Using tsunami sediment transport experiments to improve paleohydraulic inverse models

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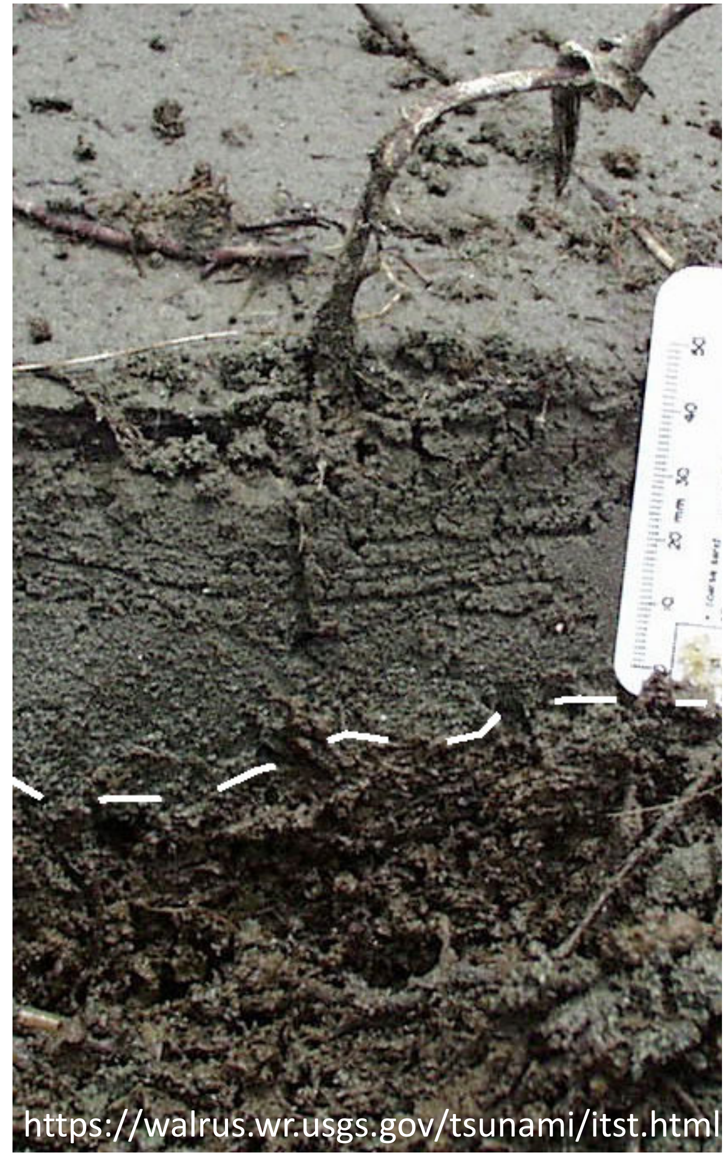
Johnson et al., 2016 (Geomorphology)
Johnson et al., 2017 (JGR-Earth Surface)

Motivation

- Use sediment deposit to infer **tsunami** or **storm surge** flow depth, velocity.
- Risk estimation: extend magnitude/frequency record of extreme events.

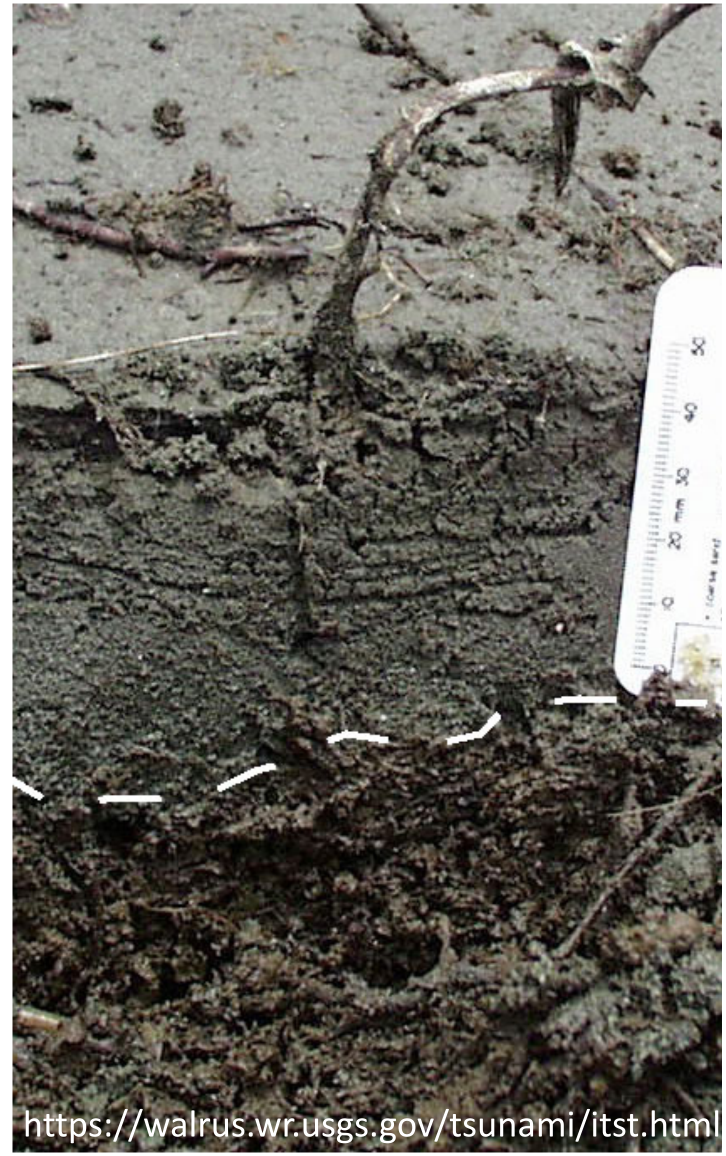
e.g., Jaffe and Gelfenbaum, 2007; Moore et al., 2007; Soulsby et al., 2007; Woodruff et al., 2008; Tang and Weiss, 2016 (arXiv); Naruse and Abe, 2017.



Motivation

- Use sediment deposit to infer **tsunami** or **storm surge** flow depth, velocity.
- Risk estimation: extend magnitude/frequency record of extreme events.

- Challenges:
    - Field data: key variables underconstrained (flow characteristics, source GSD).
    - Therefore, difficult to evaluate inverse model **accuracy** and **uncertainty**.



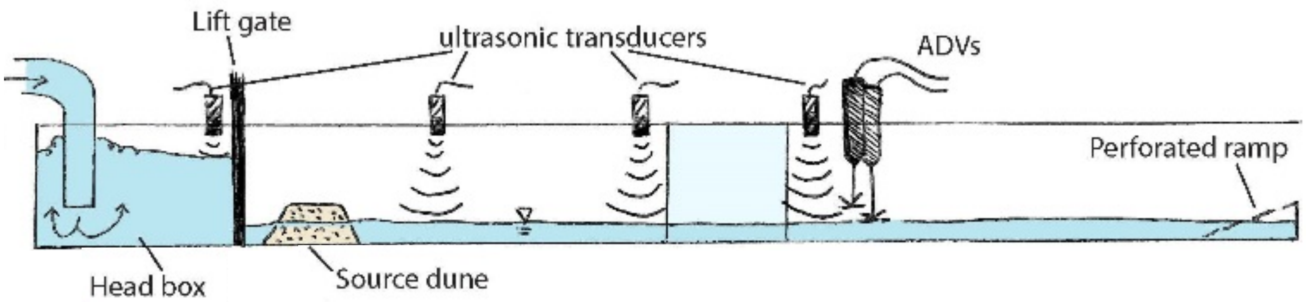
Goals

- Experiments for model validation and benchmarking.
- Evaluate model accuracy, uncertainty.
- Understand the physics of non-equilibrium entrainment, transport, deposition.

  - What factors control deposit GSD?
    - Source GSD proximally, sorting distally.
    - **Dispersion controls coarse and fine GSD tails.**

Flume: 32 m long, 0.8 m deep, 0.5 m wide.

- Lift gate, source dune, depth & velocity sensors.



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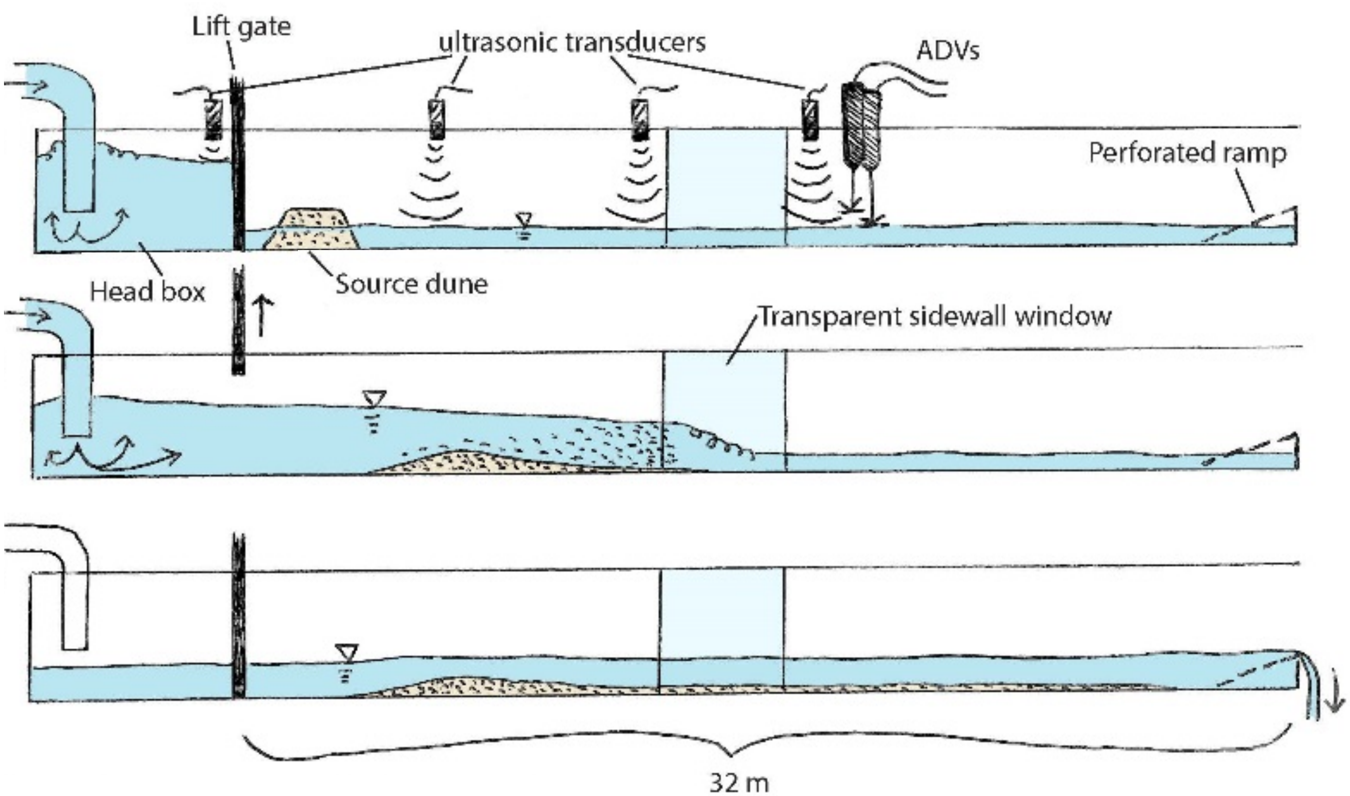
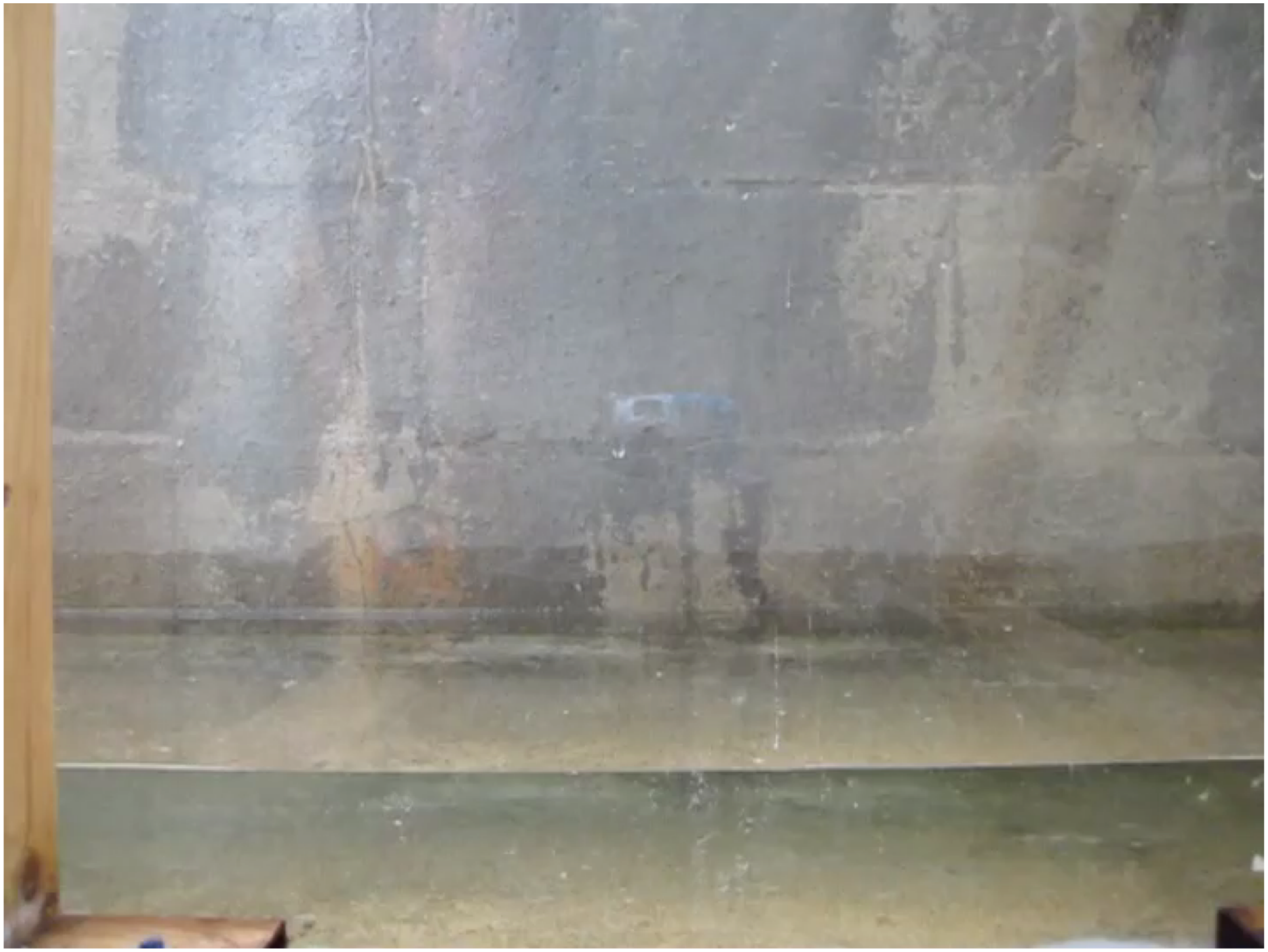


6 Experiments:

- **Sand:** ≈0.1 to 0.9 mm
- **Source GSDs**: 3 finer expts, 3 coarser
- 3 ponded **depths** (0, 8-10, 19 cm)

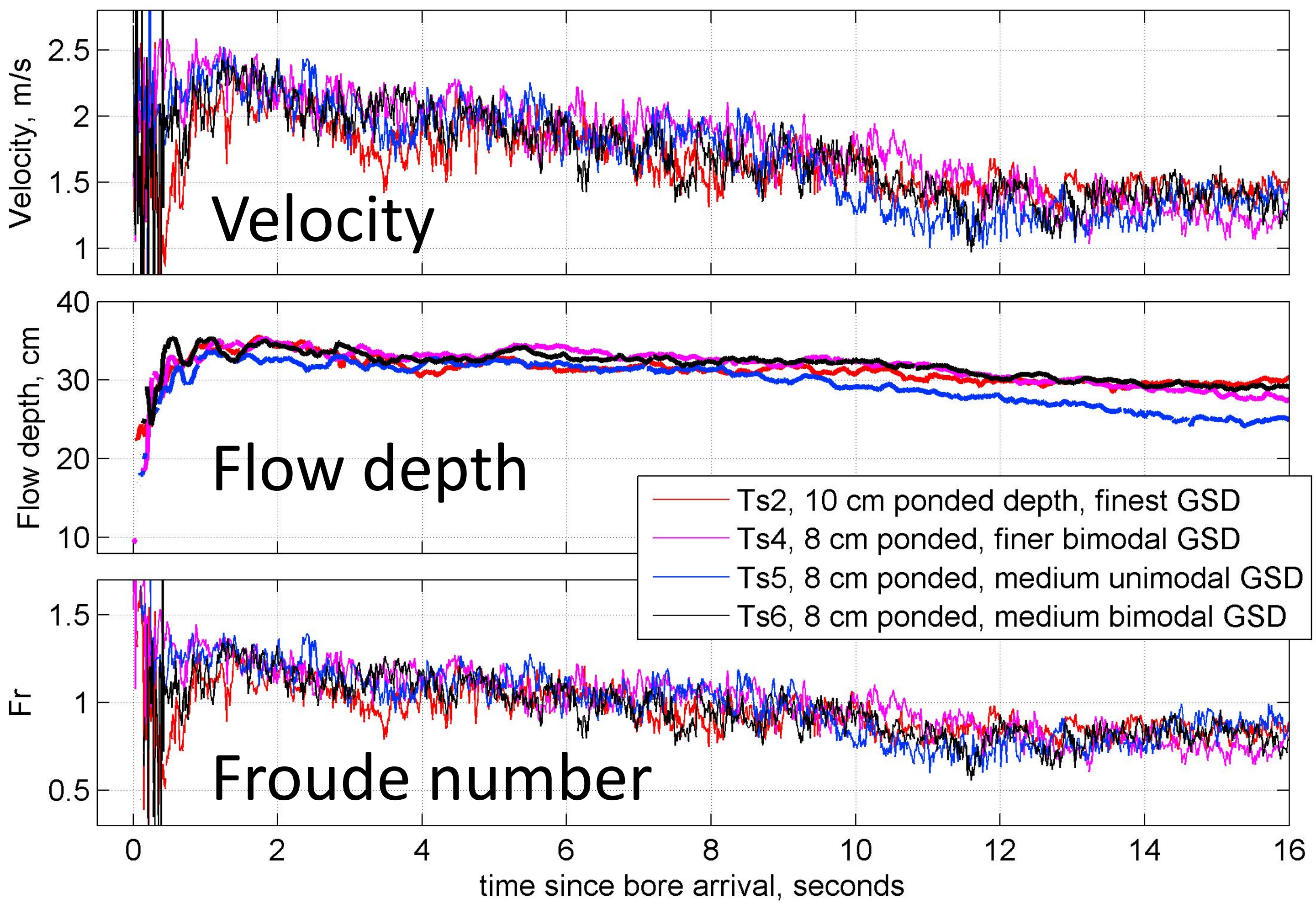
Data collected:

- Flow depth
- Velocity
- Deposit Thickness
- Deposit GSD



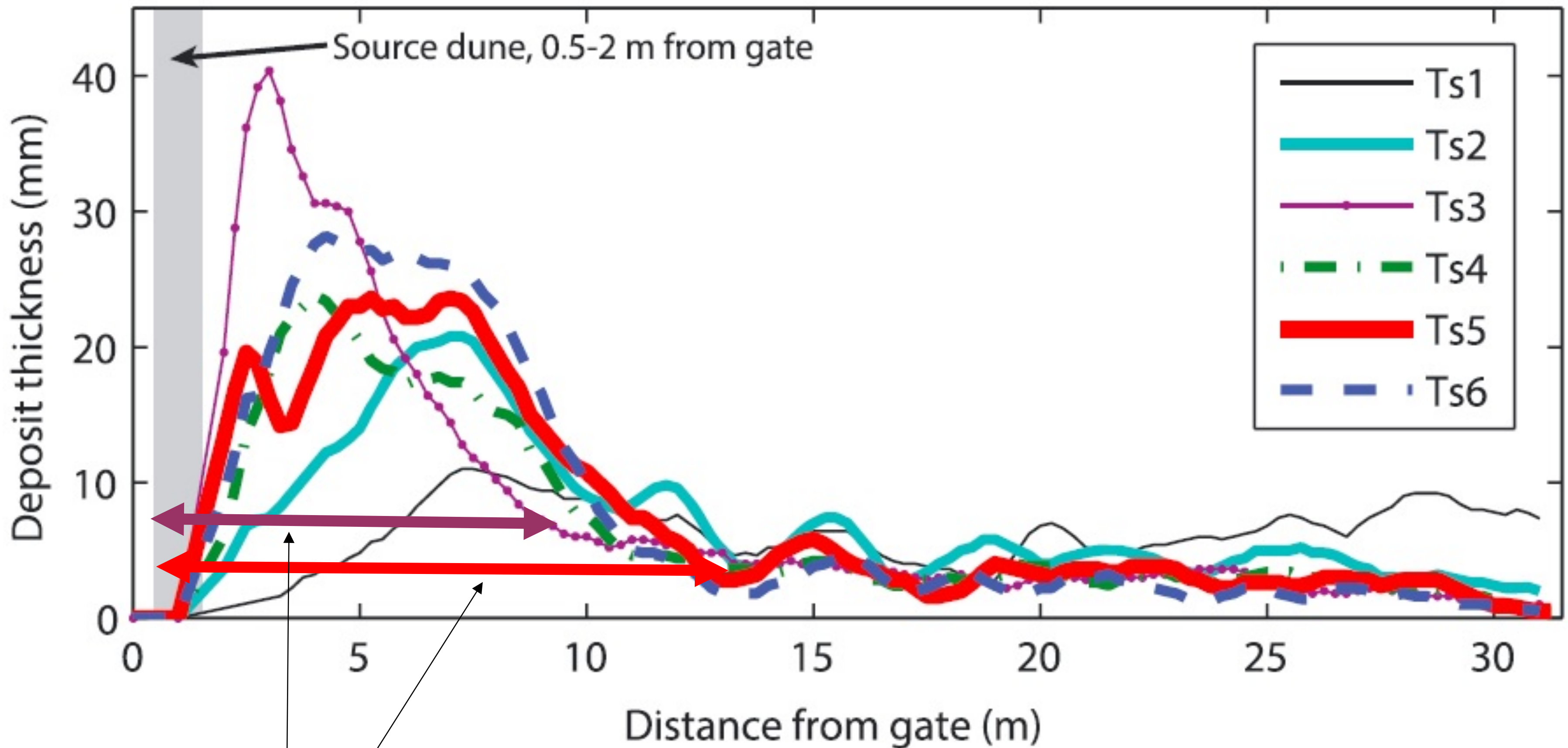
Experiment Ts6.

- 8 cm initial ponded water depth.
- Field of view ~35 cm (foreground).

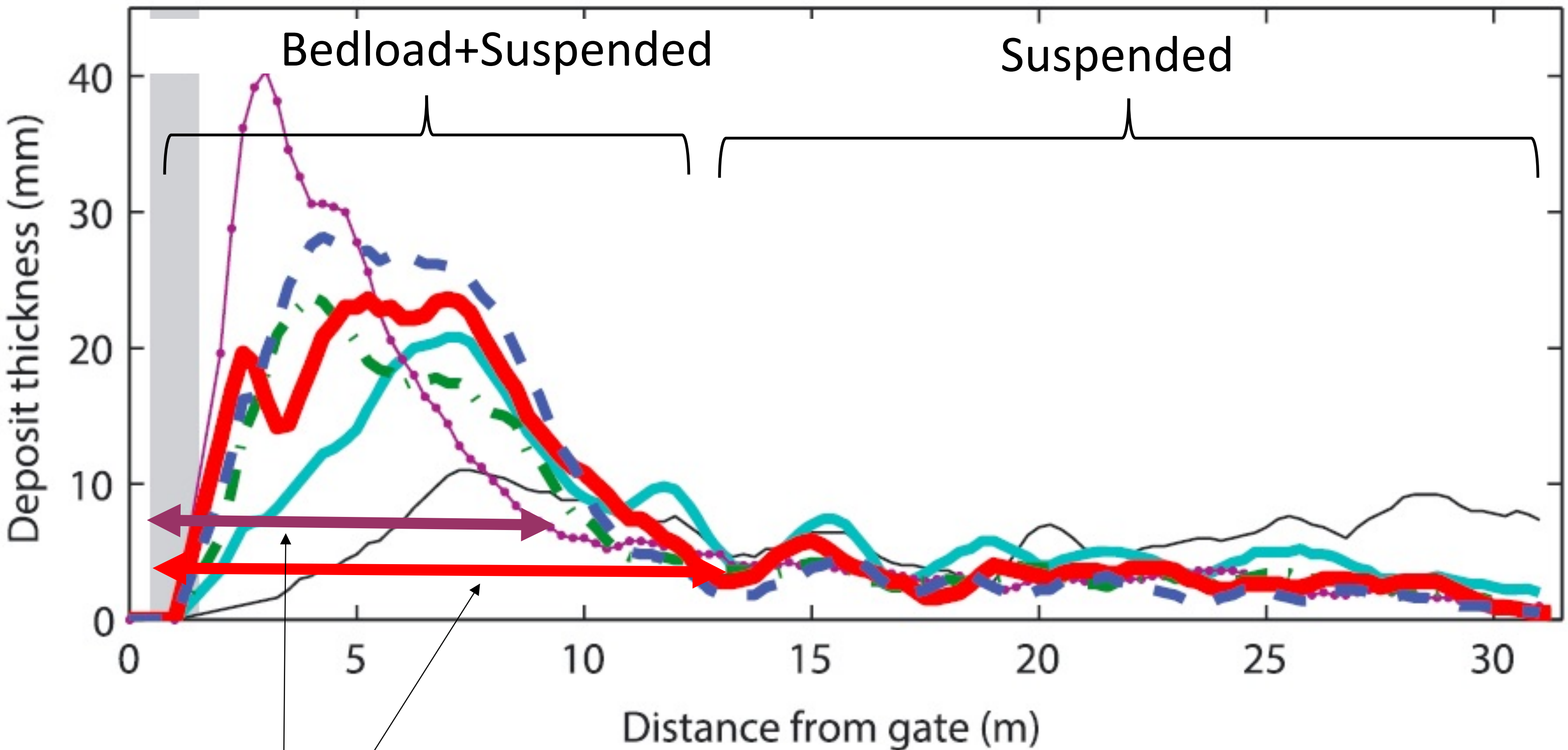


Reproducible flows.

- Average *Fr*≈1 for runs shown; *Fr* = 0.74, 1.38 for other experiments.

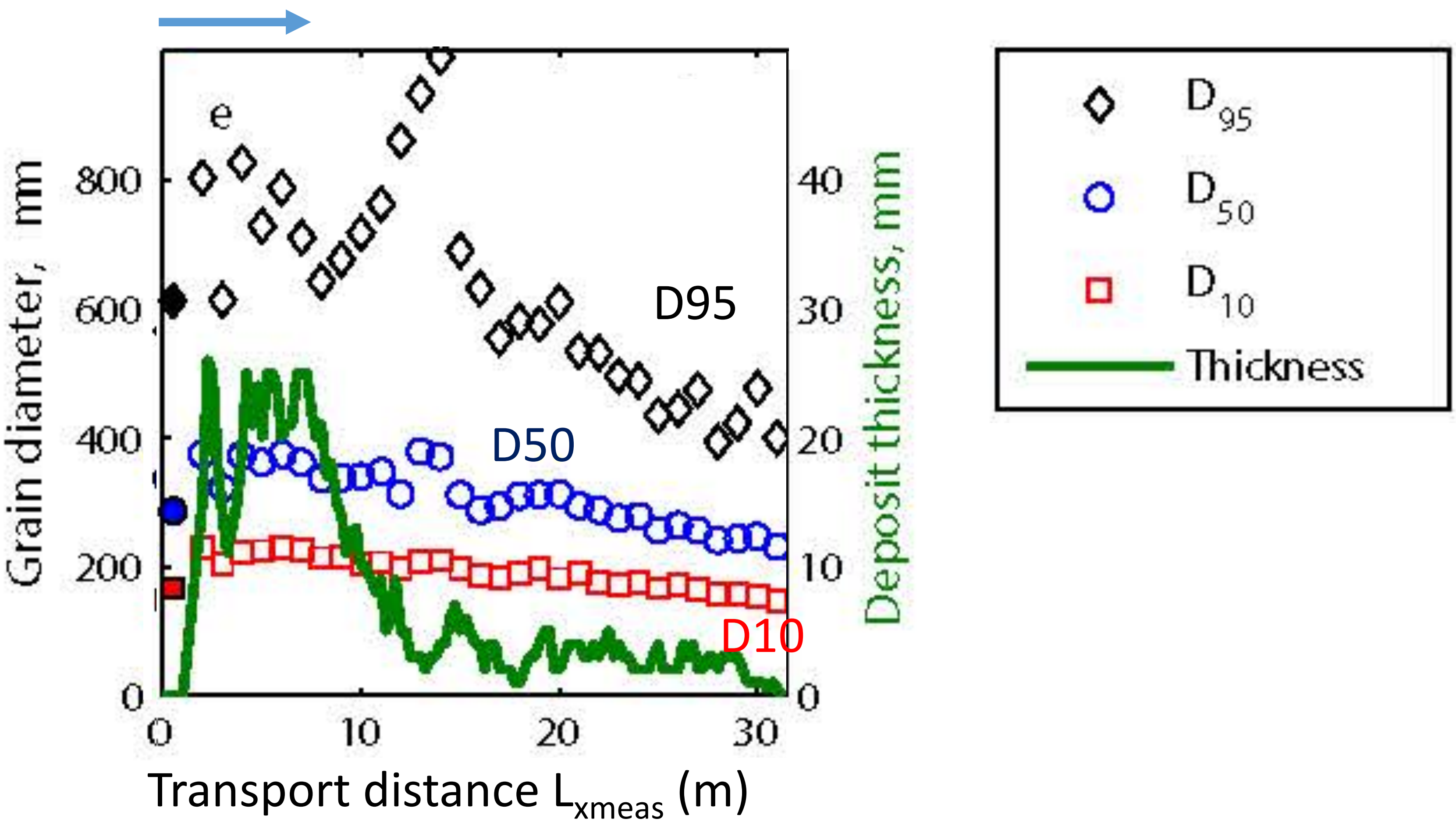


Predictions of bedload transport distance, *f*(shear velocity) (Martin et al., 2012).

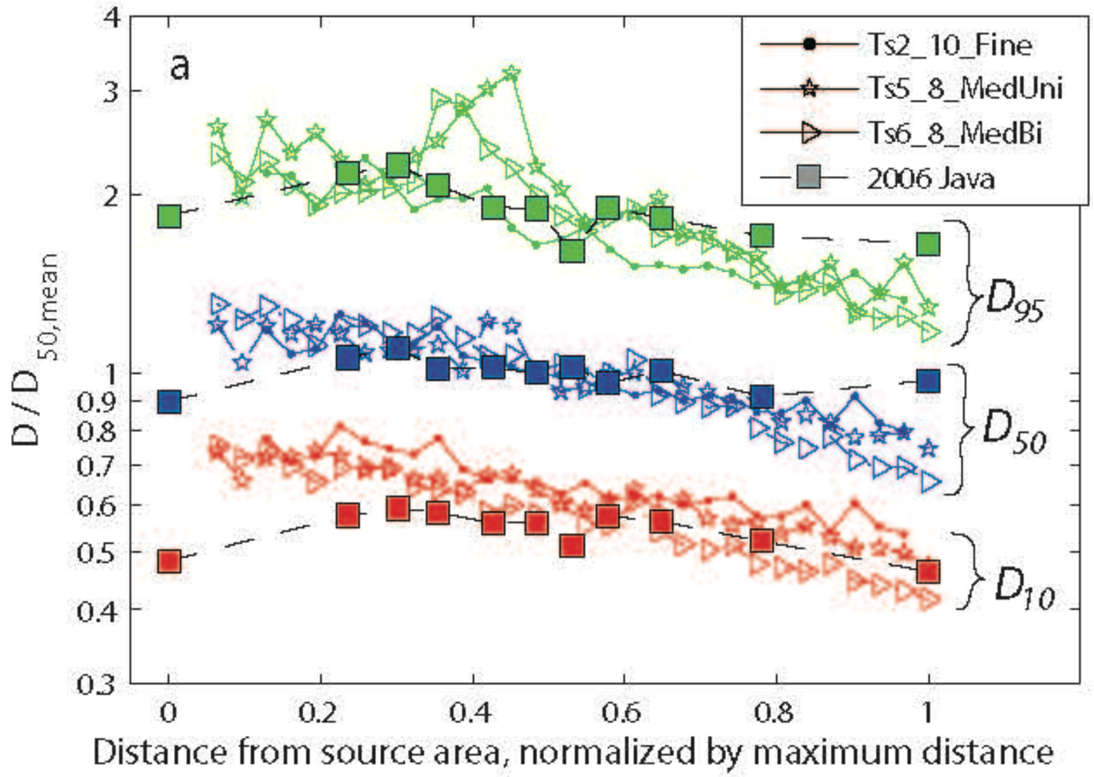


Predictions of bedload transport DISTANCE as fcn of shear velocity (Martin et al., 2012).

Deposit: downstream ***fining***



Grain size trends, field vs flume



2006 Java (Moore et al., 2011)

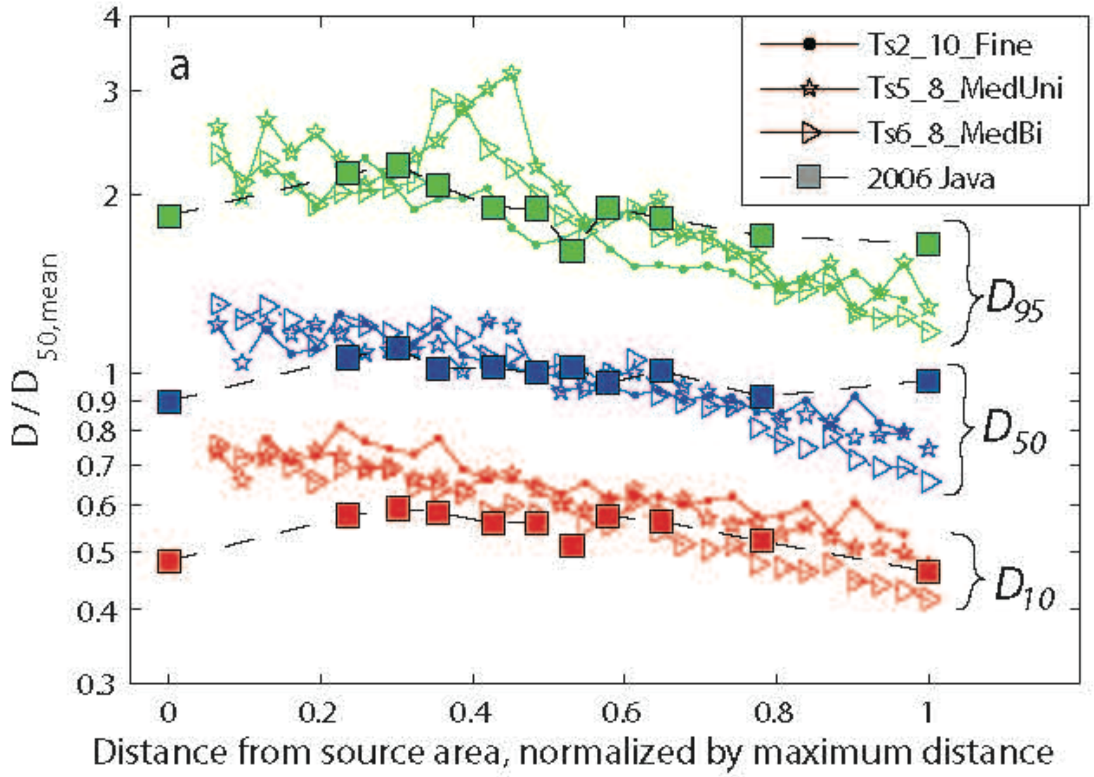
Scaling (Geometric, Fr)

- Expts are ~1/10 to 1/100 scale models.

Field conditions:

- ≈3-30 m deep.
- Velocity: 1.75 m/s expt scales to 5.5-17.5 m/s field.
- Duration: ≈20 s expt scales to 1-4 minutes field.
- Fully suspendable: Rouse # 0.9 to 1.9 for D95.

Grain size trends, field vs flume



2006 Java (Moore et al., 2011)

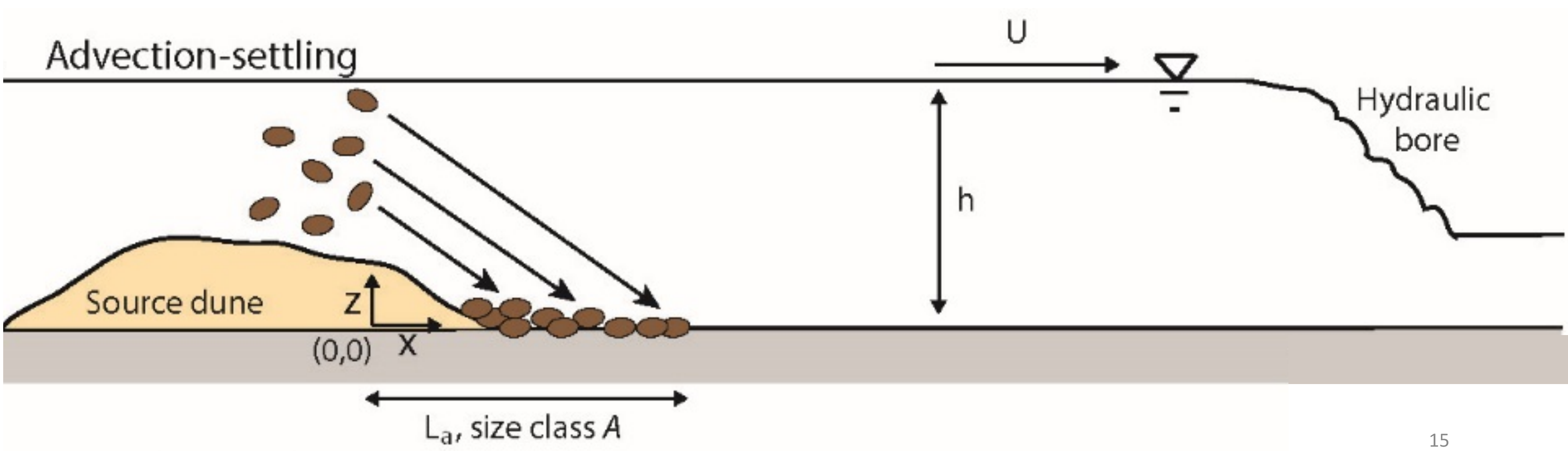
Next: Use deposit GSD trends to evaluate **advection-settling model**.

Advection-Settling Model

Moore et al. (2007); Woodruff et al. (2008)

Assumptions:

- Diameter, depth (h), velocity (U) control transport distance.



Advection-Settling Model

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Assumptions:

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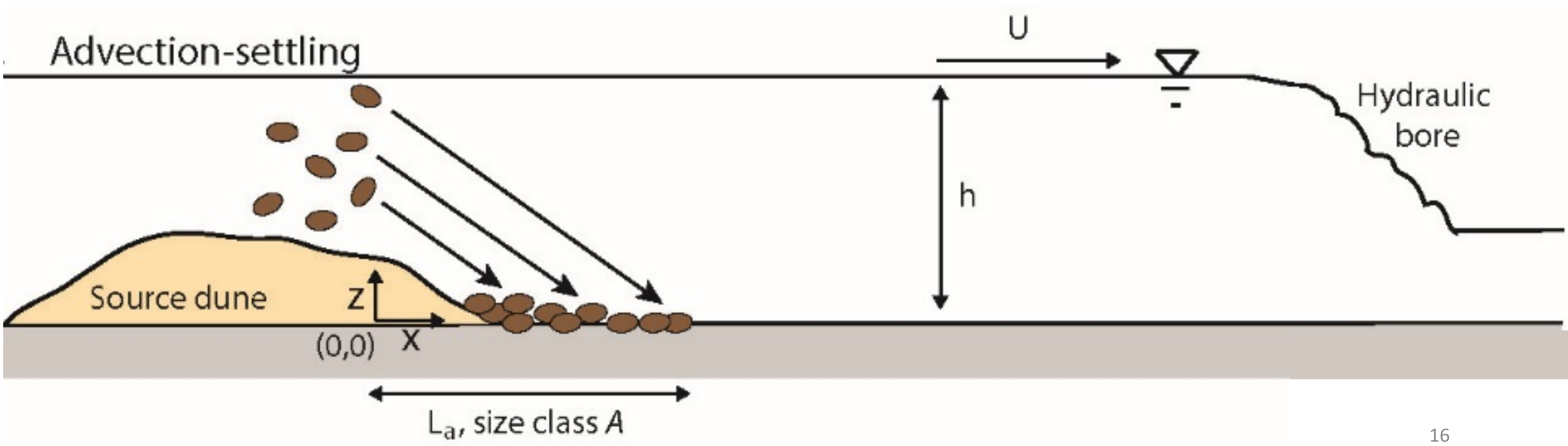
Advection length scale:

$$L_a = \frac{Uh}{w_{ssw}}$$

"Still water" settling velocity—no turbulence.



Advection-Settling Model

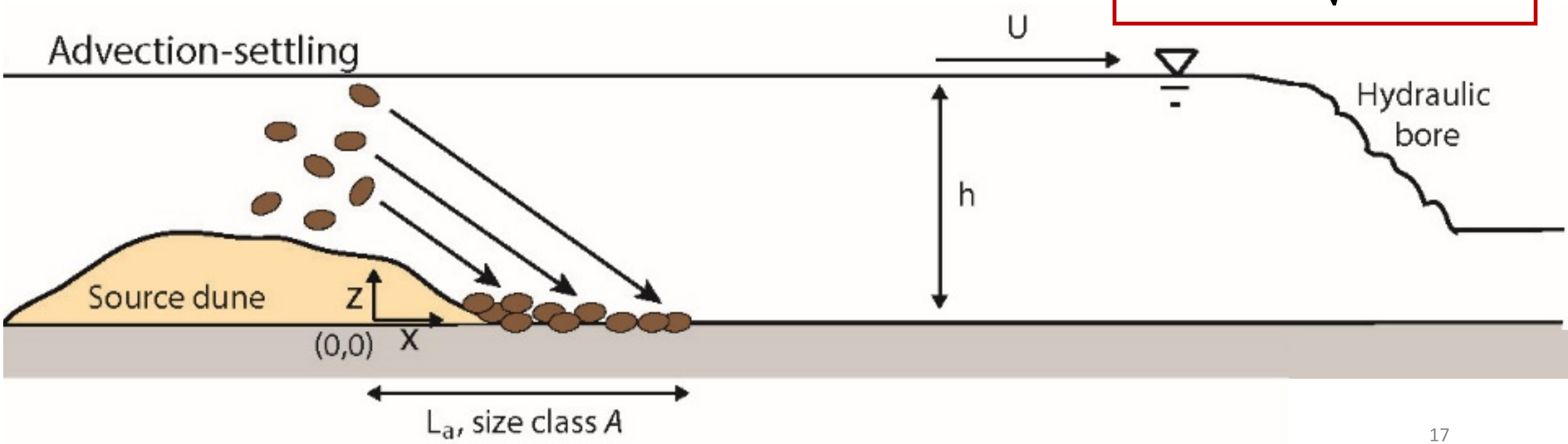
Moore et al. (2007); Woodruff et al. (2008)

Assumptions:

- Diameter, depth (h), velocity (U) control transport distance.
- Transport distance $L_{xmeas} = L_a$.

$$L_a = \frac{Uh}{w_{ssw}}$$

$$Fr = \frac{U}{\sqrt{gh}}$$



Advection-Settling Model

Moore et al. (2007); Woodruff et al. (2008)

Assumptions:

- Diameter, depth (h), velocity (U) control transport distance.
- Transport distance $L_{xmeas} = L_a$.
- 2 equations, 2 unknowns (U, h).

$$L_a = \frac{Uh}{w_{ssw}}$$

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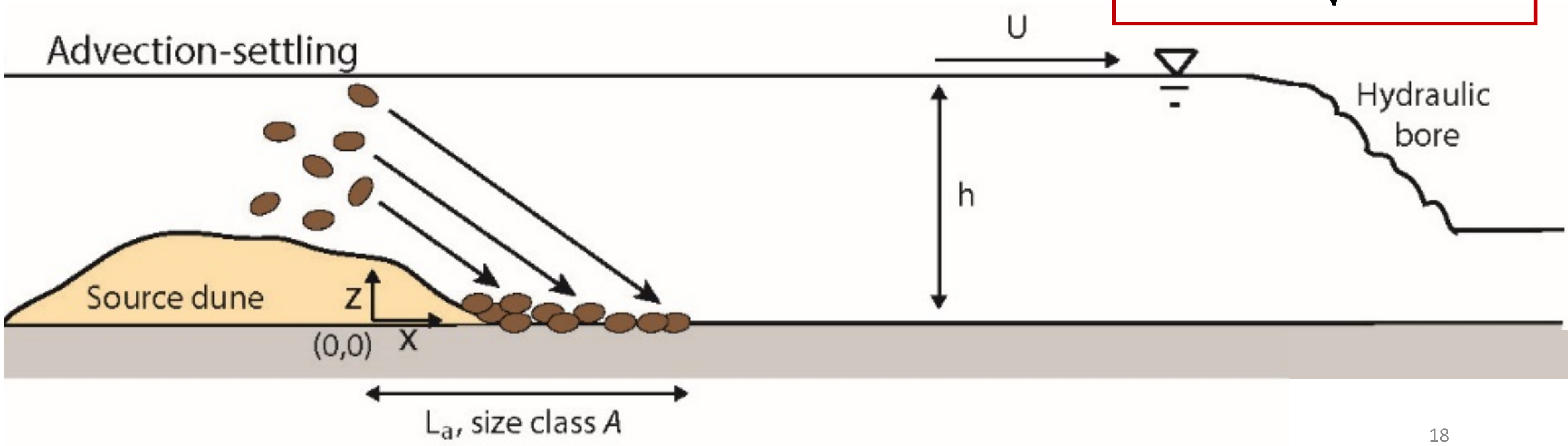

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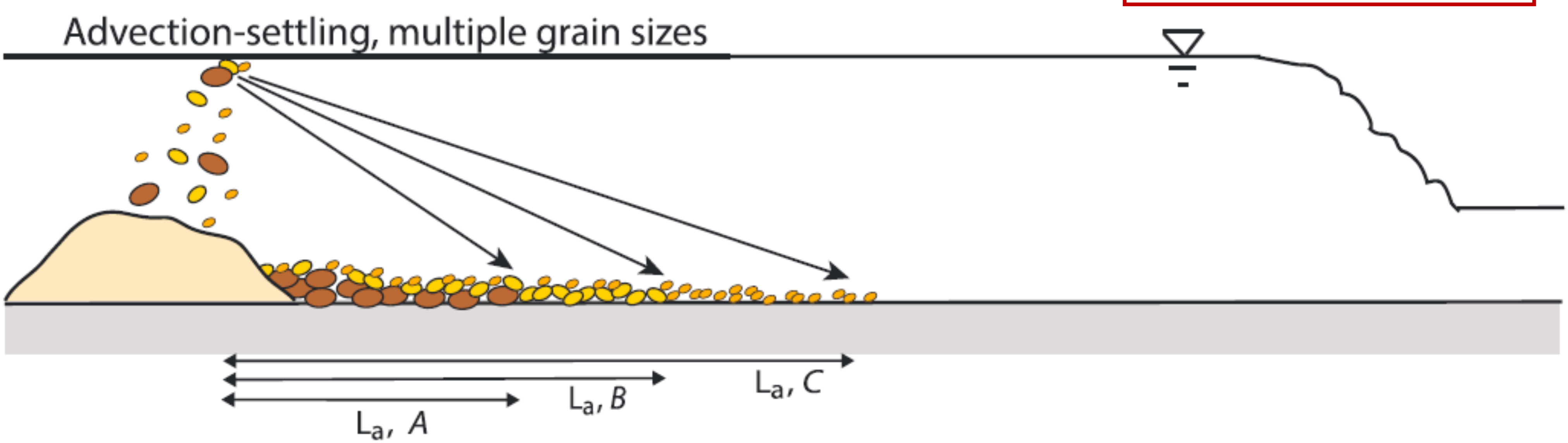


Advection-Settling Model

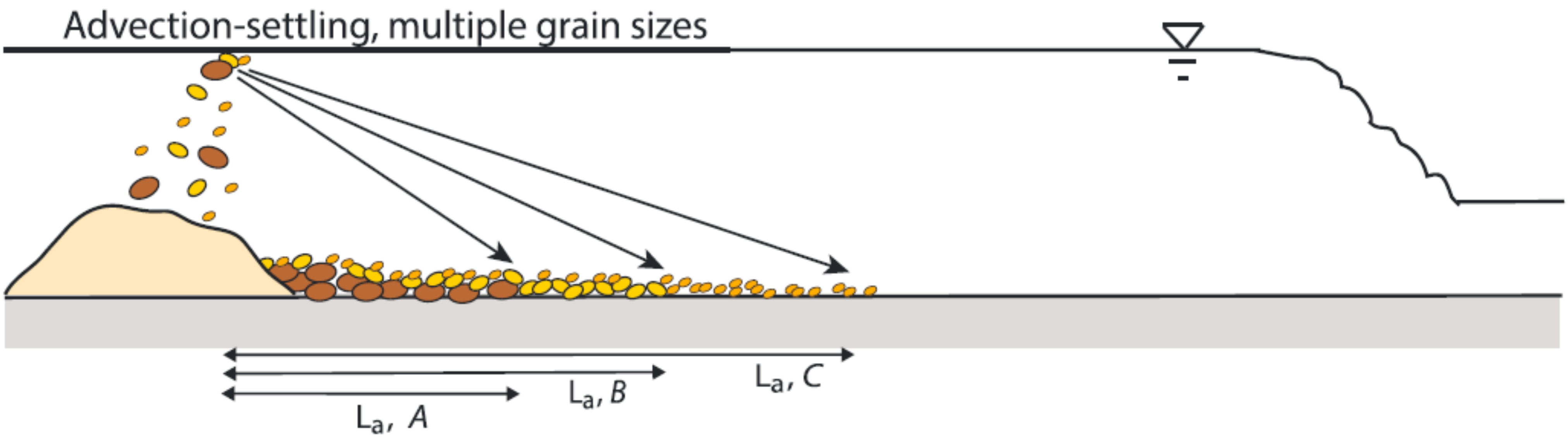
Moore et al. (2007); Woodruff et al. (2008)

$$L_a = \frac{Uh}{w_{ssw}}$$

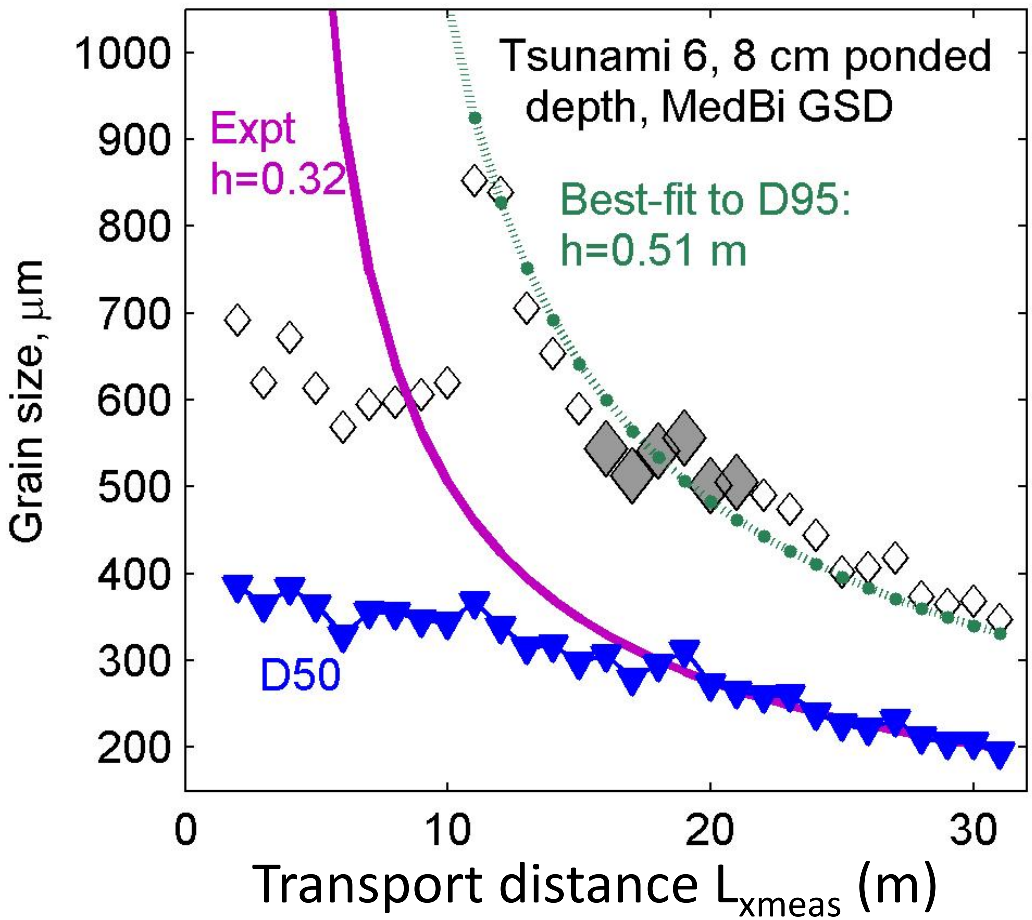
$$Fr = \frac{U}{\sqrt{gh}}$$

What GSD diameter should be used to calculate w_{ssw}?

- Assumption to test: **COARSEST** grains from deposit GSD (≈D95) at a given transport distance should best predict *U, h* .



Advection-Settling Model fits to Deposit **D95**



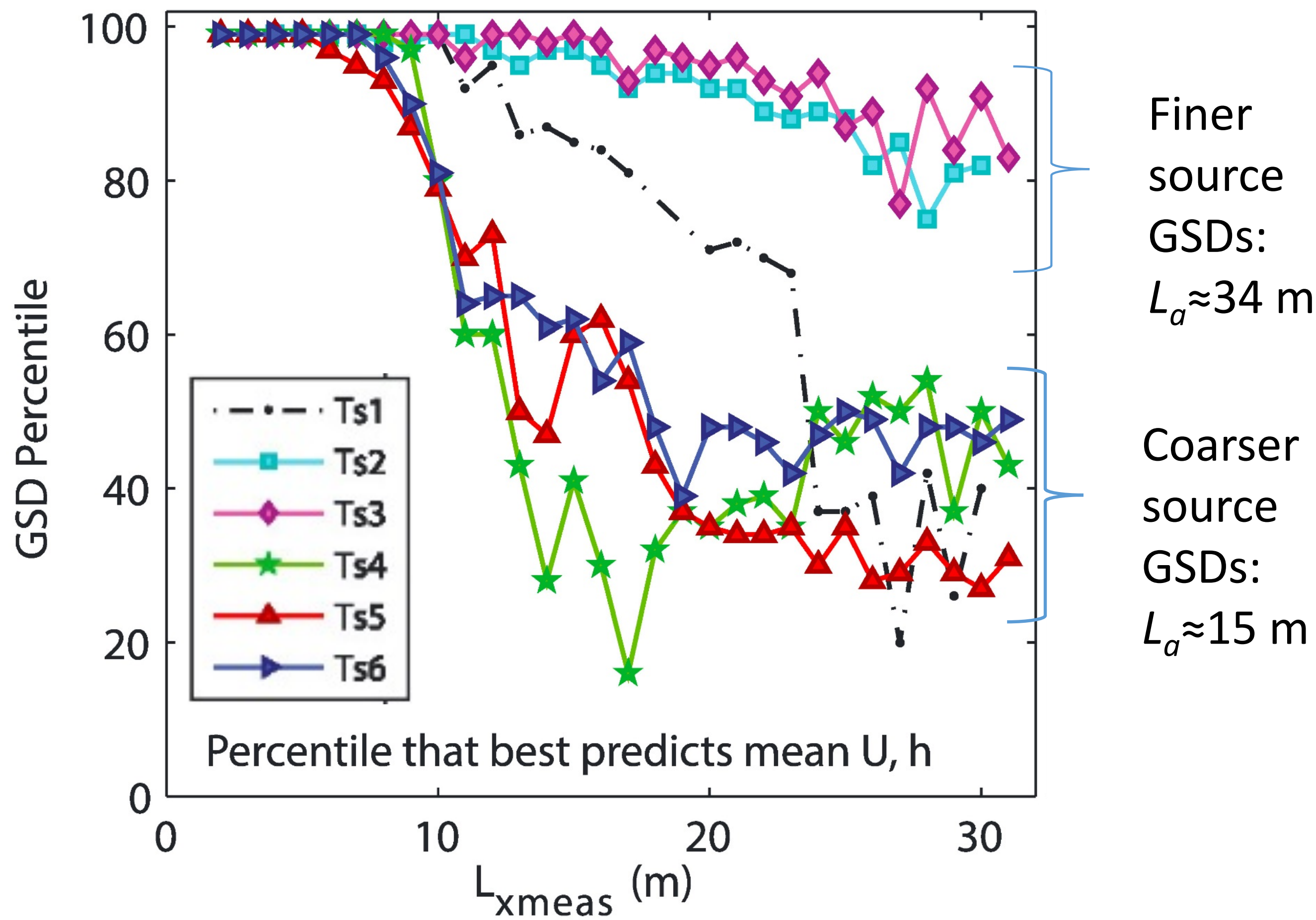
Experiment Ts6:

- Downstream: **D95** overpredicts flow depth, velocity by almost 2x.
- Downstream: **D50** predicts depth, velocity accurately.
- Upstream: model doesn't match data (source GSD).

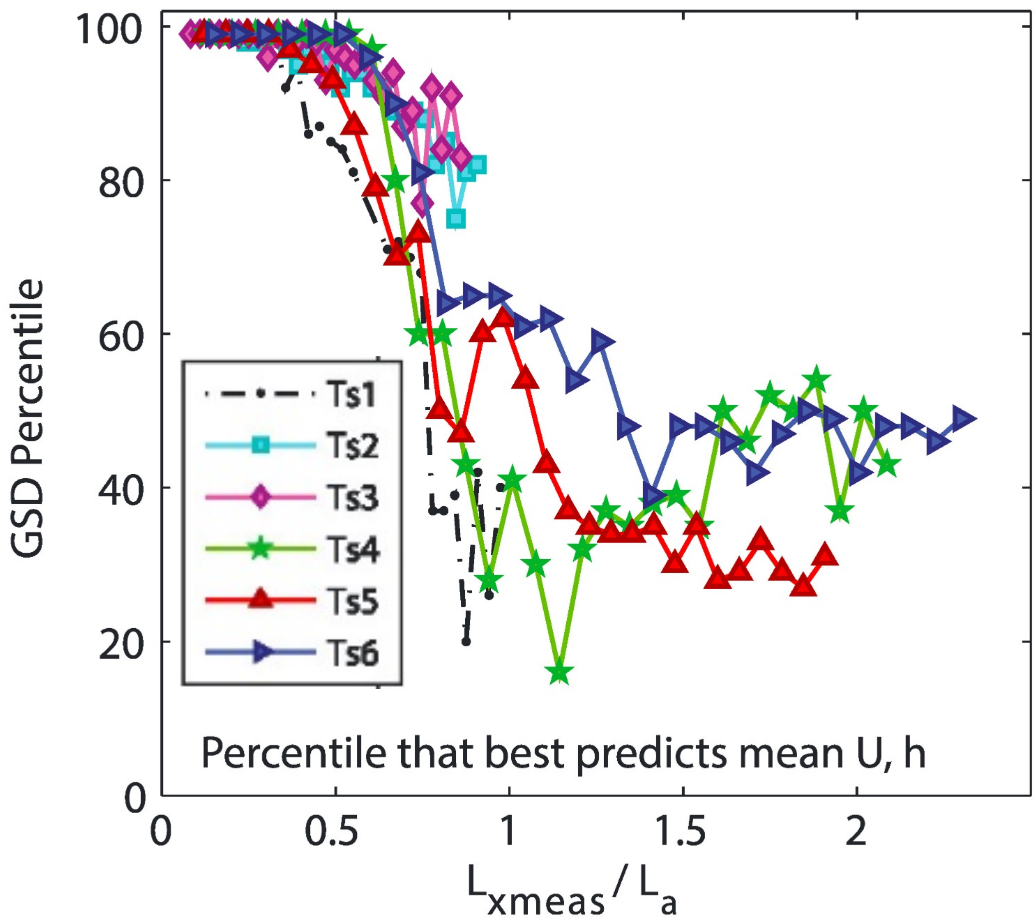
GSD percentiles along flume that best predict U, h

Downstream:
best-fit percentiles vary.

Next: Normalize transport distance (L_{xmeas}) by source D50 advection length scale (L_a).



GSD percentiles along flume that best predict U, h

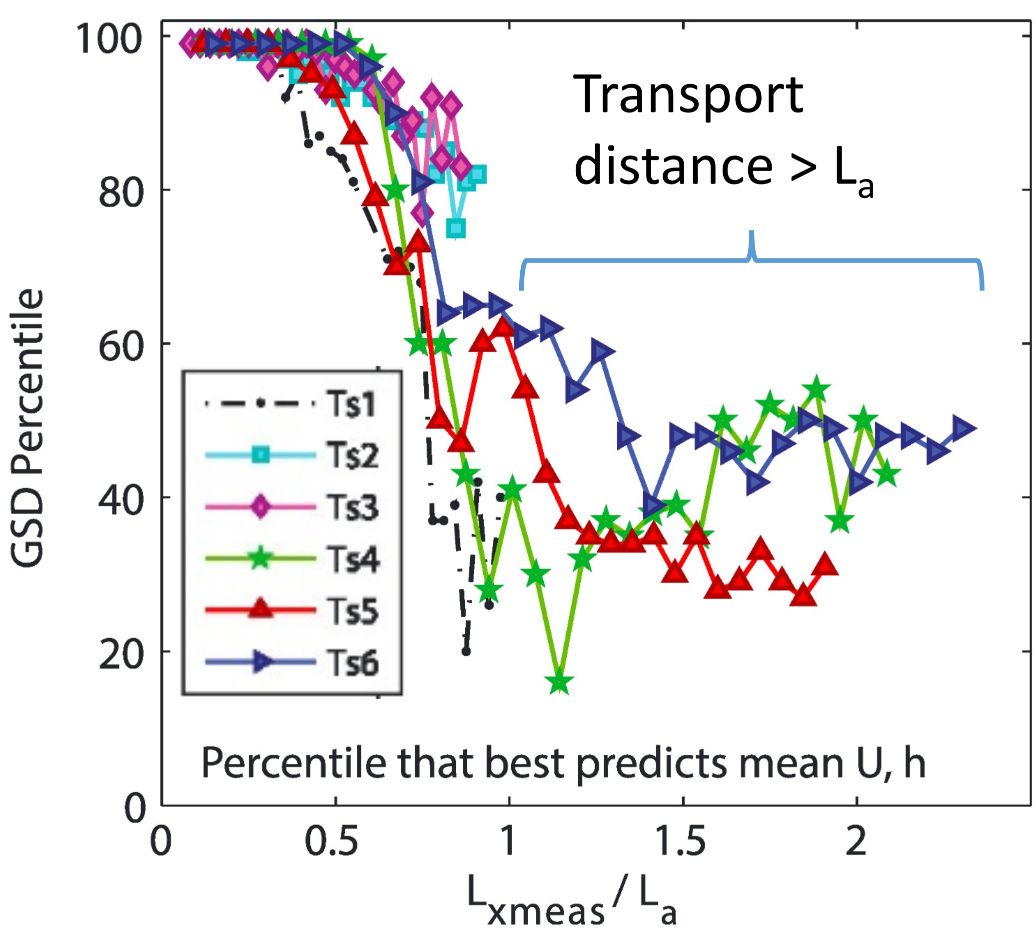


GSD percentiles along flume that best predict U, h

Interpretation:

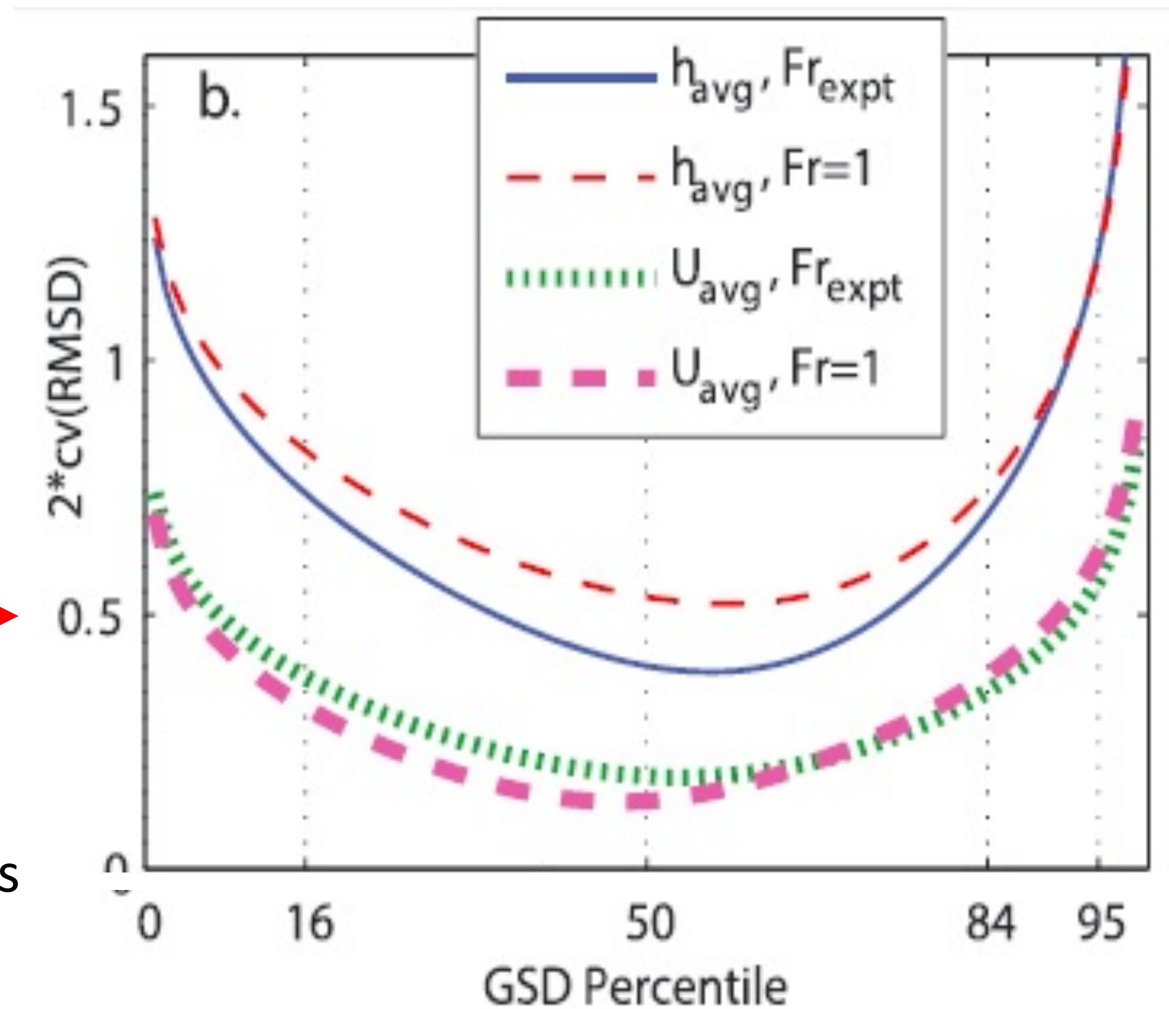
- Deposit GSDs for transport > L_a reflect sorting, sensitive to *U, h*.

- Deposit GSDs for transport < L_a dominantly reflects *source* GSD.



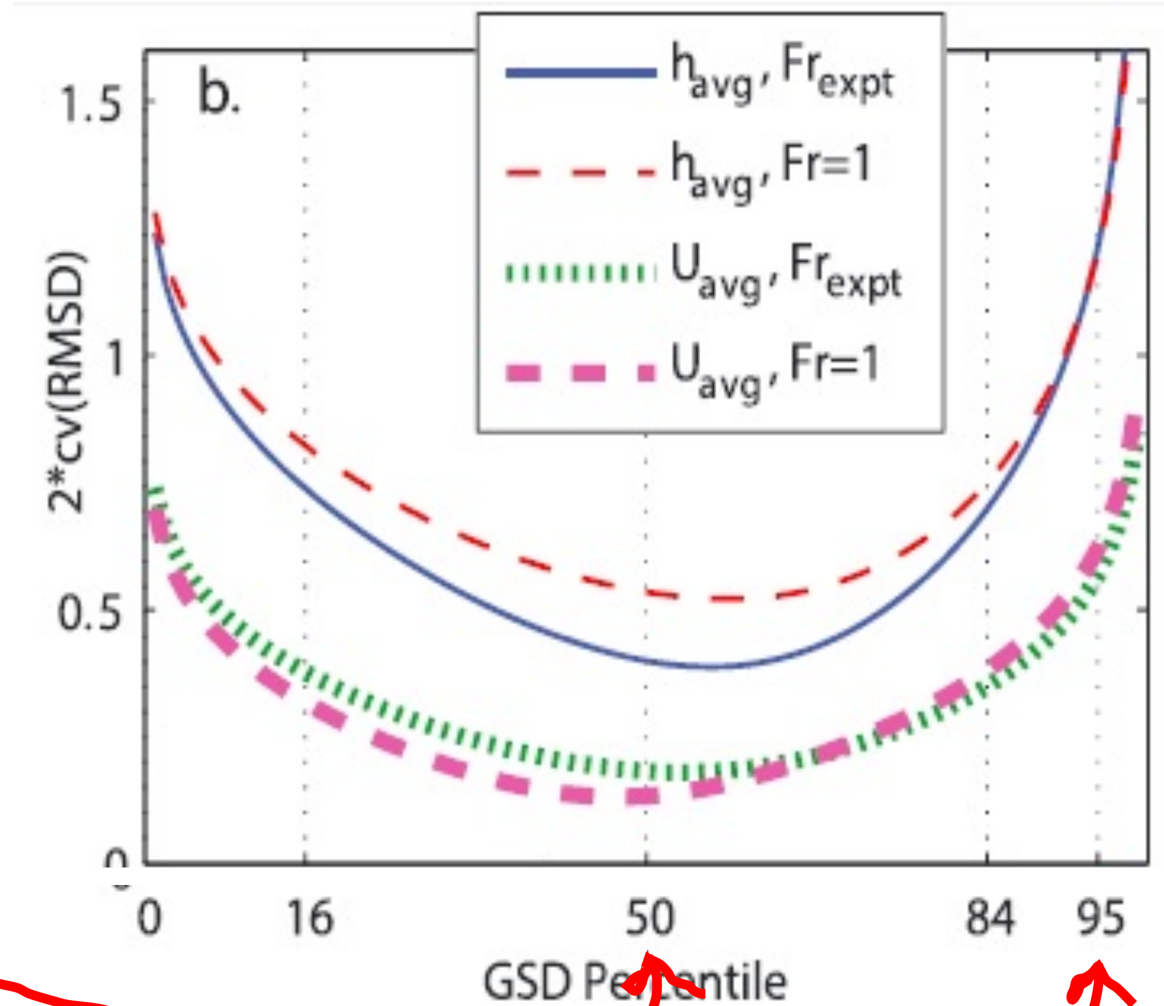
Prediction uncertainties for different GSD percentiles:

- At 95% confidence, depth predictions within ±50% of “correct” experimental value.
- Uncertainties are fairly insensitive to exactly what intermediate GSD percentile is used.



Prediction uncertainties for different GSD percentiles:

Next: ***Why*** is D50 better than D95 for predicting depth and velocity?

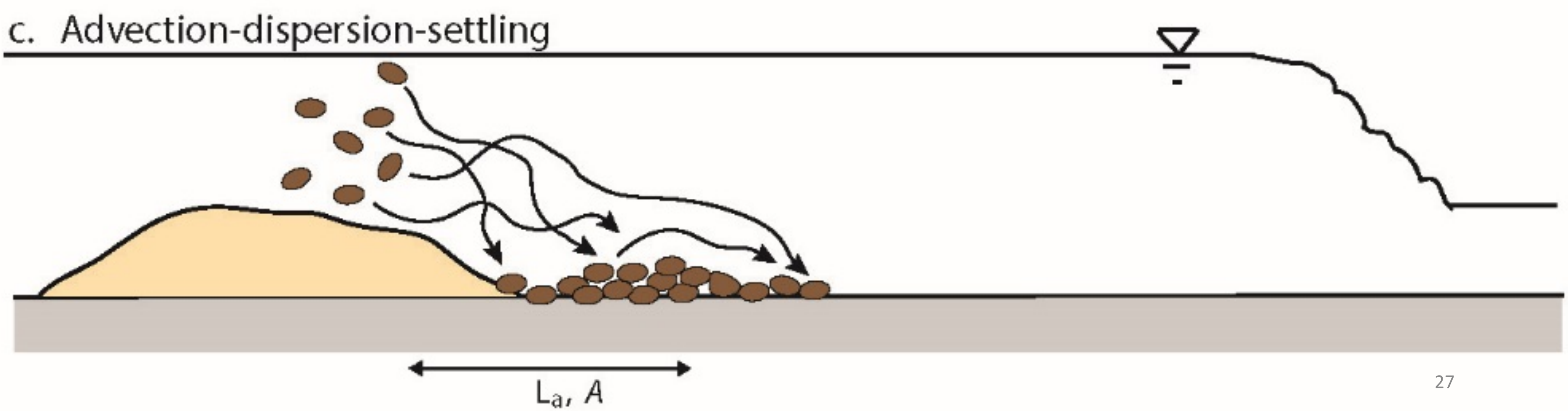


Add ***turbulence*** to conceptual model

Advection length scale:

$$L_a = \frac{Uh}{w_{ssw}}$$

- Turbulence causes a ***distribution*** **of settling velocities and transport distances**.
- $L_{xmeas} \approx L_a$ for intermediate diameters (≈D50), not coarsest grains.
- Intermediate diameters (≈D50) best represent *mean* U, h, settling.
- Coarse and fine tails of deposit GSDs reflect **dispersion**.



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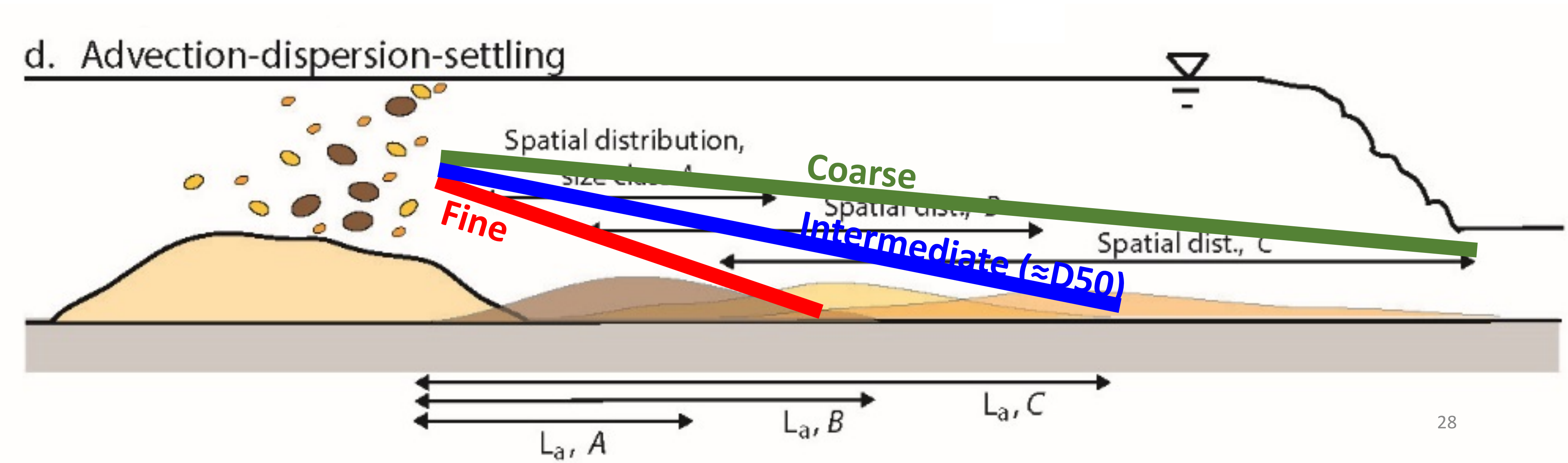

For a given grain size:

- L_a is constant.
- Dispersion causes distribution of transport distances (L_{xmeas}).

Advection length scale:

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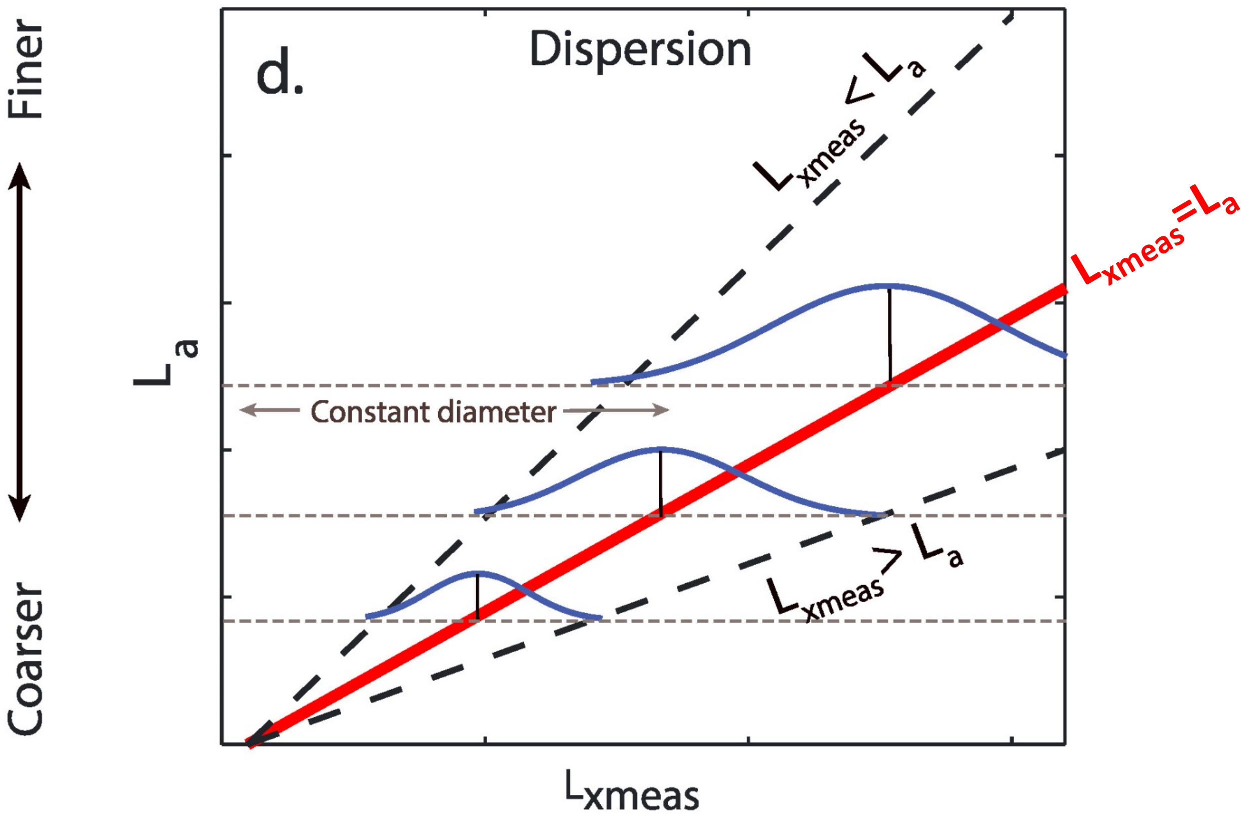
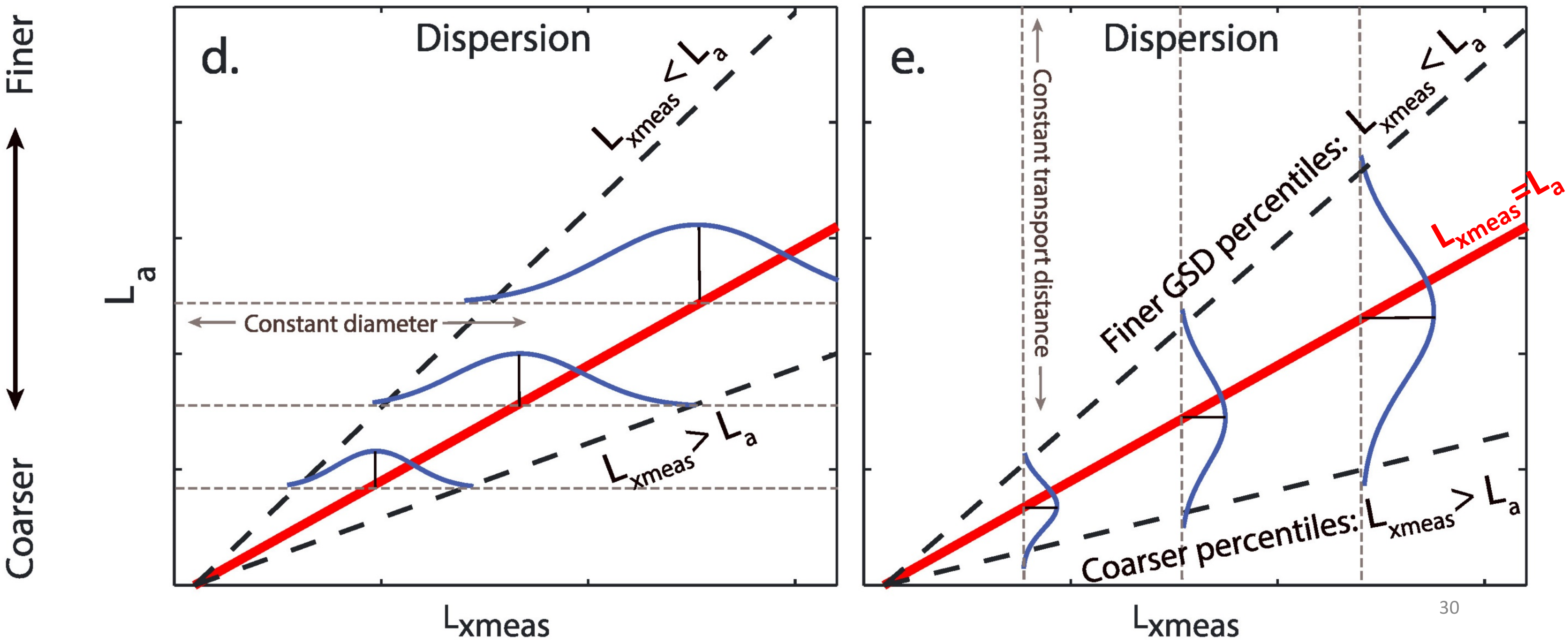


For a given grain size:

- L_a is constant
- Dispersion causes distribution of transport distances (L_{xmeas})

Testable prediction for dispersion:

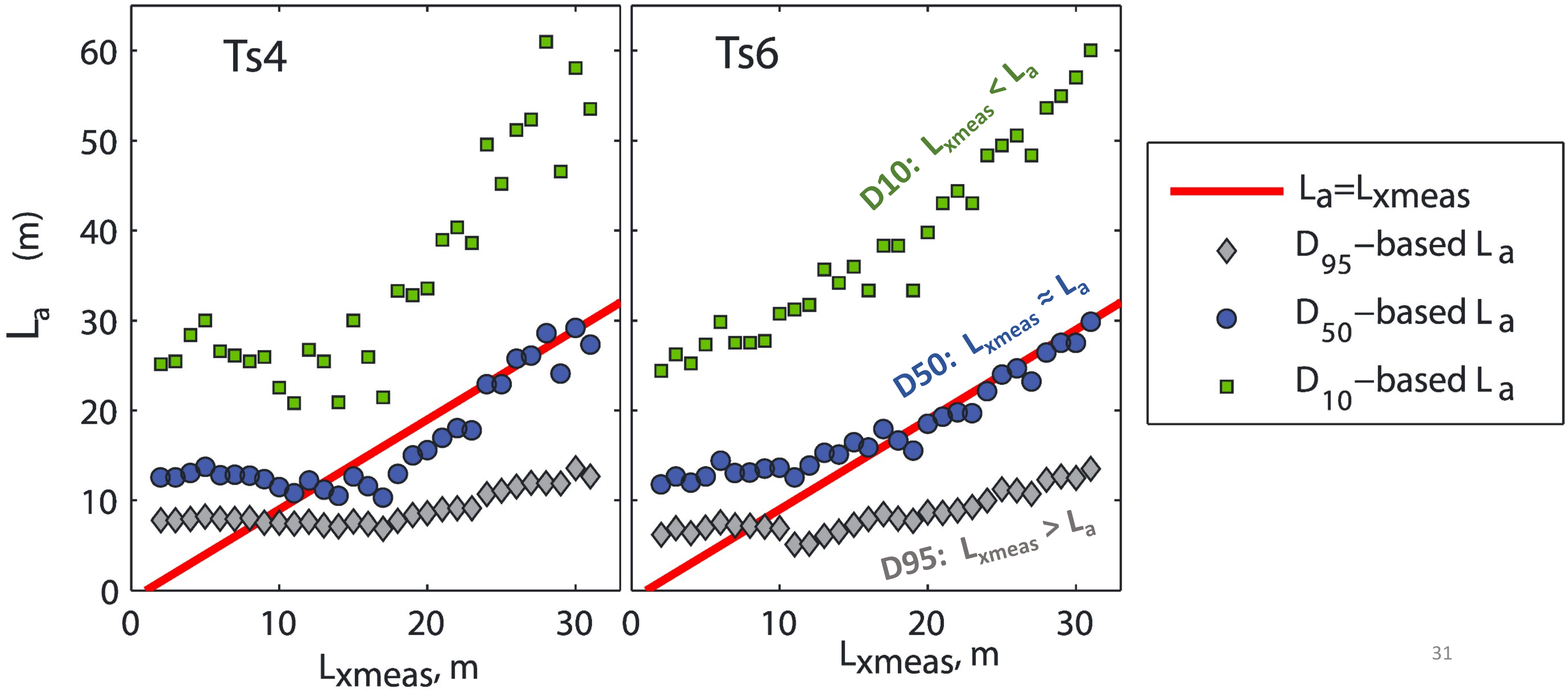
- Finer GSD percentiles: $L_{xmeas} < L_a$
- Coarser GSD percentiles: $L_{xmeas} > L_a$
- Intermediate percentiles: $L_{xmeas} = L_a$



Experimental data follows expected pattern for dispersion:

- Finer GSD percentiles: $L_{xmeas} < L_a$
- Coarser GSD percentiles: $L_{xmeas} > L_a$
- Intermediate percentiles: $L_{xmeas} \approx L_a$

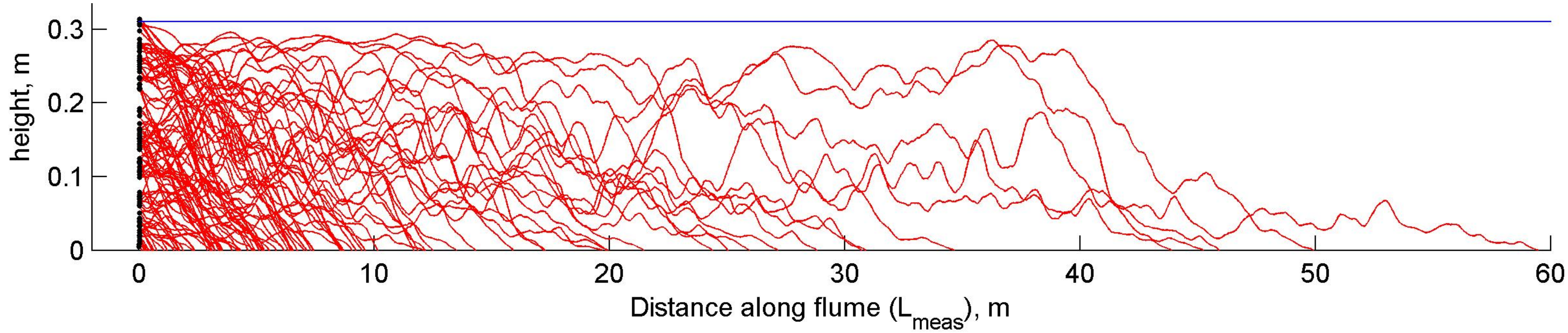
$$L_a = \frac{Uh}{w_{ssw}}$$

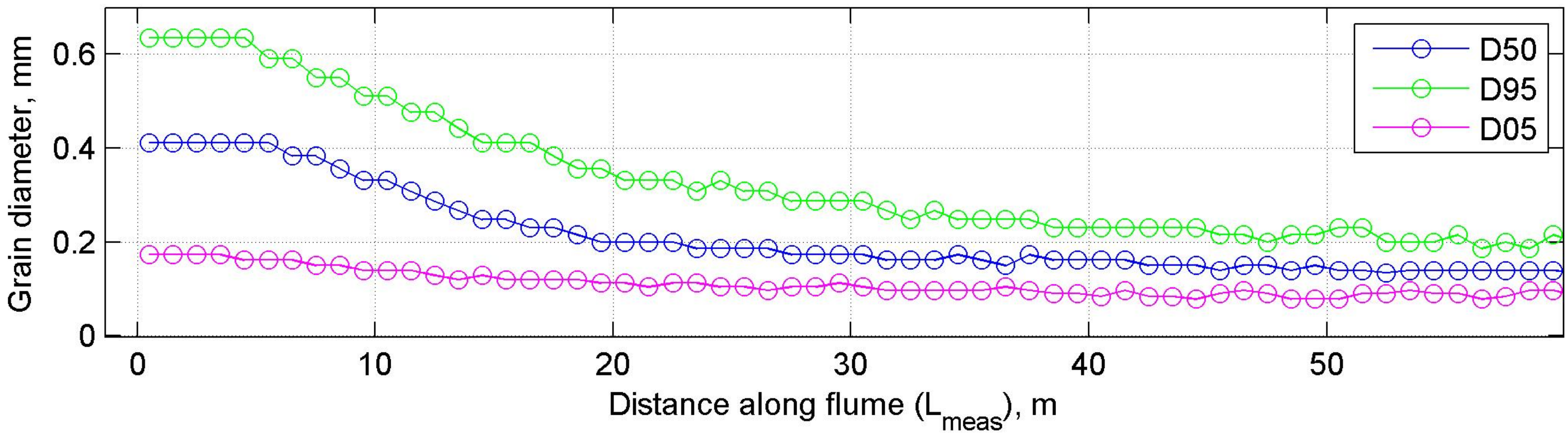


Future work: Compare expts to particle tracking model

w/ Mariela Perignon, Brandon McElroy, Suleyman Naqshband, Cristian Escauriaza

- Inverse model sensitivity to resuspension? Bed load? Turbulent damping?





Conclusions:

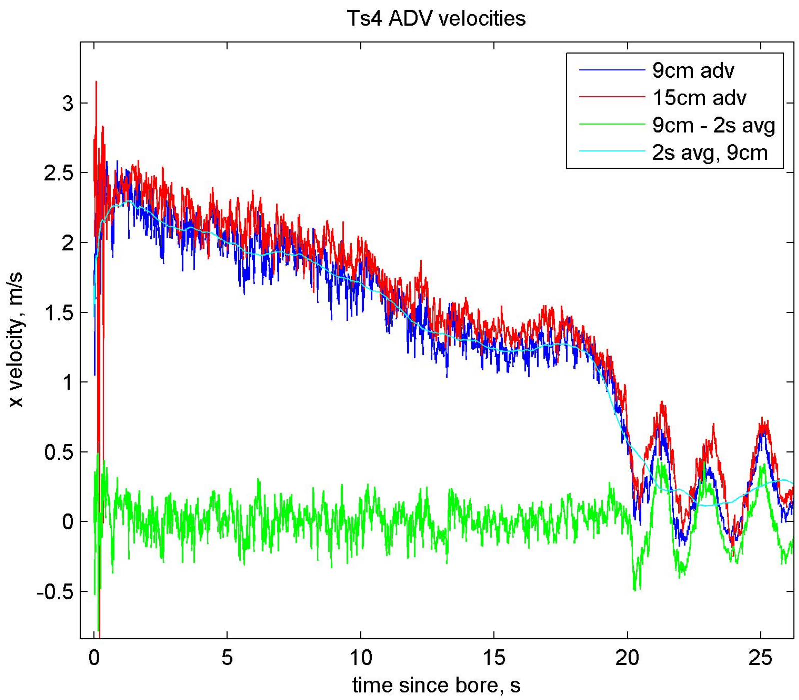
- Tsunami sediment transport experiments work great! Flow & sediment scaling.
- Benchmark/Validation data set for model evaluation (Tang and Weiss, 2016, arXiv)—use me!
- Leaving dispersion out of advection-settling models was an oversimplification of the physics of transport and sorting.
- Transport ≥ 1 advection length scale is required for deposit GSD to reflect flow depth and velocity, rather than source GSD.
- Dispersion preferentially affects deposit GSD tails.

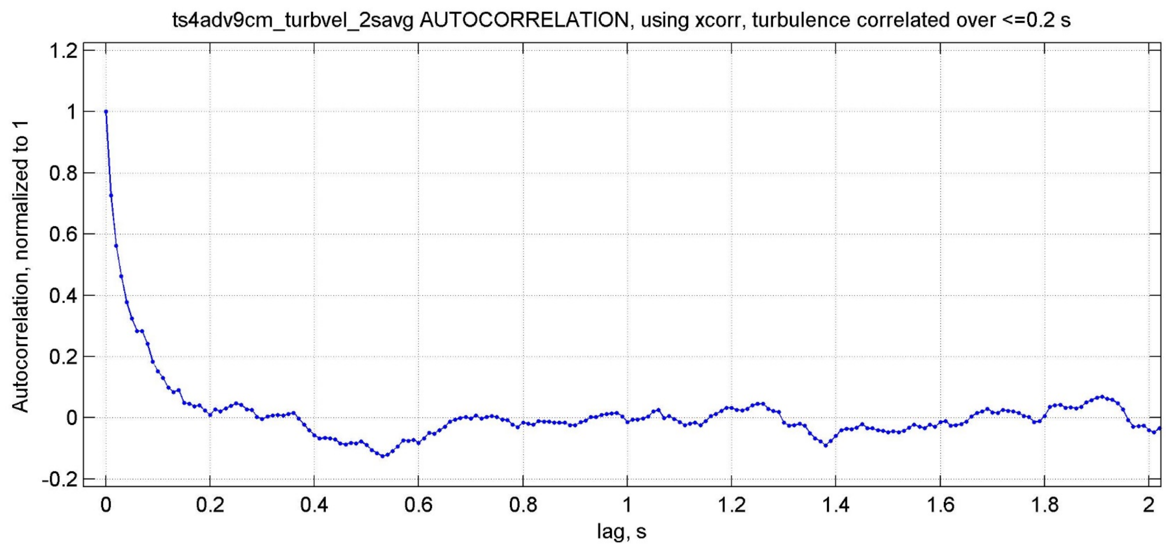
Funding: ACS PRF   NSF   ESI REU Program   TEXAS

Thanks to Shannon Boesch, Peter Polito, Jim Buttles.

Experimental tsunami turbulence: from expt Ts4. Autocorrelation (using xcorr) shows <=0.2 s correlation.

--Turbulence velocities come from subtracting out 2 s moving avg from the velocity record (left plot).
1 stdev of the turbulence is 0.1174 m/s for 0-18 s, 0.1061 m/s for 2-18 s (removing bore), calling it 0.11 m/s avg to use for modeling.
Mean velocity 1.72 m/s for 9 cm depth, 1.85 m/s for 15 cm depth, calling it 1.75 m/s avg x vel.



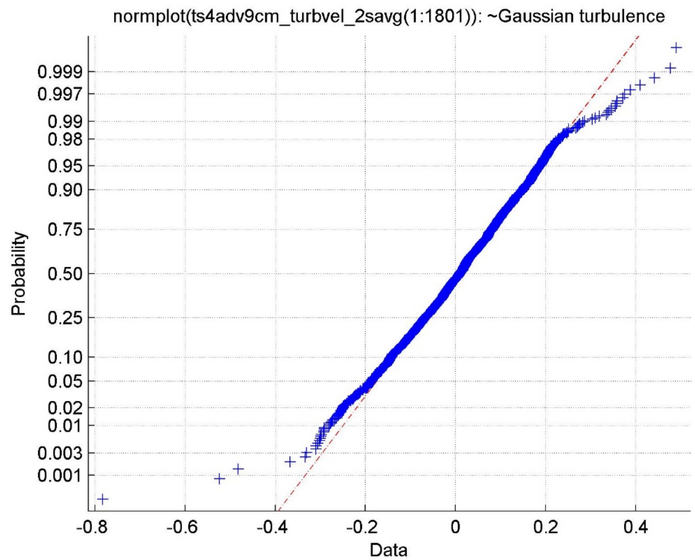


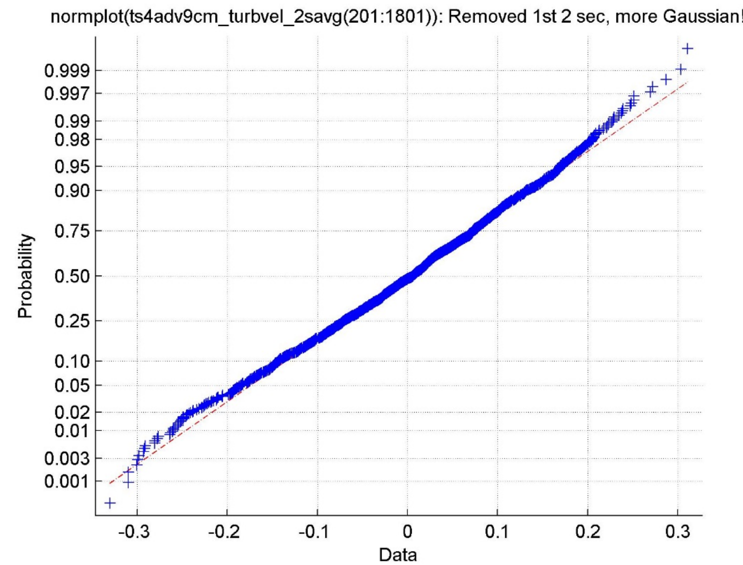
Normplots—red line is a Gaussian.

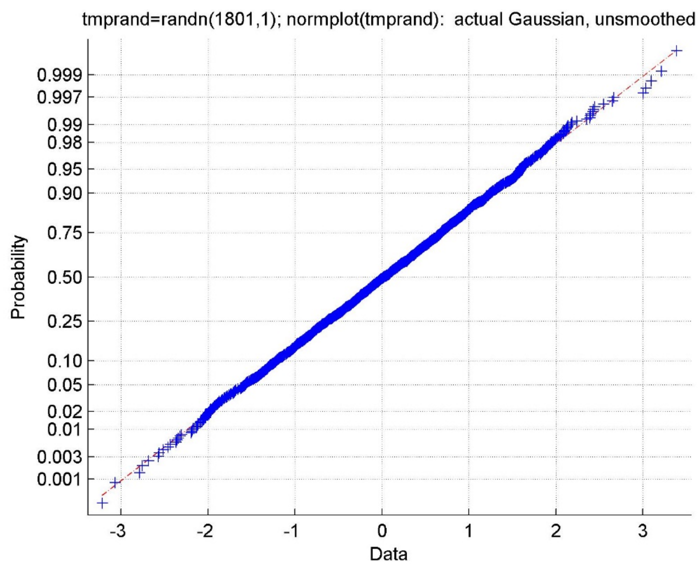
TOP ROW: experimental

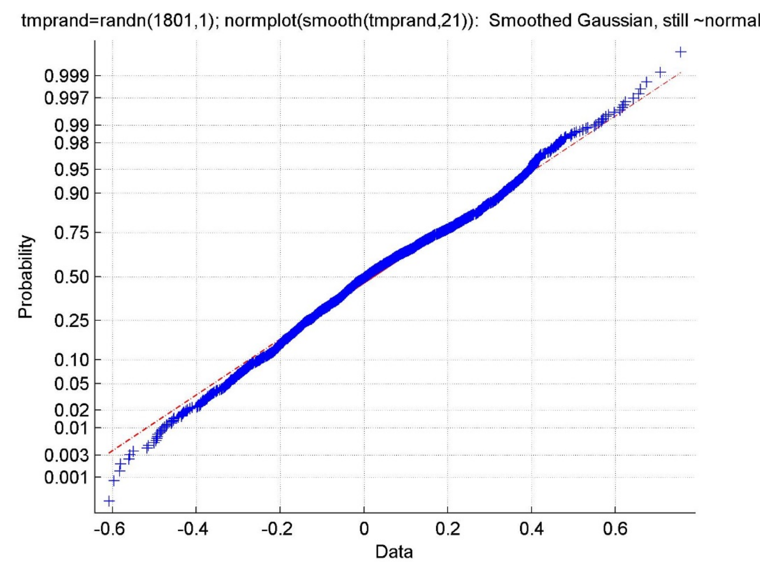
BOTTOM ROW: Gaussian, and smoothed Gaussian (smoothed over 21 pts, about same correlation as in experimental autocorrelation).

Point is that the experimental data are sufficiently Gaussian to justify using a smoothed Gaussian distribution as my synthetic turbulence timeseries.







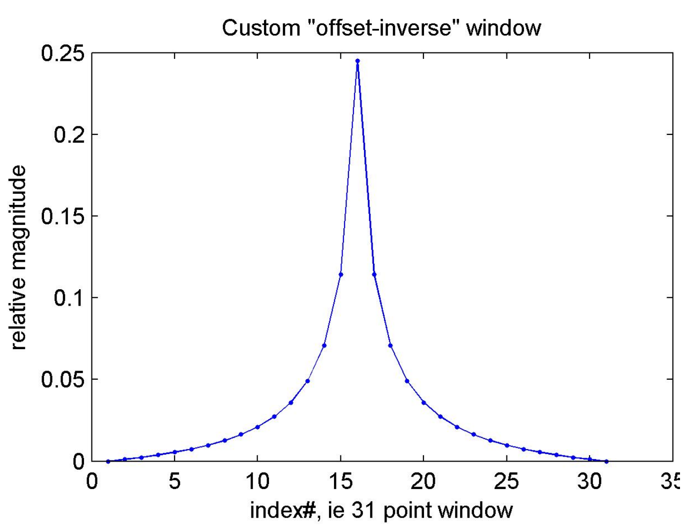


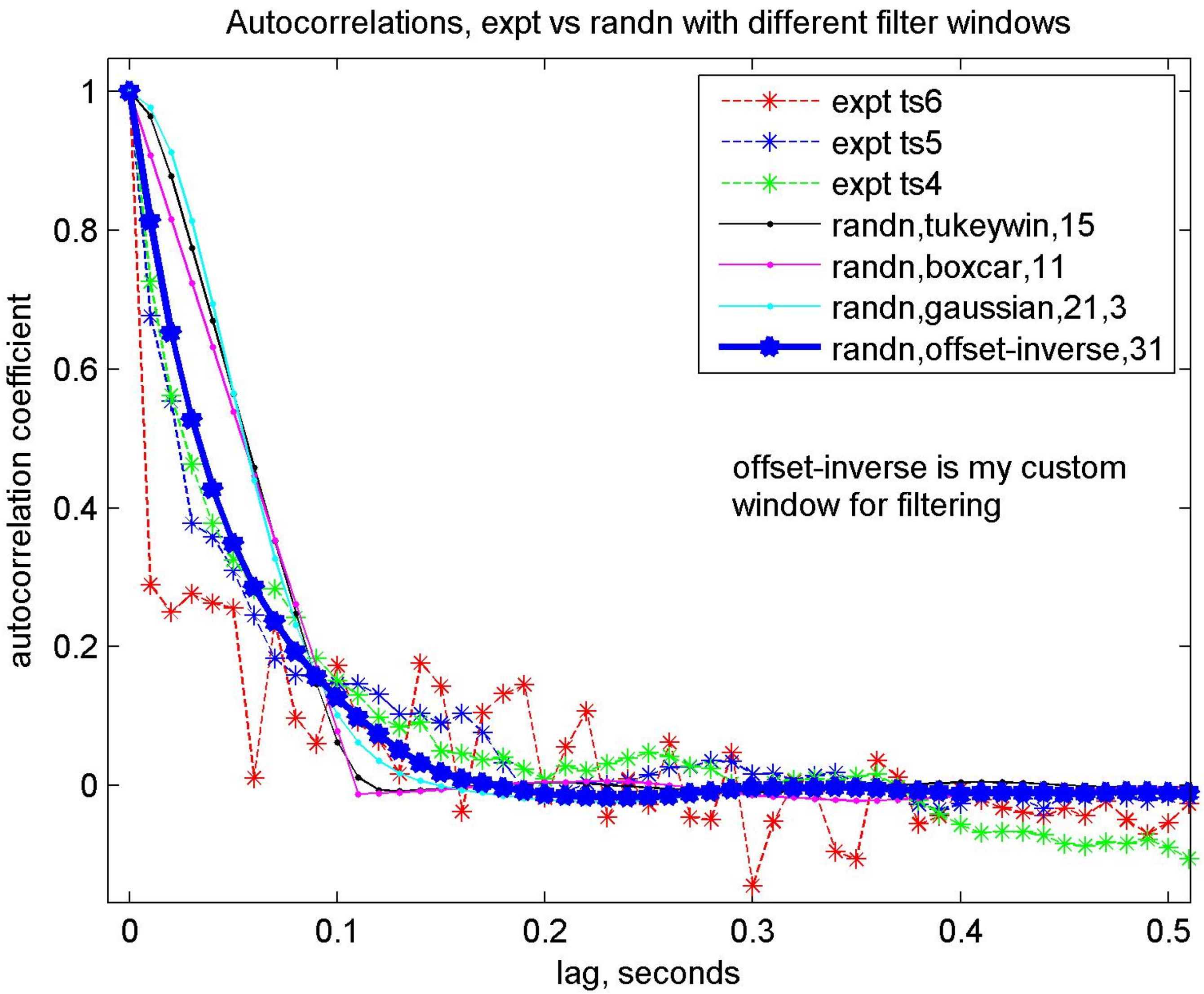
Comparing different filters to try and approximate shape of autocorrelation dropoff of experimental data.

I made one that works pretty well!
My name—offset-inverse window:

```
>> w=1./(1:16);
>> w=([fliplr(w) w(2:16)]);
>> w=w-w(31);
>> w=w./sum(w);
```

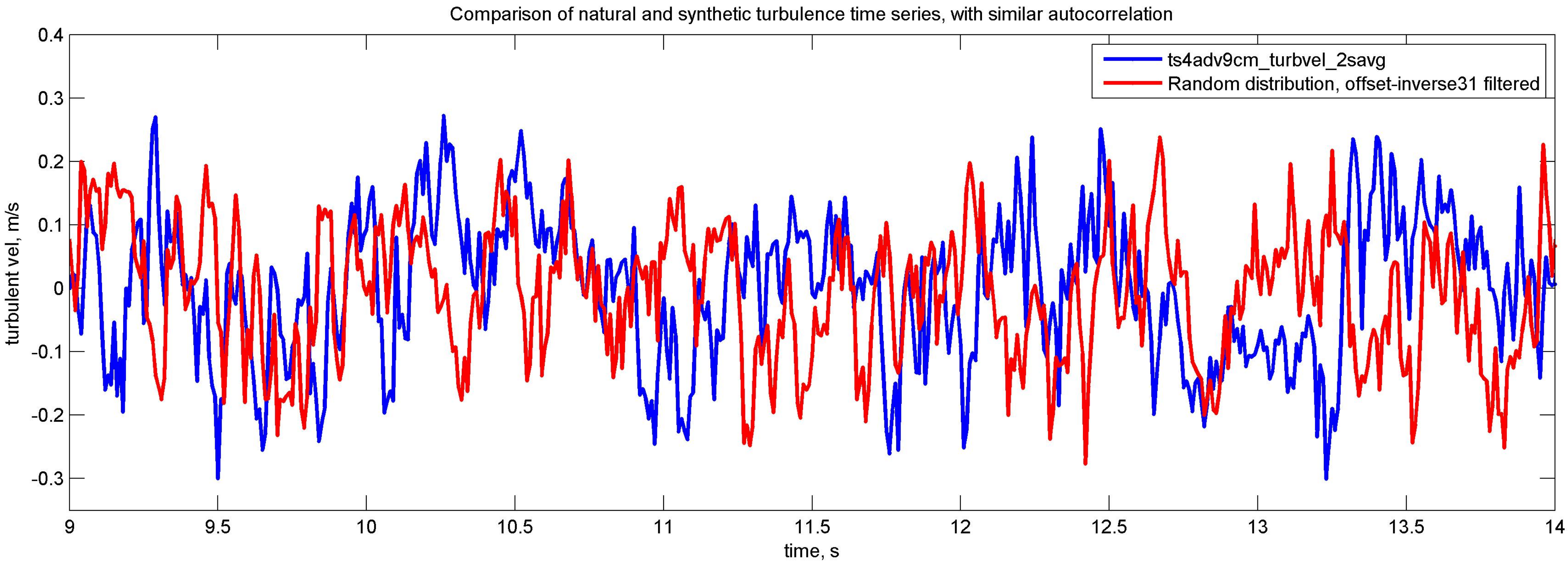
This gives a 31 entry long filtering window, Offset to zero at boundaries (so really 29 entries long included in the averaging).





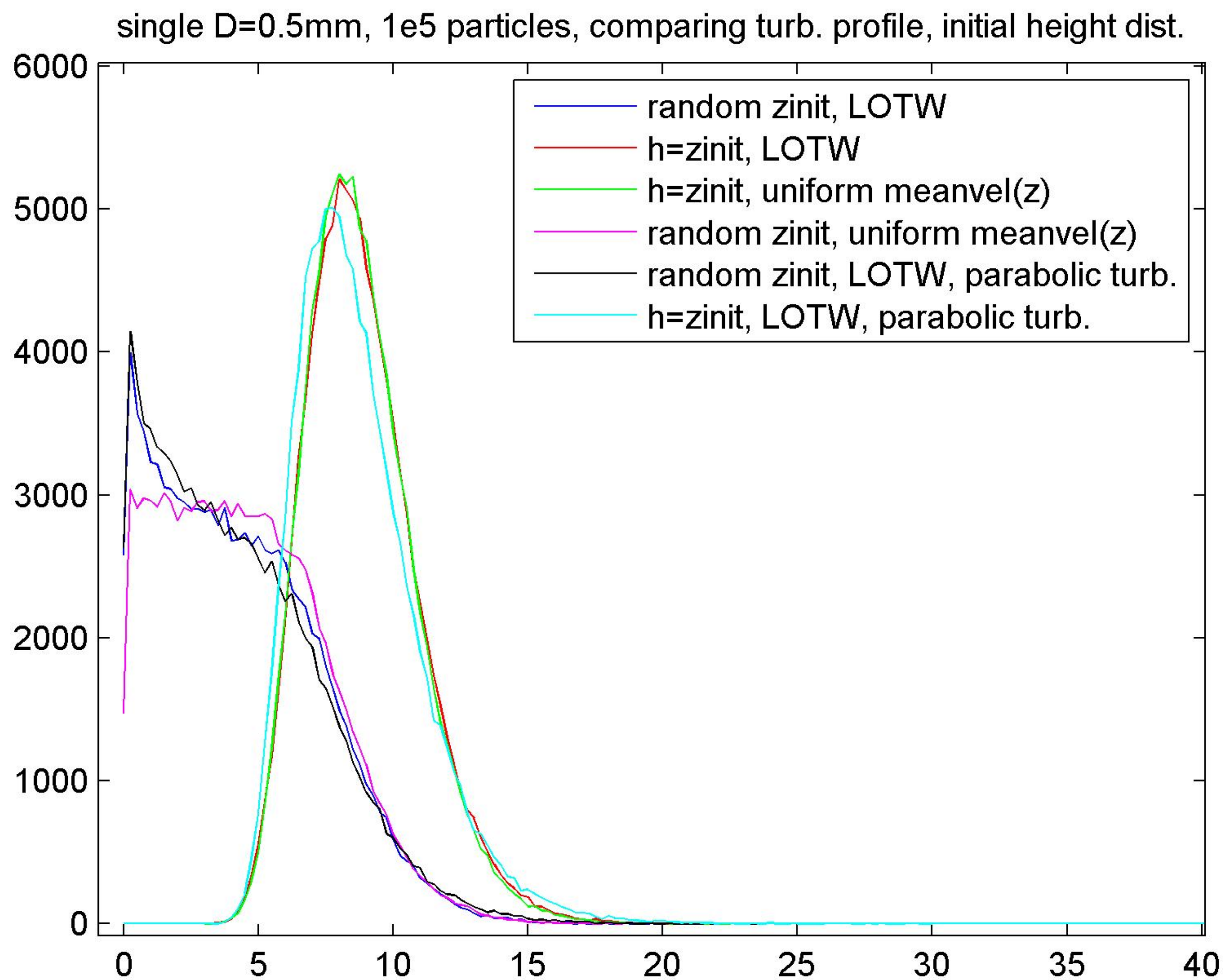
Closeup of 5 seconds of turbulence (x direction) from expt 4, calculated using a 2 s smoothing window subtracted to remove avg vel trend.

Red line is my synthetic turbulence, randn, filtered using custom offset-inverse window of length 31 points. Std offset to be same for both signals.



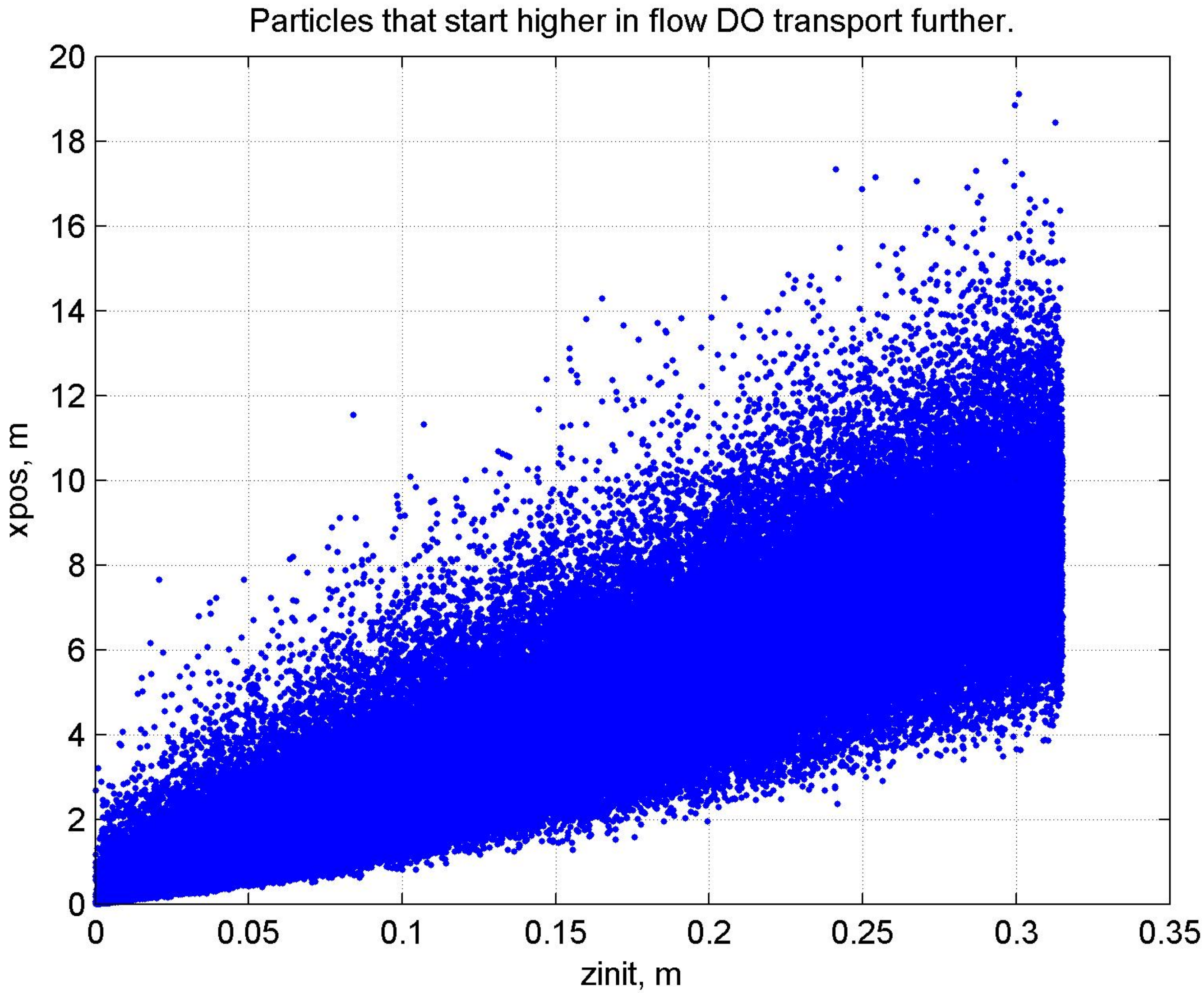
Particles released from top of flow vs uniformly distributed throughout flow: makes a big difference to the distribution.

Vertical distribution of mean velocity, and vertical distribution of turbulence, make measurable but much smaller differences.

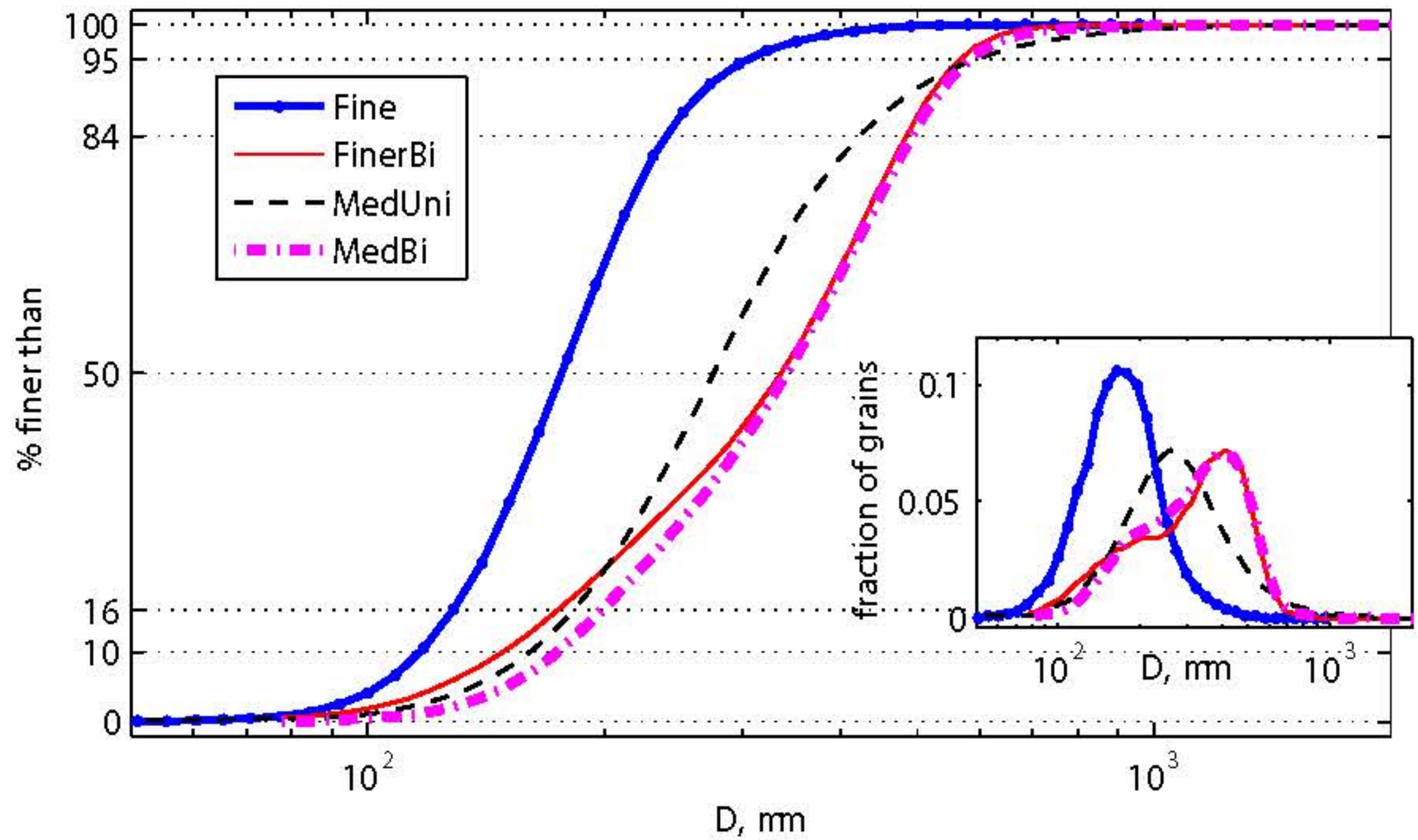


The initial height of a particle in the flow at x=0 DOES has a big influence on the transport distance before settling to bed.

You see dispersion.

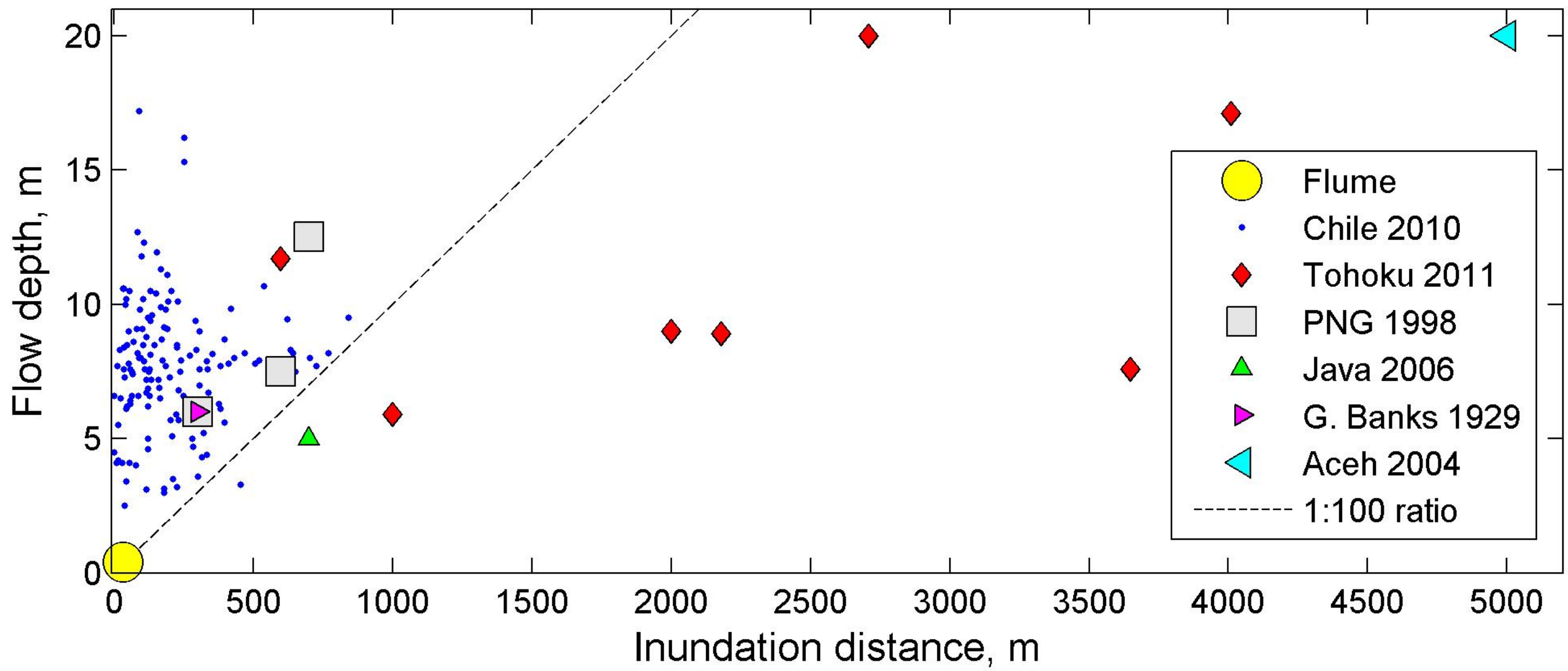


Four Experimental Source Grain Size Distributions



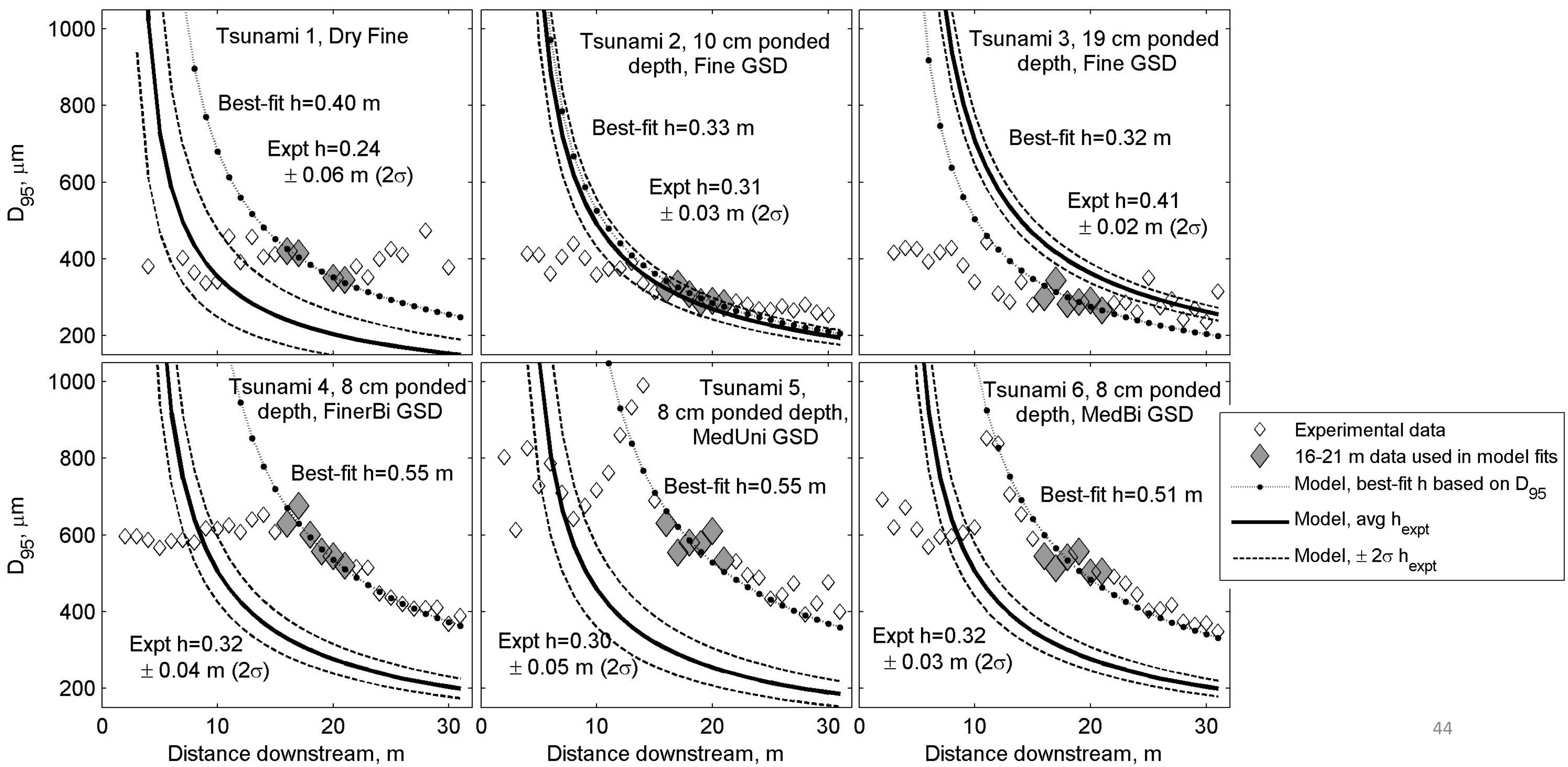
Source GSD	D_{10}	D_{50}	D_{84}	D_{95}
	µm	µm	µm	µm
Fine	116	176	240	304
FinerBi	148	336	484	565
MedUni	166	285	422	612
MedBi	174	341	492	580

Field and experimental geometric scaling: depth, distance, duration



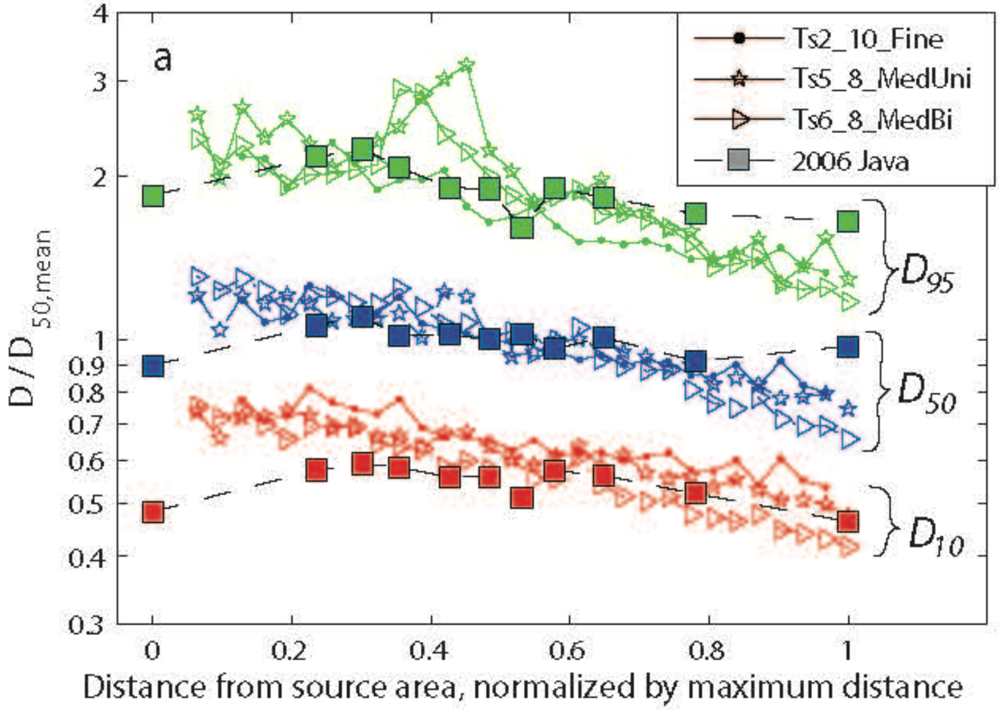
For field events 10-100 times deeper and longer: Fr similarity suggests experiments scale to durations and velocities 10^0.5 to 100^0.5 times (3-10x) larger:

- Velocities: 1.75 m/s experiment scales to 5.5-17.5 m/s field.
- Durations of flow: 15-25 s experiment scales to 50 s to 4.2 minutes field.

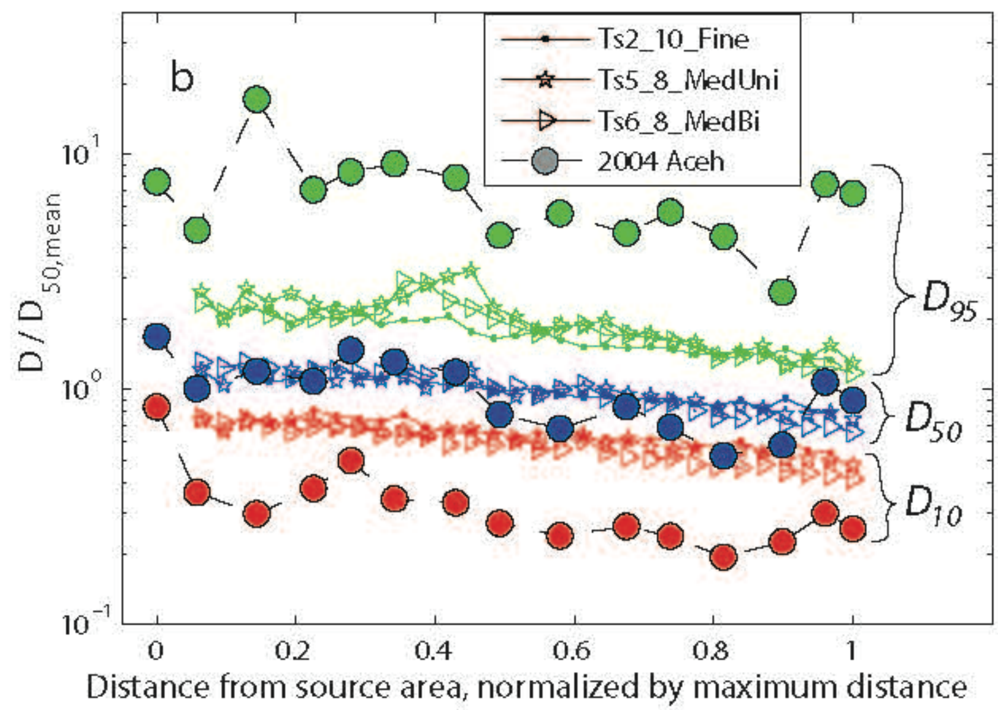

Tsunami 1, Dry Fine
Best-fit h=0.40 m
Expt h=0.24
± 0.06 m (2σ)
Tsunami 2, 10 cm ponded depth, Fine GSD
Best-fit h=0.33 m
Expt h=0.31
± 0.03 m (2σ)
Tsunami 3, 19 cm ponded depth, Fine GSD
Best-fit h=0.32 m
Expt h=0.41
± 0.02 m (2σ)
Tsunami 4, 8 cm ponded depth, FinerBi GSD
Best-fit h=0.55 m
Expt h=0.32
± 0.04 m (2σ)
Tsunami 5, 8 cm ponded depth, MedUni GSD
Best-fit h=0.55 m
Expt h=0.30
± 0.05 m (2σ)
Tsunami 6, 8 cm ponded depth, MedBi GSD
Best-fit h=0.51 m
Expt h=0.32
± 0.03 m (2σ)
D_{95}, μm
Distance downstream, m
Experimental data
16-21 m data used in model fits
Model, best-fit h based on D_{95}
Model, avg h_{expt}
Model, ± 2σ h_{expt}

Comparing normalized experimental and field grain size trends

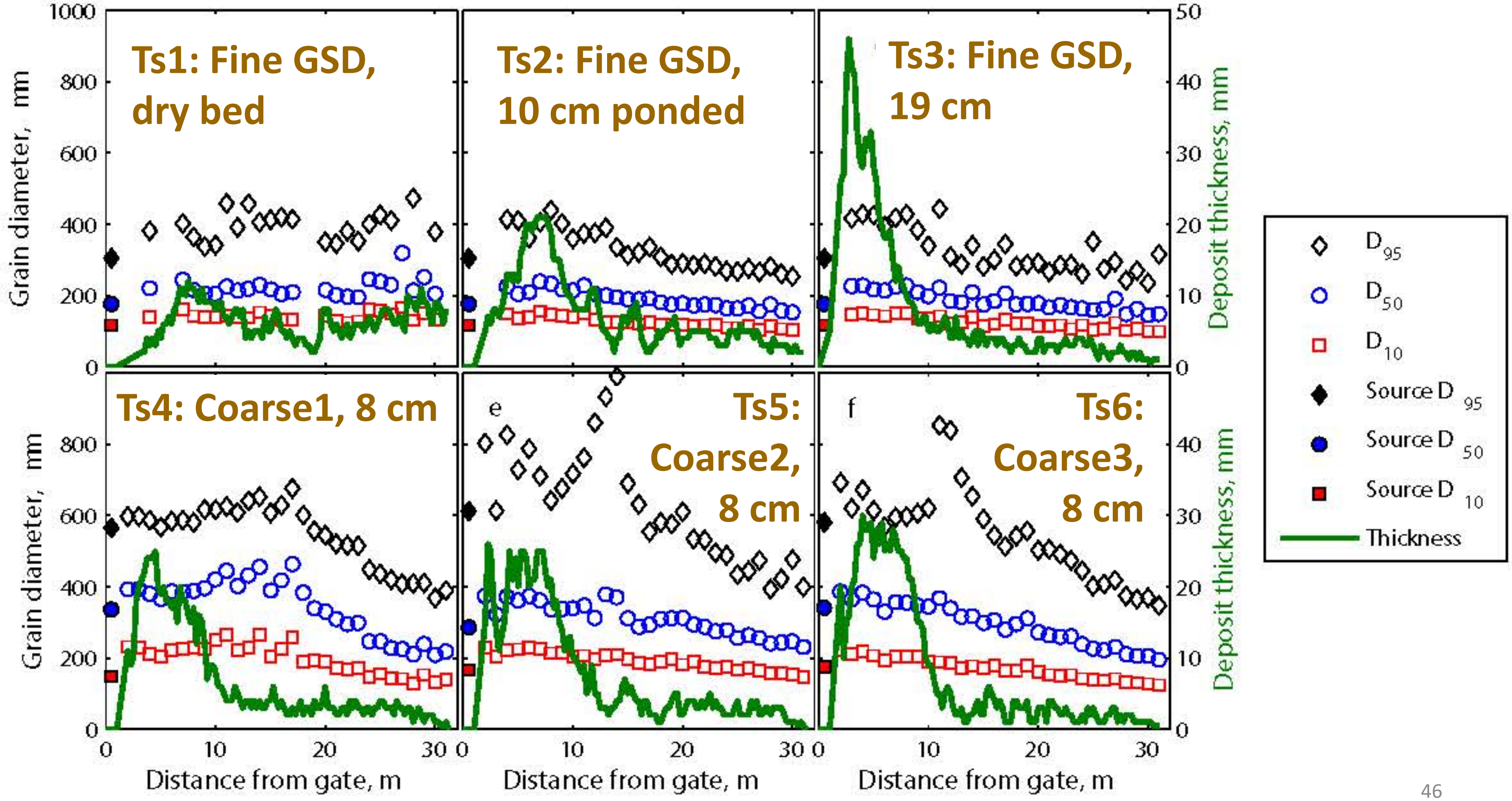
2006 Java (Moore et al., 2011)

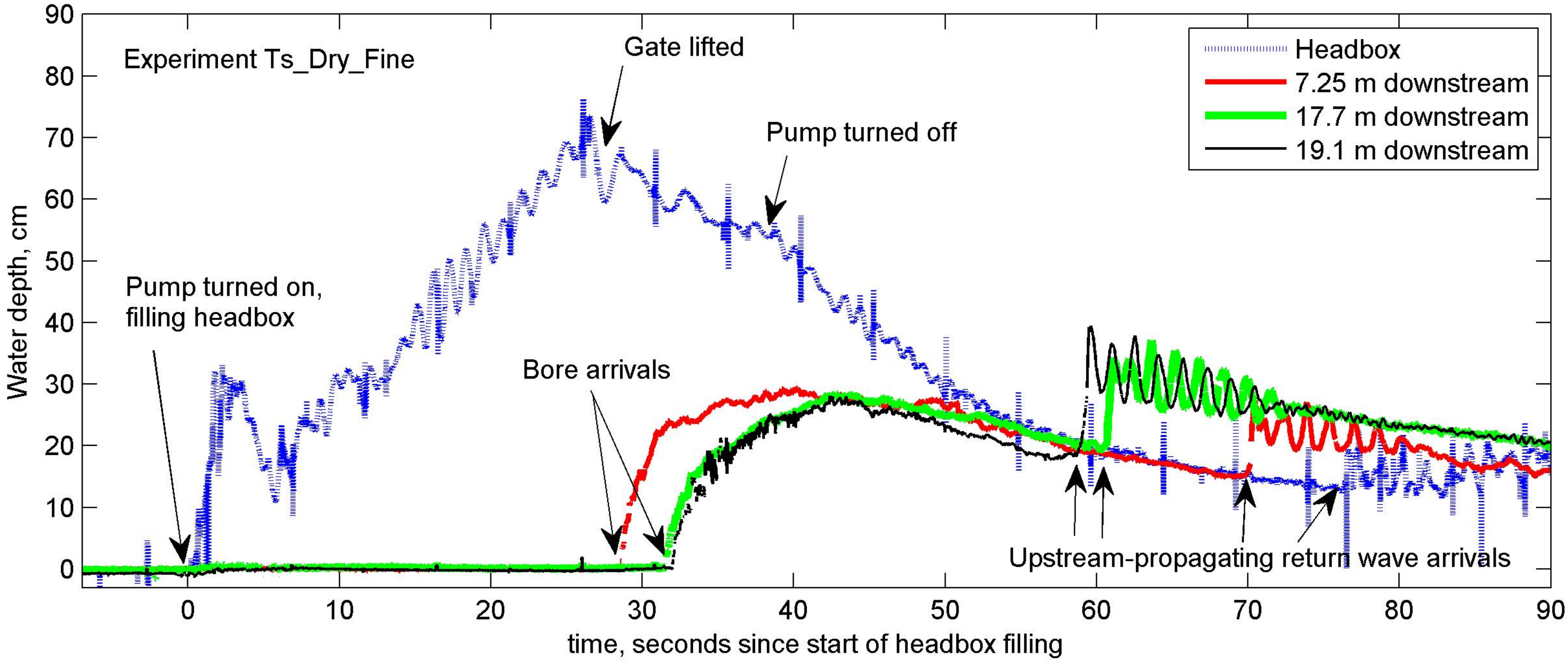


2004 Aceh (Moore et al., 2006)



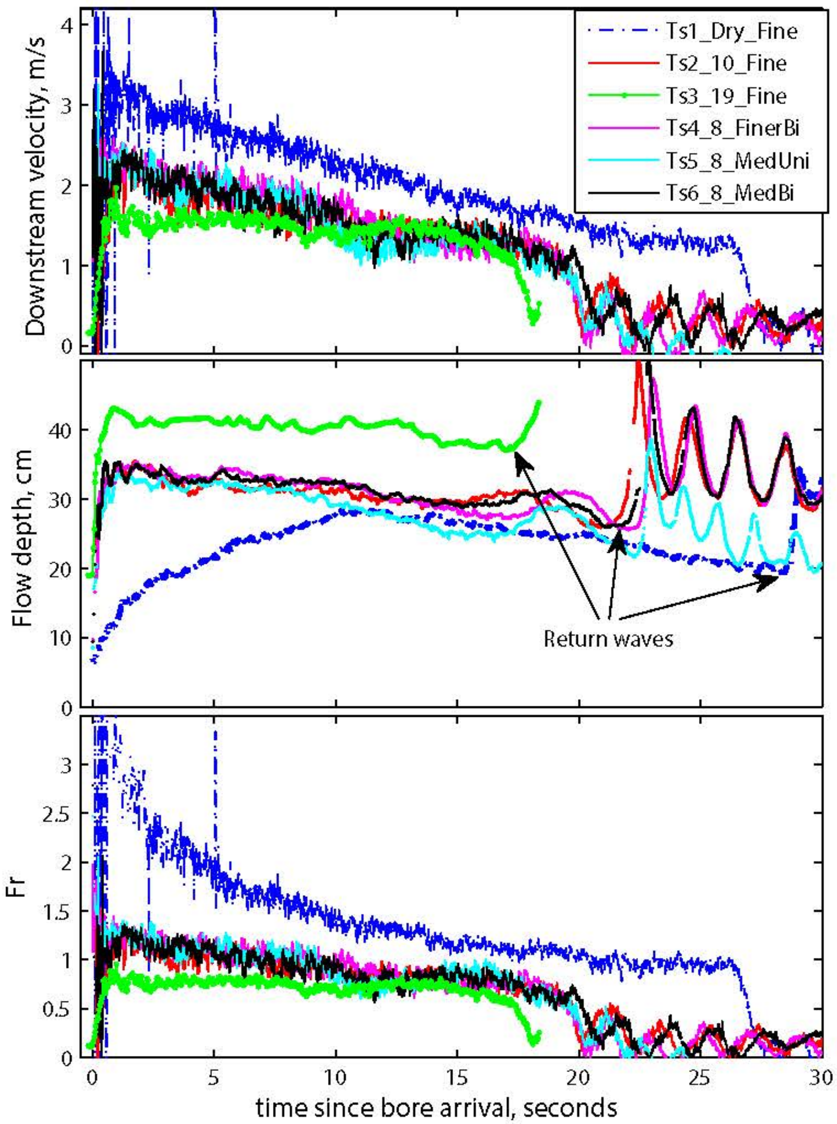
Deposit: downstream *thinning* and *fining*





Experiment Ts_Dry_Fine
Gate lifted
Pump turned off
Pump turned on,
filling headbox
Bore arrivals
Upstream-propagating return wave arrivals
Headbox
7.25 m downstream
17.7 m downstream
19.1 m downstream
Water depth, cm
time, seconds since start of headbox filling
0
10
20
30
40
50
60
70
80
90

Experiment # and name	Ponded water depth	Source GSD	Bore velocity	Water velocity, avg. ± 1 σ	Flow depth, maximum	Flow depth, avg. ± 1 σ	Fr, avg. ± 1 σ
	cm		m/s	m/s	cm	cm	
1, Ts1_Dry_Fine	0	Fine	3.04	2.07 ± 0.57	28.5	24.1 ± 3.2	1.38 ± 0.44
2, Ts2_10_Fine	10	Fine	2.65	1.71 ± 0.24	35.5	31.3 ± 1.5	0.95 ± 0.12
3, Ts3_19_Fine	19	Fine	3.03	1.44 ± 0.12	43.1	40.5 ± 1.2	0.74 ± 0.05
4, Ts4_8_FinerBi	8	FinerBi	2.84	1.84 ± 0.36	34.6	32.0 ± 2.0	1.0 ± 0.20
5, Ts5_8_MedUni	8	MedUni	3.00	1.75 ±0.38	33.7	29.7 ± 2.6	0.98 ± 0.18
6, Ts6_8_MedBi	8	MedBi	2.98	1.70 ±0.31	35.4	32.0 ±1.6	0.96 ± 0.16



Downstream velocity, m/s
Ts1_Dry_Fine
Ts2_10_Fine
Ts3_19_Fine
Ts4_8_FinerBi
Ts5_8_MedUni
Ts6_8_MedBi
Flow depth, cm
Return waves
Fr
time since bore arrival, seconds

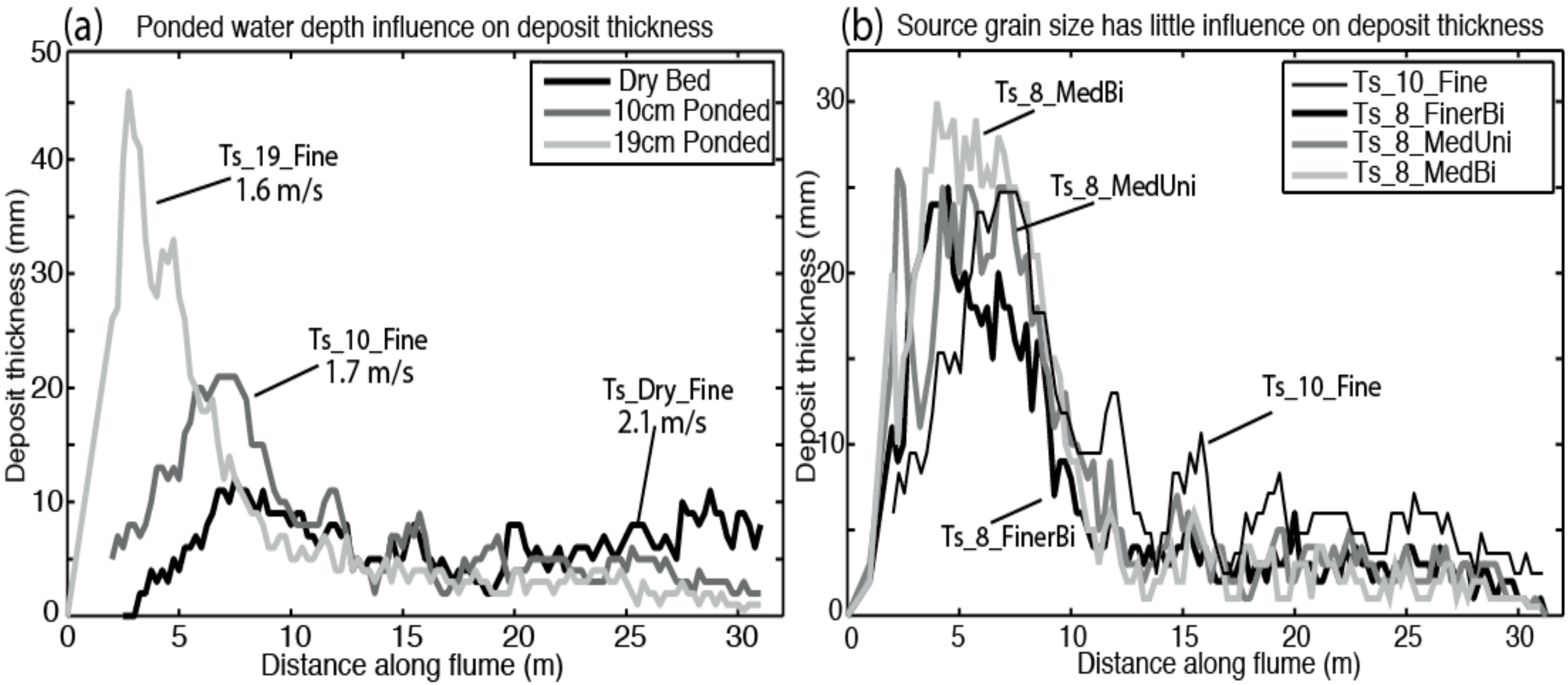

(a) Ponded water depth influence on deposit thickness
Dry Bed
10cm Ponded
19cm Ponded
Ts_19_Fine
1.6 m/s
Ts_10_Fine
1.7 m/s
Ts_Dry_Fine
2.1 m/s
Deposit thickness (mm)
Distance along flume (m)
(b) Source grain size has little influence on deposit thickness
Ts_10_Fine
Ts_8_FinerBi
Ts_8_MedUni
Ts_8_MedBi
Ts_8_MedBi
Ts_8_MedUni
Ts_10_Fine
Ts_8_FinerBi
Deposit thickness (mm)
Distance along flume (m)

Figure 1

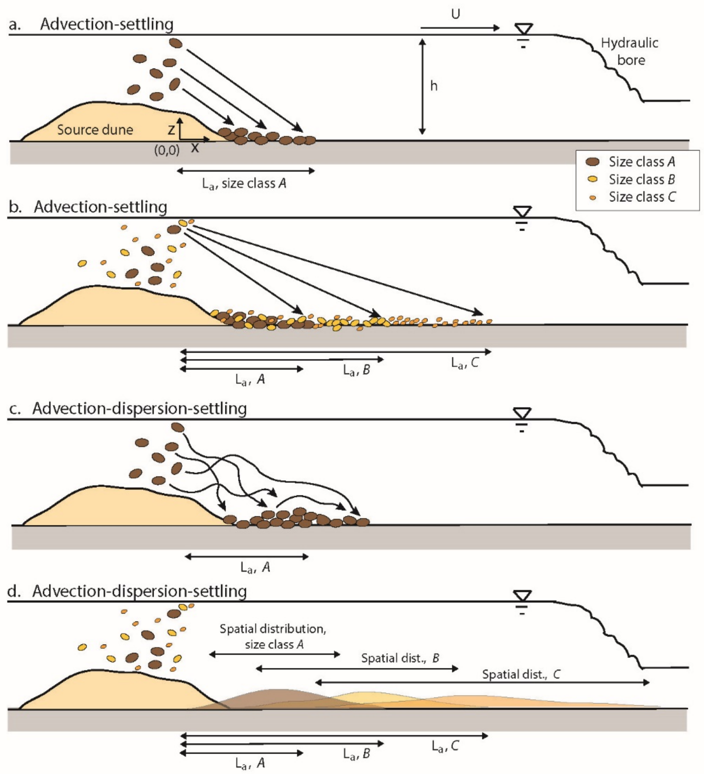
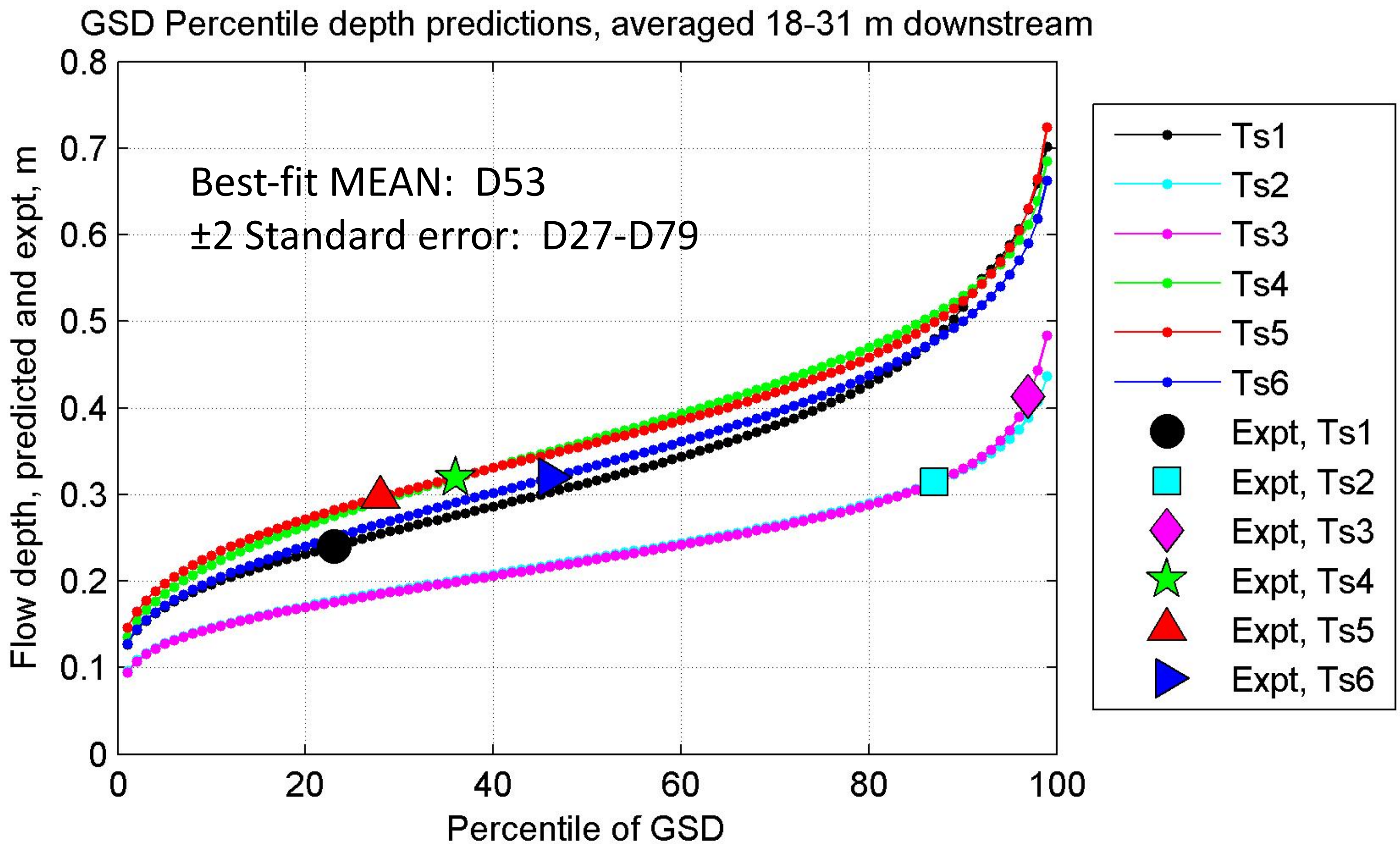
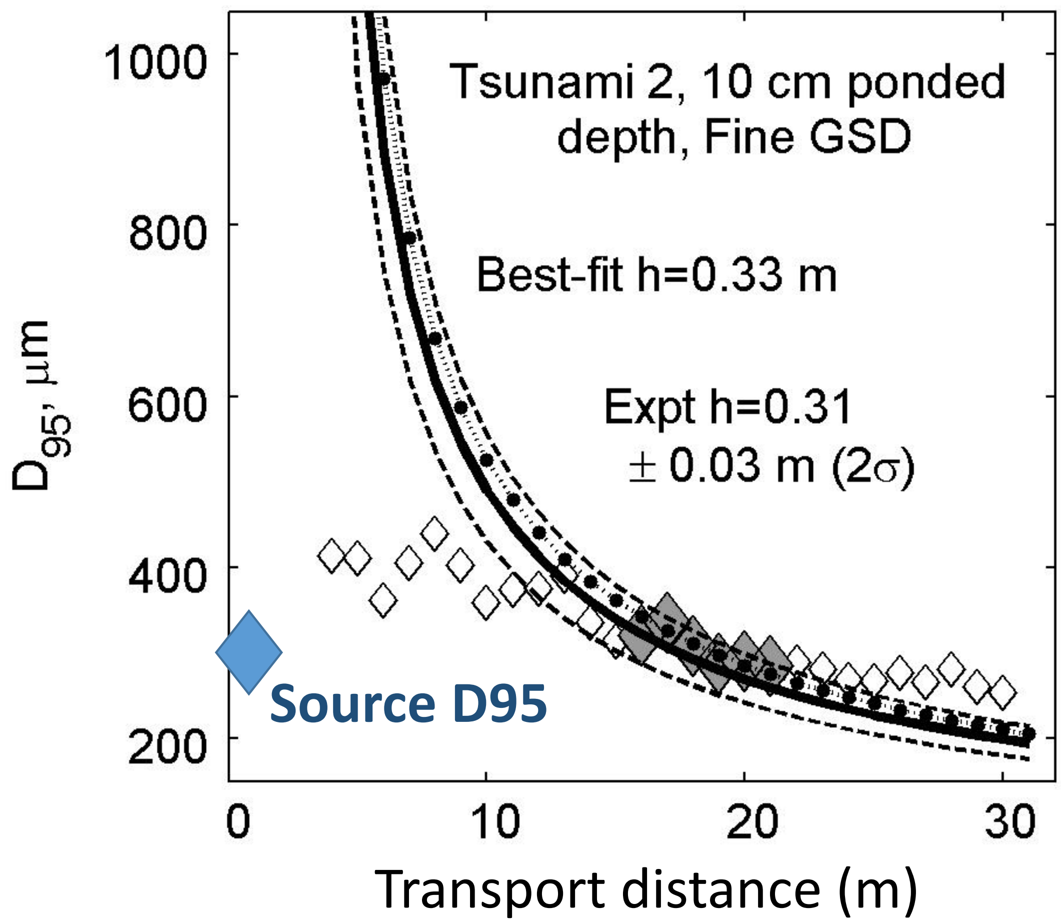


Figure 1. Conceptual illustration of underlying model assumptions. a, b. The advection--settling model proposed by Woodruff et al. (2008). c, d. A modified conceptual understanding that includes turbulent dispersion of grains, in addition to advection and settling.

Advection-Settling Model: What percentile best predicts flow depth?



Advection-Settling Model fits to Deposit **D95**



Experiment Ts2:

- Fine source GSD.
- Downstream: **D95** predicts flow depth, velocity well.

- Upstream: Model predicts grain size should be MUCH larger.
    - At short transport distances, ***source*** **GSD** limits deposit GSD.