Comparison of techniques for coupled earthquake and tsunami modeling

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[4] Ludwig Maximilians University of Munich

One-Way Coupled Techniques

Pass information from an earthquake simulation

one-way information flow

To separate tsunami simulation

Coupled earthquake and tsunami modeling
Comparison of Model Techniques

	Static Initial Conditions
Earthquake Simulation	Final earthquake seafloor or sea surface uplift recorded
Tsunami Simulation	Set initial tsunami sea surface height
Citations	(Kajiura, 1963, 1970) (Tanioka & Satake, 1996) (Saito, 2019)

Static Technique

Pass information from an earthquake simulation

one-way information flow

To separate tsunami simulation

Coupled earthquake and tsunami modeling
Comparison of Model Techniques

	Static Initial Conditions	Time-dependent Seafloor Velocity as Forcing
Earthquake Simulation	Final earthquake seafloor or sea surface uplift recorded	Record earthquake seafloor velocity
Tsunami Simulation	Set initial tsunami sea surface height	Set time-dependent forcing in the tsunami mass balance
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Time-dependent forcing

Pass information from an earthquake simulation

one-way information flow

To separate tsunami simulation

Coupled earthquake and tsunami modeling

Comparison of Model Techniques

	Static Initial Conditions	Time-dependent Seafloor Velocity as Forcing	Time-dependent Sea Surface Velocity as Forcing
Earthquake Simulation	Final earthquake seafloor or sea surface uplift recorded	Record earthquake seafloor velocity	Solves earth and ocean response without gravity
Tsunami Simulation	Set initial tsunami sea surface height	Set time-dependent forcing in the tsunami mass balance	Use sea surface velocity as a forcing term in a tsunami simulation
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Do not account for compressibility effects (Static Initial Conditions; Time-dependent Seafloor Velocity as Forcing)

Pass information from an earthquake simulation

one-way information flow

To separate tsunami simulation

Coupled earthquake and tsunami modeling

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Approximate approaches

Pass information from an earthquake simulation

one-way information flow

To separate tsunami simulation

Coupled earthquake and tsunami modeling
Comparison of Model Techniques

	Static Initial Conditions	Time-dependent Seafloor Velocity as Forcing	Time-dependent Sea Surface Velocity as Forcing	Fully Coupled Method (SeisSol)
Earthquake Simulation	Final earthquake seafloor or sea surface uplift recorded	Record earthquake seafloor velocity	Solves earth and ocean response without gravity	Simultaneously solves earthquake rupture, seismic waves, and ocean response (including gravity) http://www.seissol.org/
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Approximate approaches

Considered "ground truth"
Newly implemented in 3D

Coupled earthquake and tsunami modeling
Comparison of Model Techniques

New in 3D

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Model the full-wave field

One-Way Coupled Techniques

Pass information from an earthquake simulation

one-way information flow

To separate tsunami simulation

Model techniques:

- Static initial conditions vs time-dependent forcing
- Incompressible vs compressible ocean

How is modeled data affected by:

1. long rupture duration
2. acoustic wave generation

Problem setup

- We want to examine how long duration rupture and compressibility affect wave generation in the four modeling techniques

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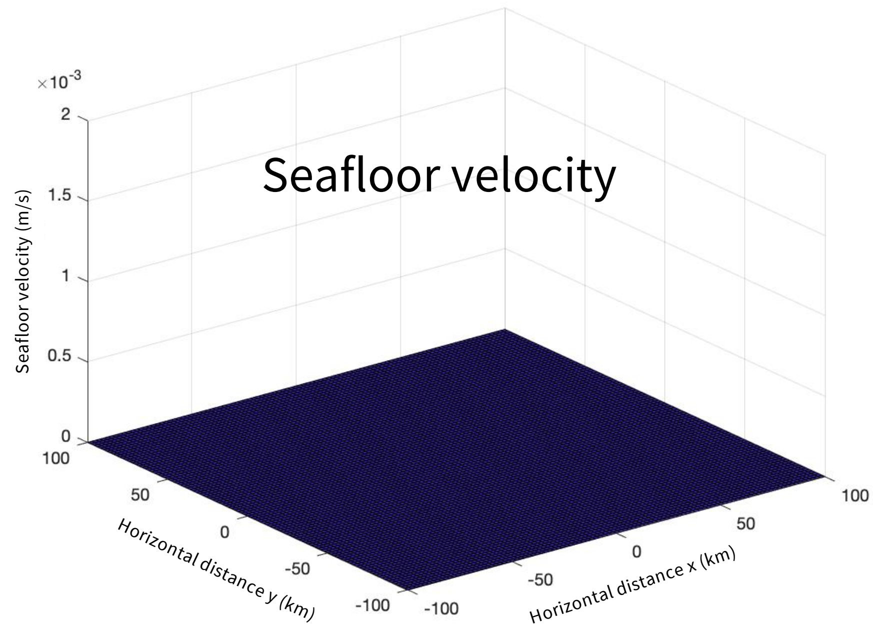

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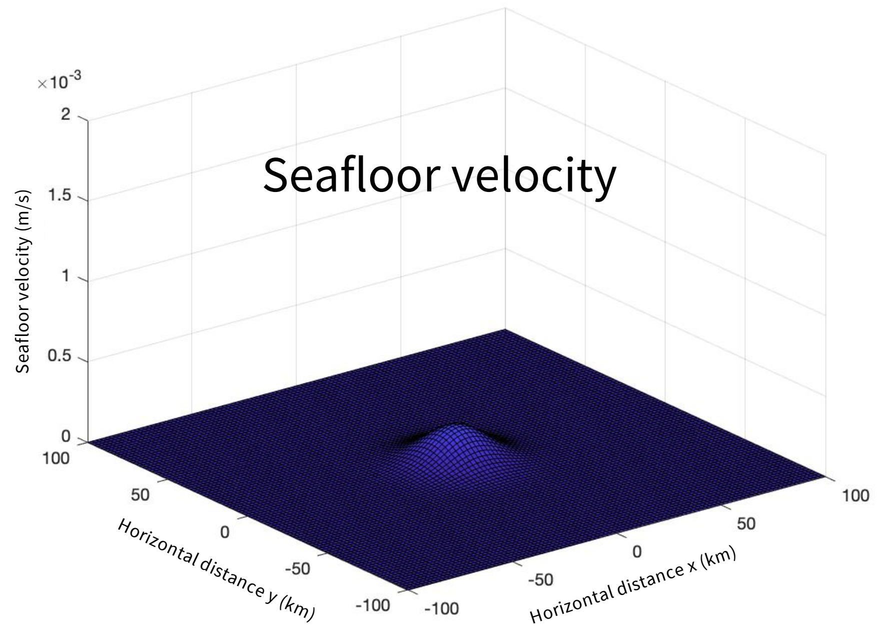

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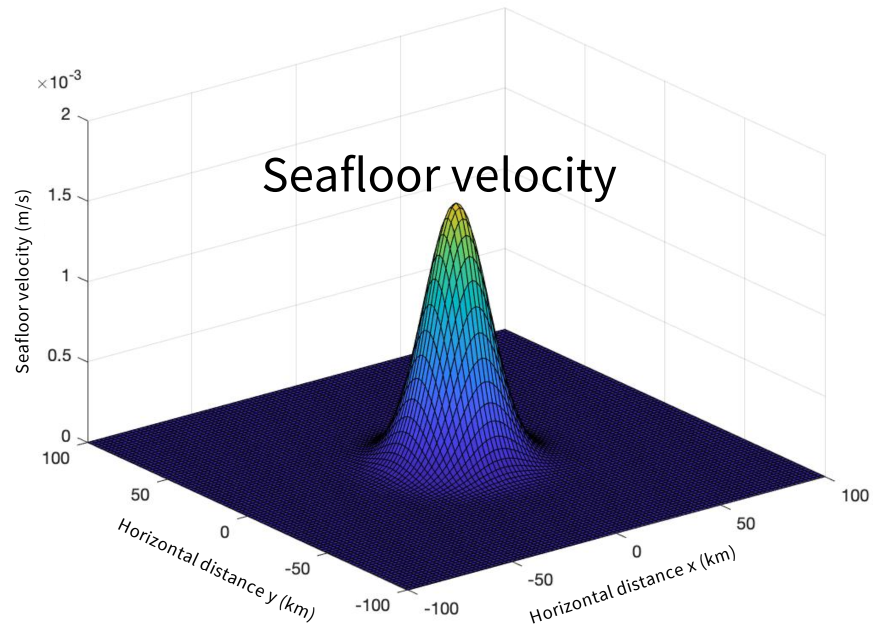

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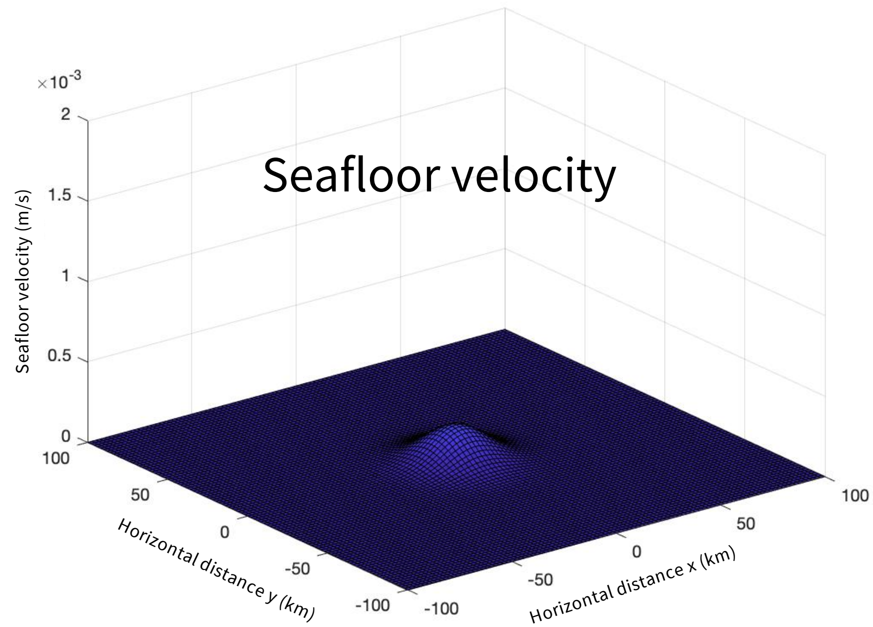

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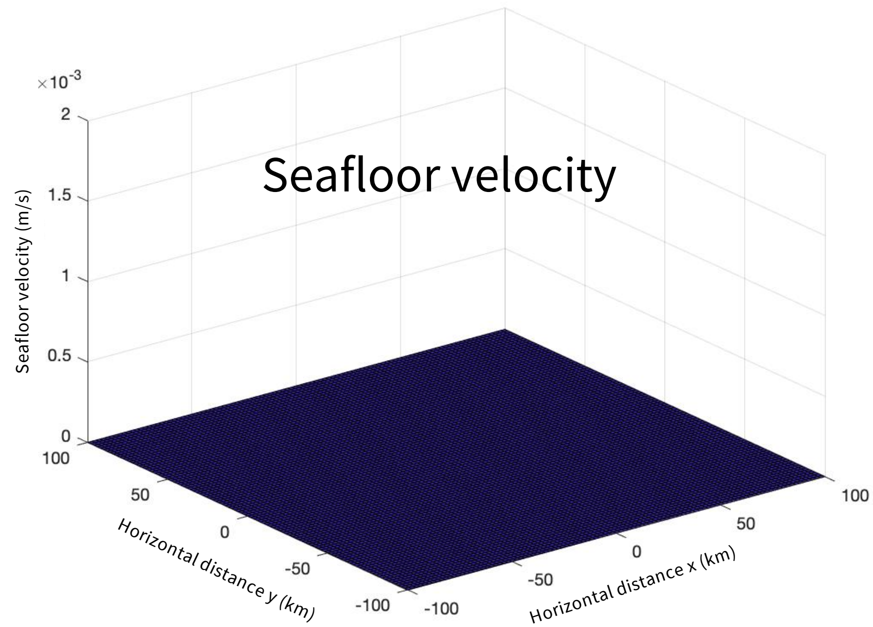
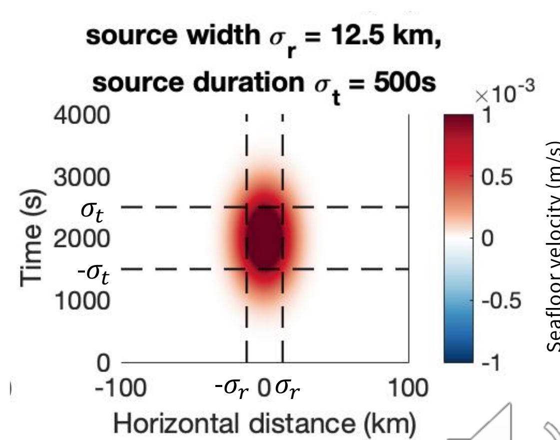


Problem setup

- We want to examine how long duration rupture and compressibility affect wave generation in the four modeling techniques
- We vary source width (σ_r) and duration (σ_t) in the earthquake simulation to test different scenarios setups



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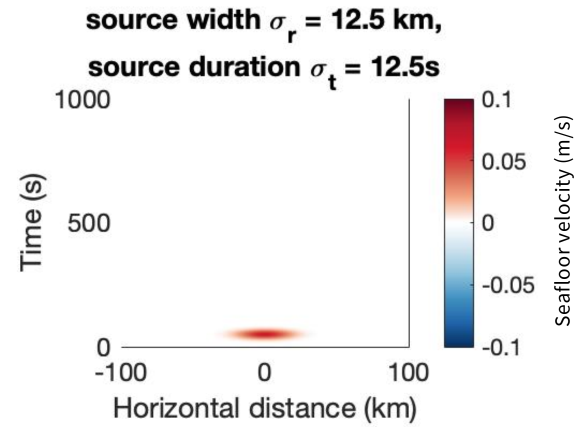
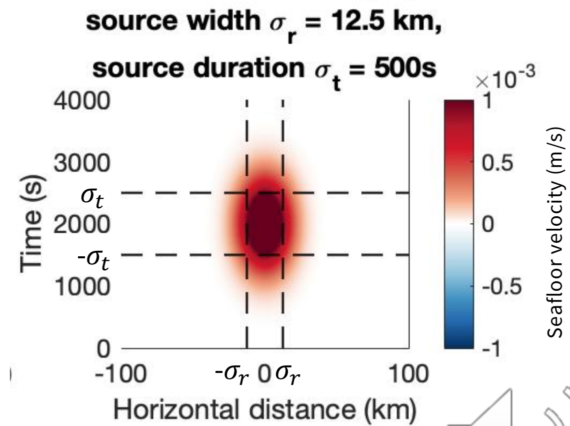
Short rupture duration σ_t



Long rupture duration σ_t



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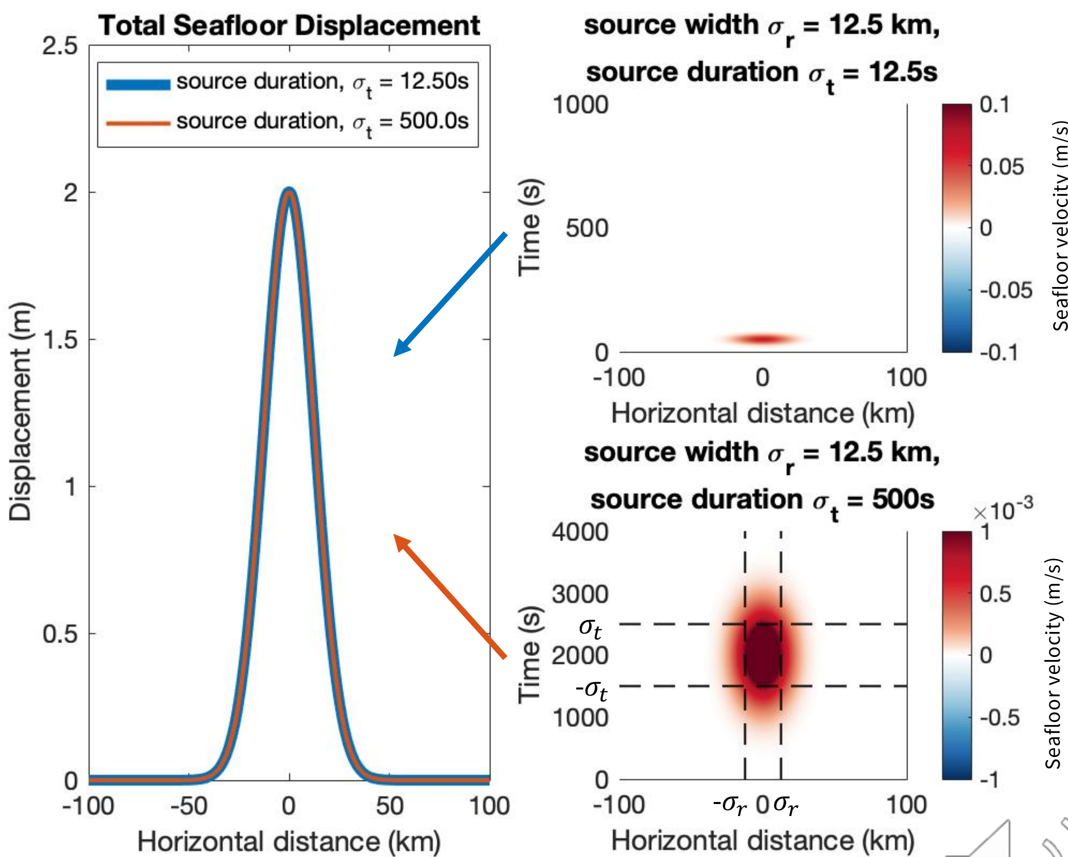


Problem setup

- We want to examine how long duration rupture and compressibility affect wave generation in the four modeling techniques
- We vary source width (σ_r) and duration (σ_t) in the earthquake simulation to test different scenarios setups

Within shallow water limit?
No if:

$$\frac{H}{\sigma_r} \gg 1$$

Tsunami propagates over source duration?
No if:

$$\frac{\sigma_r}{\sigma_t\sqrt{gH}} \gg 1$$

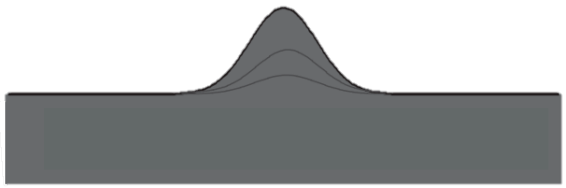
Acoustic waves significant?
No if:

$$\frac{c\sigma_t}{H} \gg 1$$

Where, the ocean depth is $H = 4\text{km}$, tsunami wave speed is $\sqrt{gH}$, and acoustic wavespeed c

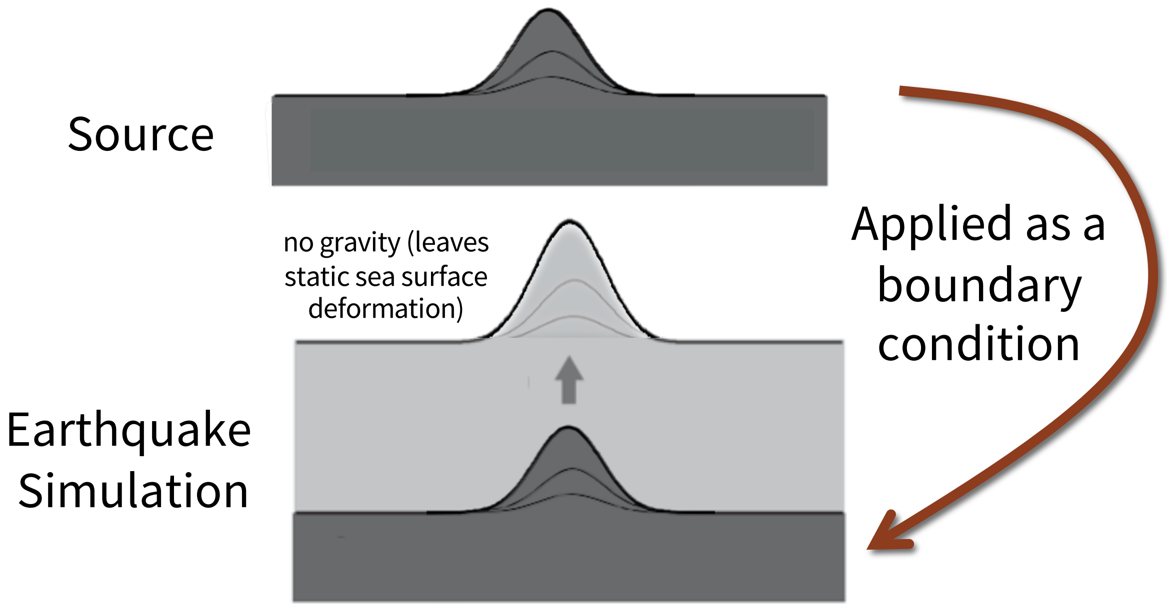
Problem setup

Source



(modified from Saito et al., 2019)

Problem setup



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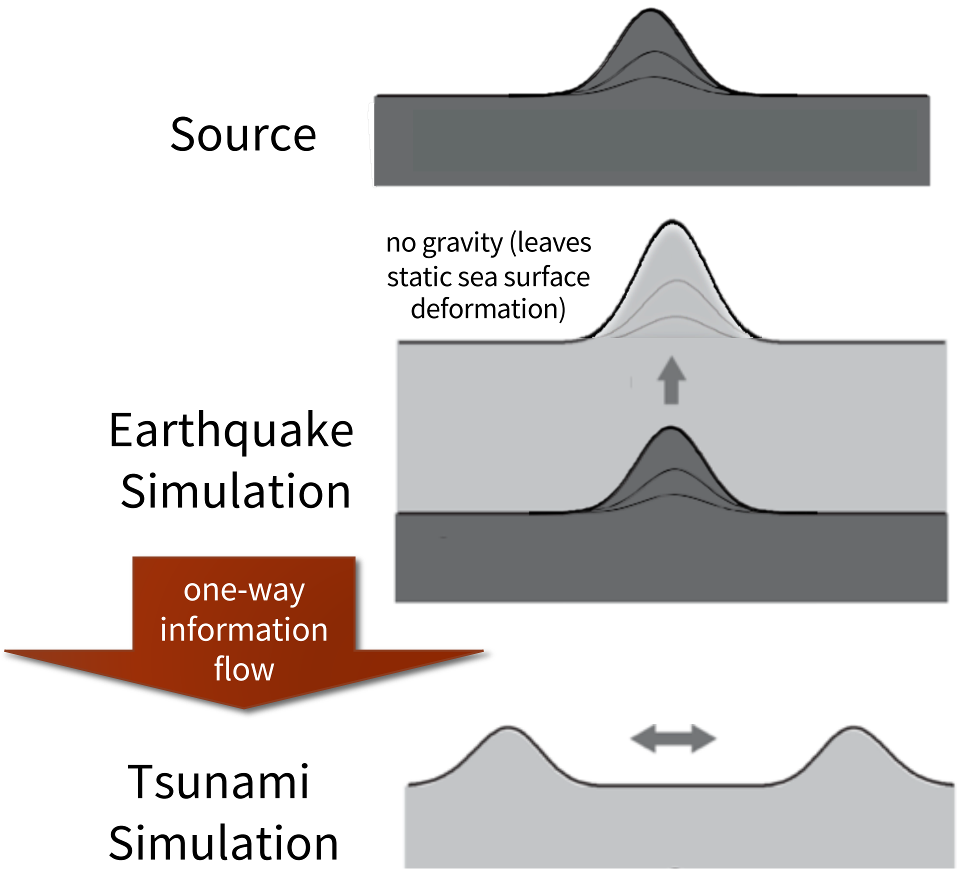

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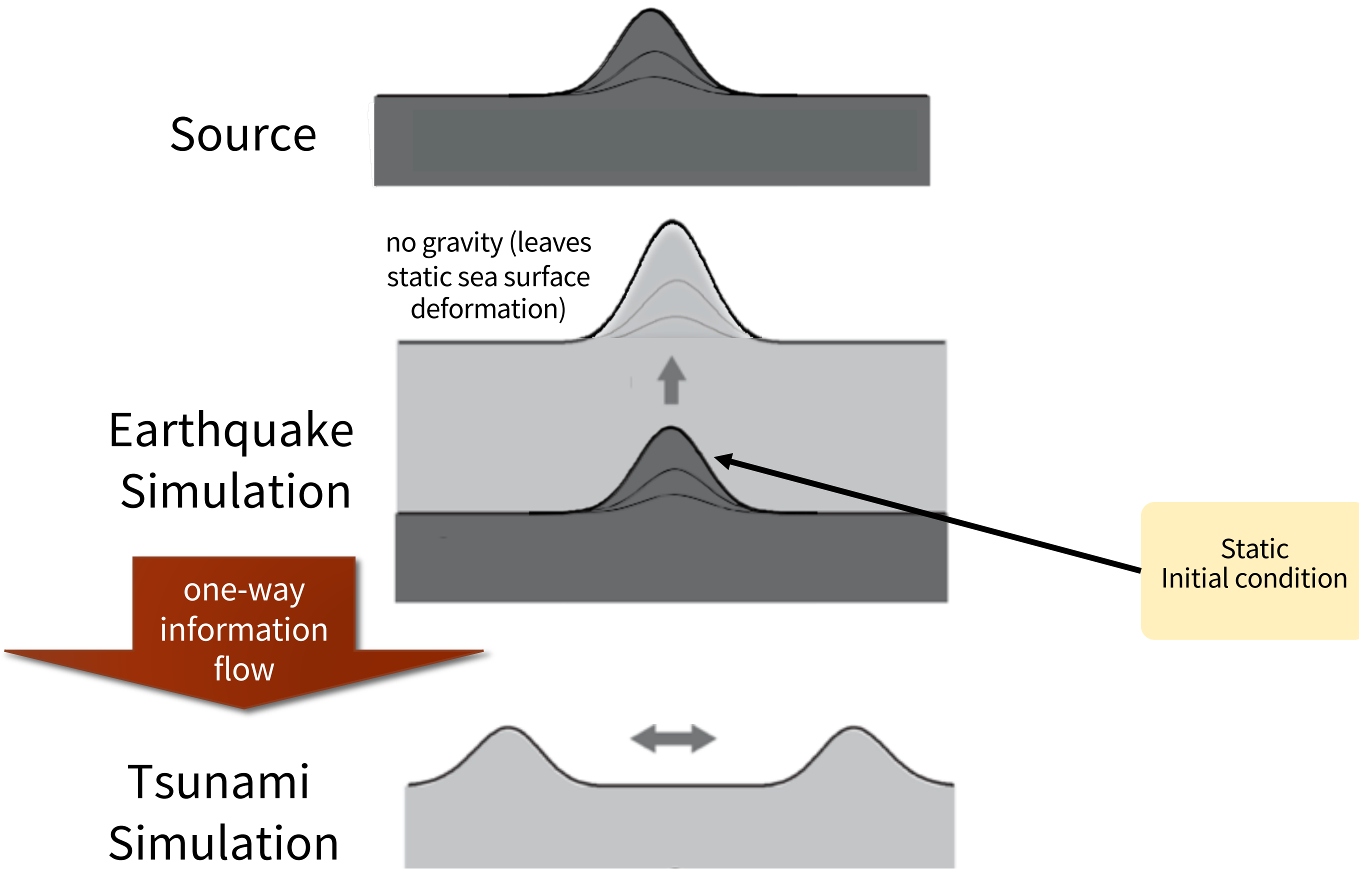

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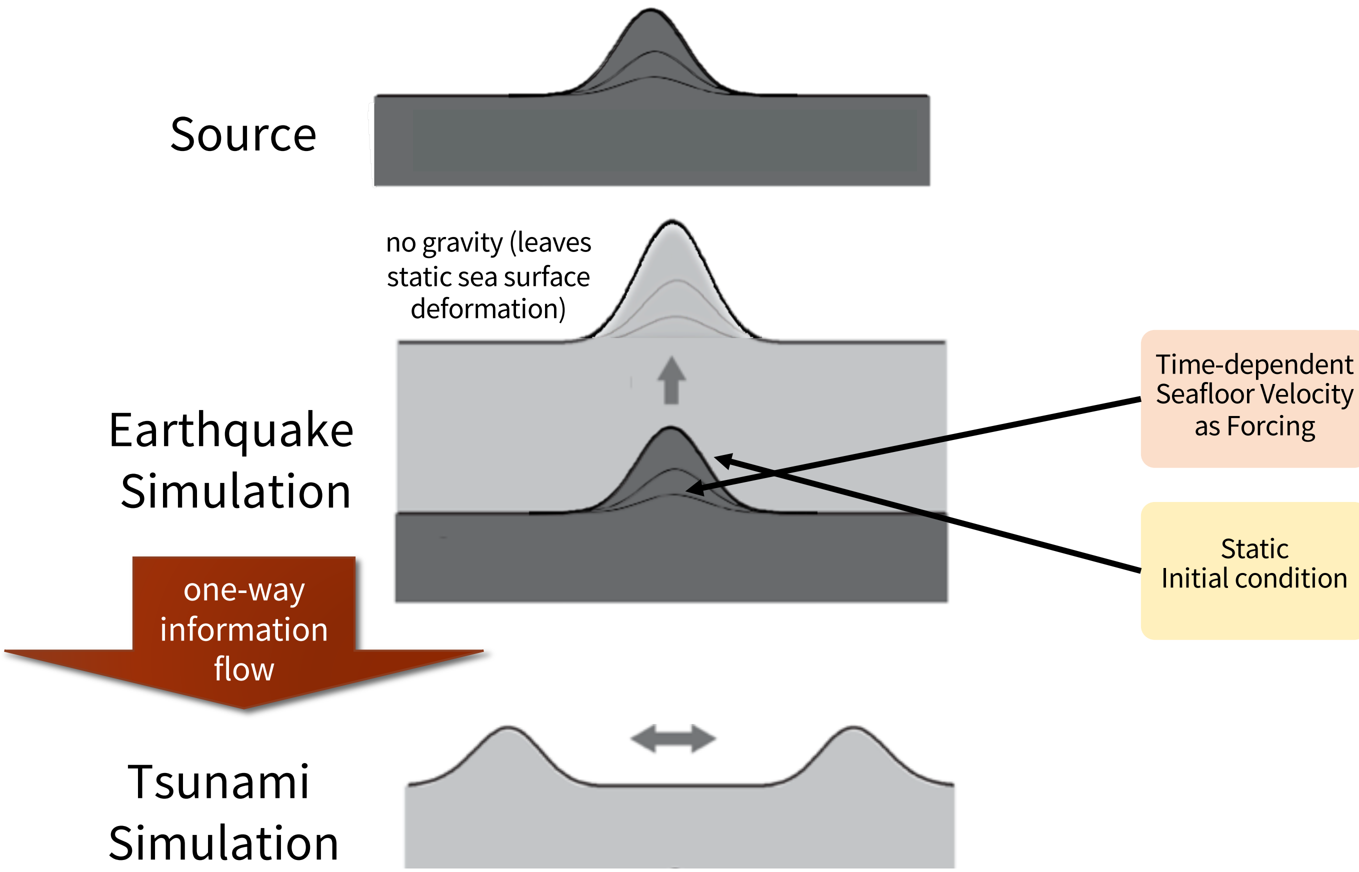

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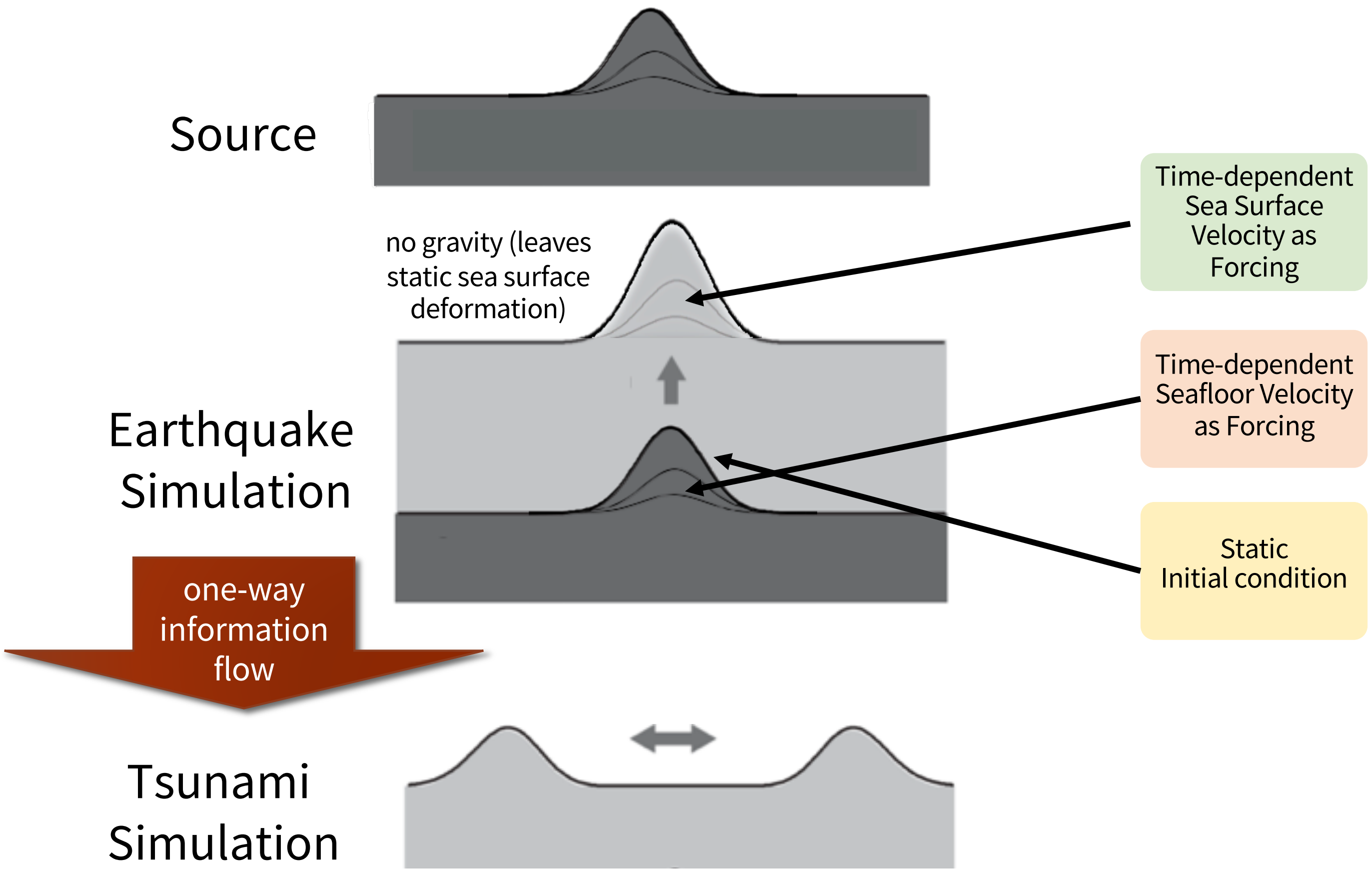

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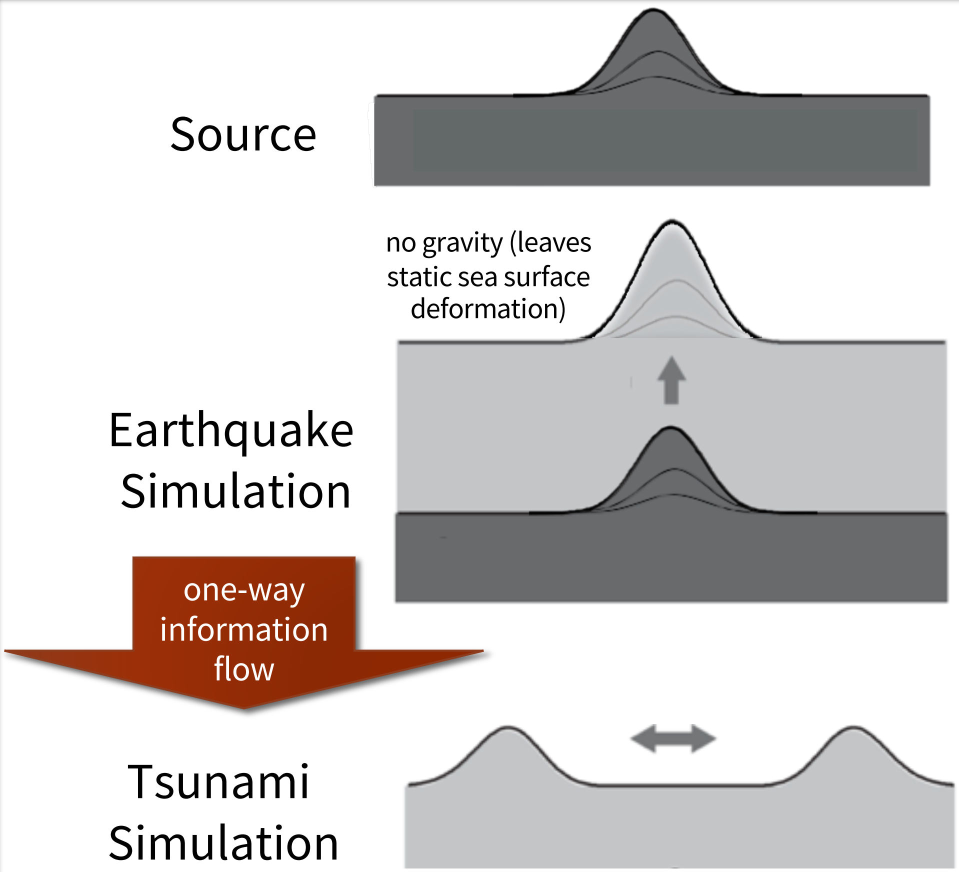

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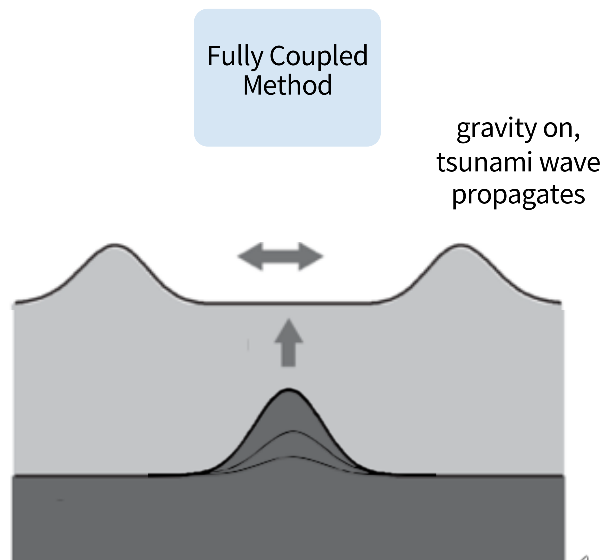

Revised Slides Begin here

Research is always ongoing, this talk has been revised to show new exciting results!

Method 1. Static Initial condition

Method 2. Time-dependent Seafloor Velocity as Forcing

Method 3. Time-dependent Sea Surface Velocity as Forcing

Method 4. Fully Coupled Method

Example 1:

Source Width : σ_r = 12.5 km

Source Duration : σ_t = 500 s

Within shallow water limit?

Yes: $\frac{H}{\sigma_r} = 0.32 < 1$

Tsunami propagates over source duration?

Yes: $\frac{\sigma_r}{\sigma_t\sqrt{gH}} = 0.13 < 1$

Acoustic waves significant?

No: $\frac{c\sigma_t}{H} = 187.5 > 1$

We can anticipate method 1 (using a static initial condition) will be incorrect

Source Width : σ_r = 12.5 km
Source Duration : σ_t = 500 s
Yes: Within shallow water limit?
Yes: Tsunami propagates over source duration?
No: Acoustic waves significant?

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Static Initial condition

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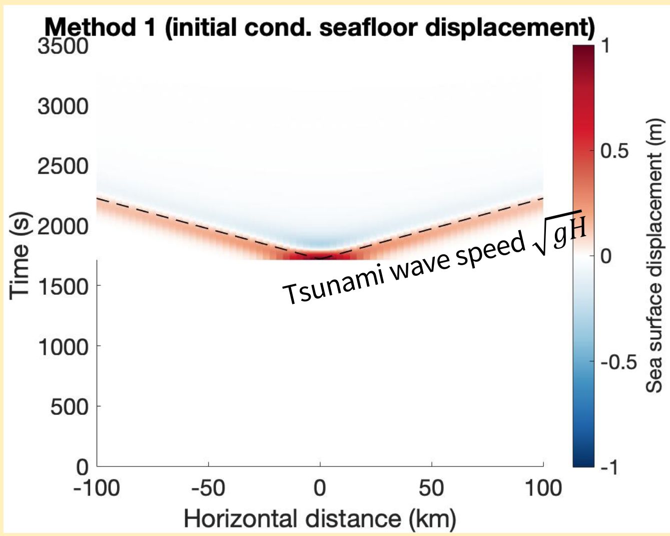
Seafloor displacement as initial conditions



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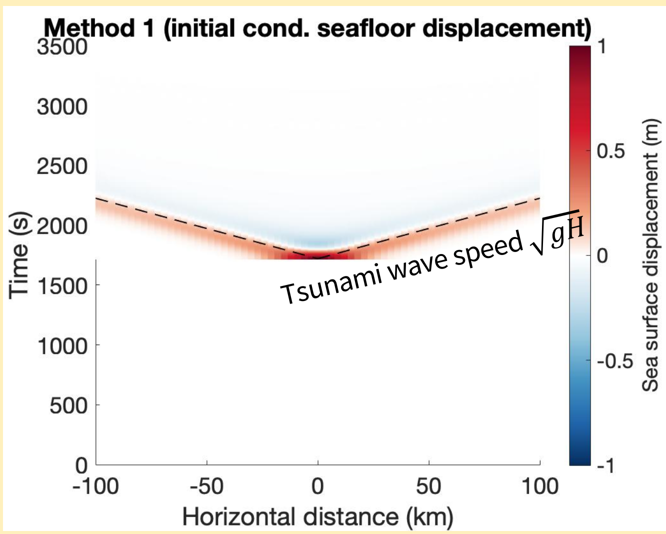
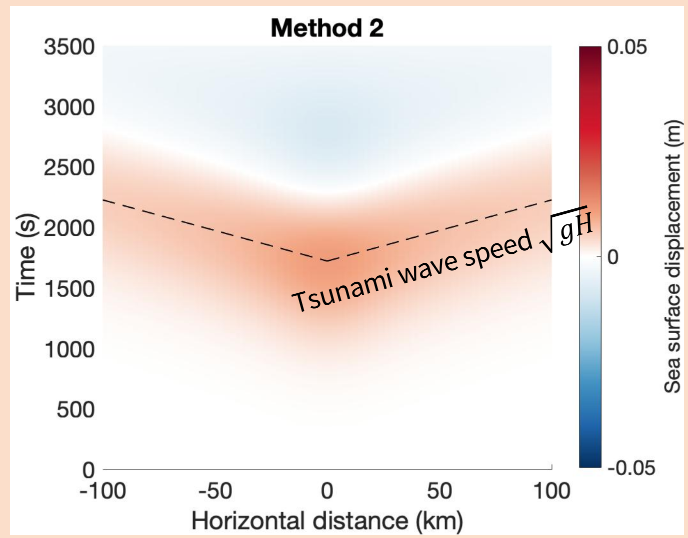


Seafloor velocity as forcing



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Method 4. Fully Coupled Method

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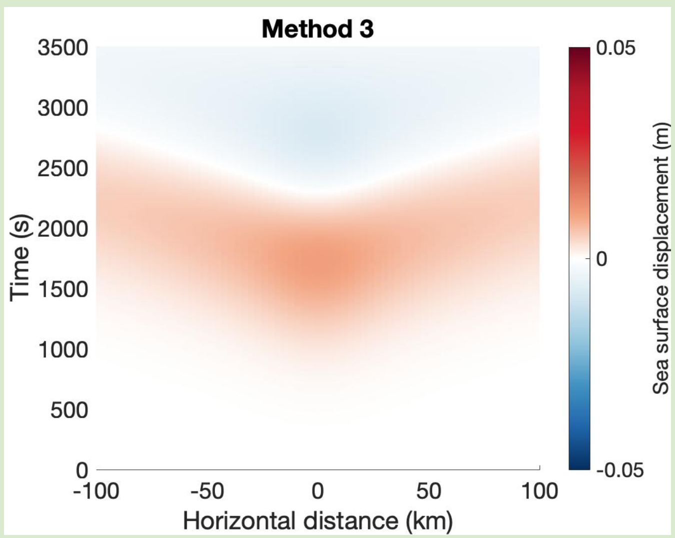
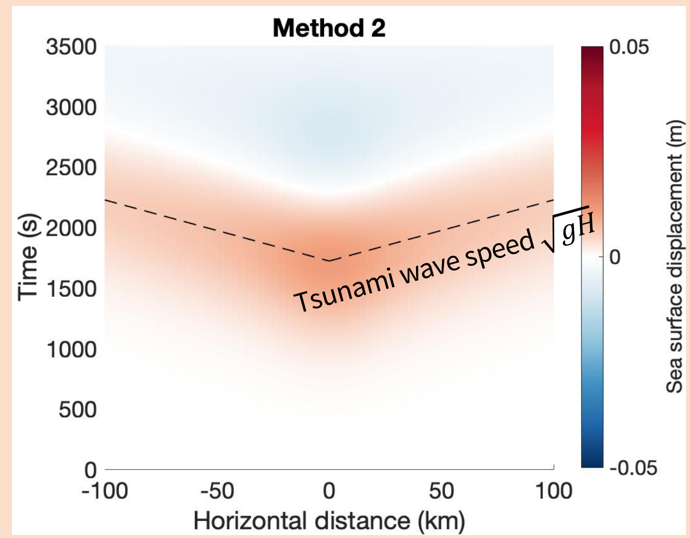


Seafloor velocity as forcing



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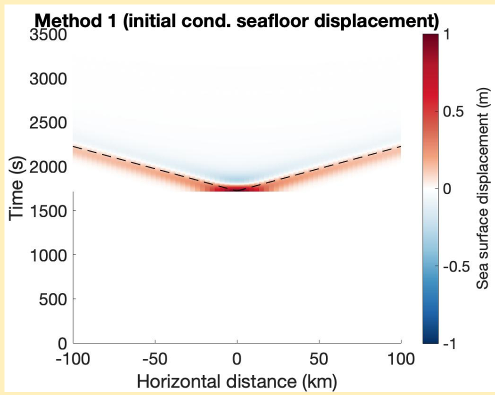

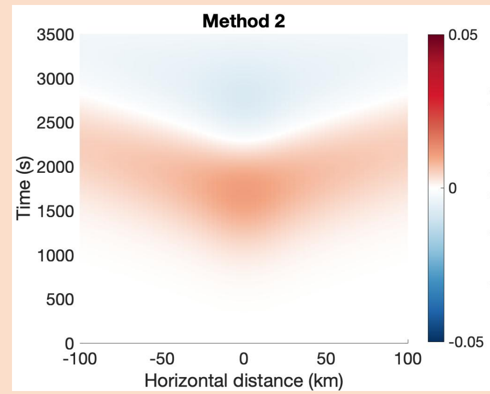

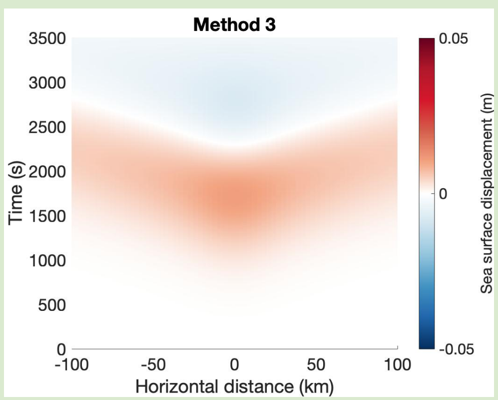

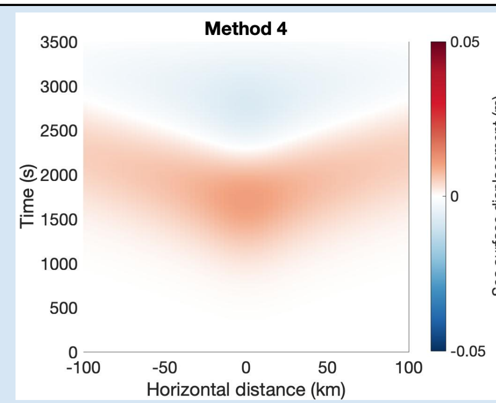

Example 2:

Method 1. Static Initial condition

Method 2. Time-dependent Seafloor Velocity as Forcing

Method 3. Time-dependent Sea Surface Velocity as Forcing

Method 4. Fully Coupled Method

Source Width : σ_r = 12.5 km

Source Duration : σ_t = 1.25 s

Within shallow water limit?

Yes: $\frac{H}{\sigma_r} = 0.32 < 1$

Tsunami propagates over source duration?

No: $\frac{\sigma_r}{\sigma_t \sqrt{gH}} = 50.5 > 1$

Acoustic waves significant?

Yes: $\frac{c\sigma_t}{H} = 0.47 < 1$

Method 1 and 2 do not model acoustic wave generation, we anticipate the results will differ compared to methods 3 and 4

Source Width : σ_r = 12.5 km
Source Duration : σ_t = 1.25 s
Yes: Within shallow water limit?
No: Tsunami propagates over source duration?
Yes: Acoustic waves significant?

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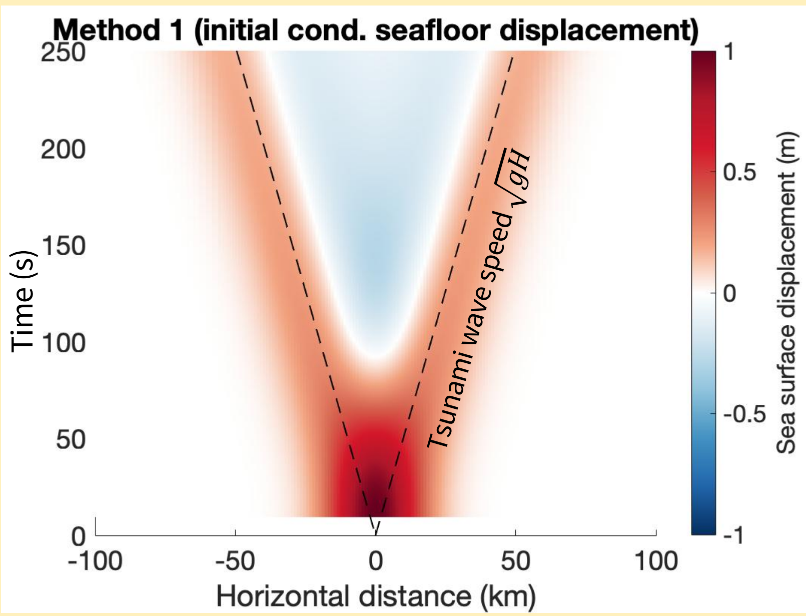
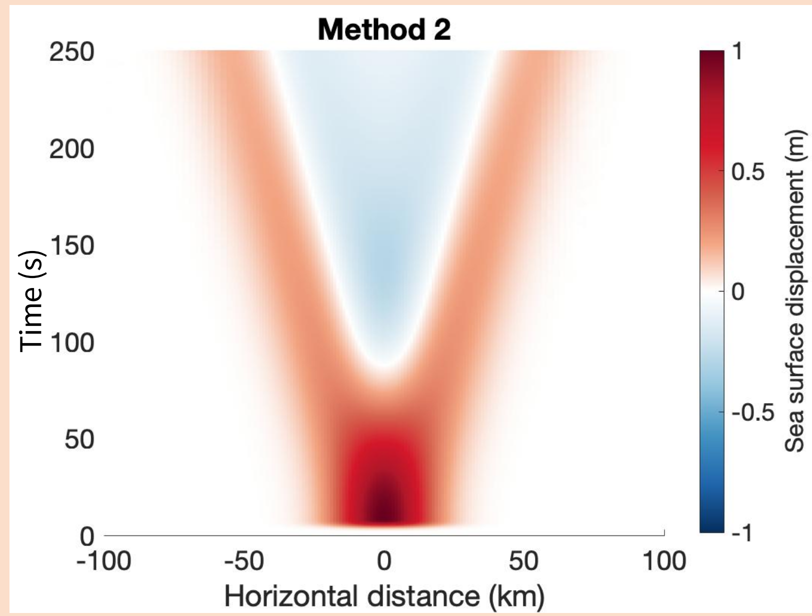


Seafloor velocity as forcing



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Source Duration : σ_t = 1.25 s
Yes: Within shallow water limit?
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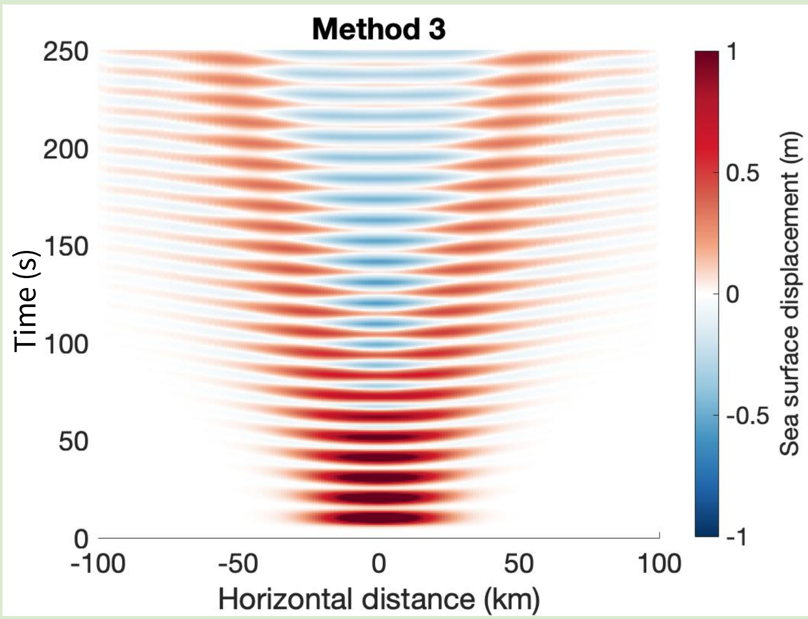
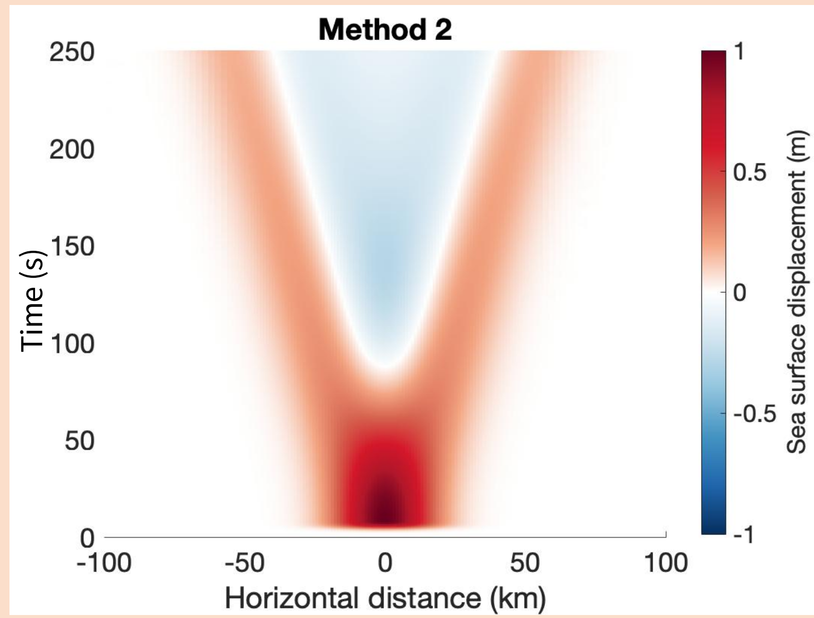
Full wavefield



No acoustic waves



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Source Duration : σ_t = 1.25 s
Yes: Within shallow water limit?
No: Tsunami propagates over source duration?
Yes: Acoustic waves significant?

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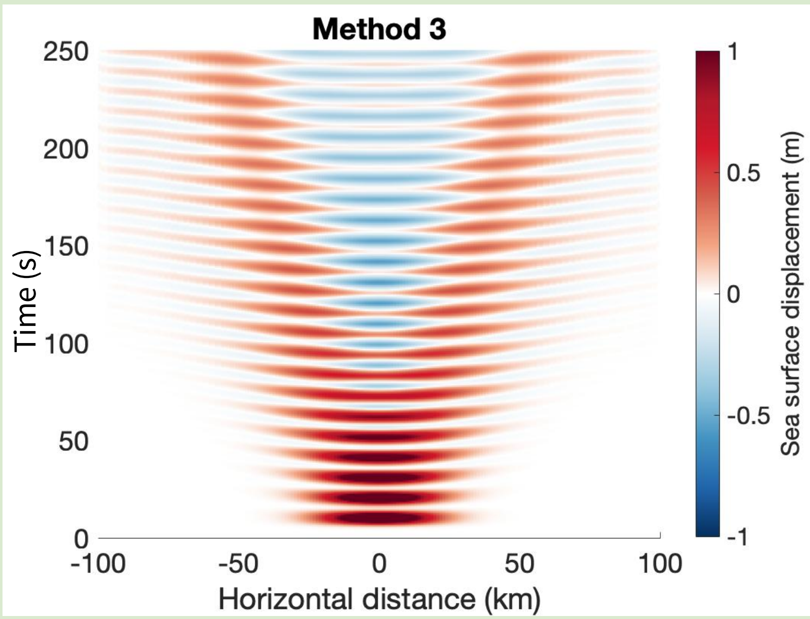
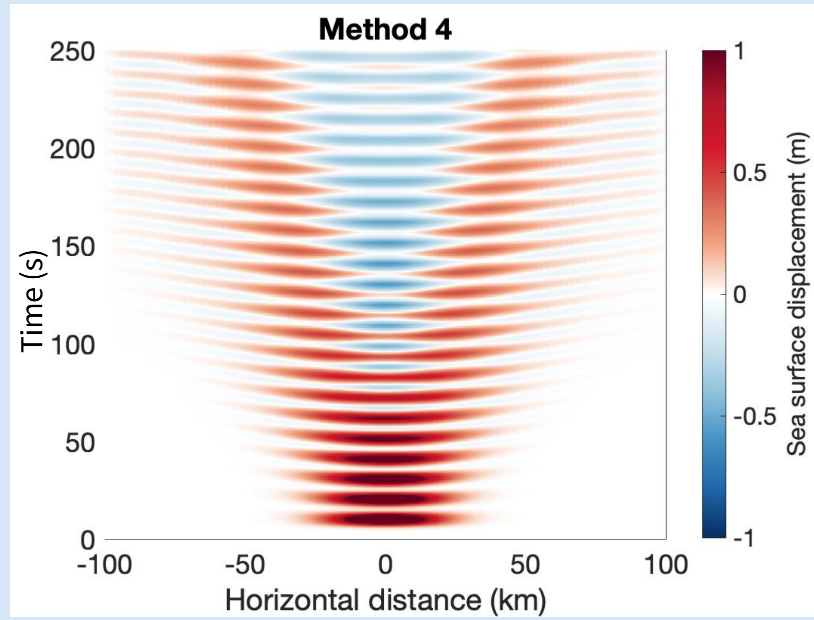
Full wavefield (one-way coupling)



Full wavefield (fully coupled)



Source Width : σ_r = 12.5 km
Source Duration : σ_t = 1.25 s
Yes: Within shallow water limit?
No: Tsunami propagates over source duration?
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Method 1. Static Initial condition

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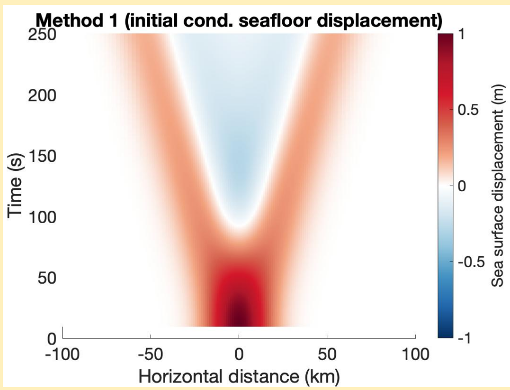
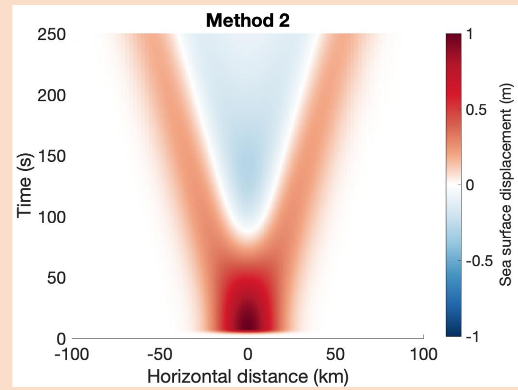
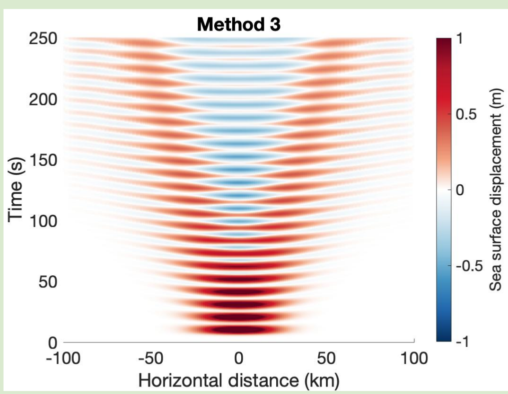
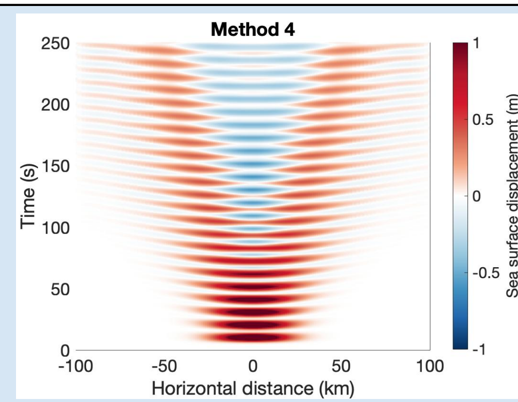
Method 4. Fully Coupled Method









Source Width : σ_r = 12.5 km
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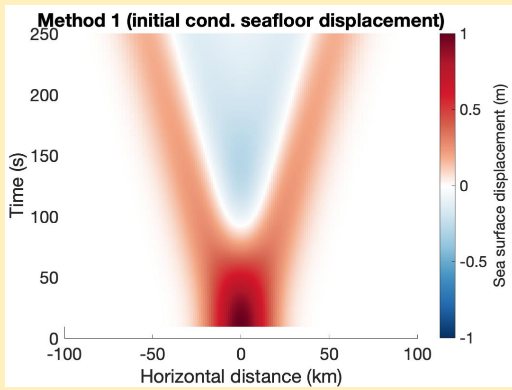
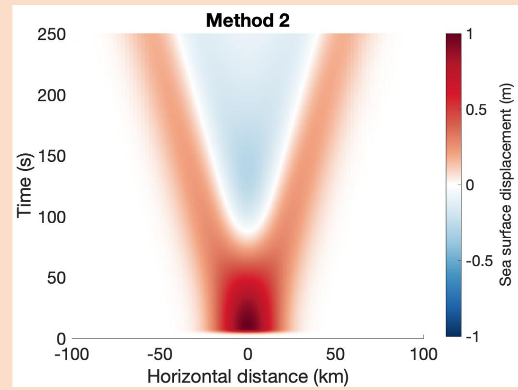
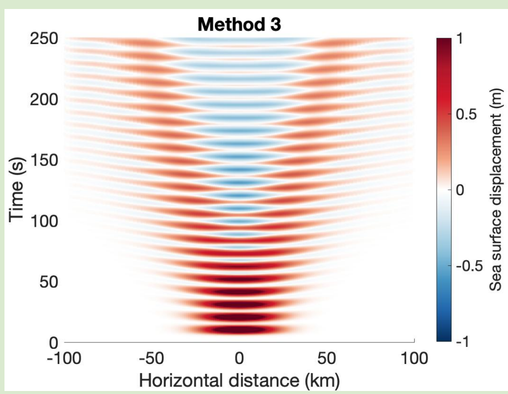
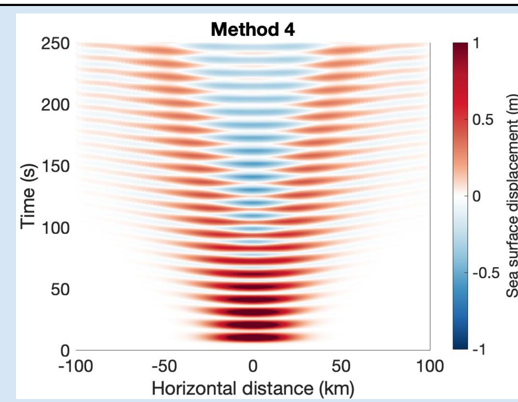








Method 1. Static Initial condition

Method 2. Time-dependent Seafloor Velocity as Forcing

Method 3. Time-dependent Sea Surface Velocity as Forcing

Method 4. Fully Coupled Method

Example 3:

Source Width : σ_r = 1.25 km

Source Duration : σ_t = 1.25 s

Within shallow water limit?

No: $\frac{H}{\sigma_r} = 3.20 > 1$

Tsunami propagates over source duration?

No: $\frac{\sigma_r}{\sigma_t\sqrt{gH}} = 5.05 > 1$

Acoustic waves significant?

Yes: $\frac{c\sigma_t}{H} = 0.47 < 1$

Method 1 and 2 do not model acoustic wave generation, we anticipate the results will differ compared to methods 3 and 4

*Note, in this study Method 1, 2, and 3 all use a linear shallow water solver not accounting for dispersion affects

Source Width : σ_r = 1.25 km
Source Duration : σ_t = 1.25 s
No: Within shallow water limit?
No: Tsunami propagates over source duration?
Yes: Acoustic waves significant?

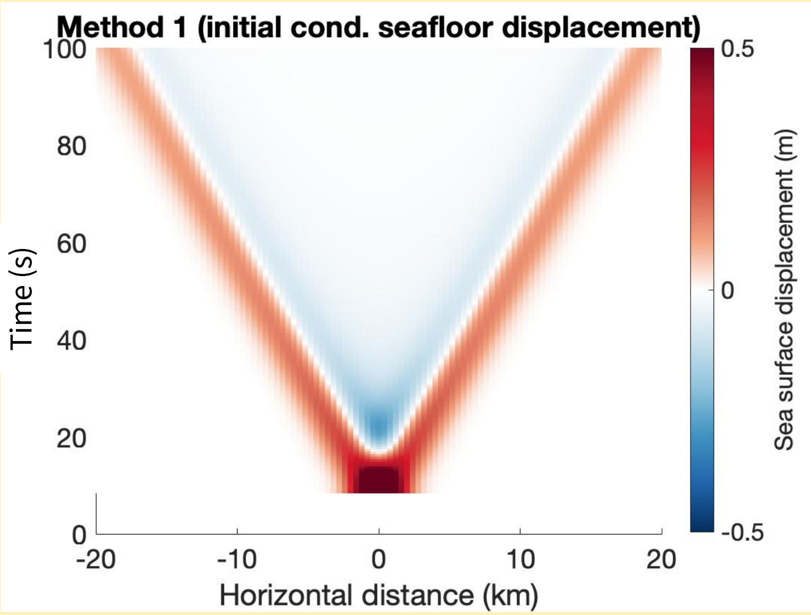
Method 1. Static Initial condition

Method 2. Time-dependent Seafloor Velocity as Forcing

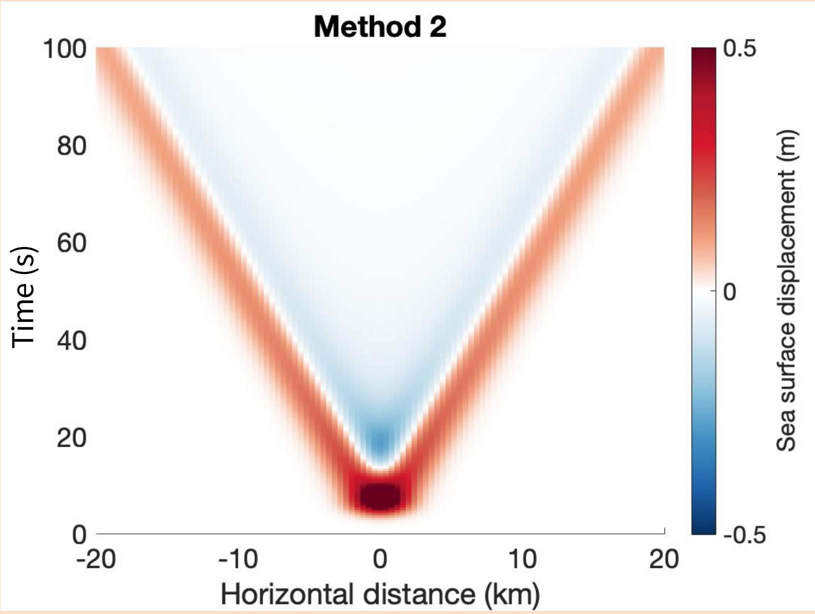
Method 3. Time-dependent Sea Surface Velocity as Forcing

Method 4. Fully Coupled Method

Seafloor displacement as initial conditions



Seafloor velocity as forcing



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Method 3. Time-dependent Sea Surface Velocity as Forcing

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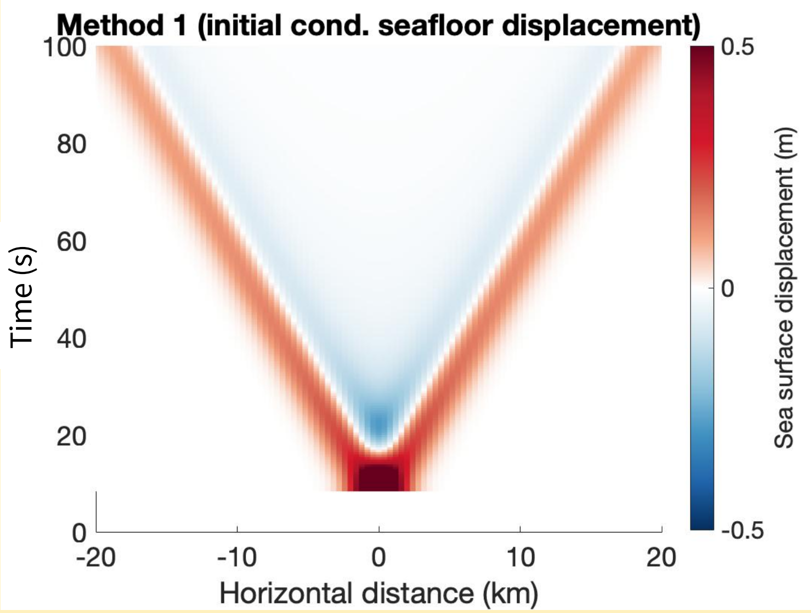
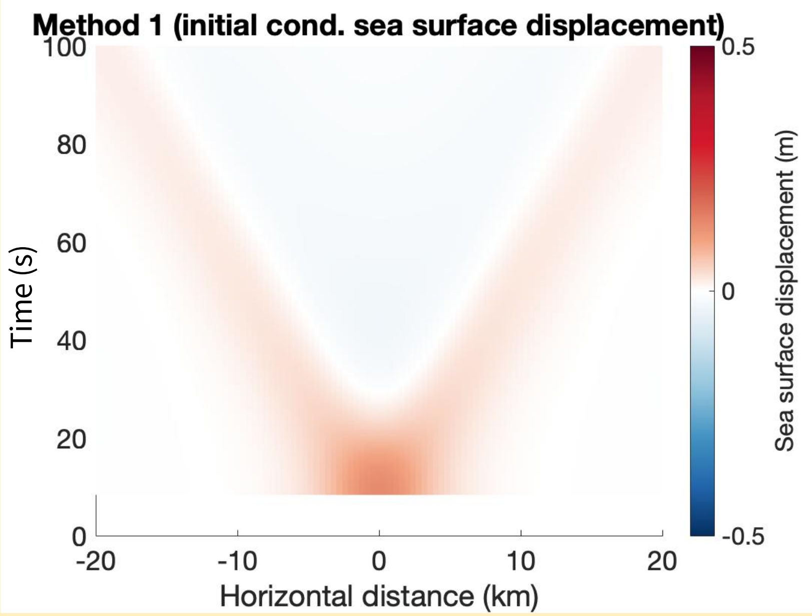
With short wavelengths



Without short wavelengths



Source Width : σ_r = 12.5 km
Source Duration : σ_t = 1.25 s
Yes: Within shallow water limit?
No: Tsunami propagates over source duration?
No: Acoustic waves significant?

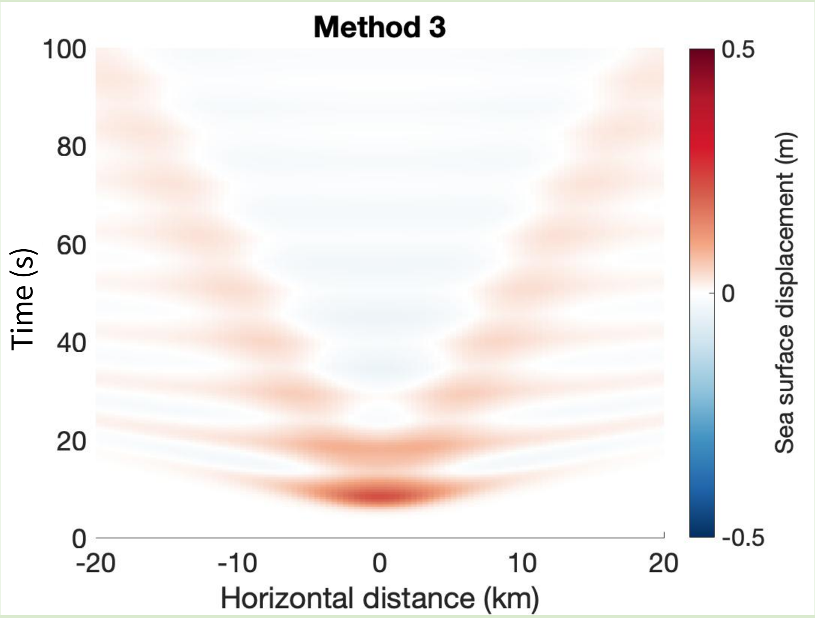
Method 1. Static Initial condition

Method 2. Time-dependent Seafloor Velocity as Forcing

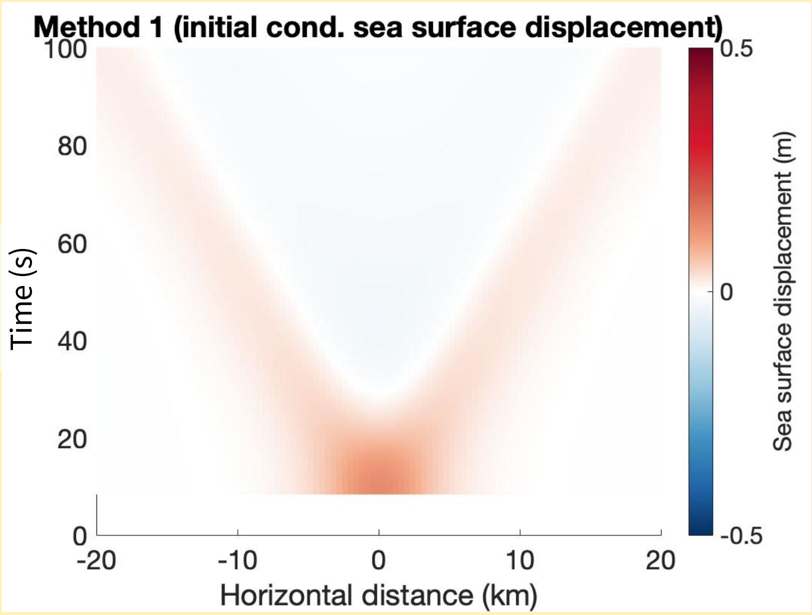
Method 3. Time-dependent Sea Surface Velocity as Forcing

Method 4. Fully Coupled Method

Sea surface velocity as forcing



Sea surface displacement as initial condition, without short wavelengths



Source Width : σ_r = 12.5 km
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Yes: Within shallow water limit?
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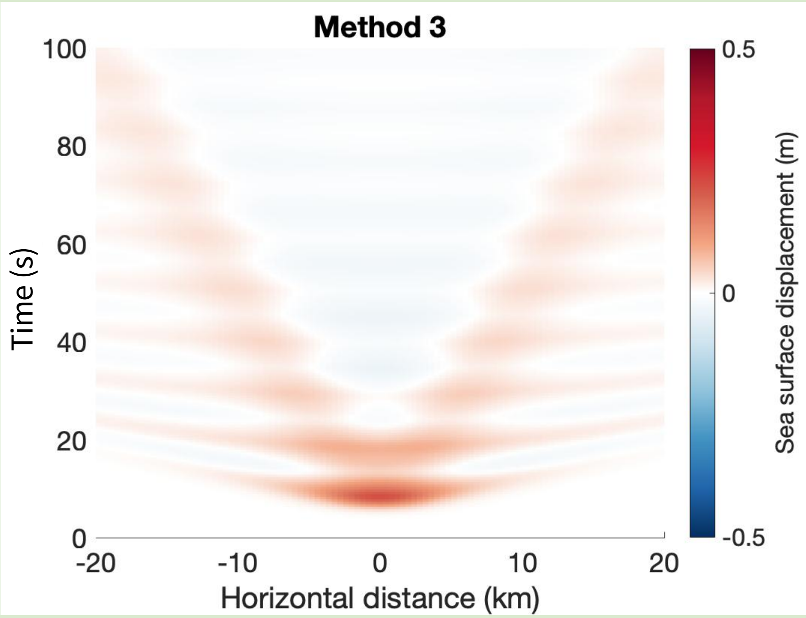
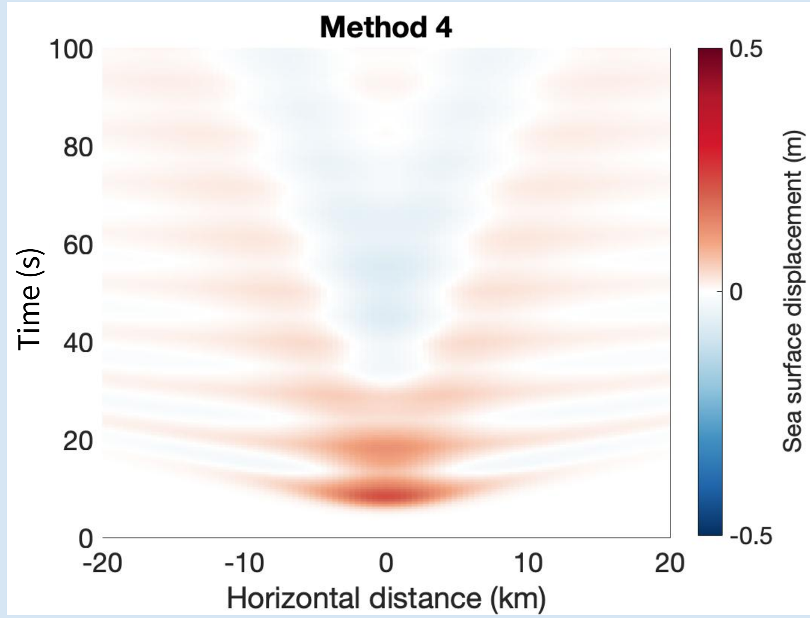
Method 1. Static Initial condition	Method 2. Time-dependent Seafloor Velocity as Forcing	Method 3. Time-dependent Sea Surface Velocity as Forcing	Method 4. Fully Coupled Method

Full wavefield (one-way coupling)



Full wavefield (fully coupled)



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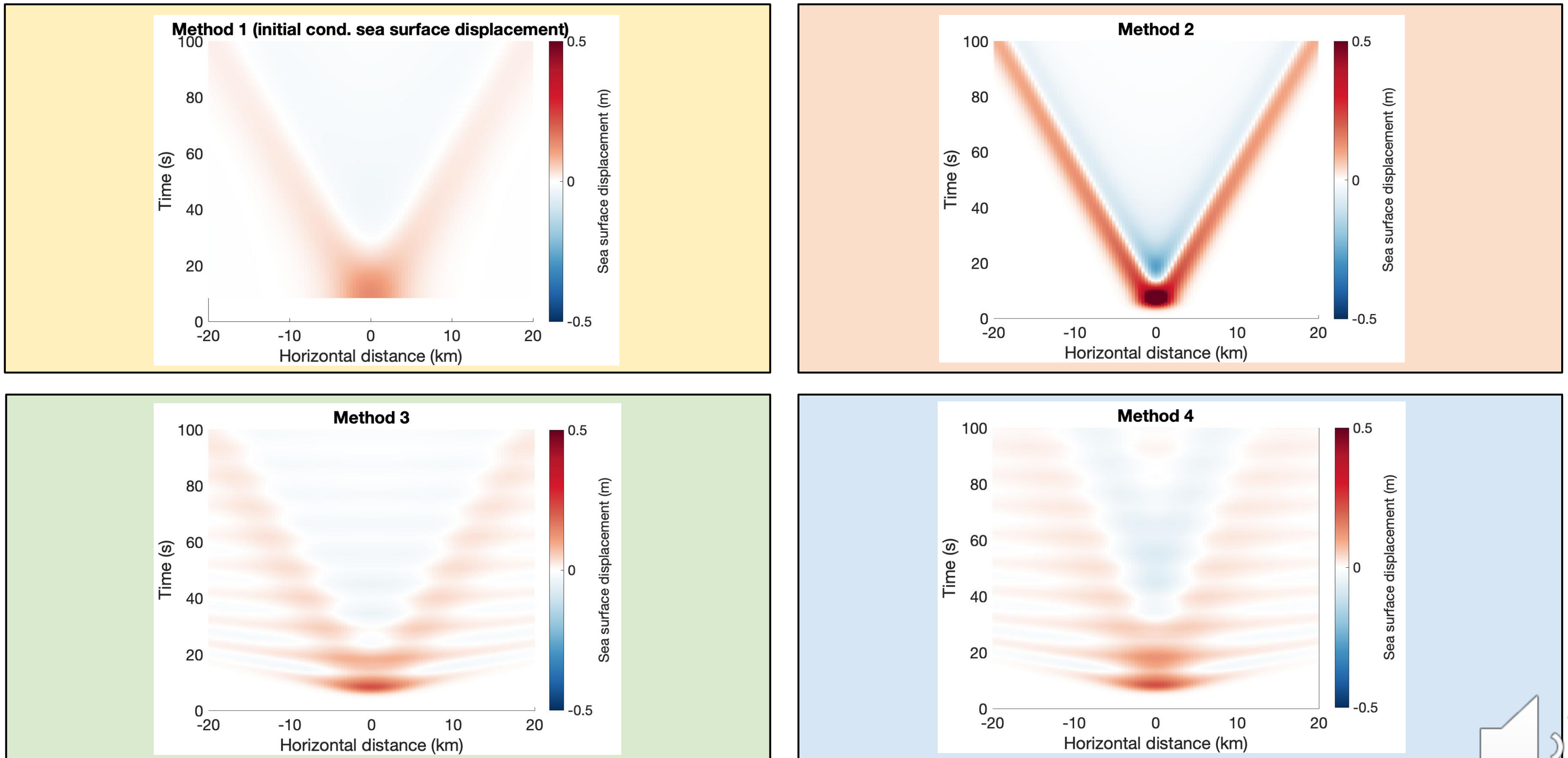

In Summary

Static Initial Conditions

- Final earthquake seafloor or sea surface uplift recorded
- Set initial tsunami sea surface height

Requires:
Shallow water limit (if short wavelength are not filtered)

$$\frac{H}{\sigma_r} \ll 1$$

Tsunami waves do not propagate over source duration

$$\frac{\sigma_r}{\sigma_t\sqrt{gH}} \gg 1$$

And acoustic waves are not generated

$$\frac{c\sigma_t}{H} \gg 1$$

Time-dependent Seafloor Velocity as Forcing

- Record earthquake seafloor velocity
- Set time-dependent forcing in the tsunami mass balance

Requires:
Shallow water limit

$$\frac{H}{\sigma_r} \ll 1$$

And acoustic waves are not generated

$$\frac{c\sigma_t}{H} \gg 1$$

Time-dependent Sea Surface Velocity as Forcing

- Solves earth and ocean response without gravity
- Use sea surface velocity as a forcing term in a tsunami simulation

If non-dispersive shallow water solver, requires:
Shallow water limit

$$\frac{H}{\sigma_r} \ll 1$$

If Boussinesq tsunami solver:
We expect valid in more cases

Fully Coupled Method (SeisSol)

- Simultaneously solves earthquake rupture, seismic waves, and ocean response (including gravity)

  http://www.seissol.org/

Valid in all cases

In Summary

Static Initial Conditions

- Final earthquake seafloor or sea surface uplift recorded
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In Summary

Static Initial Conditions	Time-dependent Seafloor Velocity as Forcing	Time-dependent Sea Surface Velocity as Forcing	Fully Coupled Method (SeisSol)
Final earthquake seafloor or sea surface uplift recorded	Record earthquake seafloor velocity	Solves earth and ocean response without gravity	Simultaneously solves earthquake rupture, seismic waves, and ocean response (including gravity) http://www.seissol.org/
Set initial tsunami sea surface height	Set time-dependent forcing in the tsunami mass balance	Use sea surface velocity as a forcing term in a tsunami simulation	

Static Initial Conditions

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If non-dispersive shallow water solver, requires:
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Valid in all cases

Citation

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