# Breaking Water Waves in Deep and Intermediate Depths: 2D and 3D Experiments and Simulations

Sidebar: I have done friction drag reduction research for many years; includes a book

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26 October 2017

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# Outline

Manner in which waves are known to break

Results from previous/older research

First X-configuration experiments on weakly 3D waves

Second set of X-configuration experiments

Surprising results and their explanation

Substantiation via Navier-Stokes simulations

# Wave Breaking:
## In the Absence of Structures & any Additional Energy Input

**<u>Superposition and exceedance of energy density threshold</u>**

**Benjamin-Feir sideband and other instabilities**

} **Believed to cause "rogue" waves**

Stokes waves – "corner"

Shallow water shoaling

Crest particle velocity exceeds phase speed

Waves on opposing currents

Etc.

# Annual Review Paper on Breaking Waves

Perlin, Choi, Tian 2013

Progress on geometry, onset, 3D effects, kinematic & dynamic criteria, dissipation, field measurements, and simulations

Our work had been mostly experimental and 2D, and has used frequency focusing/superposition to generate breaking waves

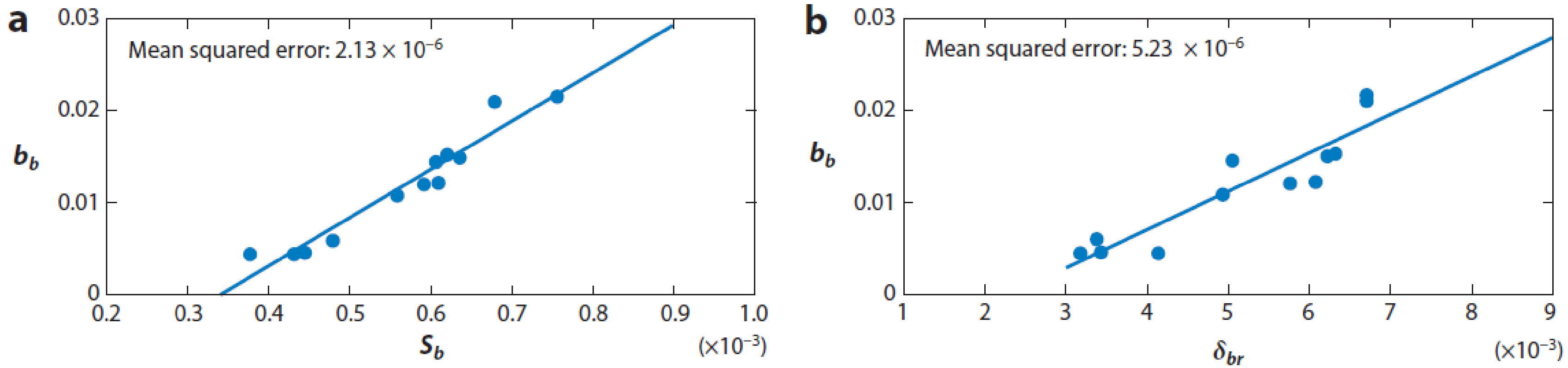


Figure 6

Normalized energy dissipation rate [breaking strength parameter ($b_b$)] as (*a*) a function of local wave steepness ($S_b$) and (*b*) the breaking criterion parameter $\delta_{br}$ by Song & Banner (2002). Figure adapted from Tian et al. (2010).

# Annual Review Paper on Breaking Waves – cont

Perlin, Choi, Tian 2013

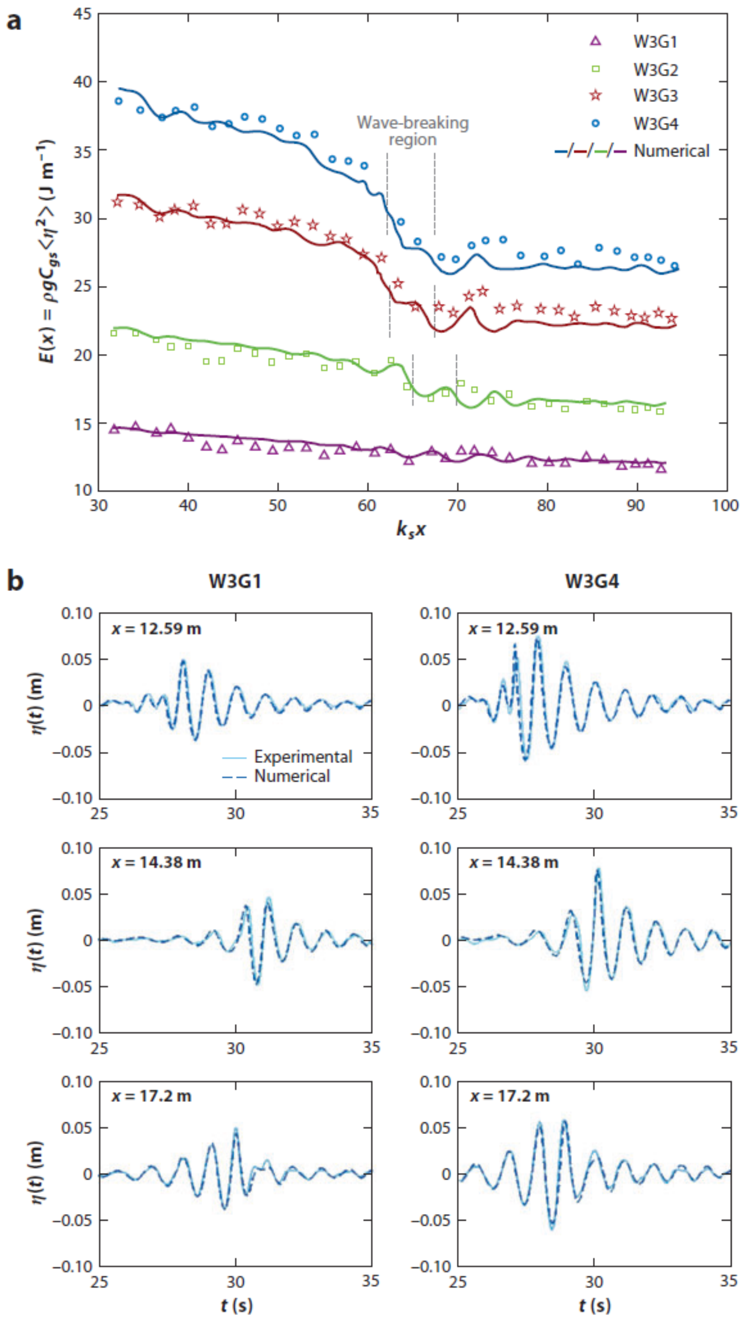


Figure 10

(*a*) Comparison of the total energy as a function of space. The symbols represent experimental measurements, and the solid lines are numerical results. The vertical dashed lines indicate the wave-breaking region. (*b*) Comparison of the surface elevation measured from three wave stations. The solid lines represent experimental measurements, and the dashed lines are numerical results. The curves in the left column are from the postbreaking-wave groups; the figures of the most violent breaking-wave group are in the right column. The breaking region is given by 13.09 m $< x <$ 14.24 m. Figure adapted from Tian et al. (2010).

Tian, Perlin, Choi 2010 used an eddy viscosity model based on their measurements, and found good agreement.

$$\upsilon_{eddy} = \alpha H_{br} L_{br} / T_{br}$$

where these scales are those during active breaking and

$A$ was found to be 0.02

**Excellent agreement between measurements and simulations including breaking, both in surface elevation and energy dissipation.**

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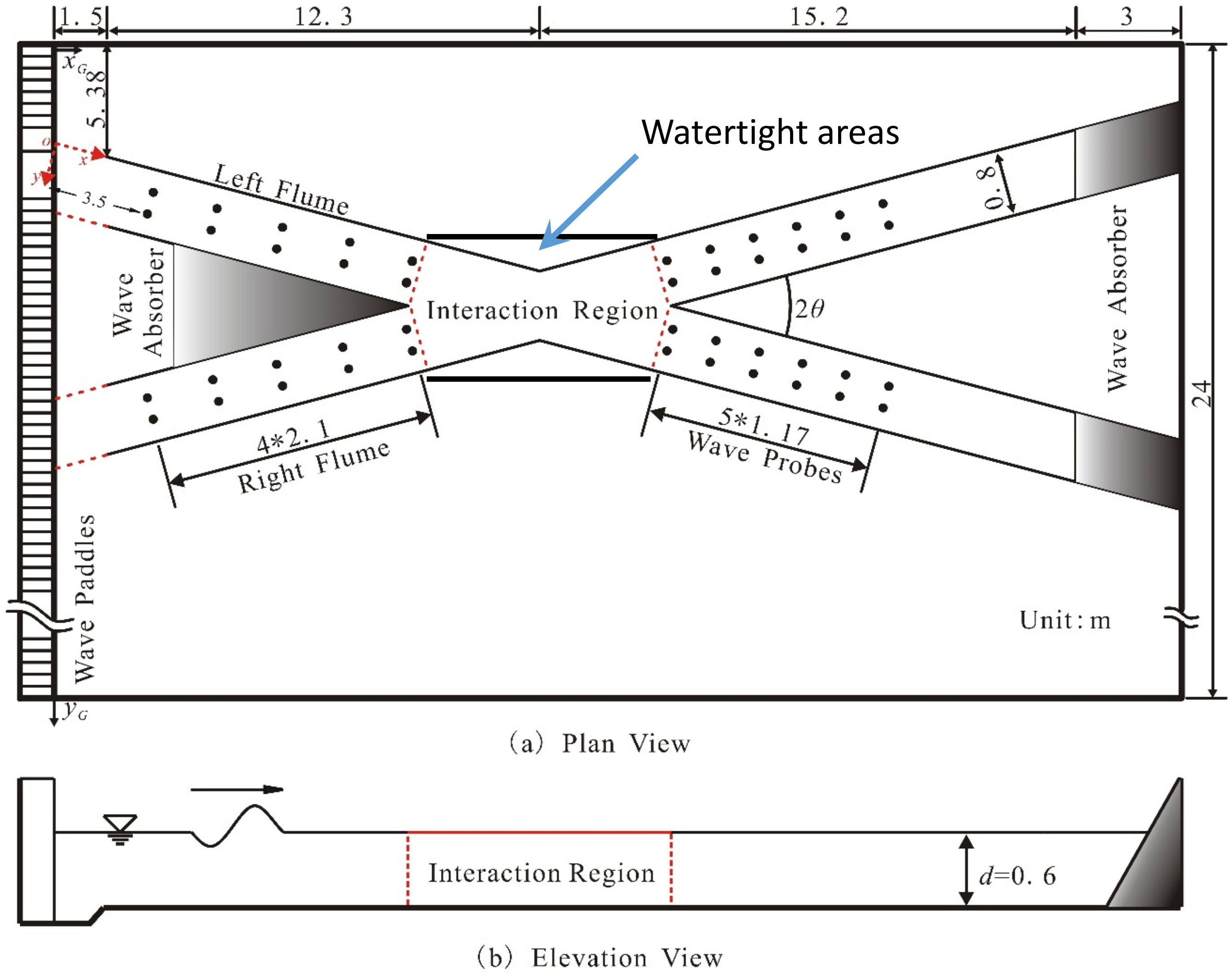
# To Move to 3D Experiments:

## Major Shortcomings of Previous Quantitative 3D Experiments

- Aside from wave probes, options are limited!
- Even pre-breaking and air entrainment, optical fluid mechanics techniques (PIV, laser sheets, etc.) essentially are precluded.
- How do we circumvent these measurement issues?

# To Facilitate these Techniques One Requires a Dry Setup Area and Optical Access: Hence the "X-configuration" with Glass Walls !

Computer controlled paddles




In collaboration with colleagues at Dalian University of Technology, this setup was constructed first with a 16° and then with a 24° angle for $2Q$.

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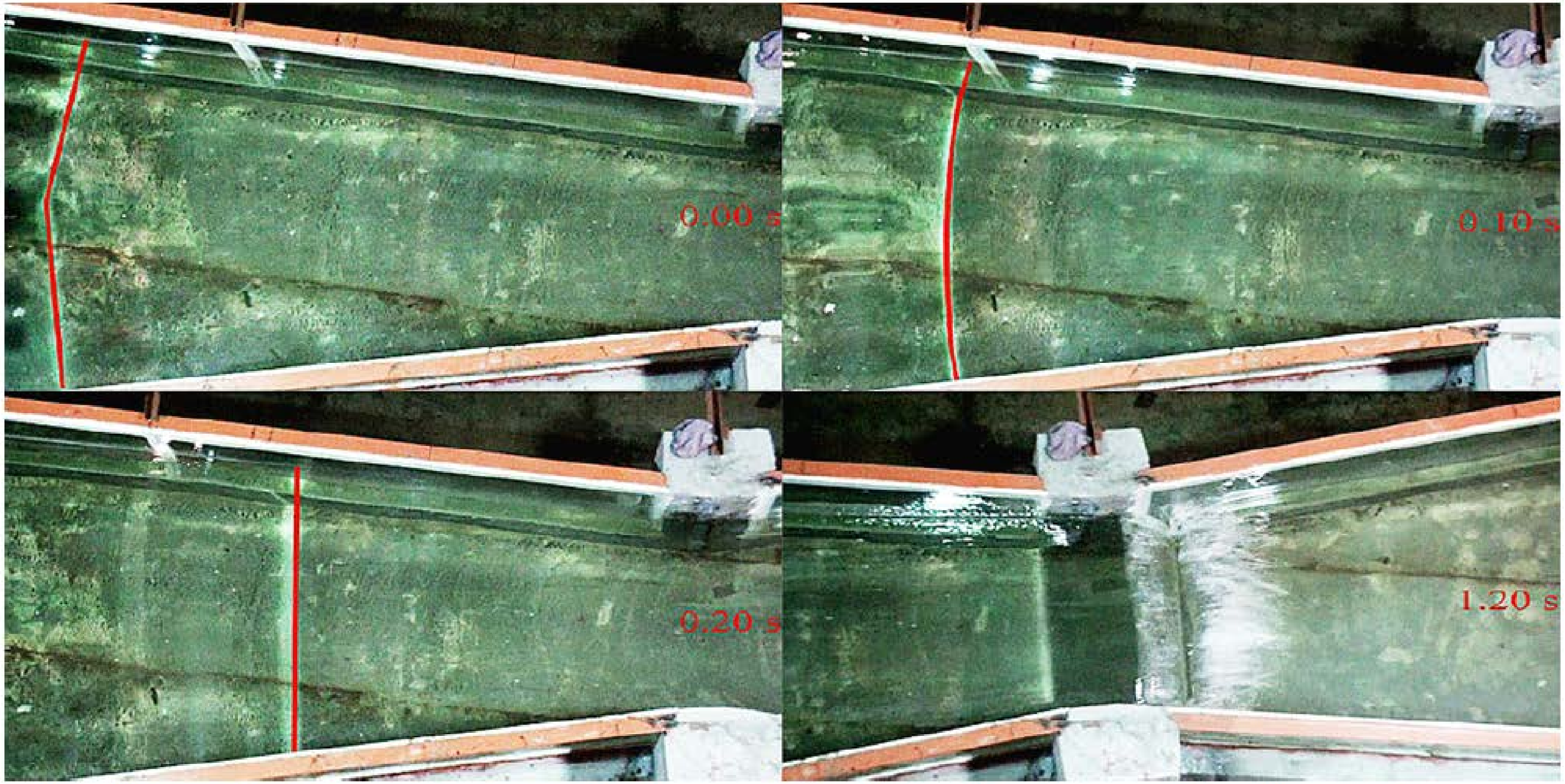
# Results from $2\theta = 16^{o}$ X-configuration Experiments




(a) Recorded from above the interaction region with the waves traveling left to right in the images. The red lines mark the wave crests.

**Note rapid change to a straight crest!**

# (Strange) Results from $2\theta = 16^o$ X-configuration Experiments – cont

Note that waves were generated in only one channel (with walls inserted) as well as in both intersecting channels.

**Downstream of the interaction/breaking region, the waves returned to 2D.**

In the 3D experiment, there was LESS dissipation for larger initial steepness waves. If energy density is the reason waves break, how can two exact wave trains superposed exhibit less dissipation? **Detuning!**

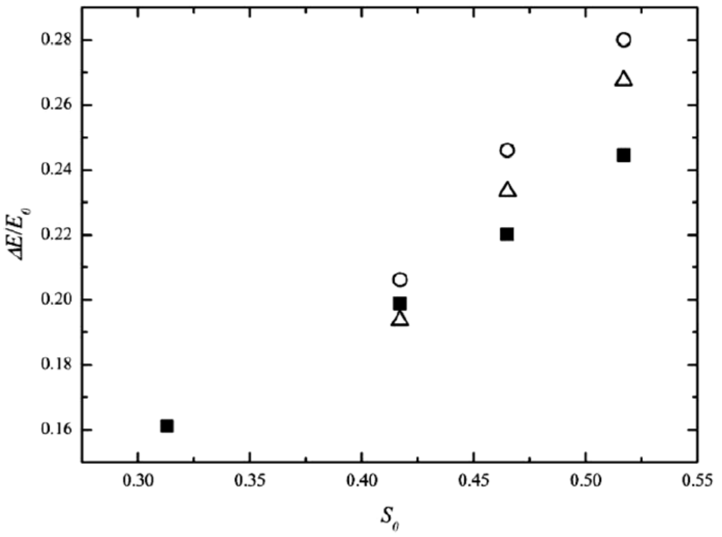



Fig. 12. Energy dissipation as a function of steepness $S_0$. The solid squares represent the WTD experiment; the open circles represent for 4.7% viscous dissipation while open triangles are for 9.5% viscous dissipation in the TD experiment.

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# A Second X-configuration Experiment with Increased Angle

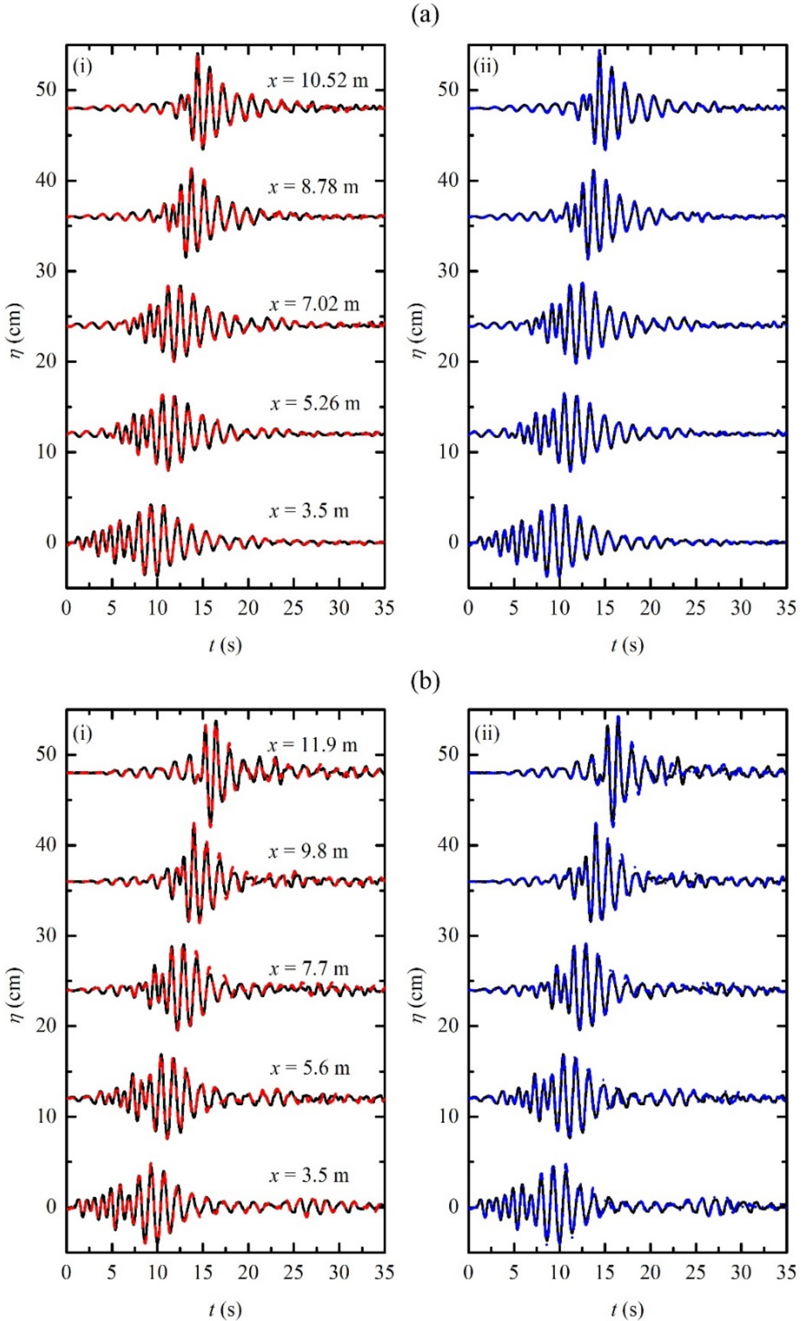
$2\theta = 24^o$

Intuitively, it is expected that two superposed collinear waves would generate the largest total surface elevation and have the most significant interaction (as the overlay time is a max), and that as the angle of approach increases, the interaction would decrease as the waves have less time to interact.

**Thus for $24^o$, the breaking was expected to be less significant than for those of the $16^o$ cases.**

An identical sea surface elevation was generated both cases other than the waves were generated with the two distinct angles.

# A Second X-configuration Experiment with Increased Angle – cont




$2\theta = 24^o$ compared with $2\theta = 16^o$

To demonstrate that the wave maker is generating the same surface elevations for the two cases, we compare directly the probe measurements.

**Fig. 3.** Comparison among the surface profiles measured before superposition for Case F1 along the two flumes: (a) $\theta = 8^\circ$; (b) $\theta = 12^\circ$. (i) A comparison of the lateral surface profiles of the left flume; (ii) A comparison of the surface profiles at the same positions but in the right leg. The black solid lines represent the surface profile measured on the right side in the left flume; the red dash lines represent the surface profile measured on the left side in the left flume; the blue dash-dot lines represent the surface profile measured on the left side in the right flume.

# A Second X-configuration Experiment with Increased Angle – cont

$2\theta = 24^{o}$

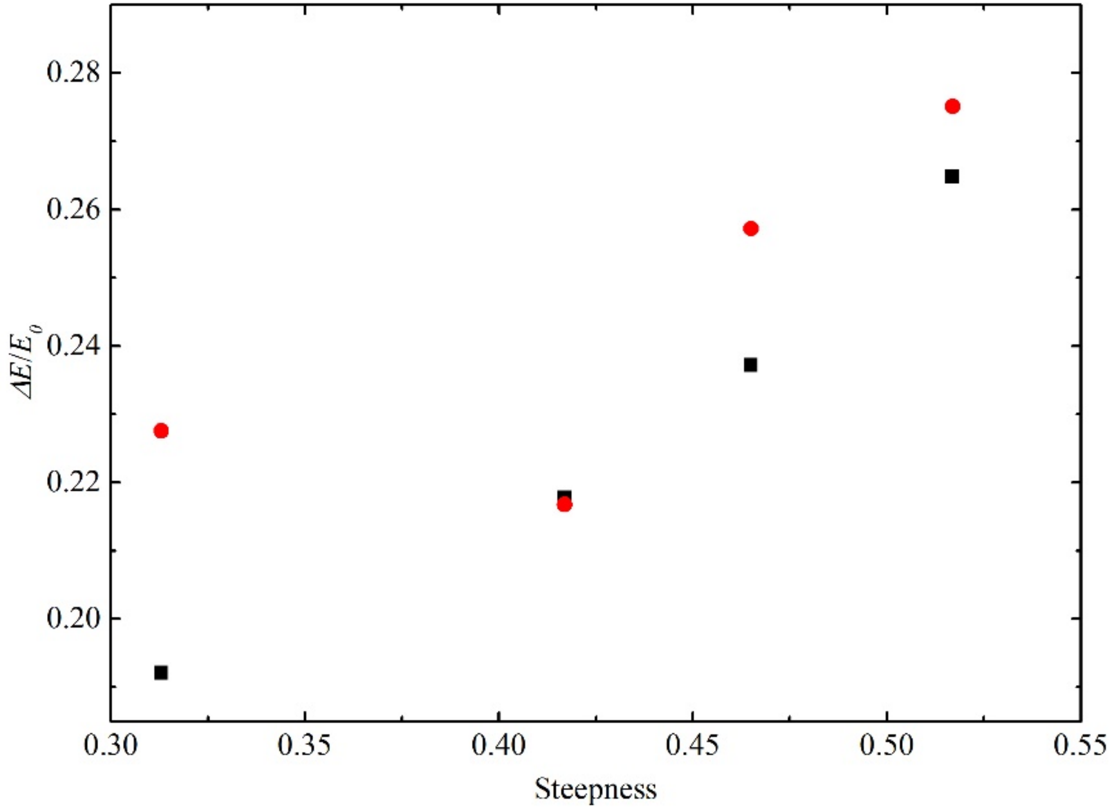



**Fig. 12.** Energy dissipation as a function of steepness. The squares represent the experiment with $\theta$ = 8°; the circles represent the case with $\theta$ = 12°

As the angle was increased, so was the dissipation. A larger approach angle increased the interaction.

**Counter-intuitive!**

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# A Second X-configuration Experiment with Increased Angle – cont

$2\theta = 24^{o}$

## In fact this is what Nepf et al. 1998 measured and stated:

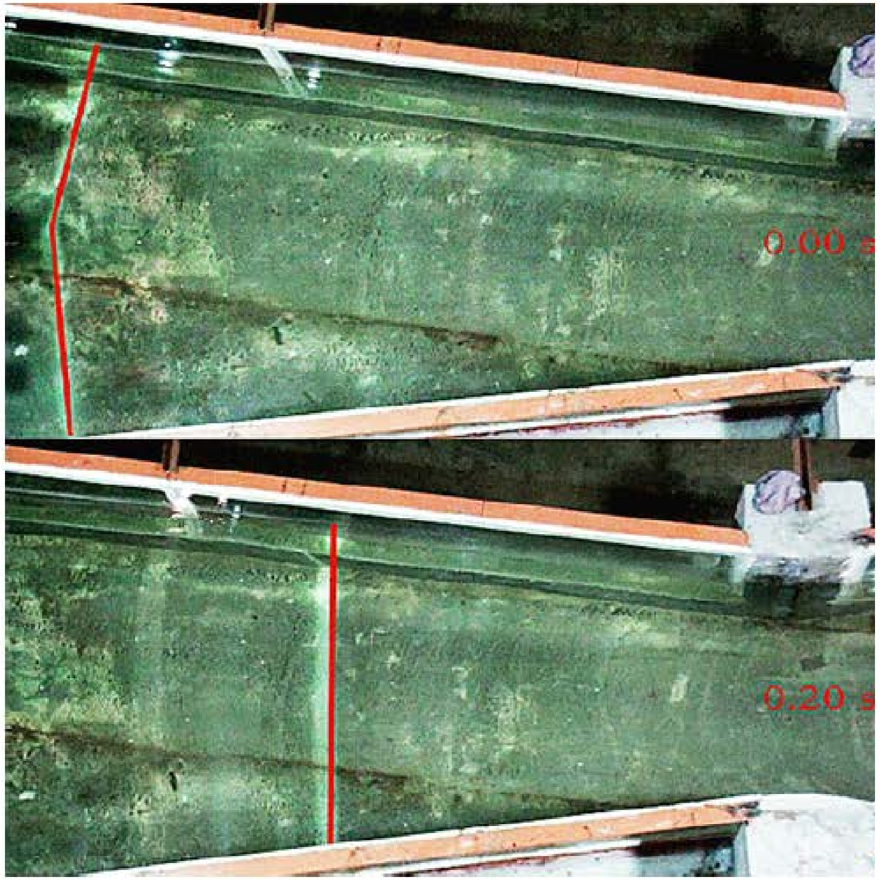
"Interestingly, this trend is counter to that suggested for the superposition of unidirectional, multifrequency progressive waves, described above. However, the observed increase in breaking steepness with focusing angle is consistent with Penney and Price (1952), who used a limiting acceleration criteria to predict that the breaking steepness of a standing wave, that is, maximum focusing angle, exceeds that of a progressive wave by 50%. Taylor (1953) verified this prediction qualitatively in a laboratory tank, but suggested that three-dimensional modulation, which appeared as the predicted limiting wave height was approached, assisted in the precipitation of breaking."

## This is what Le Mehaute's 1986 simple model also predicted:

## $H_c$ increases as the wave angle increases.

# A Second X-configuration Experiment with Increased Angle – cont

$2\theta = 24^{o}$




The other observations with which we were concerned were (1) the rapidity with which the crests go from two distinct angles as they enter the interaction region to a straight crest – within a fraction of the wave length and (2) downstream of the interaction the waves become 2D again with each downstream leg having the same 2D surface.

# X-configuration Experiment with Increased Angle – cont

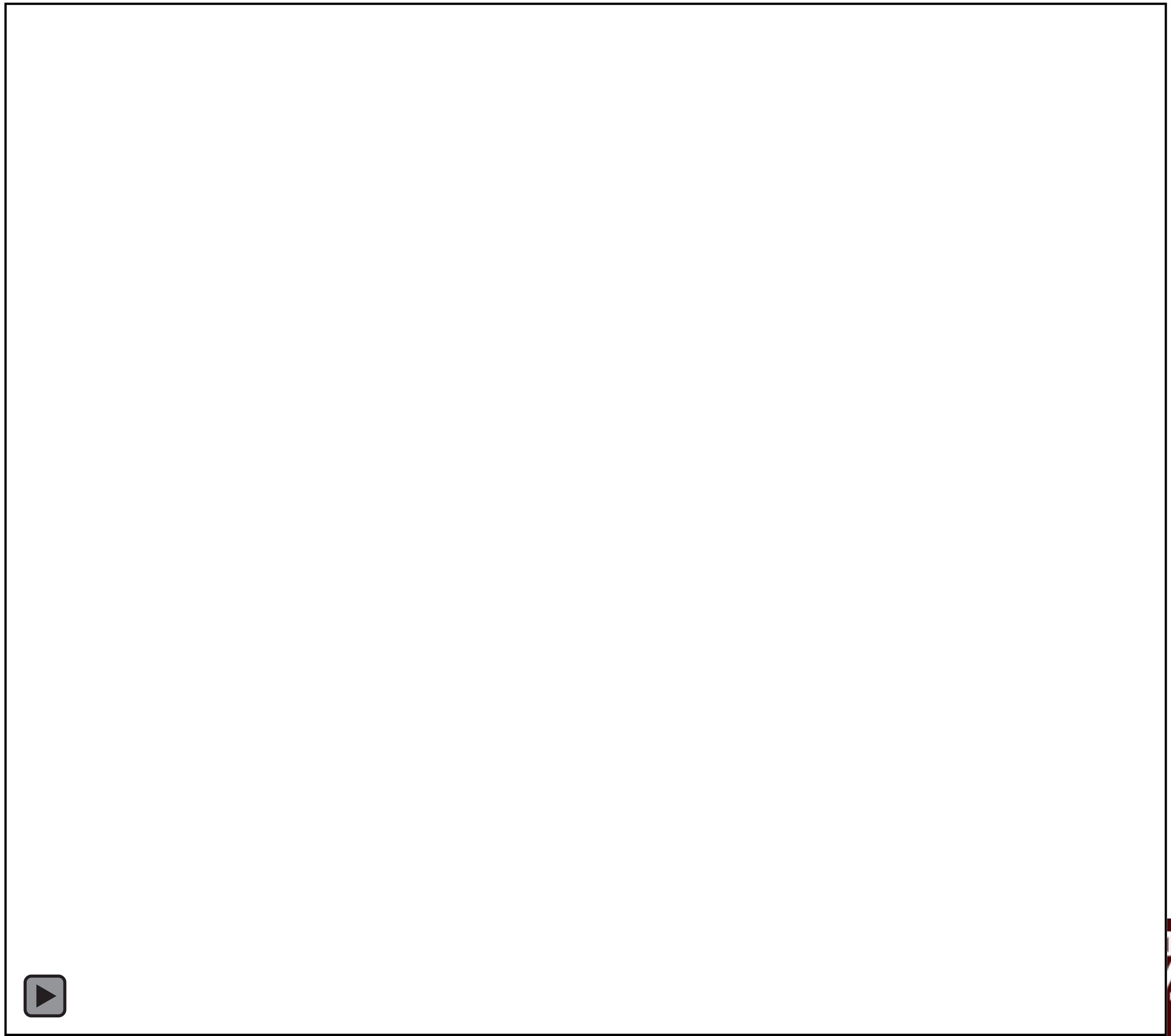
$2\theta = 24^o$

After considering this, it was recognized eventually that diffraction throughout the region (outward in both areas) was the reason for (1) and (2). We confirmed this via numerical Navier-Stokes simulations (neglecting breaking effects).

Additional computations were used to demonstrate other physics.

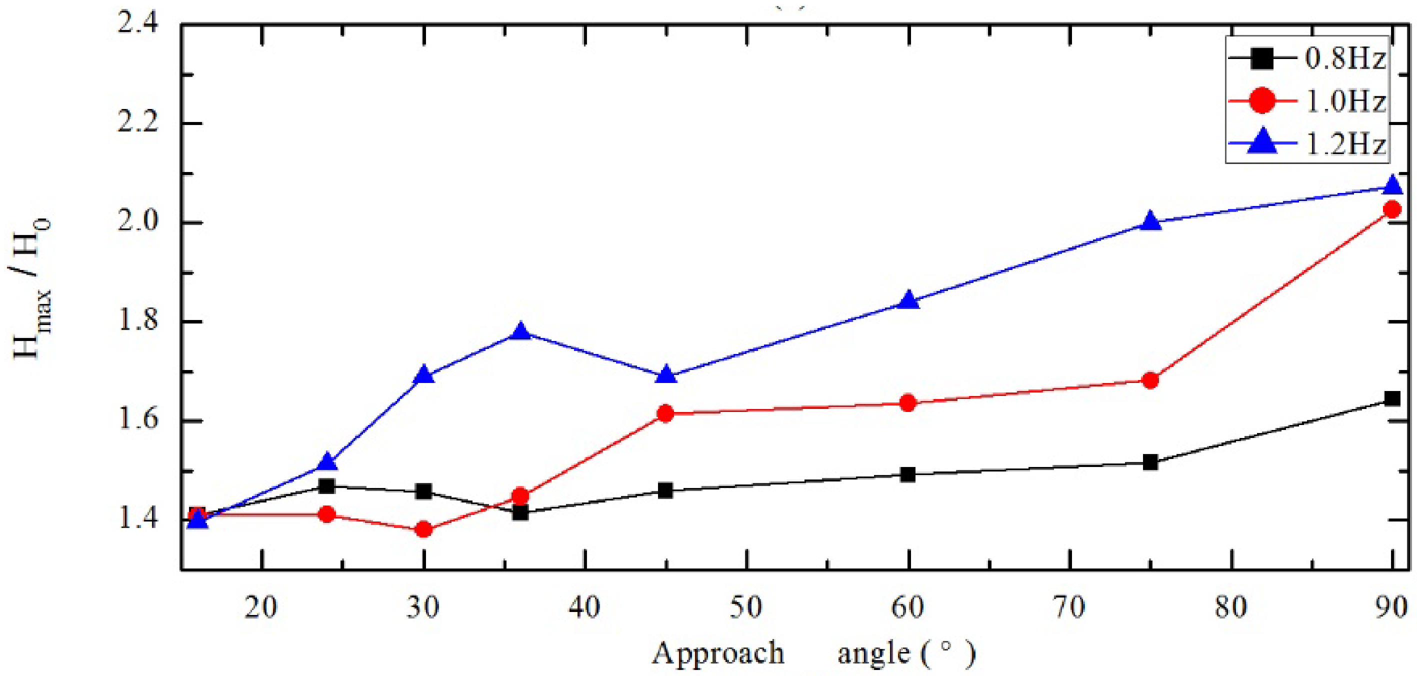
# X-configuration Simulations – $2\theta = 24^{o}$

# X-configuration Simulations – $2\theta = 24^{o}$ with Elongated Interaction Region



# X-configuration Simulations– $2\theta = 24^{o}$ with Semi-Infinite Downstream Region

# Results from several Numerical Simulations




The maximum wave height in the interaction region as a function of interaction angle.

That is where we are presently $\longrightarrow$ Questions ?