SCSTW-7, Taichung, 18-22 Nov. 2014

Tsunami Waveforms in South China Sea and Runup of Undular Bores

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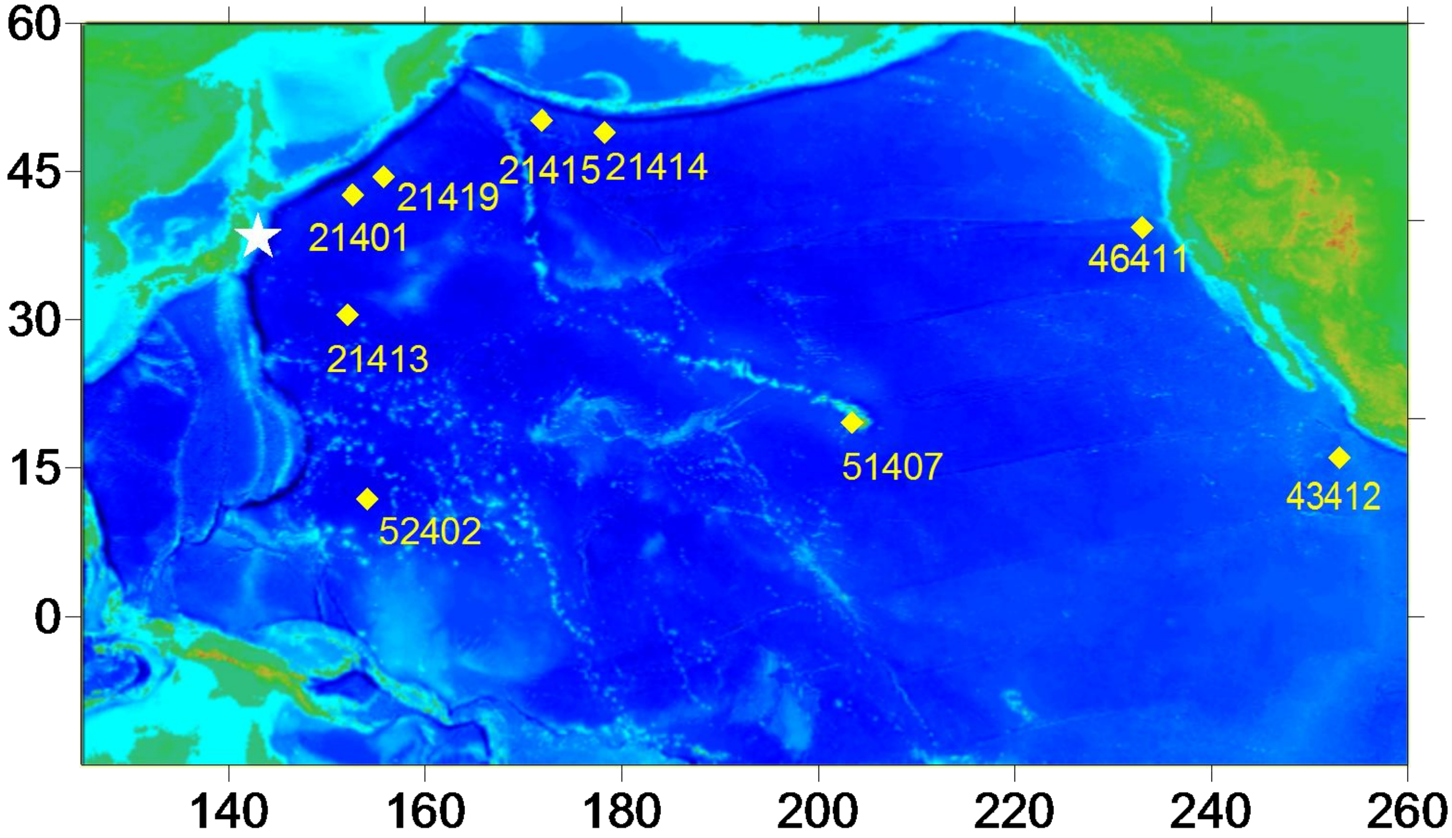
Contents

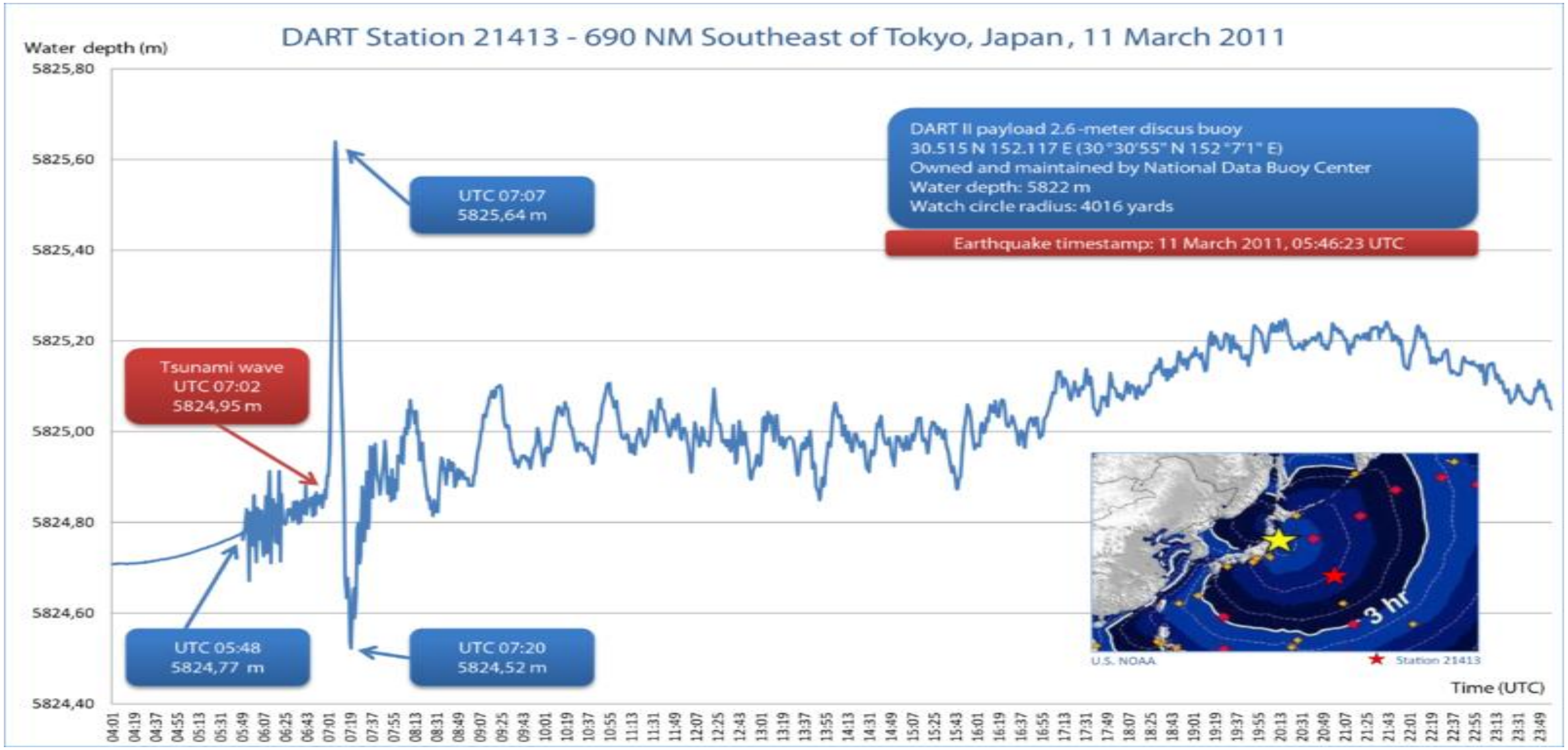
2011 Japan Tohoku Tsunami



- Propagation of tsunami in Pacific Ocean
- Propagation of tsunami to China Coast

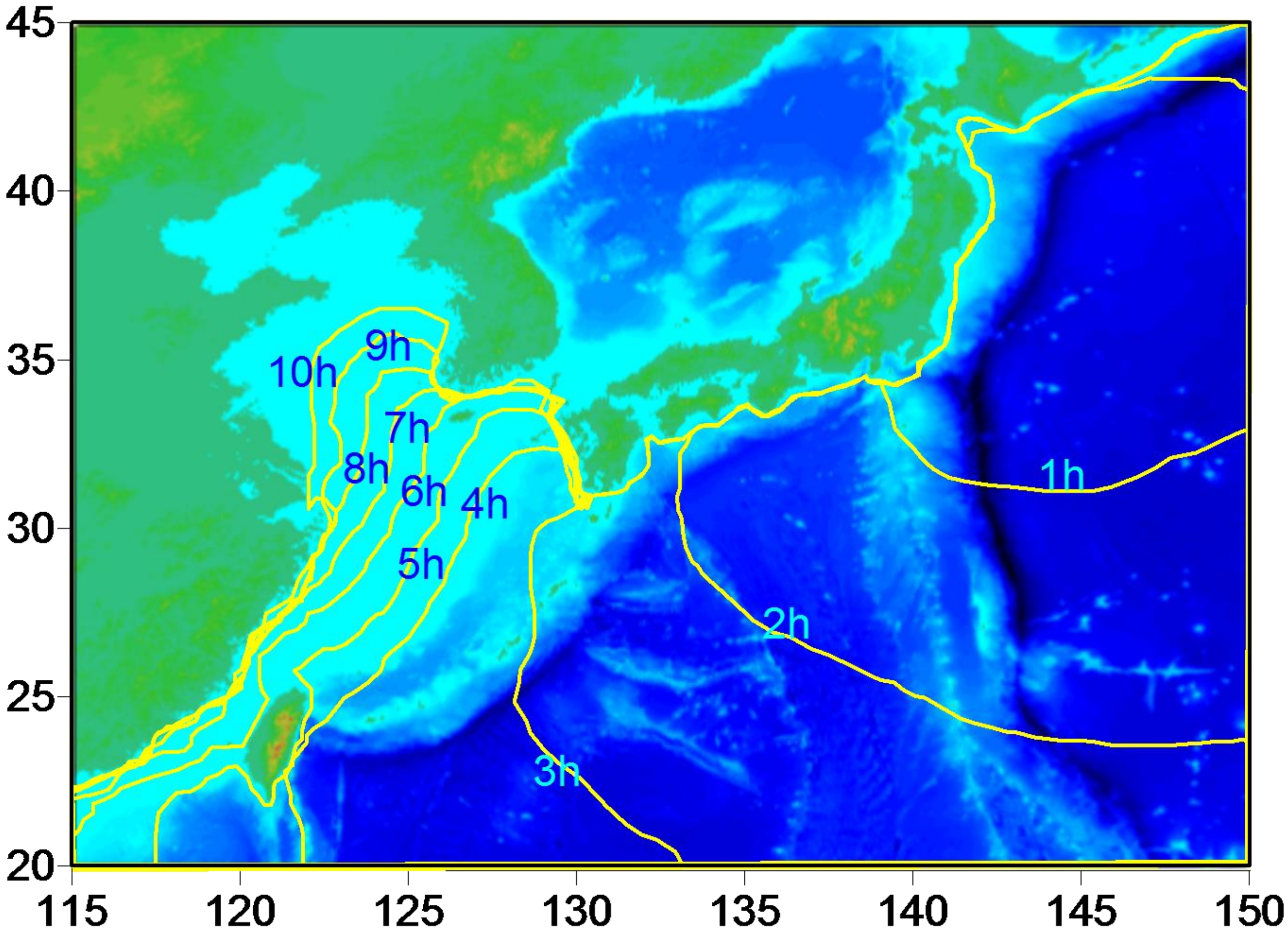
2011 Japan Tohoku Tsunami

- Tsunami wave recorded with DART Station



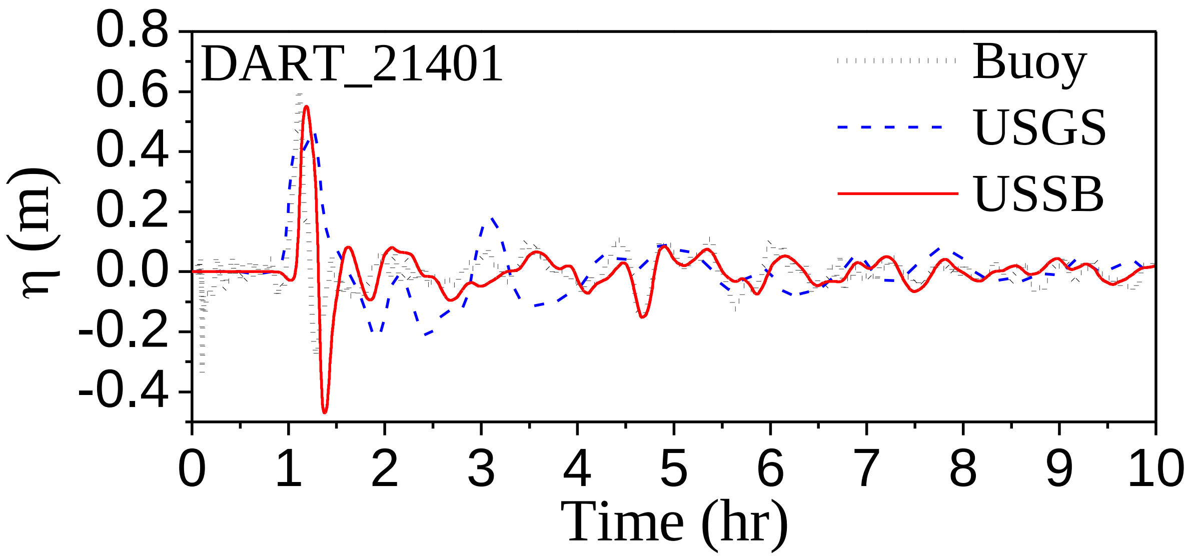
H=1.12m, T/2=13min (from crest to trough), d=5822m

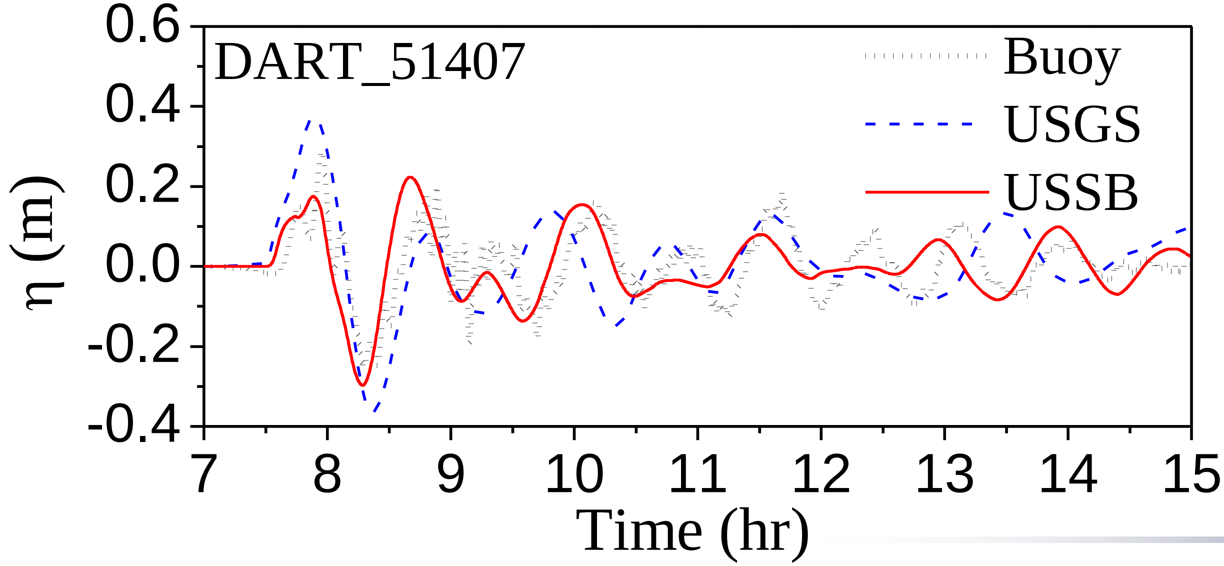
2011 Japan Tohoku Tsunami



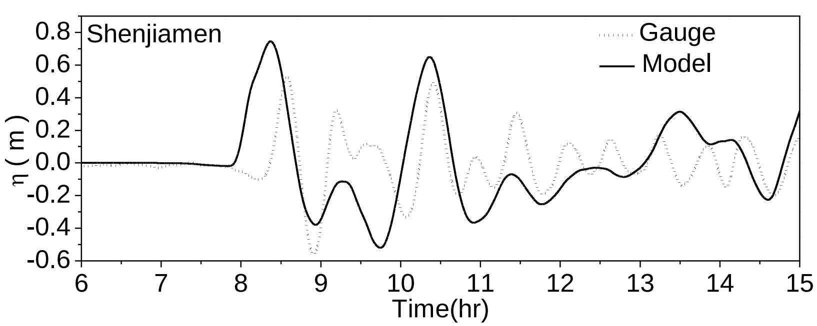
- Contours of tsunami arrival time in China seas

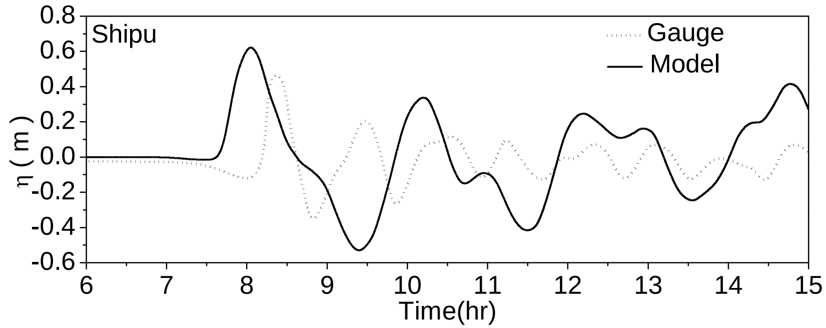
2011 Japan Tohoku Tsunami

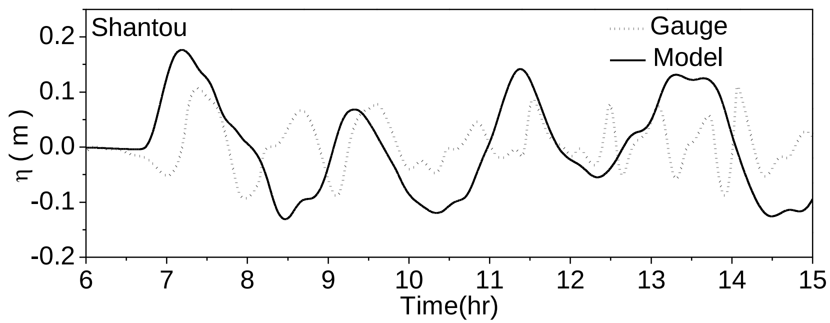




2011 Japan Tohoku Tsunami



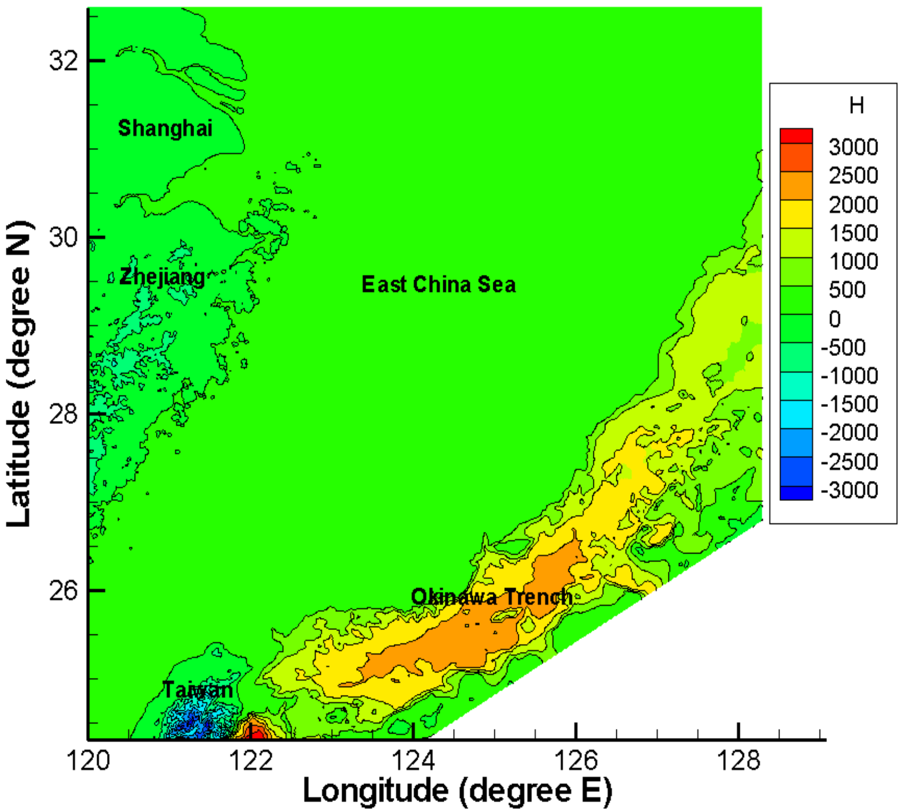


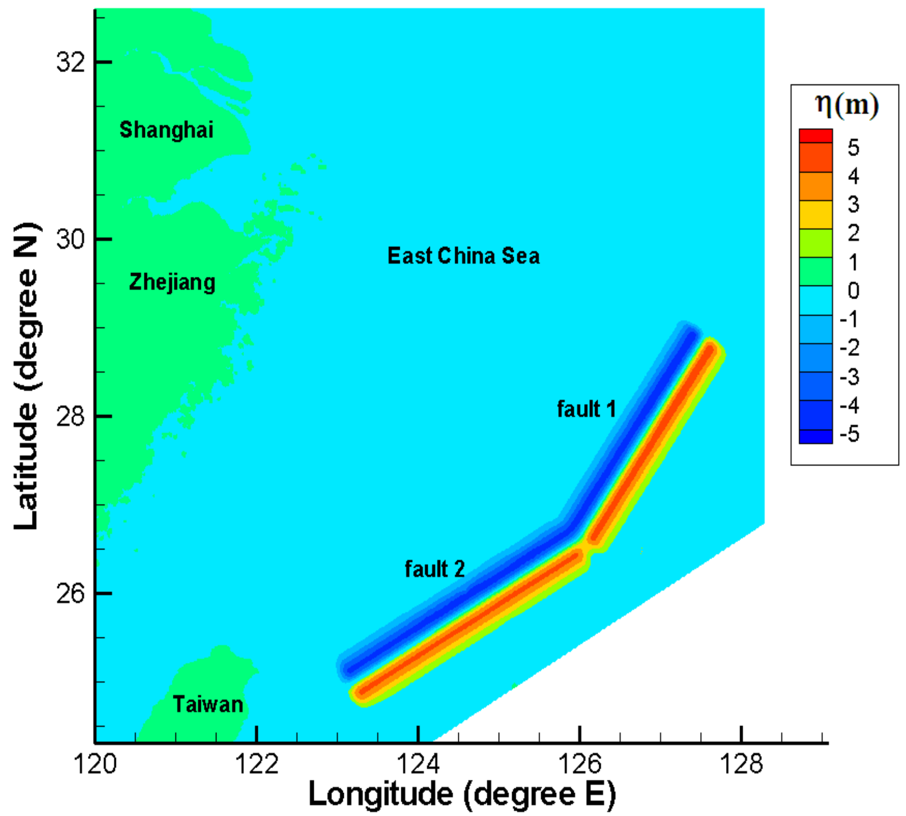


- The maximum wave height of tsunami along China coast is about 0.6m.

Scenarios of local tsunami---ECS

- Computational domain and subduction zone





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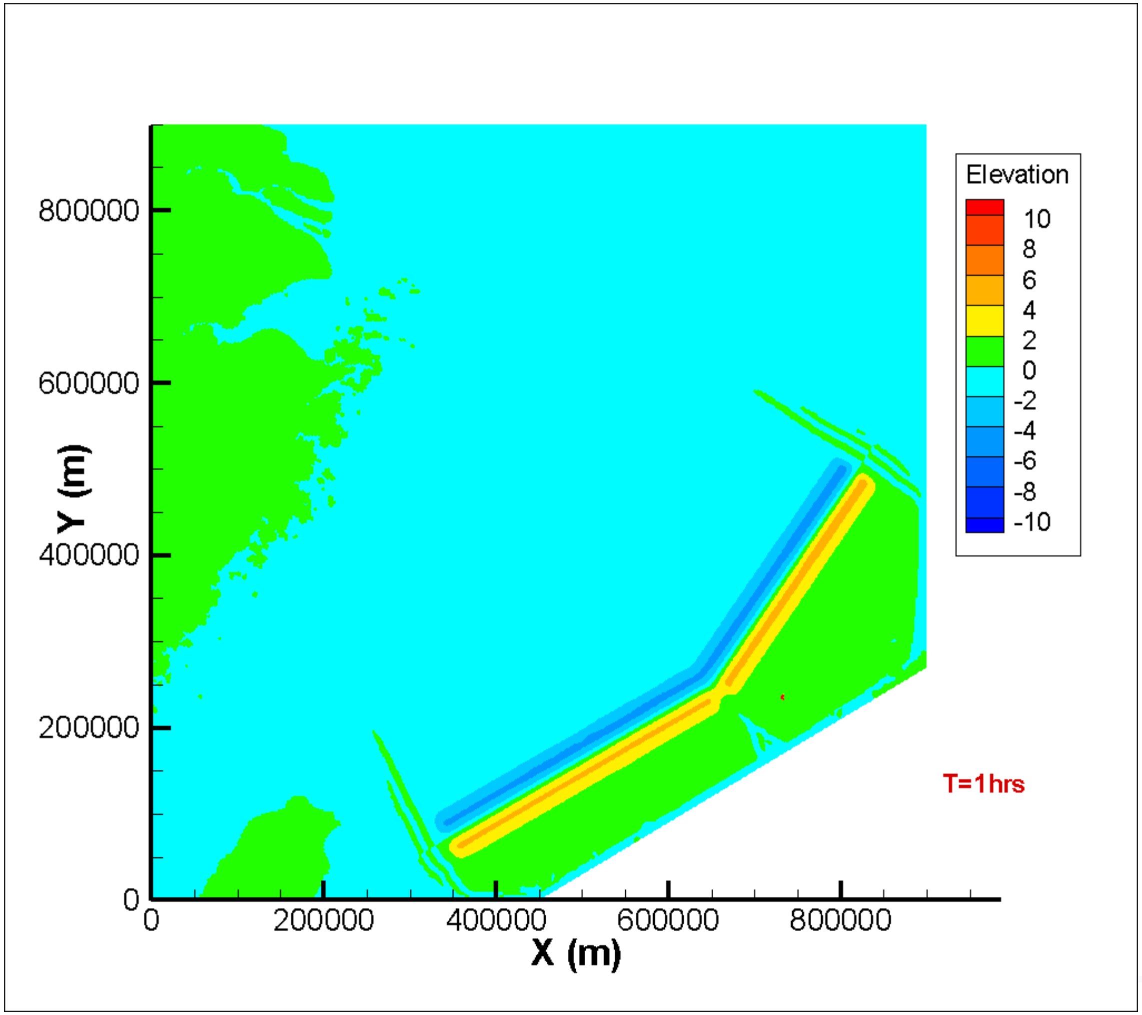
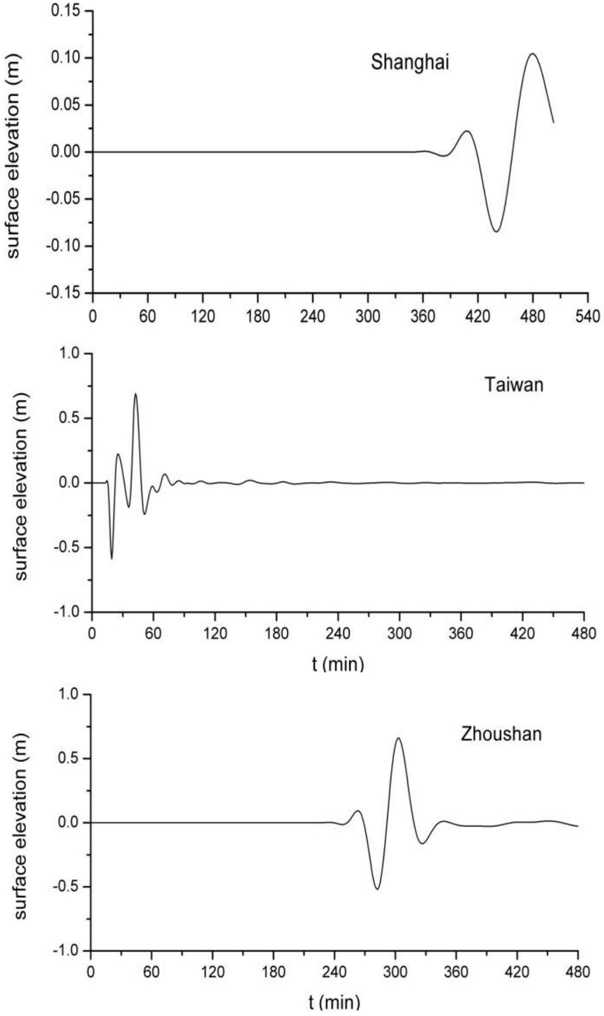
Scenarios of local tsunami---ECS

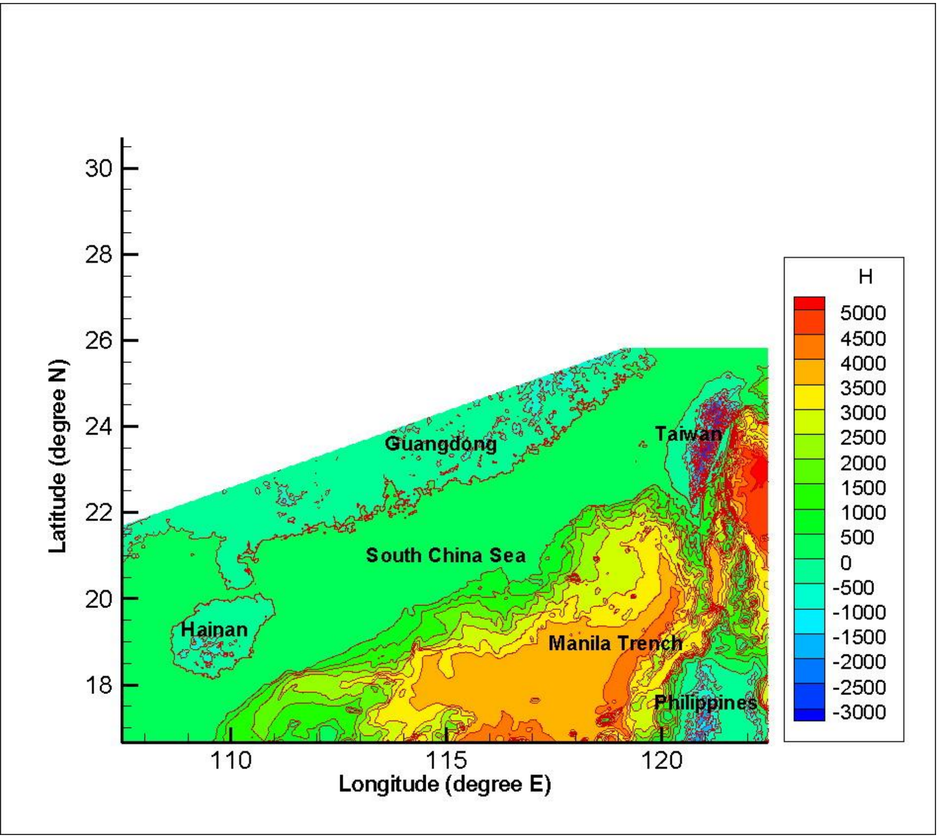
- Surface elevation

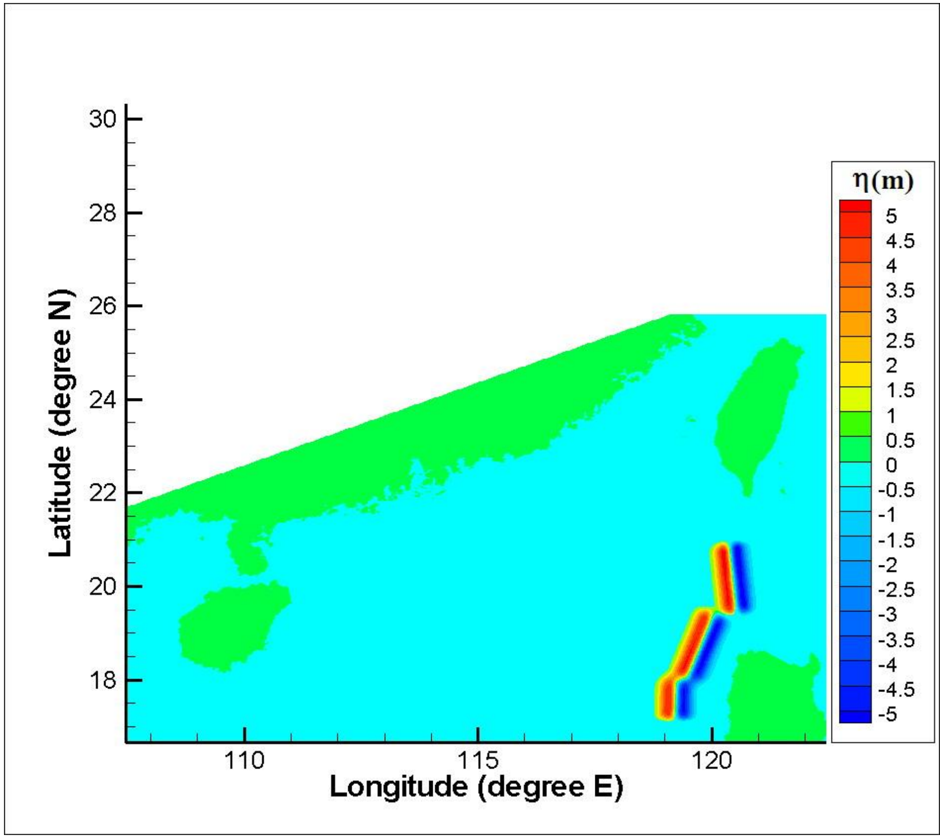




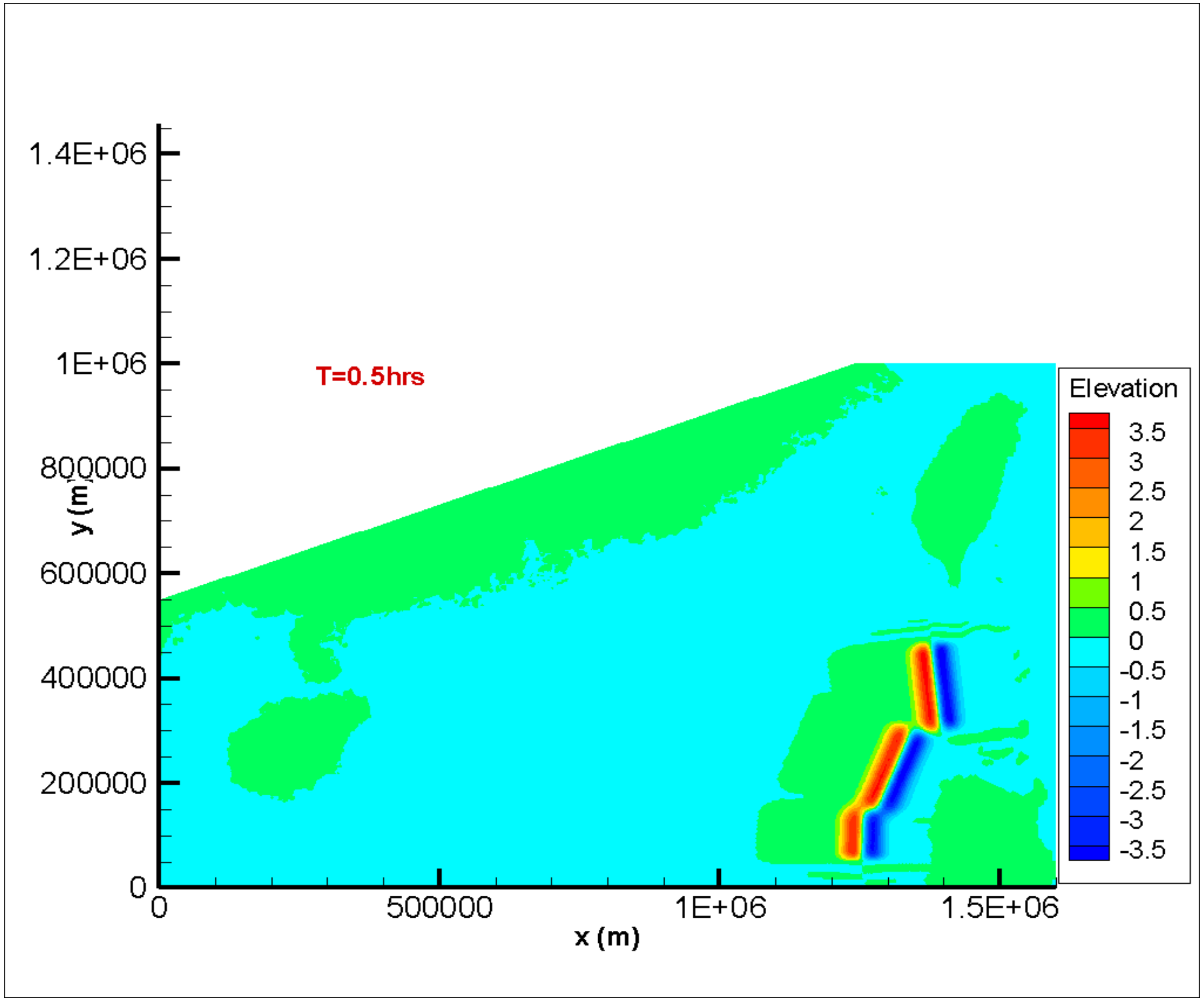
Scenarios of local tsunami---scs

- Computational domain and subduction zone in SCS

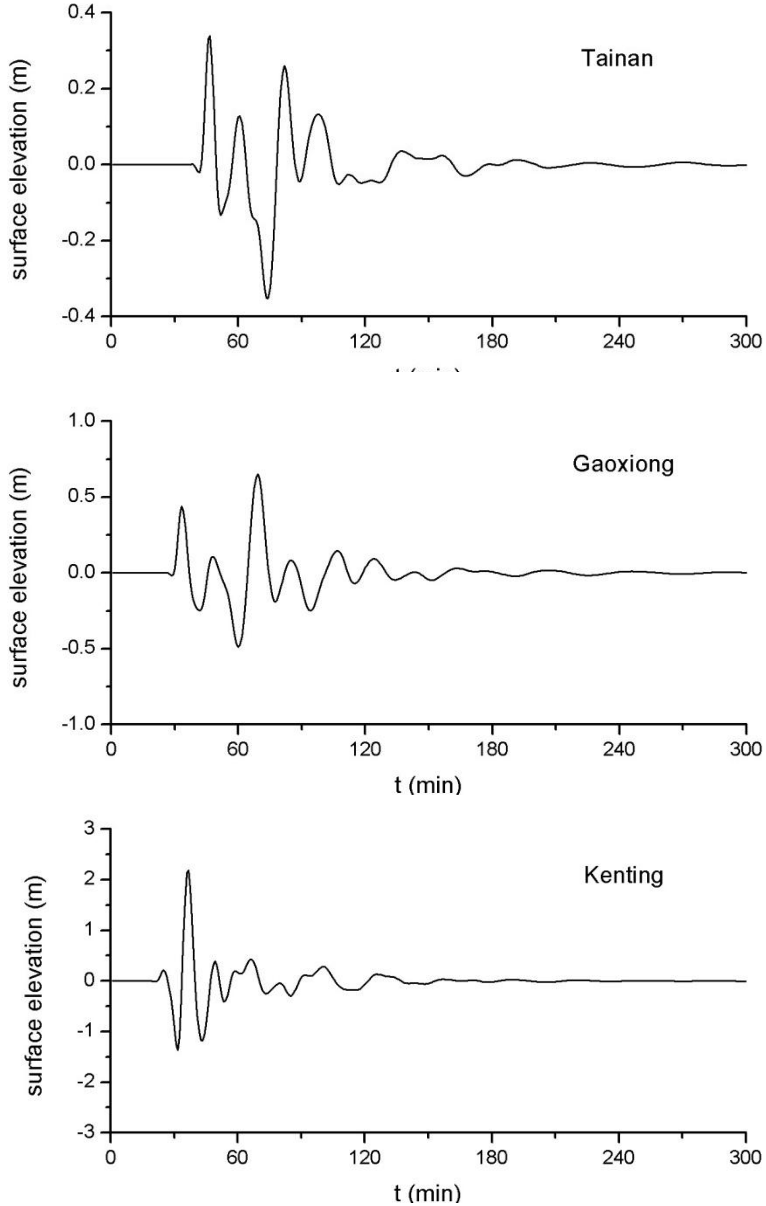




Scenarios of local tsunami---SCS



Scenarios of local tsunami---scs



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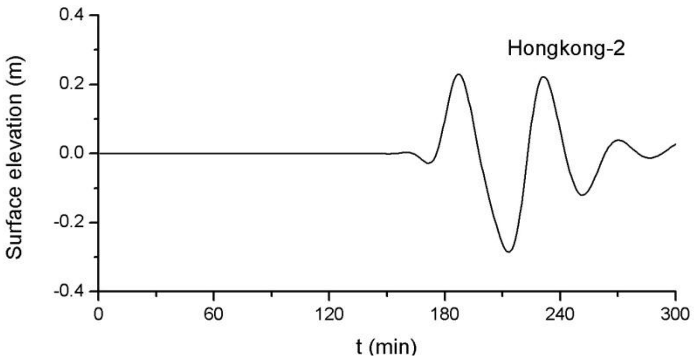
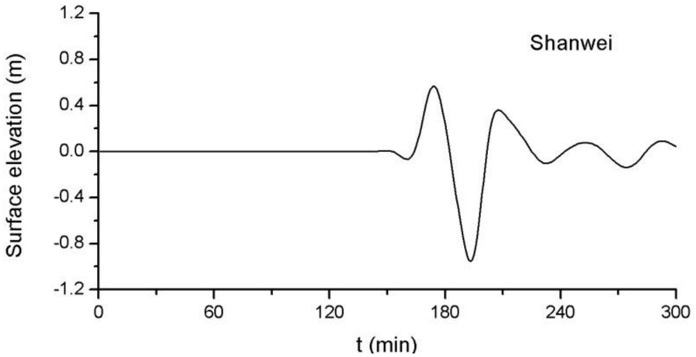
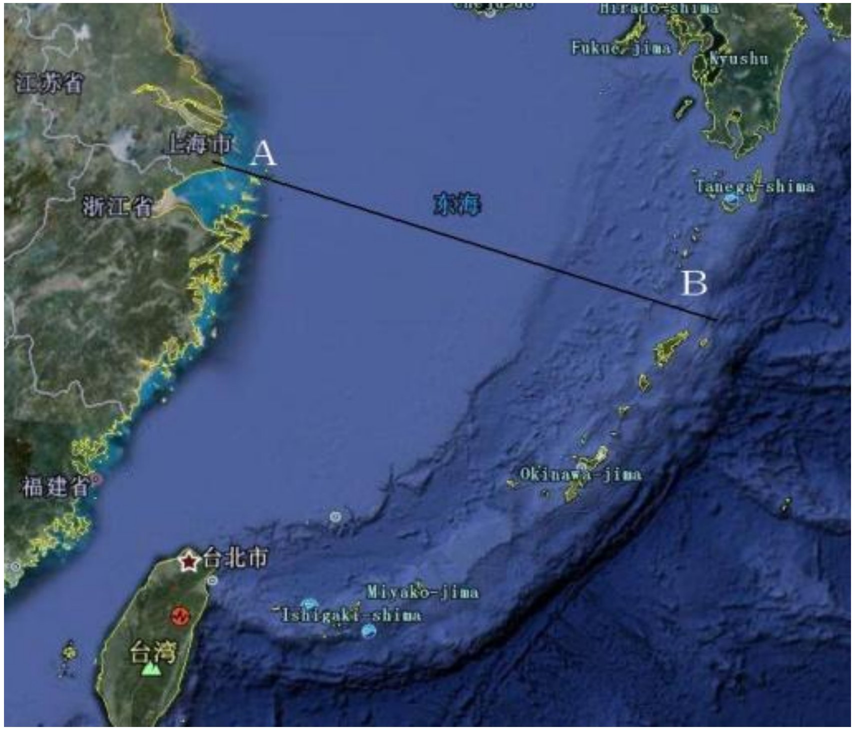
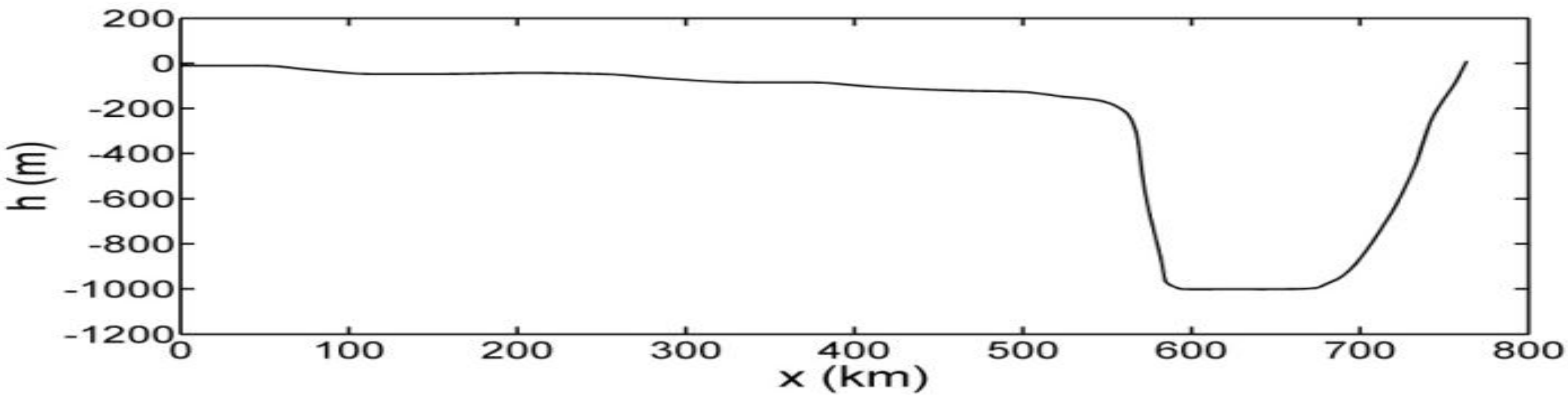




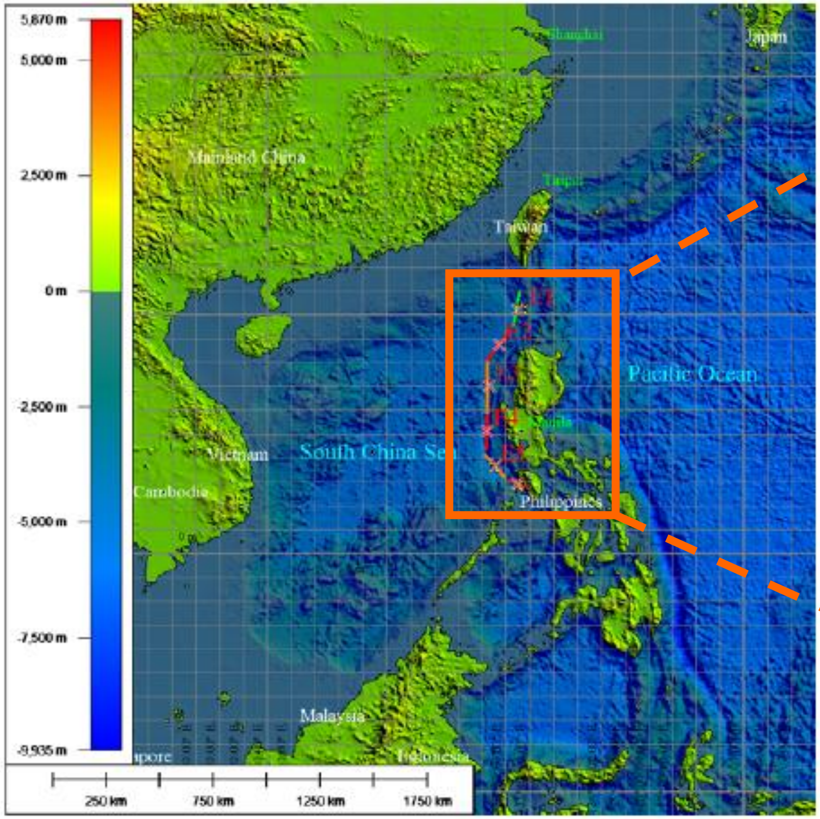
Introduction

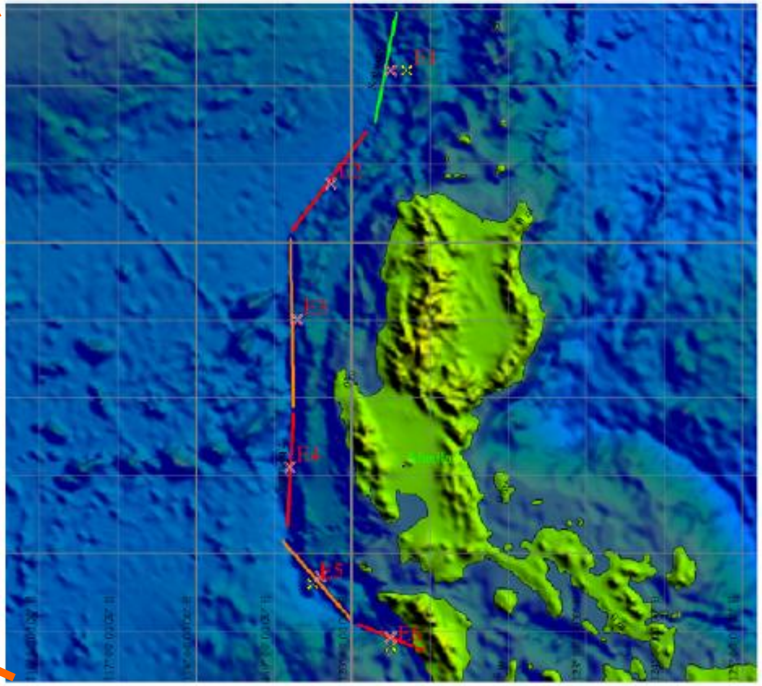


- East China Sea
- Wave patterns of the tsunami propagating over the continental shelf with a gentle slope?



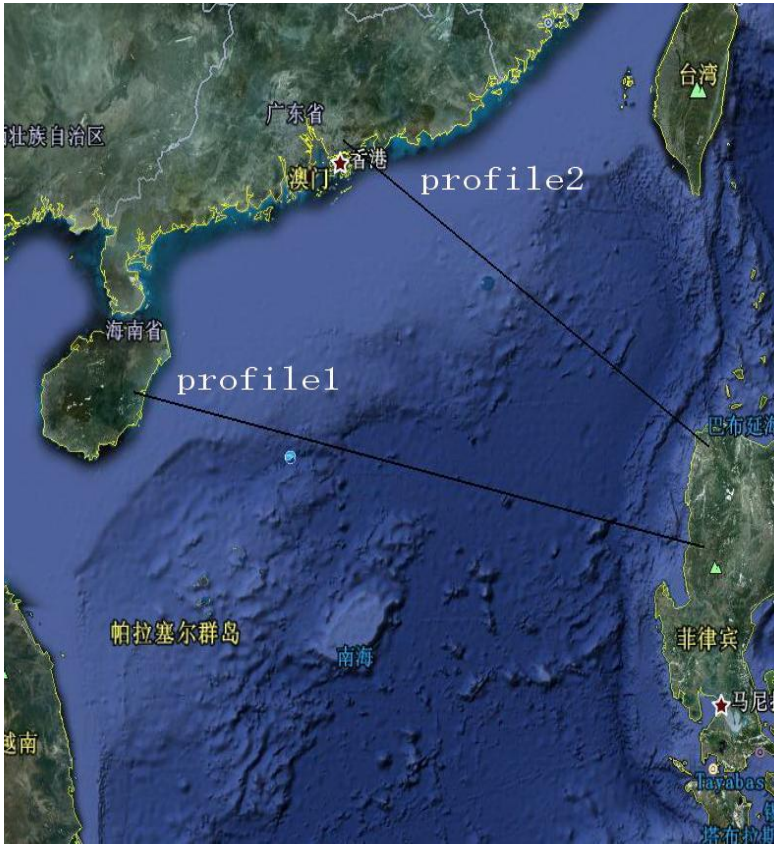
Scenarios of local tsunami---csc

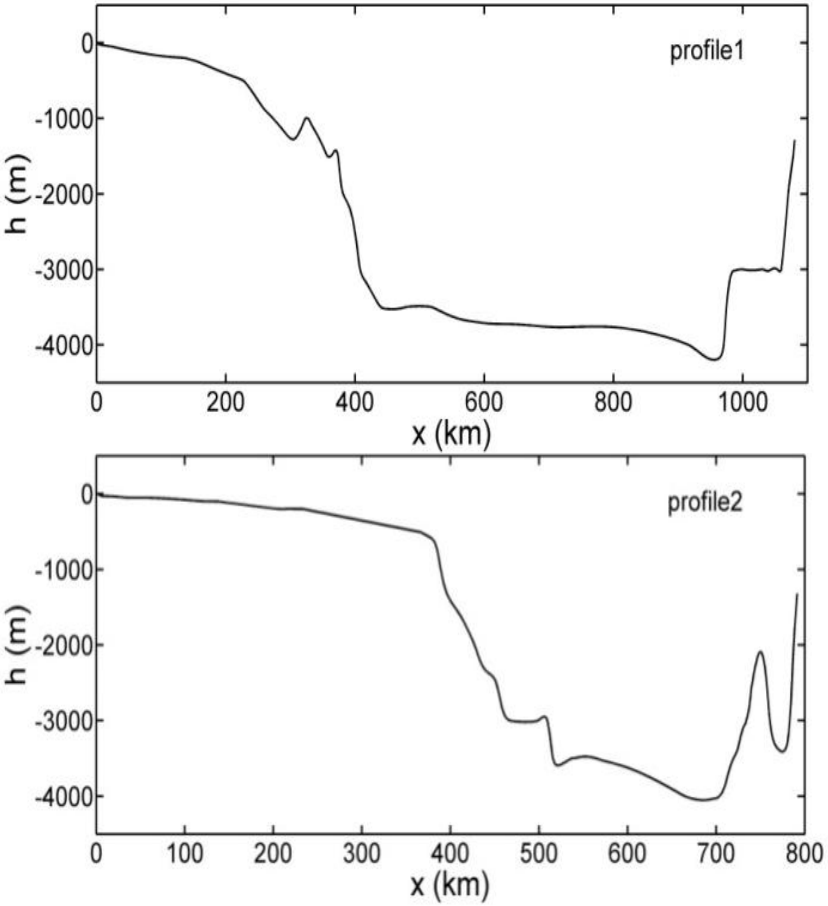




Manila trench in SCS

Introduction





- South China Sea

Introduction

- Motivation of the study

- wave patterns of tsunami propagating on continental shelf with a gentle slope

  South China Sea and East China Sea

- Runup of undular bores

Contents

Tsunami wave patterns in SCS

- Governing equations

$$\frac{\partial \zeta}{\partial t} - \tilde{w} + (\tilde{V} - \tilde{w}\nabla\zeta)\cdot\nabla\zeta = 0$$

$$\frac{\partial \tilde{V}}{\partial t} + g\nabla\zeta + \frac{1}{2}\nabla[\tilde{V}\cdot\tilde{V} - \tilde{w}^2(1+\nabla\zeta\cdot\nabla\zeta)] = 0$$

$$\tilde{V} = \tilde{\mathrm{u}} + \tilde{w}\nabla\zeta$$

$$w_b + \mathrm{u}_b\cdot\nabla h = -h_t$$

- Solution of the Laplace equation for potential flow

$$\mathbf{u}(x,y,z;t) = \cos(z\nabla)\mathbf{u}_0 + \sin(z\nabla)w_0$$
$$w(x,y,z;t) = \cos(z\nabla)w_0 - \sin(z\nabla)\mathbf{u}_0$$

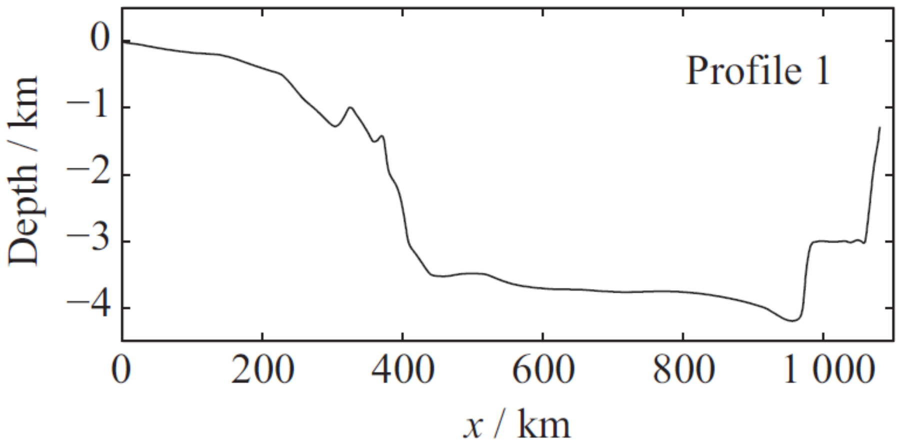
- Taylor operators

$$\cos\lambda\nabla = \sum_{n=0}^{\infty}(-1)^n\frac{\lambda^{2n}}{(2n)!}\nabla^{2n}, \quad \sin\lambda\nabla = \sum_{n=0}^{\infty}(-1)^n\frac{\lambda^{2n+1}}{(2n+1)!}\nabla^{2n+1}$$

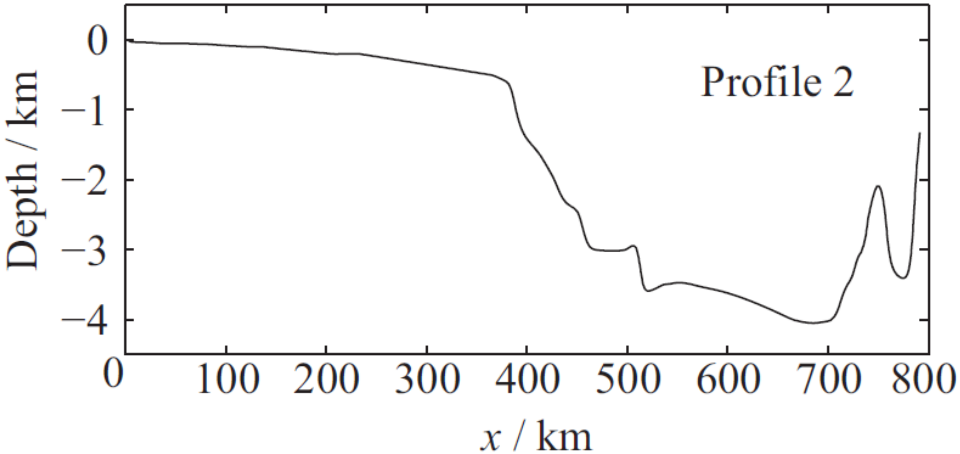
Madsen, Bingham, Liu. JFM, 2002；Wang, Liu. IJNMF, 2005.

Tsunami wave patterns in SCS

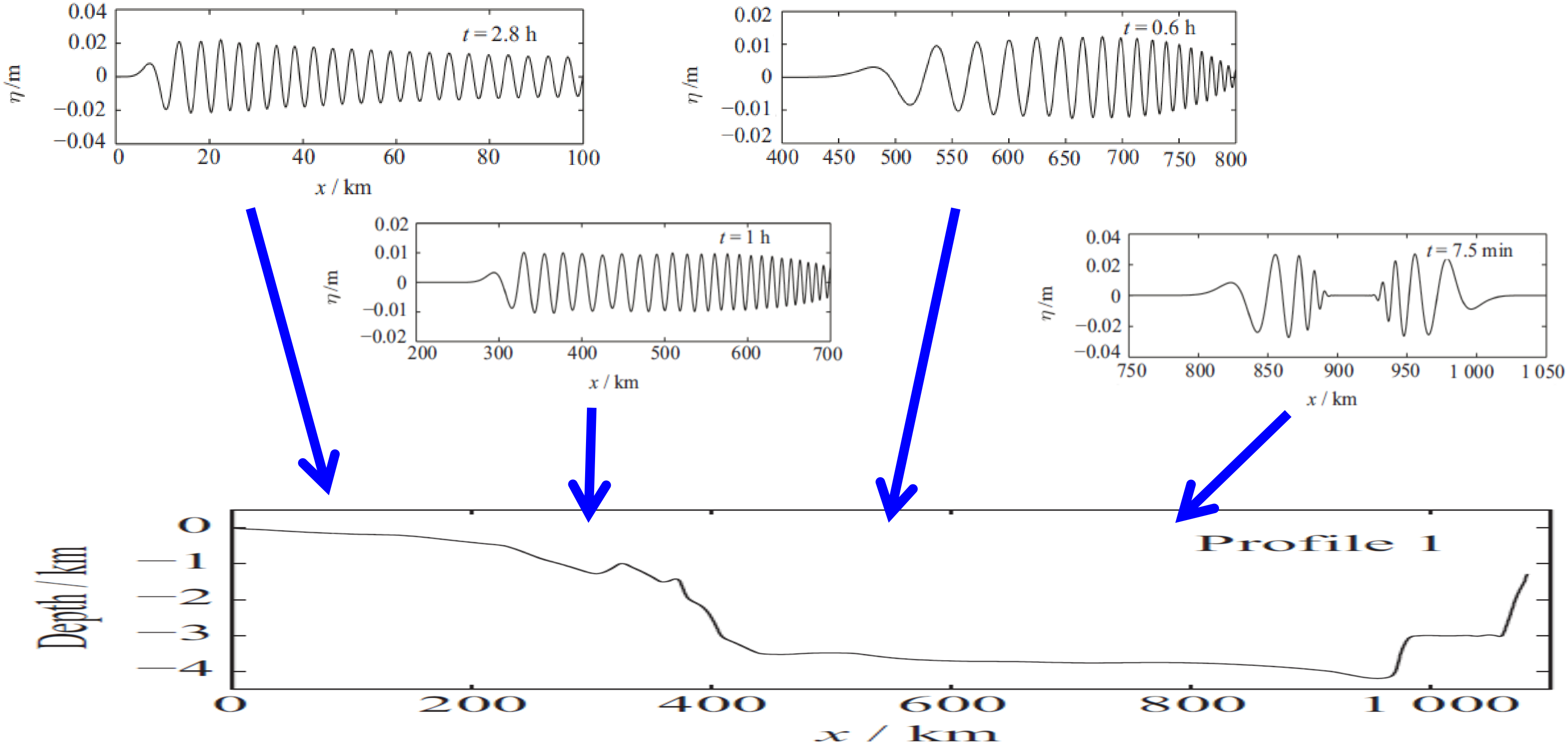
- The slope of continental shelf in SCS changes from 1:300 to 1:800.



- The length of the continental shelf is about 200 km and 400 km, respectively.

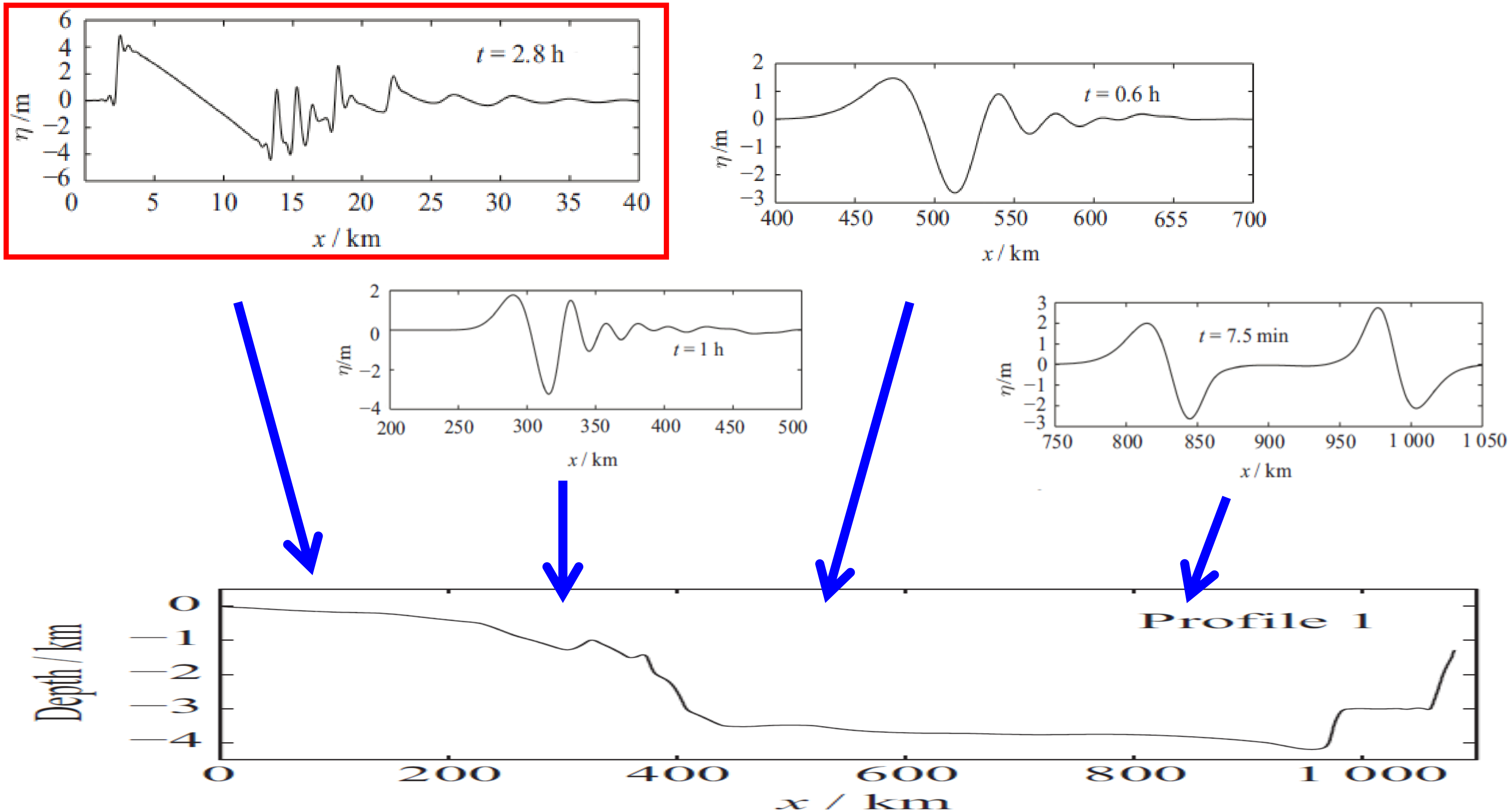


Tsunami wave patterns in SCS



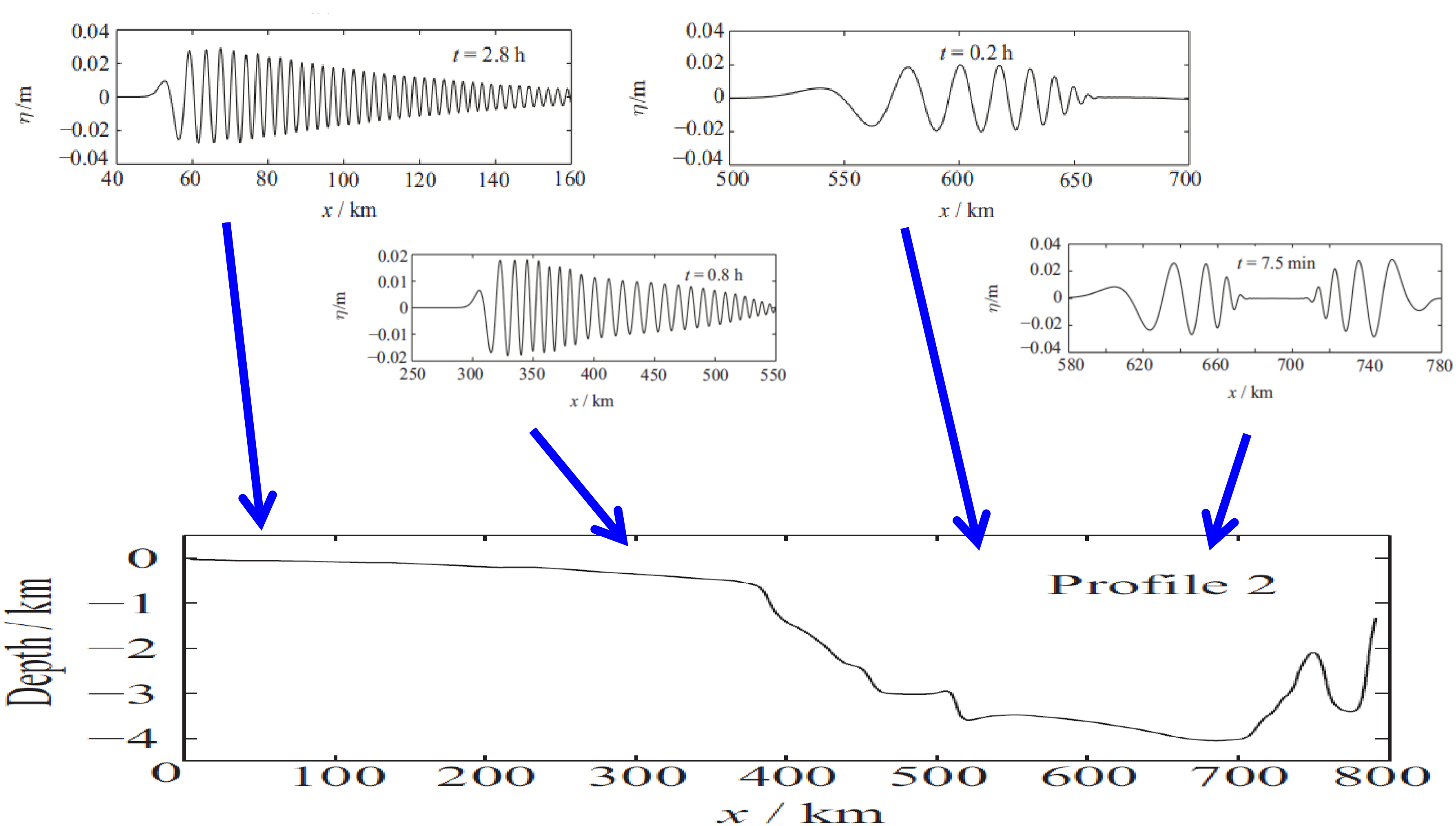
- South China Sea, Profile 1, M7.0

Tsunami wave patterns in SCS



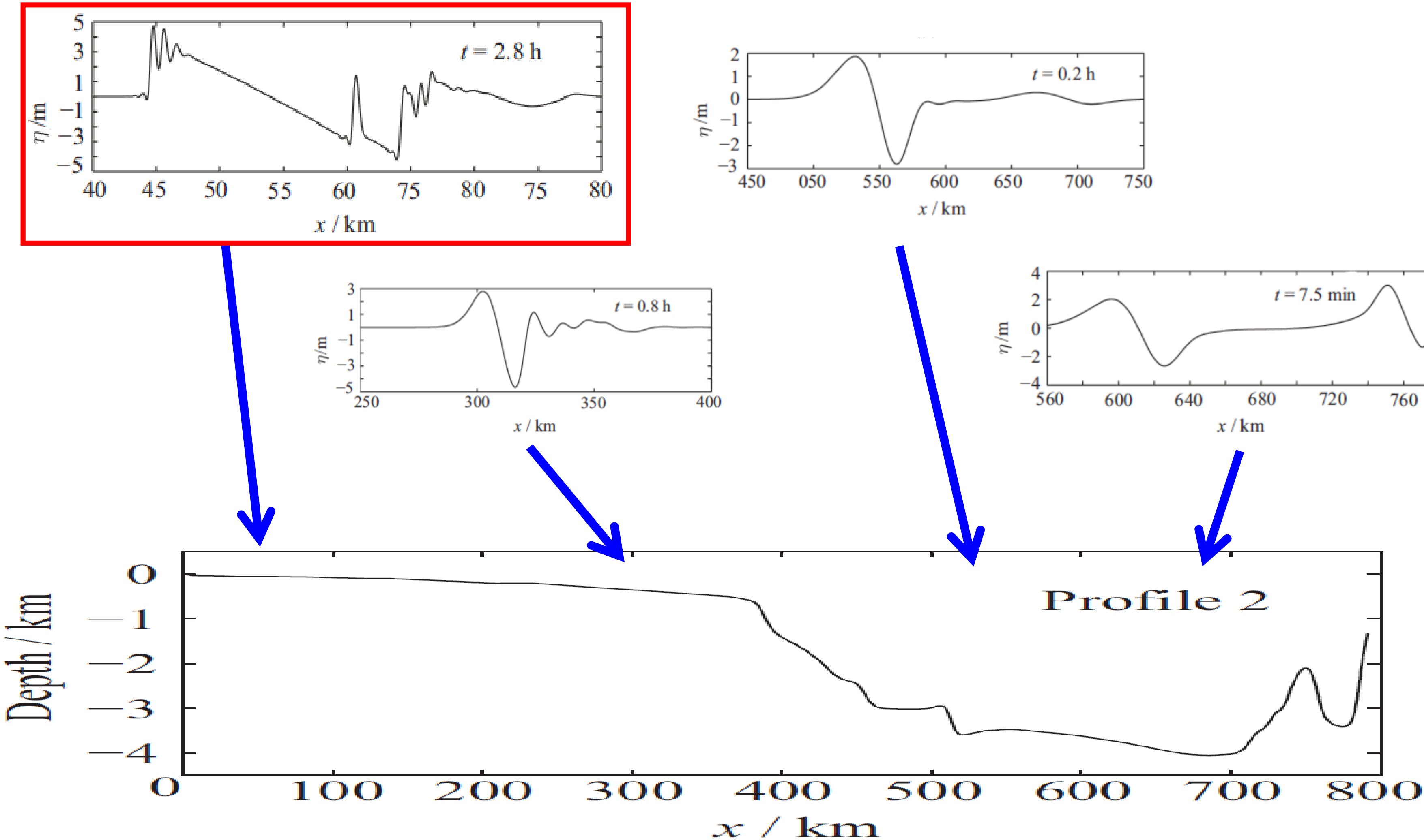
- South China Sea, Profile 1, M9.0

Tsunami wave patterns in SCS



- South China Sea, Profile 2, M7.0

Tsunami wave patterns in SCS

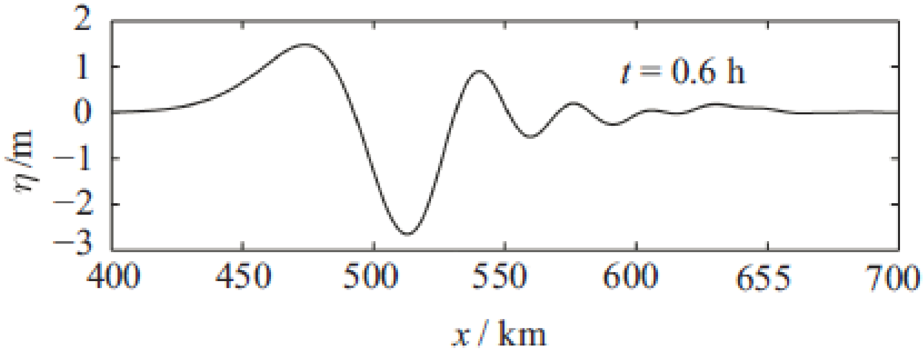


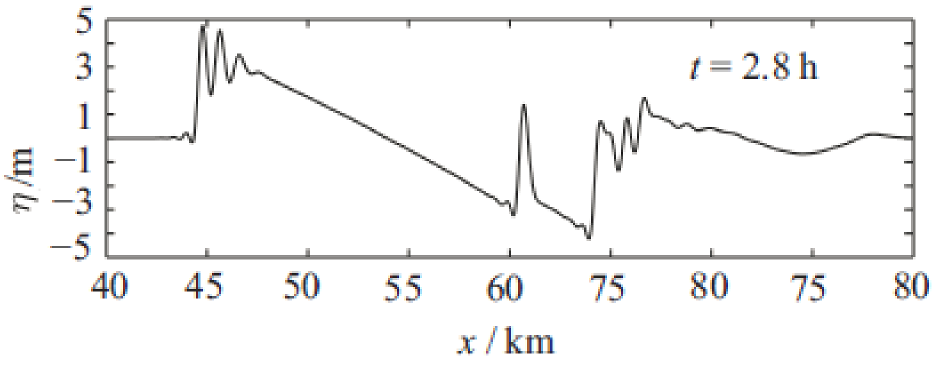
- South China Sea, Profile 2, M9.0

Contents

Runup of undular bores

- Runup of N-waves
- Amplification of wave height
- Runup of undular bores





Runup of N-waves

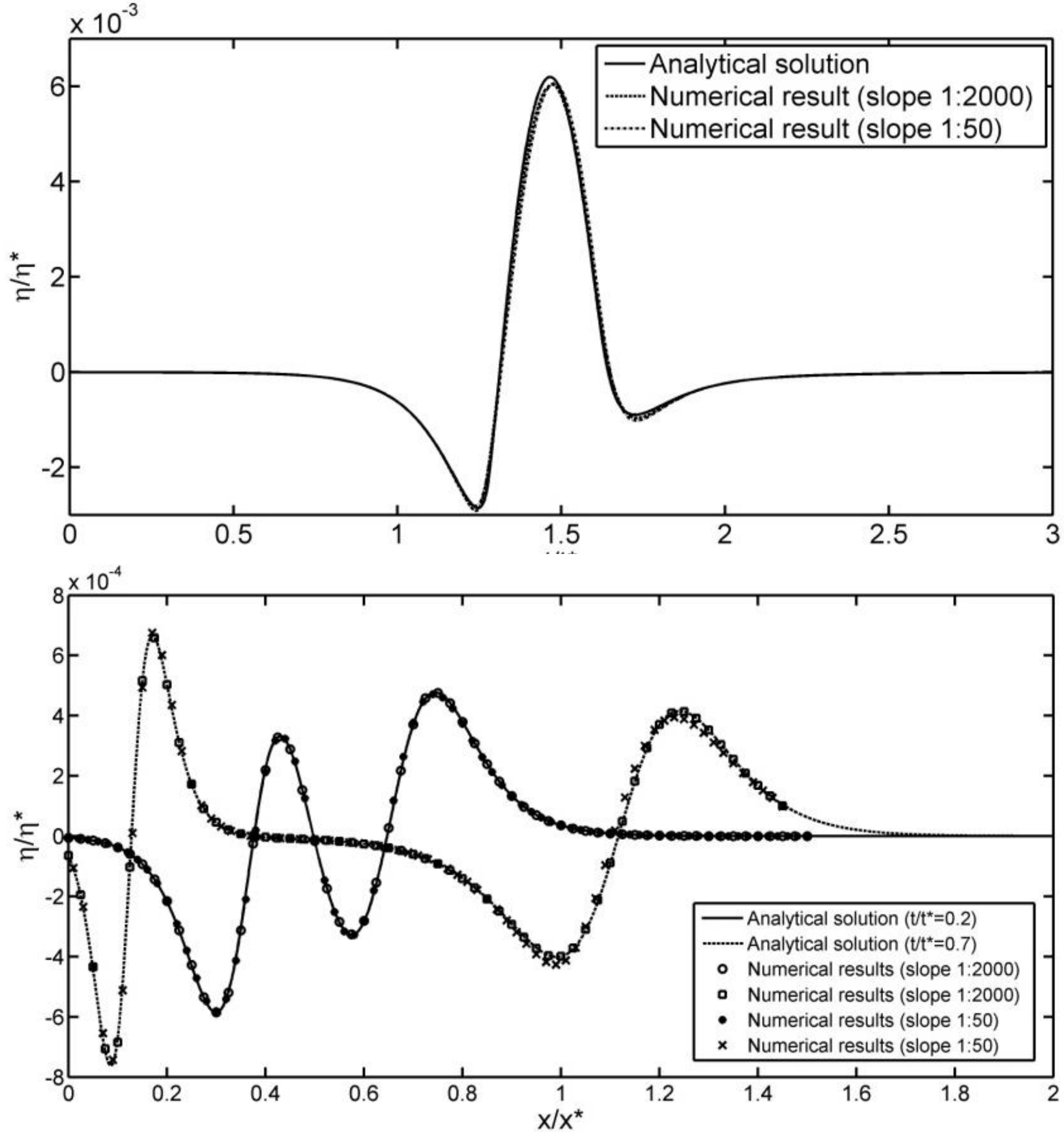
Runup of N-waves

$$\eta = \frac{3}{2}\sqrt{3}H_m \operatorname{sech}^2[k_m(x-x_1)]\tanh[k_m(x-x_1)]$$

	H_m	k_m	x_1
Case 1	0.001	7.8964	0.5
Case 2	0.01	7.8964	0.5
Case 3	0.01	5.5836	1
Case 4	0.01	4.9353	2
Case 5	0.01	4.9941	5
Case 6	0.01	8.8285	10

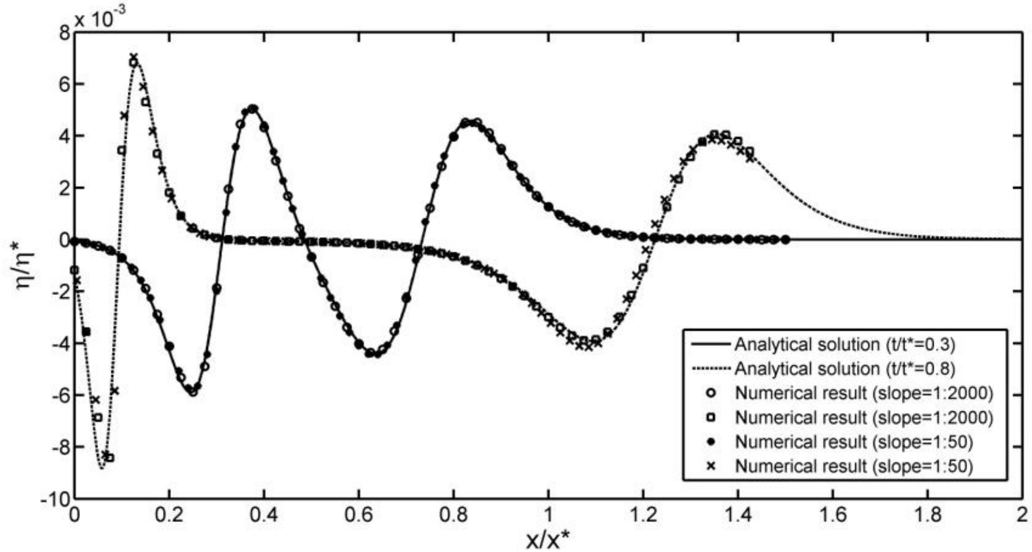
Runup of N-waves

- Case 1

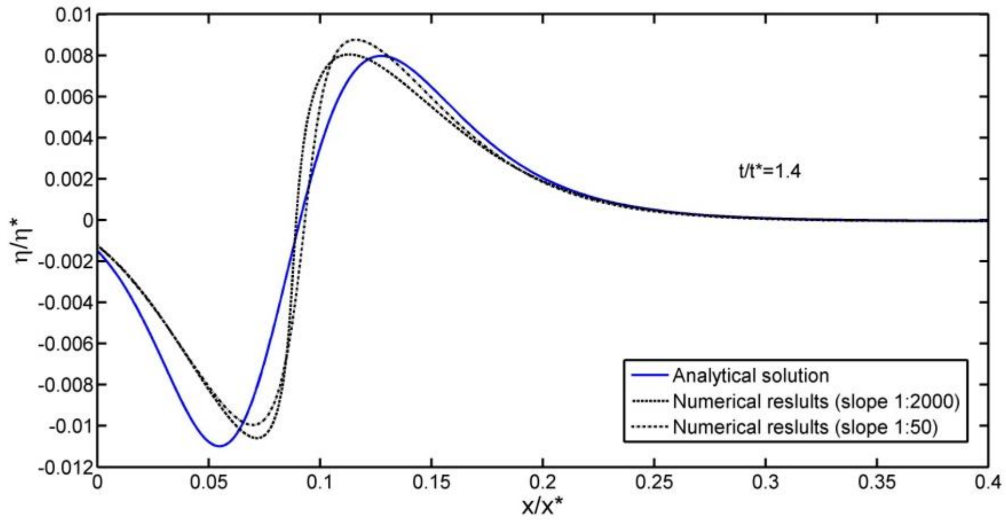


Runup of N-waves

- Case 2

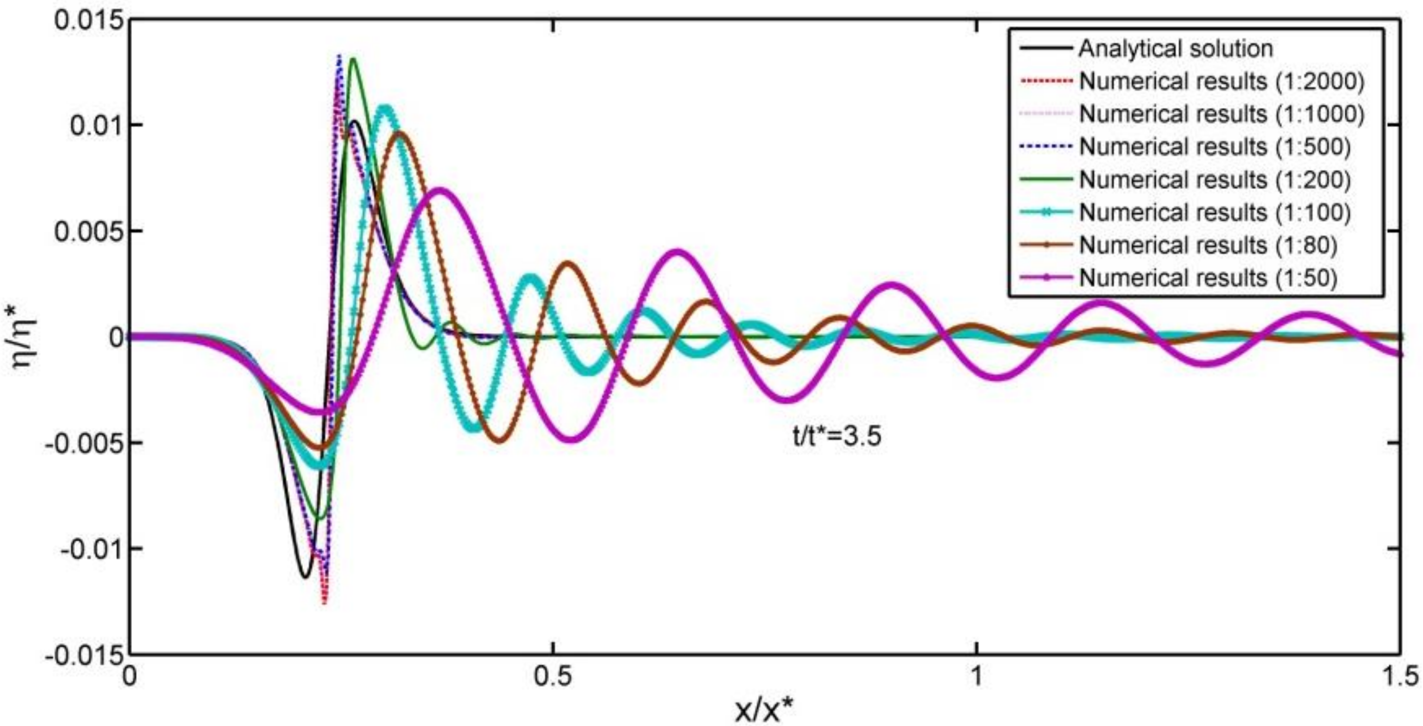


- Case 3

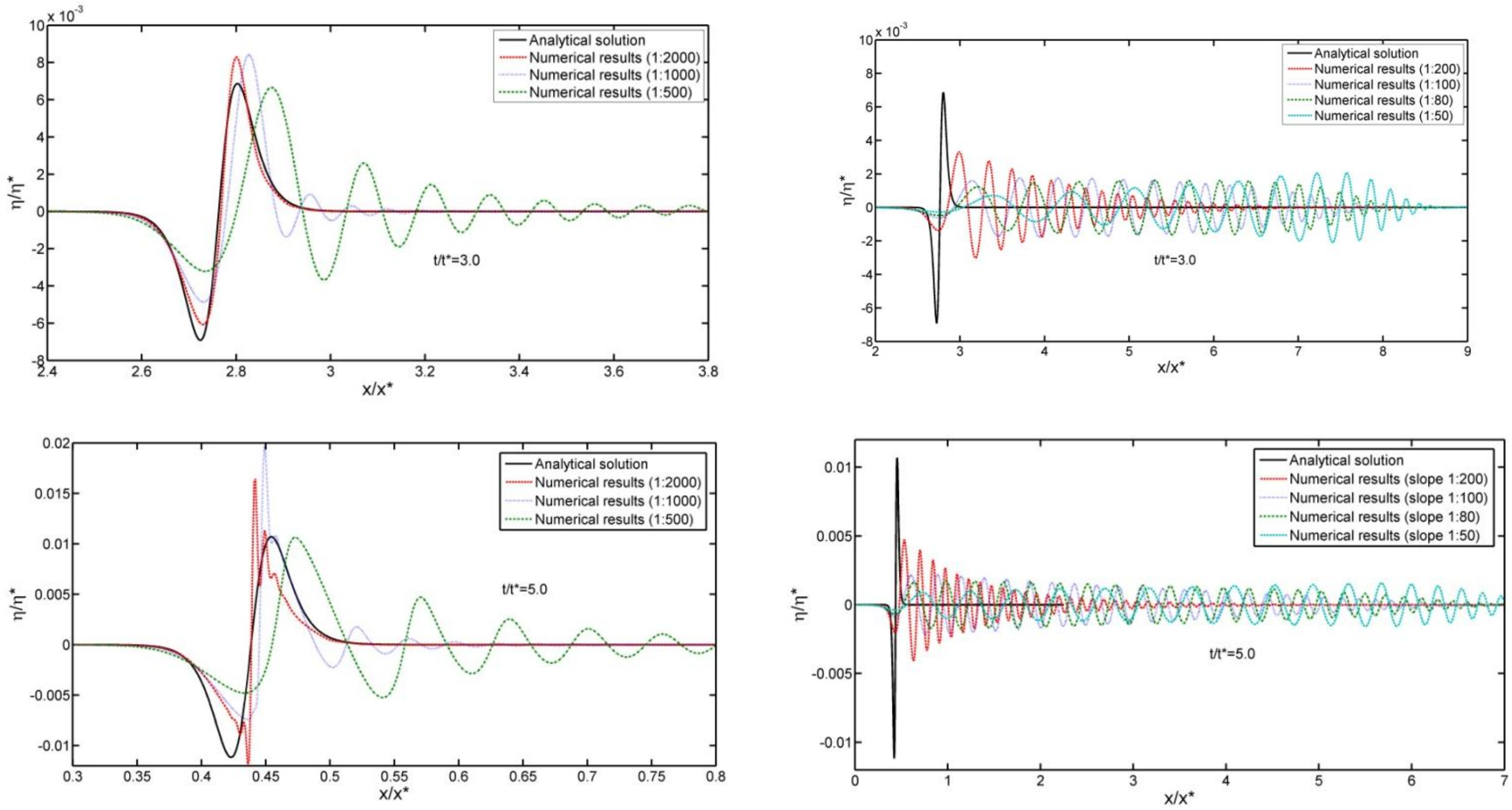


Runup of N-waves

- Case 5

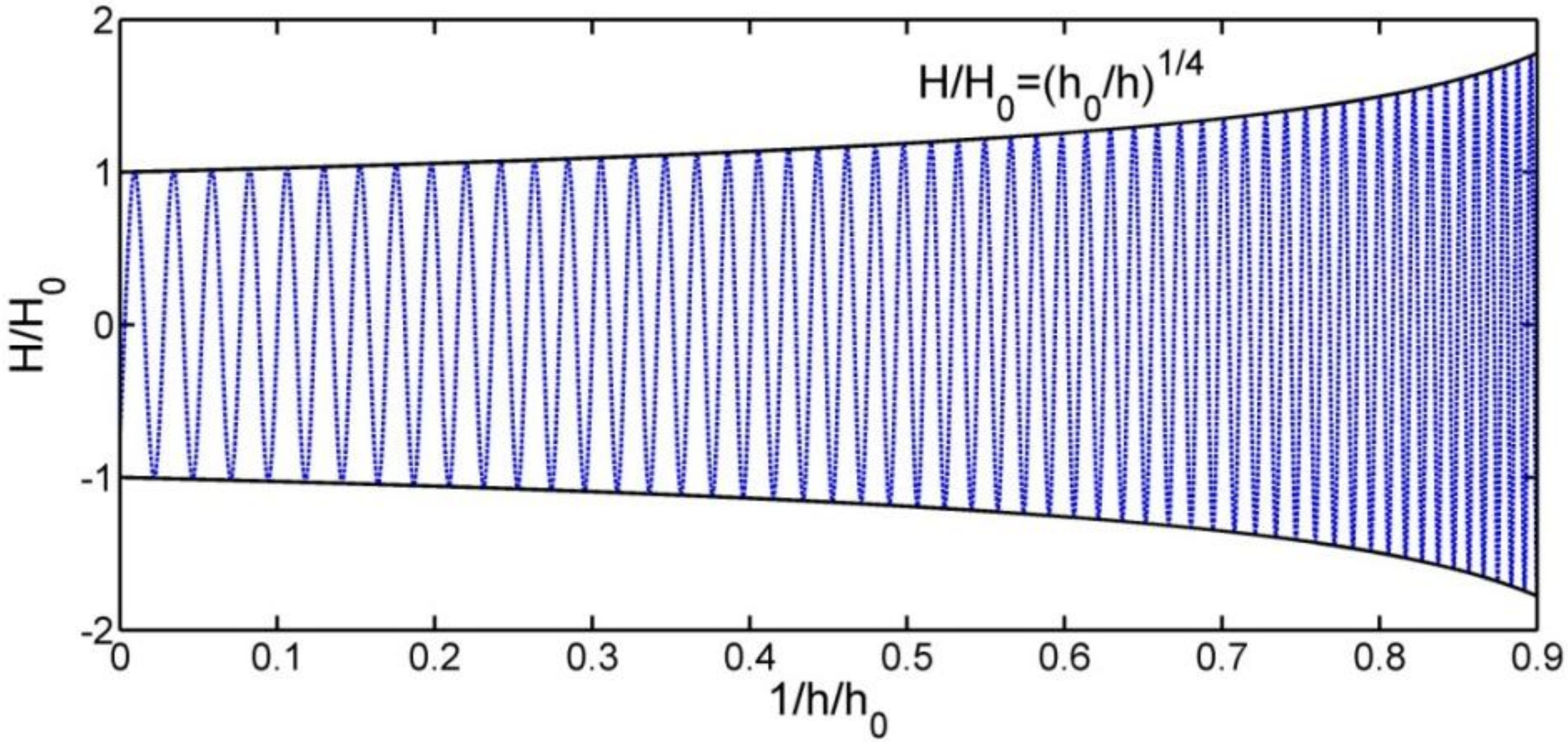


Runup of N-waves



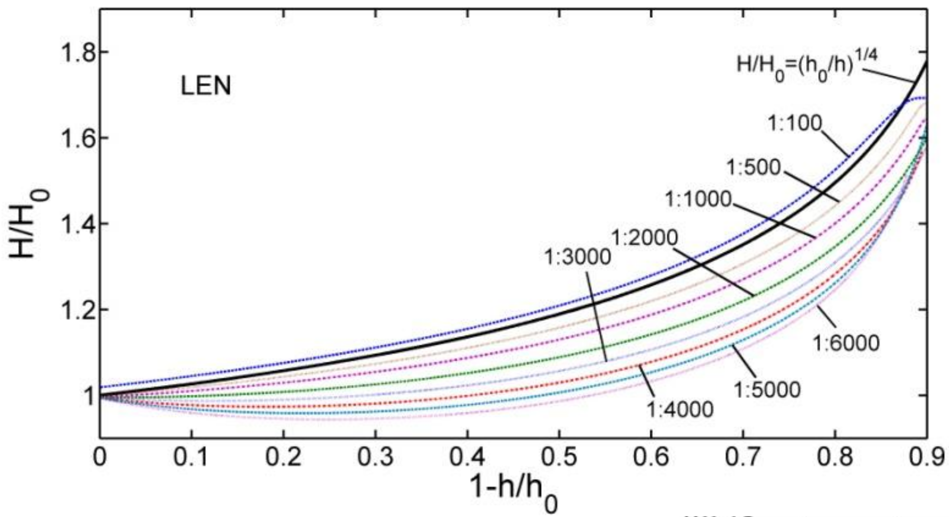
- Case 6

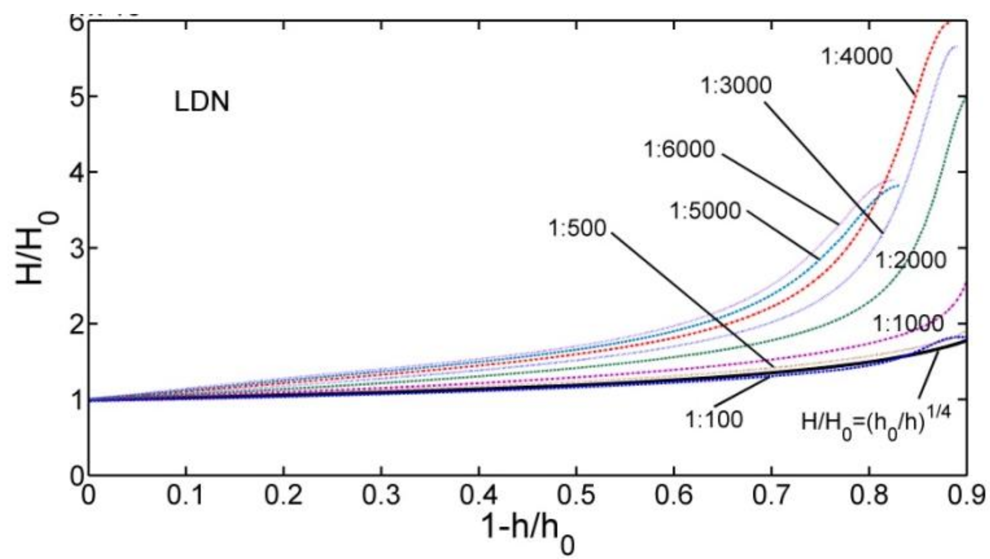
Amplification of wave height



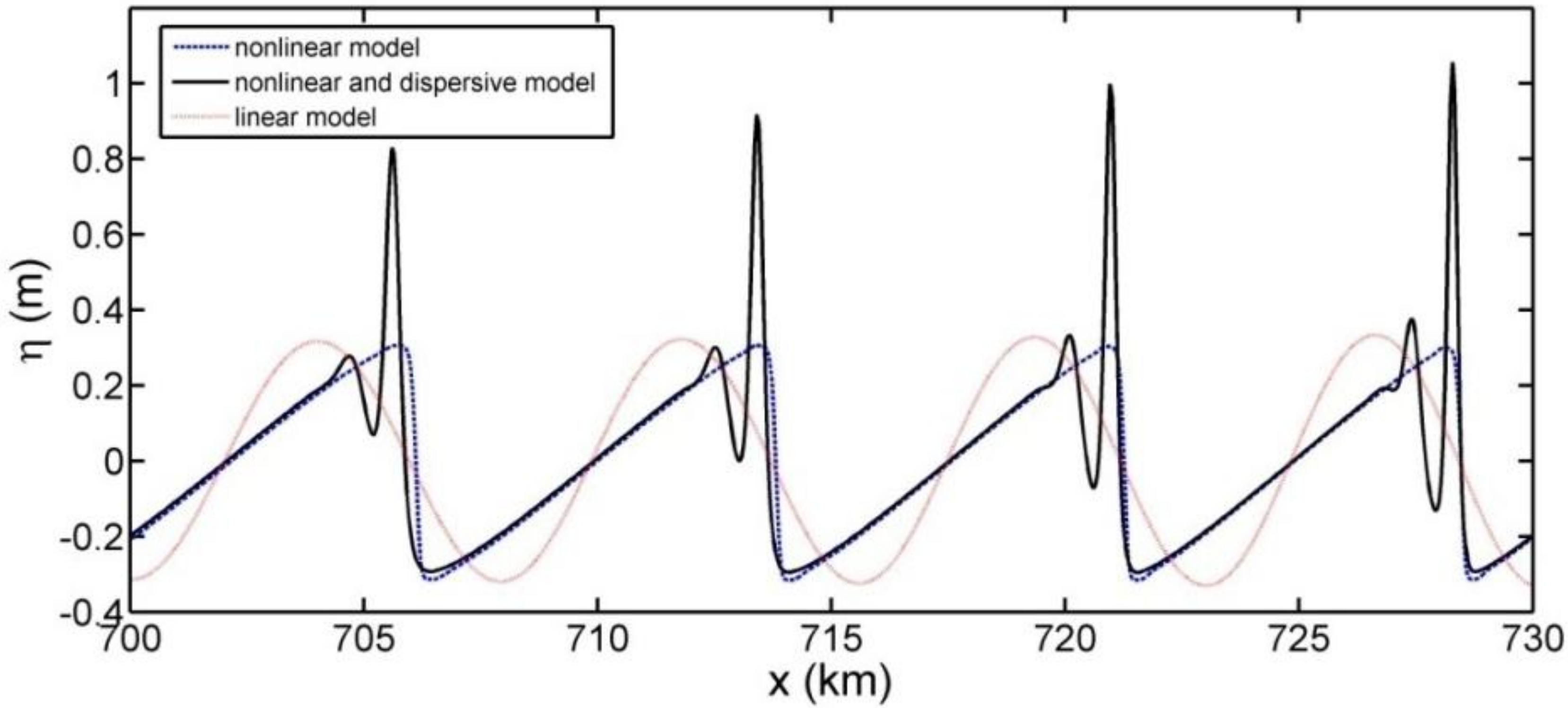
- Amplitude evolution of sinusoidal wave shoaling on a 1:4000 sloping beach

Amplification of wave height





Amplification of wave height



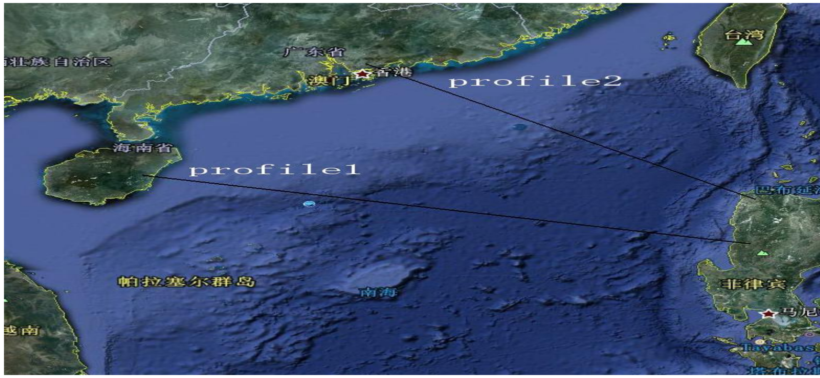
- Sinusoidal wave shoaling on a 1:4000 sloping beach by different models.
  - Dash line: nonlinear shallow water equations,
  - Dolid line: nonlinear and dispersive Boussinesq equations,
  - Dot-dash line: linear model.

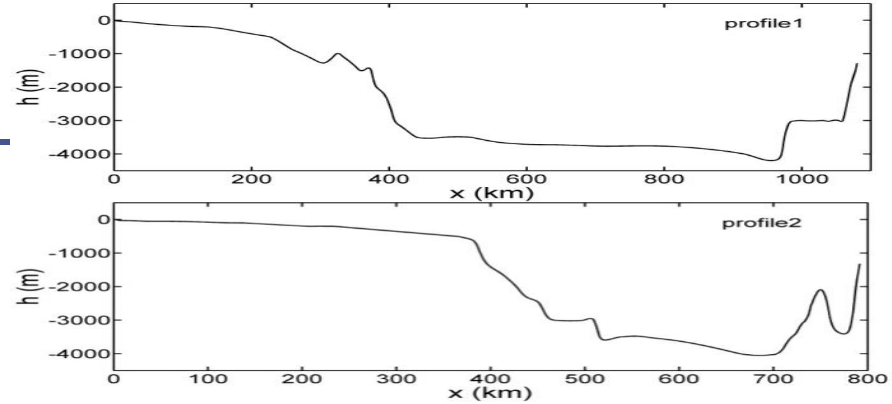
Runup of undular bores

- A simplified 1-D model for submarine earthquake

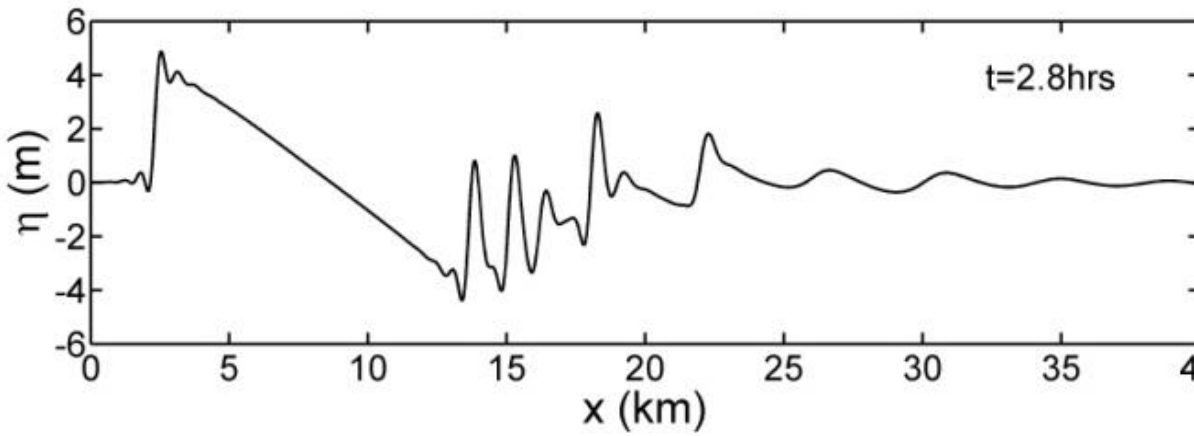
$$\zeta(x',t) = 2AC\,\mathrm{sech}^2(Cx')\tanh(Cx')\sin(\pi t/2\tau)$$

Magnitude (Richter)	W(km)	C	A	Slip distance (m)	τ (s)
6.5	8	1	0.182	0.56	2.24
7.0	14	0.5	1.3	1.0	4
7.5	25	0.27	4.27	1.78	7.12
8.0	45	0.15	13.8	3.17	12.68
8.5	79	0.1	36.8	5.66	22.64
9	141	0.05	130	10	40
9.5	251	0.03	385	17.8	71.2

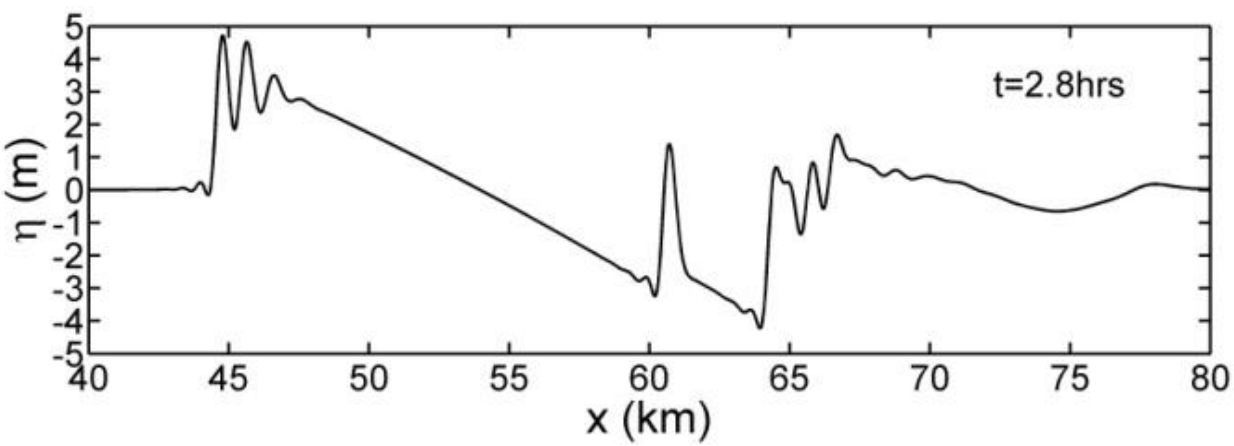




- Profile 1



- Profile 2



- Undular bores

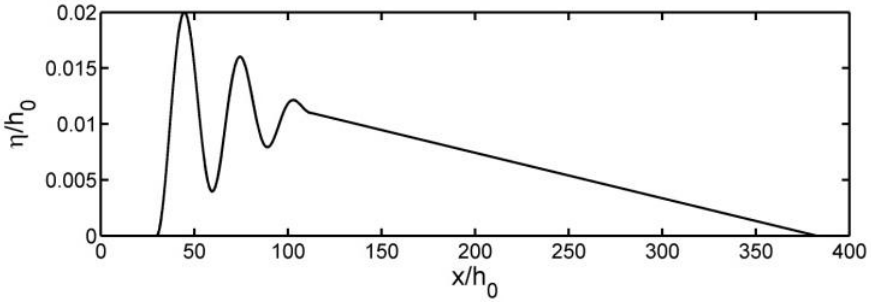
Runup of undular bores

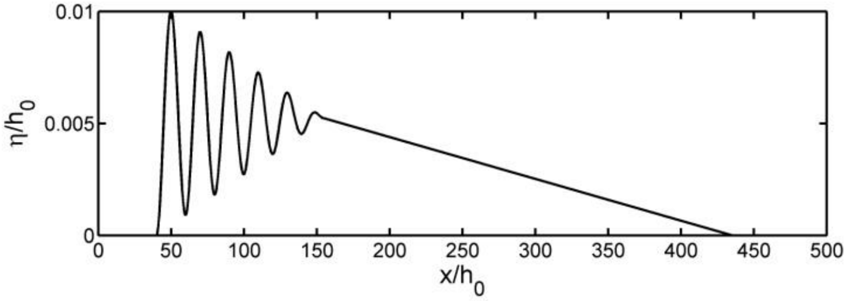
- ***A simplified model of the undular bores***

$$\eta_0 = \eta_{u0} + \eta_{b0}$$

$$\eta_{u0} = \varepsilon\{\frac{H_0}{2}\sin[k_u(x-\frac{L_u}{4}-x_0)]\cdot(-x+nL_u+x_0)/(nL_u)+\frac{H_0}{2}\} \qquad x_0 \le x \le nL_u$$

$$\eta_{b0} = \frac{H_0}{2}\cdot(-x+n\cdot L_u+x_0)/L_b+\frac{H_0}{2} \qquad nL_u \le x \le nL_u+L_b$$





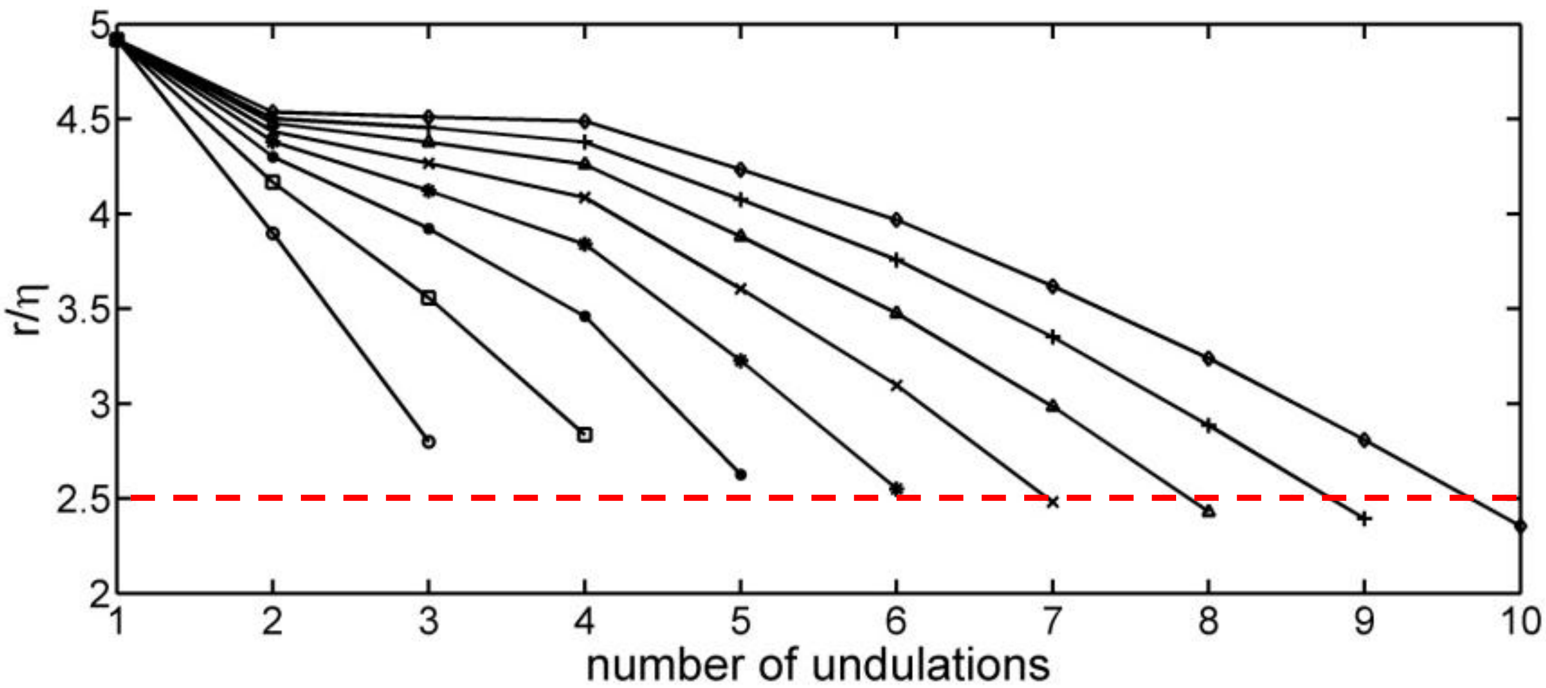
- H_0/h_0=0.02 , L_u=30h_0
- nL_u+L_b=12L_u

H_0/h_0=0.01, L_u=20h_0

nL_u+L_b=20L_u

Runup of undular bores

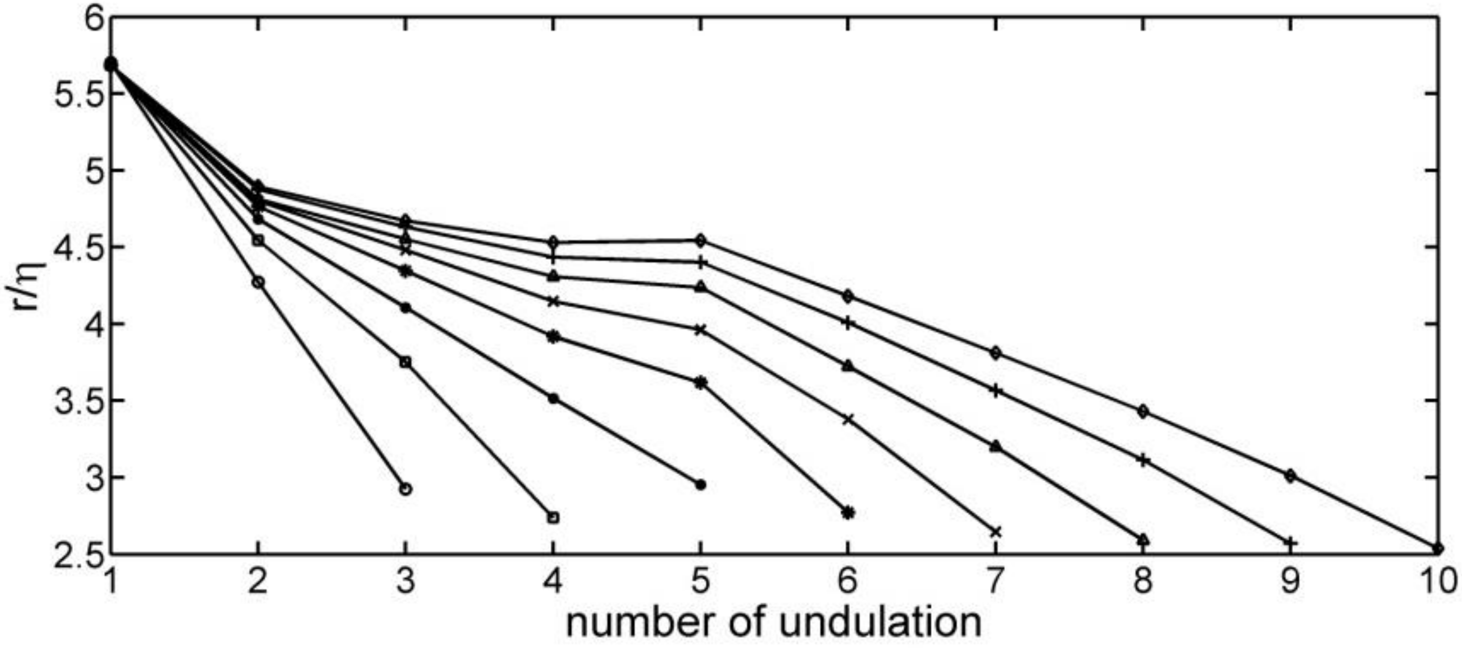
- Maximum runup of every undulation. ($L_u=30h_0$)



- The relative runup *r/η* changes only with the number of undulations. The relative wave height H_0/h_0 and the lengths of the rest part of the long bores L_b have no effect on *r/η*.

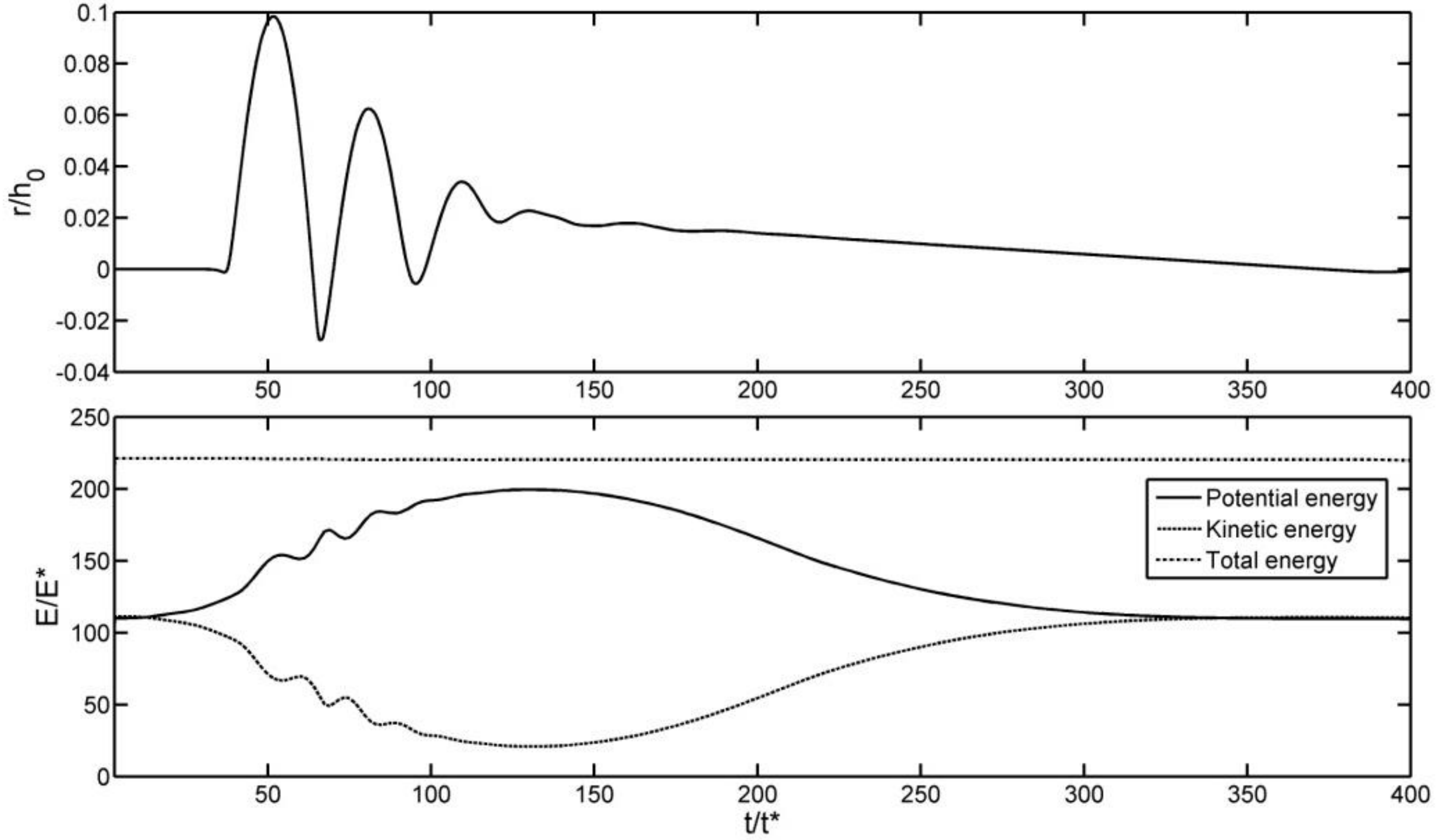
Runup of undular bores

- Maximum runup of every undulation. (L_u=20h_0)



- The relative runup *r/η* increase with the decrease of the wave length of undulations.

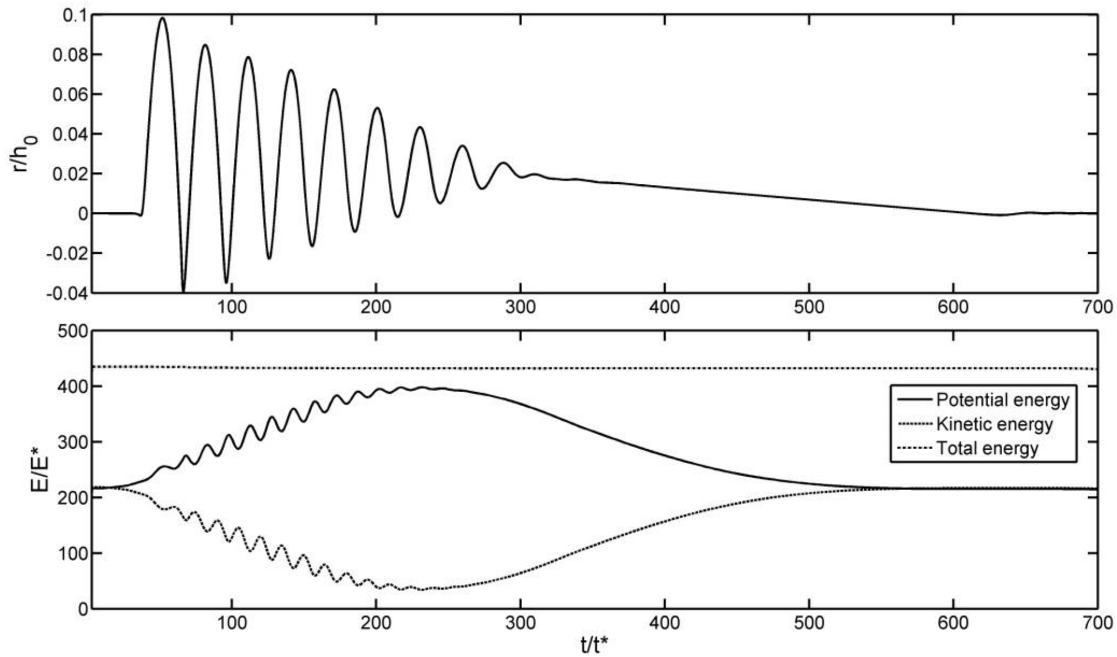
Runup of undular bores



- The shoreline movement and energy budget during the runup process. (n=3, $nL_u+L_b=12L_u$, H_0/h_0=0.02)

Runup of undular bores

- The shoreline movement and energy budget during the runup process. (n=7, $nL_u+L_b=20L_u$, H_0/h_0=0.02)



- The undulations lead the shoreline to advance and recede significantly. The long bores don't bring maximum runup but brings the maximum potential energy of the tsunami waves to the coast.

Concluding remarks

- Considering the potential earthquake in Manila trench , much attention should be paid on impacts of the tsunami on China coast and other coastal countries along the South China Sea.

- Different wave patterns appear for tsunami propagating on a continental shelf with a gentle slope. Undular bore could appear in catostrophic tsunami wave in South China Sea.

Concluding remarks

- A simplified model of undular bores is proposed using summation of short sinusoidal components and a long attenuation component.
- The large advances of the shoreline are caused by the high undulations in front of the tsunami waves. However, the runup and rundown processes of the undulations don't lead to remarkable fluctuations of the energy transformation.
- The long bores don't bring maximum runup but brings the maximum potential energy of the tsunami wave to the coast.

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SCSTW-7, Taichung, 18-22 Nov. 2014

Runup of Double Solitary Waves on Steep Slope

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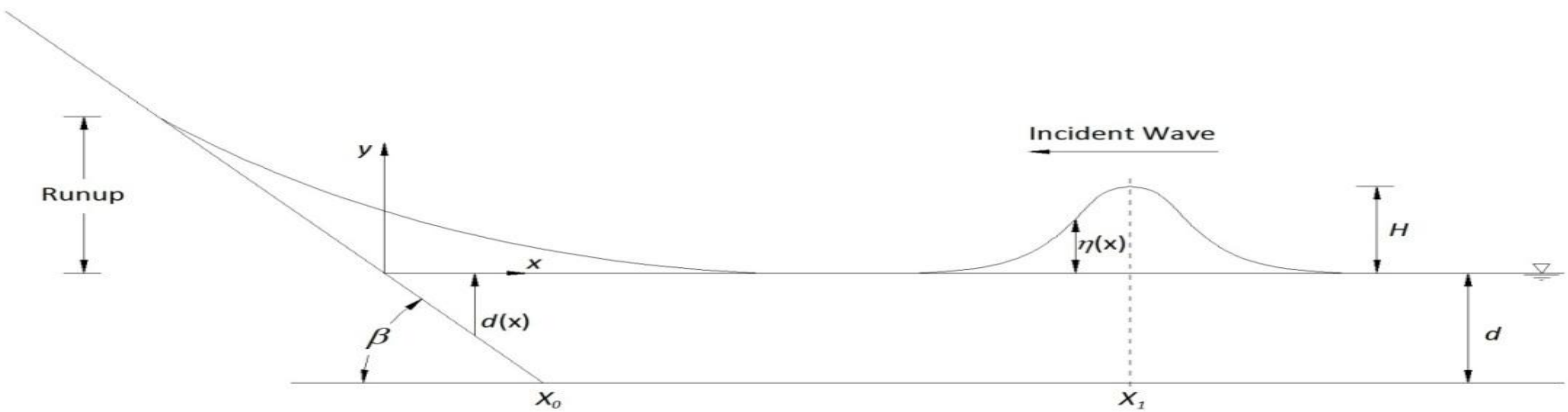
Contents

Introduction

- The run-up of single solitary wave: nonbreaking /breaking
- intensive experimental investigation
- empirical formulas for the maximum run-up height



Introduction

	H/d	$d(cm)$	$H(cm)$	tan(β)	Flume (m)	Wave generation method
Hall & Watts (1953)	0.05~0.5	15.2~68.6	1.9~10.1	1/11.4, 1/5.7, 1/3.7, 1/2.1, 1/1	25.9×4.27×1.22	ramp trajectory
Ippen & Kulin (1954)	0.20~0.7	7.6~13.7	1.5~9.6	1/43.5, 1/20, 1/15.4	9.75×0.42×0.33	dam break
Camfield & Street (1969)	<0.73	15.2~76.2	<55.6	1/100, 1/50, 1/33.3, 1/22.2	35.1×0.91×1.93	Tan-hyperbolic function
Lee *et al.* (1982)	0.11, 0.19, 0.29	3.3, 7.68, 5.91	30.2, 40.45, 20.4	-	39.6×1.10×0.61	Goring(1978)
Papanicolaou & Raichelen (1987)	0.20~0.4	27.7~43.3	8.7~14.2	1/164, 1/106, 1/79, 1/63, 1/52	39.6×1.10×0.61	Goring(1978)
Synolakis (1987)	0.01~0.6	6.25~38.3	0.2~12.3	1/19.85	37.7×0.61×0.93	Goring(1978)
Yeh *et al.* (1989)				1/7.6	9.0×1.2×0.9	dam break
Grilli *et.al.* (1994)	0.10~0.3	44.0	4.4~11.0	1/34.7	33.0×0.60×0.80	Goring(1978)
Li (2000)	0.04~0.5	7~30.5	0.3~13.7	1/19.85, 1/15	31.7×0.40×0.61	Goring(1978)
Li (2001)	0.04~0.2	30.5~76.2	1.2~15.2	1/15	45.7×0.90×0.90 CERC	Goring(1978)
Jensen *et al.* (2003)	0.12, 0.53, 0.335, 0.665		10, 20	1/5.37	10.0×0.5×1.0	SW like impuls
O' Donoghue *et al.* (2006)				1/10	20.0×0.45×0.90	dam break
Yu-Hsuan Chang *et al.* (2008)	0.05~0.31	125~325	3~49	1/60, 1/40, 1/20	300×5.00×5.20	Goring(1978) & ramp trajectory

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Introduction

- Pedersen & Gjevik(1983): shallow water equations
- Zelt & Raichlen(1990): shallow water equations
- Kim、Liu & Ligett(1983): BIEM

- Carrier & Greenpan(1958, JFM): C-G transform method
- Synolakis(1987, JFM): runup, solitary wave
- Tadepalli & Synolakis(1994, JFM): runup

- Stefanakis & Dias(2011, JFM): resonant runup
- Zhao, Wang, Liu(2012, PoF): solitary wave, runup

Introduction

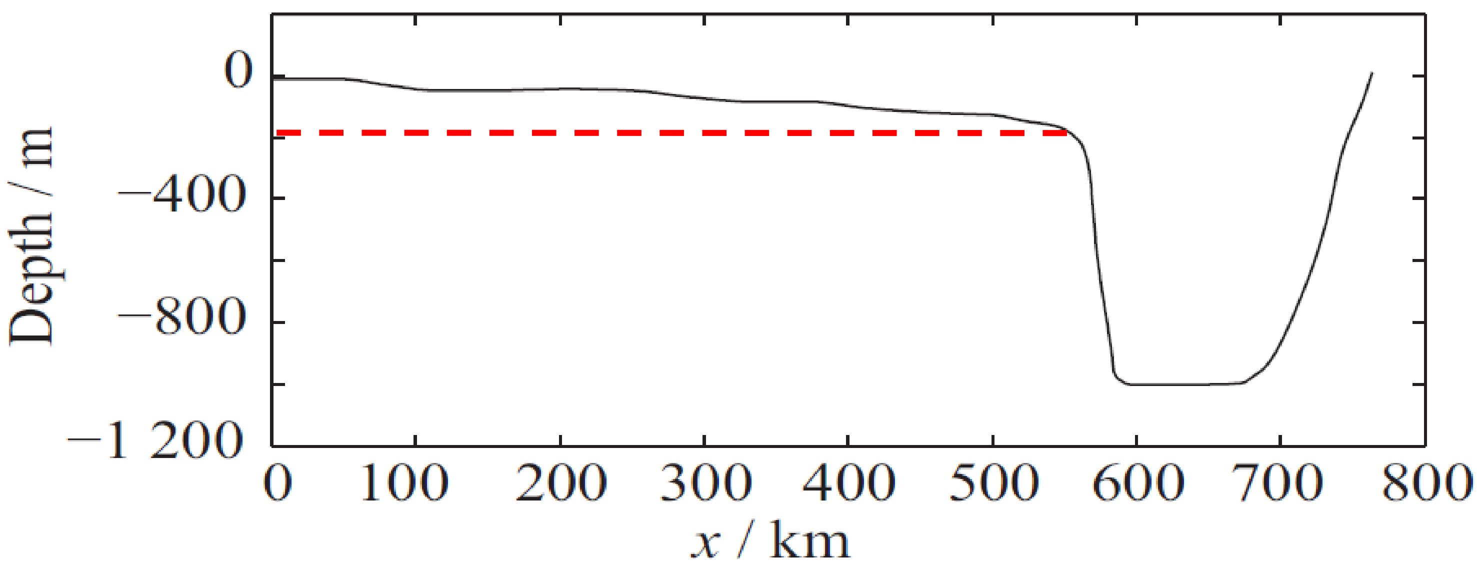
- Grue *et al*.(2008), Madsen *et al*.(2008) : undular bores appear in tsunami propagation in offshore waters.

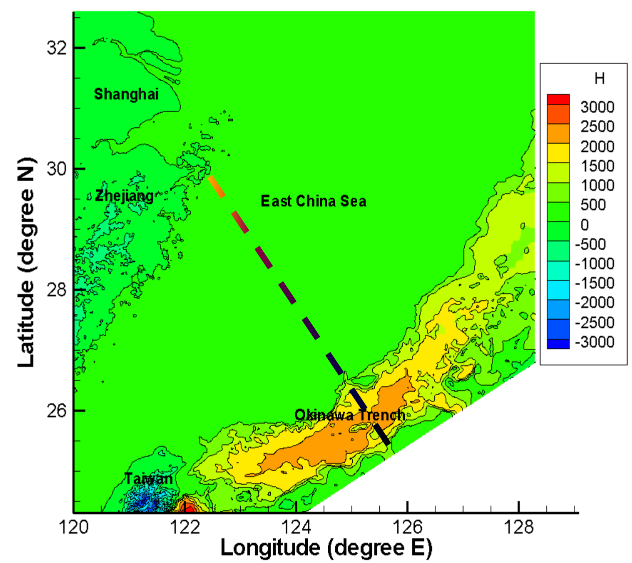
- The undular bores can be modeling as a combination of several solitary waves with different wave heights and different separation distance between the successive wave peaks.

- Lo, Park and Liu (2013): the run-up and back-wash processes of the double solitary waves consisting of two identical solitary waves, flume experiments.

  The beach slope s=1/5~ 1/20 and H/d=0.1~0.3.

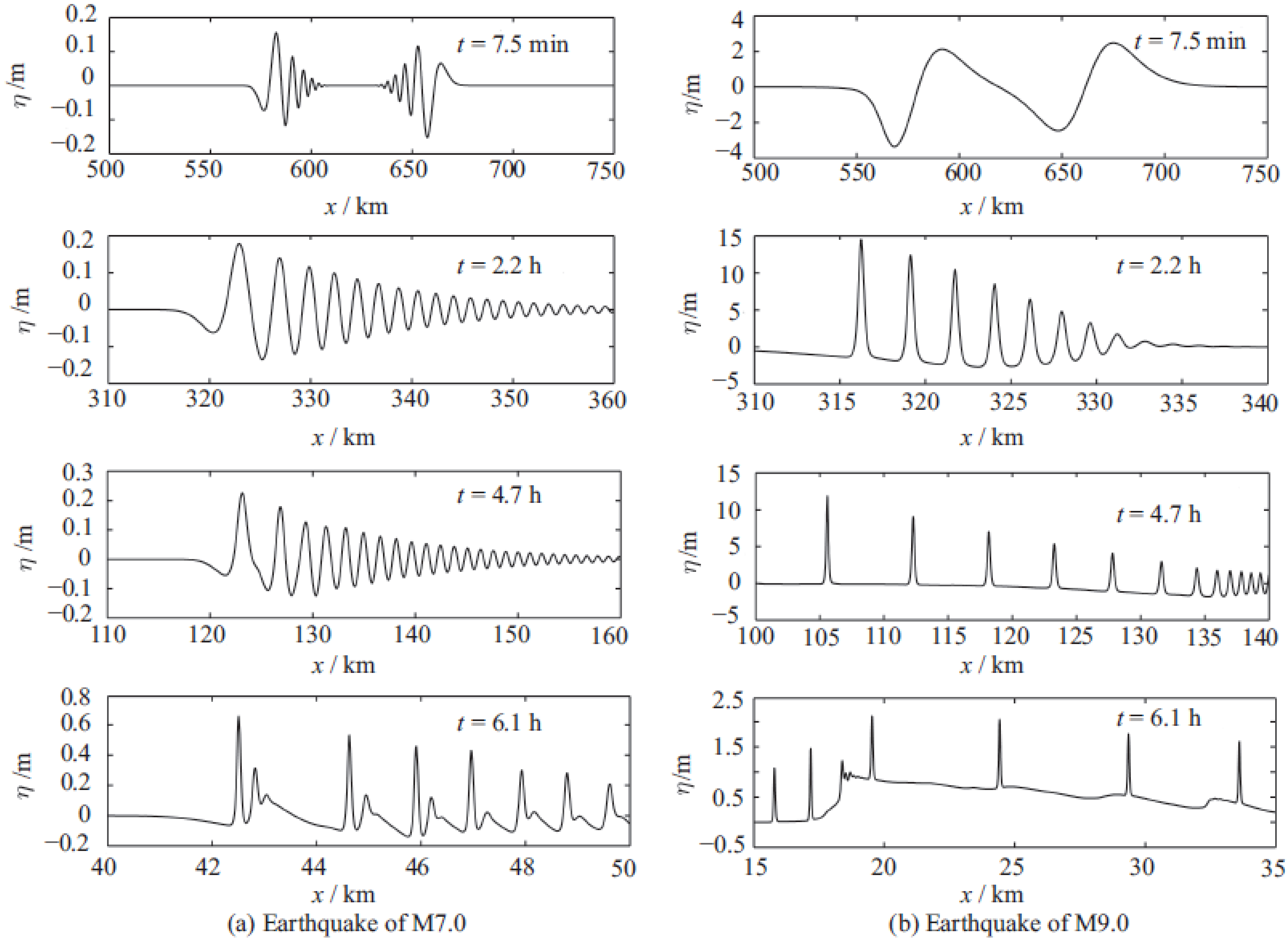
Introduction





- Topography profile from Shanghai to the Okinawa Trench in East China Sea
- slope=1:3000

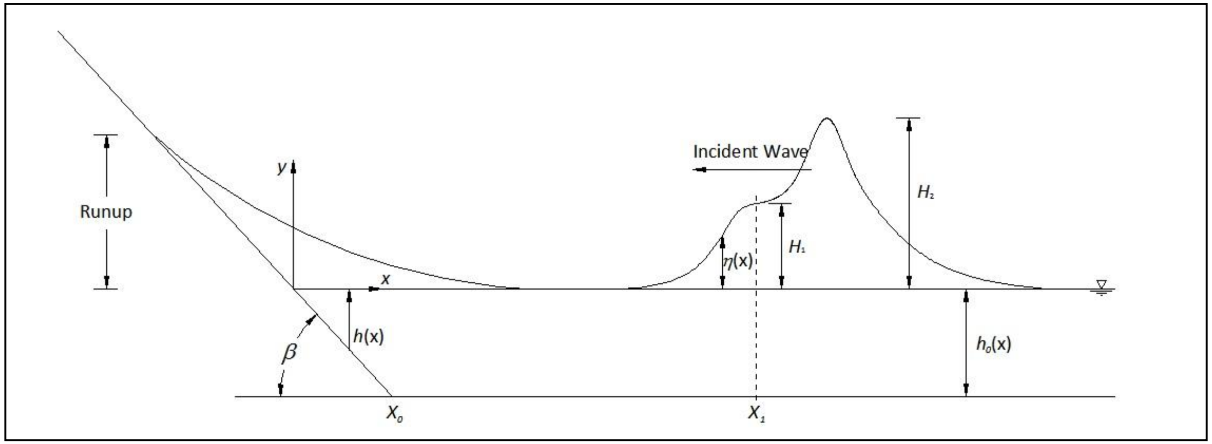
Introduction



Introduction

- Lo, Park and Liu(2013)'s Double Solitary Waves : two successive solitary waves, separated by a specified separation time, are generated by linearly combining the wave-maker trajectories of two individual solitary.

- Xuan, Wu and Liu(2013): Double Solitary Waves with unequal individual wave height



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Introduction

- Motivation of the study
- Runup of individual wave of the double solitary waves
- Velocity field and energy budge of the double solitary waves during runup on a vertical wall or a slope

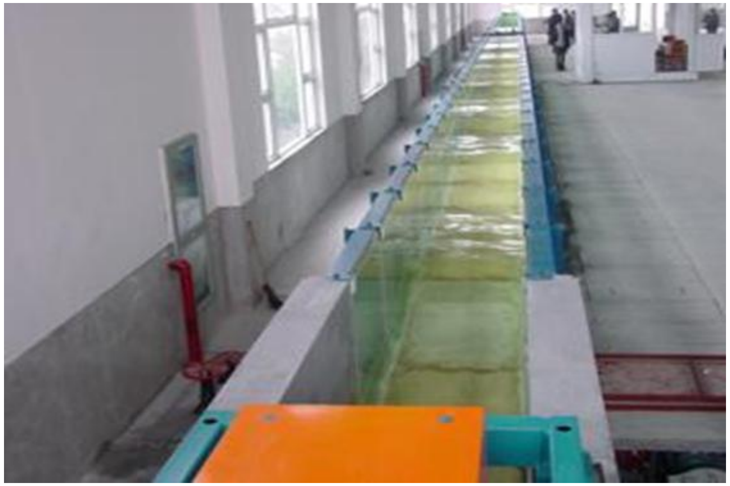
Experimental approach

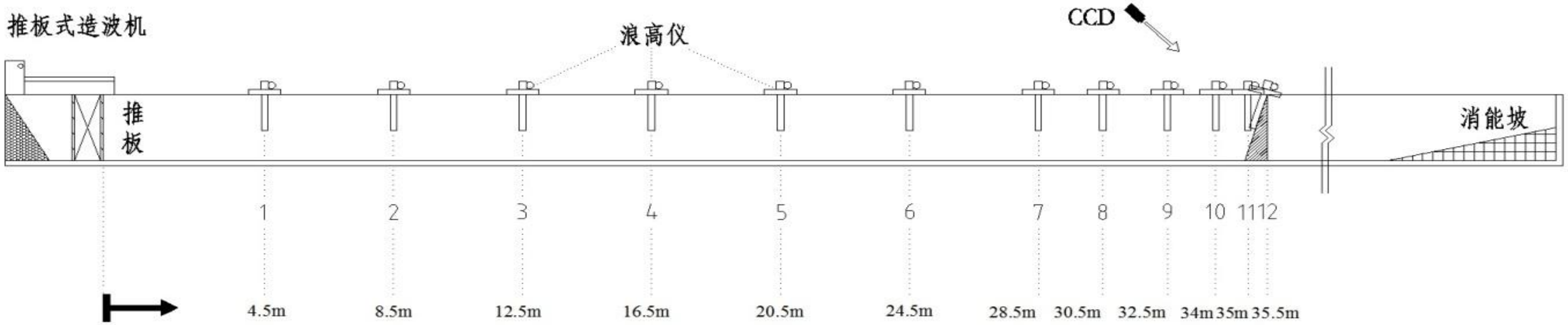
- Wave generation method

  solitary wave of large amplitude

- Runup of single solitary wave

- Runup of double solitary waves





Experimental approach

- Goring method

$$\frac{d\xi}{dt}=\bar{u}(\xi,t) \qquad \bar{u}(\xi,t)=\frac{c\eta(\xi,t)}{d+\eta(\xi,t)}$$

Solitary wave	$\eta(\xi,t)/d$	kd	$c/\sqrt{gd}$
KdV	$\alpha\mathrm{sh}^2$	$\sqrt{\frac{3}{4}\alpha}$	$\sqrt{1+\alpha}$
Grimshaw's 3rd order solitary wave	$\alpha\mathrm{sh}^2\left[1-\frac{3}{4}\alpha\mathrm{th}^2 + \alpha^2(\frac{5}{8}\mathrm{th}^2-\frac{101}{80}\mathrm{sh}^2\mathrm{th}^2)\right]$	$\sqrt{\frac{3}{4}\alpha}(1-\frac{5}{8}\alpha+\frac{71}{128}\alpha^2)$	$1+\frac{1}{2}\alpha-\frac{3}{20}\alpha^2+\frac{3}{56}\alpha^3$

- KdV $\quad \xi(t)=\frac{H}{kd}\tanh\left[k(ct-\xi)\right]$
- The 3rd order solution

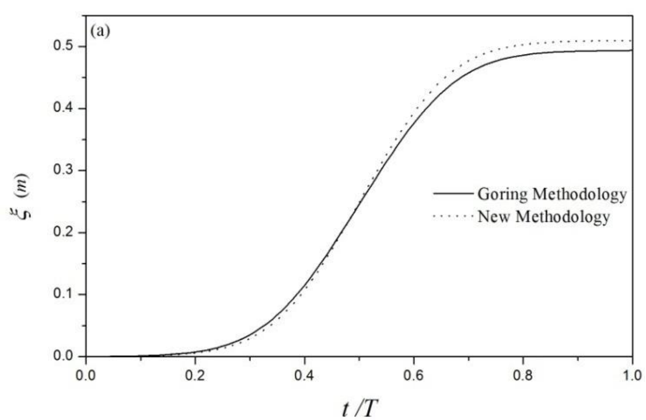
$$\xi(t)=\frac{1}{k}\left[\alpha\mathrm{th}-\frac{1}{4}\alpha^2\mathrm{th}^3+\frac{5}{24}\alpha^3\mathrm{th}^3-\frac{101}{80}\alpha^3\left(\frac{2}{15}\mathrm{th}+\frac{1}{15}\mathrm{sh}^2\mathrm{th}-\frac{1}{5}\mathrm{sh}^4\mathrm{th}\right)\right]$$

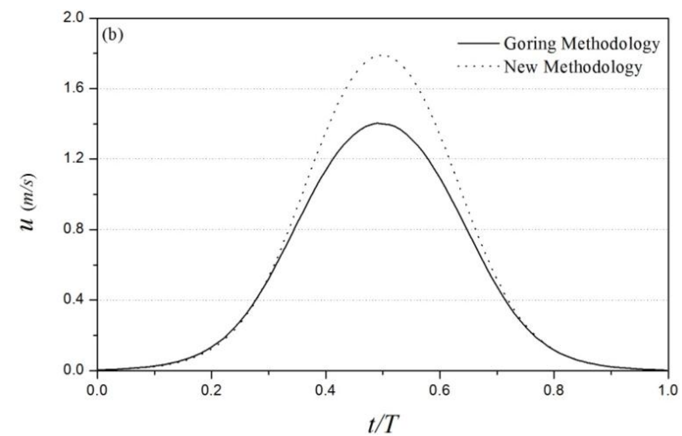
Experimental approach

- Modified Goring method (Malek-Mohammadi & Testik)

$$\frac{d\xi}{dt} = \bar{u}(\xi, t) \qquad \bar{u}_1(\xi, t) = \frac{c_u \eta(\xi, t)}{d + \eta(\xi, t)} \qquad c_u(t) = \sqrt{g\left(d + \frac{h}{2}\right)\left(1 + \frac{h}{d}\right)}$$

$$\bar{u}_1 = \frac{d\xi}{dt} = \sqrt{g\frac{\eta}{d}\left(d + \frac{\eta}{2}\right)\left(\frac{\eta}{d + \eta}\right)}$$

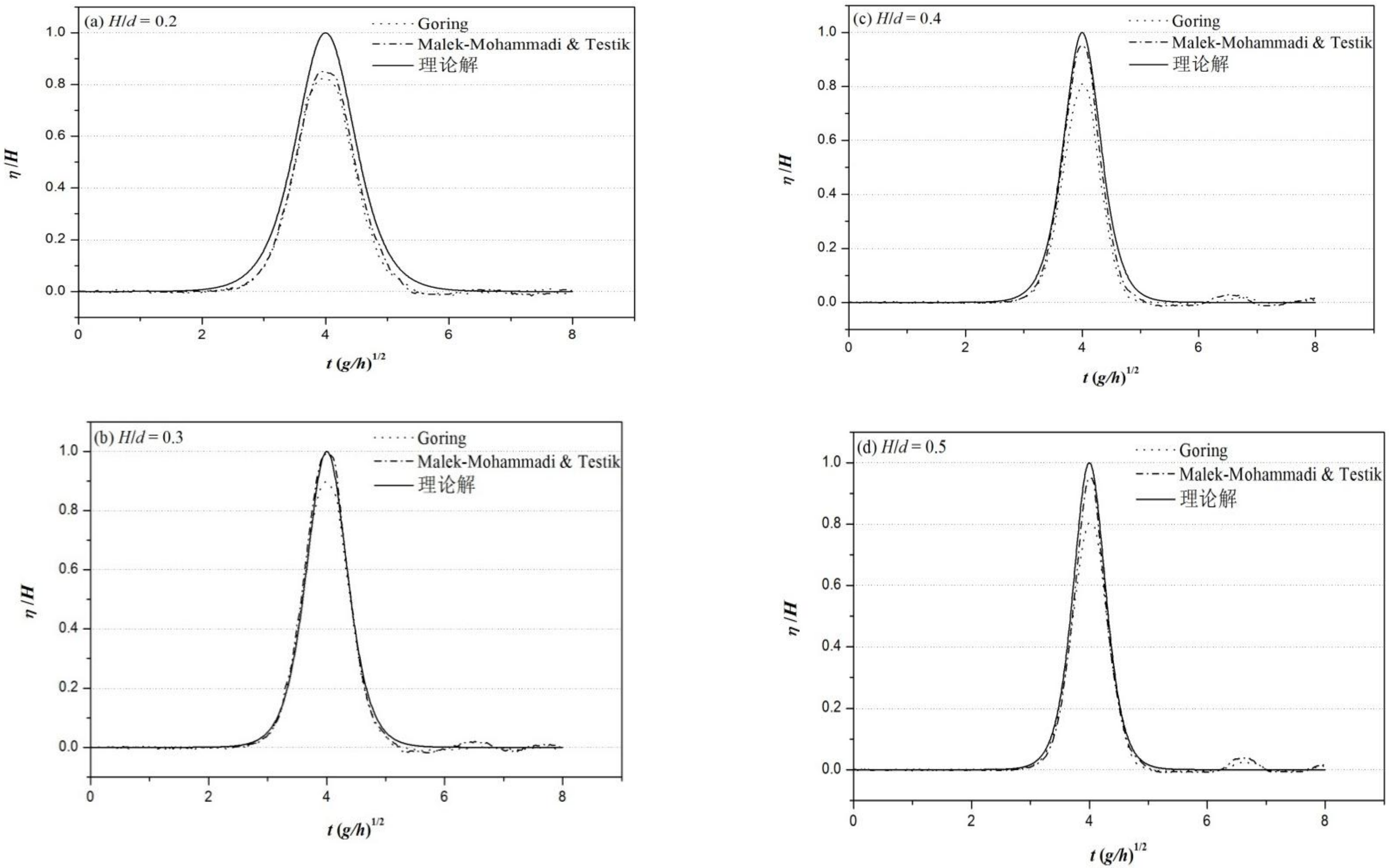




Comparison of displacement and velocity of wavemaker (α=0.5)

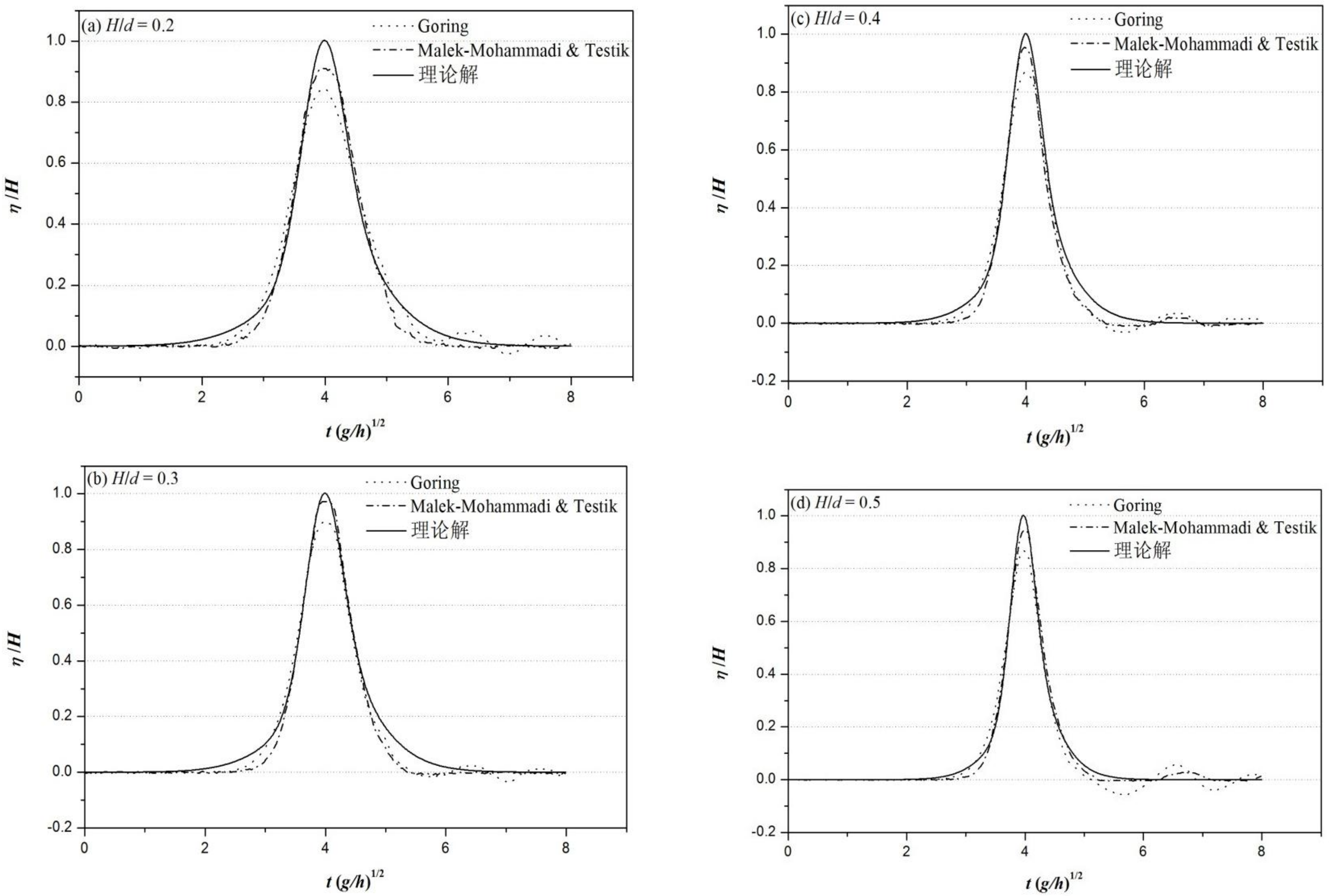
Experimental approach

- Input signal of wavemaker: The 1st order solitary wave

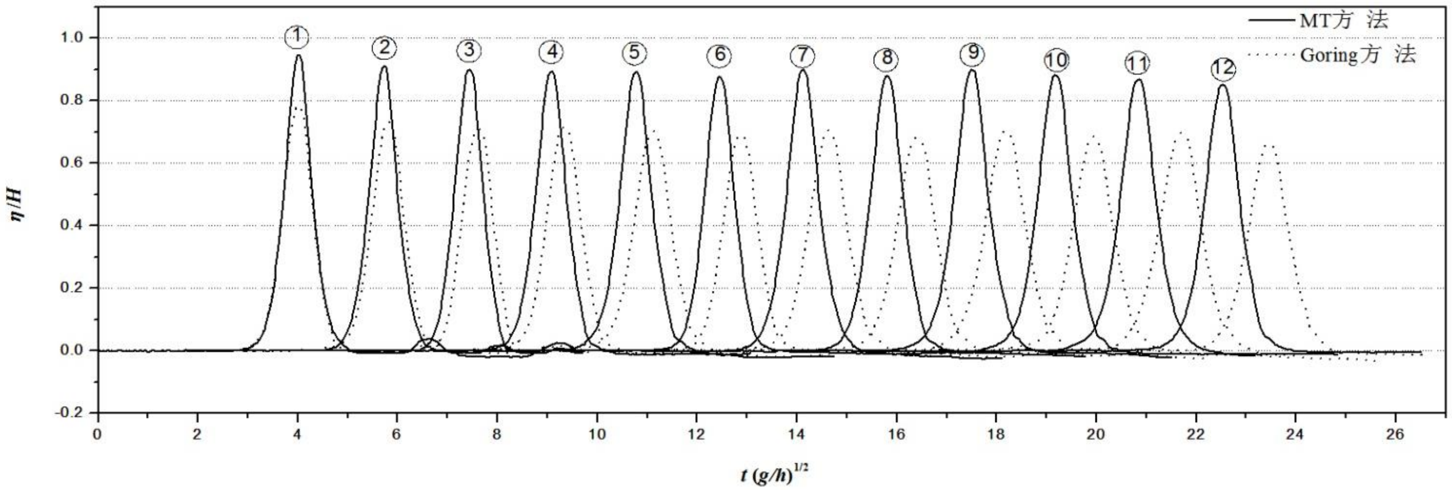


Experimental approach

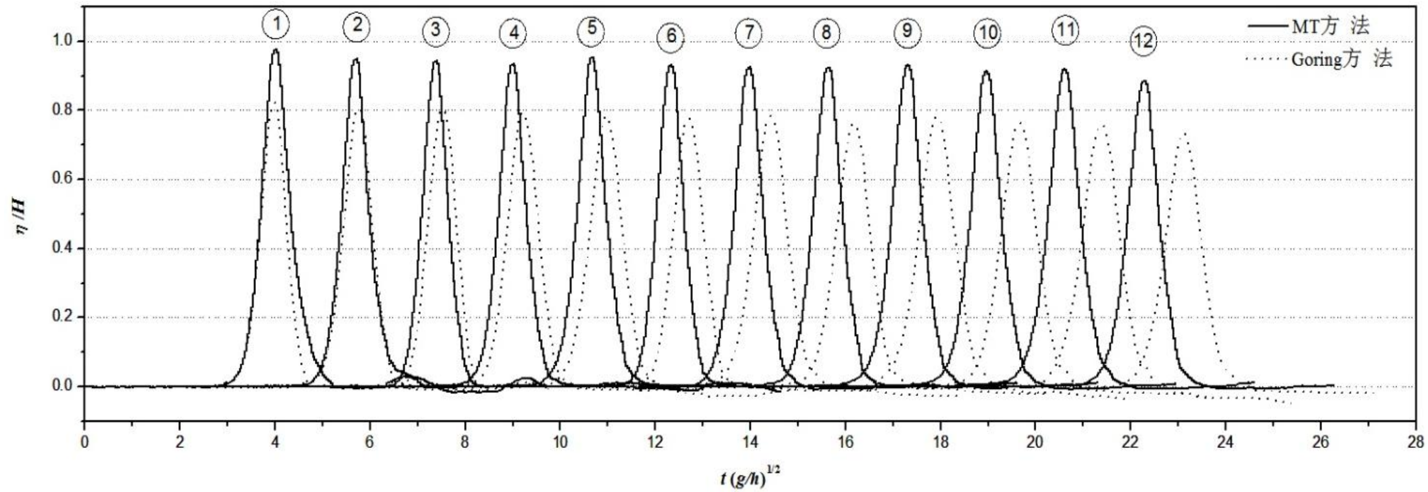
- Input signal for wavemaker: the 3rd order solitary wave



Experimental approach



- Time series of surface elevation for a solitary wave (α=0.5, KdV)



- Time series of surface elevation for a solitary wave (α=0.5, 3rd theory)

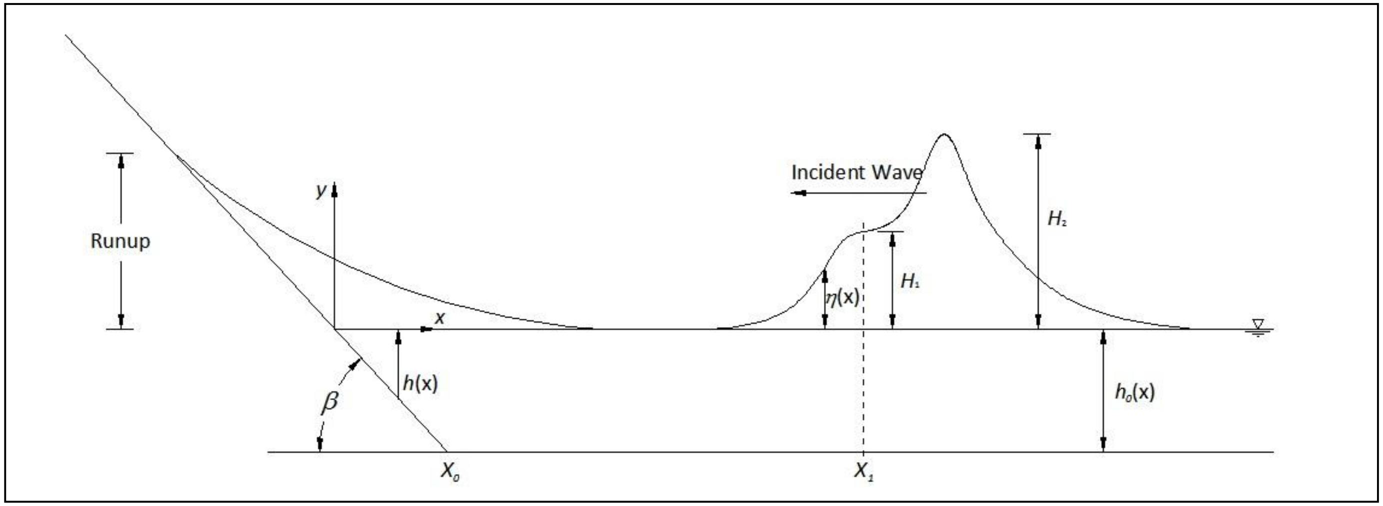
Experimental approach

- Generation of two solitary waves

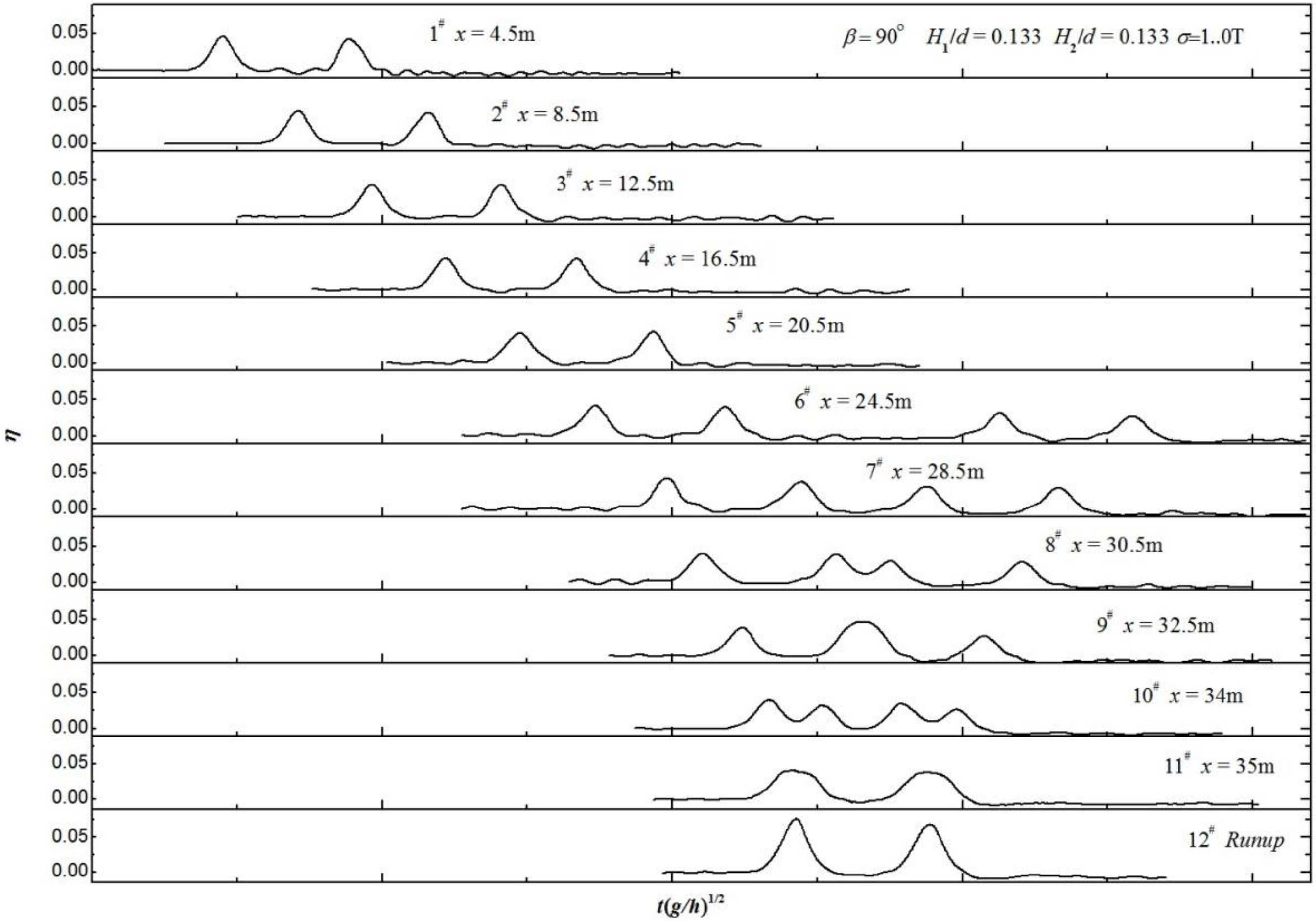
$$\frac{\eta(x,0)}{h_0}=\alpha_1\mathrm{sh}^2\left[1-\frac{3}{4}\alpha\mathrm{th}^2+\alpha^2\left(\frac{5}{8}\mathrm{th}^2-\frac{101}{80}\mathrm{sh}^2\mathrm{th}^2\right)\right]+\alpha_2\mathrm{SH}^2\left[1-\frac{3}{4}\alpha\mathrm{TH}^2+\alpha^2(\frac{5}{8}\mathrm{TH}^2-\frac{101}{80}\mathrm{SH}^2\mathrm{TH}^2)\right]$$

a_1 & a_1----relative wave sh------ $\mathrm{sech}\left[k\left(x-X_1\right)\right]$ th---- $\tanh\left[k\left(x-X_1\right)\right]$

SH---- $\mathrm{sech}\left[k\left(x-X_1\right)+\varepsilon T\right]$ TH---- $\tanh\left[k\left(x-X_1\right)+\varepsilon T\right]$

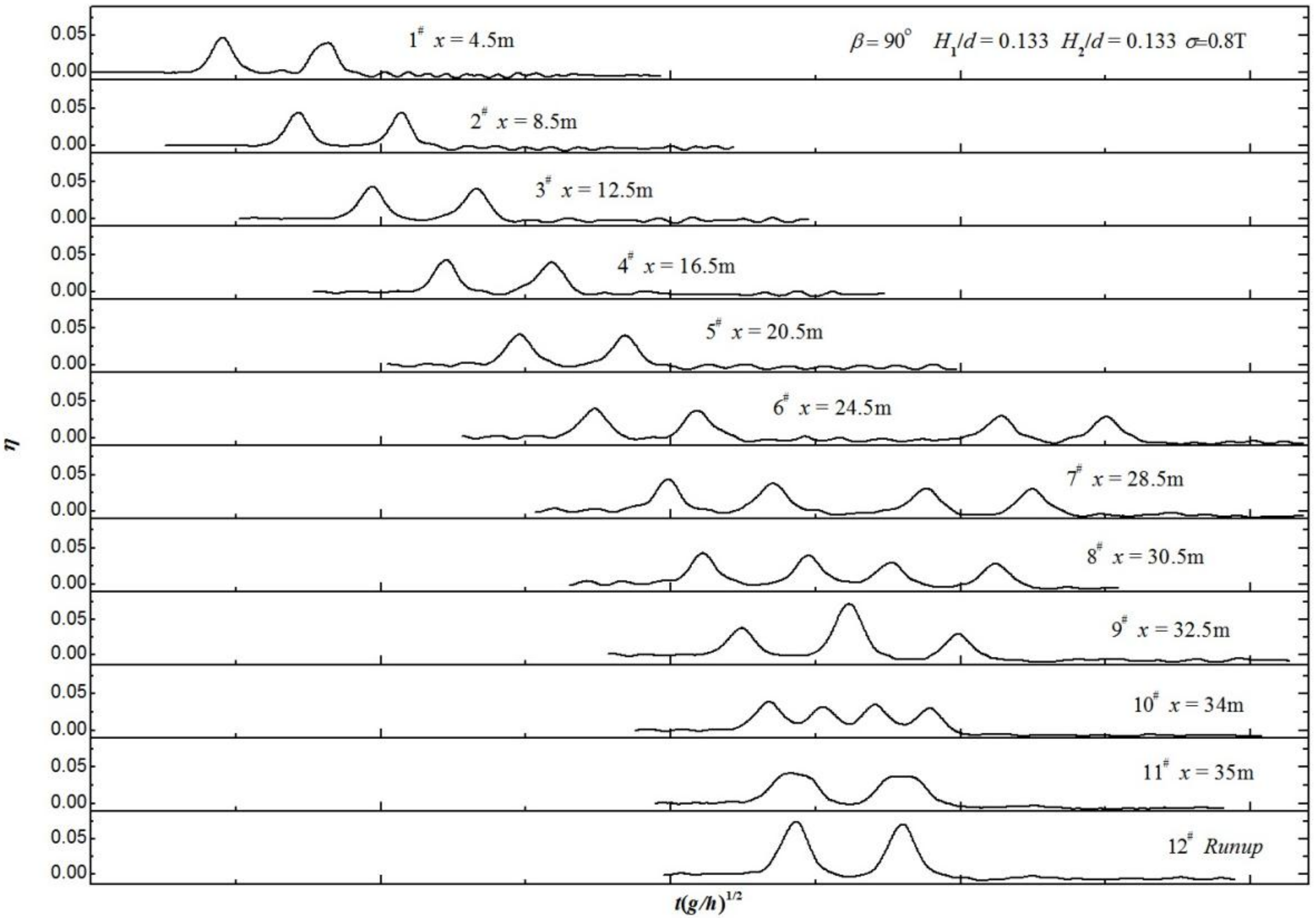


Experimental approach



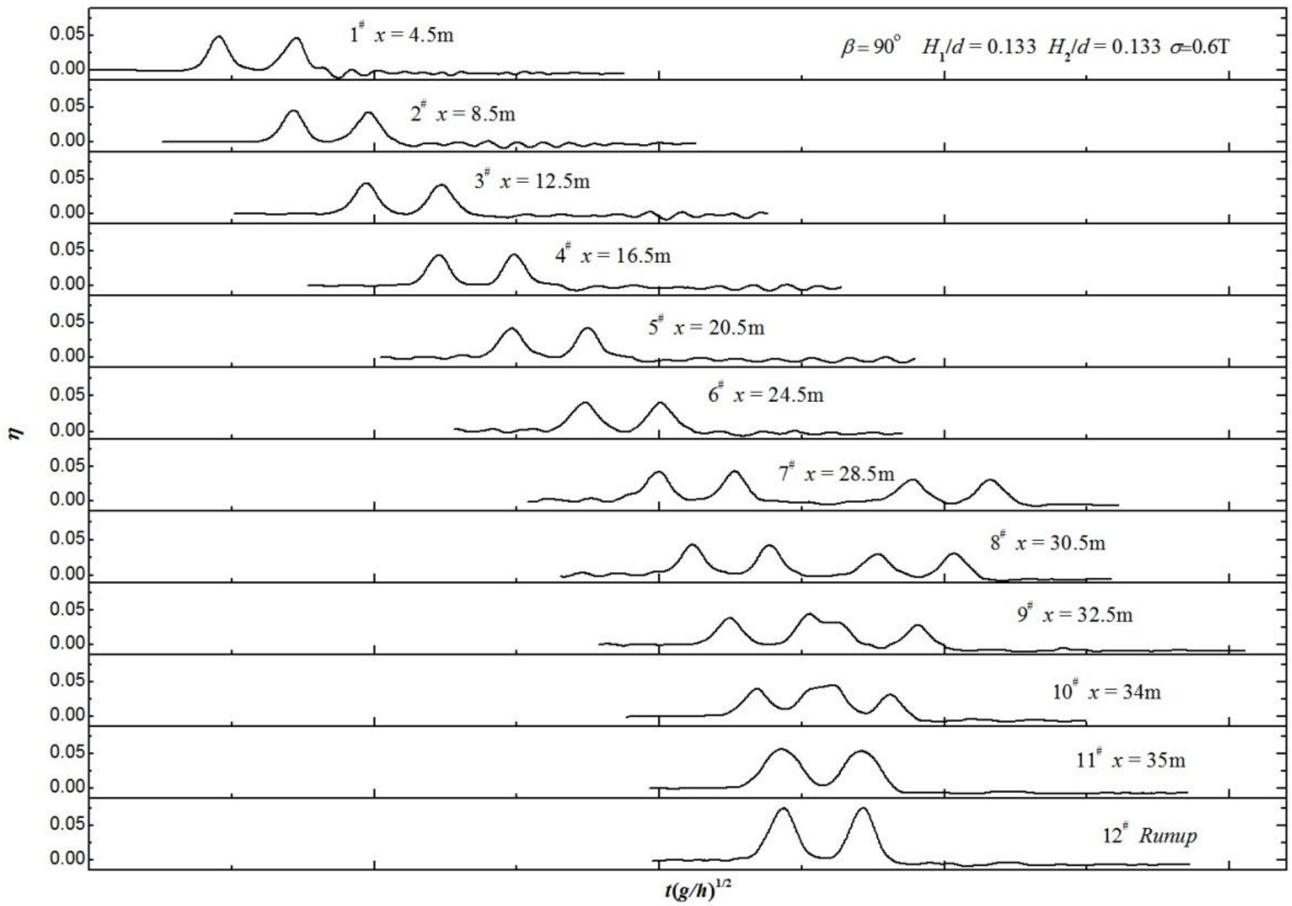
- Vertical wall reflection, H_1/d=0.133, H_2/d=0.133, εT=1.0

Experimental approach



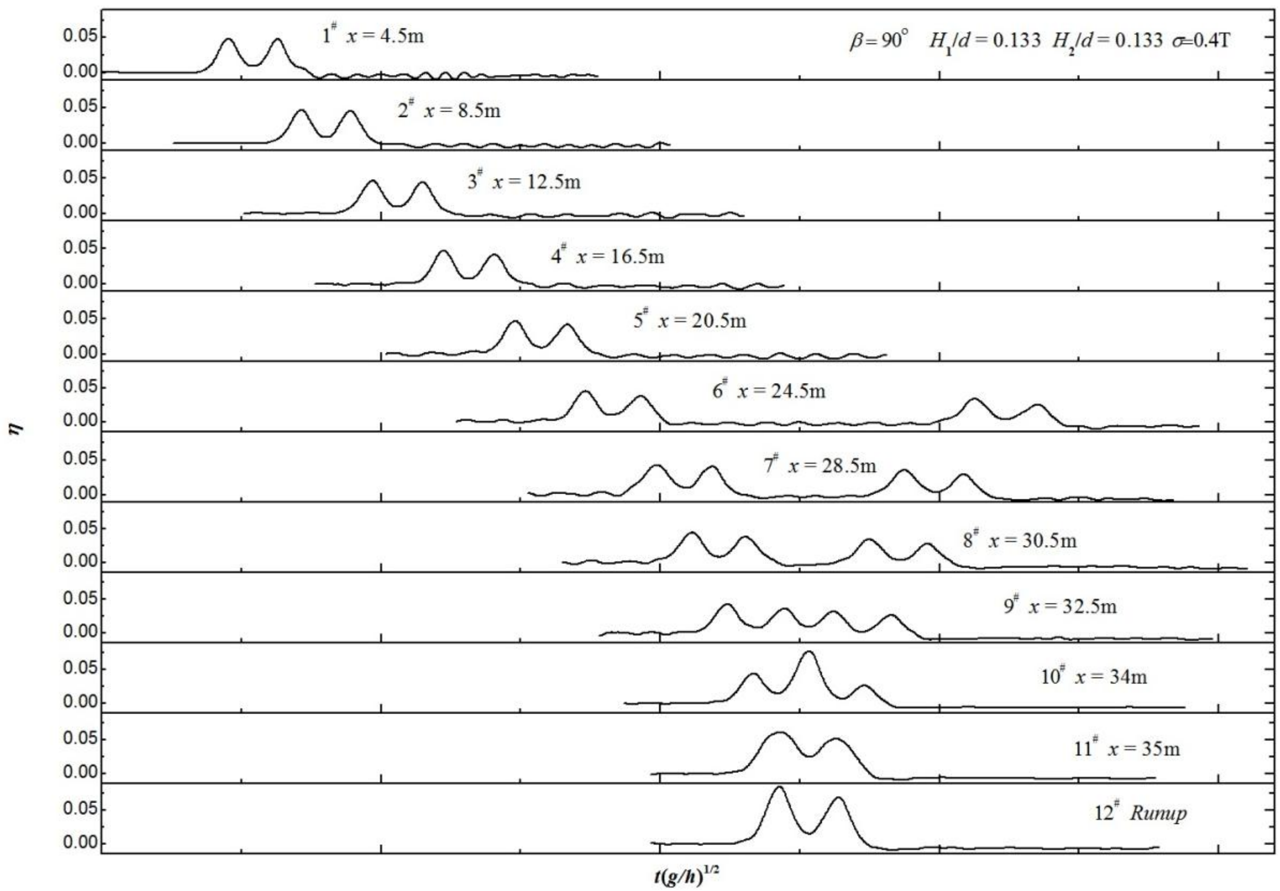
- Vertical wall reflection, H_1/d=0.133, H_2/d=0.133, εT=0.8

Experimental approach



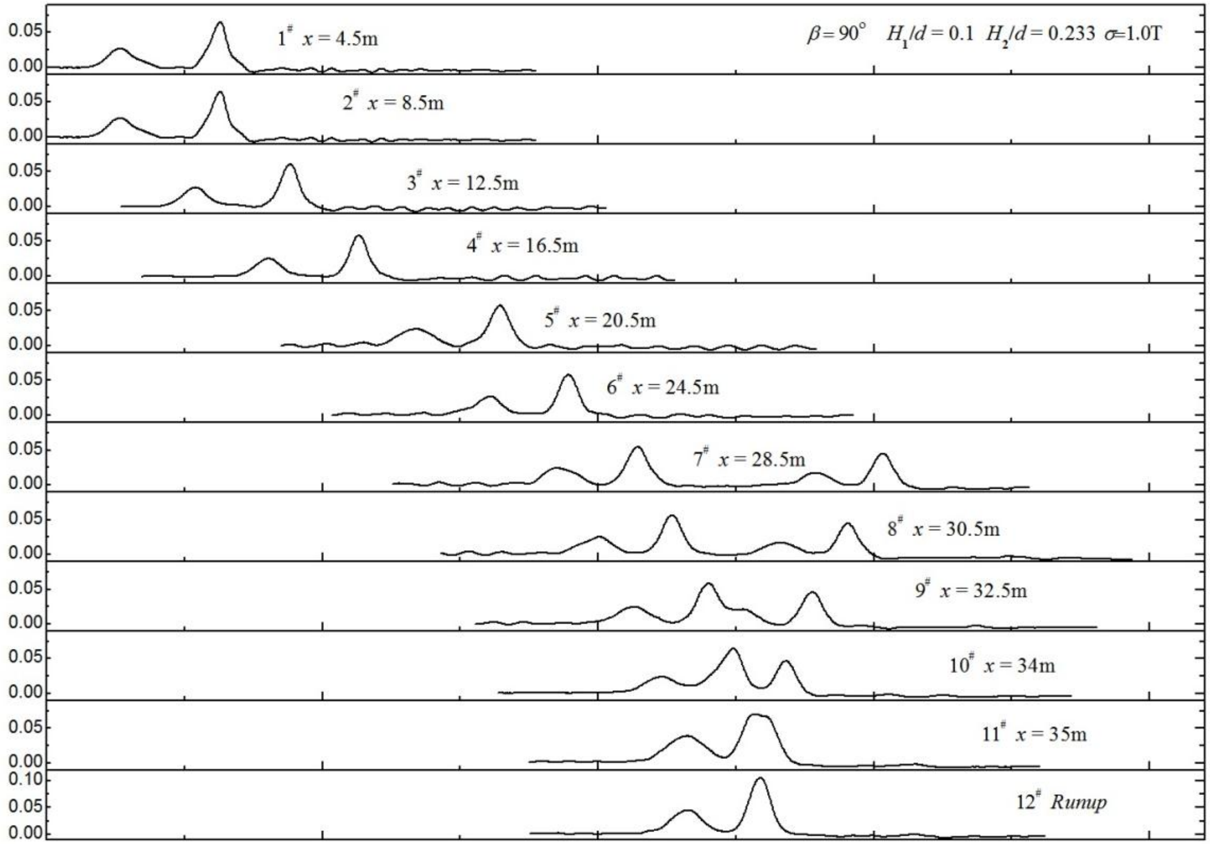
- Vertical wall reflection, H_1/d=0.133, H_2/d=0.133, εT=0.6

Experimental approach



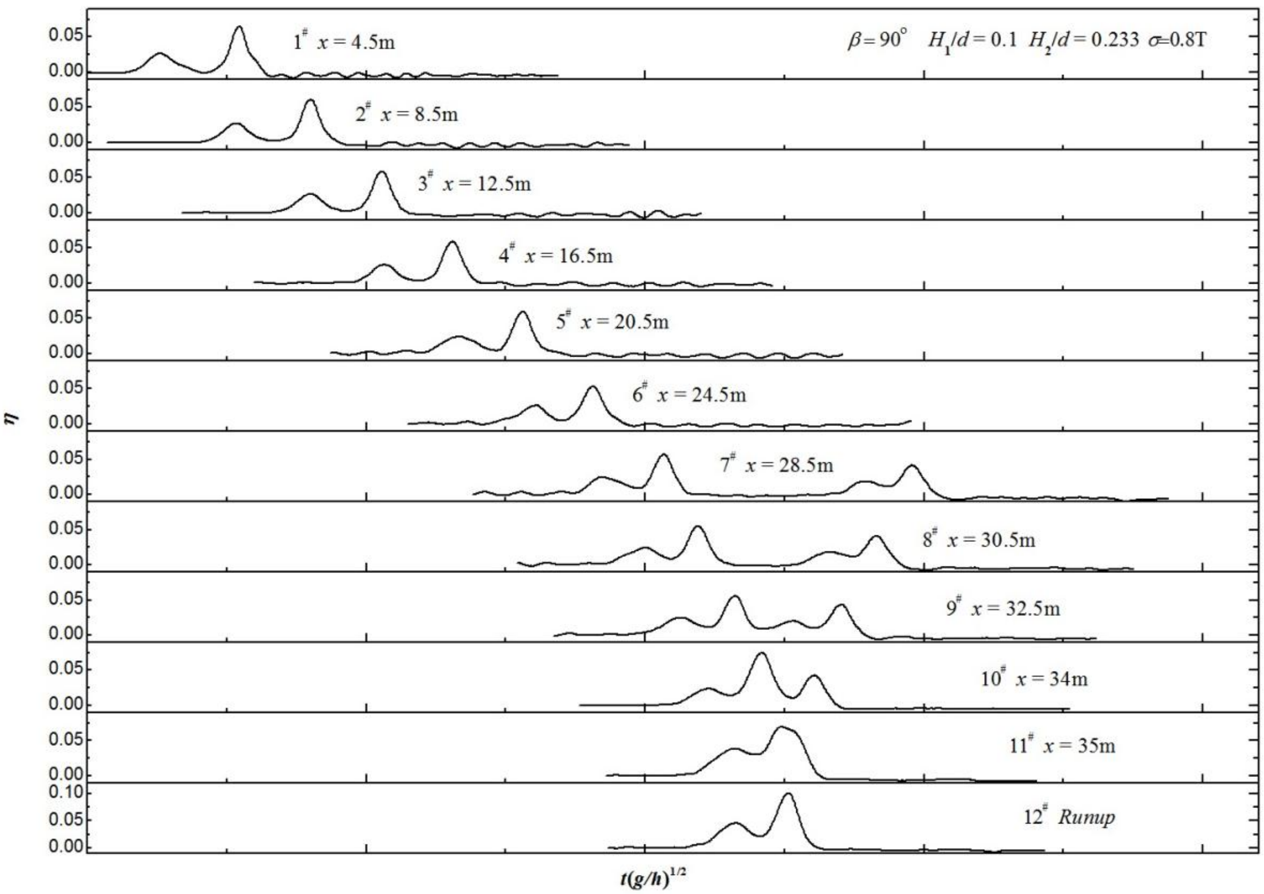
- Vertical wall reflection, H_1/d=0.133, H_2/d=0.133, εT=0.4

Experimental approach



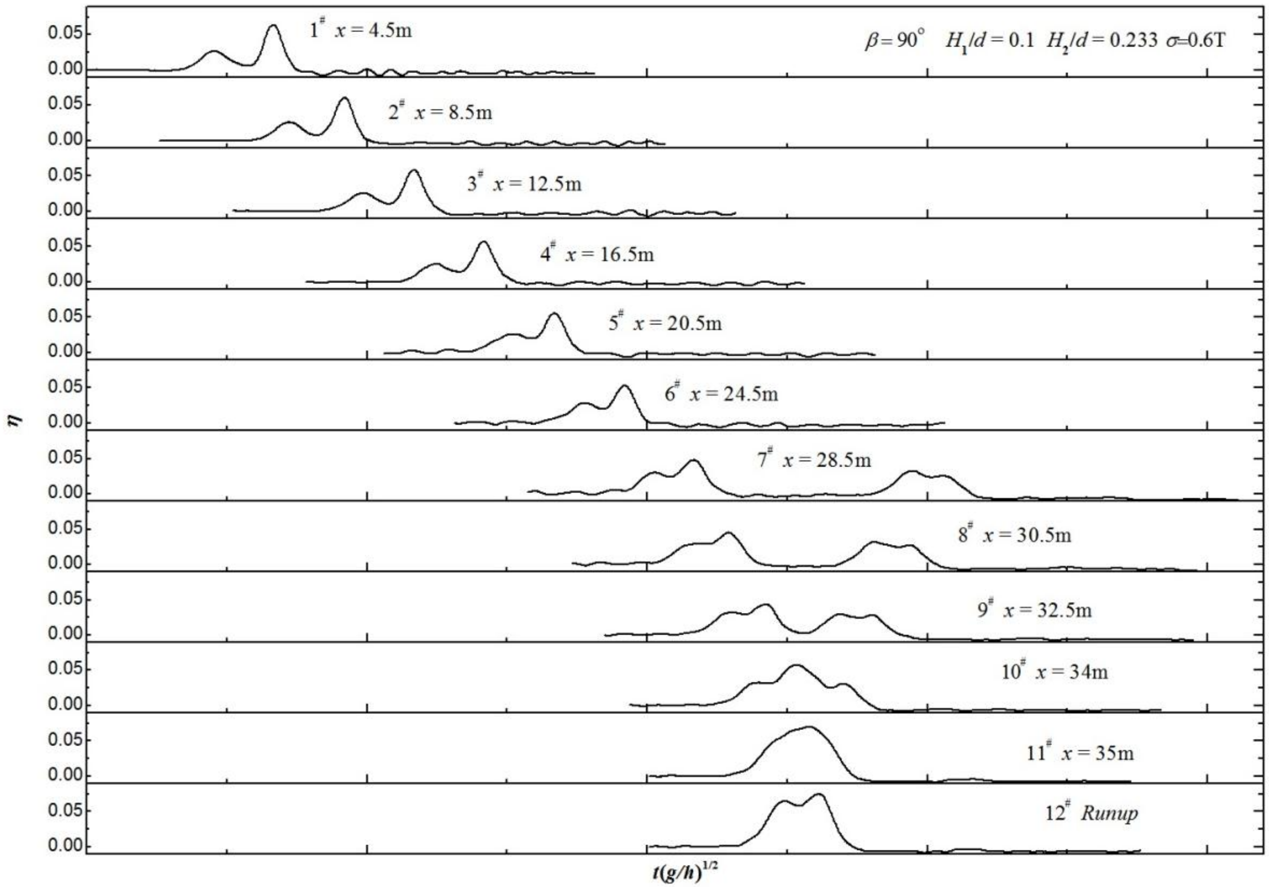
- Vertical wall reflection, H_1/d=0.1, H_2/d=0.233, εT=1.0

Experimental approach



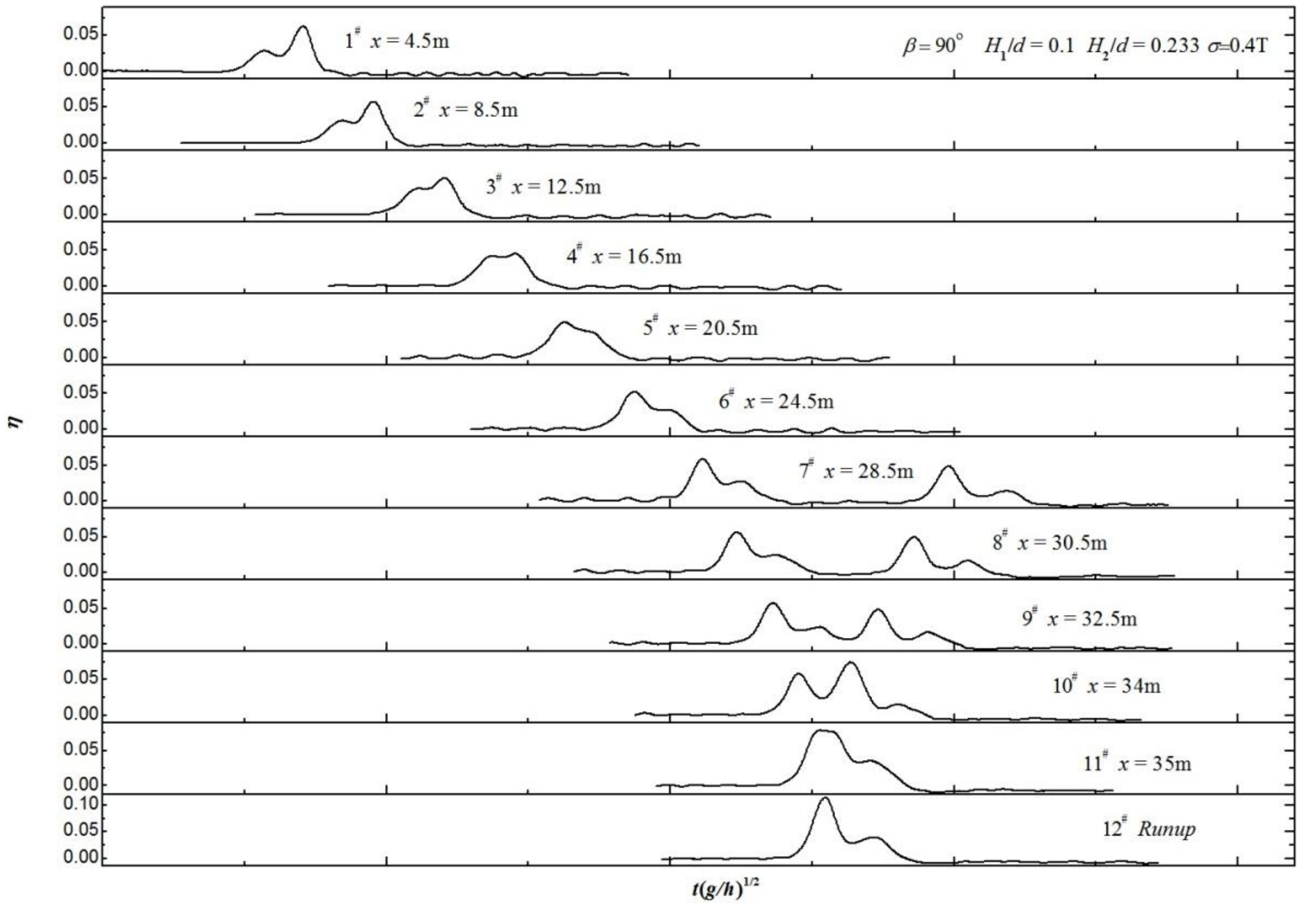
- Vertical wall reflection, H_1/d=0.1, H_2/d=0.233, εT=0.8

Experimental approach



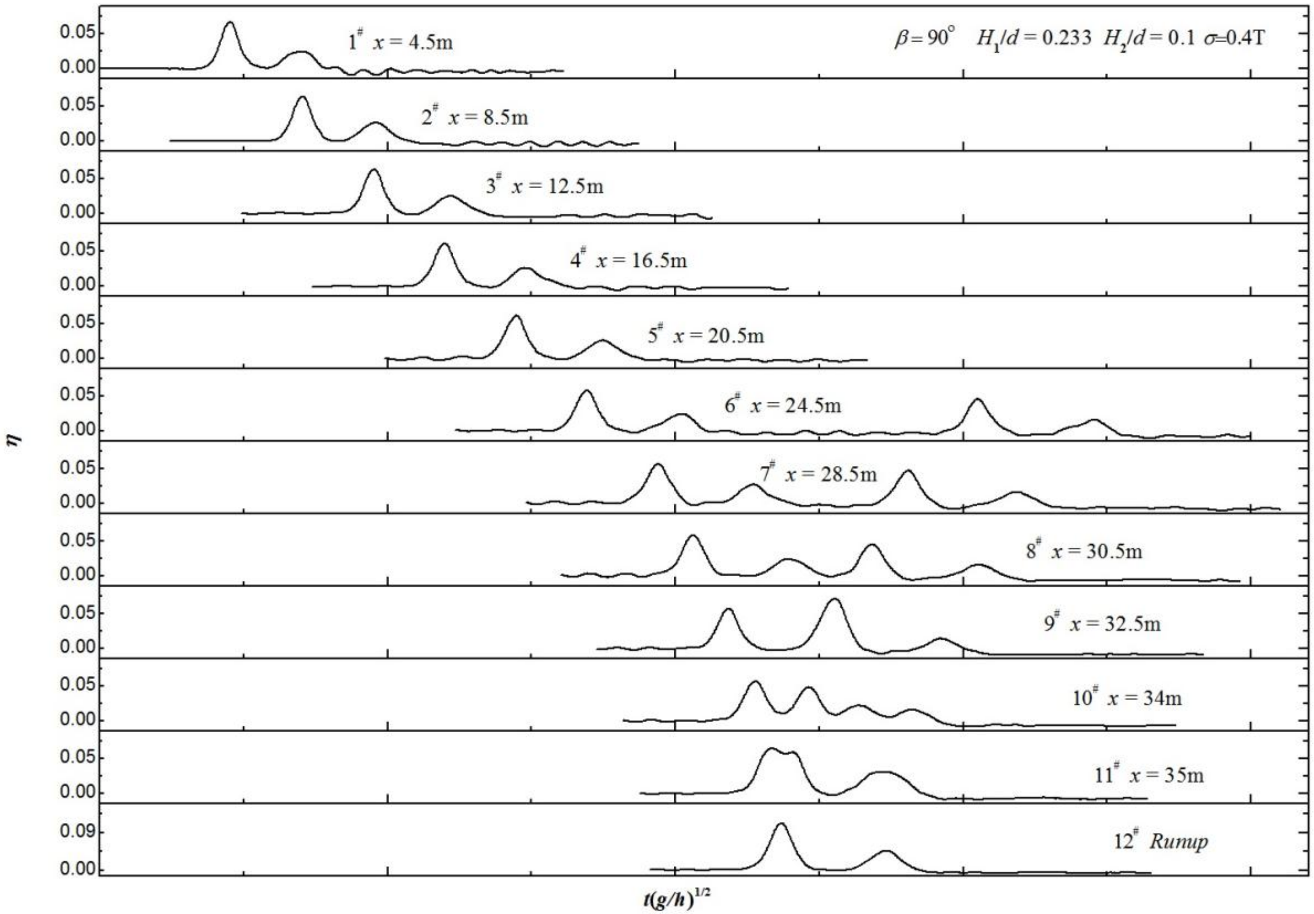
- Vertical wall reflection, H_1/d=0.1, H_2/d=0.233, εT=0.6

Experimental approach



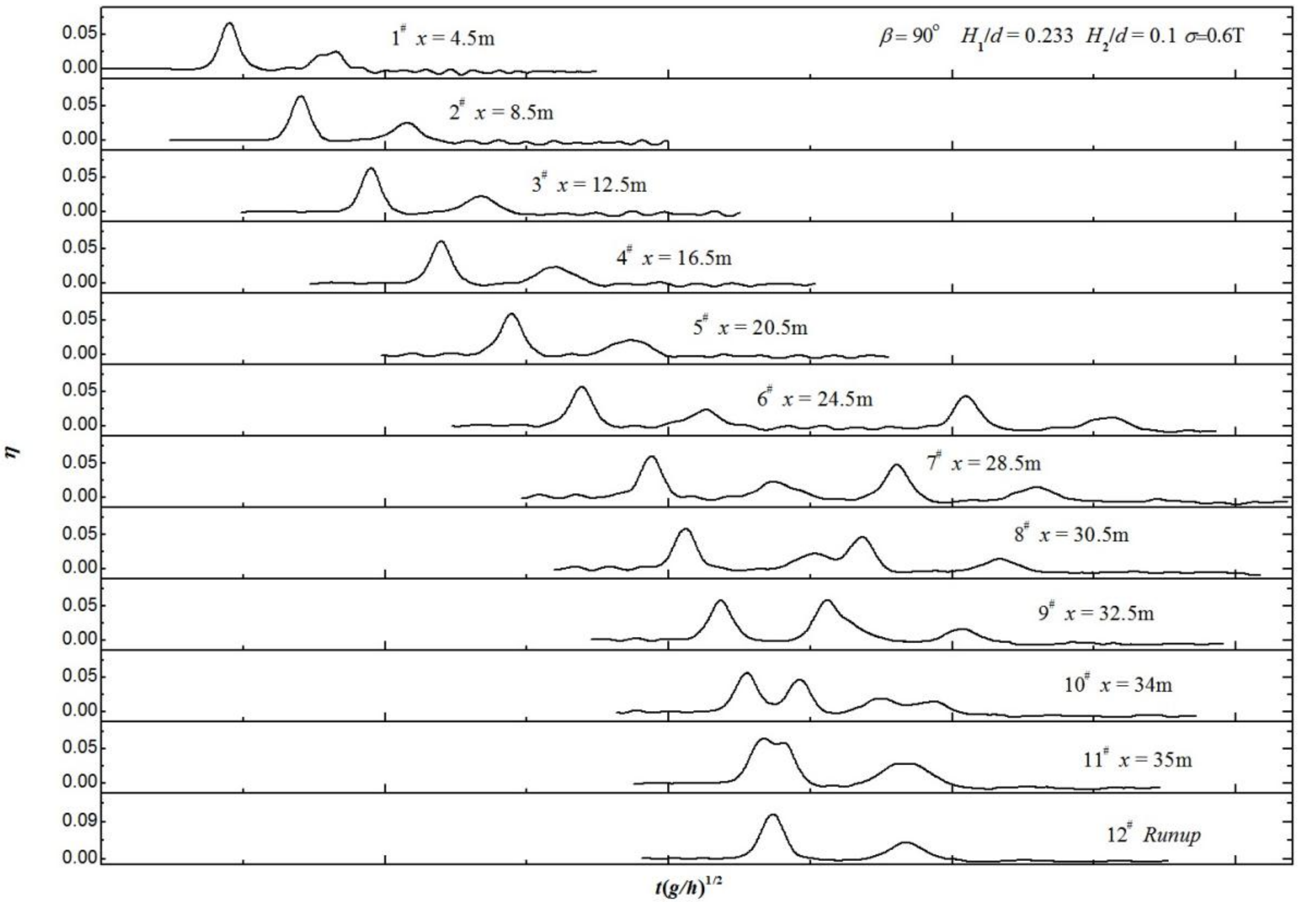
- Vertical wall reflection, H_1/d=0.1, H_2/d=0.233, εT=0.4

Experimental approach



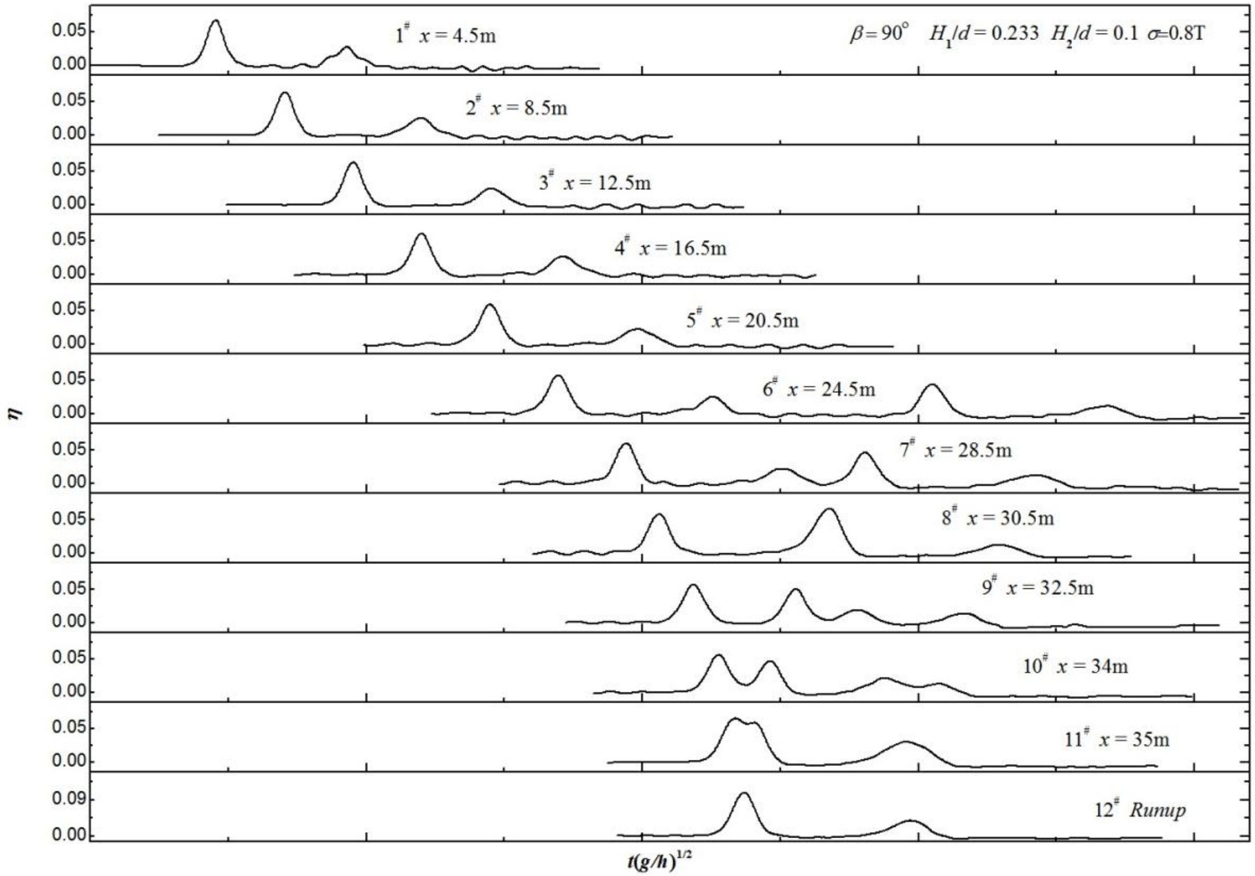
- Vertical wall reflection, H_1/d=0.233, H_2/d=0.1, εT=0.4

Experimental approach



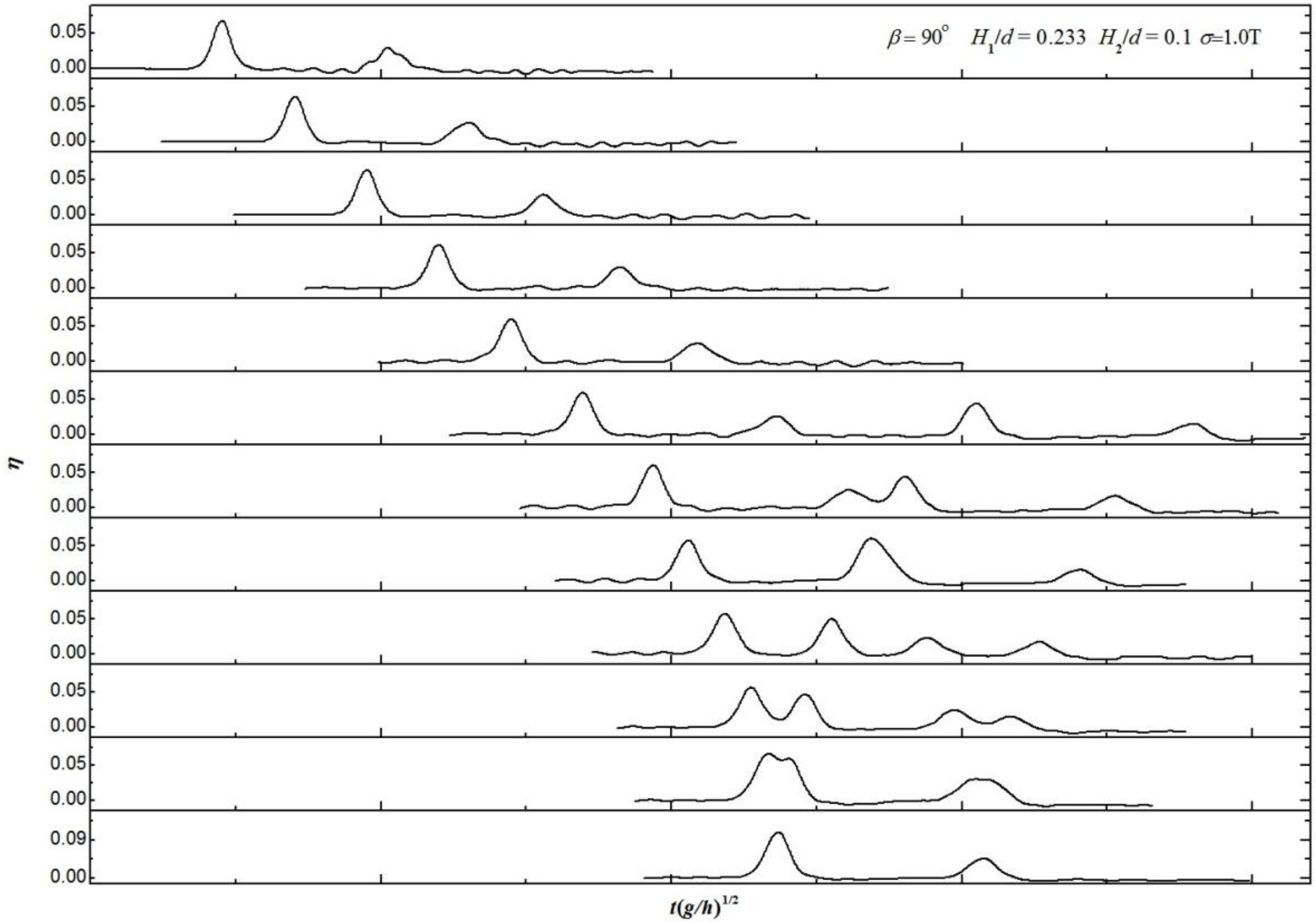
- Vertical wall reflection, H_1/d=0.233, H_2/d=0.1, εT=0.6

Experimental approach



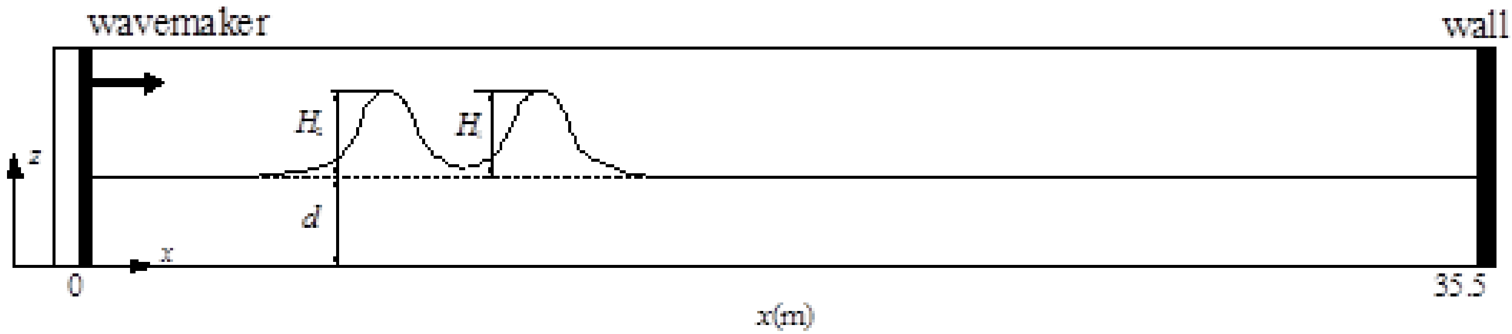
- Vertical wall reflection, H_1/d=0.233, H_2/d=0.1, εT=0.8

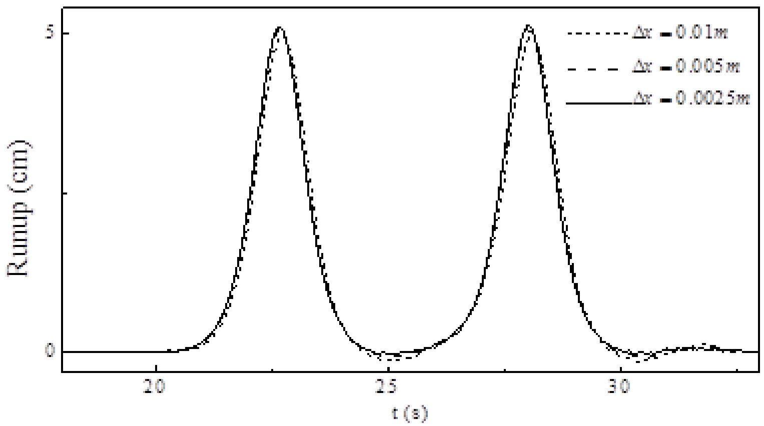
Experimental approach

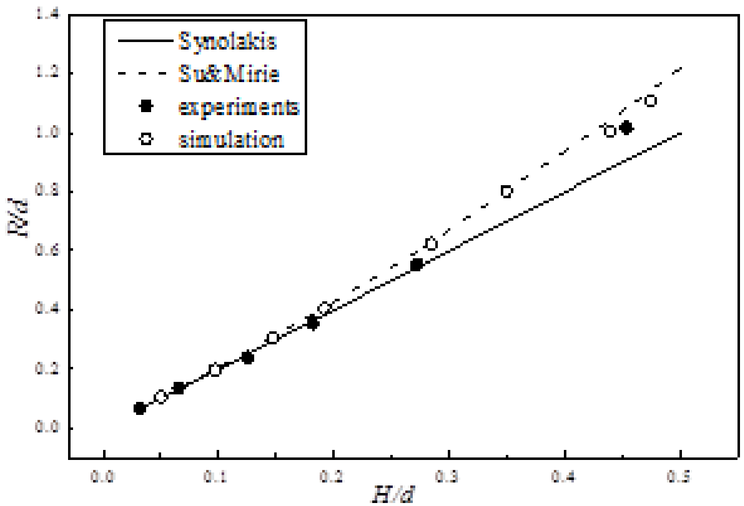


- Vertical wall reflection, H_1/d=0.233, H_2/d=0.1, εT=1.0

Numerical Wave Flume

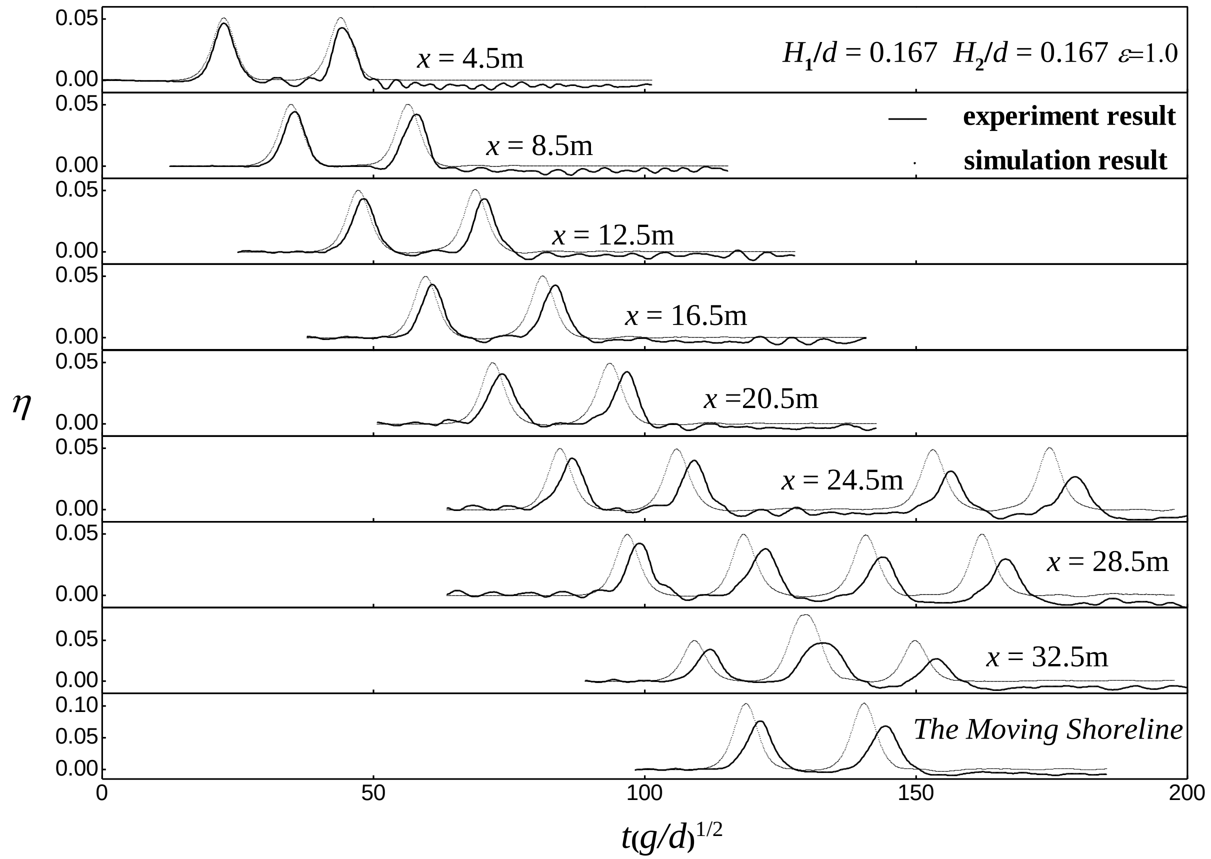






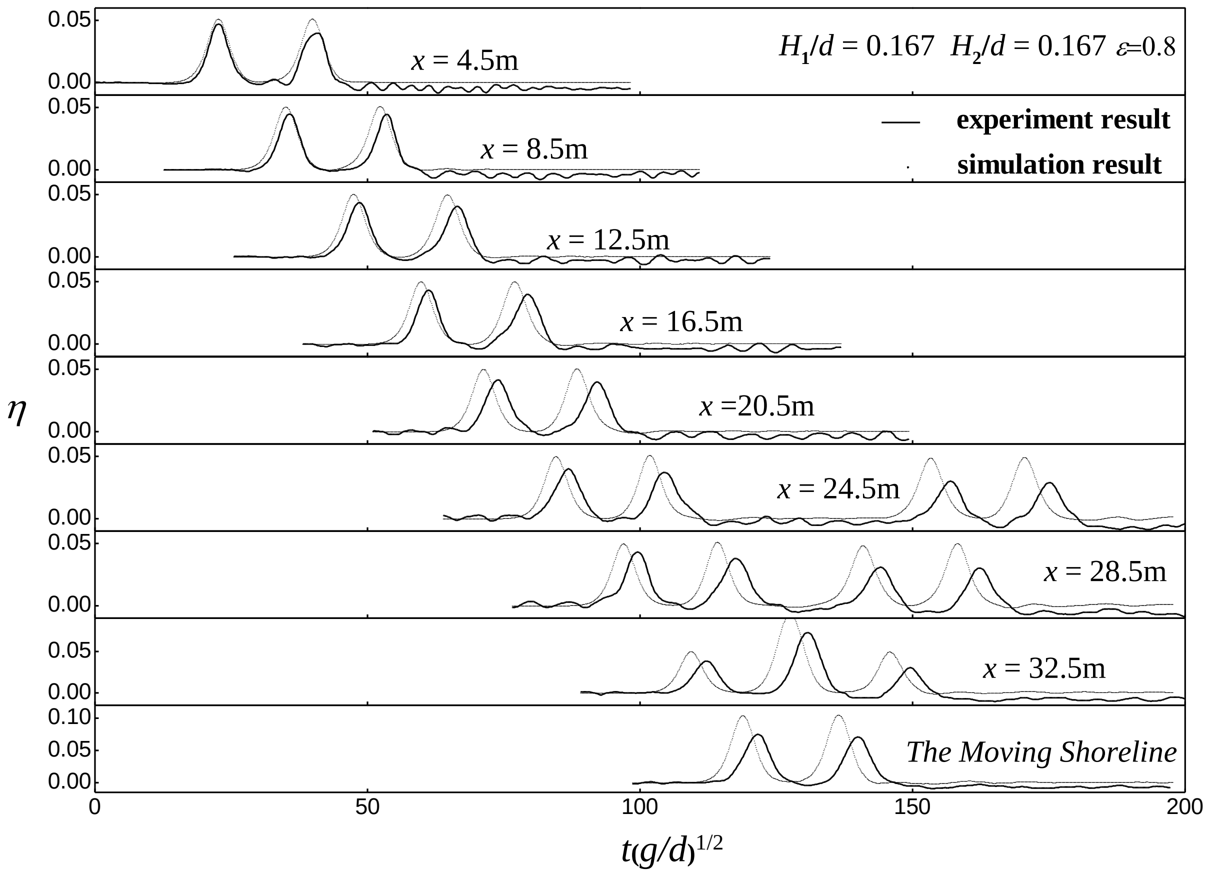
- Guo, Wang, Liu(2014, JWWEN): RANS+RNG k-e model+VOF

Results and discussion

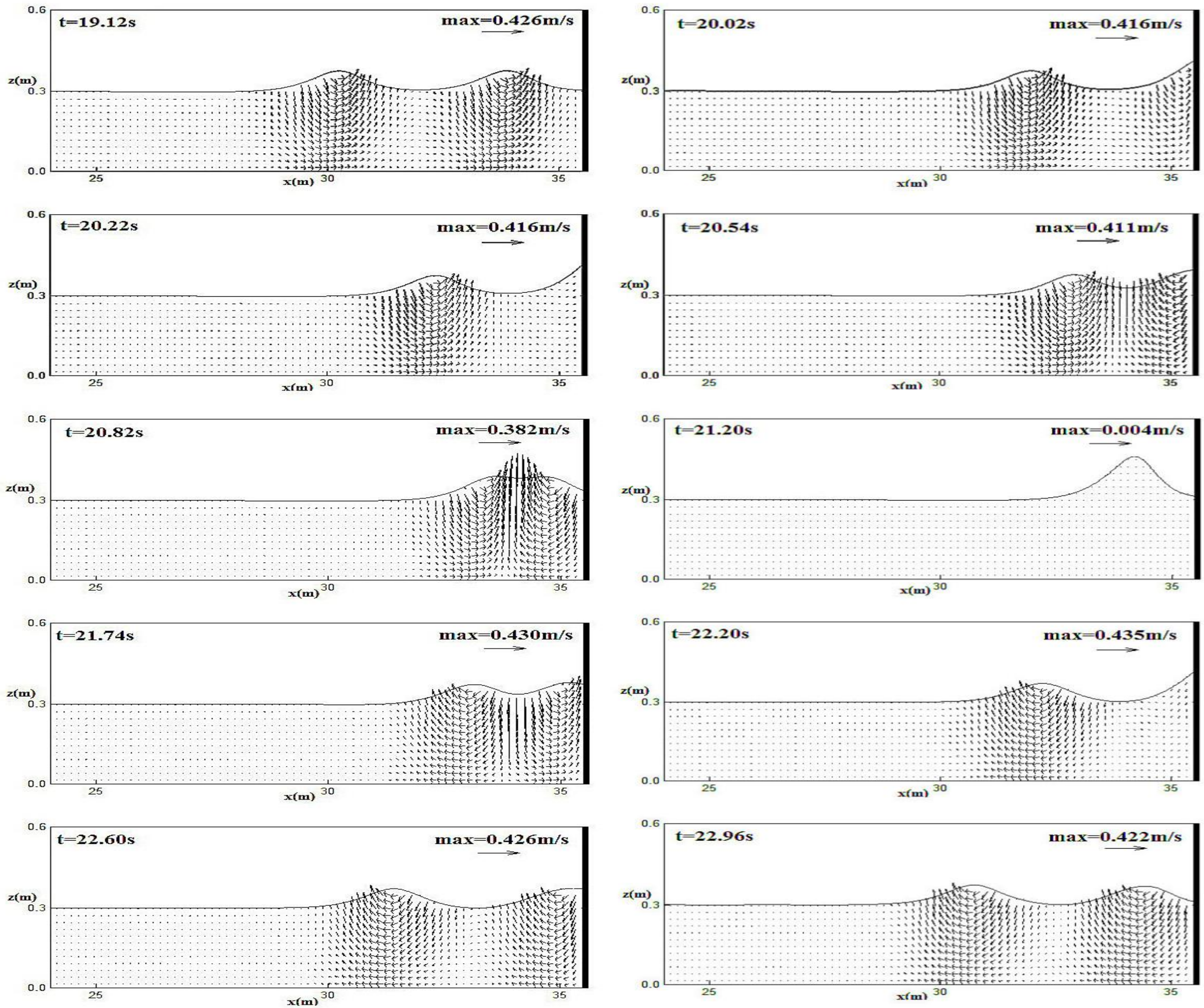


- 等波高孤立波的直墙爬高

Results and discussion



- 等波高孤立波的直墙爬高


t=19.12s
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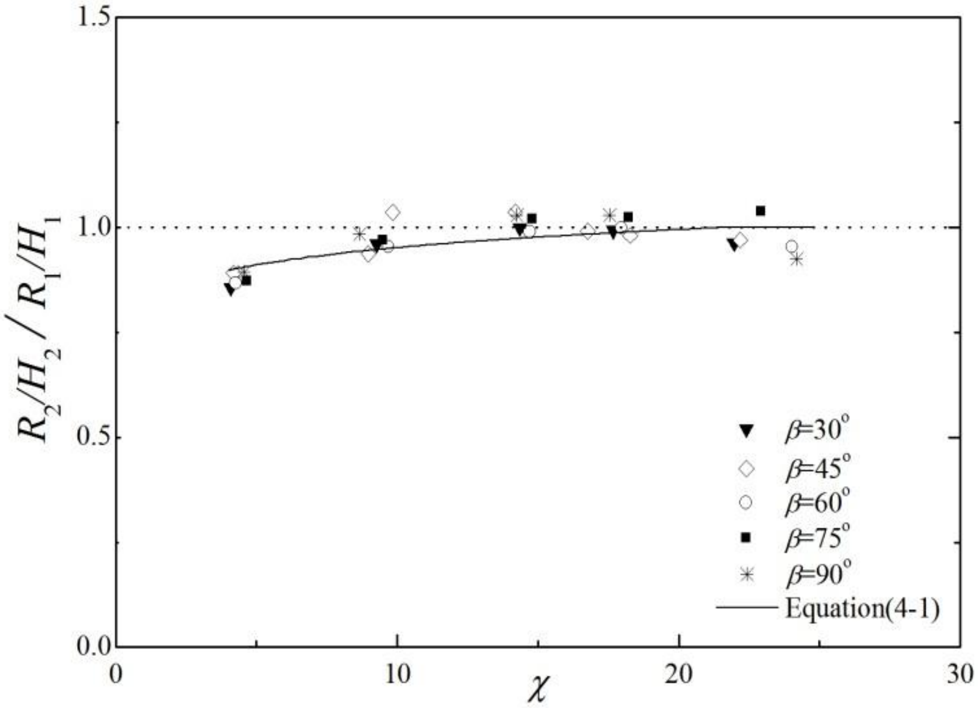
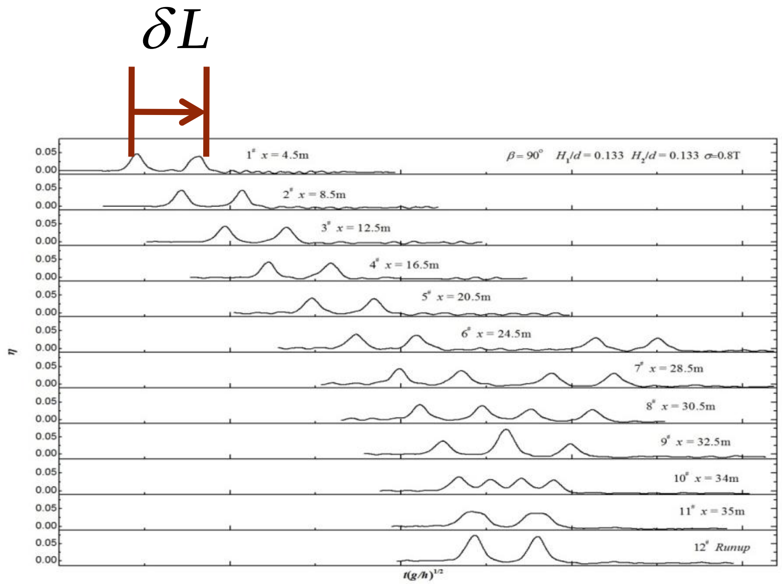
t=20.02s
max=0.416m/s
t=20.22s
max=0.416m/s
t=20.54s
max=0.411m/s
t=20.82s
max=0.382m/s
t=21.20s
max=0.004m/s
t=21.74s
max=0.430m/s
t=22.20s
max=0.435m/s
t=22.60s
max=0.426m/s
t=22.96s
max=0.422m/s
z(m)
x(m)
0.0
0.3
0.6
25
30
35

Results and discussion



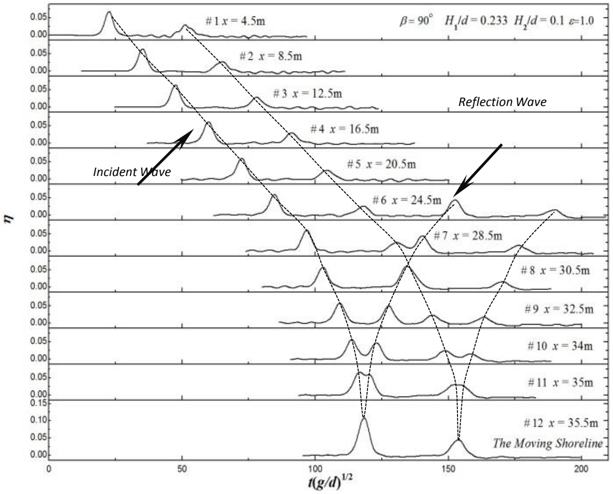


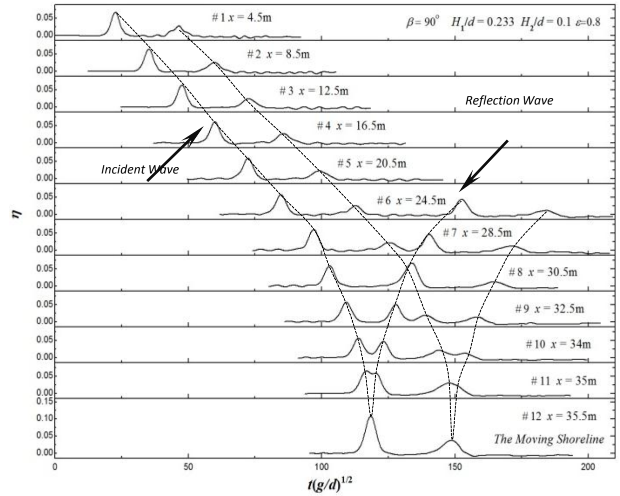
$$\chi = (\delta L / d) / (H_1 / H_2)$$

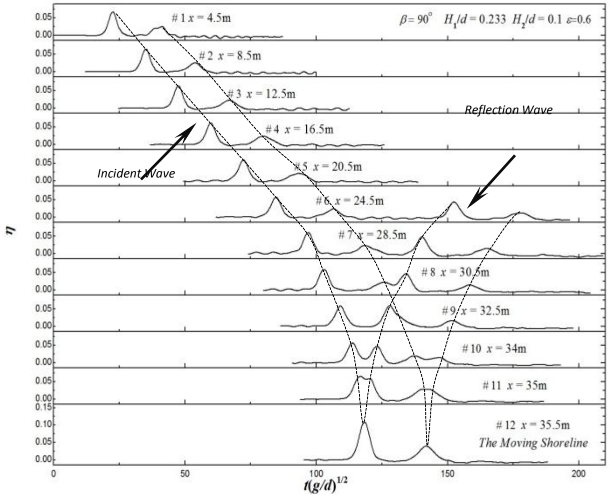
$$\frac{R_2/H_2}{R_1/H_1} = 0.8219\chi^{0.0637}, 4.0 < \chi < 25.0$$

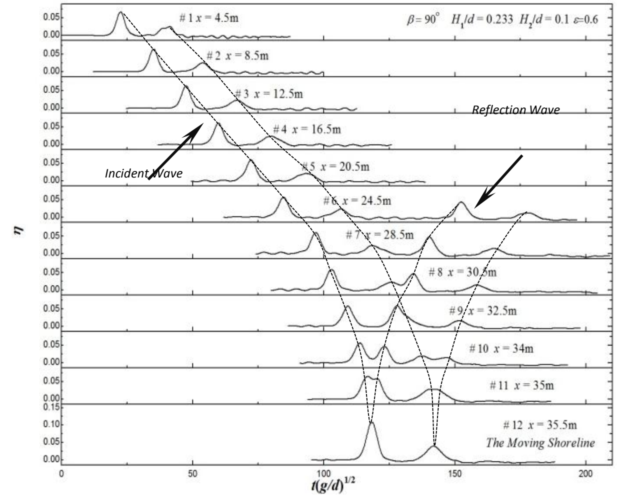
- The relationship between the run-up amplification coefficient and the similarity factor for the double solitary wave with identical individual wave height

Results and discussion



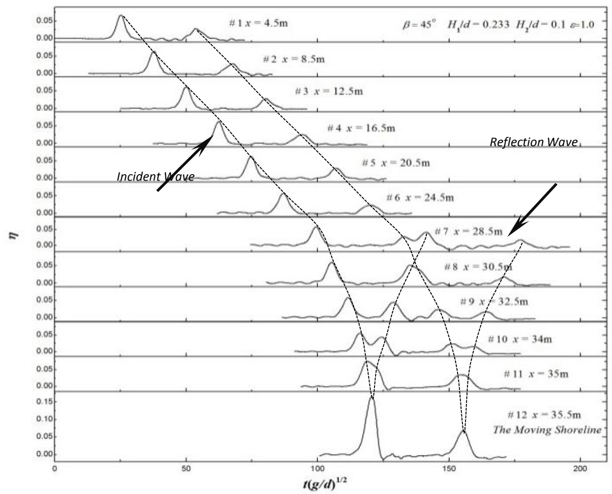


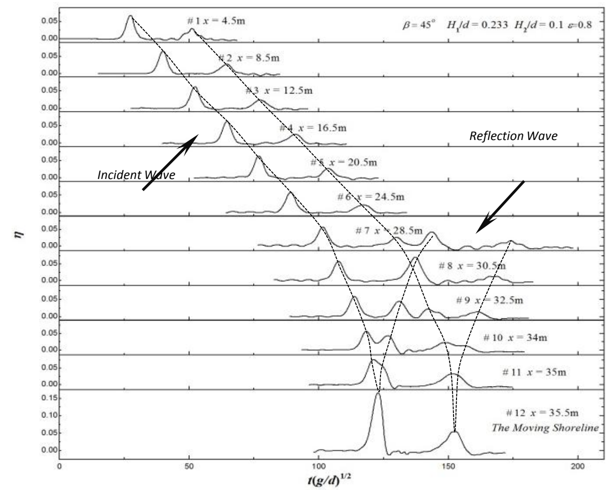


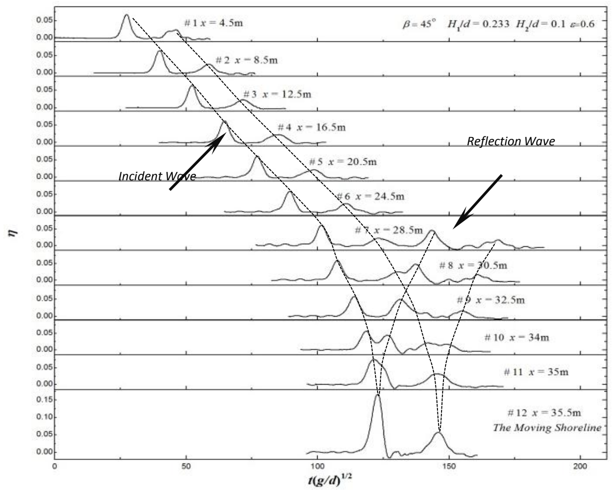


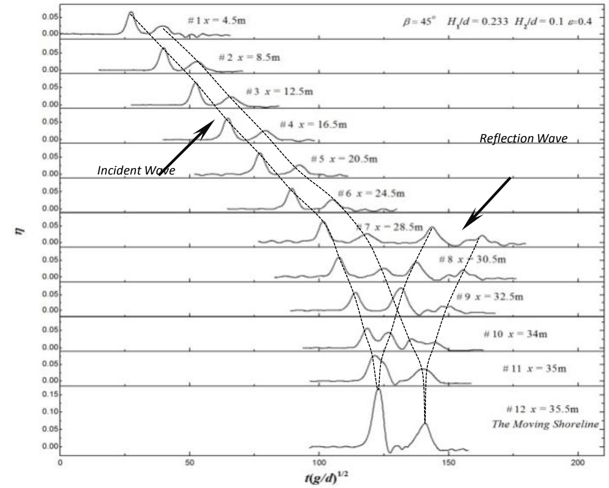
- Waveforms evolution and moving shoreline of the double solitary waves (L+S pattern): vertical wall

Results and discussion



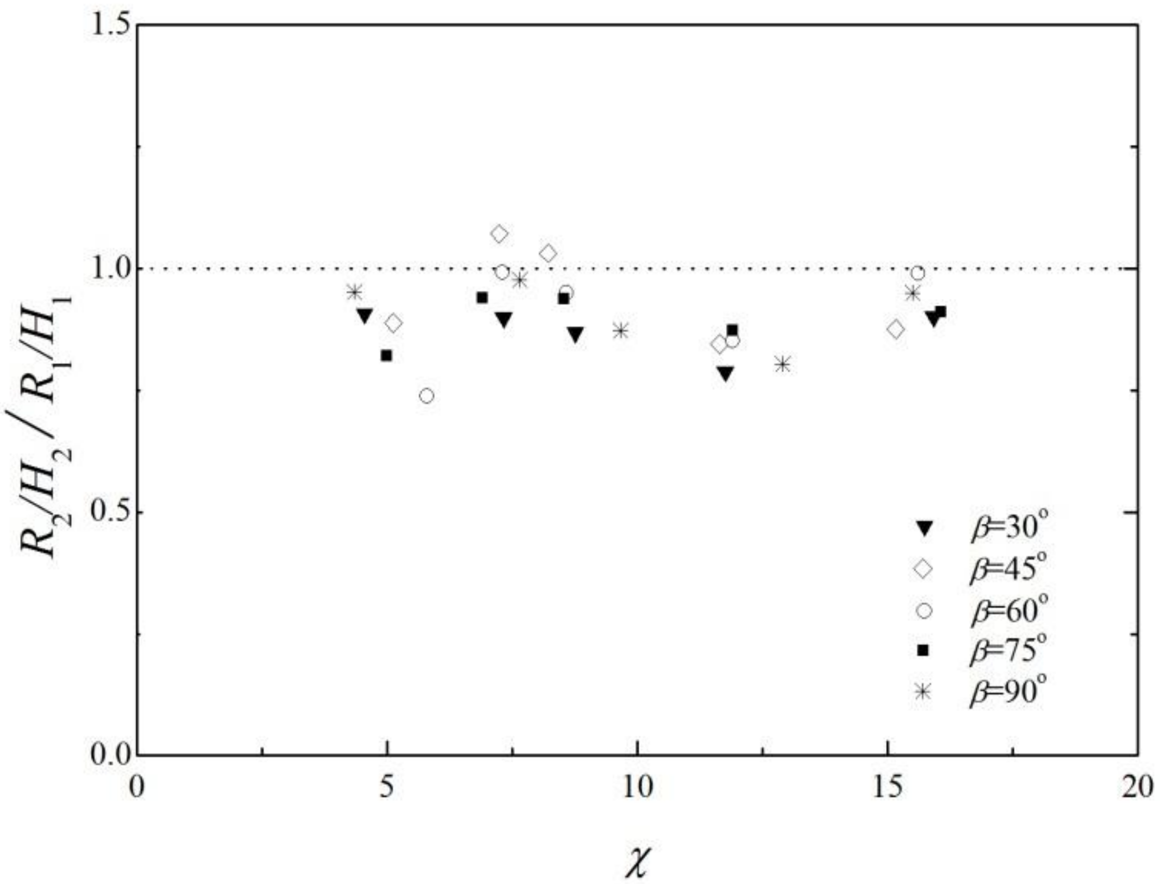






- Waveforms evolution and moving shoreline of the double solitary waves (L+S pattern): $\beta=45^o$

Results and discussion



- The relationship between the run-up amplification coefficient and the similarity factor for the double solitary waves (L+S pattern)

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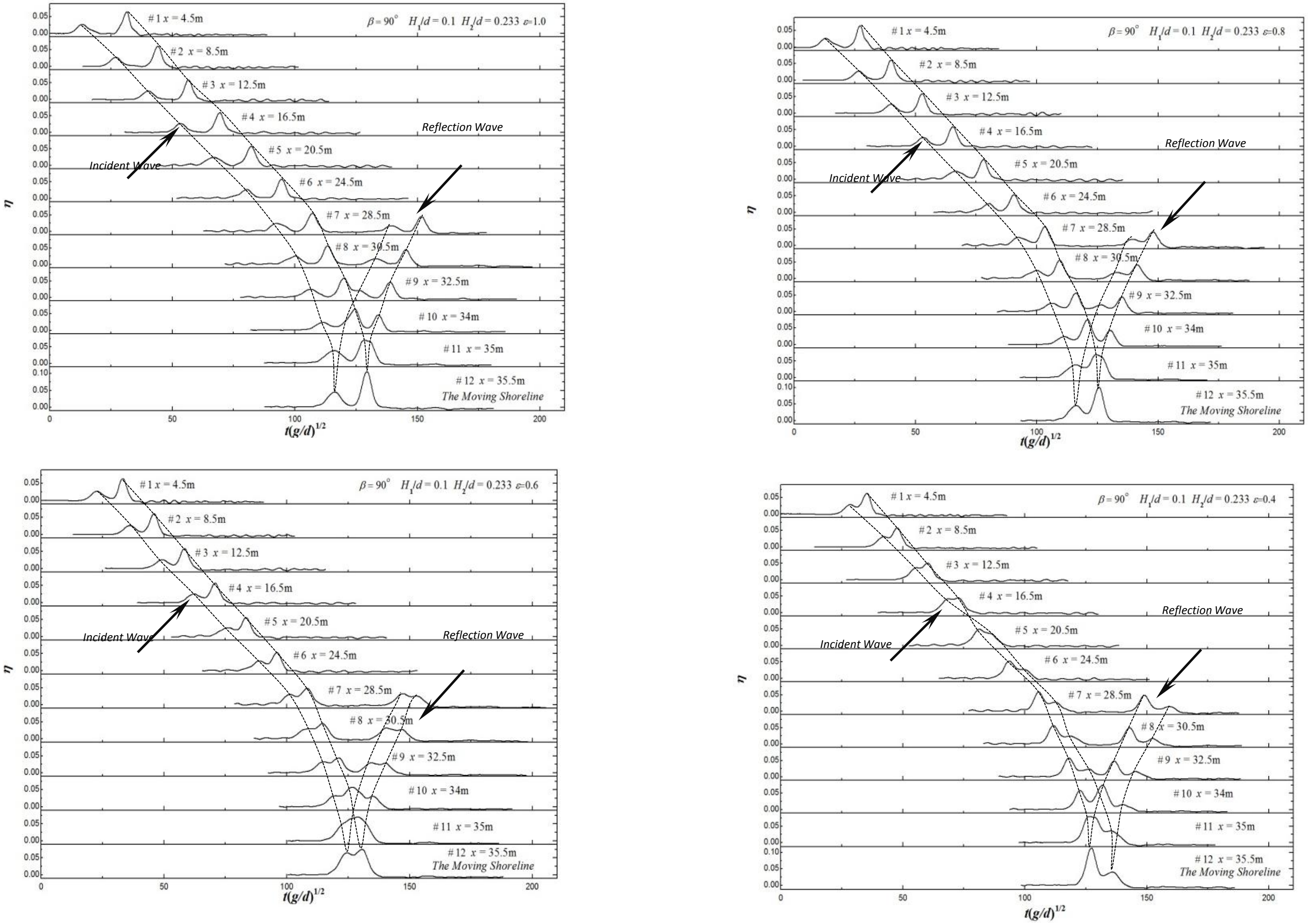
Results and discussion



- Waveforms evolution and moving shoreline of the double solitary waves (S+L pattern): vertical wall

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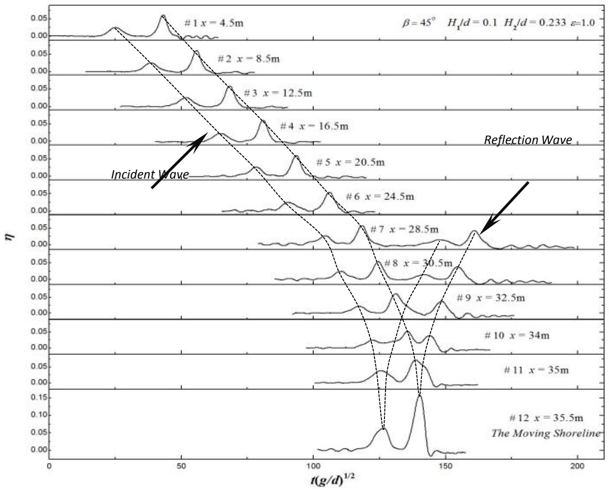
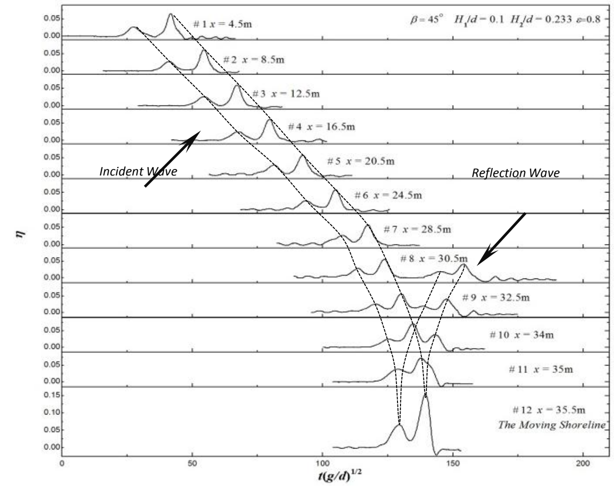
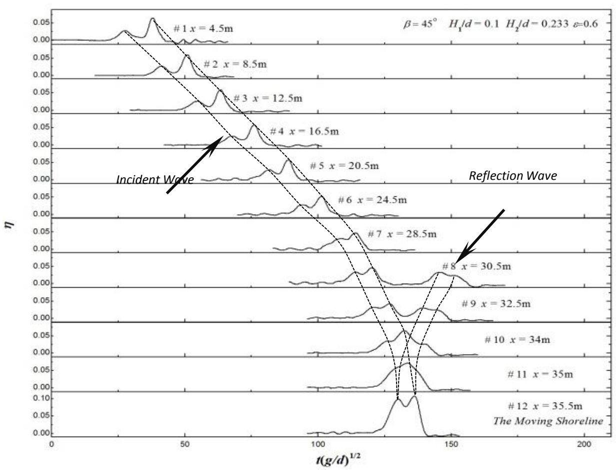
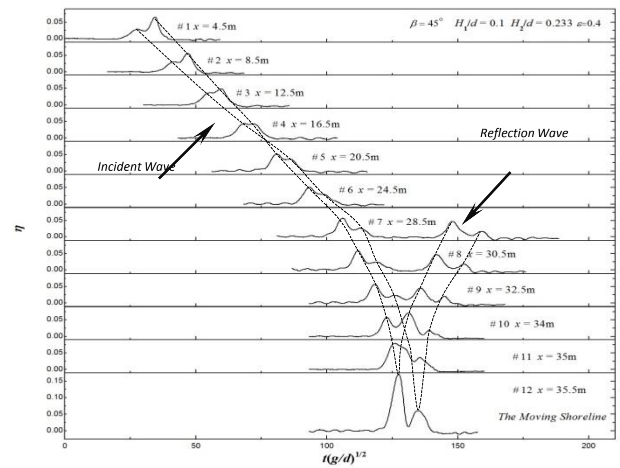
Results and discussion



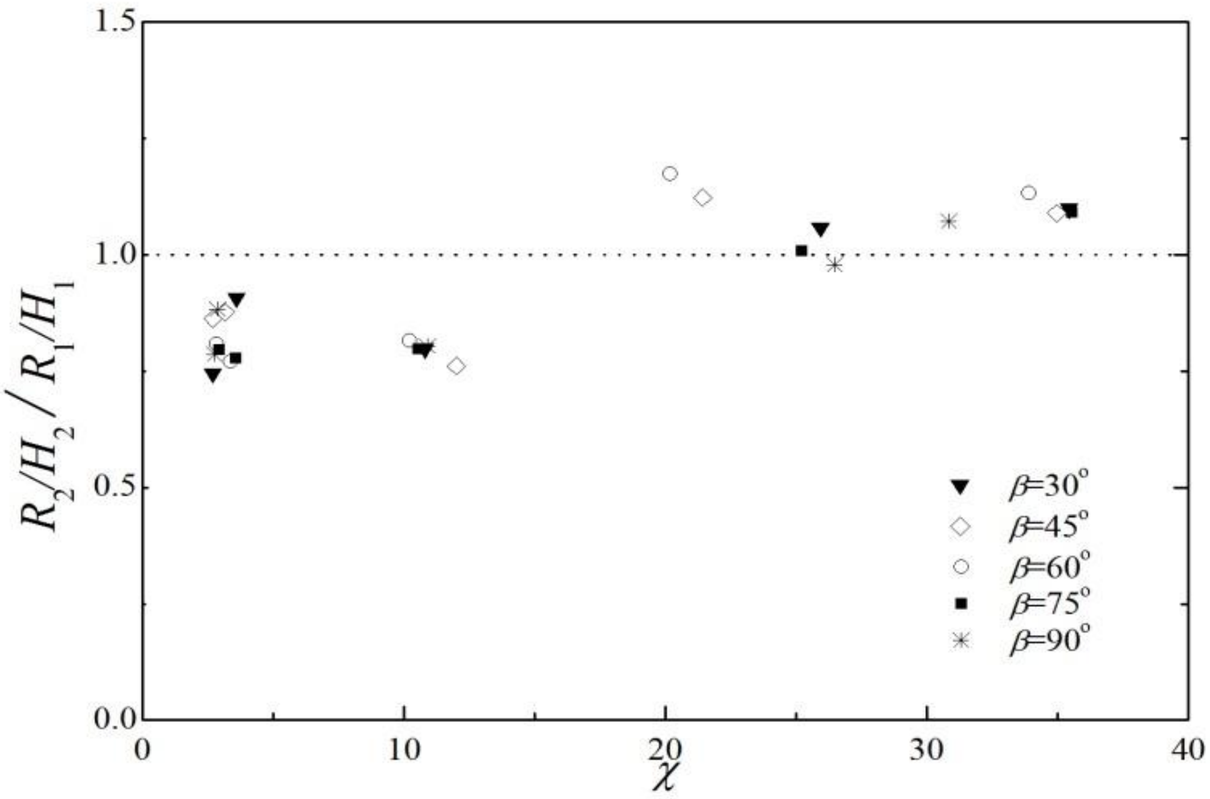






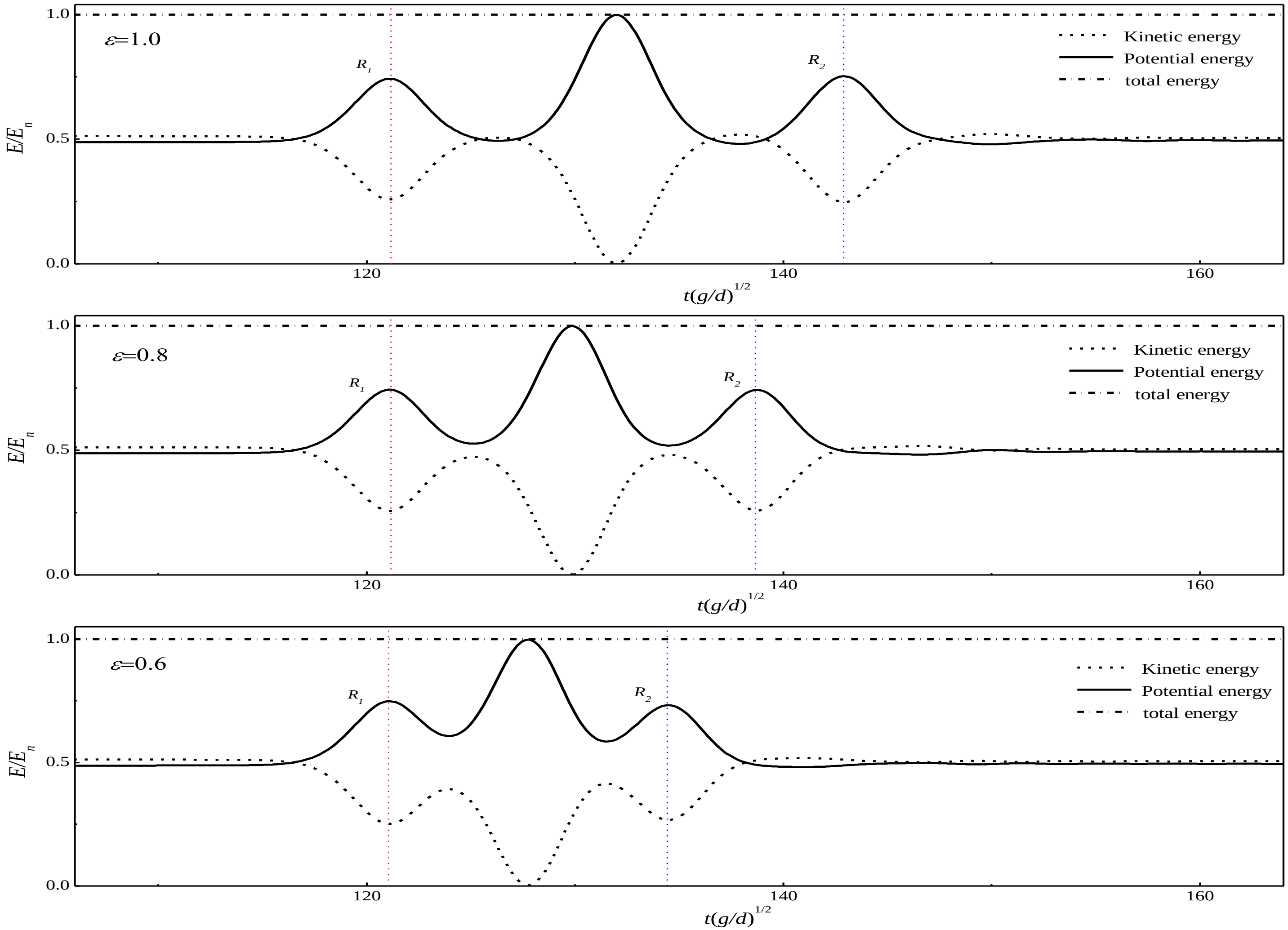
- Waveforms evolution and moving shoreline of the double solitary waves (S+L pattern): β=45°

Results and discussion



- The relationship between the run-up amplification coefficient and the similarity factor for the double solitary waves (S+L pattern)

Results and discussion



- **Zhao, Wang, Liu (2012, PoF): energy budge, single solitary wave, slope beach**

Concluding Remarks

- For the runup of the double solitary waves with equal wave height, the runup amplification coefficient is less than 1.0 for the case of as the small distance between two wave crests.

- For the case of the double solitary waves, which consists of one smaller wave followed by a larger wave at the initial time (S+L pattern), the runup amplification is less than 1.0 for the cases of smaller values of the similarity factor χ. It is found that the solitary wave with larger amplitude overtakes the first smaller wave before the runup begins.

Concluding Remarks

- If the factor χ is larger than a threshold value, which represents the cases that the leading smaller wave runup on the slope at first, the runup amplification of the second wave with larger amplitude is larger than that of the first wave.

- There are three peaks in the time series of the total potential energy of the wave field during the period of the runup of the double solitary waves against a vertical wall.

Thank You！