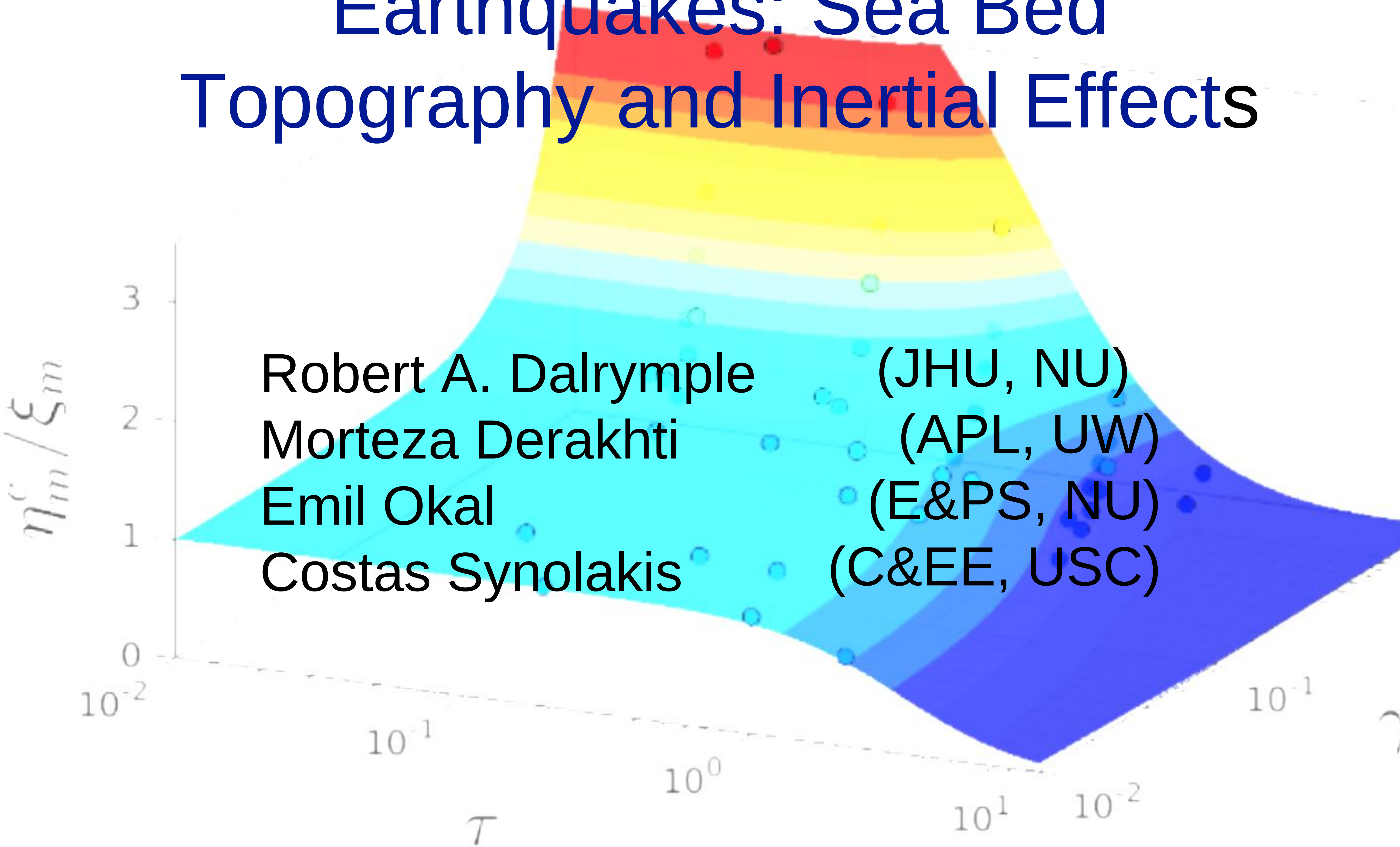
Tsunami Generation by Earthquakes: Sea Bed Topography and Inertial Effects



Robert A. Dalrymple (JHU, NU)
Morteza Derakhti (APL, UW)
Emil Okal (E&PS, NU)
Costas Synolakis (C&EE, USC)

Genesis of the Paper

Bus ride with Costas Synolakis at the 35th ICCE in Turkey.

Purpose: Originally, to examine the effect of shape of bottom displacement on the initial water surface displacement.

Later, to examine the importance of fluid inertia over the source area and possible ballistic behavior of the water.

Initial Surface Displacement

Most tsunami propagation models assume that the surface displacement is the same as the bottom displacement, although it is known that it must be different (e.g., Kajiura, 1963; Saito and Furumura, 2009)

If rate of displacement is slow, then no response of the free surface.

GPUSPH 4.1

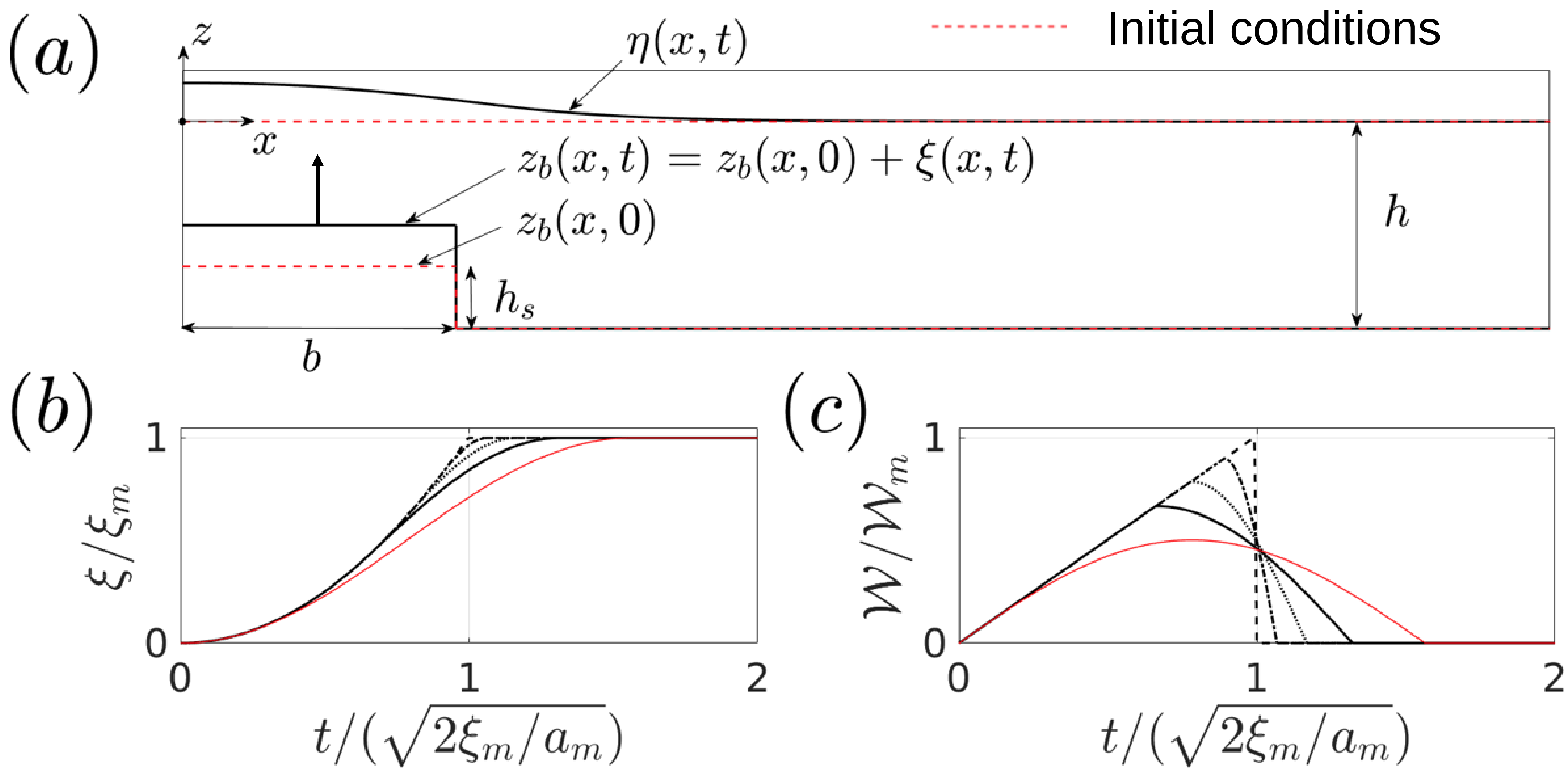
www.gpusph.org

Weakly compressible SPH (single/multi-fluid)
SPS viscosity, k-epsilon
Homogeneous accuracy (Hérault et al., 2014)
CUDA C++
Multi-node, multi-GPU
Project Chrono (moving bodies)

(50 particles over the depth; actual sound speed)

NVIDIA

Simple Piston Bottom Motion, $0 < t < t_r$



Bottom Displacement

Bottom Velocity

$$\xi_1 = \begin{cases} \frac{1}{2}a_m t^2 & 0 < t \le t_0 \\ \frac{1}{2}a_m t_0^2\left[1 + \frac{4\epsilon}{\pi}\sin\frac{\pi(t-t_0)}{2\epsilon t_0}\right] & t_0 < t \le t_r, \end{cases}$$

$\mathcal{W}_m = a_m t_0$

a_m constant acceleration

$$t_0 = \sqrt{2\xi_m/\left[a_m(1+4\epsilon/\pi)\right]}$$

$$\xi_2 = \frac{1}{2}\xi_m\left[1 - \cos\frac{\pi t}{t_r}\right] \qquad 0 < t \le t_r$$

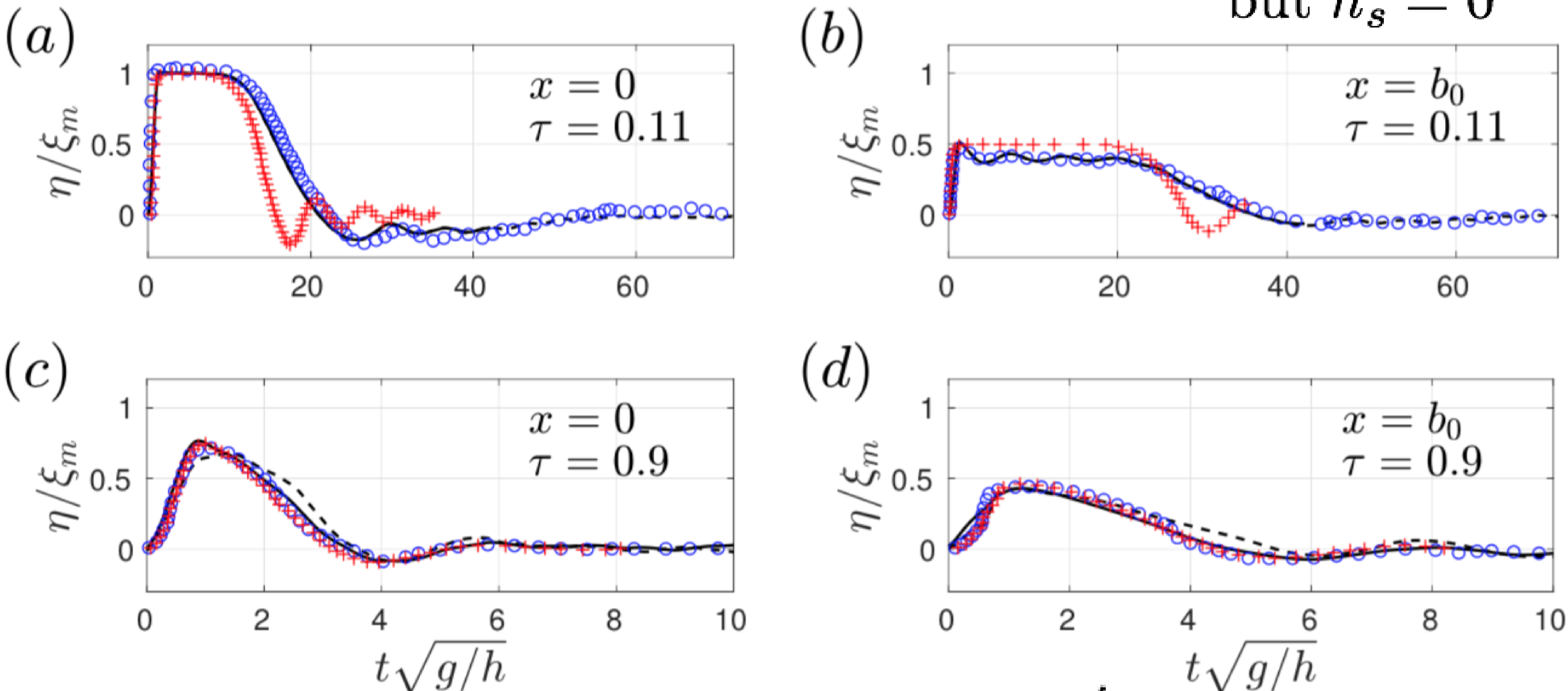
$$\mathcal{W}_m = \pi\xi_m/(2t_r)$$

Red (solid) lines correspond to Hammack (1973) experiment

Comparison to Experiments

(a) and (b) Impulsive Uplift: small $\tau = \frac{t_r}{t_c}$, $t_c = b/\sqrt{g(h - h_s)}$

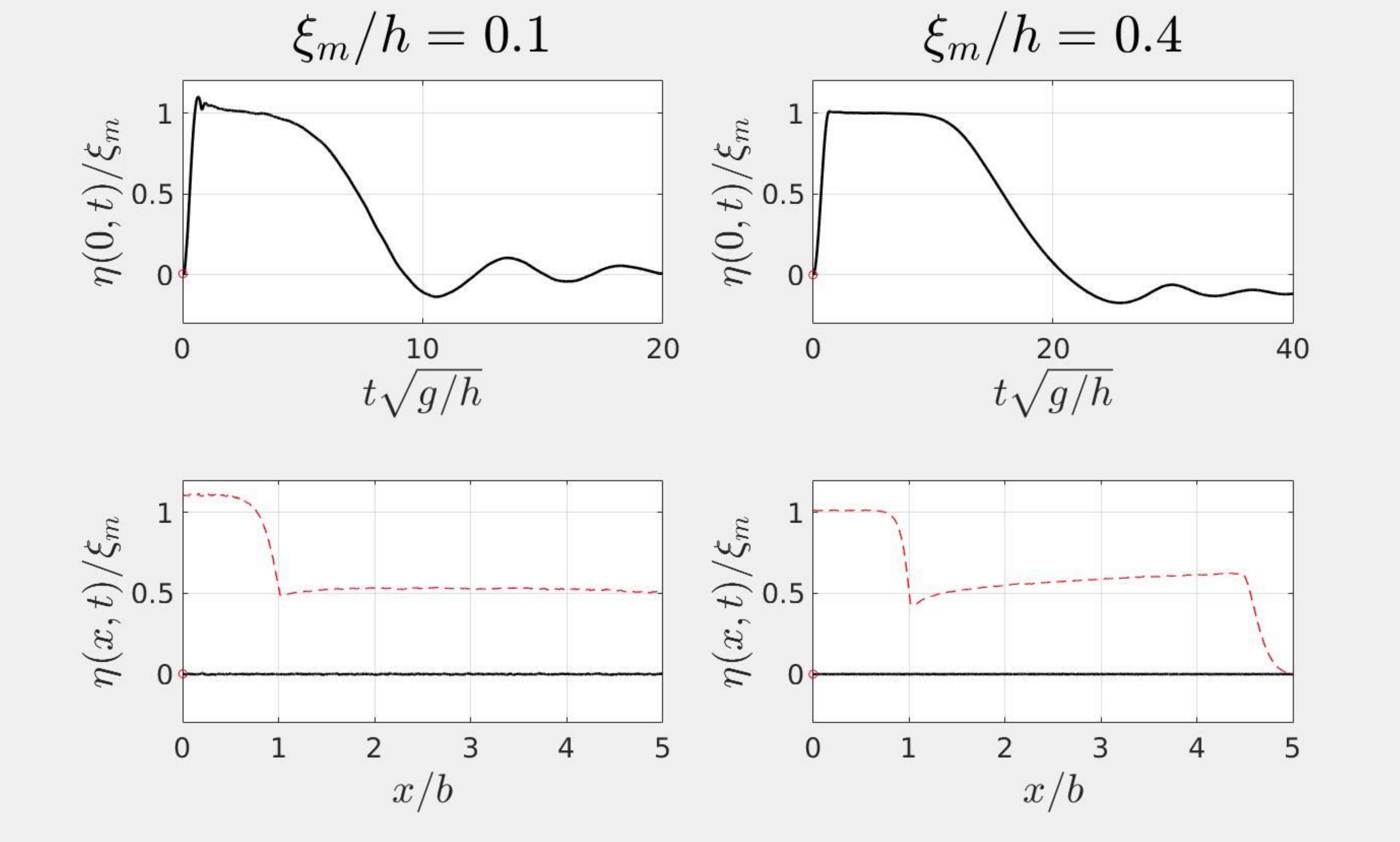
but $h_s = 0$



(c) and (d) Transitional Uplift: larger $\tau = \frac{t_r}{t_c}$

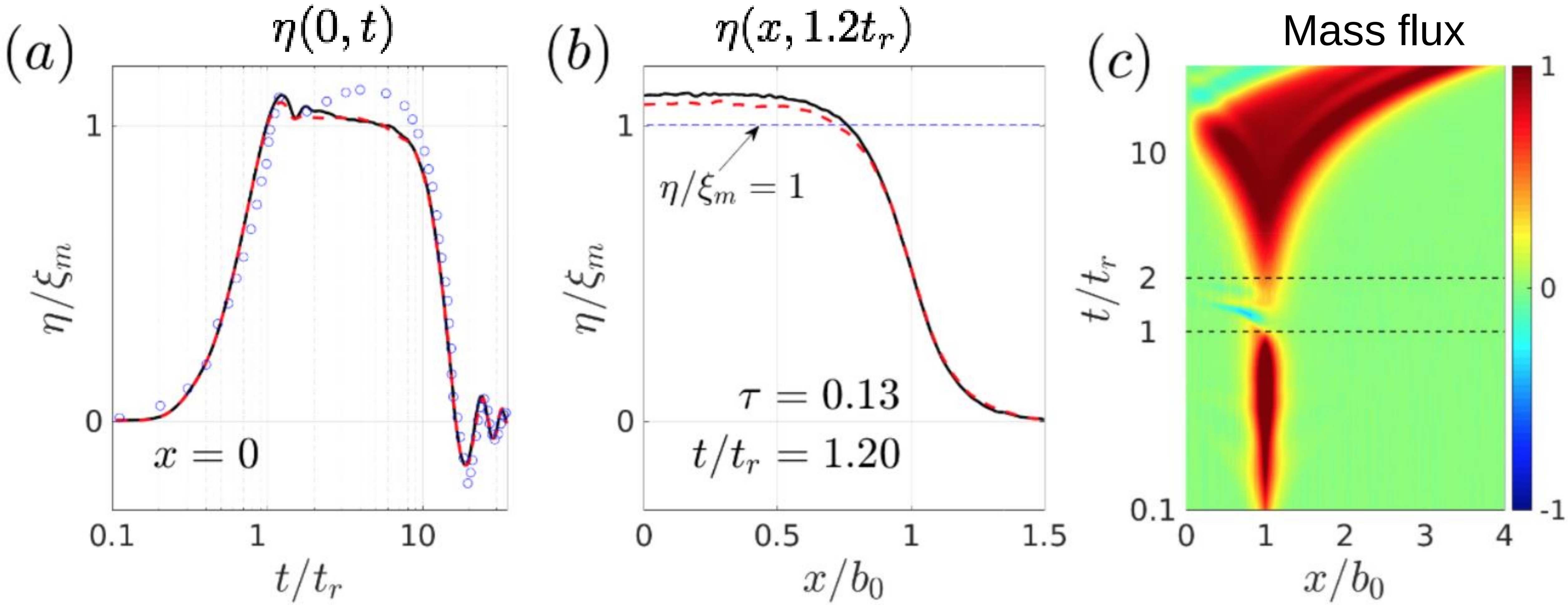
Hammack (1973): linear theory; Hammack (1973): lab data

Impulsive cases: small & large amplitude



$\tau = 0.13$ $\tau = 0.11$

Water Surface Overshoot, $\eta(0)/\xi_m > 1$



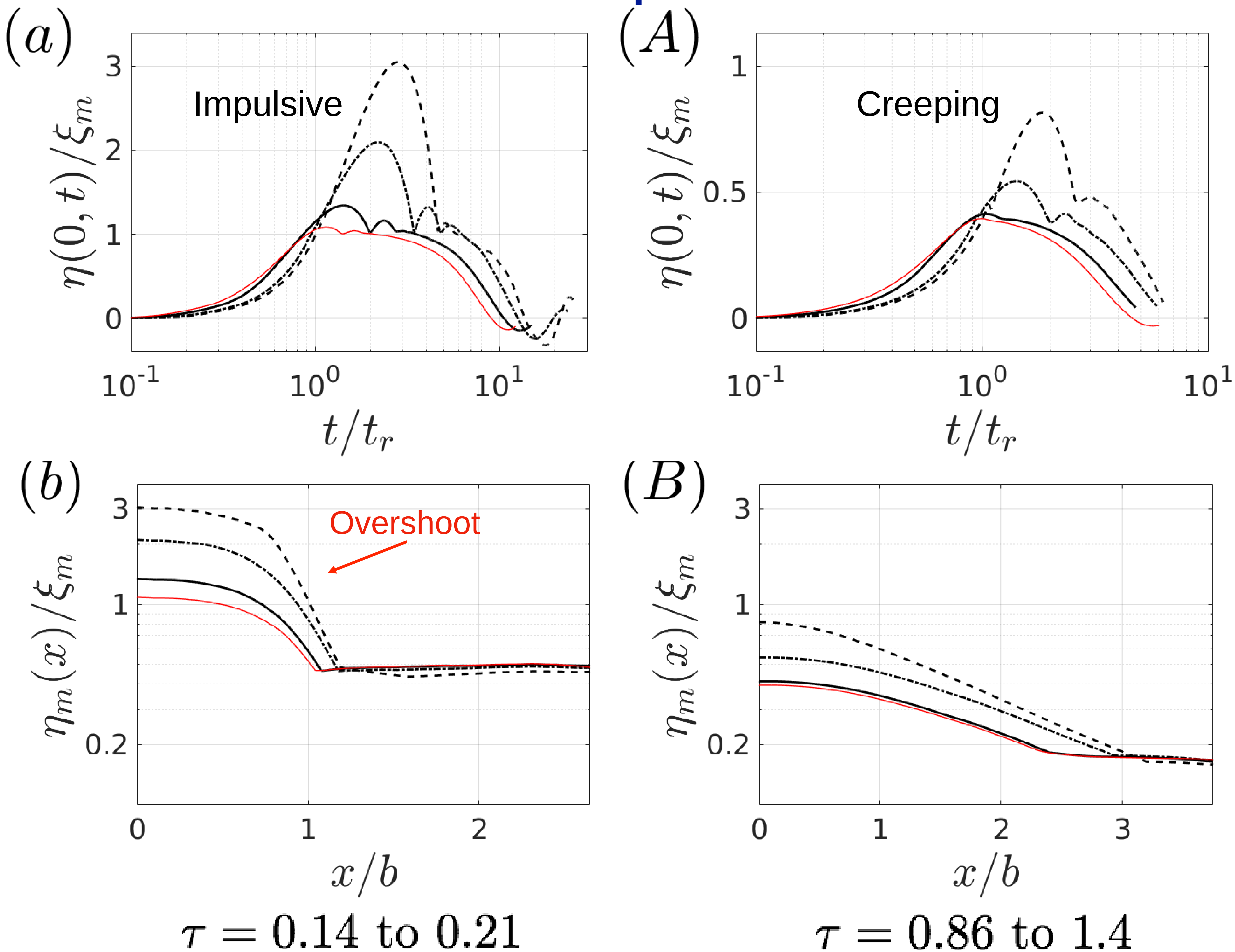
Suction at edge of uplift zone for mass conservation

Data from Hammack (1973)

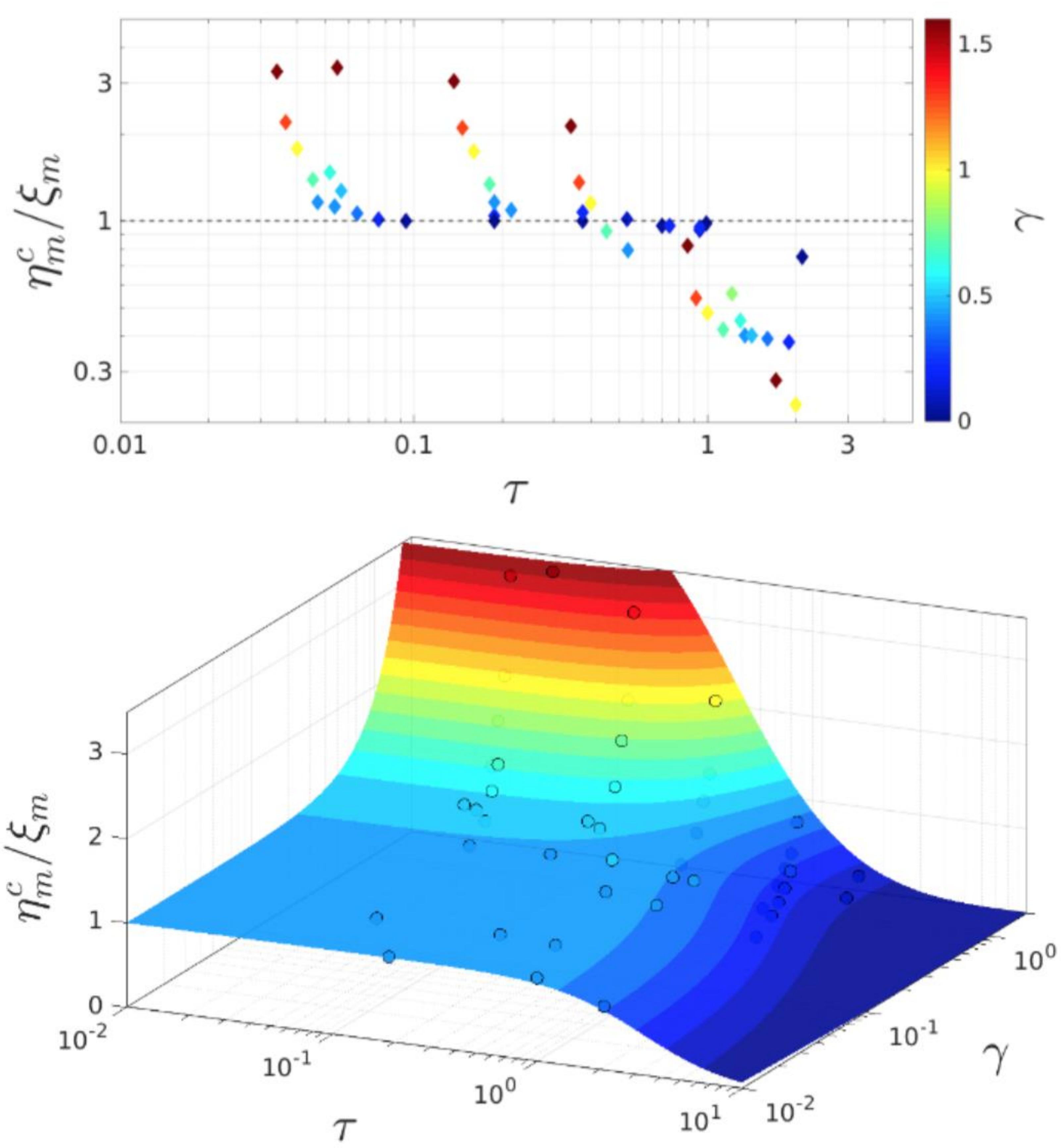
Black line: $\Delta p = 0.01h$

Red dashes: $\Delta p = 0.02h$

Surface Displacements



Max Water Surface Displacement vs Rise Time, t_r



η_m^c displacement

ξ_m max displacement

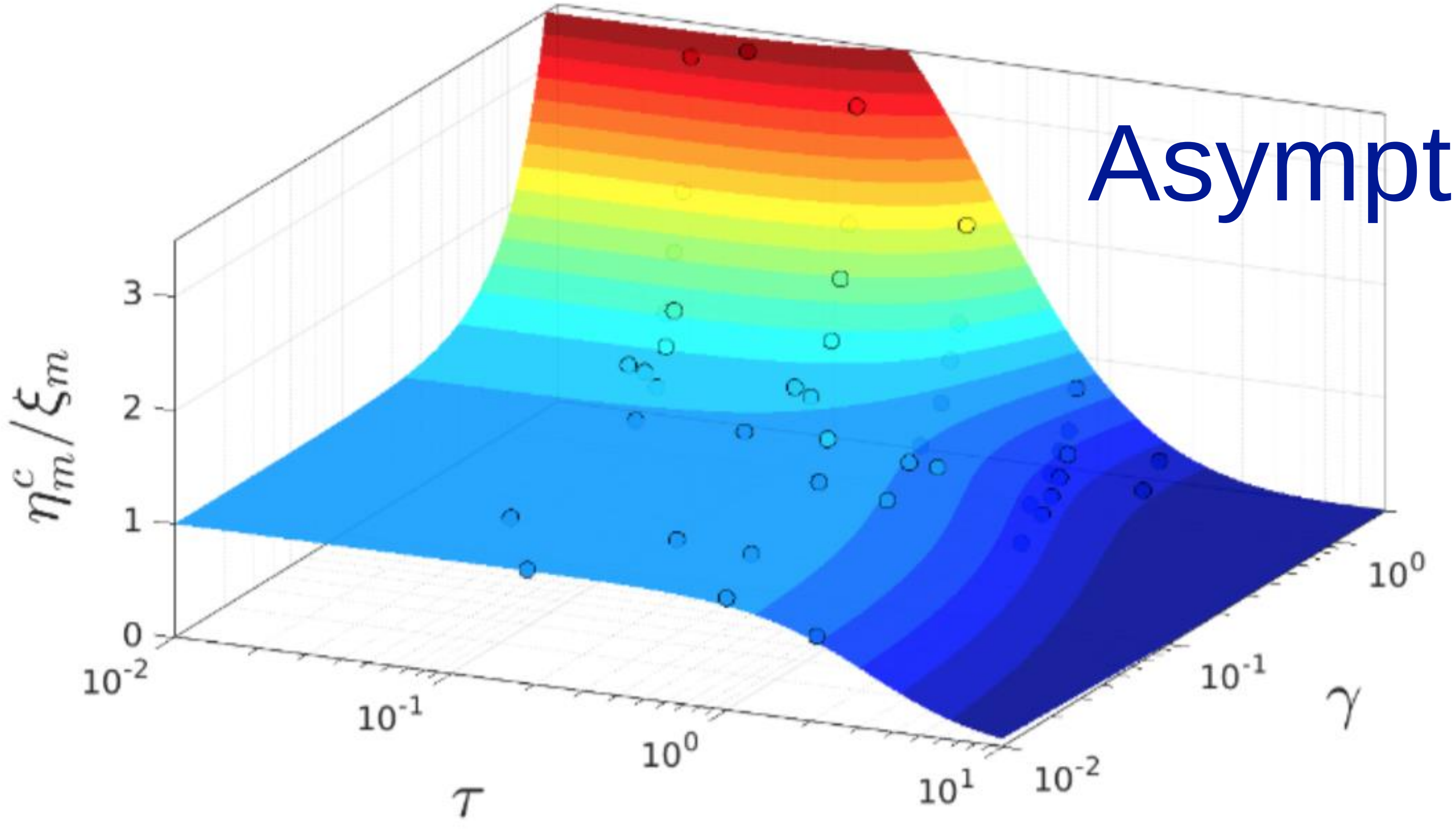
$$\tau = \frac{t_r}{t_c}$$

$$t_c = b/\sqrt{g(h - h_s)}$$

$$\gamma = \mathcal{W}_m^2/(2g\xi_m)$$

velocity head

Asymptotic Relationships



$$F = (1+\alpha_1\gamma^2)(\frac{1}{1+\alpha_2\tau^{\alpha_3}})(\frac{1}{1+\alpha_4\tau^{\alpha_5}\gamma^{\alpha_6}}) \text{ with } \alpha_i = [0.9, 0.08, 2.1, 2, 1.6, 1.25]$$

For very small τ

$$F_\tau = (1+\alpha_1\gamma^2)$$

For very small γ

$$F_\gamma = \frac{1}{1+\alpha_2\tau^{\alpha_3}}$$

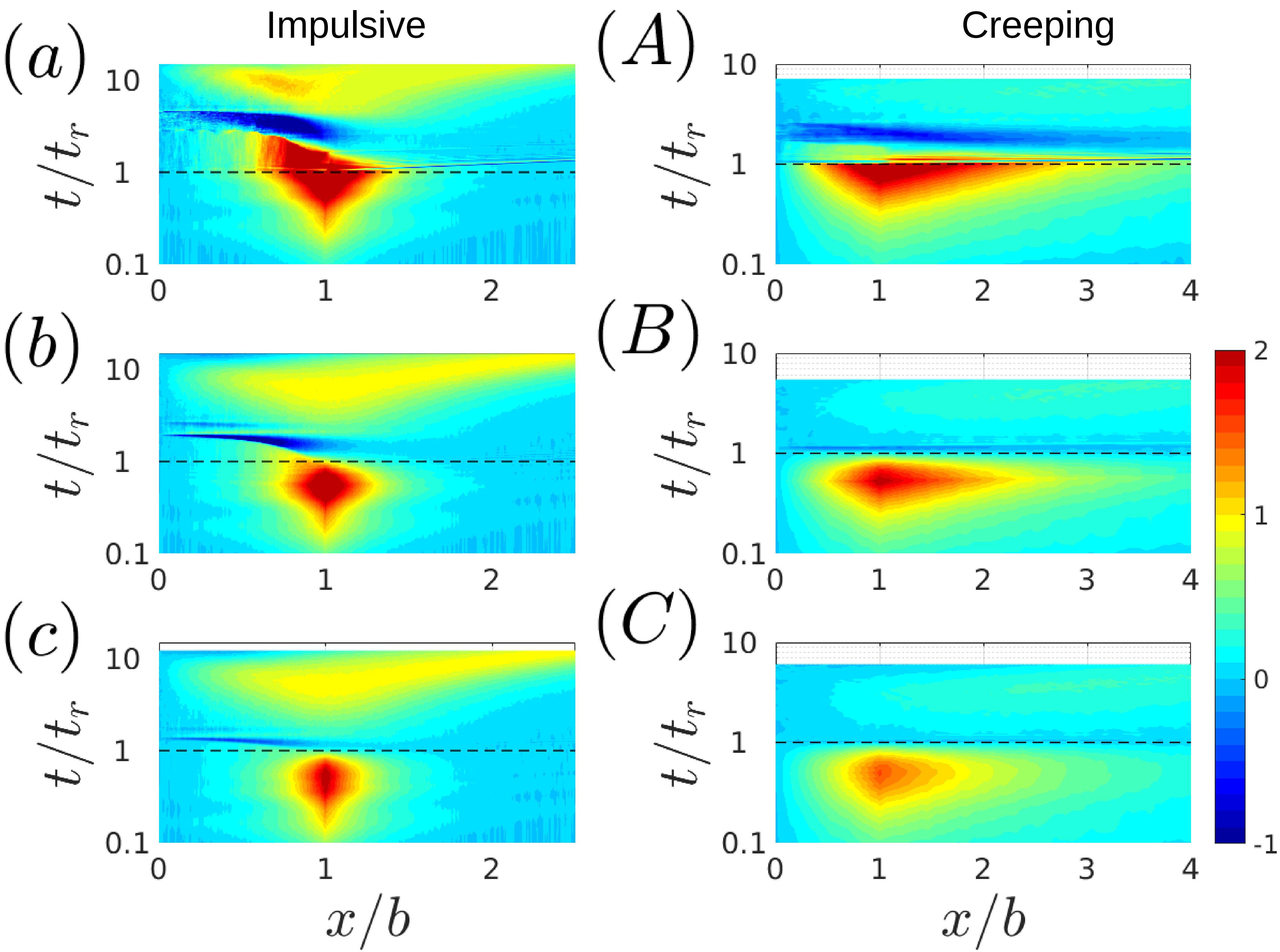
For very large τ

$$F \rightarrow 0$$

For very large γ

$$F = (1+\alpha_1\gamma^2)(\frac{1}{1+\alpha_2\tau^{\alpha_3}})$$

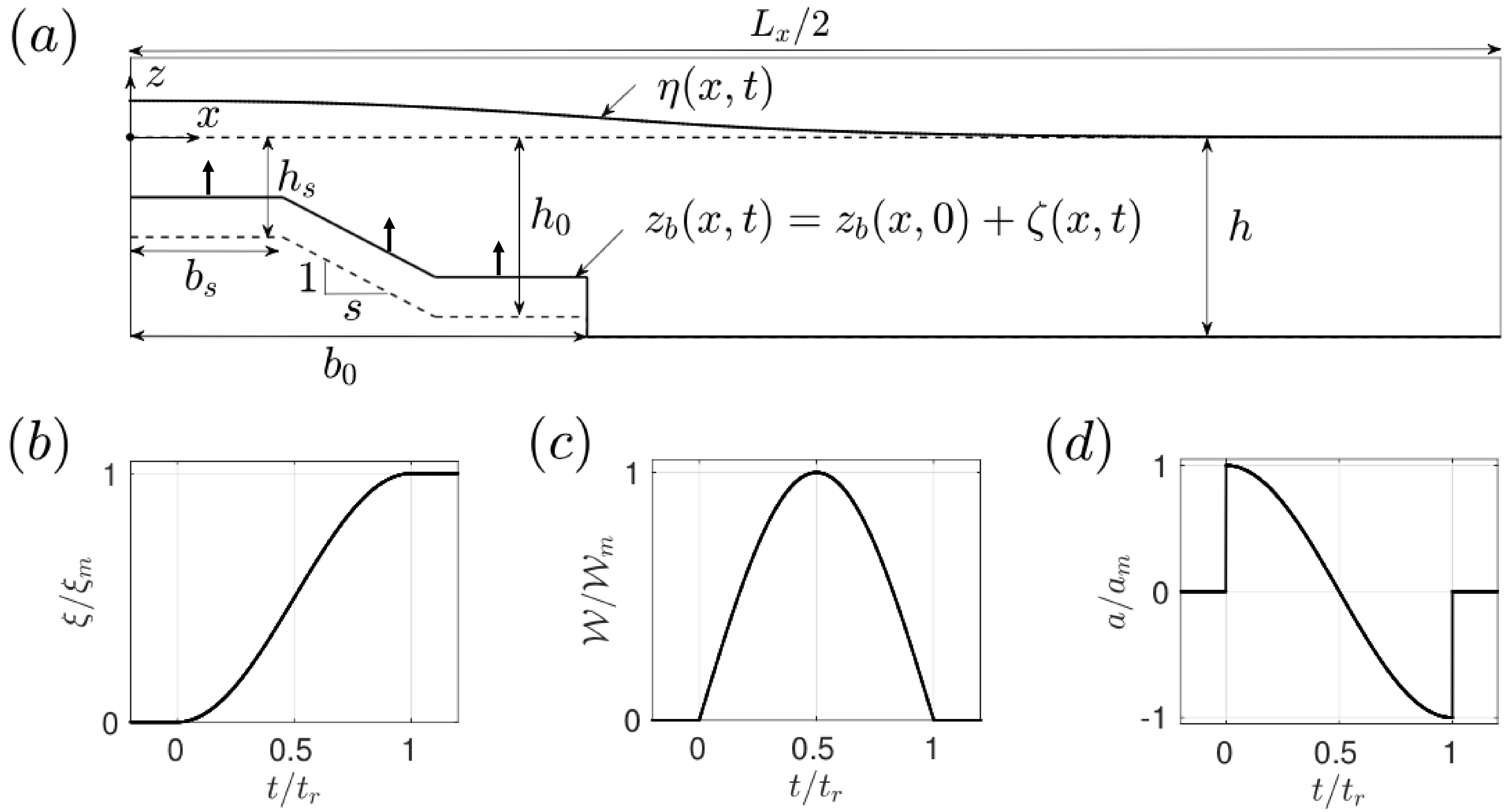
Horizontal Volume Flux



$\tau = 0.14, 0.18, 0.21, b/h = 2.5$ $\tau = 0.86, 1.13, 1.34, b/h = 0.4$

Effect of Displacement Shape

Is water surface displacement same as bottom displacement?
What is the effect of shape of bottom displacement?

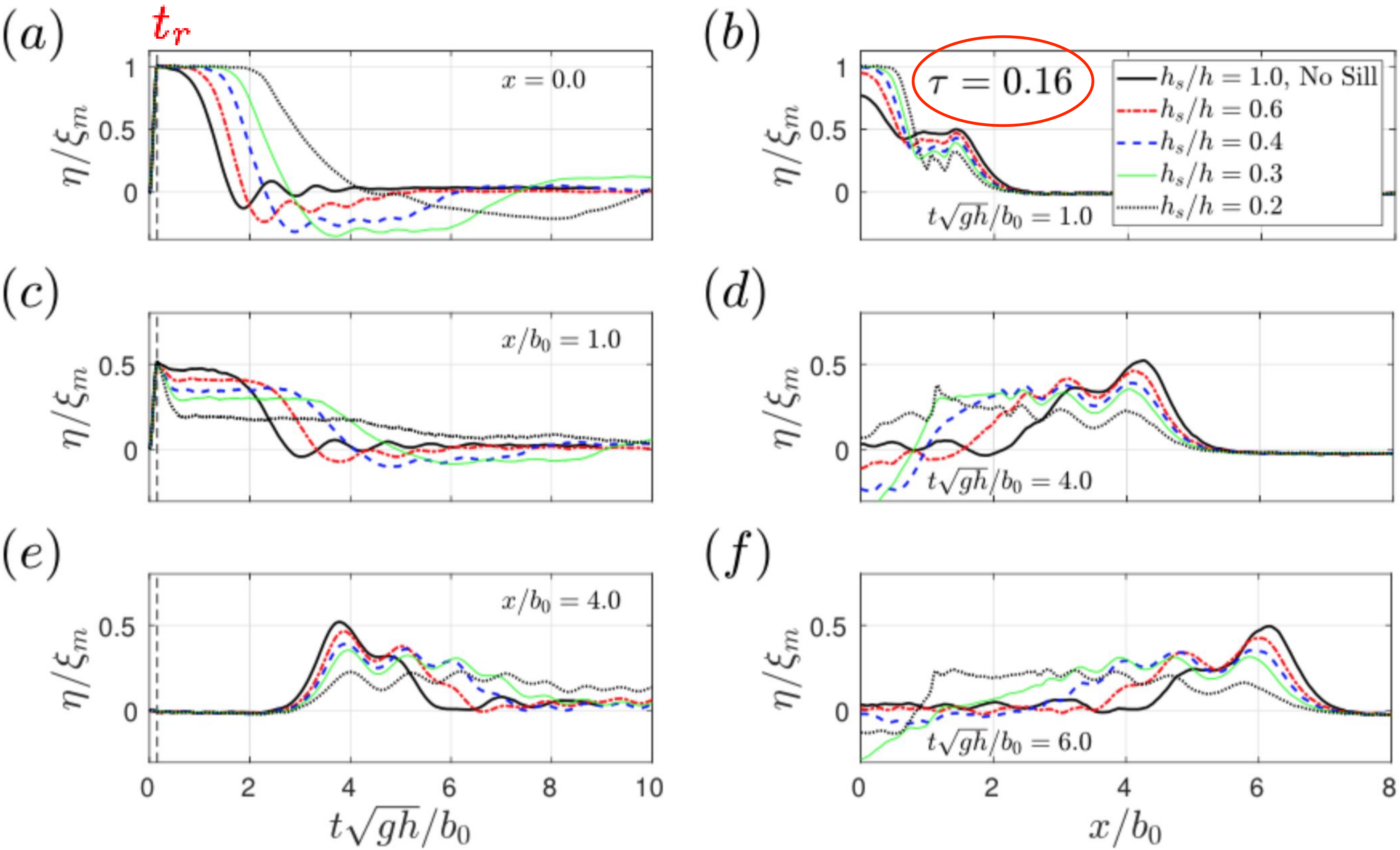


Bottom Uplift Bottom Velocity Bottom Acceleration

t_r is rise time, $\overline{h_s} = -b_0^{-1}\int_0^{b_0} z_b(x,0)dx$, $\tau_s = \dfrac{t_r}{b_0/\sqrt{g\overline{h_s}}} = \tau\sqrt{\dfrac{\overline{h_s}}{h}}$

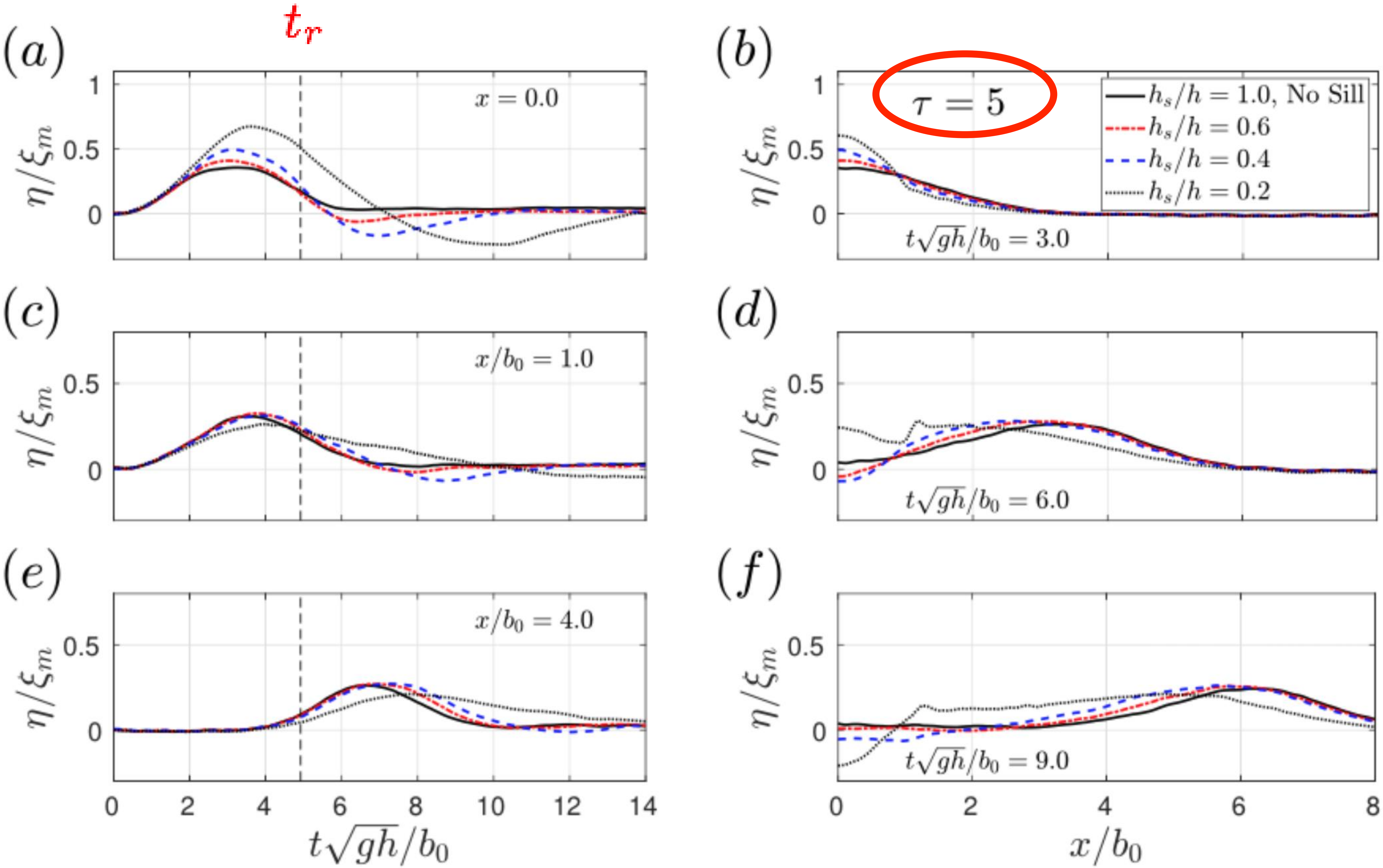
Case no.	h (m)	b_0/h	h_0/h	b_s/b_0	h_s/h	s	ξ_m/h	a_m/g	τ	τ_s
$A1$	200	10.0	1.0	1.00	1.0	0.0	0.10	0.81	0.08	0.08
$A2$	200	10.0	1.0	0.96	0.6	1.0	0.10	0.81	0.08	0.06
$A3$	200	10.0	1.0	0.94	0.4	1.0	0.10	0.81	0.08	0.05
$A4a$	200	10.0	1.0	1.00	0.3	0.0	0.10	0.81	0.08	0.04
$A4b$	200	10.0	1.0	0.93	0.3	1.0	0.10	0.81	0.08	0.04
$A4c$	200	10.0	1.0	0.80	0.3	1.0	0.10	0.81	0.08	0.05
$A4d$	200	10.0	1.0	0.70	0.3	1.0	0.10	0.81	0.08	0.05
$A4e$	200	10.0	1.0	0.50	0.3	1.0	0.10	0.81	0.08	0.06
$A4f$	200	10.0	1.0	0.25	0.3	1.0	0.10	0.81	0.08	0.07
$A5$	200	10.0	1.0	0.92	0.2	1.0	0.10	0.81	0.08	0.04
$B1$	200	5.0	1.0	1.00	1.0	0.0	0.10	0.81	0.16	0.16
$B2$	200	5.0	1.0	1.00	0.6	0.0	0.10	0.81	0.16	0.12
$B3a$	200	5.0	1.0	1.00	0.4	0.0	0.10	0.81	0.16	0.10
$B3b$	200	5.0	1.0	0.88	0.4	1.0	0.10	0.81	0.16	0.10
$B3c$	200	5.0	1.0	0.70	0.4	1.0	0.10	0.81	0.16	0.11
$B3d$	200	5.0	1.0	0.50	0.4	1.0	0.10	0.81	0.16	0.13
$B3e$	200	5.0	1.0	0.25	0.4	1.0	0.10	0.81	0.16	0.14
$B3f$	200	5.0	1.0	0.40	0.4	5.0	0.10	0.81	0.16	0.12
$B4$	200	5.0	1.0	1.00	0.3	0.0	0.10	0.81	0.16	0.09
$B5a$	200	5.0	1.0	1.00	0.2	0.0	0.05	0.81	0.11	0.05
$B5b$	200	5.0	1.0	1.00	0.2	0.0	0.10	0.81	0.16	0.07
$B5c$	200	5.0	1.0	0.84	0.2	1.0	0.10	0.81	0.16	0.08
$B5d$	200	5.0	1.0	0.67	0.2	1.0	0.10	0.81	0.16	0.10
$B5e$	200	5.0	1.0	0.50	0.2	1.0	0.10	0.81	0.16	0.11
$B5f$	200	5.0	1.0	0.25	0.2	1.0	0.10	0.81	0.16	0.13
$B5g$	200	5.0	1.0	0.50	0.2	3.0	0.10	0.81	0.16	0.10
$B5h$	200	5.0	1.0	0.20	0.2	5.0	0.10	0.81	0.16	0.11
$C1-C3$	200	5.0	1.0	1.00	1.0, 0.4, 0.2	0.0	0.10	0.081	0.5	0.5-0.2
$D1-D3$	200	5.0	1.0	1.00	1.0, 0.4, 0.2	0.0	0.10	0.020	1.0	1.0-0.4
$E1-E4$	200	5.0	1.0	1.00	1.0, 0.6, 0.4, 0.2	0.0	0.10	0.005	2.0	2.0-0.9
$F1-F4$	200	2.0	1.0	1.00	1.0, 0.6, 0.4, 0.2	0.0	0.10	0.005	5.0	5.0-2.2
$G1, G2$	200	1.0	1.0	1.00	1.0, 0.2	0.0	0.05	0.0025	10.0	10.0,4.5
$H1, H2$	200	1.0	1.0	1.00	1.0, 0.2	0.0	0.05	0.0005	22.0	22.0,9.8
$I1, I2$	200	0.25	1.0	1.00	1.0, 0.2	0.0	0.05	0.0005	88.0	88.0,39.4

Different Initial Sill Heights, Impulsive Case



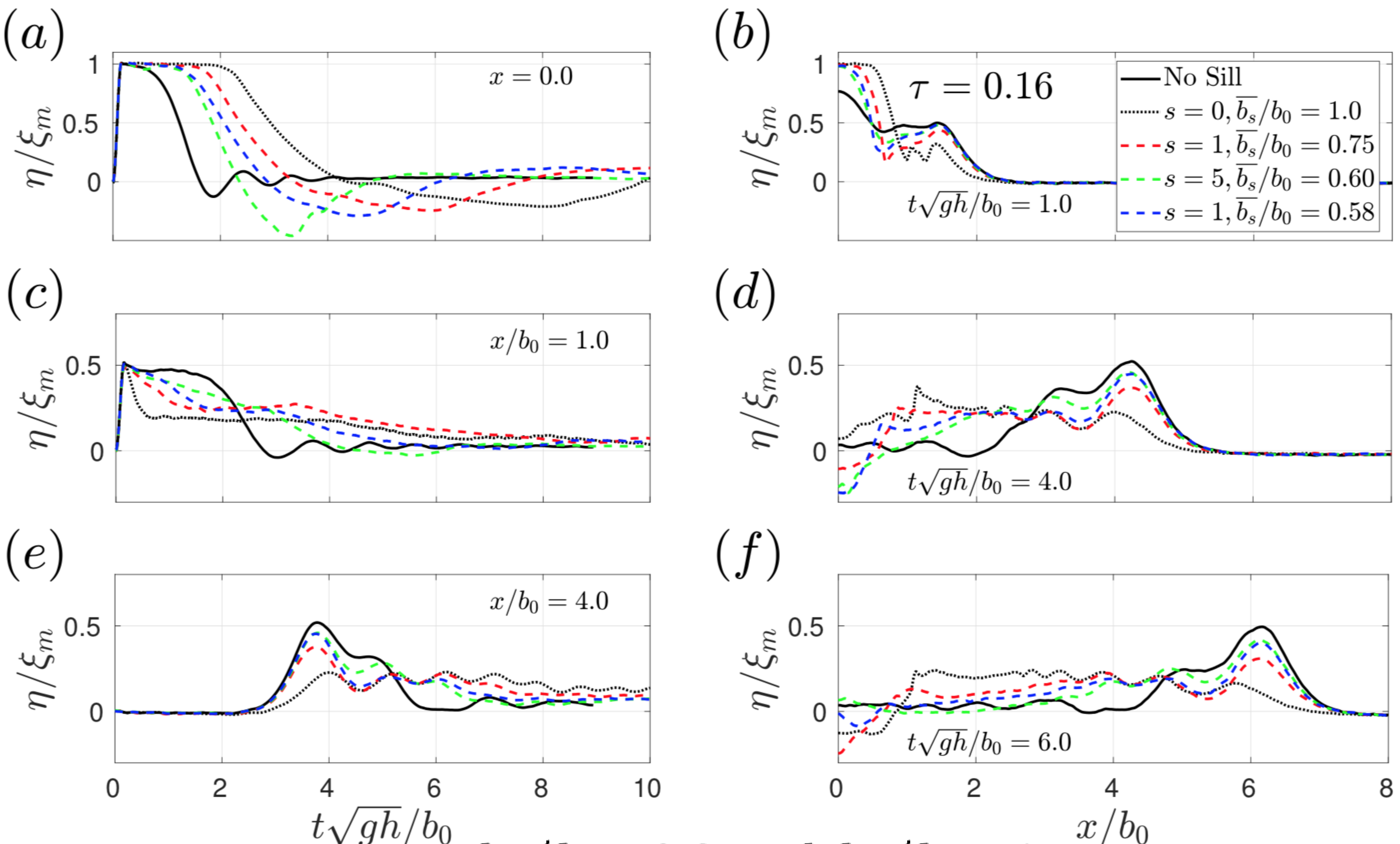
$$b_s/b_0 = 1 \text{ and } h_0/h = 1$$

Different Initial Sill Heights, Creeping Case



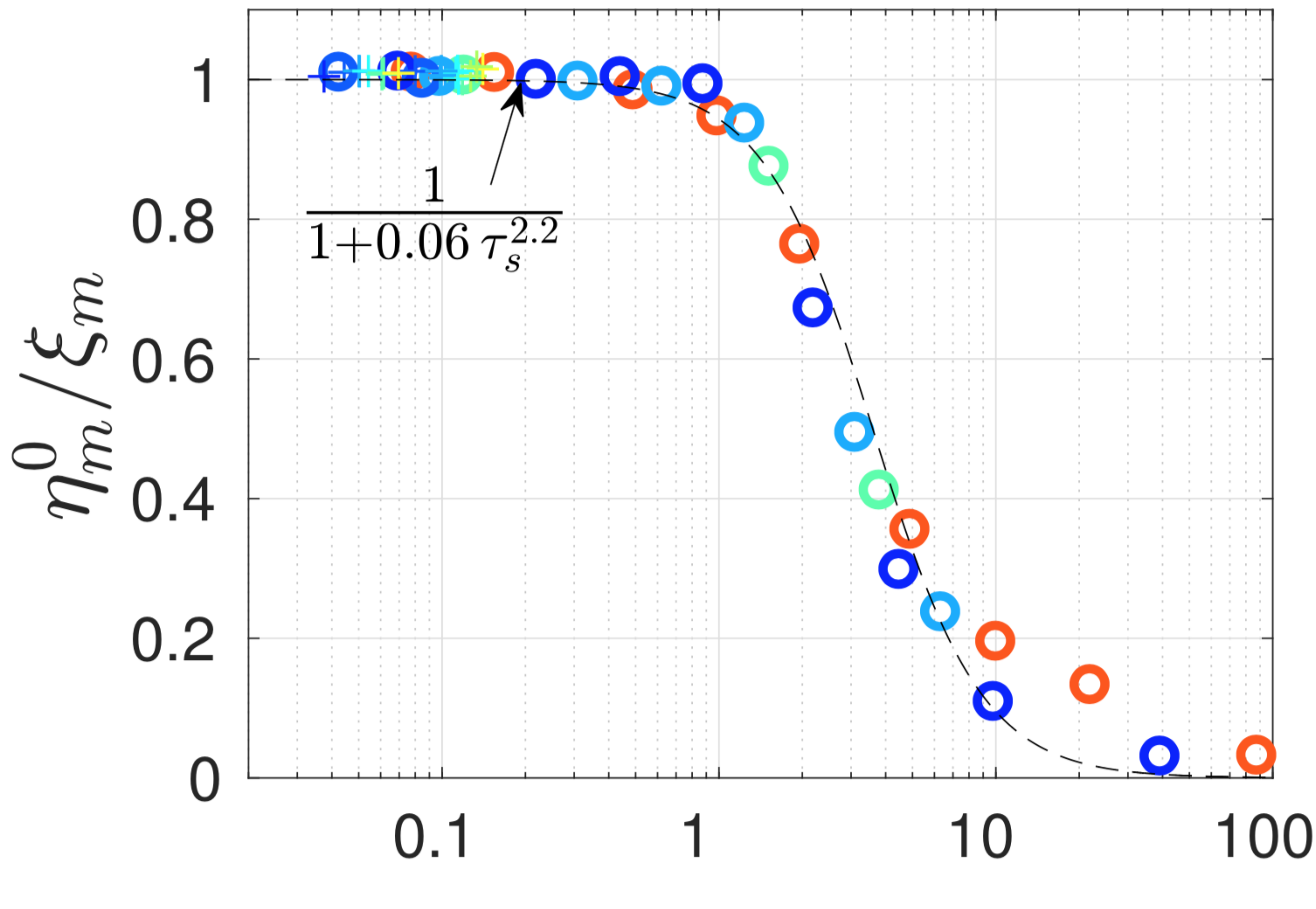
$$b_s/b_0 = 1 \text{ and } h_0/h = 1$$

Varying Sill Width: $\overline{b_s} = b_s + s(h_0 - h_s)/2$



$h_s/h = 0.2$ and $h_0/h = 1$

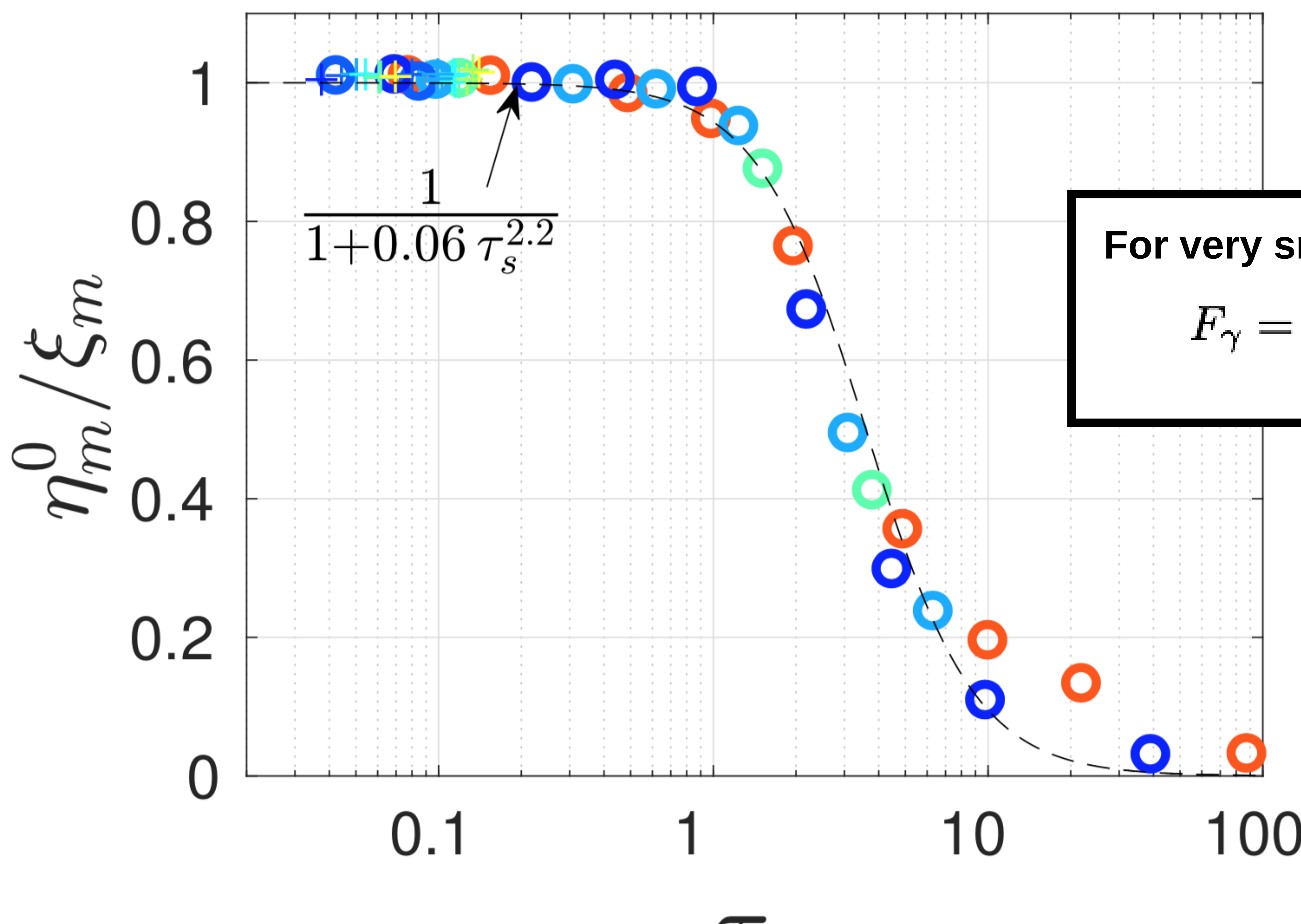
Asymptotic Relationship



Colors denote $\overline{h_s}/h$

$$\tau_s = \frac{t_r}{b_0/\sqrt{g\overline{h_s}}}$$

Asymptotic Relationship



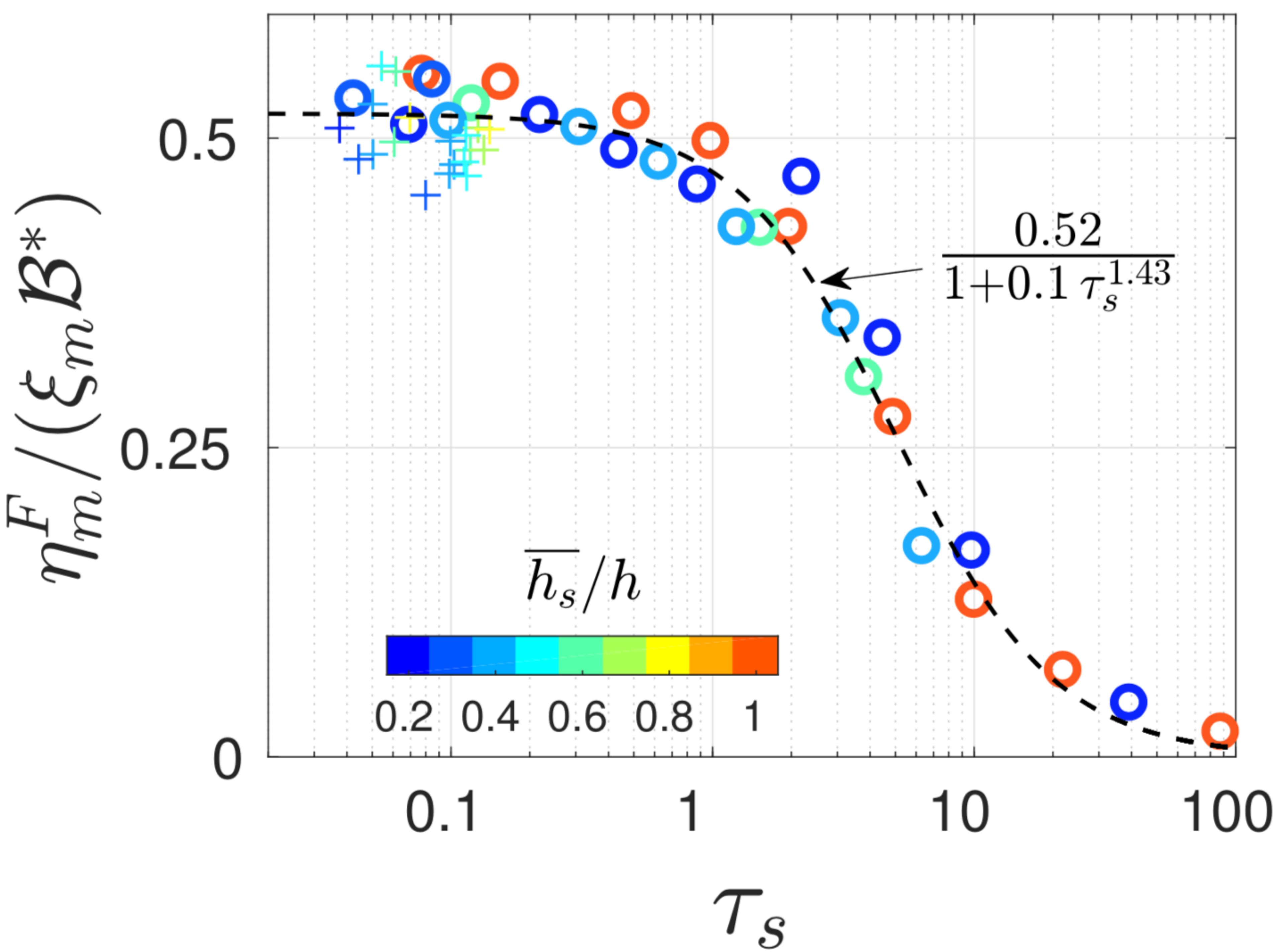
For very small γ

$$F_\gamma = \frac{1}{1+\alpha_2 \tau^{\alpha_3}}$$

Colors denote $\overline{h_s}/h$

$$\tau_s = \frac{t_r}{b_0/\sqrt{g\overline{\overline{h_s}}}}$$

Far Field Leading Wave



$$\mathcal{B}^*(h_s/h, b_s^*) = \frac{1 + 0.06(h_s/h)^{-2}(1 - \mathrm{Max}[b_s^*, 1/3])^{0.5}}{1 + 0.049(h_s/h)^{-2}}$$

Sea Quakes

Martin, O.L. (1962)

Conclusions/Possibilities

Tsunami over the source very different than that assumed

Large uplift velocities lead to larger waves over source

Far-field wave mostly affected by volume of water over source

Seaquakes are real: P and S wave effects

But also sound waves and inertial loading
Cavitation possible with high uplift velocity
Water hammer effect?
Loss of buoyancy over source?