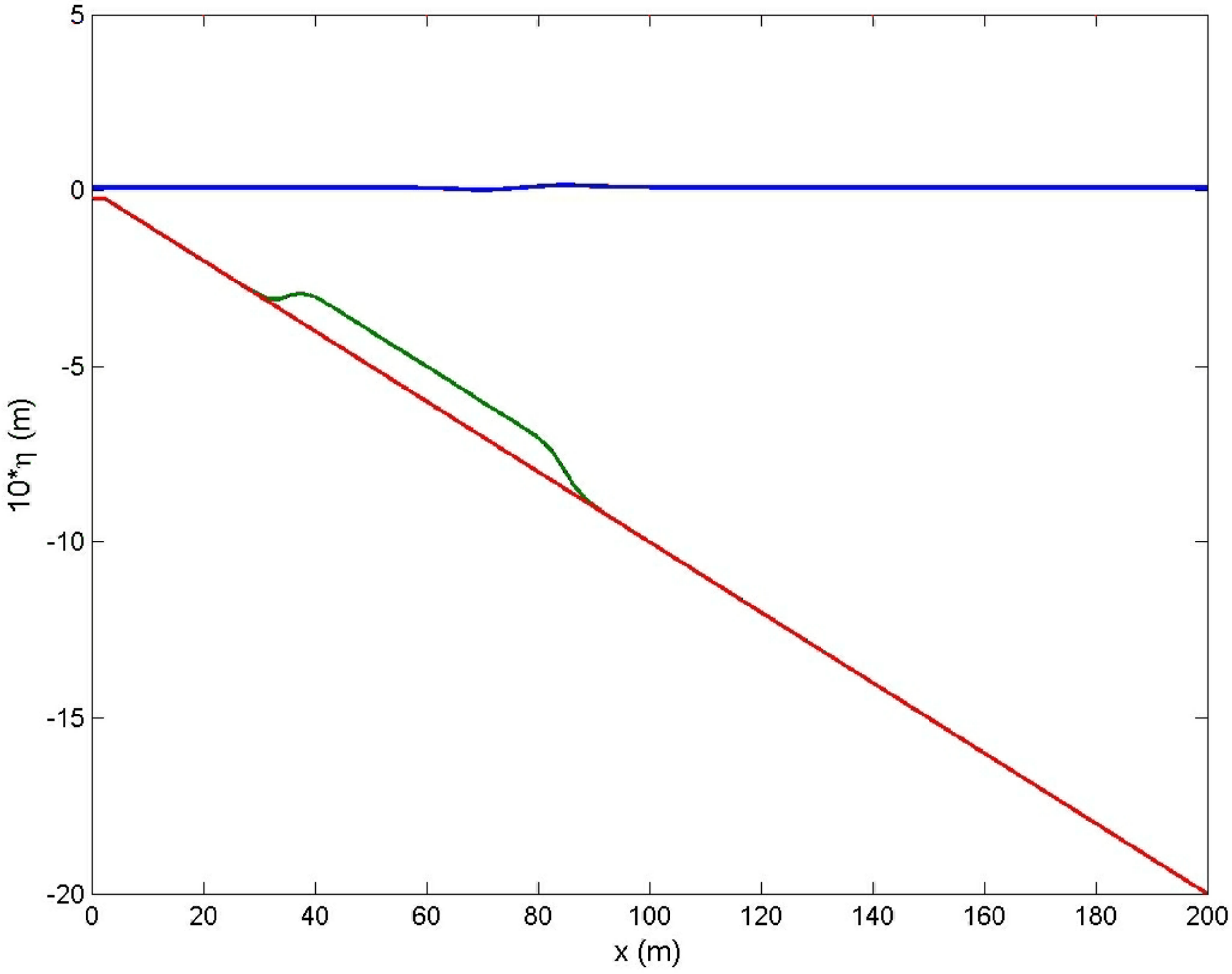
  - Duration of slumping (rotational)
- Measure of slide mass cohesion (Nc distribution)
- Failure "patchiness", a fraction of failure in the lateral direction

Outputs:

- Probabilistic distribution of Height, Period, # of Waves

Probabilistic Approach for the Waves Generated by a Specified Landslide

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



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