University of Rome
“Roma Tre”

Environmental and Maritime
Hydraulic Laboratory – University
of L’Aquila

University of Rome
“Tor Vergata”

Tsunami experimental modeling: 2D and 3D wave propagation, 2D runup and overtopping

Dr. Marcello DI RISIO

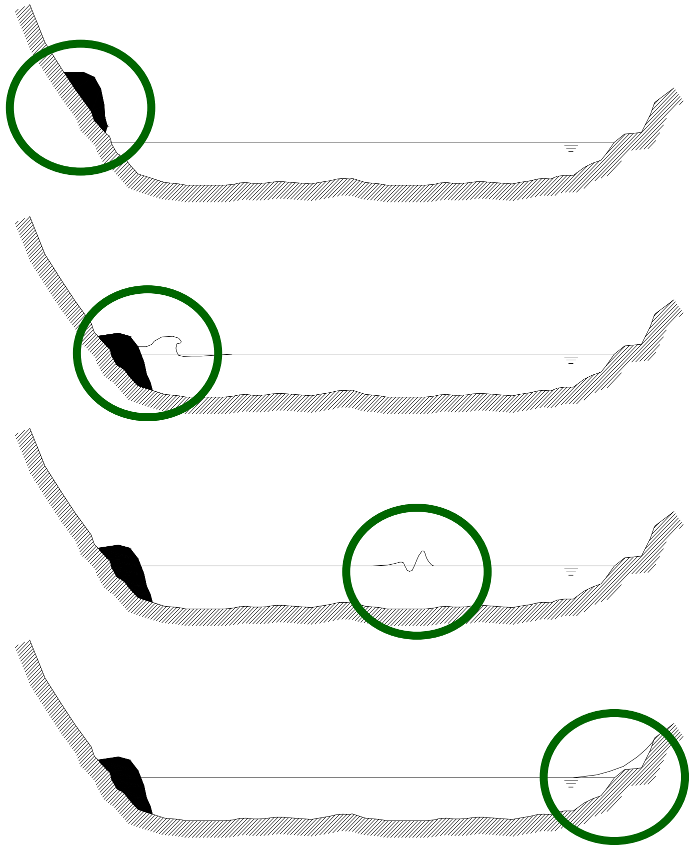
The phenomenon of landslides-tsunami event

i. **The landslide starts to move from one of the boundaries of the water body**

ii. **The landslide interacts with the free surface initially at rest and a transient perturbation is generated**

iii. **The perturbation propagates into the water body**

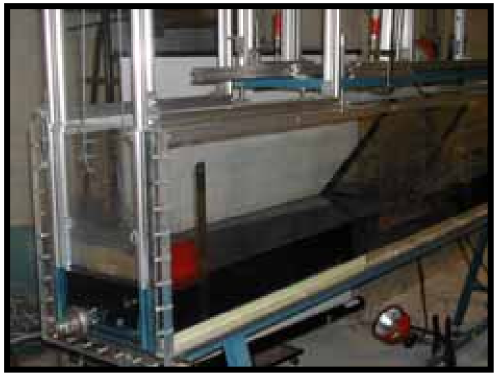
iv. **The perturbation reaches the coastal boundaries and wave runup occurs (if a dam exists wave overtopping may occur)**



Experimental facilities

- **Wave flume**

(18.0 m x 0.30 m x 0.45 m)



- **Wave tank**

(12.00 m x 6.00 m x 0.80 m)

- **Wave gauges**

  (time series of free surface oscillations)

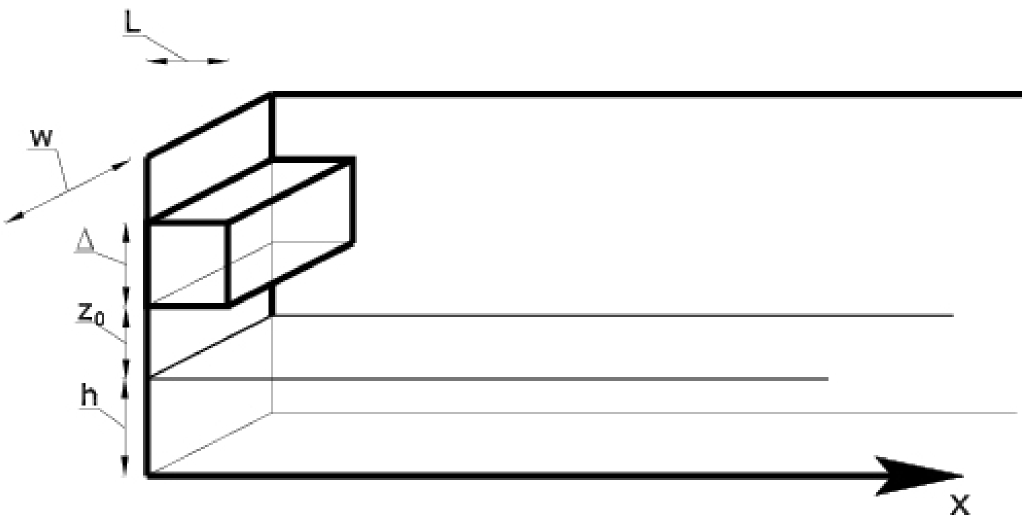
- **Accelerometer**

  (time series of landslide accelerations)

- **Digital video system**

  (visualization of the phenomenon)

Generation and propagation of vertical slump generated waves: the 2D problem



$$\Theta = f\left(L, w, \Delta, h, z_0, x, v_0, p, \rho_s, \rho, \mu, g, t, T_u, \Delta V\right).$$

$$\Pi_\Theta = \phi\left(\frac{L}{h}, \cancel{\frac{w}{h}}, \frac{\Delta}{h}, \cancel{\frac{z_0}{h}}, \frac{v_0}{\sqrt{gh}}, \frac{x}{h}, p, \frac{\rho_s}{\rho}, \cancel{\frac{\mu}{\rho h\sqrt{gh}}}, t\sqrt{\frac{g}{h}}, \cancel{T_u\sqrt{\frac{g}{h}}}, \cancel{\frac{\Delta V}{\sqrt{gh}}}\right)$$

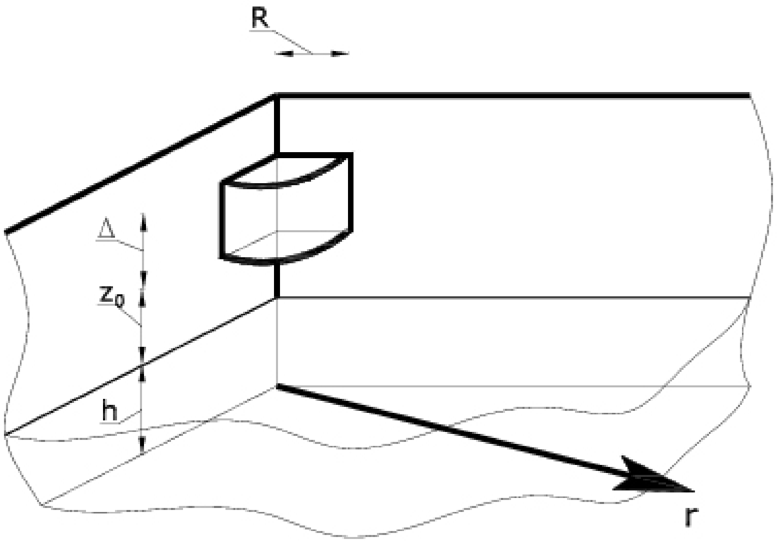
2D

Shear stresses are negligible

Landslide dimensions and energy

- **L, w, Δ: landslide dimensions**
- **h: water depth**
- **z_0: initial position above still water level**
- **x: distance from generation area**
- **v_0: impact velocity**
- **p: landslide porosity**
- **ρ_s: landslide density**
- **ρ: water density**
- **μ: water dinamic viscosity**
- **g: gravitational acceleration**
- **t: elapsed time**
- **T_u: underwater phase duration**
- **ΔV: velocity variation at impact**

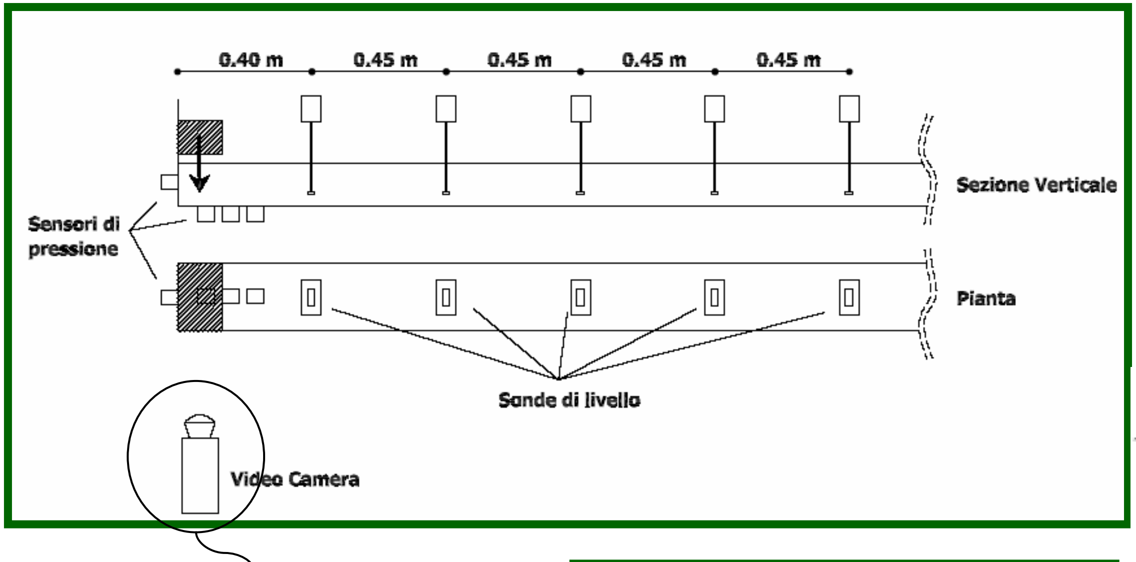
Generation and propagation of vertical slump generated waves: the 3D problem



$$\Theta = f\left(R, \Delta, h, z_0, r, v_0, p, \rho_s, \rho, \mu, g, t, T_u, \Delta V\right)$$

- **R,Δ: landslide dimensions**
- **h: water depth**
- **z_0: initial position above still water level**
- **r: distance from generation area**
- **v_0: impact velocity**
- **p: landslide porosity**
- **ρ_s: landslide density**
- **ρ: water density**
- **μ: water dinamic viscosity**
- **g: gravitational acceleration**
- **t: elapsed time**
- **T_u: underwater phase duration**
- **ΔV: velocity variation at impact**

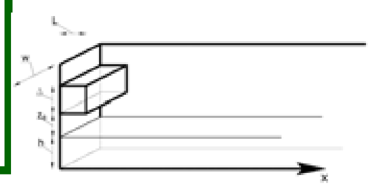
Generation and propagation of vertical slump generated waves: the experiments



Experimental parameters

(90 tests - 720 experimental points)

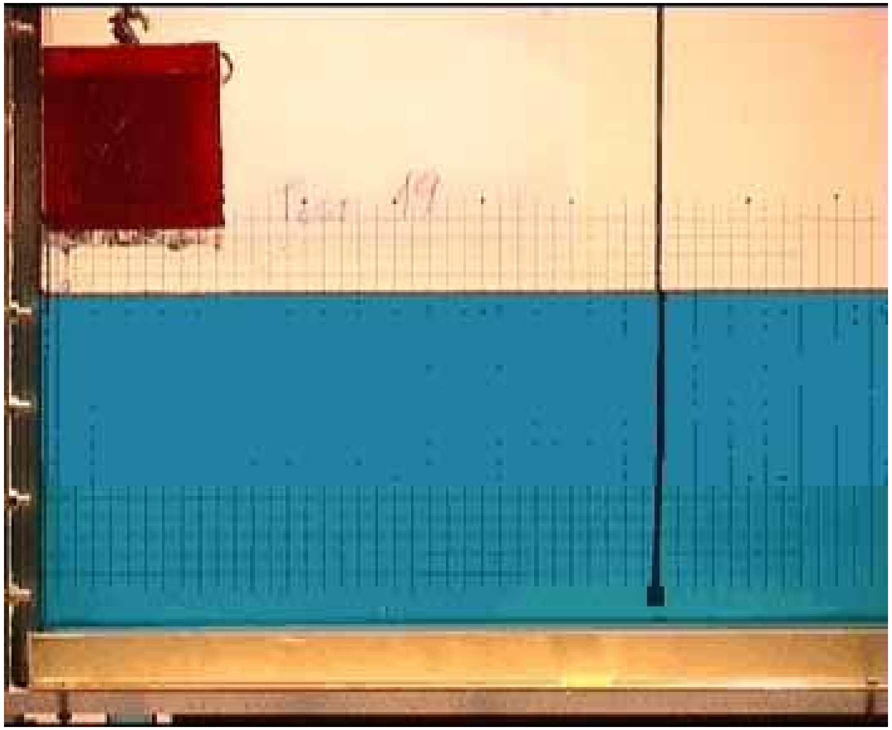
h [m]	L [m]	z_0 [m]	x [m]
0.06	0.05	0.01	0.40
0.10	0.10	0.03	0.85
0.18	0.15	0.05	1.30
0.23		0.07	1.75
		0.10	2.20
		0.15	3.10
		0.20	4.00
			5.35



$$\frac{H}{h} = \phi_H\left(\frac{L}{h}, \frac{v_0}{\sqrt{gh}}, \frac{x}{h}\right)$$

$$T\sqrt{\frac{g}{h}} = \phi_T\left(\frac{L}{h}, \frac{v_0}{\sqrt{gh}}, \frac{x}{h}\right)$$

Generation and propagation of vertical slump generated waves: the experiments

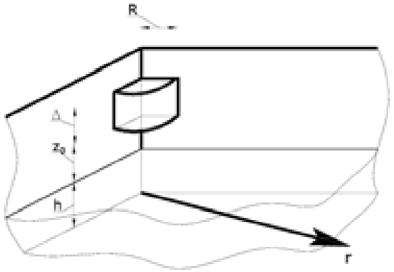


Generation and propagation of vertical slump generated waves: the experiments

Experimental parameters

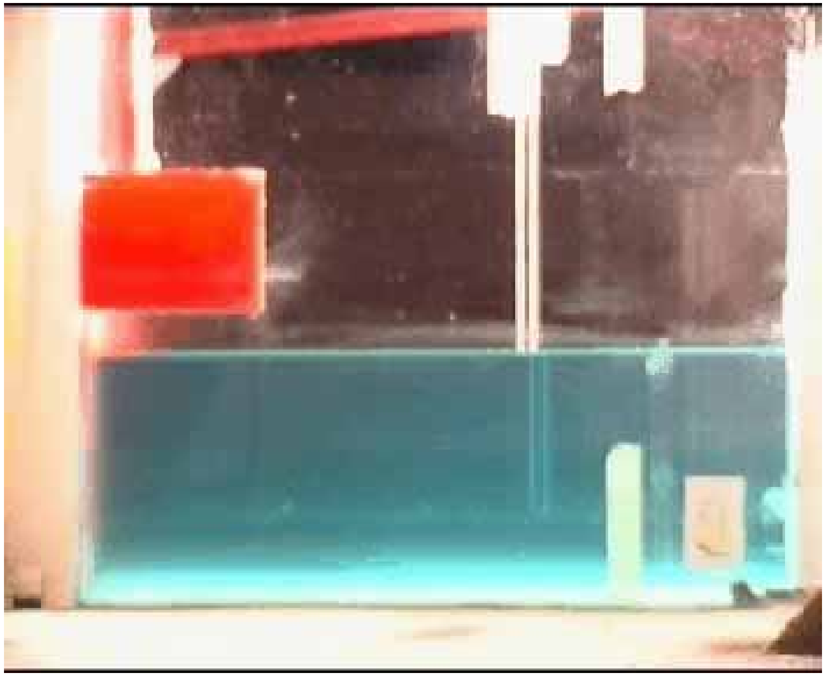
(88 tests - 440 experimental points)

h $[m]$	R $[m]$	z_0 $[m]$	r $[m]$
0.09	0.157	0.015	0.63 (0.86)
0.16	0.215	0.047	1.33 (1.83)
0.28		0.078	2.04 (2.80)
0.36		0.094	2.75 (3.76)
		0.109	3.45 (4.73)
		0.141	
		0.157	
		0.188	
		0.235	
		0.314	

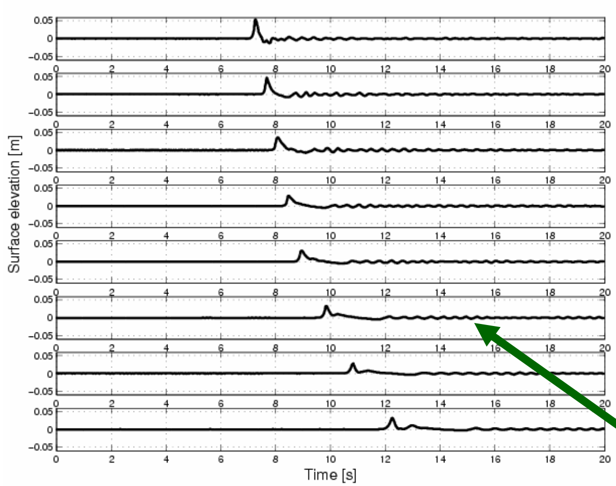


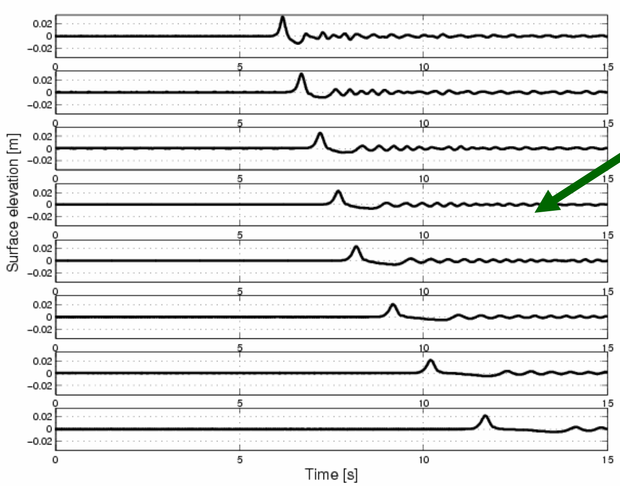
$$\frac{H}{h} = \phi_H\left(\frac{R}{h}, \frac{v_0}{\sqrt{gh}}, \frac{r}{h}\right), T\sqrt{\frac{g}{h}} = \phi_T\left(\frac{R}{h}, \frac{v_0}{\sqrt{gh}}, \frac{r}{h}\right)$$

Generation and propagation of vertical slump generated waves: the experiments



Generation and propagation of vertical slump generated waves: 2D experiments





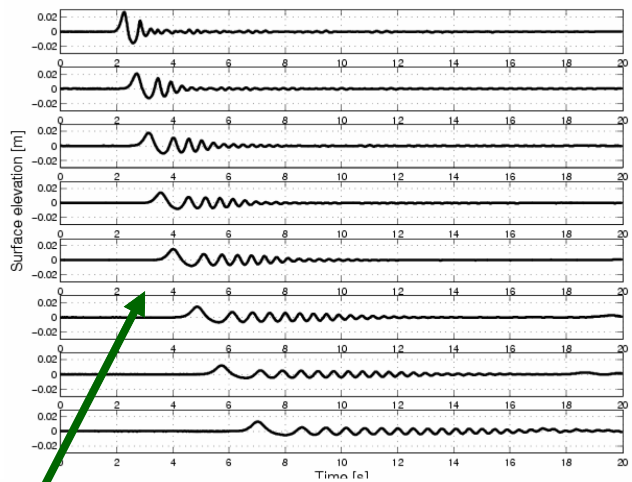
A wide range of wave type was generated during experiments

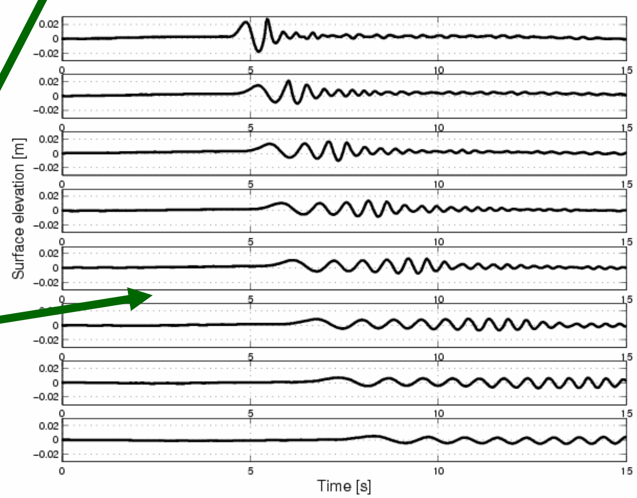
likebore waves

solitary waves

cnoidal waves

linear waves

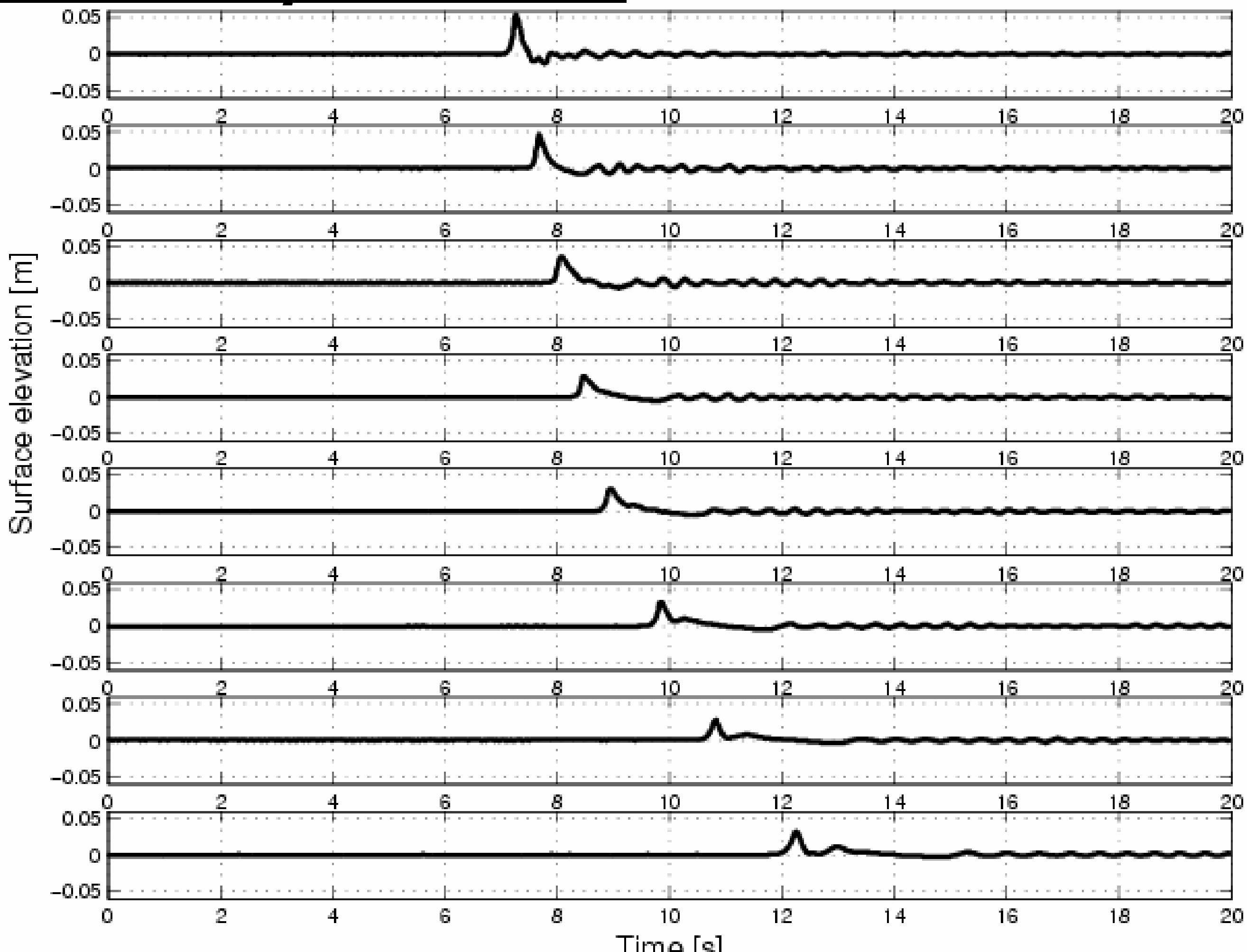




Generation and propagation of vertical slump generated waves: 2D experiments

2D experiments:

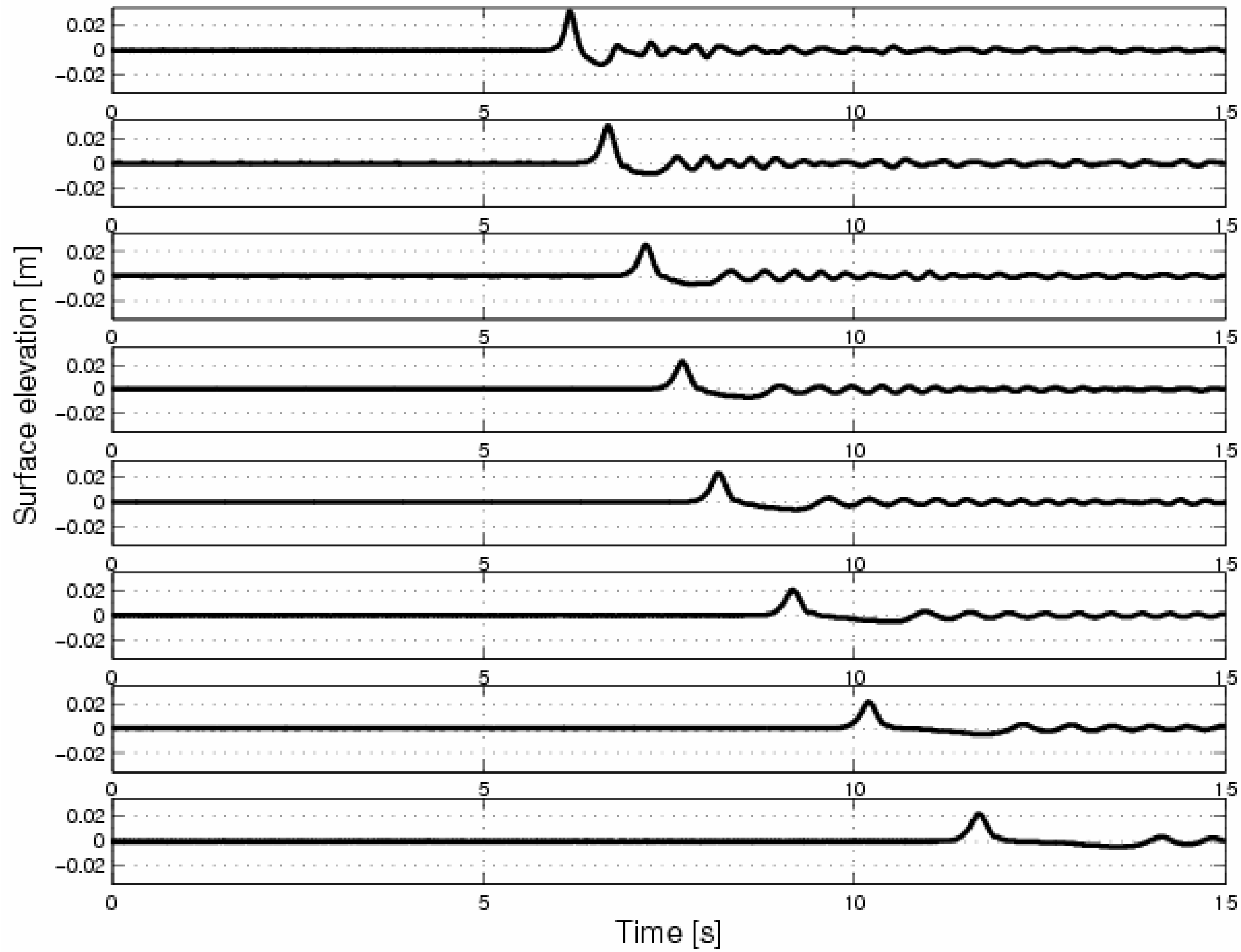
Likebore waves



Generation and propagation of vertical slump generated waves: 2D experiments

2D experiments:

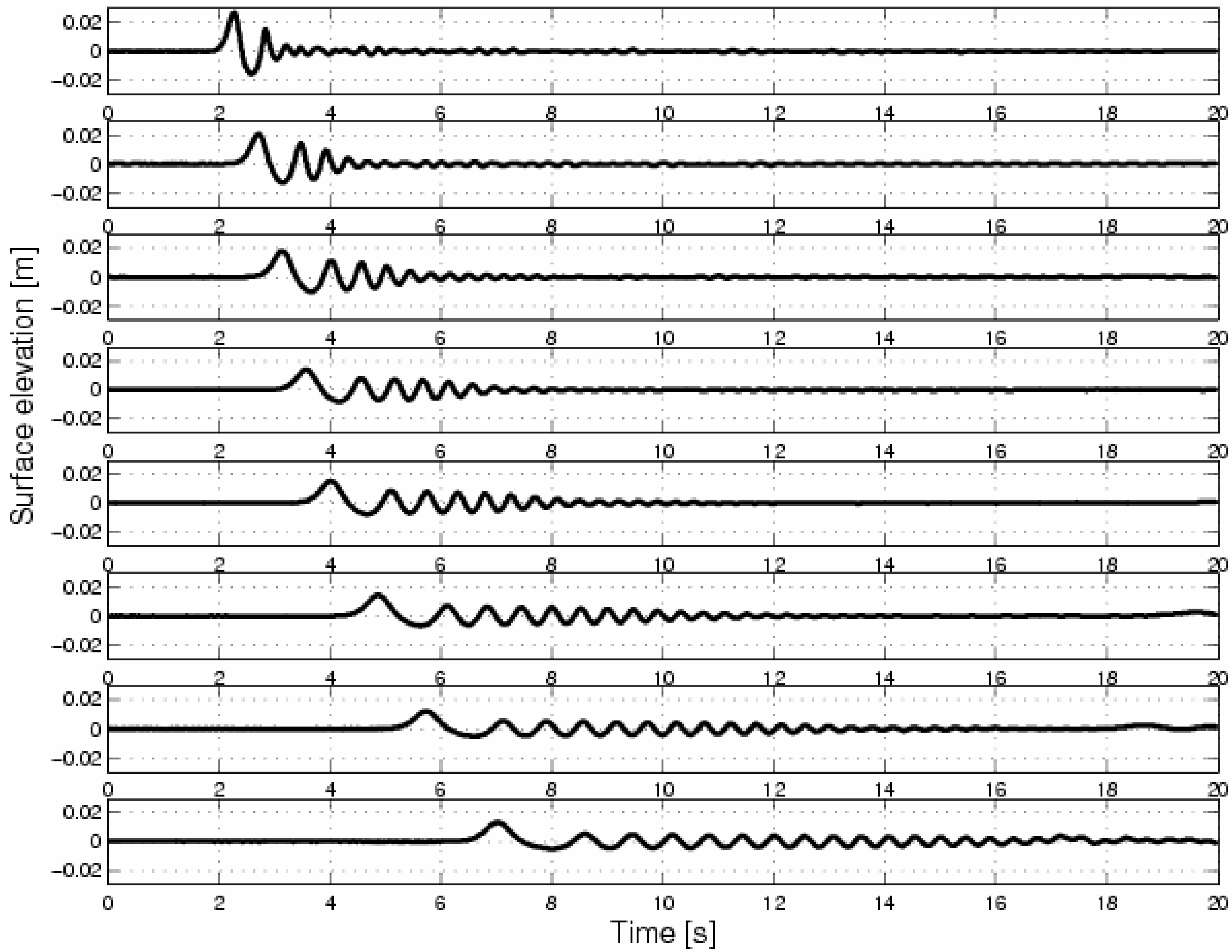
Solitary waves



Generation and propagation of vertical slump generated waves: 2D experiments

2D experiments:

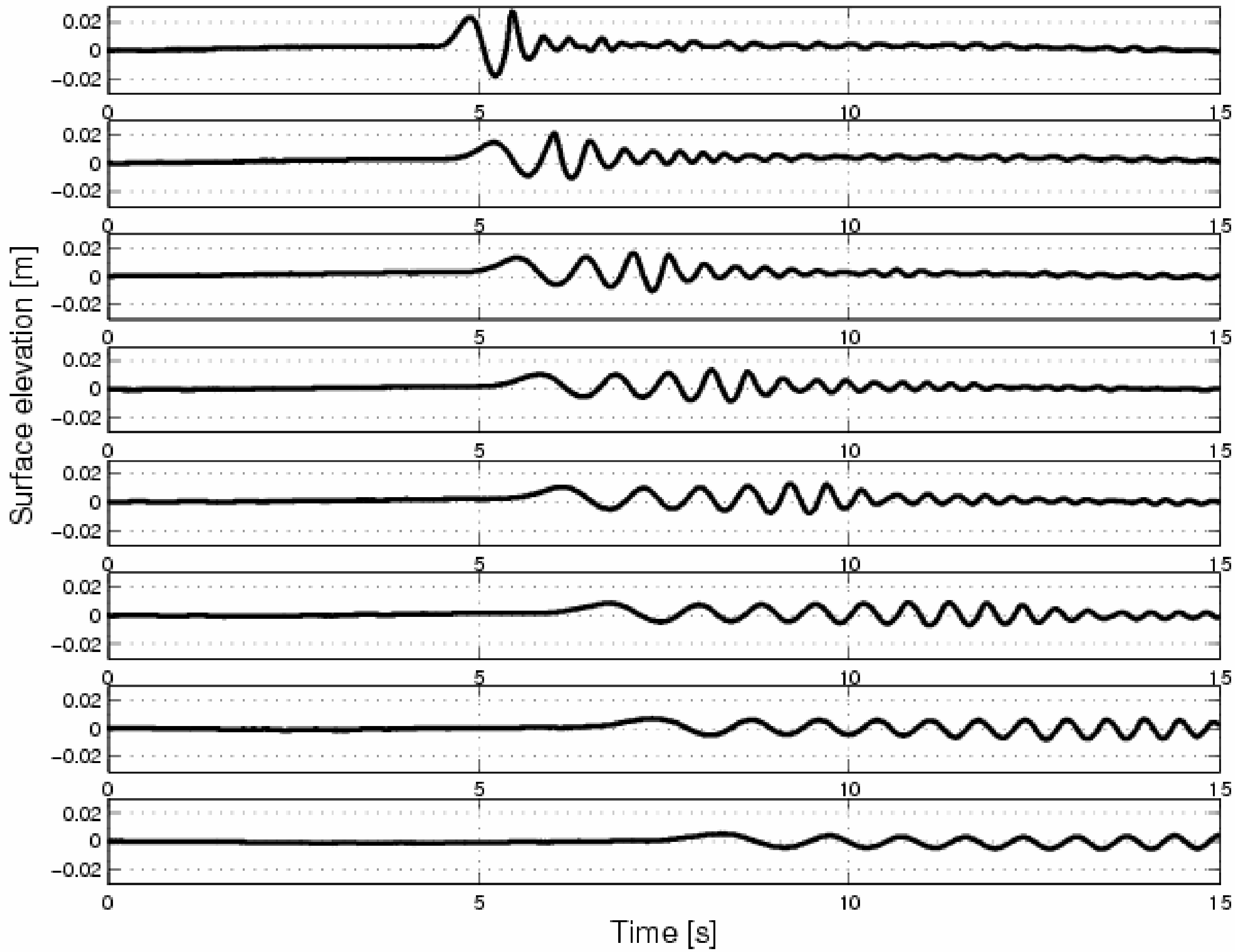
Cnoidal waves



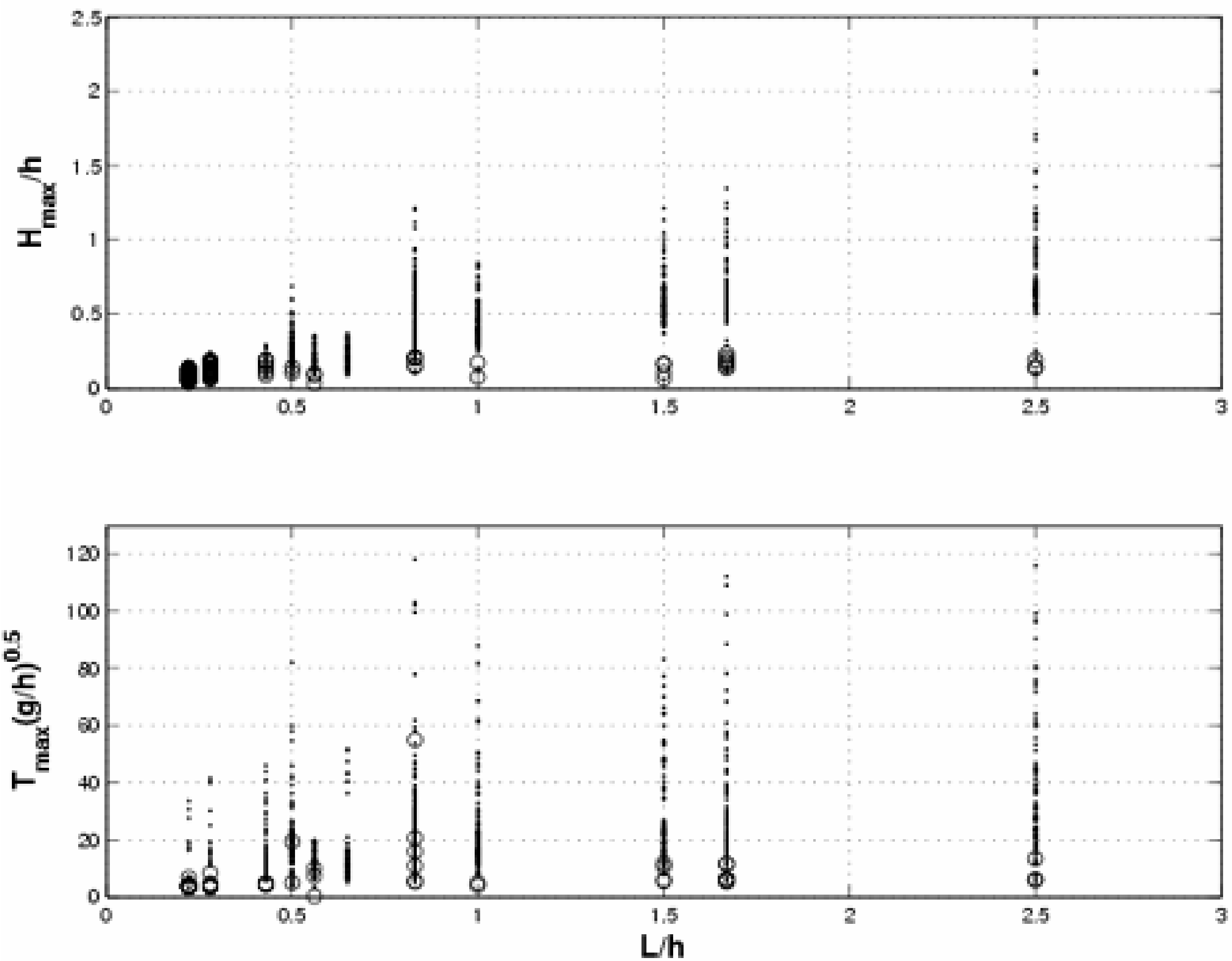
Generation and propagation of vertical slump generated waves: 2D experiments

2D experiments:

Linear waves



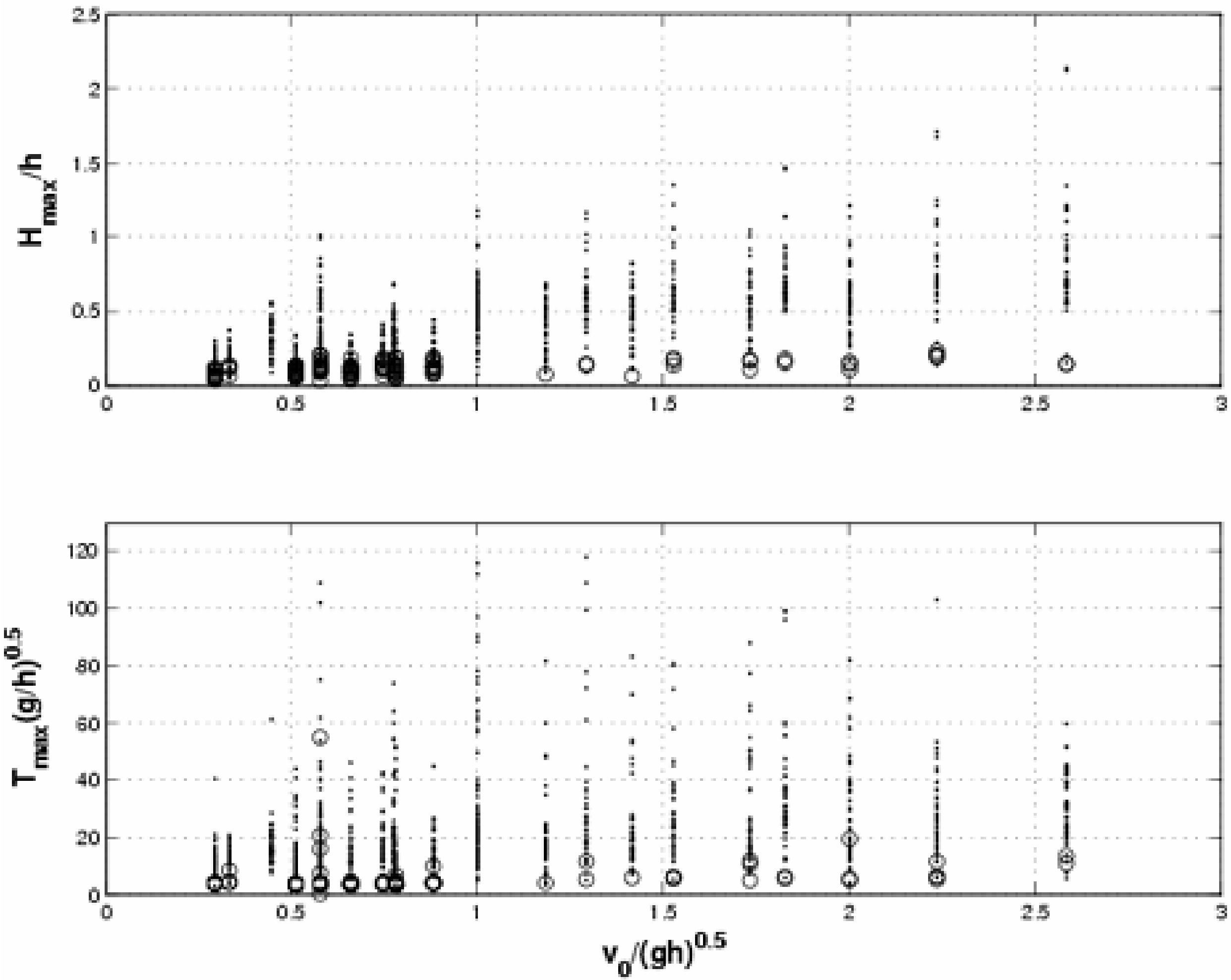
Generation and propagation of vertical slump generated waves: 2D experiments



2D experiments:

- in 12% of tests the first wave is not the highest
- Maximum wave height increases as landslide length increases
- Wave period related to maximum wave height increases as landslide length increases

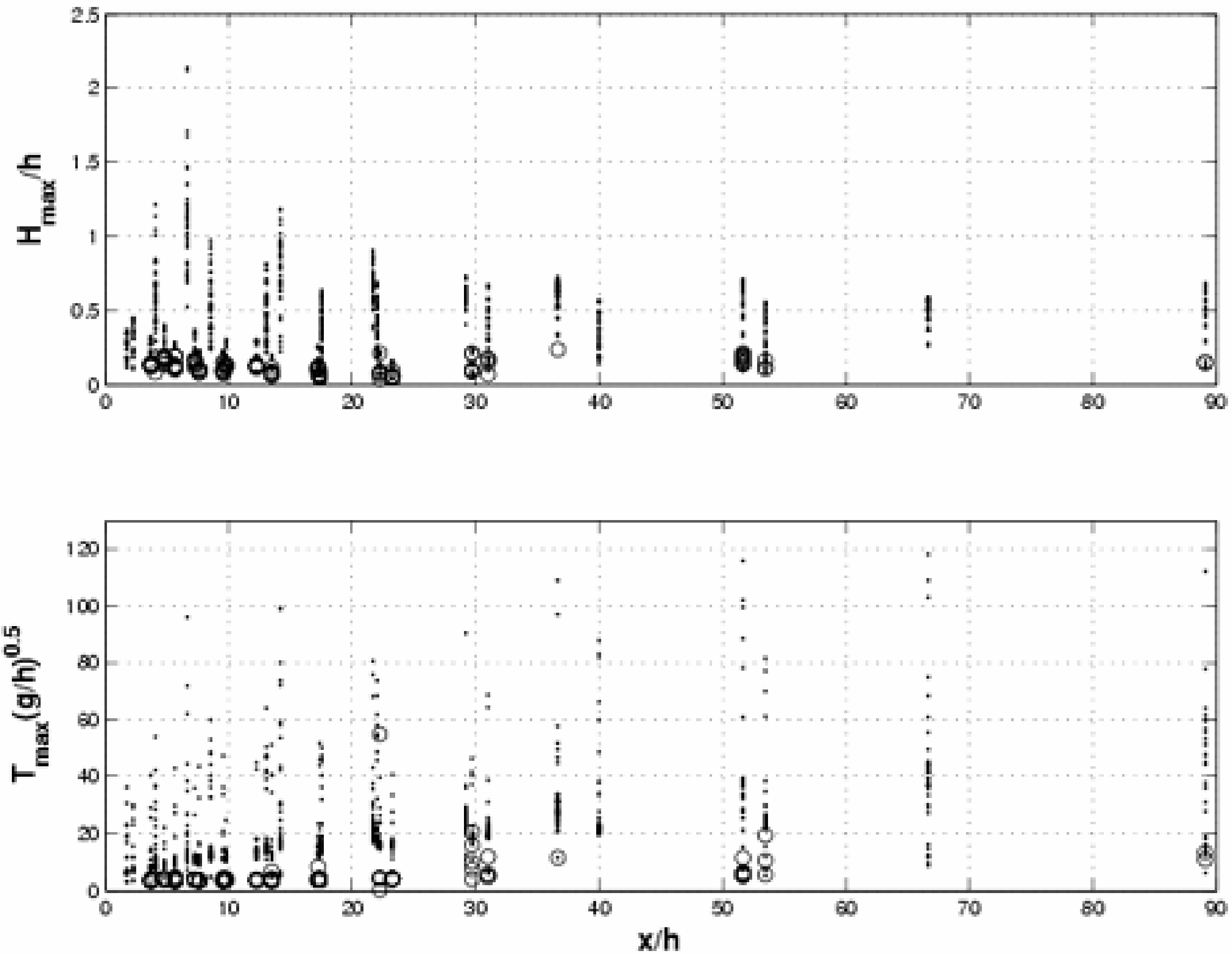
Generation and propagation of vertical slump generated waves: 2D experiments



2D experiments:

- **Maximum wave height increases as landslide energy increases**
- **Wave period related to maximum wave height slightly increases as landslide energy increases**

Generation and propagation of vertical slump generated waves: 2D experiments

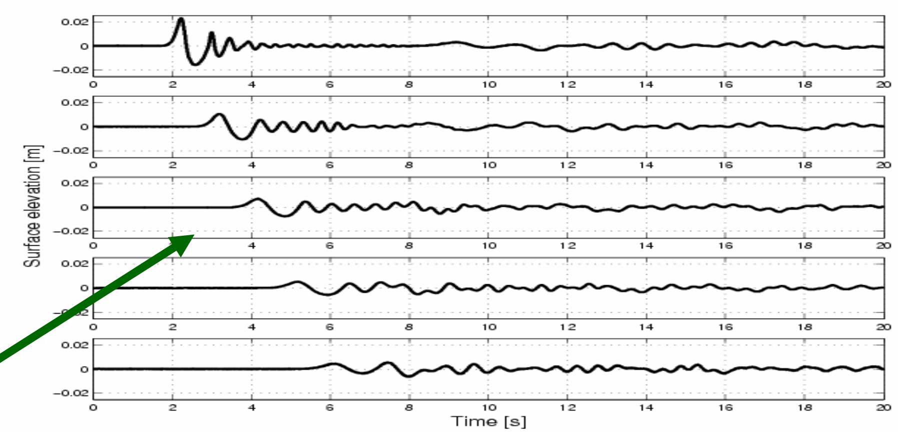


2D experiments:

- Maximum wave height decreases as distance from generation area increases
- Wave period related to maximum wave height increases as distance from generation area increases (frequency dispersion)

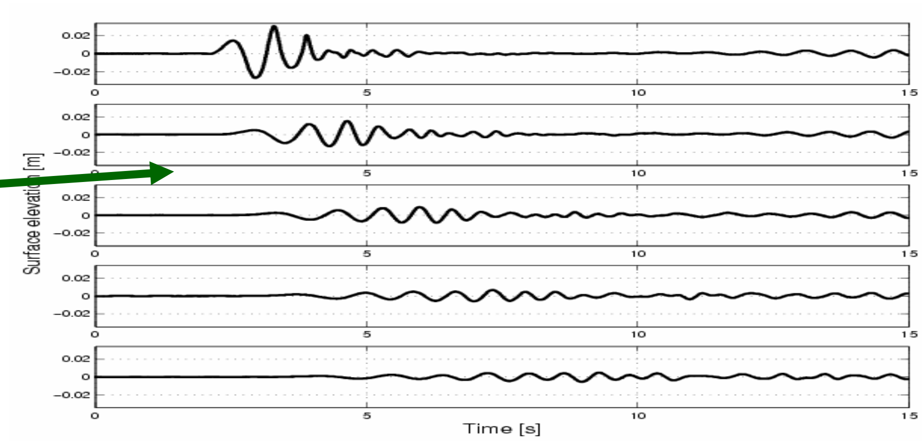
Generation and propagation of vertical slump generated waves: 3D experiments

Also in this tests a wide range of wave type was generated during experiments



cnoidal waves

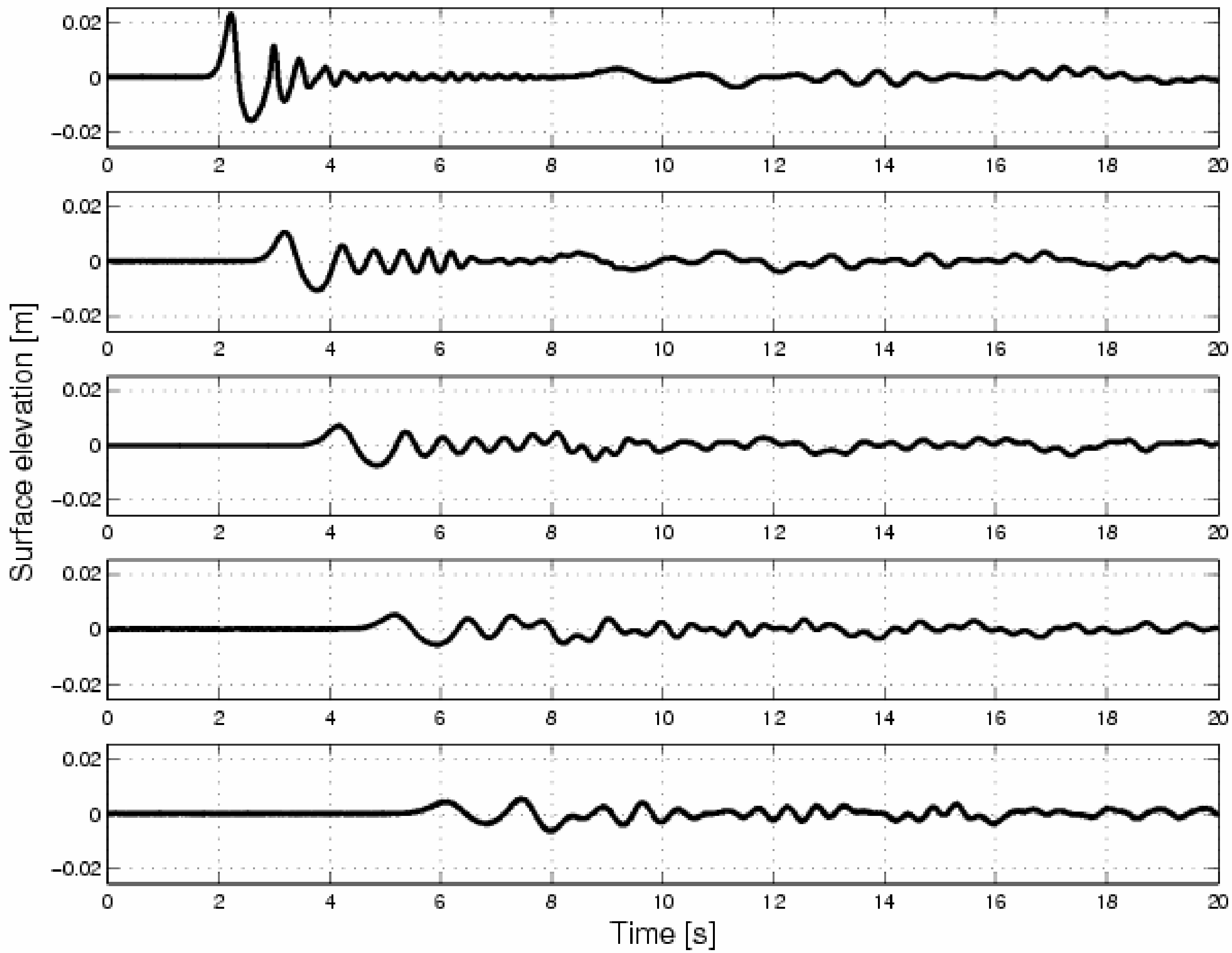
linear waves



Generation and propagation of vertical slump generated waves: 3D experiments

3D experiments:

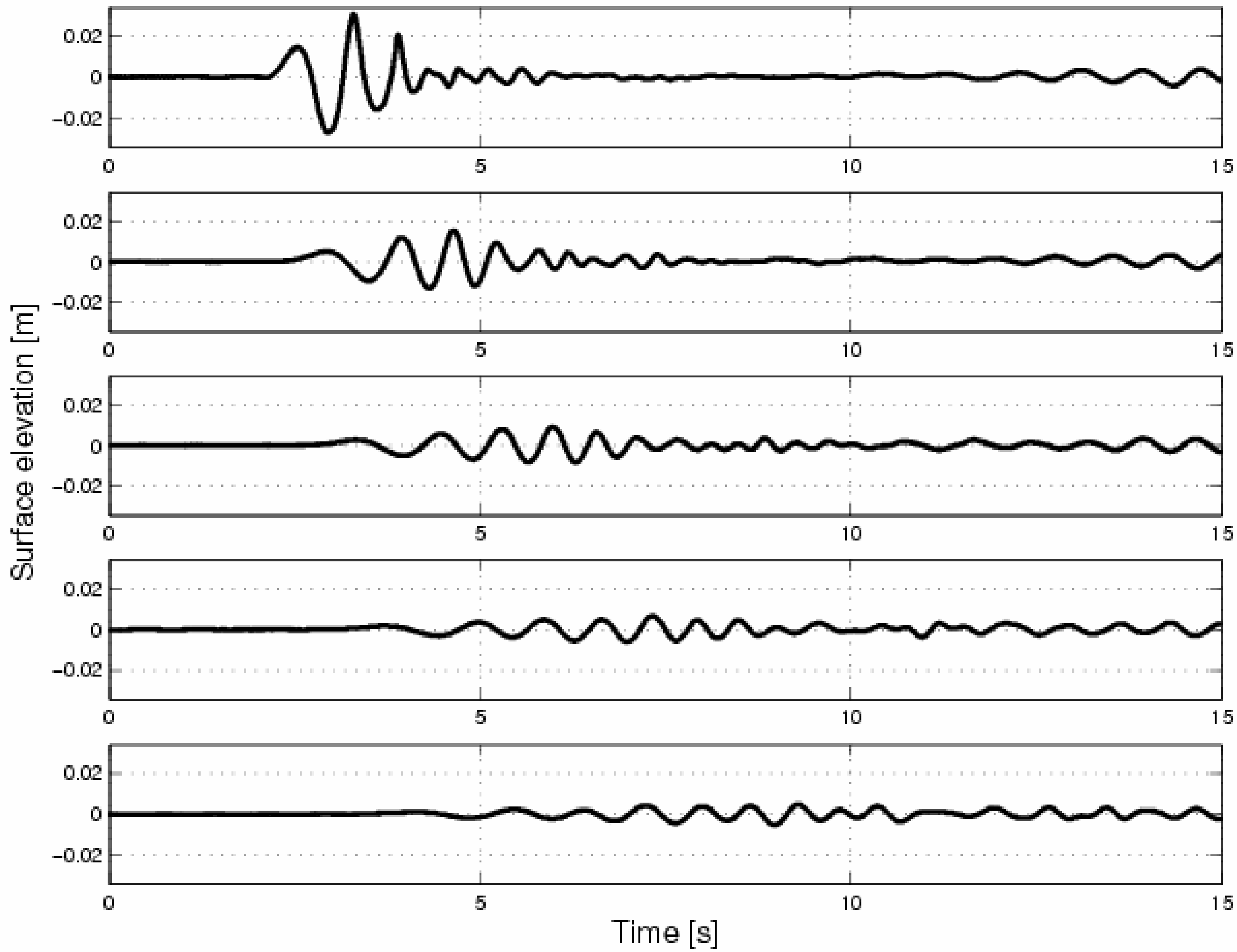
Cnoidal waves



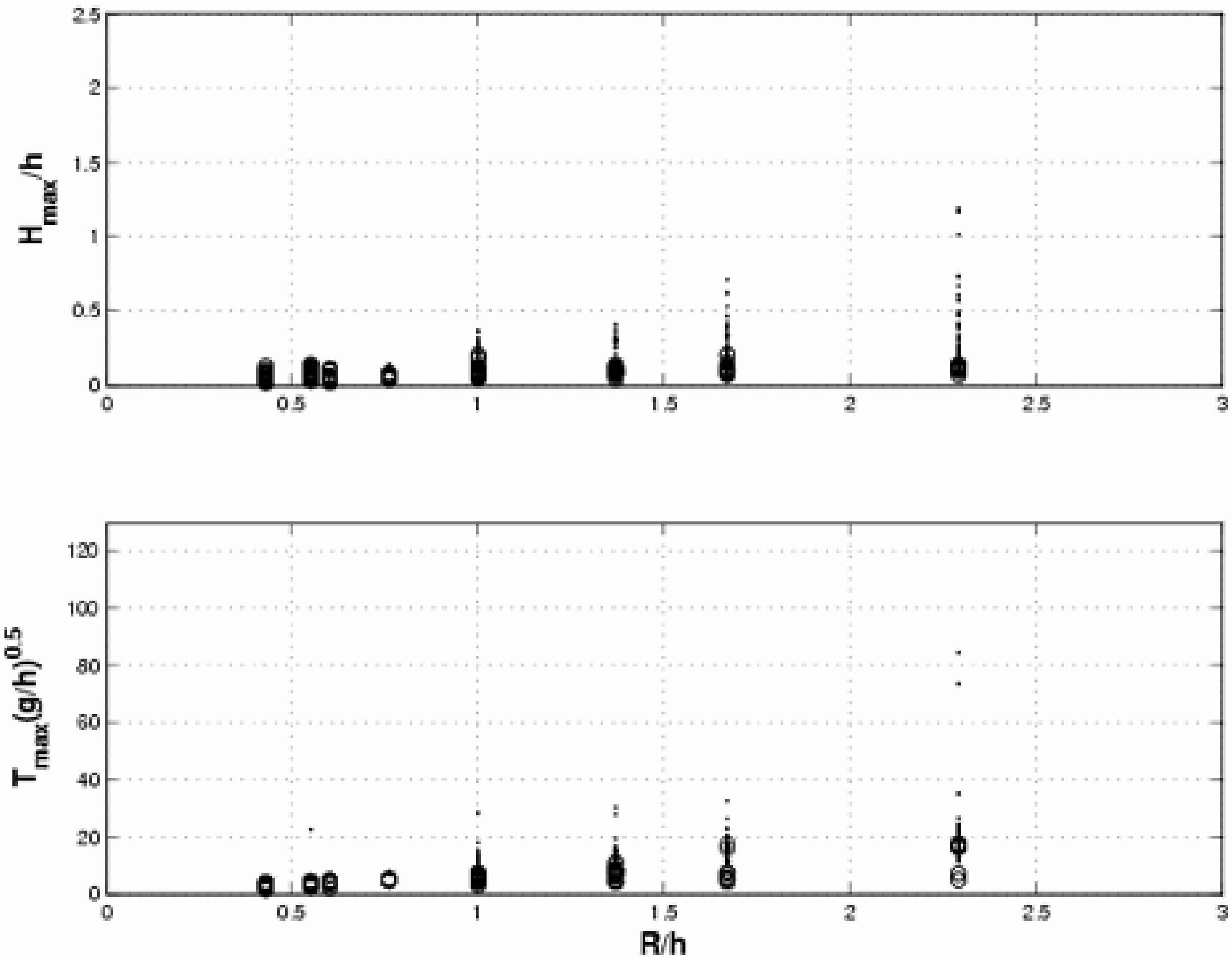
Generation and propagation of vertical slump generated waves: 3D experiments

3D experiments:

Linear waves



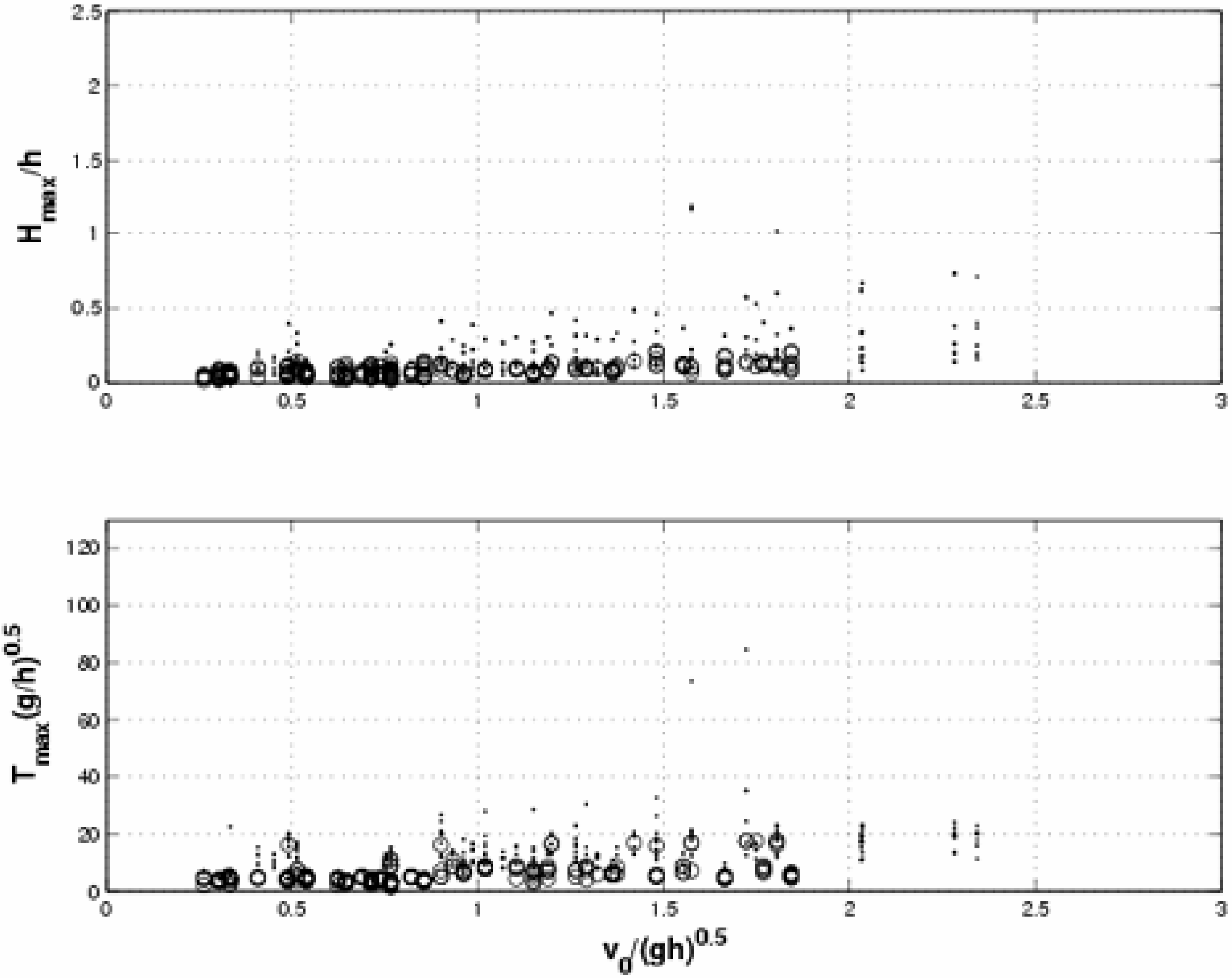
Generation and propagation of vertical slump generated waves: 3D experiments



3D experiments:

- in the 50% of tests the first wave is not the highest
- Maximum wave height increases as landslide length increases
- Wave period related to maximum wave height increases as landslide length increases

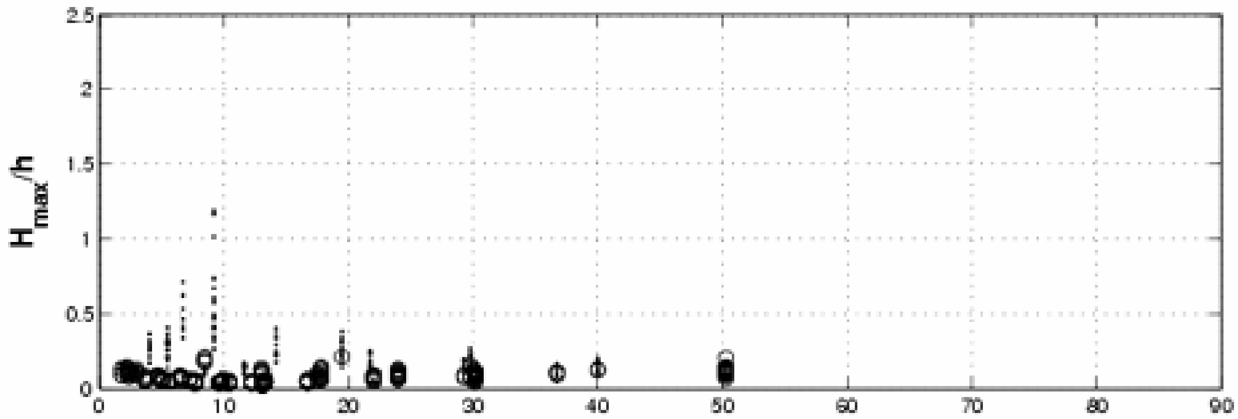
Generation and propagation of vertical slump generated waves: 3D experiments

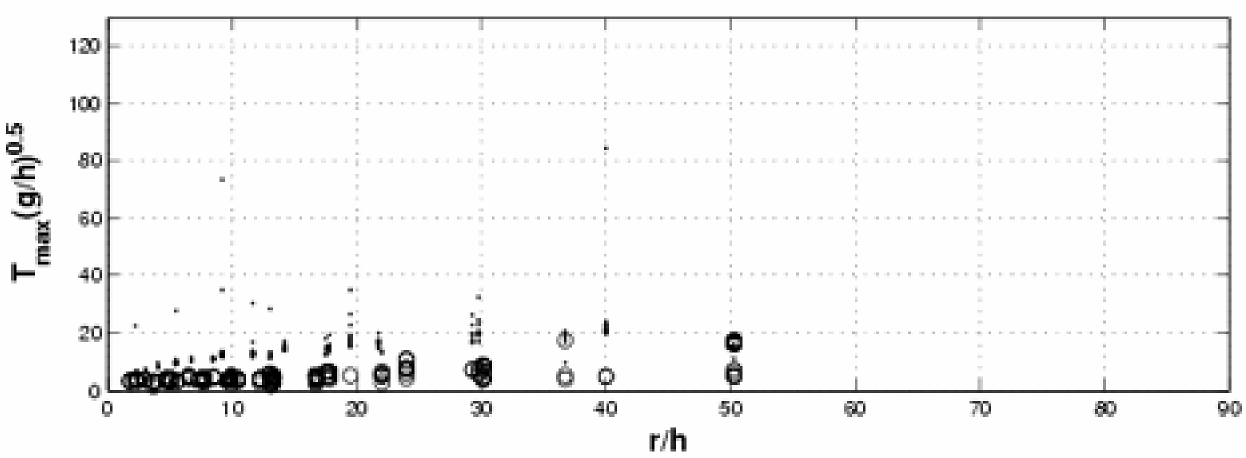


3D experiments:

- **Maximum wave height increases as landslide energy increases**
- **Wave period related to maximum wave height slightly increases as landslide energy increases**

Generation and propagation of vertical slump generated waves: 3D experiments





3D experiments:

- **Maximum wave height decreases as distance from generation area increases**
- **Wave period related to maximum wave height increases as distance from generation area increases (frequency dispersion)**

Generation and propagation of vertical slump generated waves: the experimental findings

2D experiments:

- **likebore waves, solitary waves, cnoidal waves and linear waves were observed**
- **in 12% of tests the first wave is not the highest**
- **Maximum wave height increases as landslide length increases**
- **Wave period related to maximum wave height increases as landslide length increases**
- **Maximum wave height increases as landslide energy increases**
- **Wave period related to maximum wave height slightly increases as landslide energy increases**
- **Maximum wave height decreases as distance from generation area increases**
- **Wave period related to maximum wave height increases as distance from generation area increases (frequency dispersion)**

Generation and propagation of vertical slump generated waves: the experimental findings

3D experiments:

- cnoidal waves and linear waves were observed
- in 50% of tests the first wave is not the highest
- Maximum wave height increases as landslide length increases
- Wave period related to maximum wave height increases as landslide length increases
- Maximum wave height increases as landslide energy increases
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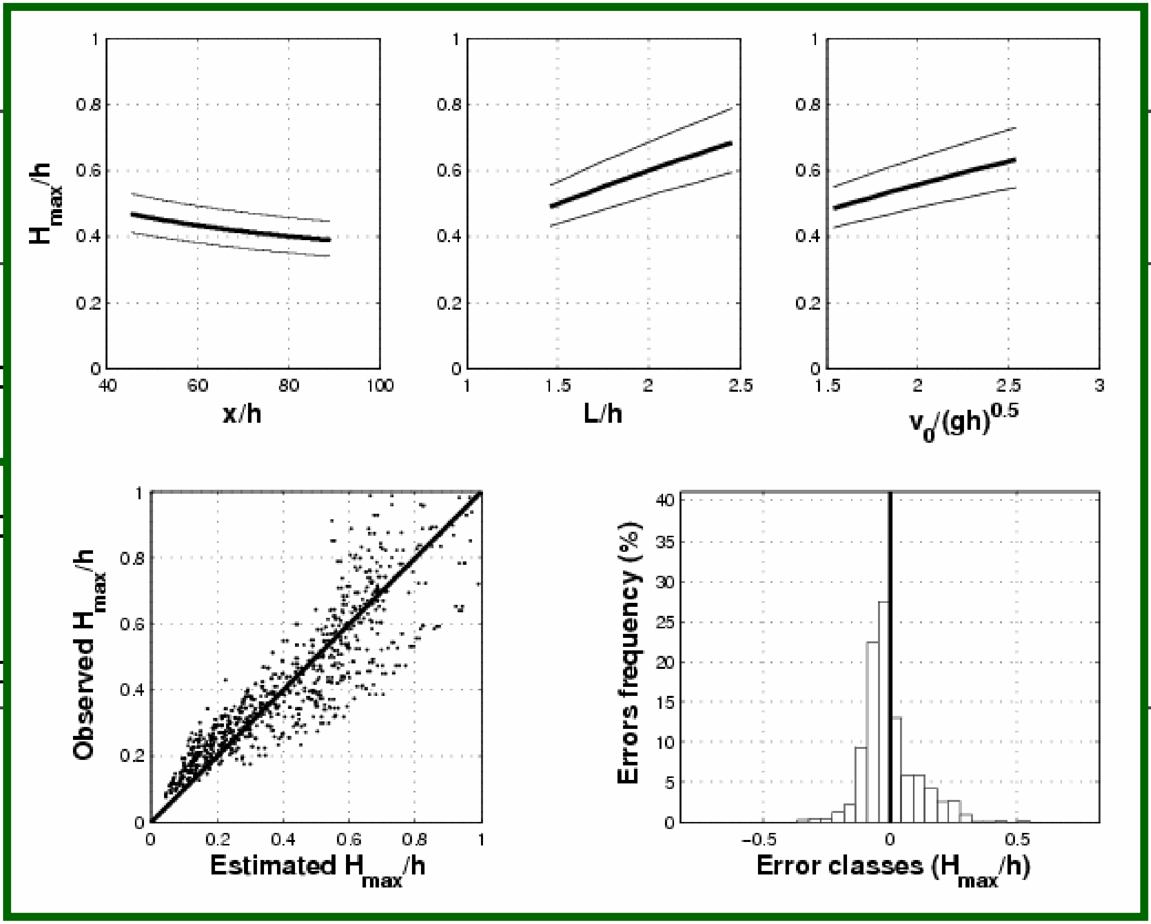
Generation and propagation of vertical slump generated waves: the new empirical formulations

2D empirical formulation:



	R^2	$\bar{\varepsilon}$
H_{max}	0.84953	0.07802
a_{max}	0.87447	0.062935
T_{max}	0.91291	1.0238

Generation and propagation of vertical slump generated waves: the new empirical formulations

2D empirical formulation:

	R^2	$\bar{\varepsilon}$
H_{max}	0.84953	0.07802
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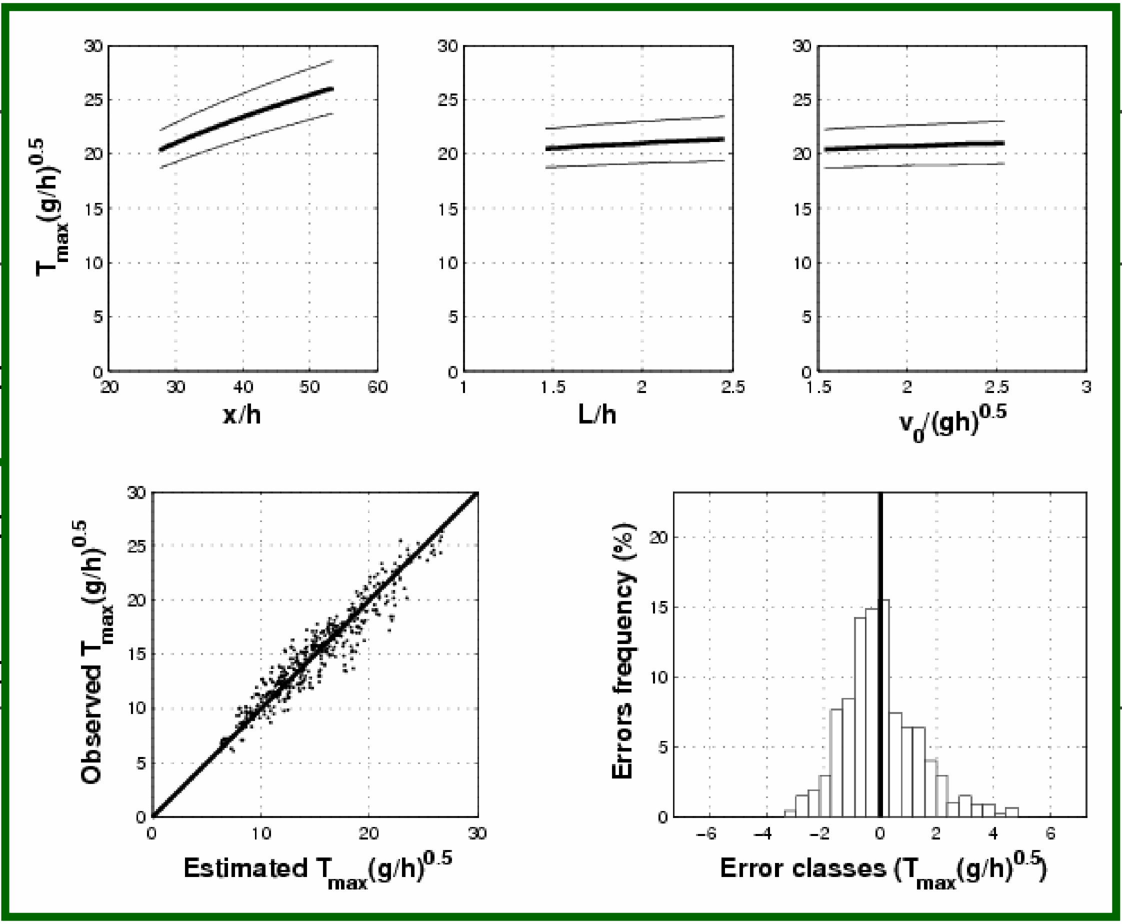
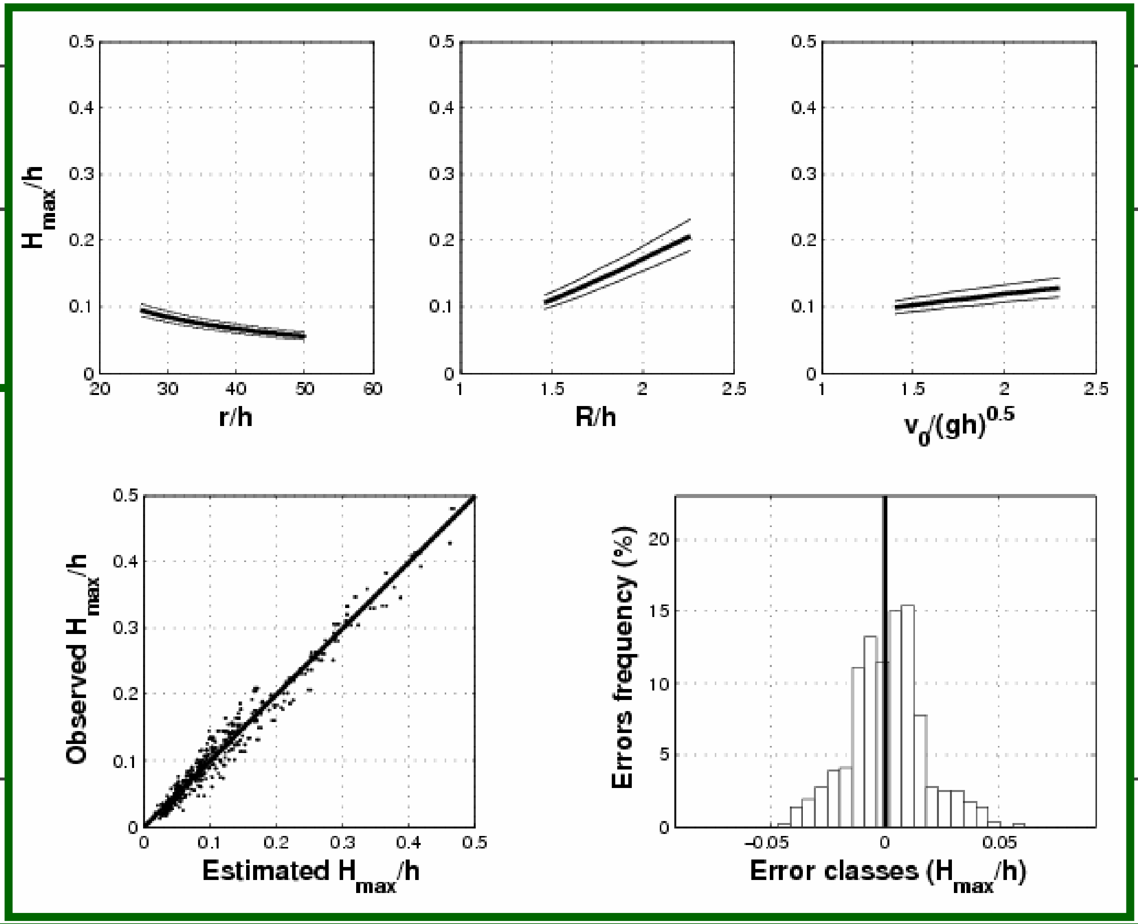


Generation and propagation of vertical slump generated waves: the new empirical formulations

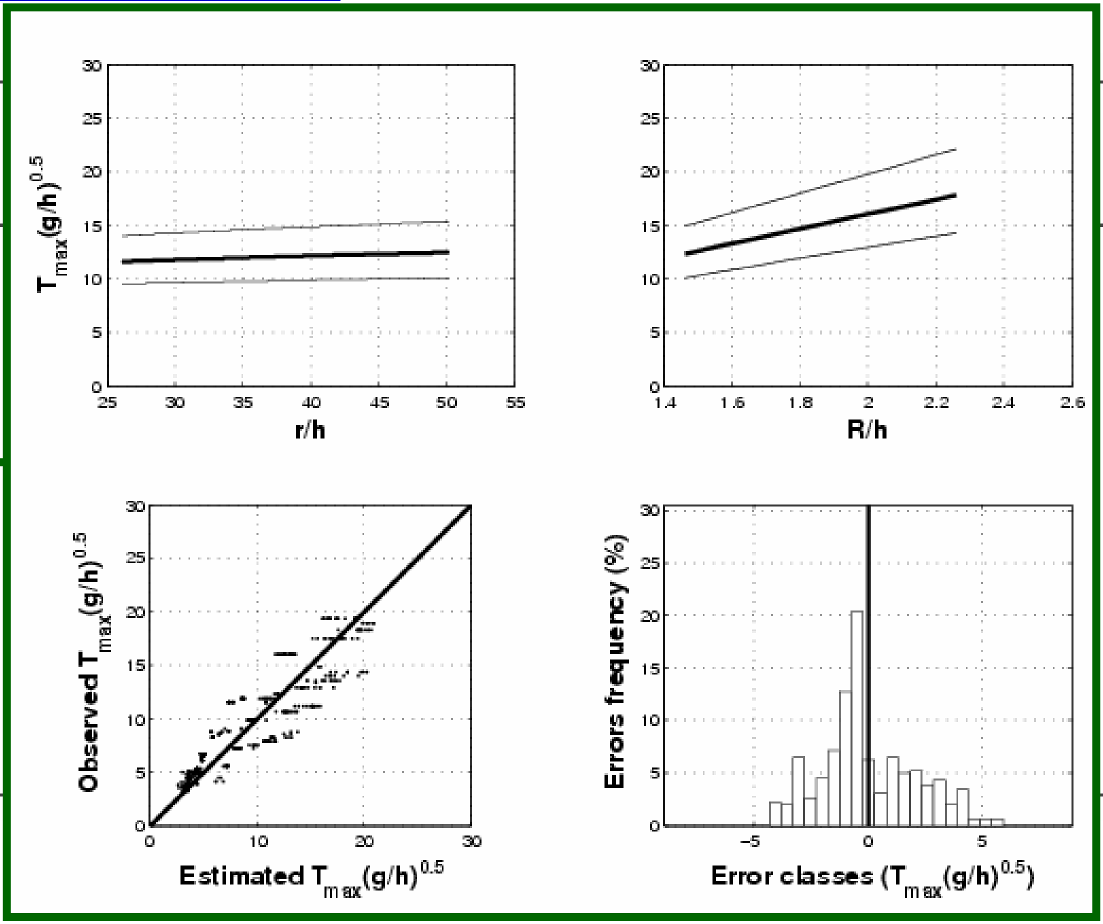
3D empirical formulation:

	R^2	$\bar{\varepsilon}$
H_1	0.95632	0.018128
T_1	0.83259	1.7056
H_{max}	0.97483	0.012894
T_{max}	0.83704	1.7085



Generation and propagation of vertical slump generated waves: the new empirical formulations

3D empirical formulation:



	R^2	$\bar{\varepsilon}$
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H_{max}	0.97483	0.012894
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Generation and propagation of vertical slump generated waves: comparison with existing formulae

	Factor	x/h	L/h	$v_0/(\sqrt{gh})$	R^2	$\bar{\varepsilon}$
	a_1	a_2	a_3	a_4		
H_{max}	0.8967	-0.2725	0.6417	0.5308		
	± 0.0383	± 0.0160	± 0.0289	± 0.0313	0.84953	0.07802
a_{max}	0.5718	-0.2145	0.8322	0.3975		
	± 0.0257	± 0.0162	± 0.0308	± 0.0318	0.87447	0.062935
T_{max}	5.6384	0.3744	0.0782	0.0527		
	± 0.2007	± 0.0116	± 0.0168	± 0.0159	0.91291	1.0238

	Factor	r/h	R/h	$v_0/(\sqrt{gh})$	R^2	$\bar{\varepsilon}$
	a_1	a_2	a_3	a_4		
H_1	0.8790	-0.9341	1.7114	0.5531		
	± 0.0424	± 0.0251	± 0.0485	± 0.0353	0.95632	0.018128
T_1	6.6322	0.1774	0.5083	0.1115		
	± 0.4605	± 0.0263	± 0.0487	± 0.0353	0.83259	1.7056
H_{max}	0.7650	-0.8281	1.5350	0.5270		
	± 0.0234	± 0.0153	± 0.0311	± 0.0272	0.97483	0.012894
T_{max}	6.229	0.1104	0.8472			
	± 0.4865	± 0.0297	± 0.0537		0.83704	1.7085

$$\frac{H_{max}}{h} = 0.12\left(\frac{r}{h}\right)^{-0.4}\left(\frac{w}{h}\right)^{0.79}\left(\frac{s}{h}\right)^{0.5}\left(\frac{v_0}{\sqrt{gh}}\right)^{0.17} e^{0.6\cos\theta - 0.8\sin\gamma}$$

$$T_{max}\sqrt{\frac{g}{h}} = 2.5\left(\frac{l}{h}\right)^{0.1}\left(\frac{v_0}{\sqrt{gh}}\right)^{0.29}\left(\frac{r}{h}\right)^{0.18} e^{0.22\sin\gamma}$$

Panizzo, 2004

Generation and propagation of vertical slump generated waves: comparison with existing formulae

	Factor	x/h	L/h	$v_0/(\sqrt{gh})$	R^2	$\bar{\varepsilon}$
	a_1	a_2	a_3	a_4		
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	Factor	r/h	R/h	$v_0/(\sqrt{gh})$	R^2	$\bar{\varepsilon}$
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T_{max}	6.229	0.1104	0.8472			
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$$\frac{H_{max}}{h} = 0.12\left(\frac{r}{h}\right)^{-0.4}\left(\frac{w}{h}\right)^{0.79}\left(\frac{s}{h}\right)^{0.5}\left(\frac{v_0}{\sqrt{gh}}\right)^{0.17} e^{0.6\cos\theta - 0.8\sin\gamma}$$

$$T_{max}\sqrt{\frac{g}{h}} = 2.5\left(\frac{l}{h}\right)^{0.1}\left(\frac{v_0}{\sqrt{gh}}\right)^{0.29}\left(\frac{r}{h}\right)^{0.18} e^{0.22\sin\gamma}$$

Panizzo, 2004

Generation and propagation of vertical slump generated waves: comparison with existing formulae

	Factor a_1	x/h a_2	L/h a_3	$v_0/(\sqrt{gh})$ a_4	R^2	$\bar{\varepsilon}$
H_{max}	0.8967	-0.2725	0.6417	0.5308		
	$\pm$ 0.0383	$\pm$ 0.0160	$\pm$ 0.0289	$\pm$ 0.0313	0.84953	0.07802
a_{max}	0.5718	-0.2145	0.8322	0.3975		
	$\pm$ 0.0257	$\pm$ 0.0162	$\pm$ 0.0308	$\pm$ 0.0318	0.87447	0.062935
T_{max}	5.6384	0.3744	0.0782	0.0527		
	$\pm$ 0.2007	$\pm$ 0.0116	$\pm$ 0.0168	$\pm$ 0.0159	0.91291	1.0238

	Factor a_1	r/h a_2	R/h a_3	$v_0/(\sqrt{gh})$ a_4	R^2	$\bar{\varepsilon}$
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	$\pm$ 0.0424	$\pm$ 0.0251	$\pm$ 0.0485	$\pm$ 0.0353	0.95632	0.018128
T_1	6.6322	0.1774	0.5083	0.1115		
	$\pm$ 0.4605	$\pm$ 0.0263	$\pm$ 0.0487	$\pm$ 0.0353	0.83259	1.7056
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	$\pm$ 0.0234	$\pm$ 0.0153	$\pm$ 0.0311	$\pm$ 0.0272	0.97483	0.012894
T_{max}	6.229	0.1104	0.8472			
	$\pm$ 0.4865	$\pm$ 0.0297	$\pm$ 0.0537		0.83704	1.7085

$$\frac{H_{max}}{h} = 0.12\left(\frac{r}{h}\right)^{-0.4}\left(\frac{w}{h}\right)^{0.79}\left(\frac{s}{h}\right)^{0.5}\left(\frac{v_0}{\sqrt{gh}}\right)^{0.17} e^{0.6\cos\theta-0.8\sin\gamma}$$

$$T_{max}\sqrt{\frac{g}{h}} = 2.5\left(\frac{l}{h}\right)^{0.1}\left(\frac{v_0}{\sqrt{gh}}\right)^{0.29}\left(\frac{r}{h}\right)^{0.18} e^{0.22\sin\gamma}$$

Panizzo, 2004

Generation and propagation of vertical slump generated waves: comparison with existing formulae

	Factor	x/h	L/h	$v_0/(\sqrt{gh})$	R^2	$\bar{\varepsilon}$
	a_1	a_2	a_3	a_4		
H_{max}	0.8967	-0.2725	0.6417	0.5308		
	± 0.0383	± 0.0160	± 0.0289	± 0.0313	0.84953	0.07802
a_{max}	0.5718	-0.2145	0.8322	0.3975		
	± 0.0257	± 0.0162	± 0.0308	± 0.0318	0.87447	0.062935
T_{max}	5.6384	0.3744	0.0782	0.0527		
	± 0.2007	± 0.0116	± 0.0168	± 0.0159	0.91291	1.0238

	Factor	r/h	R/h	$v_0/(\sqrt{gh})$	R^2	$\bar{\varepsilon}$
	a_1	a_2	a_3	a_4		
H_1	0.8790	-0.9341	1.7114	0.5531		
	± 0.0424	± 0.0251	± 0.0485	± 0.0353	0.95632	0.018128
T_1	6.6322	0.1774	0.5083	0.1115		
	± 0.4605	± 0.0263	± 0.0487	± 0.0353	0.83259	1.7056
H_{max}	0.7650	-0.8281	1.5350	0.5270		
	± 0.0234	± 0.0153	± 0.0311	± 0.0272	0.97483	0.012894
T_{max}	6.229	0.1104	0.8472			
	± 0.4865	± 0.0297	± 0.0537		0.83704	1.7085

$$\frac{H_{max}}{h} = 0.12\left(\frac{r}{h}\right)^{-0.4}\left(\frac{w}{h}\right)^{0.79}\left(\frac{s}{h}\right)^{0.5}\left(\frac{v_0}{\sqrt{gh}}\right)^{0.17} e^{0.6\cos\theta - 0.8\sin\gamma}$$

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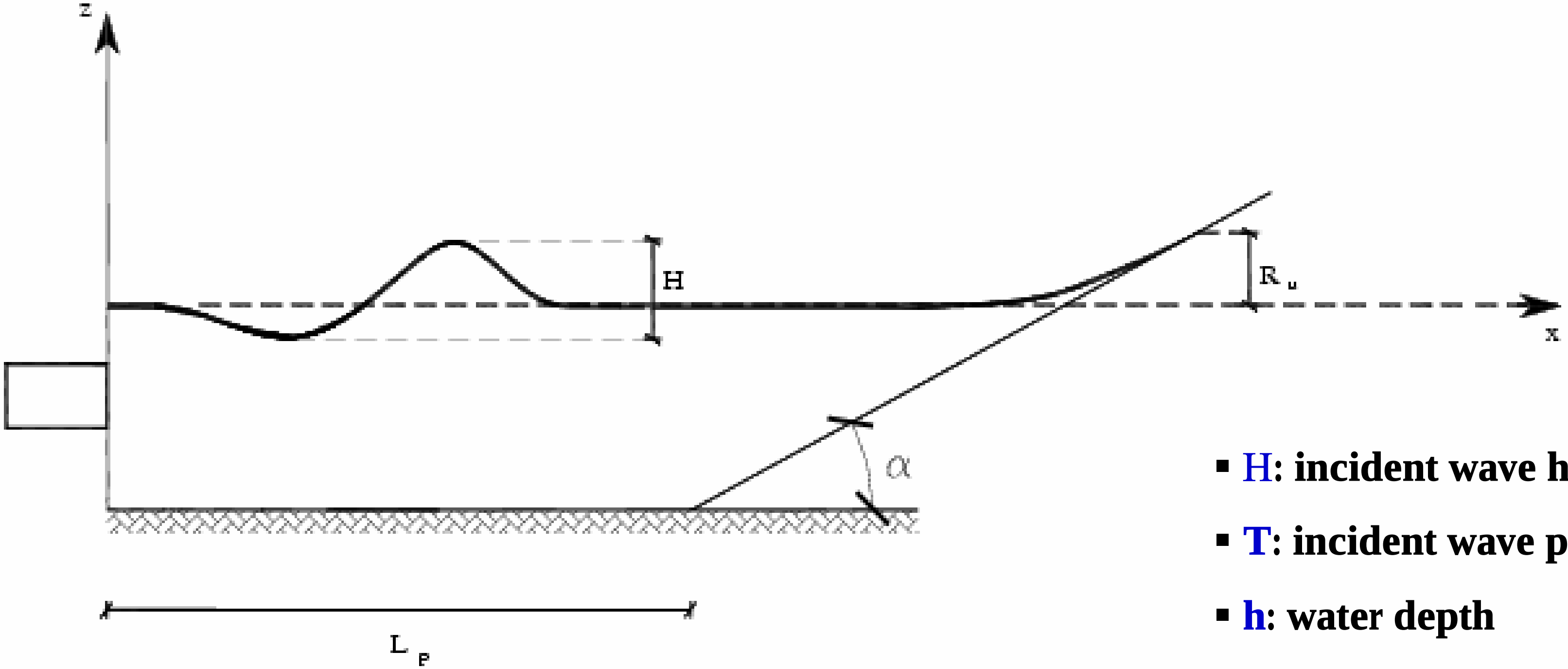
Panizzo, 2004

Impulsive wave runup: the problem

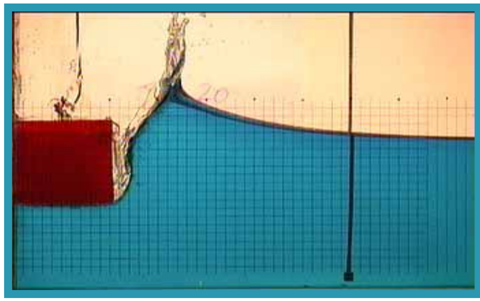


$$R_u = f\left(H, T, h, \alpha, \rho, \mu, g, \delta\right).$$

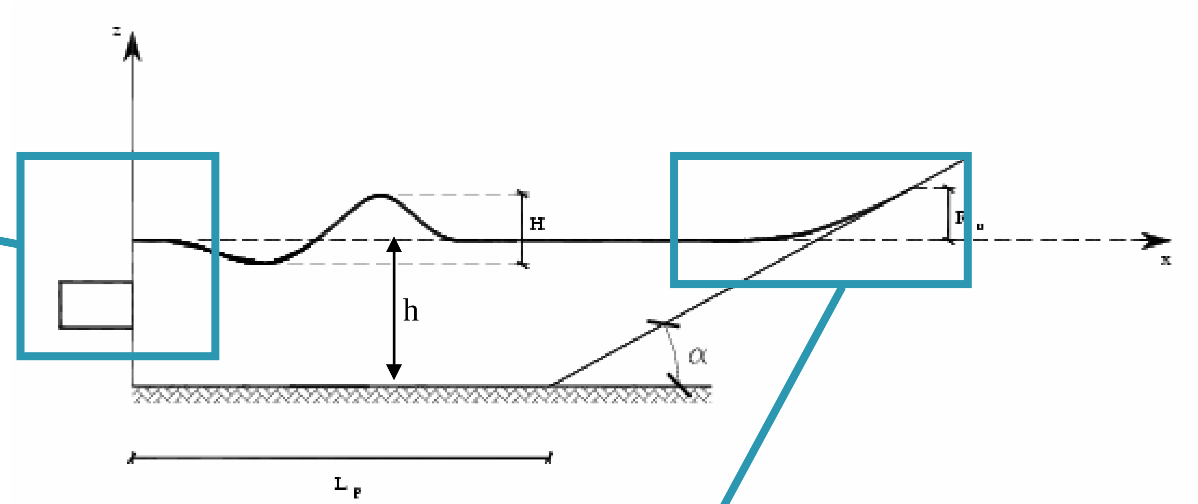
$$\frac{R_u}{h} = \phi\left(\frac{H}{h}, T\sqrt{\frac{g}{h}}, \alpha, \cancel{\frac{\mu}{\rho h\sqrt{gh}}}, \delta\sqrt{\frac{\rho\sqrt{gh}}{\mu h}}\right)$$

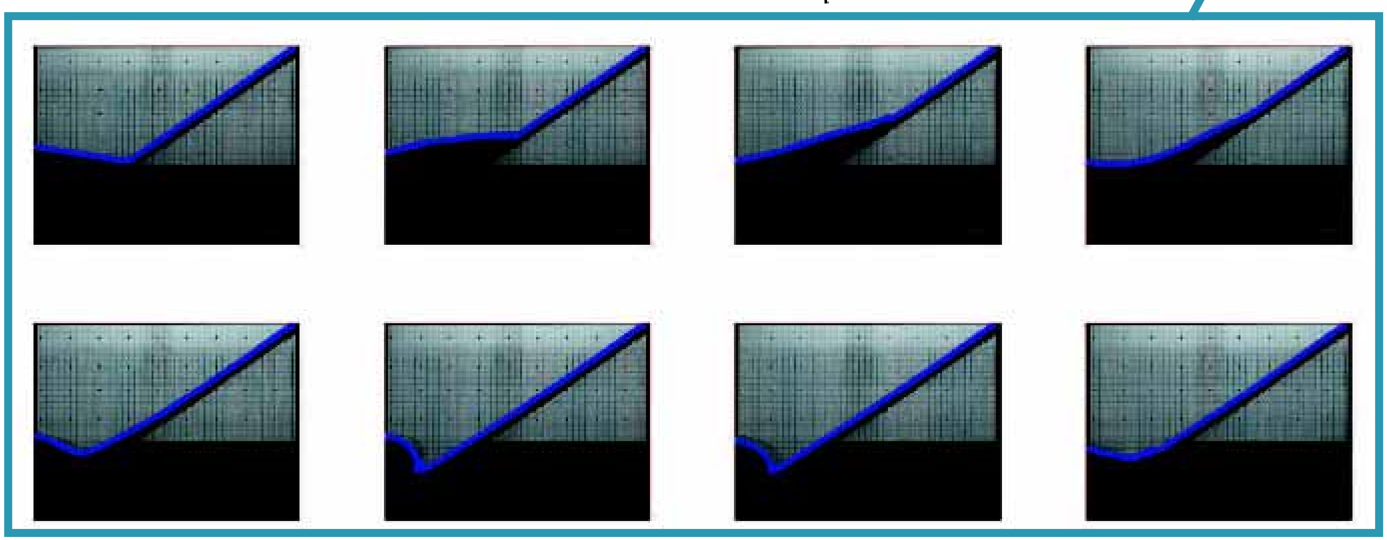
- **H: incident wave height**
- **T: incident wave period**
- **h: water depth**
- **α: beach slope**
- **ρ: water density**
- **μ: water viscosity**
- **g: gravitational acceleration**
- **δ: beach roughness**

Impulsive wave runup: the experiments

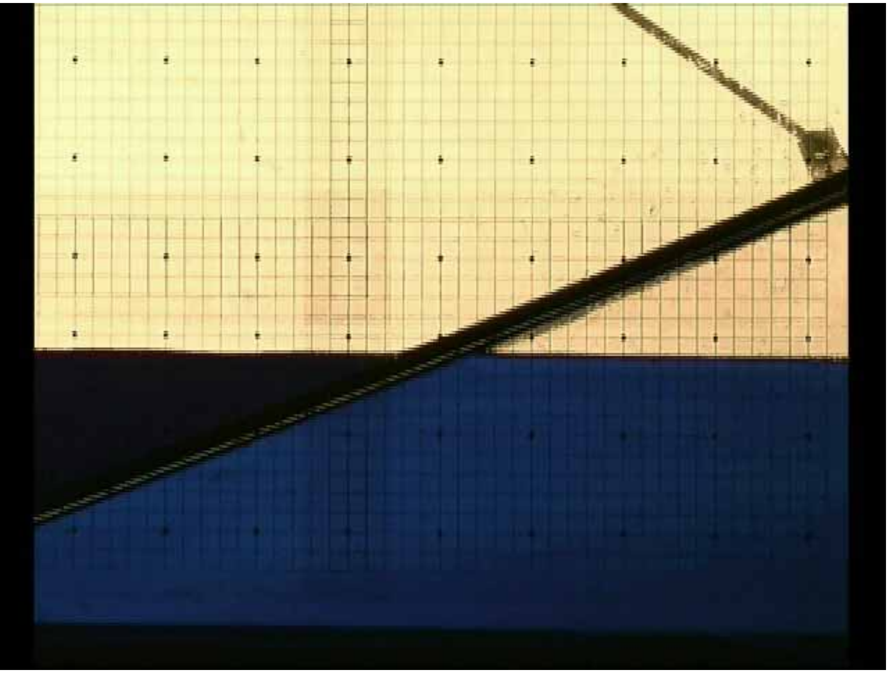


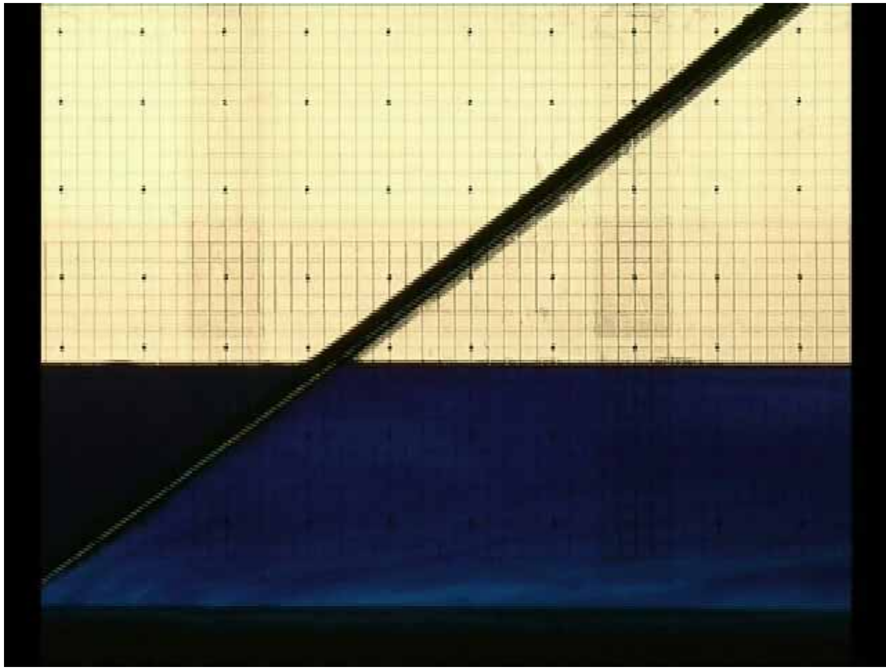
Scott Russel Wave Generator





Impulsive wave runup: the experiments





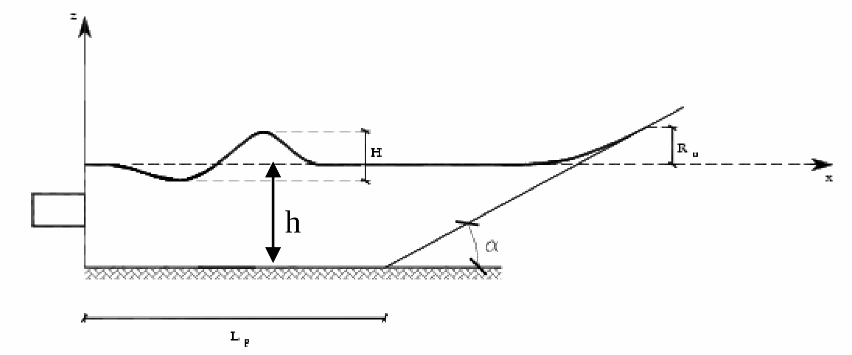
Impulsive wave runup: the experimental procedure

The experiments were performed in two phases

h [m]	L_p [m]	α [°]
0.06	0.85	22°
0.10	1.30	37°
0.18	1.75	84°

Phase 1: elevation time series were collected without the plane slope into the wave flume to get the correct incident wave parameter

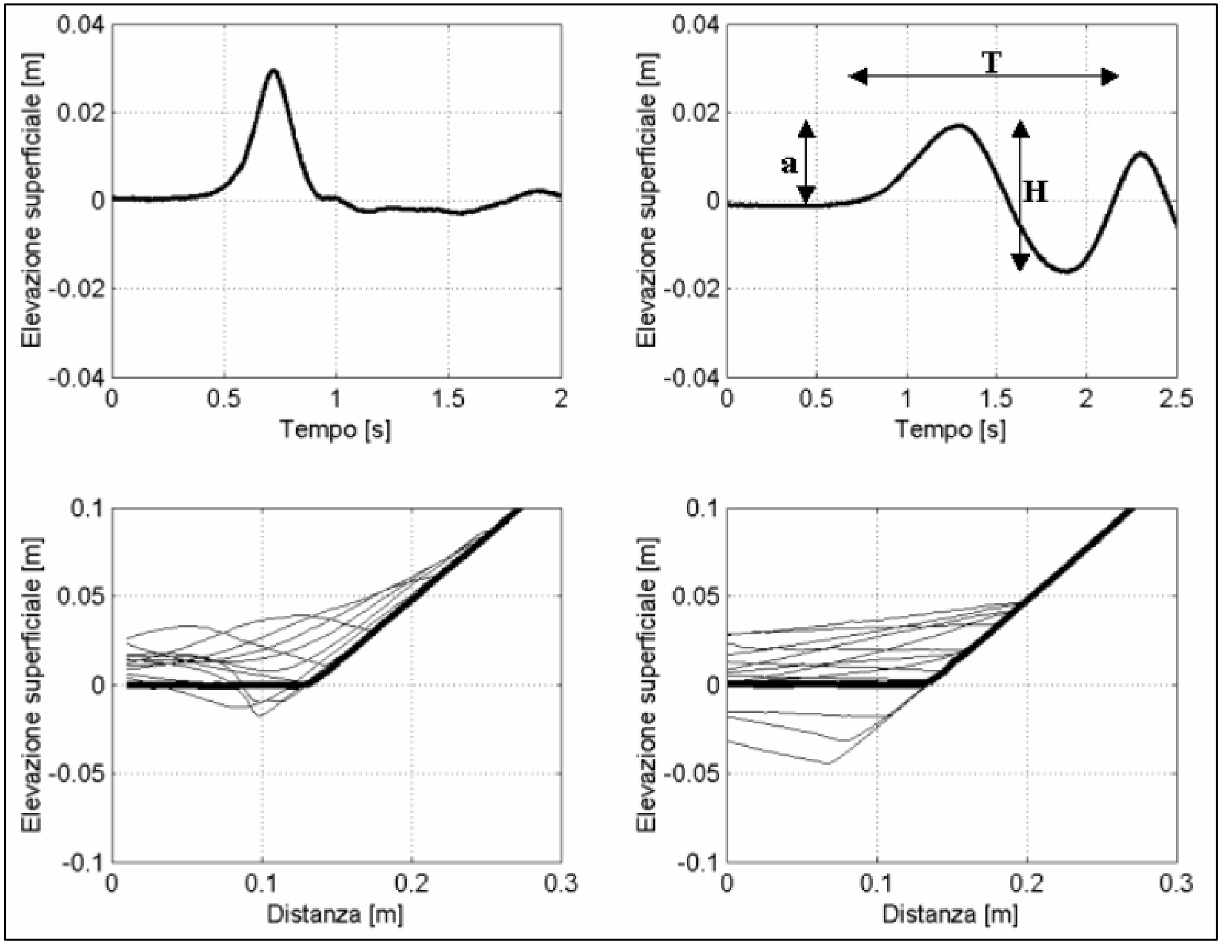
Phase 2: digital video system was employed to get the runup value on the plane beach without any wave gauges into the wave flume to avoid flow disturbance



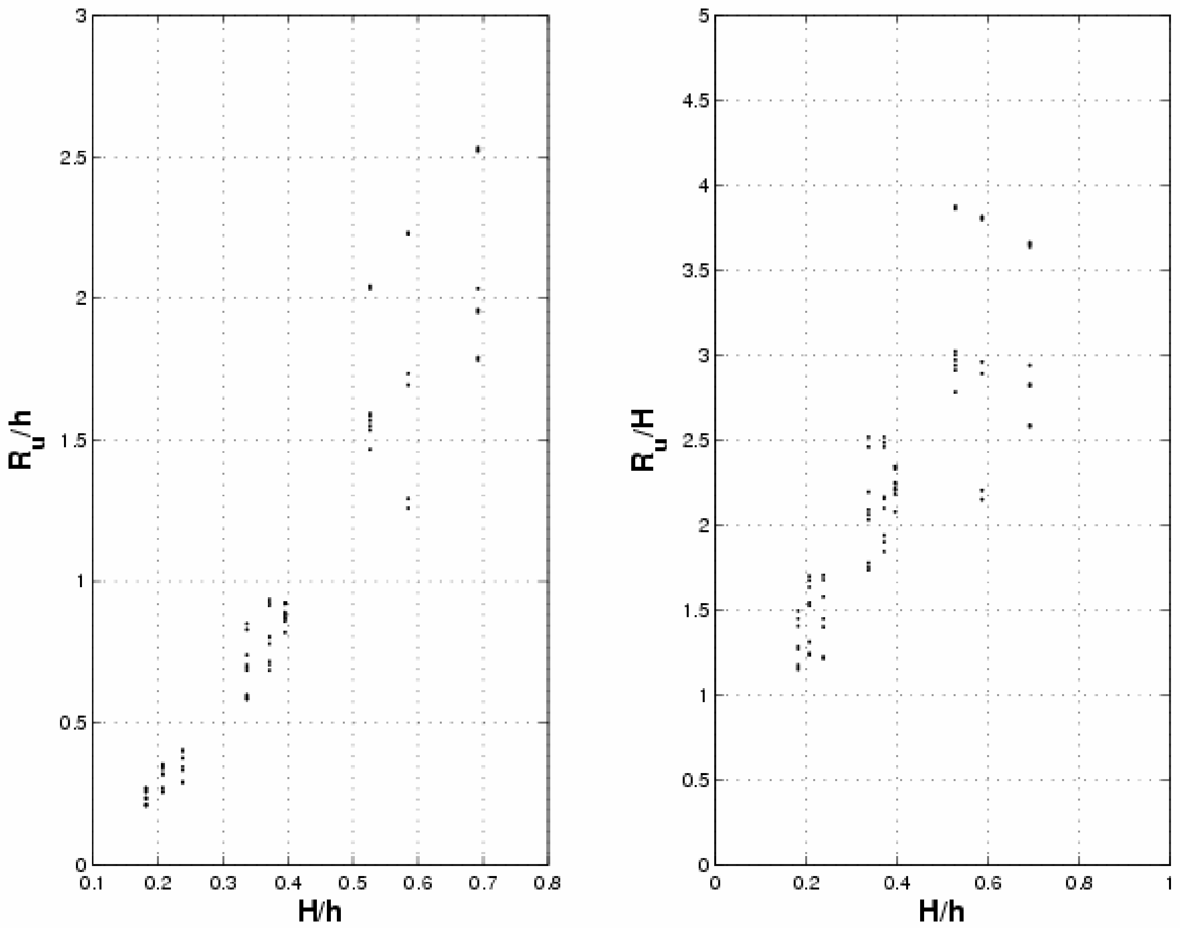
Impulsive wave runup: the experimental procedure

Phase 1:

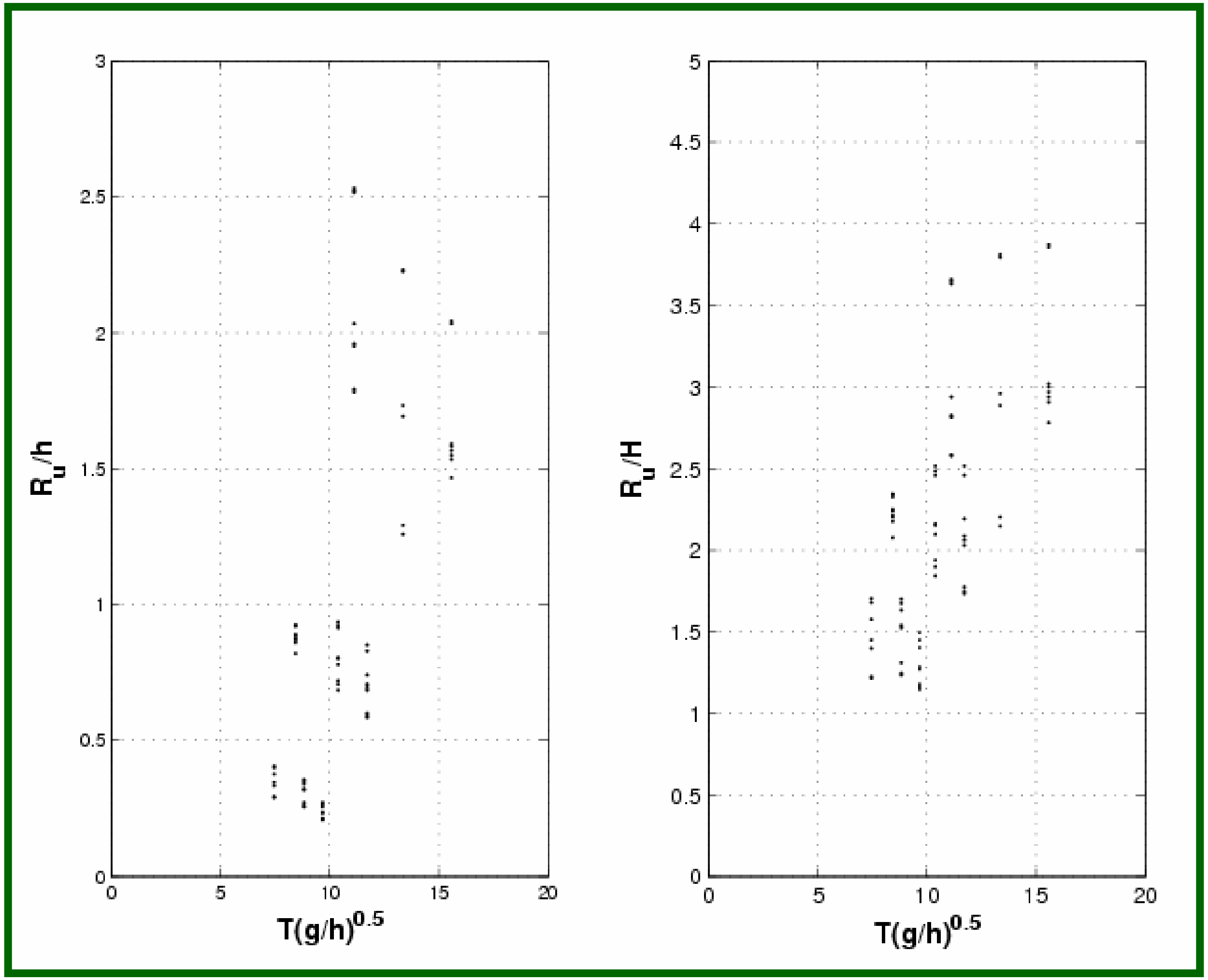
Phase 2:



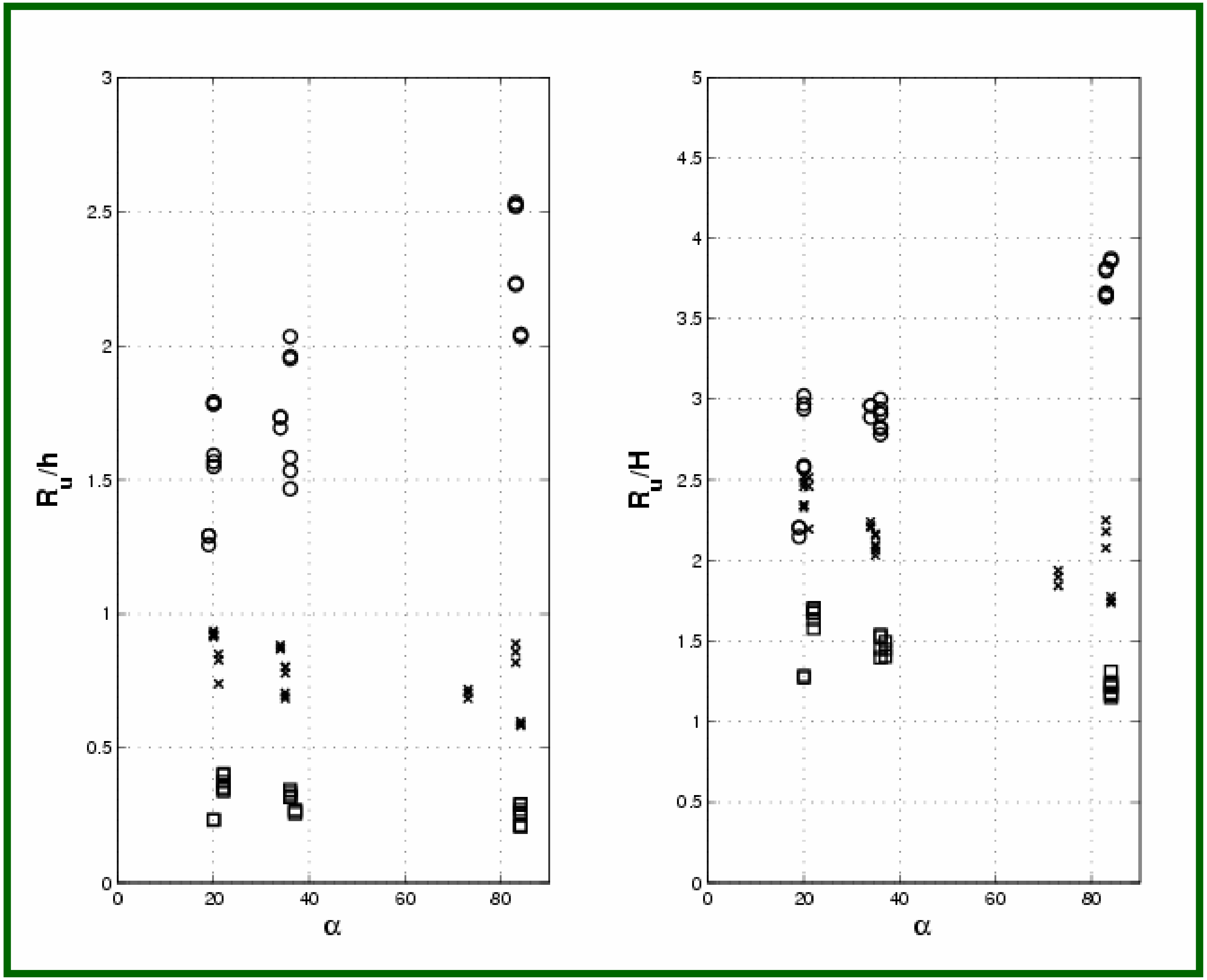
Impulsive wave runup: the experimental findings



Impulsive wave runup: the experimental findings



Impulsive wave runup: the experimental findings



Impulsive wave runup: the experimental findings

- **likebore waves, solitary waves, cnoidal waves and linear waves runup were observed**

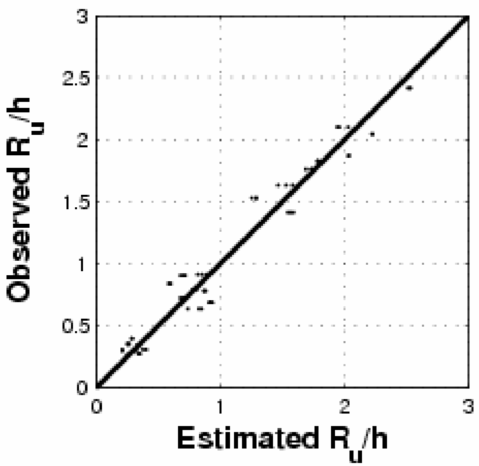
- **wave runup increases as incident wave height increases**

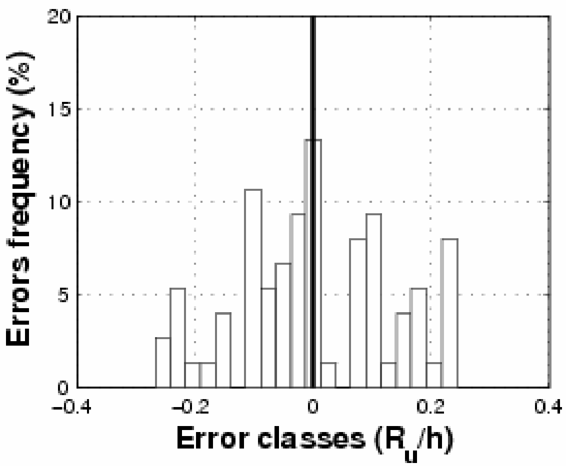
- **wave runup increases as incident wave period increases, the wave period must to be taken into account**

- **beach slope influence is different depending on incident wave type**

Impulsive wave runup: the new empirical formulation

	Factor	H/h	$T(\sqrt{g/h})$	$\sin(\alpha)$	R^2	$\bar{\varepsilon}$
	a_1	a_2	a_3	a_4		
R_u	1.3737	1.5149	0.4665	0.2633		
	± 0.5838	± 0.1078	± 0.1632	± 0.0636	0.955855	0.11011





Impulsive wave runup: comparison with existing formulae

$$\frac{R_u}{h} = 2.831\sqrt{\frac{1}{\tan\alpha}}\left(\frac{H}{h}\right)^{1.25}$$

Synolakis formula for non breaking solitary waves (1987)

$$\frac{R_u}{h} = 3.86\sqrt{\frac{1}{\tan\alpha}}\left(\frac{H}{h}\right)^{1.25}$$

Tadepalli & Synolakis formula for non breaking N-waves (1994)

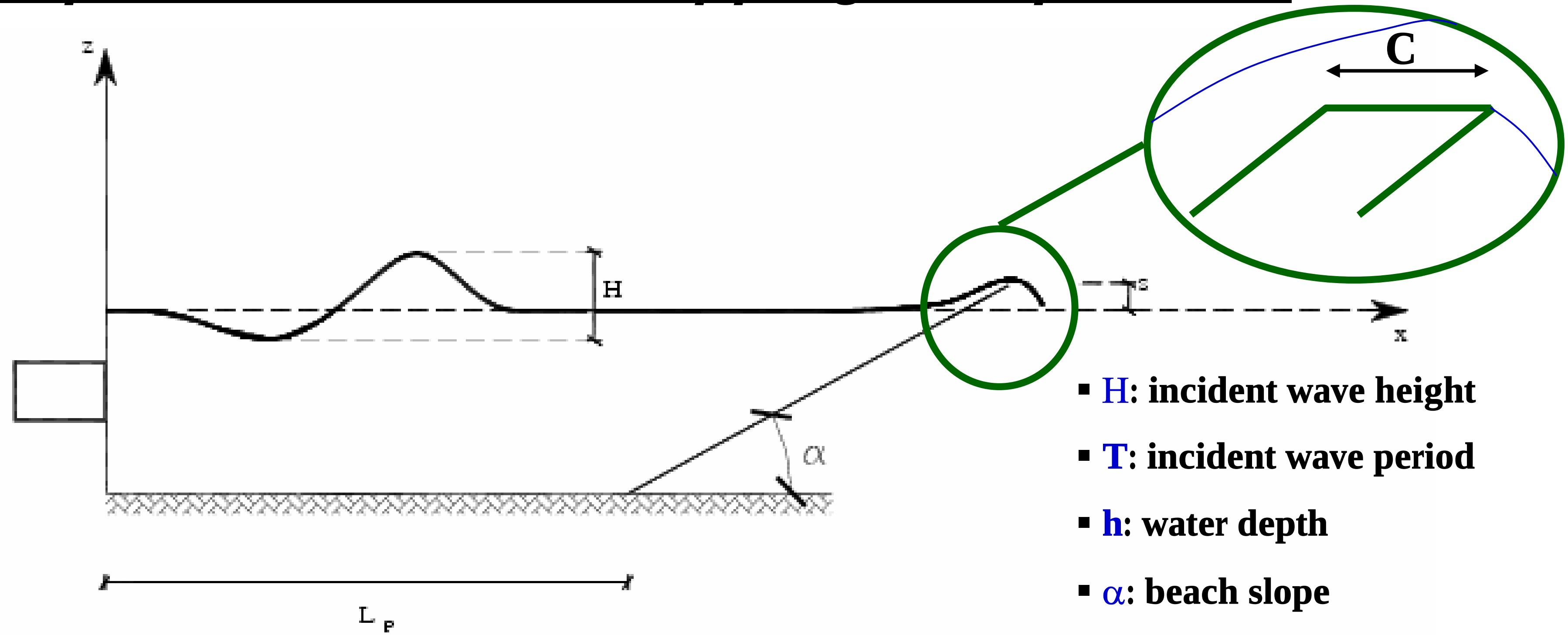
$$\frac{R_u}{h} = 1.3681\left(\frac{H}{h}\right)^{1.25}\left(\frac{H}{L}\right)^{-0.15}\alpha^{-0.20}$$

Muller empirical formulation (1995)

	Factor a_1	H/h a_2	$T(\sqrt{g/h})$ a_3	$\sin(\alpha)$ a_4	R^2	$\bar{\varepsilon}$
R_u	1.3737 $\pm$ 0.5838	1.5149 $\pm$ 0.1078	0.4665 $\pm$ 0.1632	0.2633 $\pm$ 0.0636	0.955855	0.11011

The present empirical formulation is valid for a wide range of wave type and for breaking and non breaking waves. It takes into account wave period influence

Impulsive wave overtopping: the problem



$$\Omega = f\left(H, T, w, h, \alpha, s, \rho, \mu, g, \delta, C\right)$$

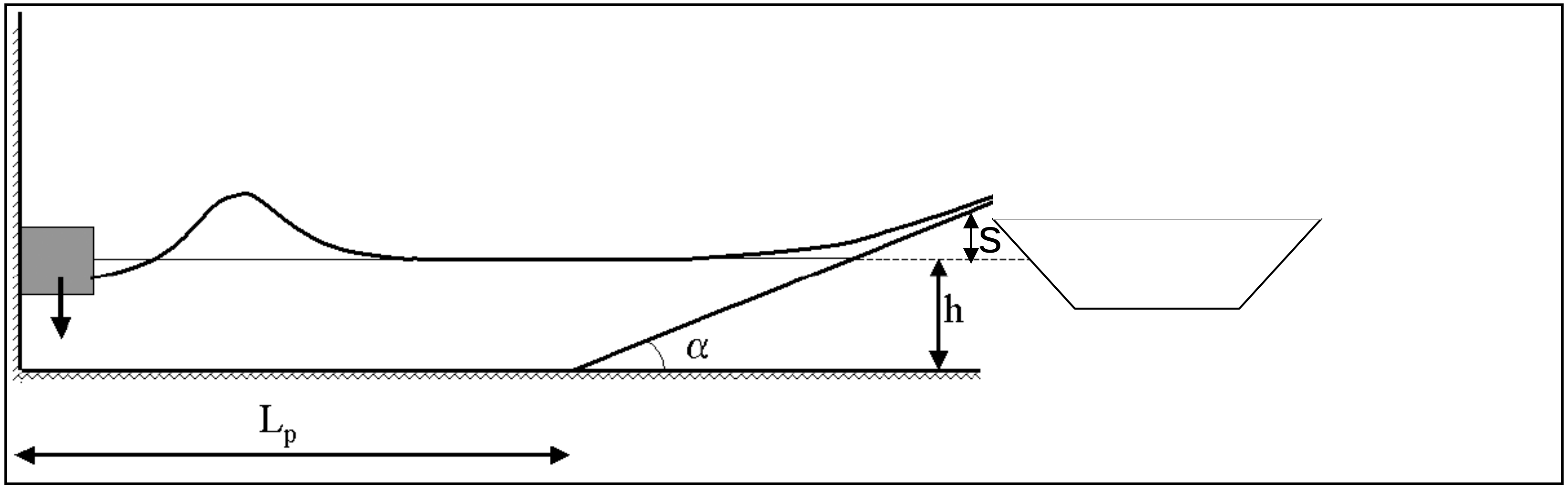
$$\frac{\Omega}{h^2 w} = \phi\left(\frac{H}{h}, T\sqrt{\frac{g}{h}}, \cancel{\frac{w}{h}}, \alpha, \cancel{\frac{\mu}{\rho h\sqrt{gh}}}, \frac{s}{h}, \delta\sqrt{\frac{\rho\sqrt{gh}}{\mu h}}, \frac{C}{h}\right).$$

- **H: incident wave height**
- **T: incident wave period**
- **h: water depth**
- **α: beach slope**
- **ρ: water density**
- **μ: water viscosity**
- **g: gravitational acceleration**
- **δ: beach roughness**
- **C: crest thickness**

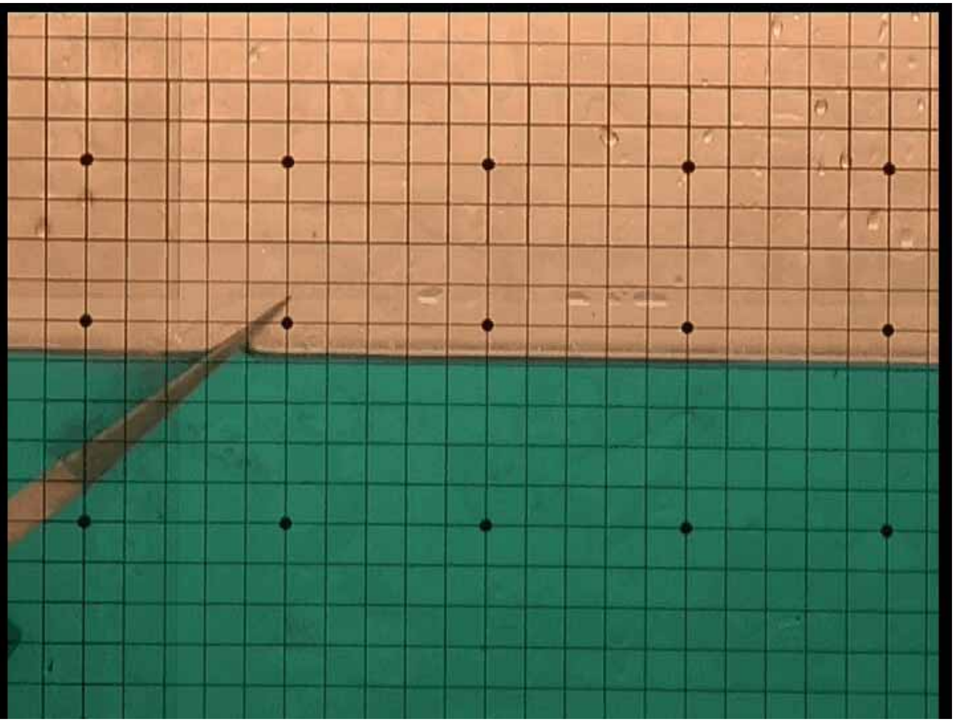
Impulsive wave overtopping: the experiments

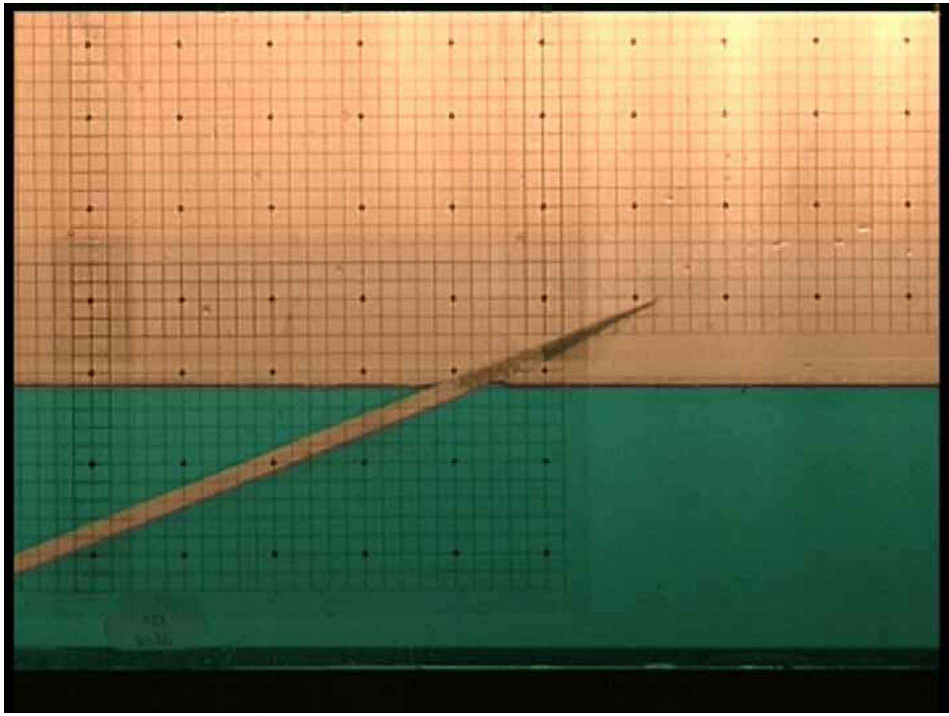
The overtopped water volume is collected by means of a small tank

h [m]	L_p [m]	α [°]	s
0.06	0.85	22°	$0.25\,R_u$
0.10	1.30	37°	$0.50\,R_u$
0.18	1.75	84°	$0.75\,R_u$

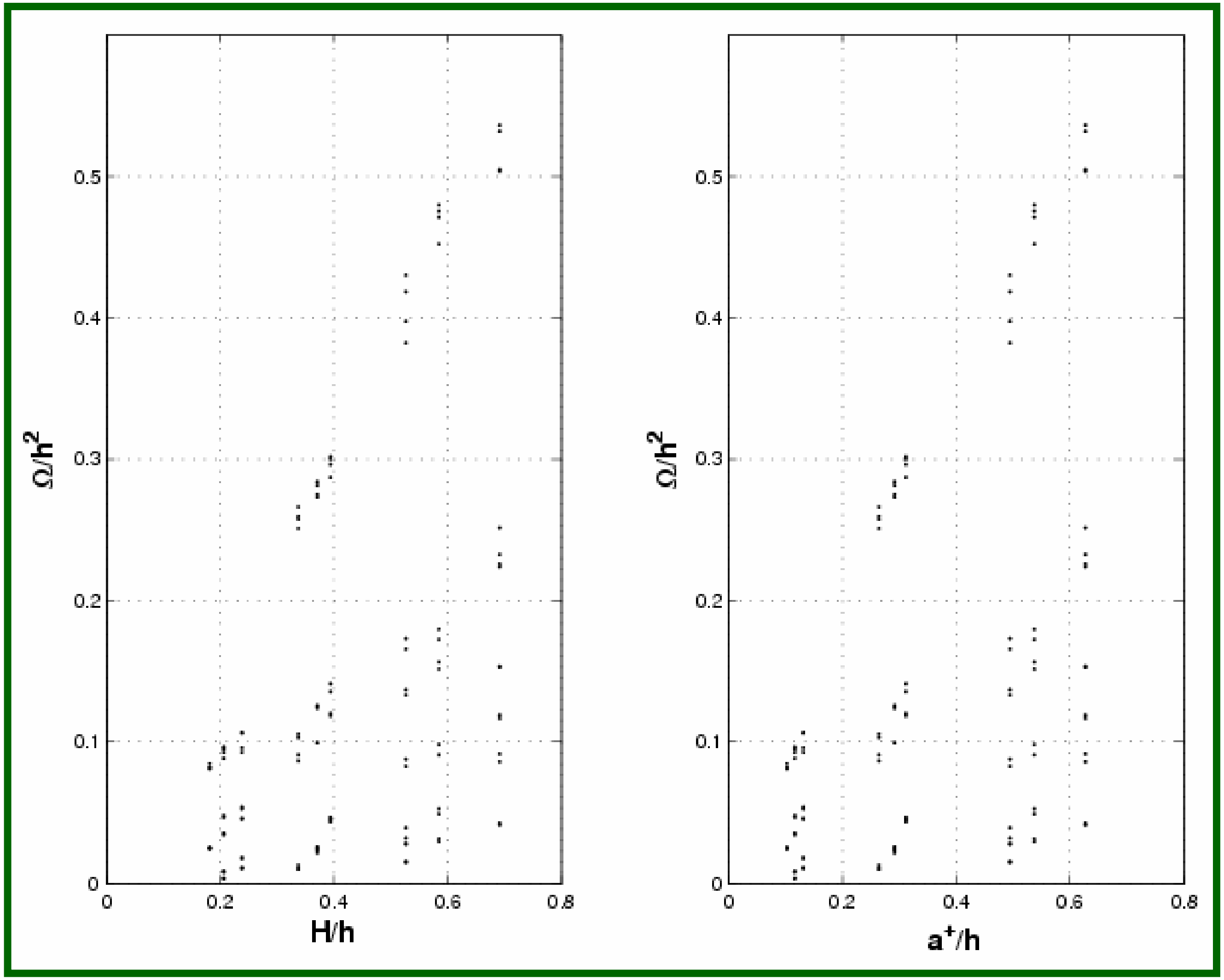


Impulsive wave overtopping: the experiments

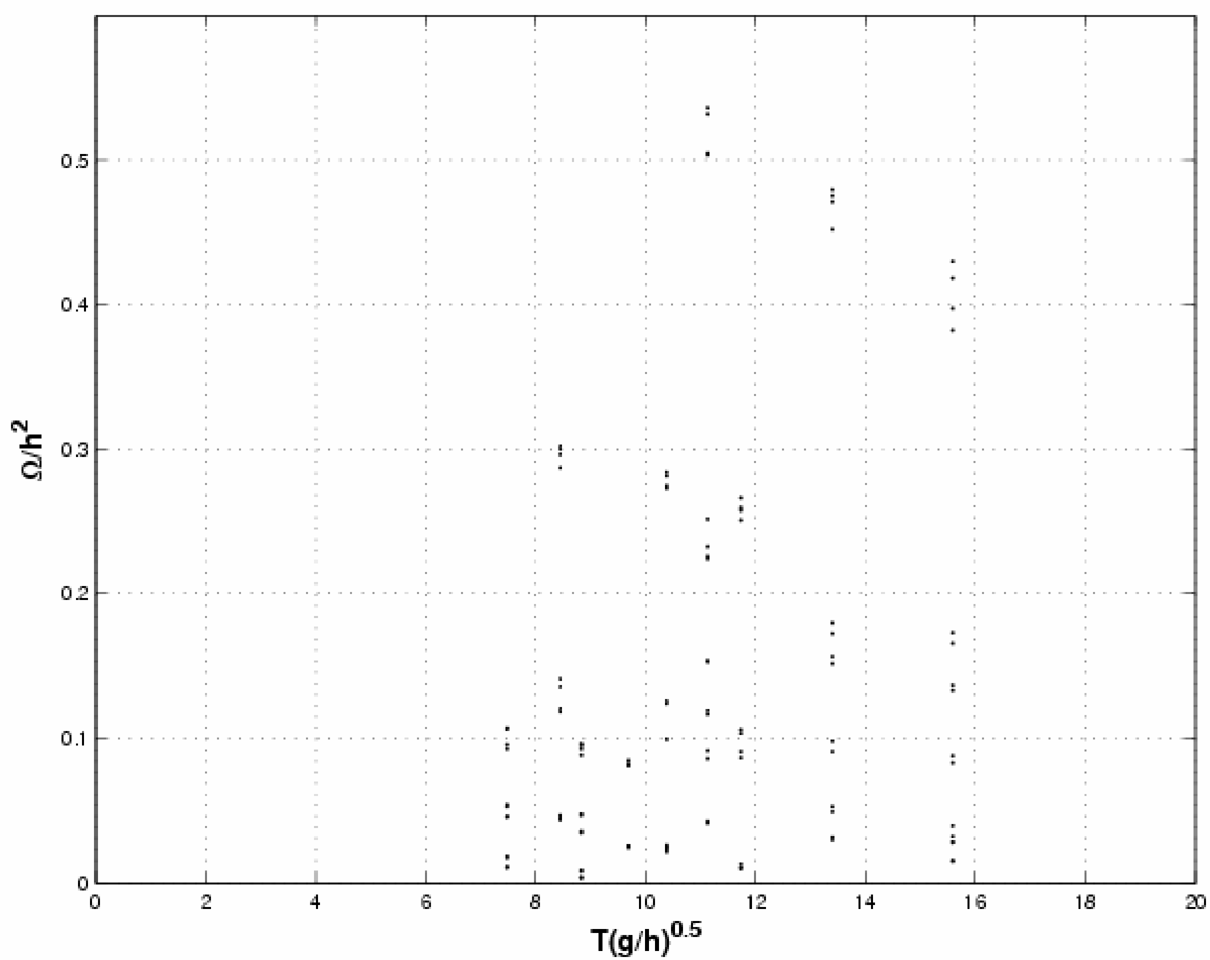




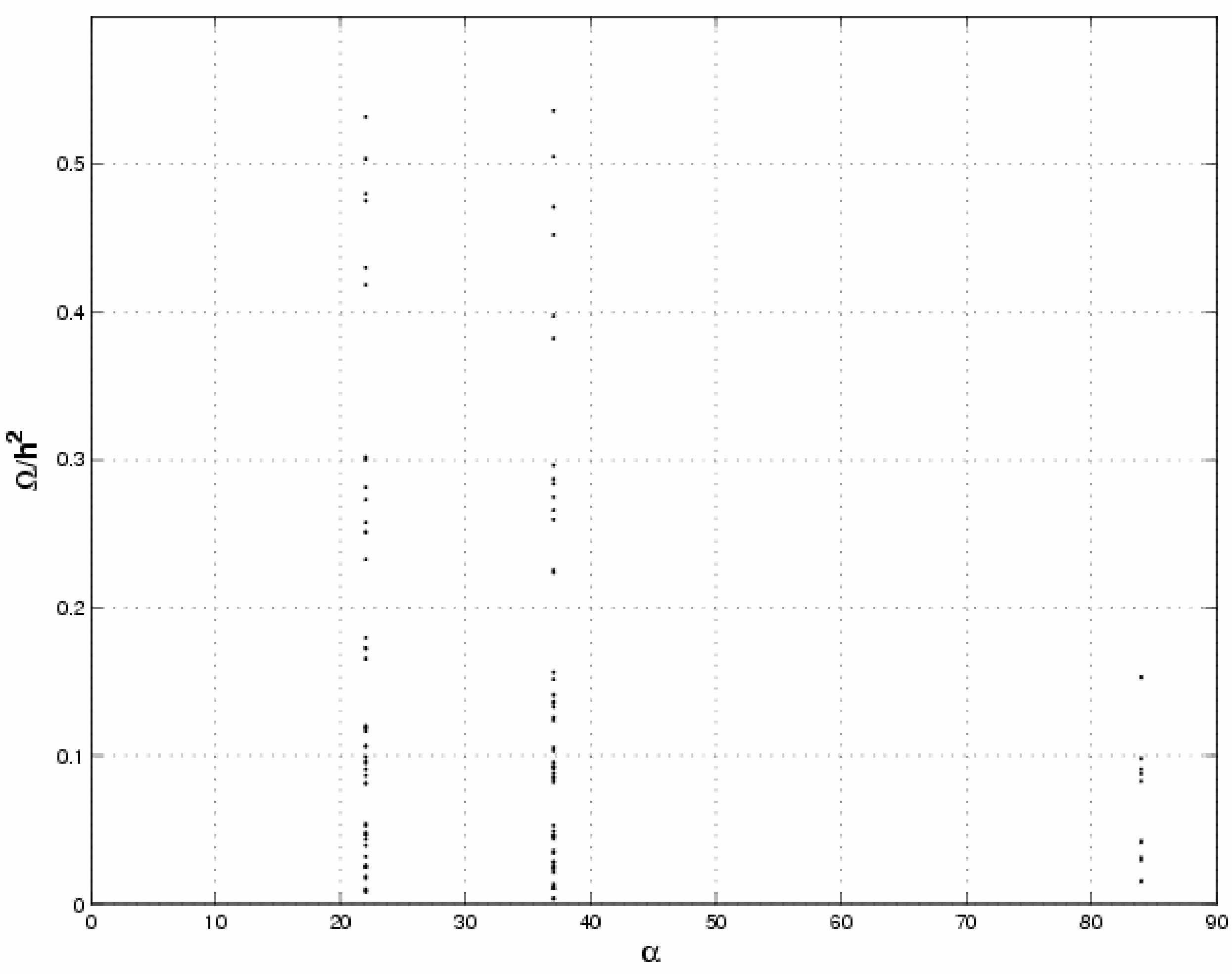
Wave overtopping: the experimental findings



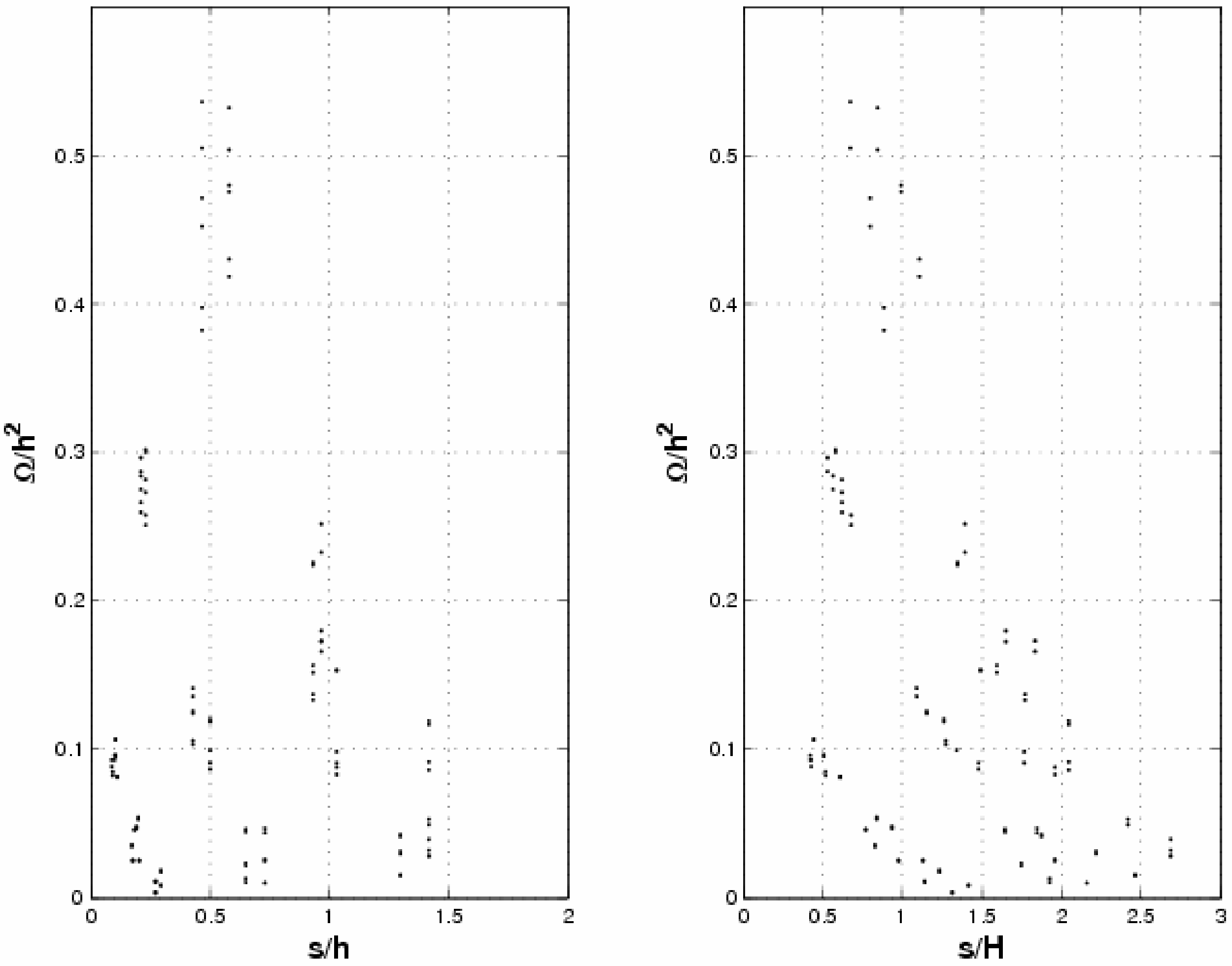
Wave overtopping: the experimental findings



Wave overtopping: the experimental findings



Wave overtopping: the experimental findings

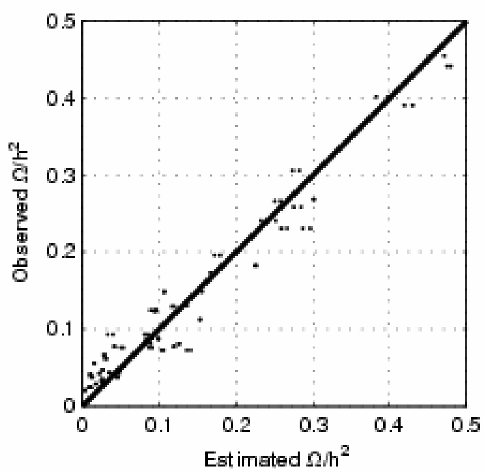


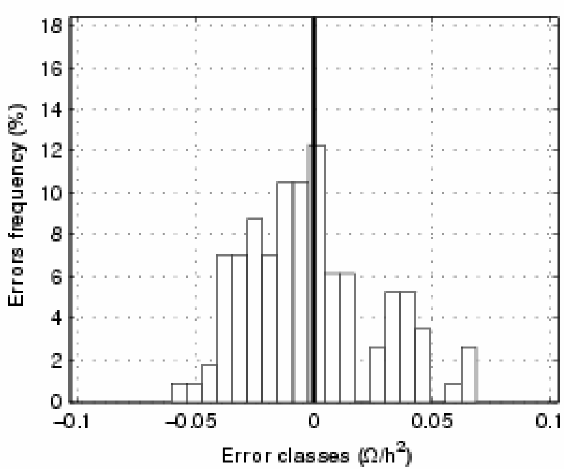
Impulsive wave overtopping: the experimental findings

- **likebore waves, solitary waves, cnoidal waves and linear waves runup were observed**
- **wave overtopping volume increases as incident wave height increases**
- **wave overtopping volume increases as incident wave period increases, the wave period must to be taken into account**
- **beach slope influence is different depending on incident wave type**
- **wave overtopping volume increases as freeboard decreases**

Impulsive wave overtopping: the new empirical formulations

	Factor a_1	H/h a_2	$T\left(\sqrt{g/h}\right)$ a_3	$\sin\left(\alpha\right)$ a_4	s/h a_5	R^2	$\bar{\varepsilon}$
Ω	0.0084 $\pm$ 0.0042	3.1765 $\pm$ 0.1558	1.5782 $\pm$ 0.1858	-0.6141 $\pm$ 0.0973	-1.6204 $\pm$ 0.0978	0.96042	0.022188





Impulsive wave overtopping: comparison with existing formulae

Muller formula (1995)

$$\frac{\Omega}{\Omega_0} = \left(1 - \frac{s}{R_u}\right)^{2.22}$$

$$\frac{\Omega_0}{Ch^2} = 1.45 c_0 \left(\frac{H}{h}\right)^{\frac{4}{3}} \left(T\sqrt{\frac{g}{h}}\right)^{\frac{4}{9}}$$

$$\frac{\Omega}{Ch^2} = 1.45 c_0 \left(1 - \frac{s}{R_u}\right)^{2.22} \left(\frac{H}{h}\right)^{1.33} \left(T\sqrt{\frac{g}{h}}\right)^{0.44}$$

	Factor	H/h	$T(\sqrt{g/h})$	$\sin(\alpha)$	s/h	R^2	$\bar{\varepsilon}$
	a_1	a_2	a_3	a_4	a_5		
Ω	0.0084	3.1765	1.5782	-0.6141	-1.6204		
	$\pm$ 0.0042	$\pm$ 0.1558	$\pm$ 0.1858	$\pm$ 0.0973	$\pm$ 0.0978	0.96042	0.022188

Conclusions

1. **An *ad hoc* experimental investigation on generation and propagation of impulsive waves generated by vertical landslides was performed.**

2. **New empirical formulations to predict vertical slump generated wave main parameters (wave height and wave period) for both 2D and 3D water bodies are proposed.**

3. **An experimental investigation aimed at gaining insight about landslide generated wave runup was performed and a new empirical formulation is proposed. For the first time the incident wave period is taken into account.**

4. **A new empirical formulation is proposed for a zero thickness overtopped structure crest (resulting in a conservative estimation) simple to use if compared to existing tools.**