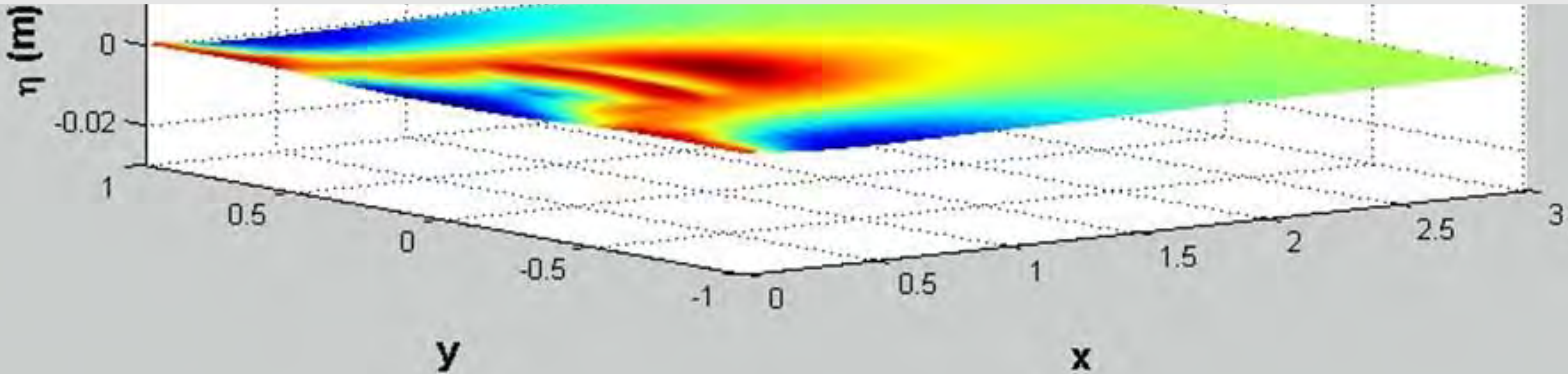
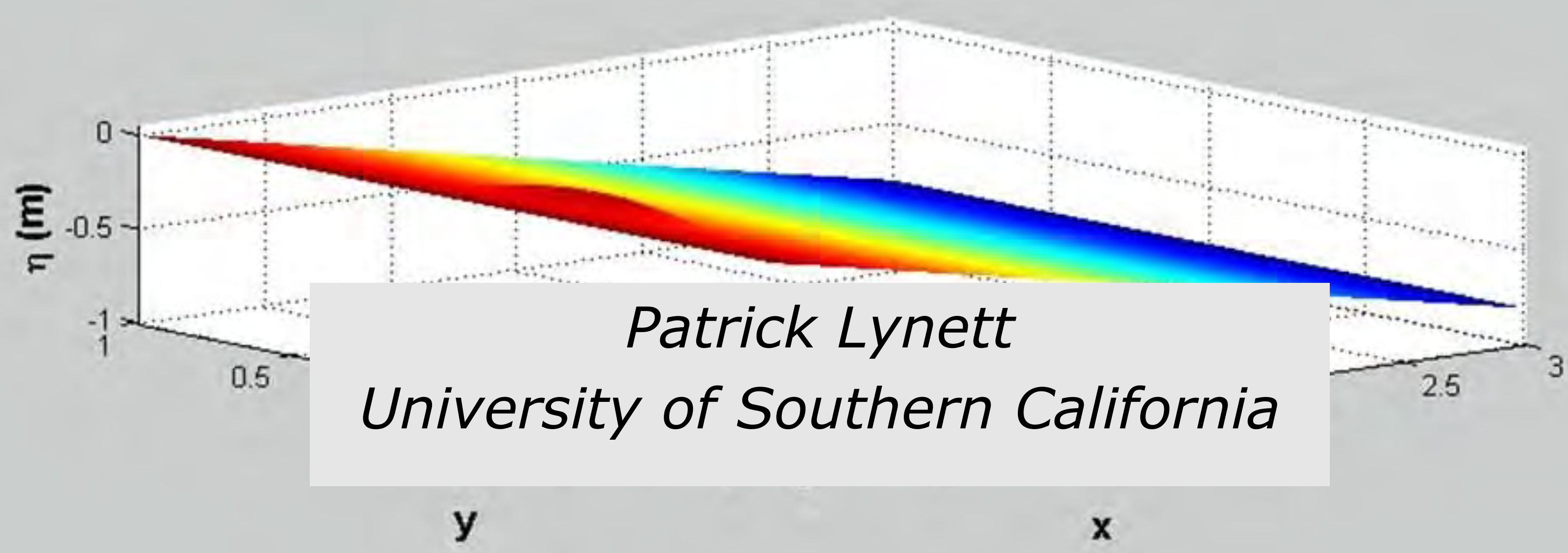
Landslide Tsunami Modeling Galveston, TX NTHMP Meeting





Patrick Lynett

University of Southern California

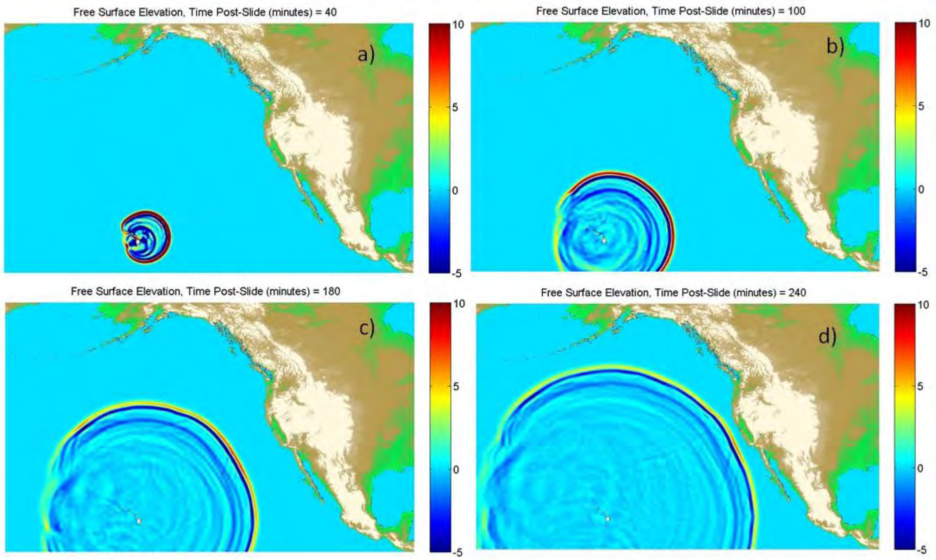
Outline & Approach

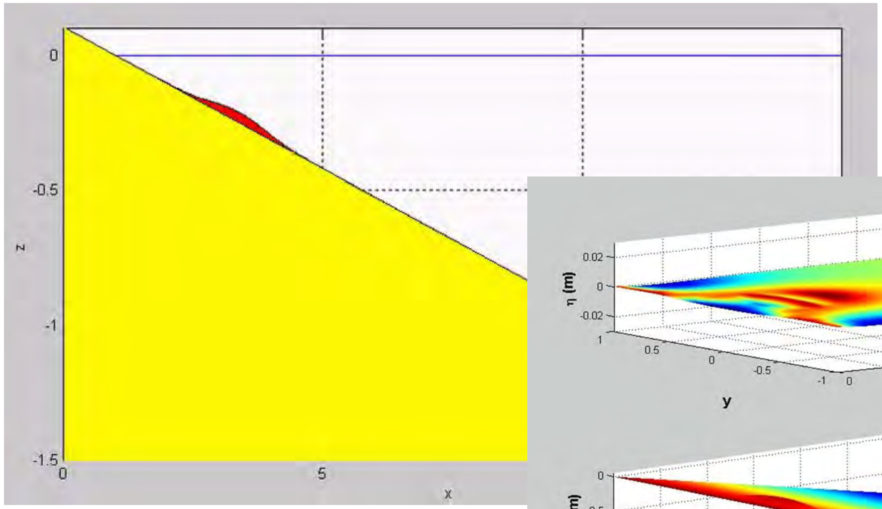
- A bit about my background and previous landslide tsunami applications

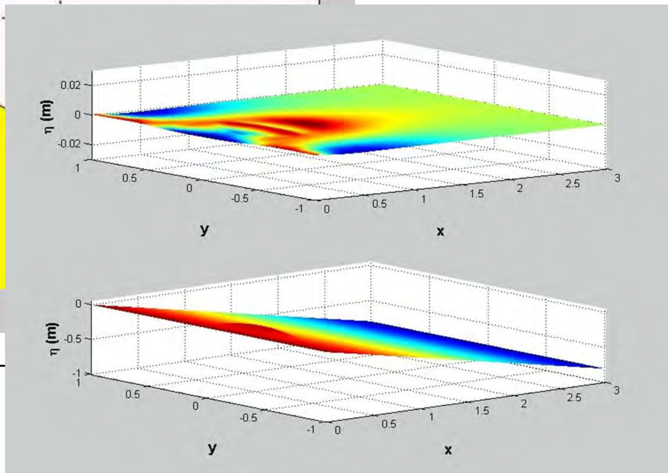
- Review of models to be used
  - Linear Mild Slope Equation model
  - Boussinesq-type equations
  - ~~OpenFOAM~~

- Benchmark #1

- Benchmark #2

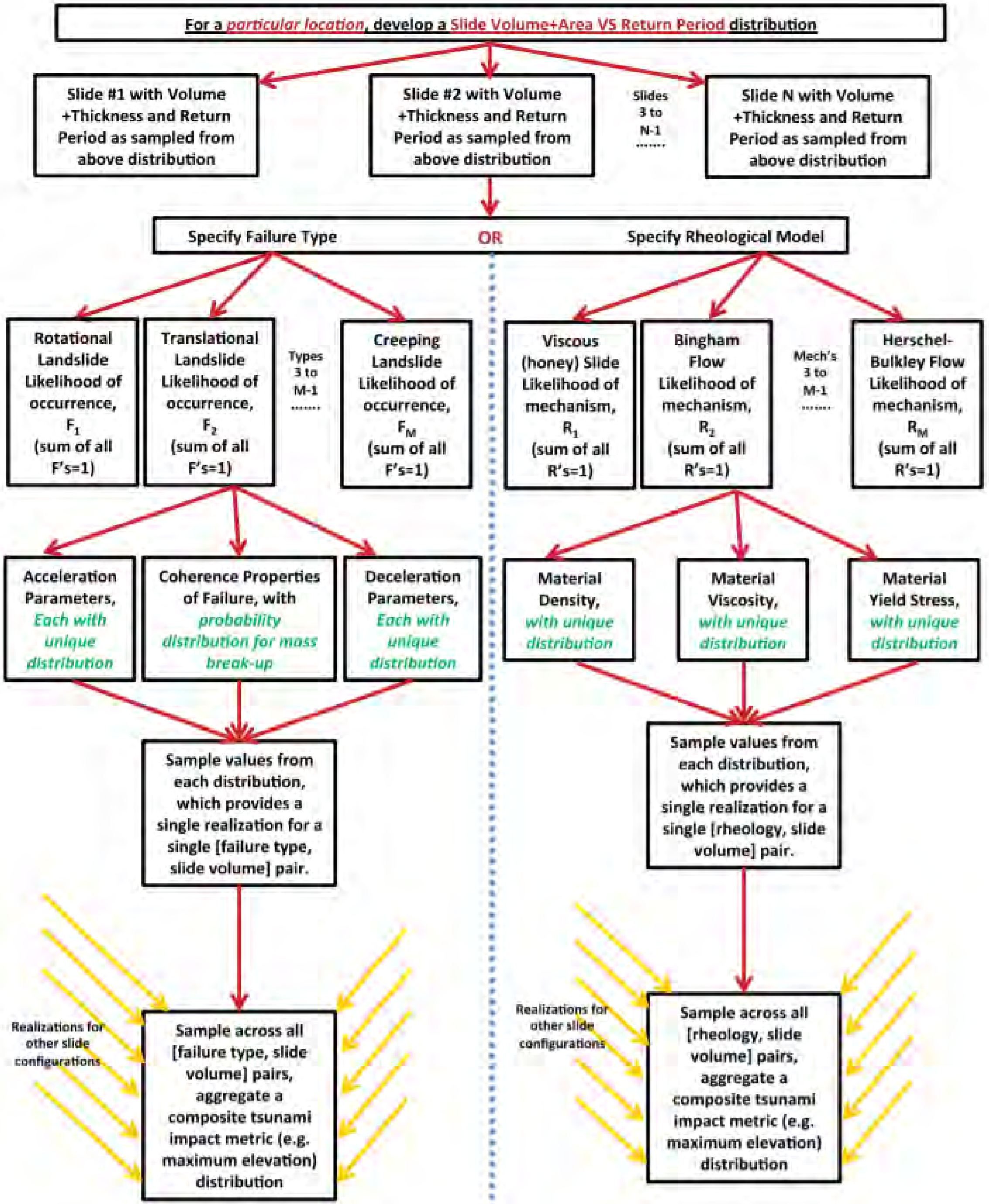






Leading thoughts

- Past few years working with USGS & NRC on NPP tsunami hazard assessment
- Would use "upper limit" conservative initial conditions for landslide sources – couldn't justify using any particular slide motion model
- Full parameter space of potential slide motion is daunting



Geist, E. and Lynett, P. (2014) "Source Process in the Probabilistic Assessment of Tsunami Hazards." Oceanography 27(2), pp. 86-93, doi: 10.5670/oceanog.2014.43.

Mild Slope Equation Model

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

- Free surface evolution equations (z=0):

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

$$\varphi_t = -g\eta$$

$$F = \frac{ccg}{g} \qquad G = \frac{w^2 - k^2 ccg}{g}$$

- Mild-Slope Equation:

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

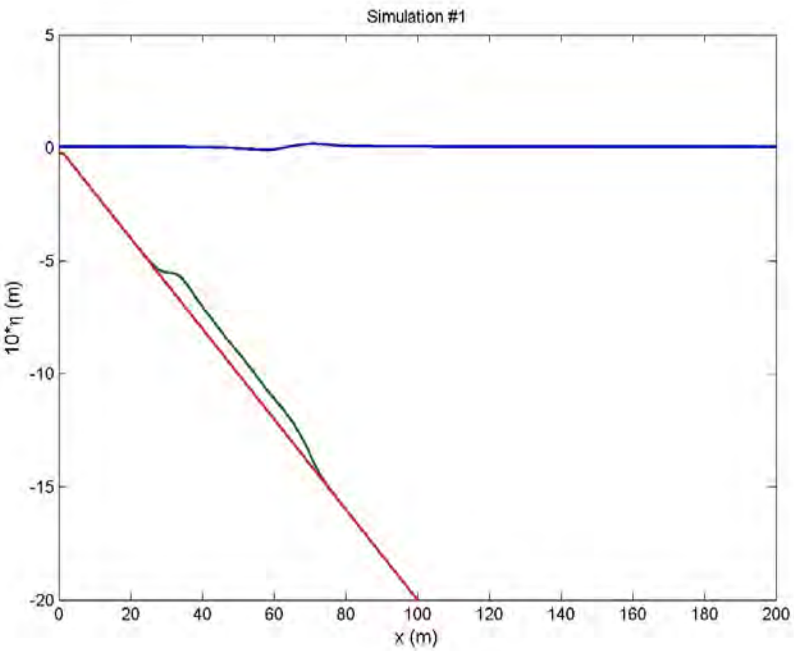
Time-dependent

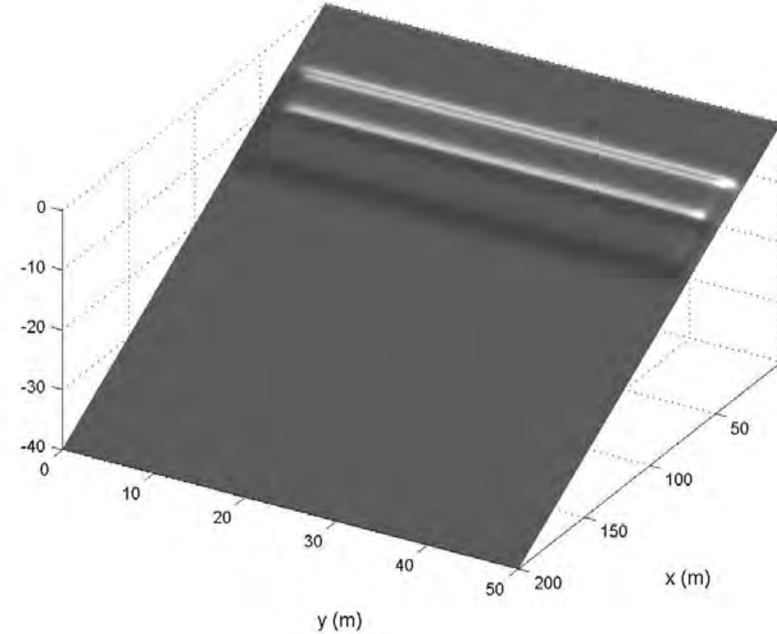
⇓ *FFT in time*

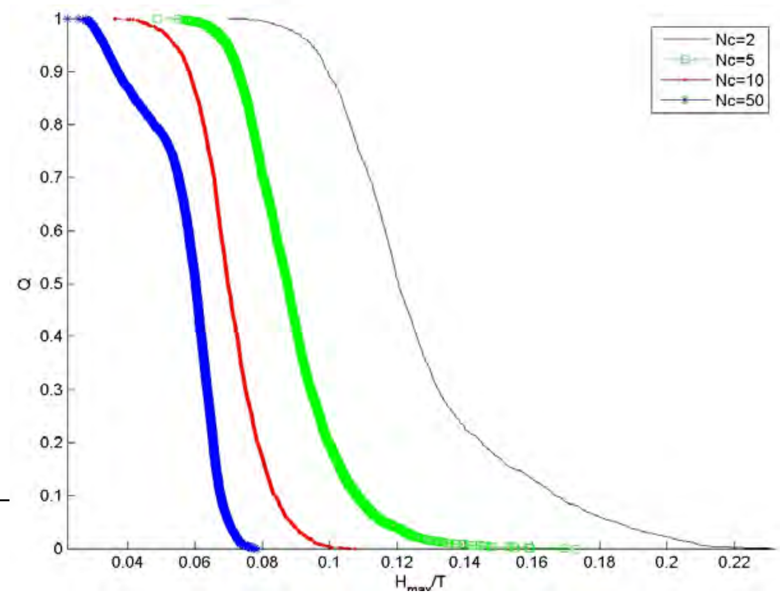
$$\nabla \cdot (ccg \nabla N) + w^2 \frac{cg}{c} N = \frac{1}{\cosh(kh)} H$$

Frequency-dependent

Mild Slope Equation Model







Fast & accurate for (linear) arbitrary slide motion

Decent engine for MC analysis

Boussinesq-type Model

(Lynett & Liu, 2002)

$$
\begin{aligned}
&\frac{1}{\varepsilon}h_t + \zeta_t + \nabla\cdot(H\boldsymbol{u}_\alpha) \\
&\qquad - \mu^2\nabla\cdot\left\{H\left[\left(\tfrac{1}{6}(\varepsilon^2\zeta^2 - \varepsilon\zeta h + h^2) - \tfrac{1}{2}z_\alpha^2\right)\nabla(\nabla\cdot\boldsymbol{u}_\alpha)\right.\right. \\
&\qquad\qquad\qquad \left.\left. + \left(\tfrac{1}{2}(\varepsilon\zeta - h) - z_\alpha\right)\nabla\left(\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right)\right]\right\} = O(\mu^4)
\end{aligned}
$$

$$
\begin{aligned}
&\boldsymbol{u}_{\alpha t} + \varepsilon\boldsymbol{u}_\alpha\cdot\nabla\boldsymbol{u}_\alpha + \nabla\zeta \\
&\quad + \mu^2\frac{\partial}{\partial t}\left\{\tfrac{1}{2}z_\alpha^2\nabla(\nabla\cdot\boldsymbol{u}_\alpha) + z_\alpha\nabla\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right]\right\} \\
&\quad + \varepsilon\mu^2\left\{\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right]\nabla\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right]\right. \\
&\qquad\quad - \nabla\left[\zeta\left(\nabla\cdot(h\boldsymbol{u}_\alpha)_t + \frac{h_{tt}}{\varepsilon}\right)\right] + (\boldsymbol{u}_\alpha\cdot\nabla z_\alpha)\nabla\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right] \\
&\qquad\quad + z_\alpha\nabla\left[\boldsymbol{u}_\alpha\cdot\nabla\left(\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right)\right] + z_\alpha(\boldsymbol{u}_\alpha\cdot\nabla z_\alpha)\nabla(\nabla\cdot\boldsymbol{u}_\alpha) \\
&\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad \left. + \tfrac{1}{2}z_\alpha^2\nabla[\boldsymbol{u}_\alpha\cdot\nabla(\nabla\cdot\boldsymbol{u}_\alpha)]\right\} \\
&\quad + \varepsilon^2\mu^2\nabla\left\{-\tfrac{1}{2}\zeta^2\nabla\cdot\boldsymbol{u}_{\alpha t} - \zeta\boldsymbol{u}_\alpha\cdot\nabla\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right] + \zeta\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right]\nabla\cdot\boldsymbol{u}_\alpha\right\} \\
&\quad + \varepsilon^3\mu^2\nabla\{\tfrac{1}{2}\zeta^2[(\nabla\cdot\boldsymbol{u}_\alpha)^2 - \boldsymbol{u}_\alpha\cdot\nabla(\nabla\cdot\boldsymbol{u}_\alpha)]\} = O(\mu^4). \qquad (3.3)
\end{aligned}
$$

Boussinesq-type Model

(Lynett & Liu, 2002)

$$\frac{1}{\varepsilon}h_t + \zeta_t + \nabla\cdot(H\boldsymbol{u}_\alpha) - \mu^2\nabla\cdot\left\{H\left[\left(\tfrac{1}{6}(\varepsilon^2\zeta^2 - \varepsilon\zeta h + h^2) - \tfrac{1}{2}z_\alpha^2\right)\nabla(\nabla\cdot\boldsymbol{u}_\alpha) + \left(\tfrac{1}{2}(\varepsilon\zeta - h) - z_\alpha\right)\nabla\left(\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right)\right]\right\} = O(\mu^4)$$

$$\begin{aligned}
&\boldsymbol{u}_{\alpha t} + \varepsilon\boldsymbol{u}_\alpha\cdot\nabla\boldsymbol{u}_\alpha + \nabla\zeta \\
&+ \mu^2\frac{\partial}{\partial t}\left\{\tfrac{1}{2}z_\alpha^2\nabla(\nabla\cdot\boldsymbol{u}_\alpha) + z_\alpha\nabla\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right]\right\} \\
&+ \varepsilon\mu^2\left\{\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right]\nabla\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right]\right. \\
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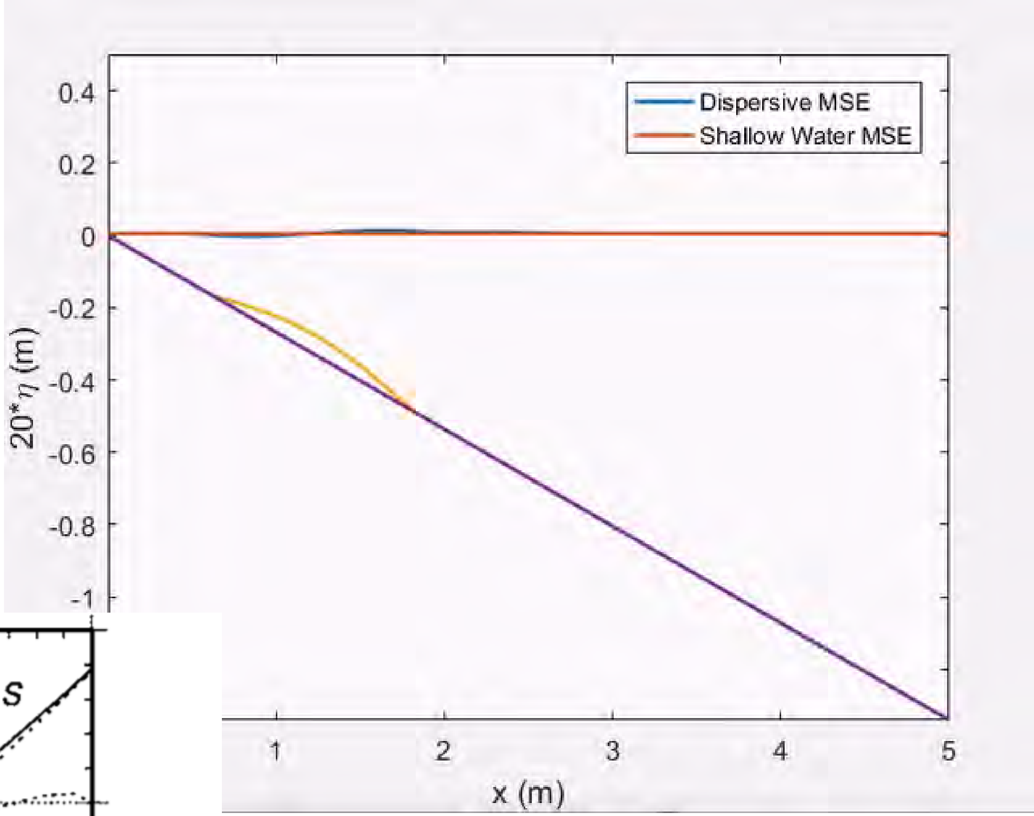
&+ \varepsilon^2\mu^2\nabla\left\{-\tfrac{1}{2}\zeta^2\nabla\cdot\boldsymbol{u}_{\alpha t} - \zeta\boldsymbol{u}_\alpha\cdot\nabla\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right] + \zeta\left[\nabla\cdot(h\boldsymbol{u}_\alpha) + \frac{h_t}{\varepsilon}\right]\nabla\cdot\boldsymbol{u}_\alpha\right\} \\
&+ \varepsilon^3\mu^2\nabla\{\tfrac{1}{2}\zeta^2[(\nabla\cdot\boldsymbol{u}_\alpha)^2 - \boldsymbol{u}_\alpha\cdot\nabla(\nabla\cdot\boldsymbol{u}_\alpha)]\} = O(\mu^4).
\end{aligned} \tag{3.3}$$

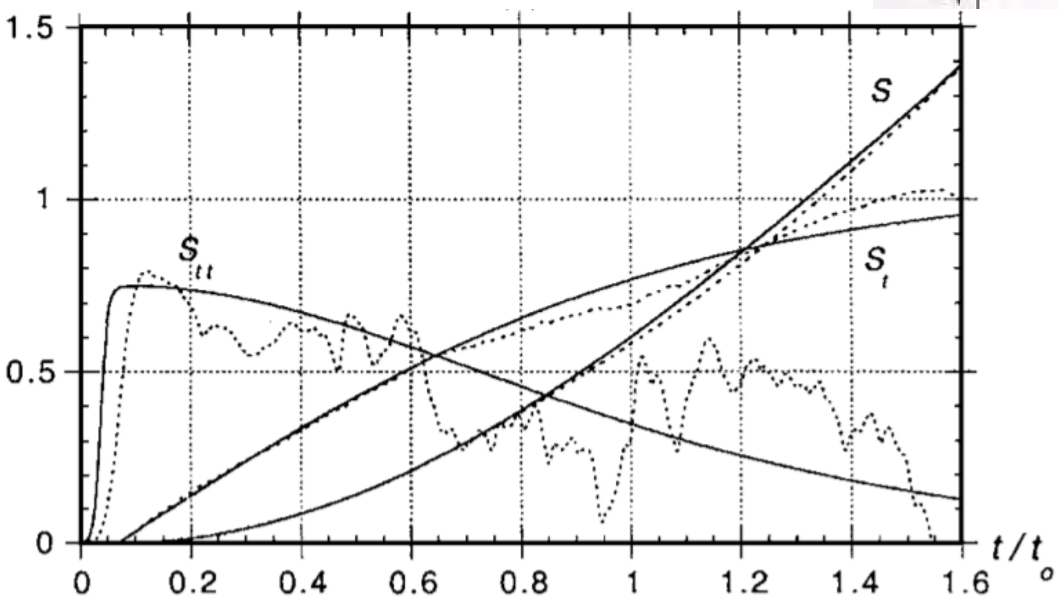
Linear and nonlinear terms are h_t, h_{xxt}, h_{xtt}

Depth evolution must be continuous in time and space

Benchmark #1

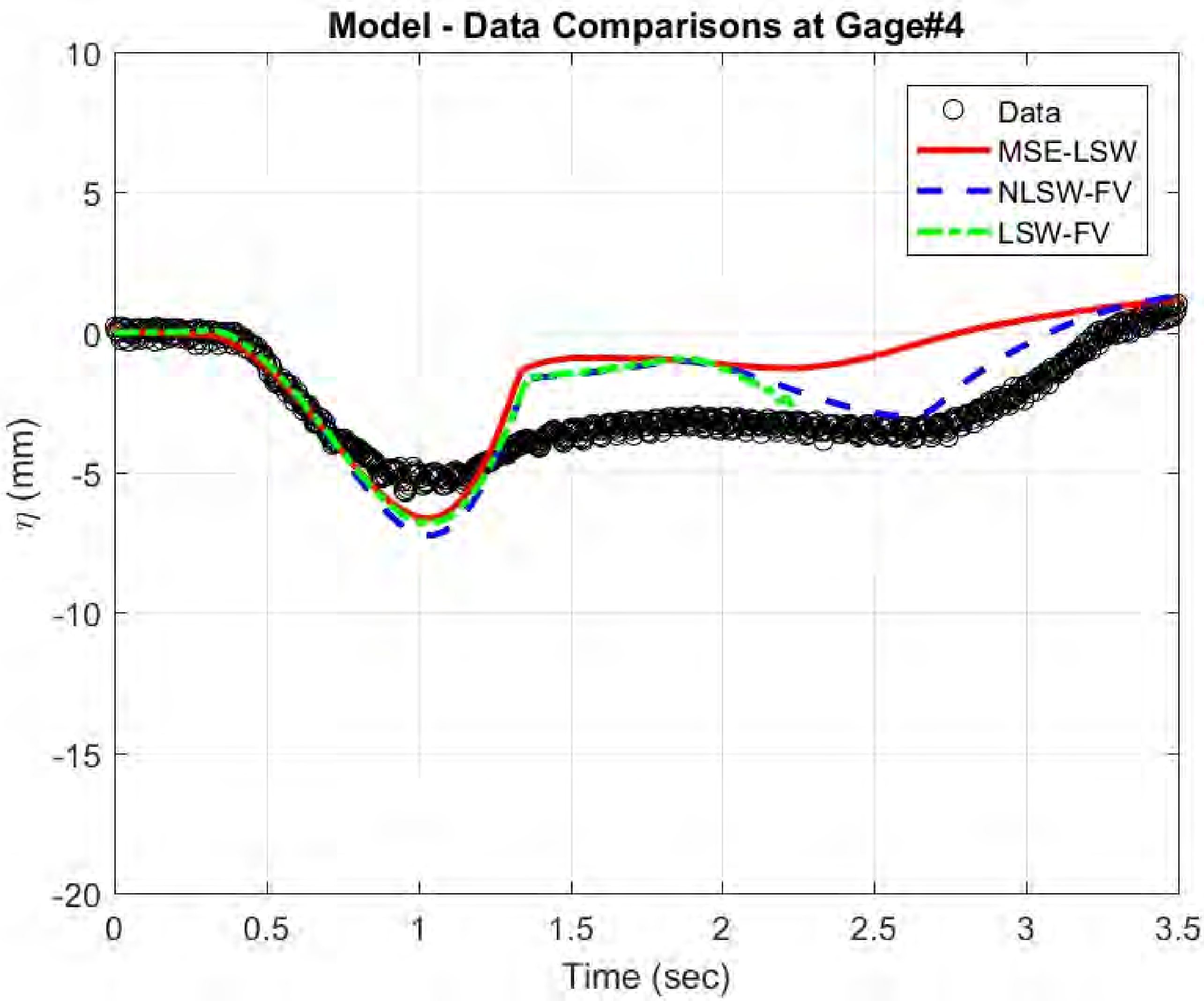
- Used the prescribed slide motion
  - Due to the max function, derivatives are not continuous in (x) – significance of slide edge effects are grid dependent
  - Did not smooth the slide shape in any way
  - Did not use the initial time acceleration correction

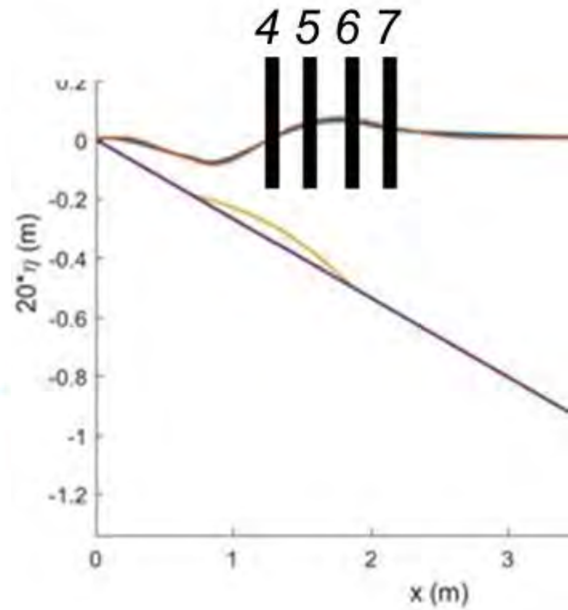




Benchmark #1

- First, do the different models produce the same results for the same setups?

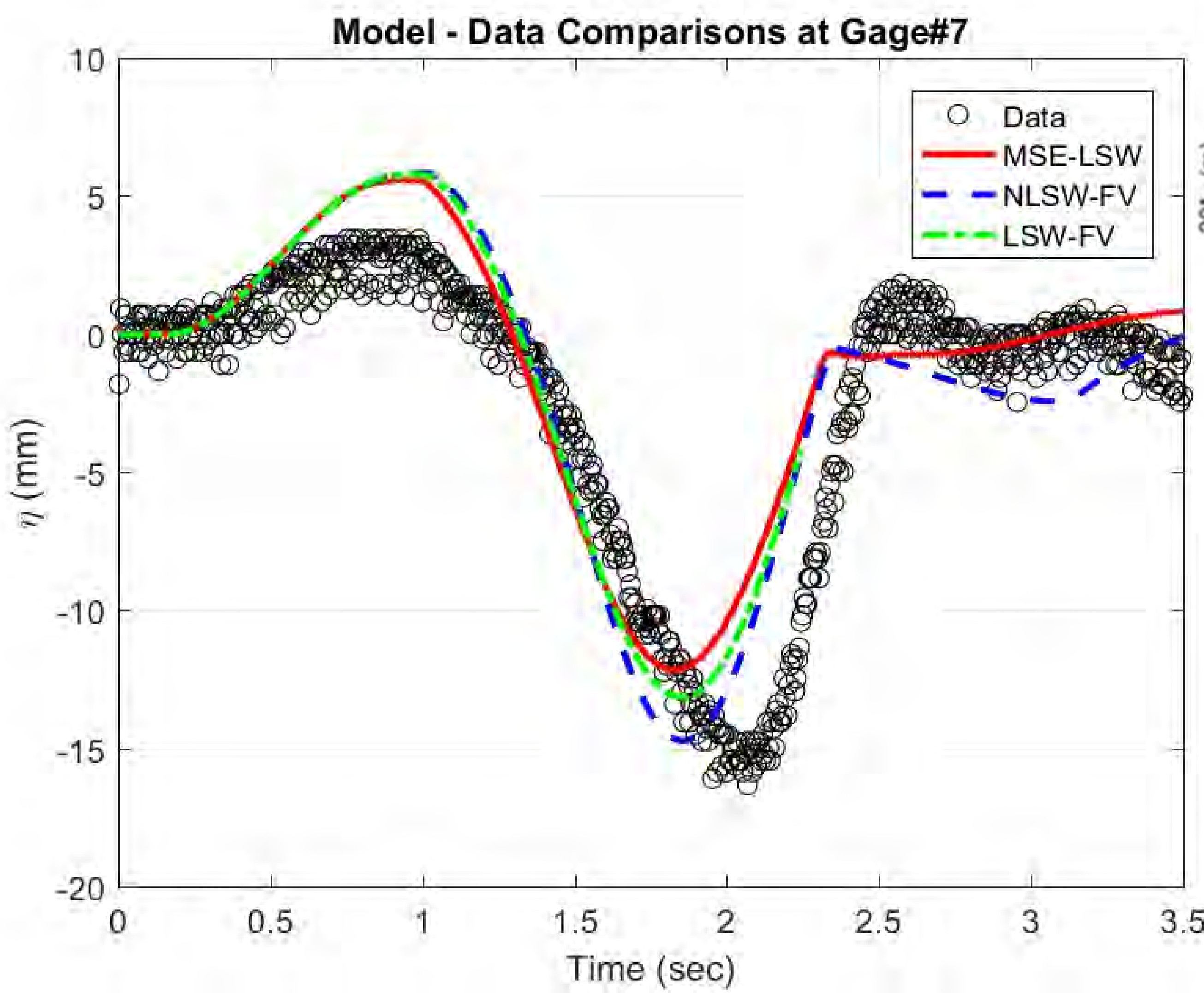


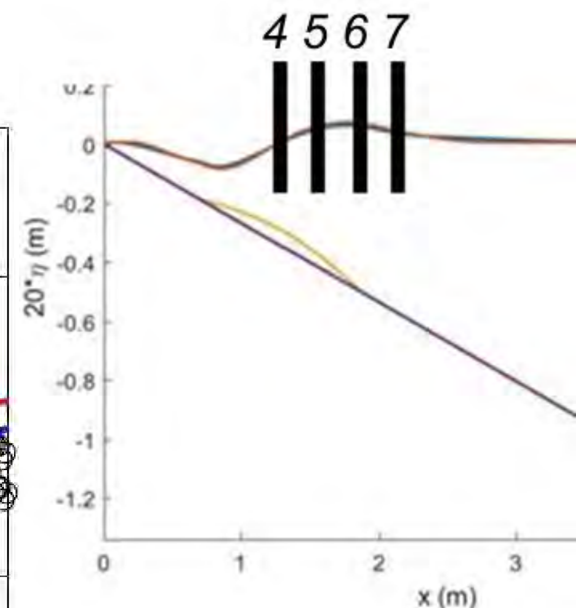


depth=	0.33	m
Period (s)	kh	c/sqrt(gh)
2	0.59	0.98
1	1.42	0.81
0.5	5.31	0.43
0.25	21.25	0.22
min resolvable kh=		103.62

Benchmark #1

- First, do the different models produce the same results for the same setups?

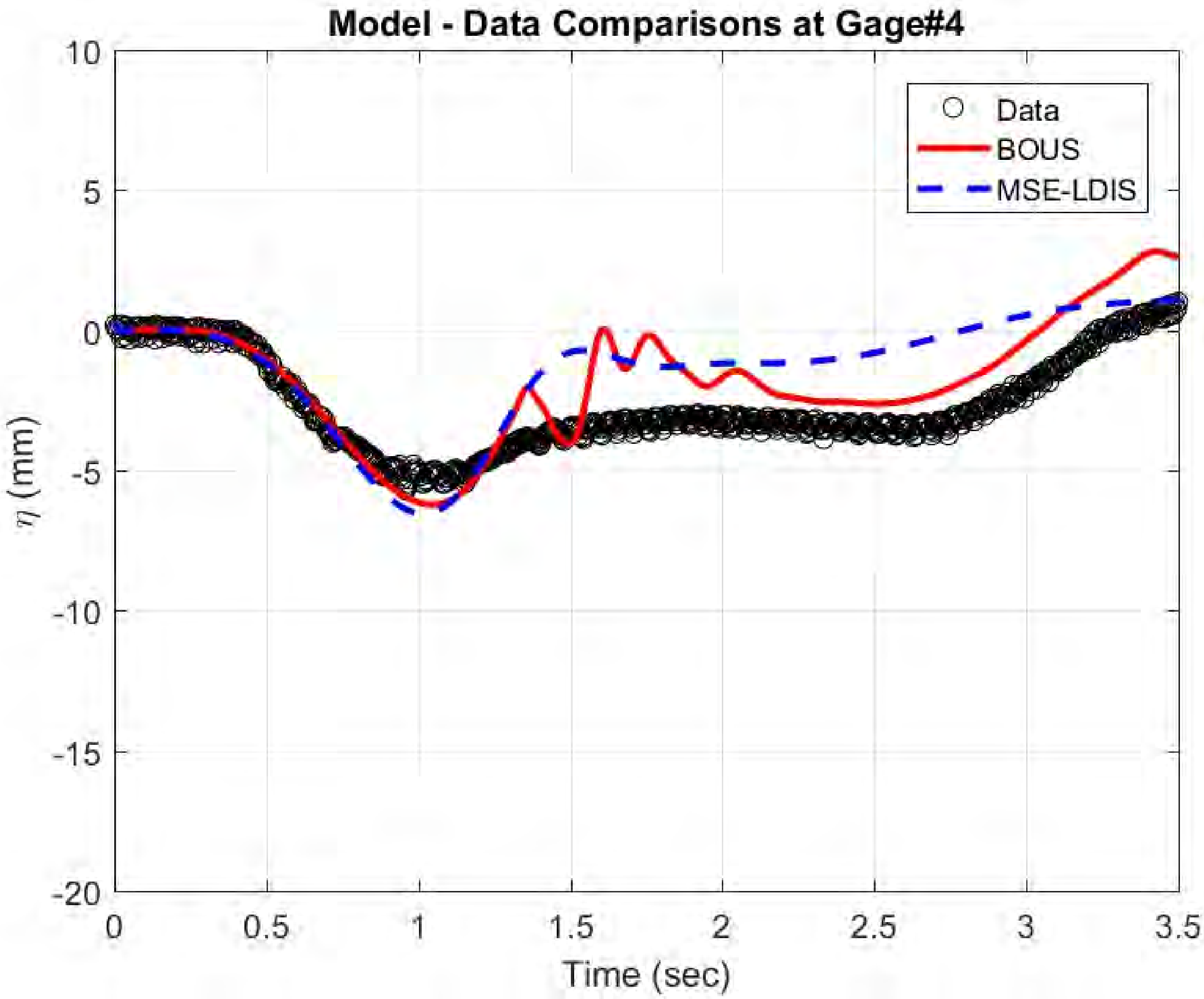


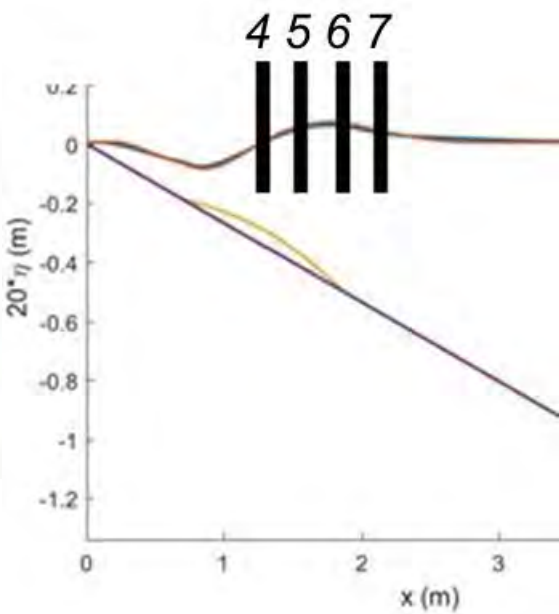


depth=	0.59	m
Period (s)	kh	c/sqrt(gh)
2	0.81	0.95
1	2.39	0.64
0.5	9.50	0.32
0.25	37.99	0.16
min resolvable kh=		185.26

Benchmark #1

- Bous vs MSE





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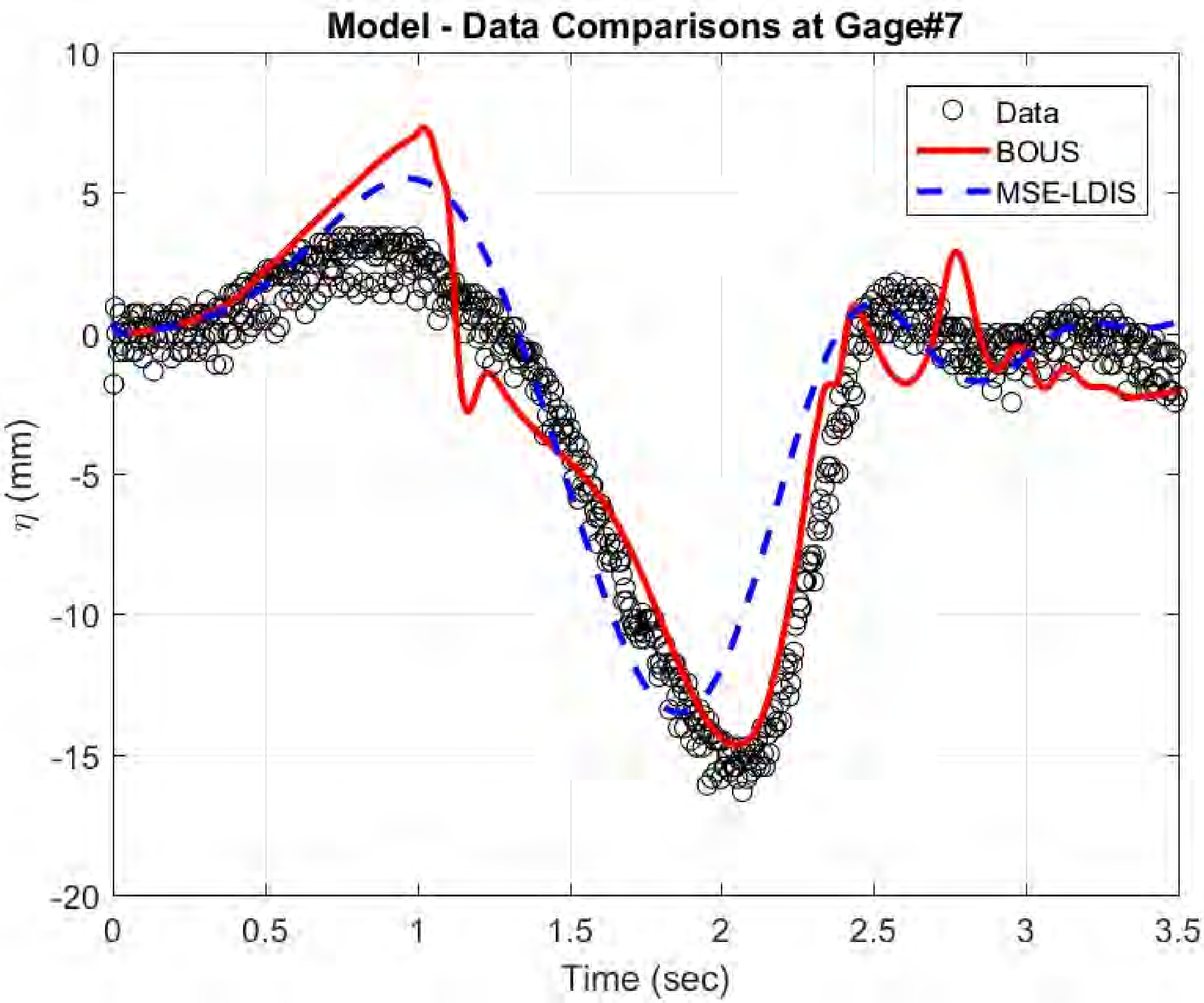

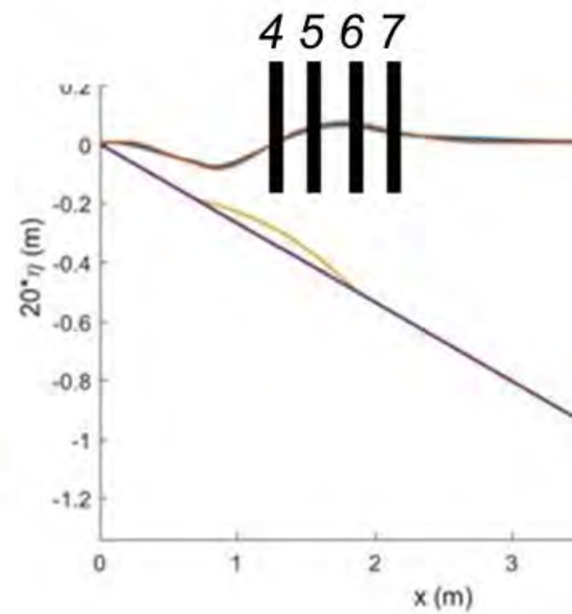

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2	0.81	0.95
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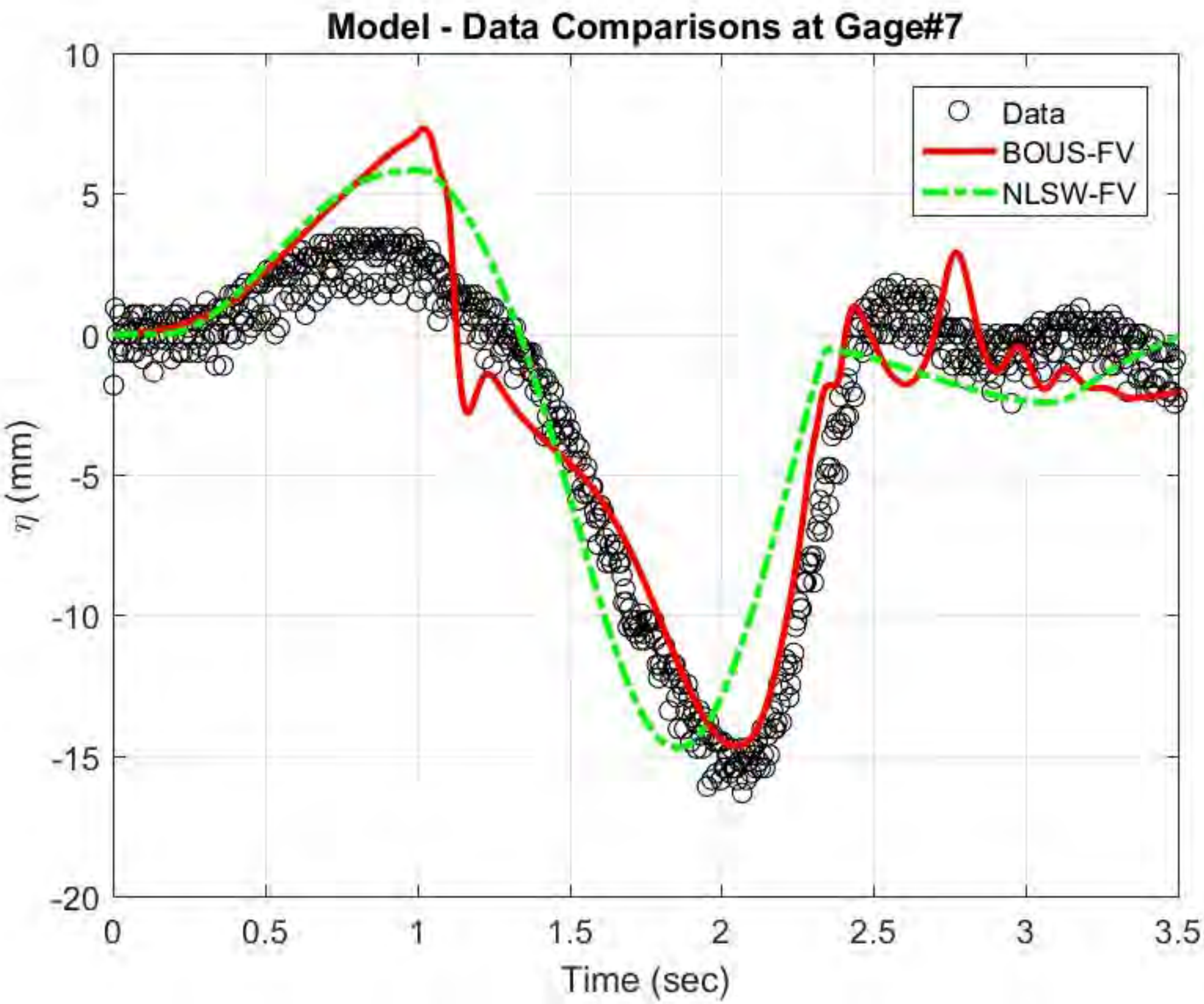
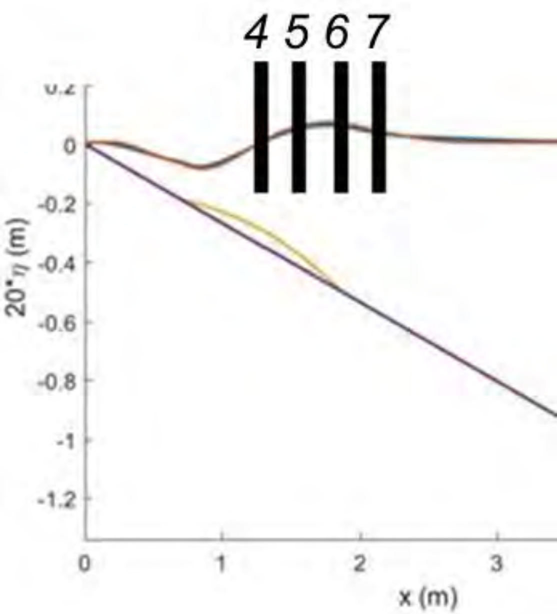
0.5	9.50	0.32
0.25	37.99	0.16
min resolvable kh=		185.26

Benchmark #1

- Bous vs NLSW – NLSW less bad?

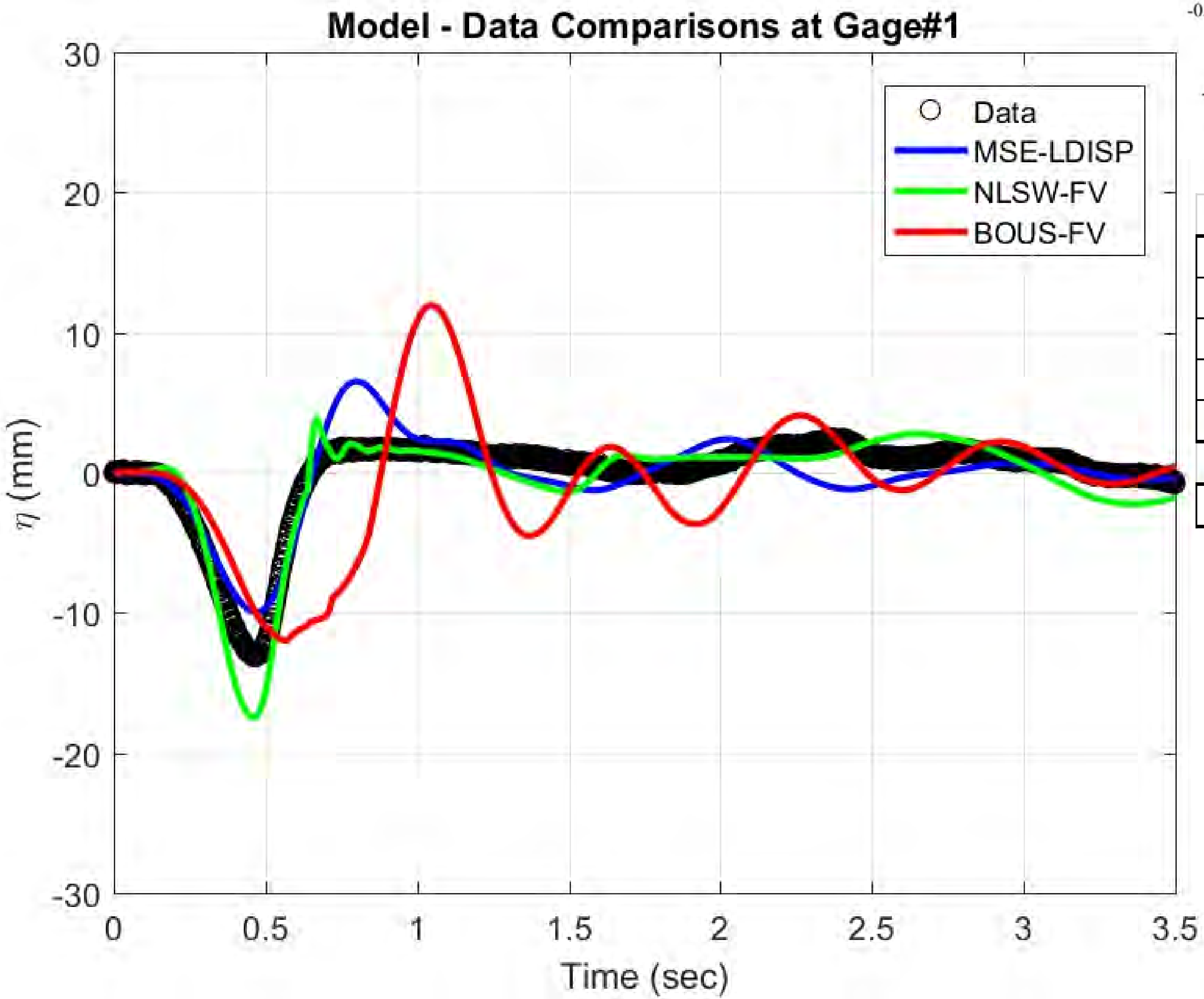


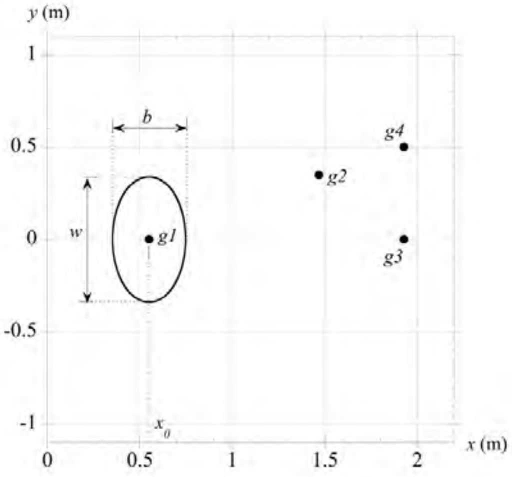


depth=	0.59	m
Period (s)	kh	c/sqrt(gh)
2	0.81	0.95
1	2.39	0.64
0.5	9.50	0.32
0.25	37.99	0.16
min resolvable kh=	185.26	

Benchmark #2

- Initial depth = 0.061m

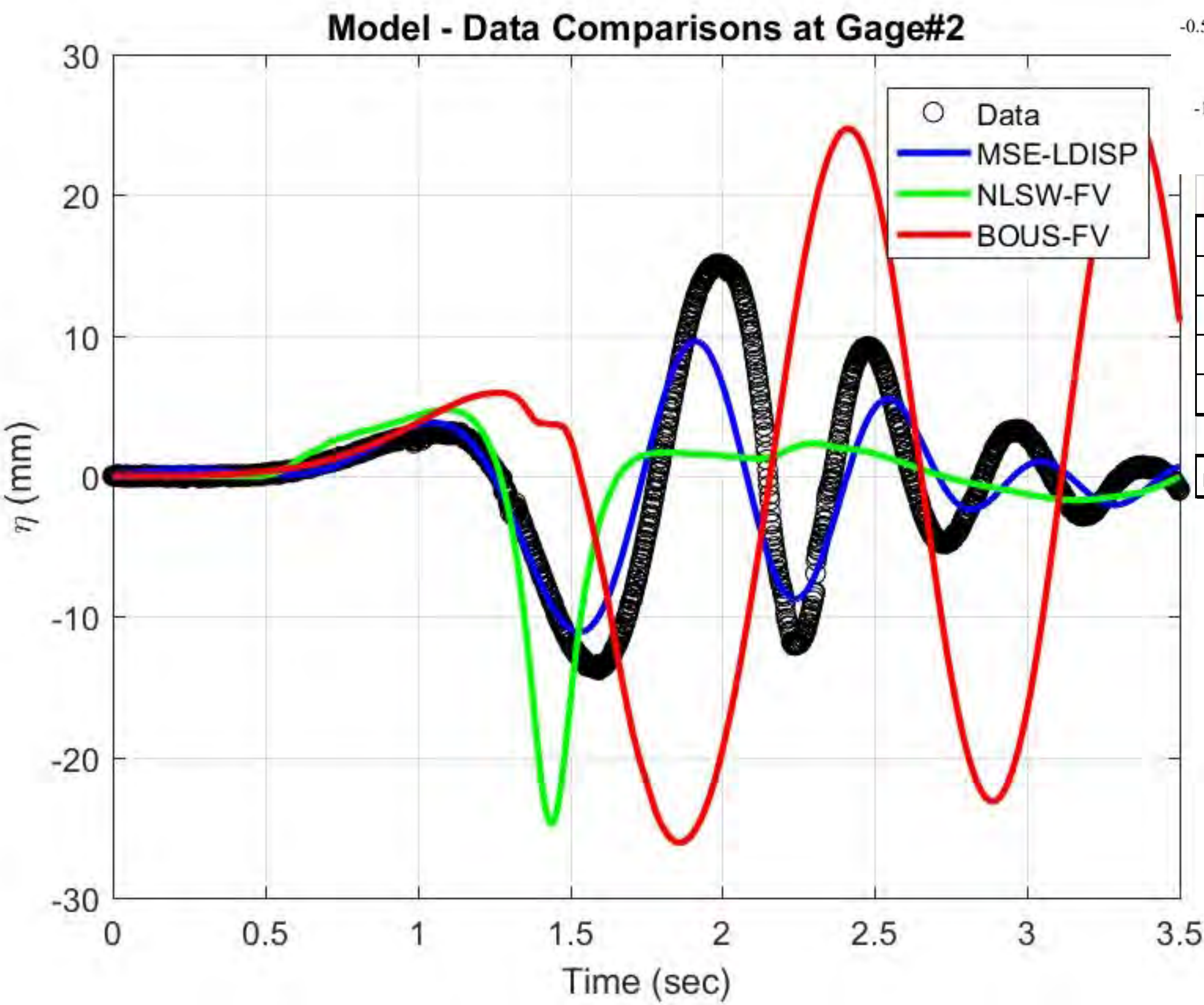


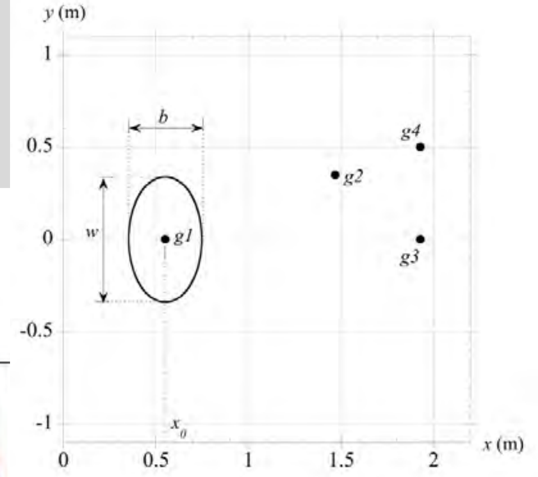


depth=	0.14	m
Period (s)	kh	c/sqrt(gh)
2	0.38	1.00
1	0.79	0.95
0.5	2.28	0.66
0.25	9.01	0.33
min resolvable kh=		13.19

Benchmark #2

- Initial depth = 0.061m

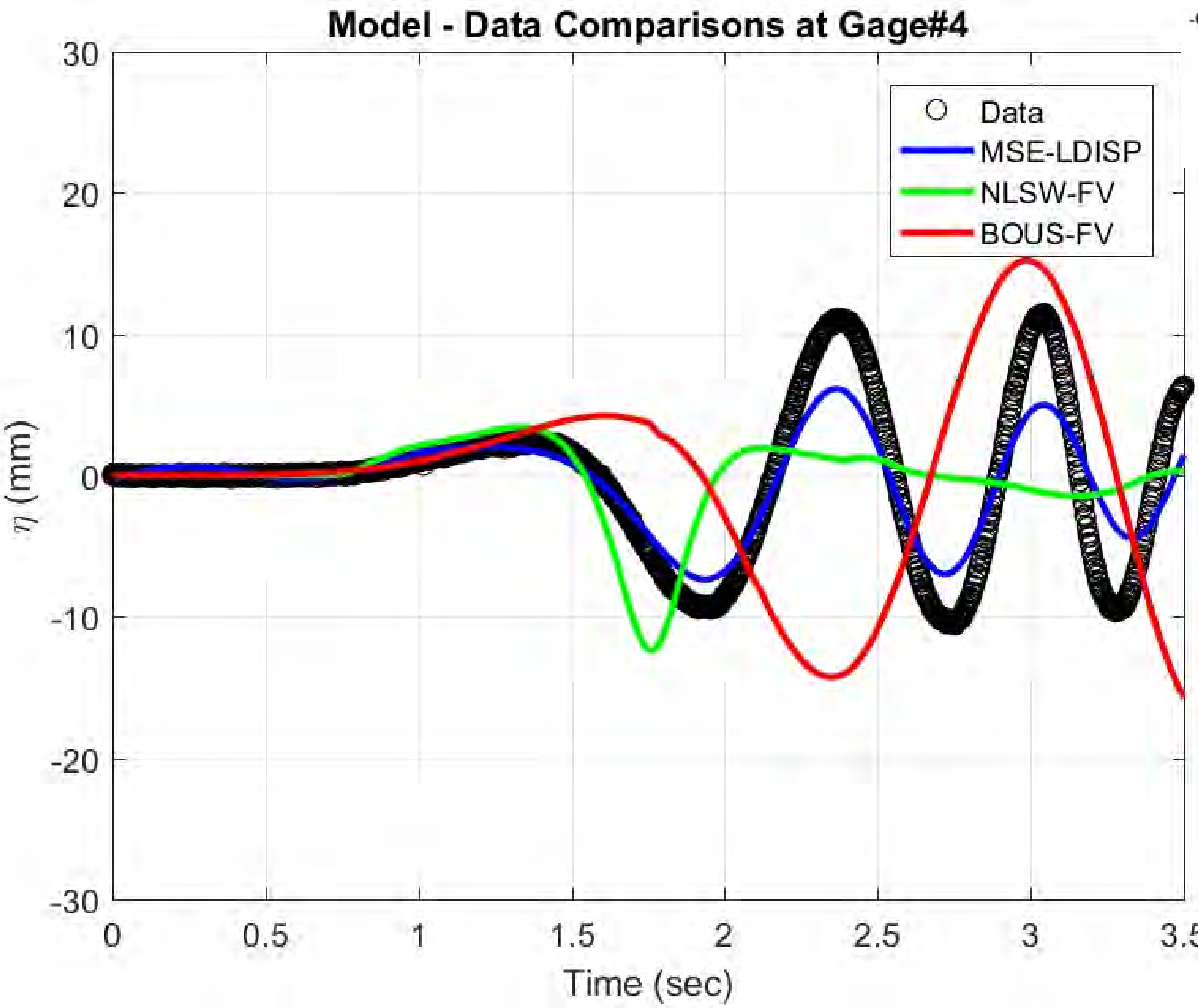


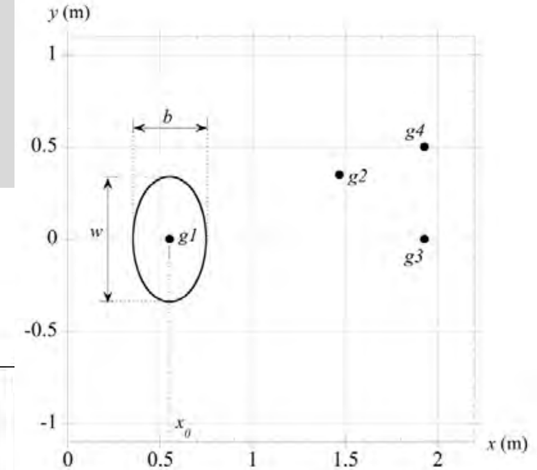


depth=	0.39	m
Period (s)	kh	c/sqrt(gh)
2	0.64	0.98
1	1.64	0.76
0.5	6.28	0.40
0.25	25.11	0.20
min resolvable kh=	36.74	

Benchmark #2

- Initial depth = 0.061m

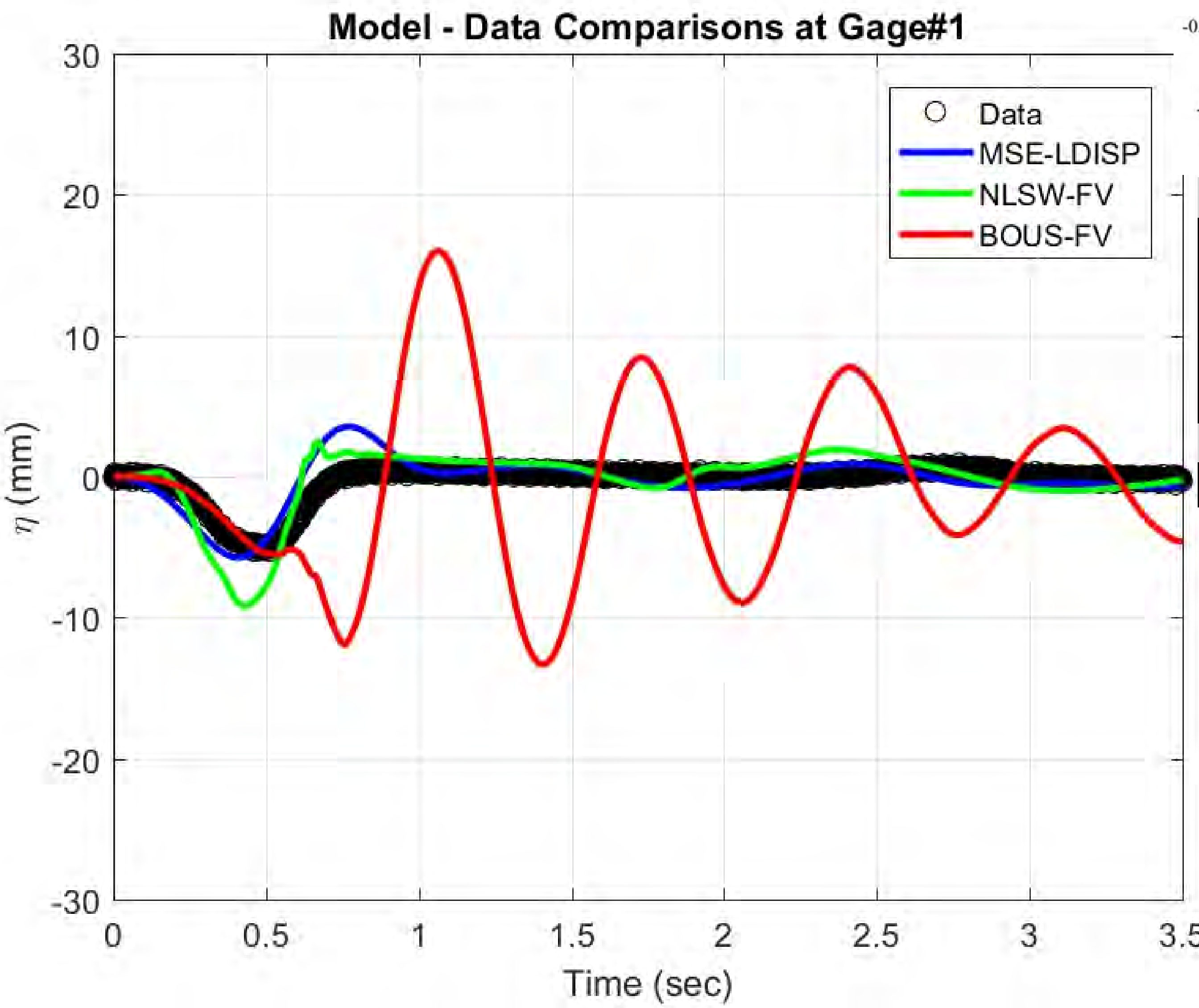


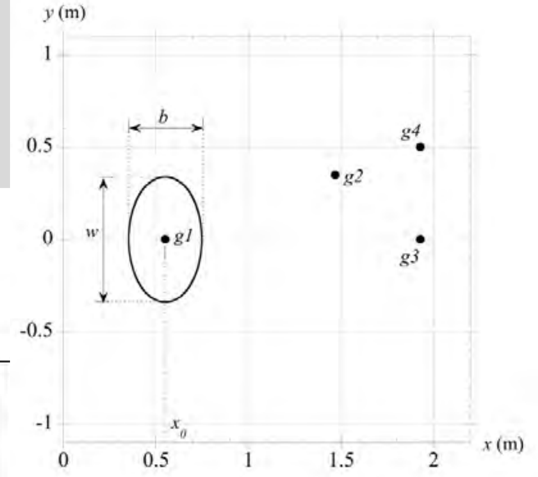


depth=	0.52	m
Period (s)	kh	c/sqrt(gh)
2	0.75	0.96
1	2.12	0.68
0.5	8.37	0.35
0.25	33.48	0.17
min resolvable kh=	48.98	

Benchmark #2

- Initial depth = 0.120m

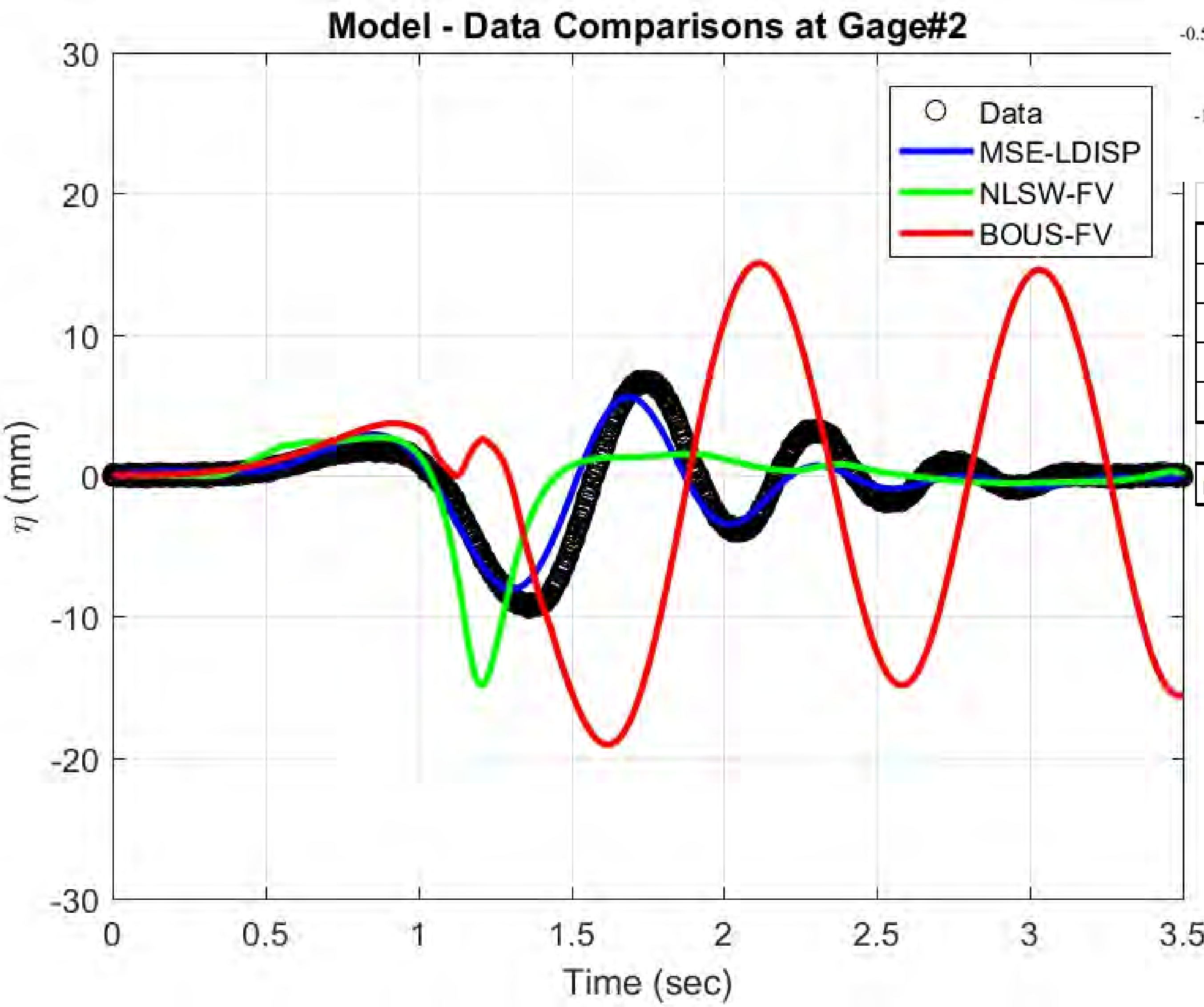


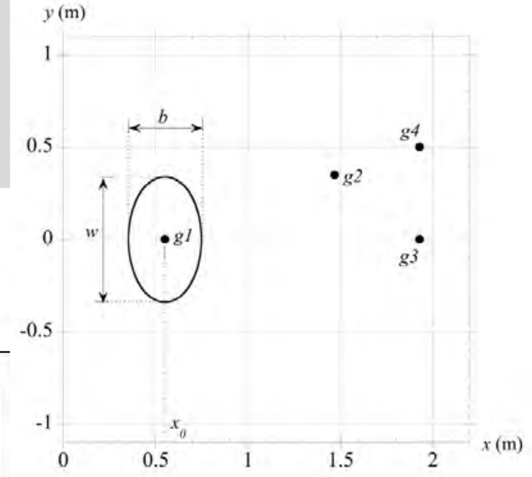


depth=	0.2	m
Period (s)	kh	c/sqrt(gh)
2	0.45	0.99
1	0.99	0.91
0.5	3.22	0.56
0.25	12.88	0.28
min resolvable kh=		18.84

Benchmark #2

- Initial depth = 0.120m



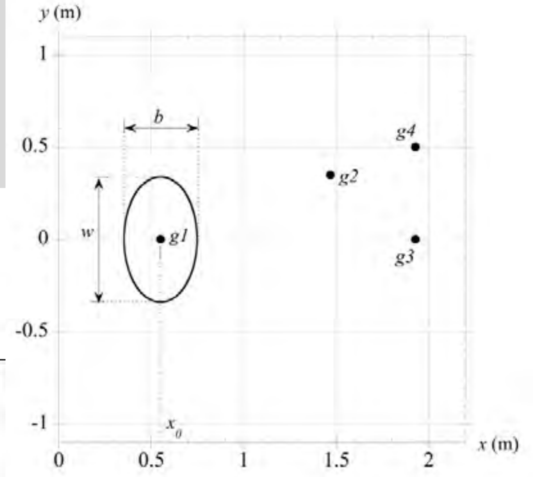


depth=	0.39	m
Period (s)	kh	c/sqrt(gh)
2	0.64	0.98
1	1.64	0.76
0.5	6.28	0.40
0.25	25.11	0.20
min resolvable kh=		36.74

MSE better for this depth

Nonlinearity less important

Benchmark #2



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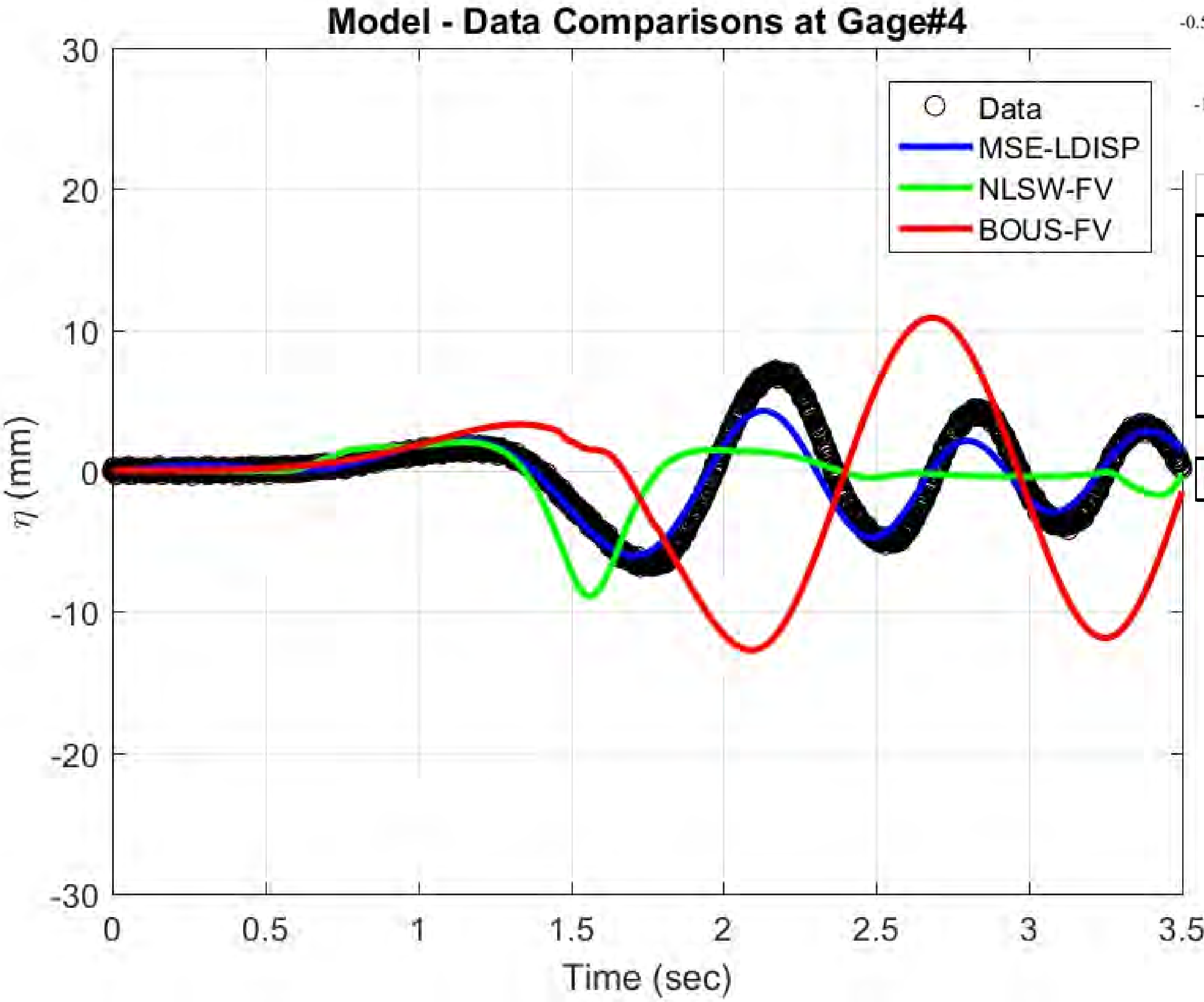

depth=	0.52	m
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2	0.75	0.96
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0.25	33.48	0.17
min resolvable kh=	48.98	

NLSW better than Bous for leading wave, but kh~3!

Conclusions& Thoughts

- NLSW can be "less wrong" than weakly dispersive models when generated wavenumbers exceed accuracy limitations of the weakly dispersive models
  - But hard to reconcile using NLSW for high kh forcing…
  - Finn's filter is probably a required approach for a general application of weakly dispersive models for arbitrary bottom forcing
- The Giorgio model (Mild Slope Equation) offers a rapid approach to estimate generated waves with arbitrary (single-valued in the horizontal) landslide shape
  - Linear
  - Needs coupling to another model for propagation away from source, viscous effects, and for runup

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- To what degree should we allow modelers to smooth / modify slide evolution to permit a stable / accurate result?
- Are we benchmarking the slide evolution or the wave generation?
  - IF we are benchmarking slide motion, then we need to use slide motion benchmarks (BM6!)
  - IF we are benchmarking wave generation, we need to be more restrictive on the slide motion
- Slides stop too! – do we need a slump-like benchmark, with a coherent de-acceleration?
- Thinking of landslide tsunami forecast (NOT hindcast) – if you had just a landslide location, approximate mass (within 20%), approximate direction of failure (with 20%), and approximate time scale (within 50%) [this is the information we might get in near realtime from seismic inversion] – how well could we forecast the waves?
  - Where is the uncertainty, or the knowledge gaps – hydro, geo, coupling?