Tsunami Load Determination for On-Shore Structures

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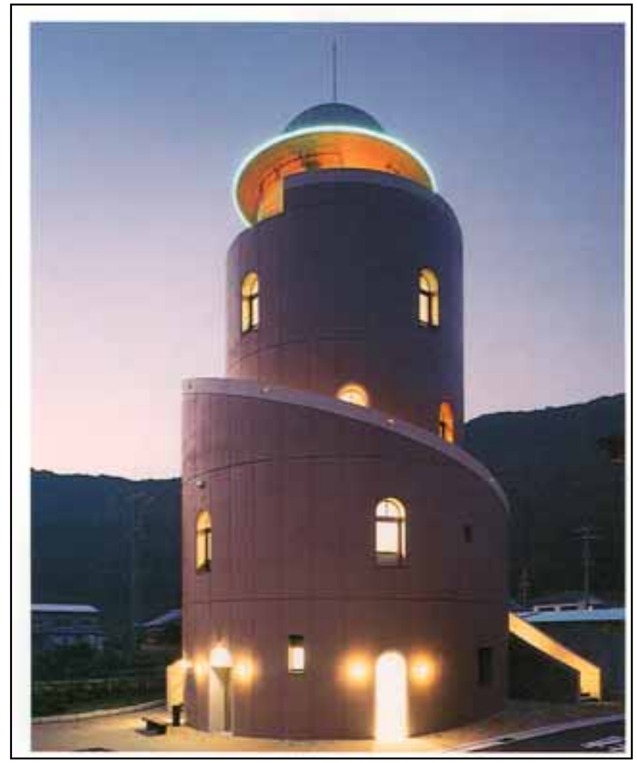
Building survival

Vertical Evacuation to Tsunami Shelters



How can we estimate the tsunami forces on such onshore structures?

Force Category in the Present Codes

***City and County of Honolulu Building Code* (2000)**

- Hydrostatic Forces
- Buoyant Forces
- Hydrodynamic Forces
- Surge Forces
- Impact Forces
- Breaking Wave Forces

Wave breaking at the shore

Typical when:
- steep beach slope
- narrow continental shelf

A collapsing breaker resulted from an undular bore. (Yeh, et al. 1989)

A sketch of Scotch Cap Lighthouse (1946 Aleutian Tsunami)

Some Considerations

Tsunami shelters are located on land some distance away from the shoreline.

Tsunami shelters are needed in the areas of relatively flat terrain where natural high-ground safe havens are not accessible.

- Formation of a surge may be the most likely flow condition.
- Wave breaking takes place offshore. The only exception is the collapsing breaker type, which occurs right at the shoreline on a steep-slope beach.

We will not consider wave-breaking force

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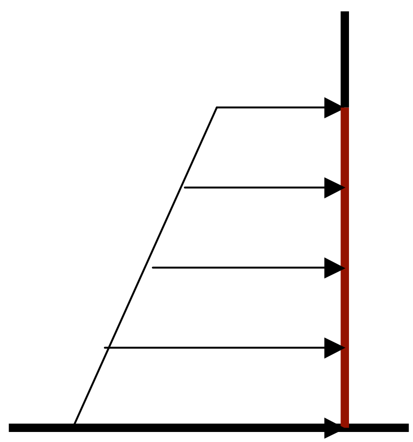
Hydrostatic Force

It is usually important for a 2-D structure such as seawalls and dikes, or for evaluation of an individual wall panel, but not for buildings

$$F_h = p_c A_w = \rho g \left(h_{\max} - \frac{h_w}{2} \right) b\, h_w \quad \text{for } h_{\max} > h_w,$$

$$\text{else } h_{\max} \rightarrow h_w$$

- p_c is the hydrostatic pressure at the centroid of the wetted portion of the wall panel,
- A_w is the wetted area of the panel
- h_{max} is the maximum water height above the base of the wall
- h_w is the height of wall panel



Buoyant Force

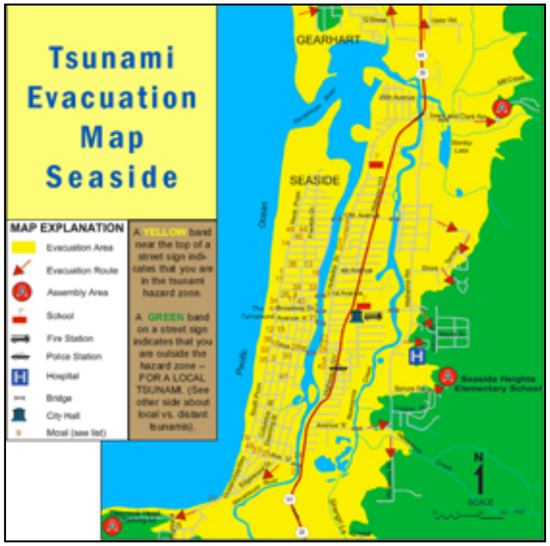
The buoyant forces act vertically through the center of mass of the displaced volume

$$F_B = \rho g V$$

- Buoyant forces are a concern for wood frame buildings, empty above-ground and below-ground tanks.
- and, for evaluation of an individual floor panel where the water level outside is substantially higher than the level inside. (Lesson learned from Hurricane Katrina)

- Case-by-case evaluation for hydrostatic force and buoyancy forces on an individual wall panel and a floor panel and alike.

- We only need the water depth *h* to compute the hydrostatic forces, which is readily estimated from the inundation maps



Force Category in the Present Codes

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Hydrodynamic Force

When "steady" water flows around a building (or structural element or other object) hydrodynamic loads are applied to the building

$$F_D = \frac{1}{2}\rho C_D A u^2$$ Drag Force

Width to Depth Ratio (w/d_s or w/h)	Drag Coefficient C_d
From 1 - 12	1.25
13 - 20	1.3
21 - 32	1.4
33 - 40	1.5
41 - 80	1.75
81 - 120	1.8
> 120	2

(FEMA CCM)

Hydrodynamic Force

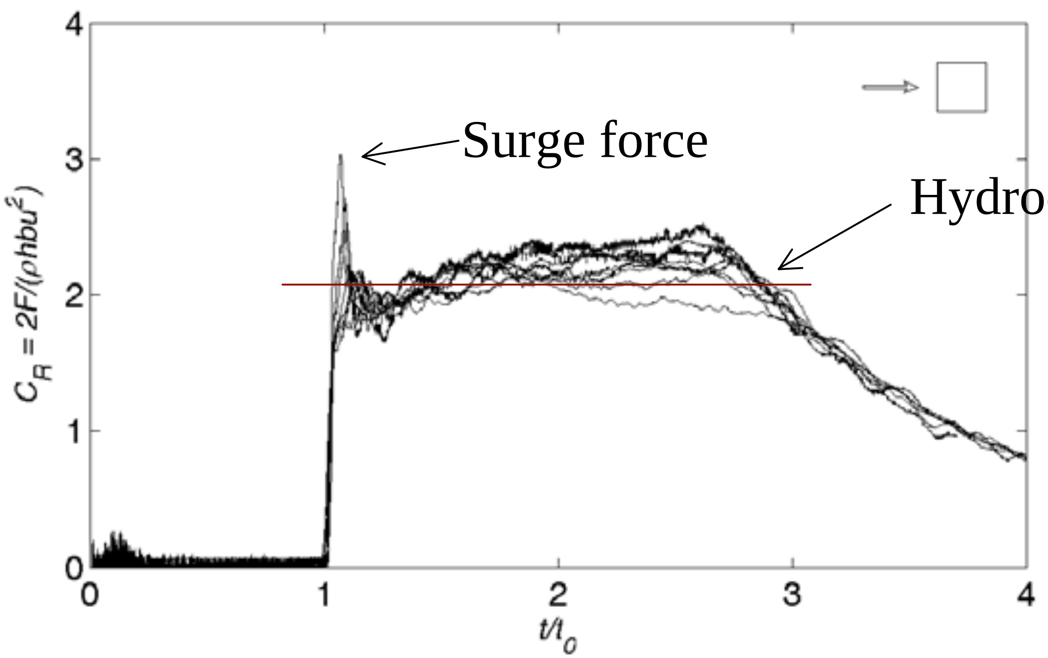
$$Force = \frac{1}{2} C_d \, \rho \, A_f \, u^2 \propto \boxed{b \; h \; u^2}$$

h: water depth

u: flow velocity

b: breadth

Laboratory Data of Tsunami Force on a Squire Column: C_d



$$C_d \approx O(1) \approx 2$$

But, how do we determine the value of $h \, u^2$?

Force Category in the Present Codes

- Hydrostatic Forces
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Surge Force (present codes)

Surge forces are caused by the leading edge of a surge of water impinging on a structure

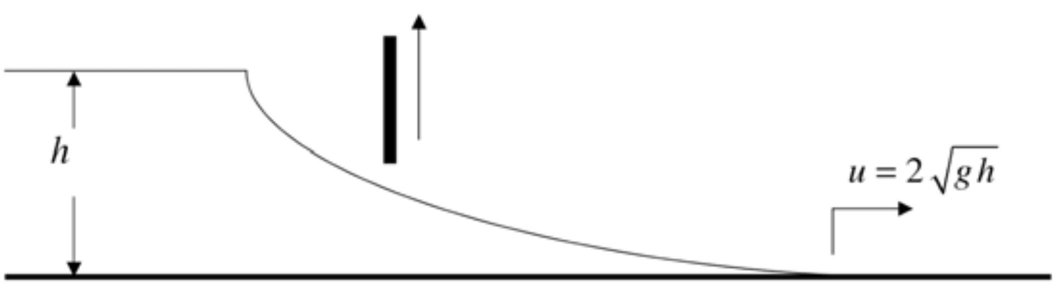
$$F_s = 4.5\,\rho g h^2 b$$

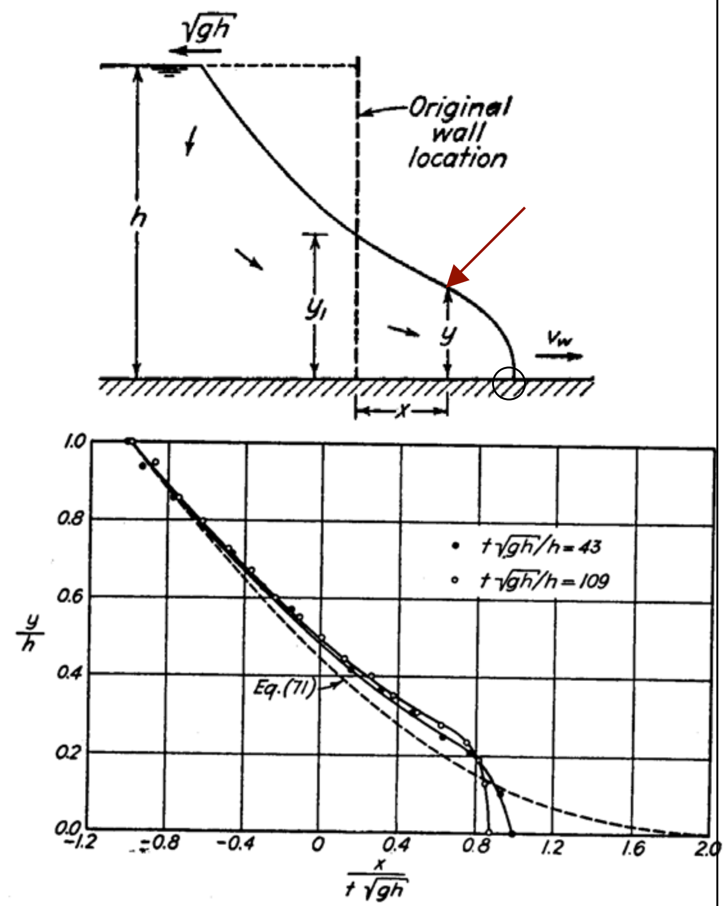
Keulegan (1950)

$$F_s/b = \frac{1}{2}\rho g h^2 + \rho u^2 h: \quad \boxed{u = 2\sqrt{g h}}$$

The identical approach by
the Building Center of Japan

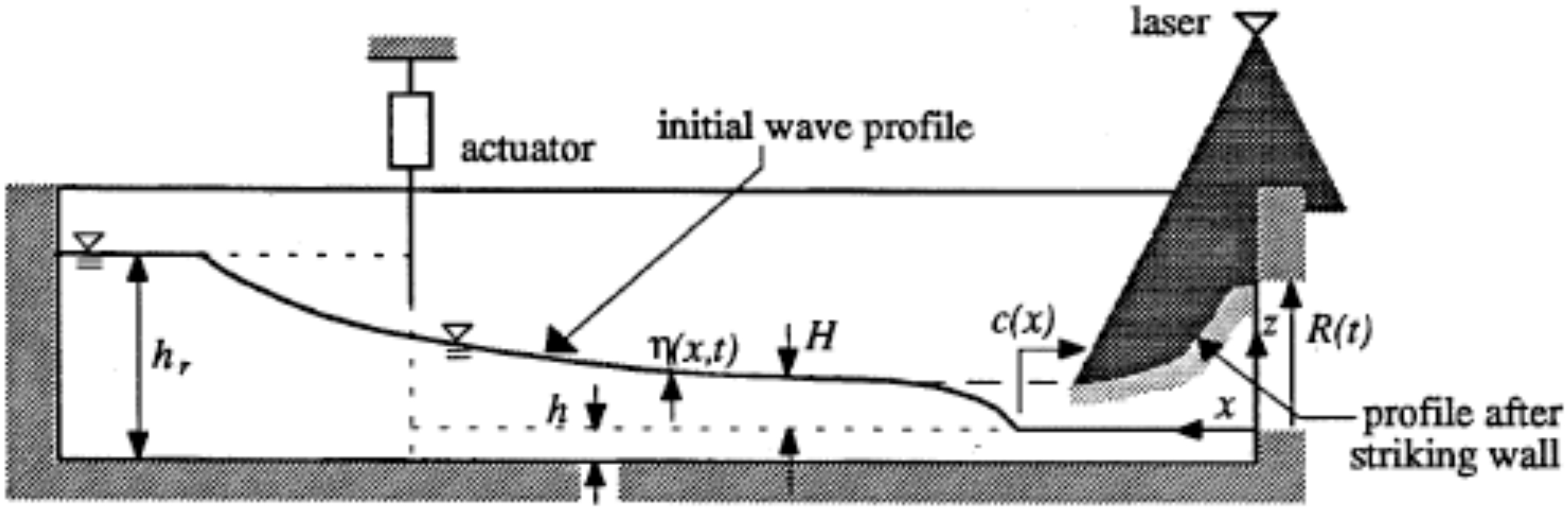
h is the surge height -- how can we determine?



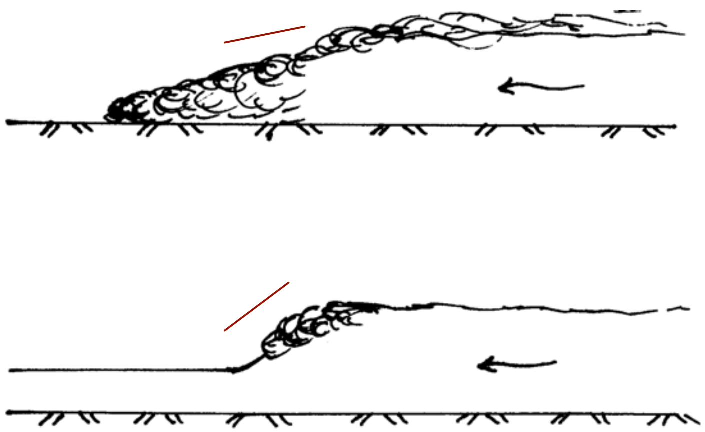


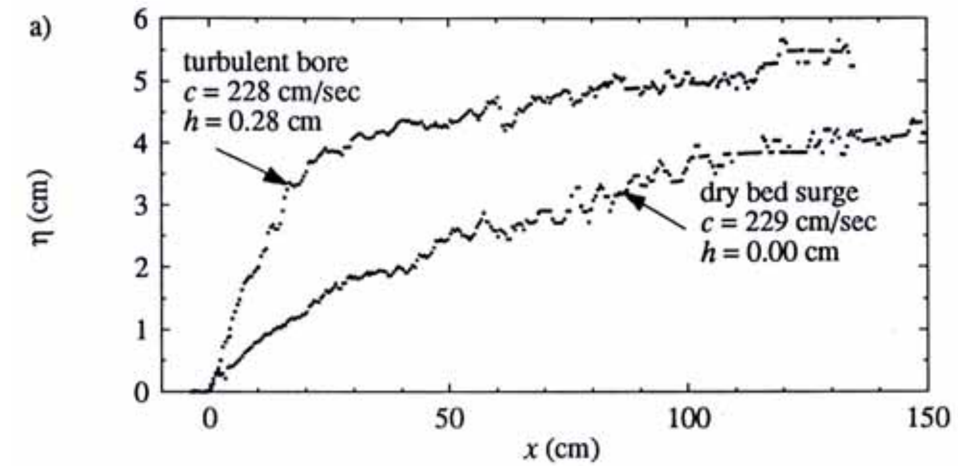
$$u = 2\sqrt{g y}$$

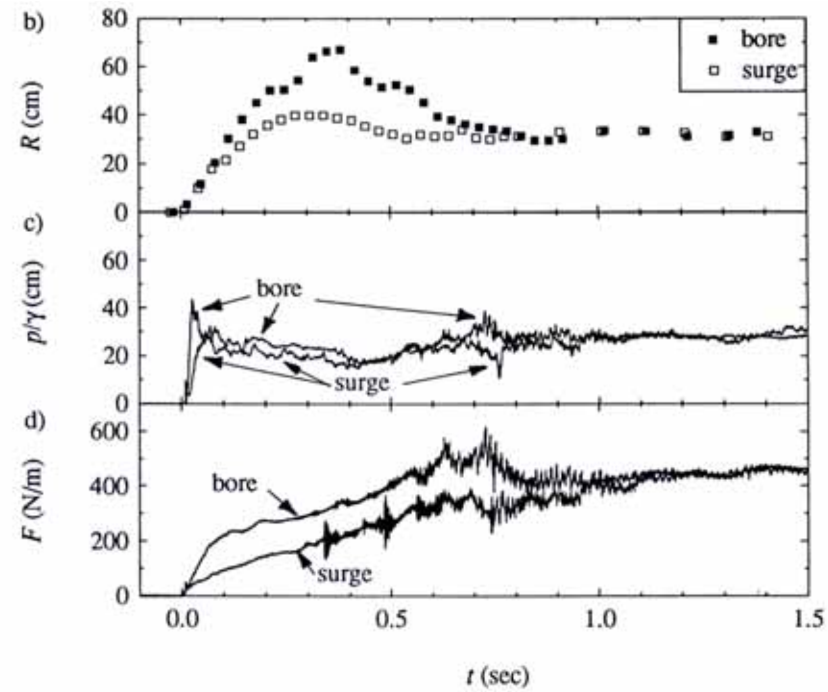
Ramsden, 1993



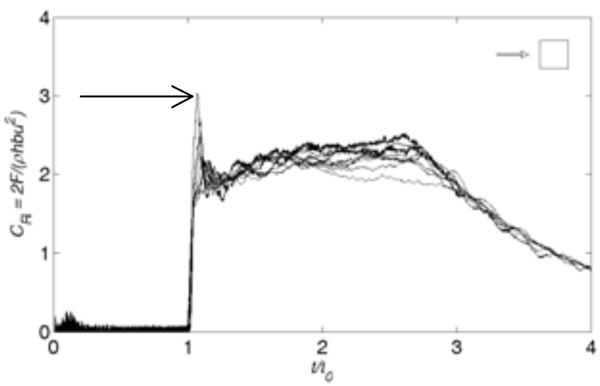
Bore vs Surge







No initial water-impact force in dry-bed surges



Comparison of the experimental a) wave profile; b) runup; c) pressure head; and d) force due to a strong turbulent bore and a dry bed surge (after Ramsden, 1993)

Force Category in the Present Codes

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- Impact Forces
- Breaking Wave Forces

Impact Force

Impact loads are those that result from debris such as driftwood, small boats, portions of houses, etc., or any object transported by floodwaters, striking against buildings and structures

Lincoln City, Oregon

Driftwood becomes hazardous

Impact Force (present codes)

$$F_I = m\frac{du}{dt} = m\frac{u_I}{\Delta t}$$

Type of construction	Duration (t) of Impact (sec)	
	Wall	**Pile**
Wood	0.7 - 1.1	0.5 - 1.0
Steel	NA	0.2 - 0.4
Reinforced Concrete	0.2 - 0.4	0.3 - 0.6
Concrete Masonry	0.3 - 0.6	0.3 - 0.6

(FEMA CCM)

This is based on the impulse-momentum approach:

$$I = \int_0^{\tau} F\,dt = d\left(m\,u\right); \quad \tau \rightarrow 0$$

Relevant Literature

- ASCE 7-02
  - ASCE Standard. 2003. Minimum design loads for buildings and other structures. SEI/ASCE 7-02.
- City and County of Honolulu Building Code (CCH, 2000)

- Matsutomi
  - J. Hydr., Coastal, Envr. Engrg., 621, 1999 & Tsunami Engineering Tech. Rep., 13, 1996
- Ikeno, et al.
  - 2001, 2003. Impulse Force of Drift Body
- Haehnel and Daly
  - 2002. USACOE Report, ERDC/CRREL TR-02-2

ASCE 7-02 (2003)

$$F = \frac{\pi\, m\, u\, C_I\, C_O\, C_D\, C_B\, R_{\max}}{2\,\Delta t}$$

m:	the debris mass,
u:	the impact velocity of object,
C_i:	the importance coefficient,
C_O:	the orientation coefficient,
C_D:	the depth coefficient,
C_B:	the blockage coefficient,
R_{max}:	the maximum response ratio for impulsive load
Δt:	the impact duration: **Δt = 0.03 sec is recommended**

- ***City and County of Honolulu Building Code* (2000) recommends Δt = 1.0 sec for wood construction, Δt = 0.5 sec for steel construction, and Δt = 0.1 sec for reinforced concrete**
- **FEMA CCM, Δt = 0.2 ~ 1.1 sec**

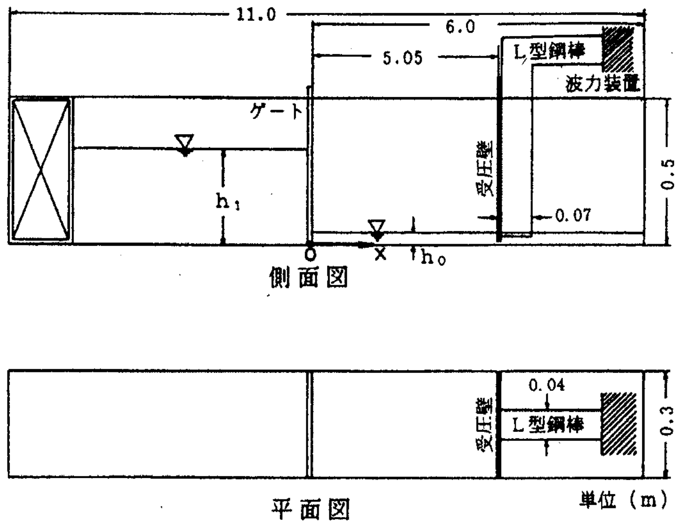
Matsutomi: J. Hydr., Coastal, Envr. Engrg., 621, 1999 & Tsunami Engineering Tech. Rep., 13, 1996

- Impact force evaluation: $F = -M \dfrac{dV}{dt}$ $\quad \int_0^{\Delta t} F(t)\, dt = C_M\, M\, V_0$

$$\boxed{\frac{F}{\gamma_w D^2 L} = 1.6\, C_M \left(\frac{u}{\sqrt{g D}} \right)^{1.2} \left(\frac{\sigma_f}{\gamma_w L} \right)^{0.4}}$$

- Specifically for lumber impact
- Using small-scale laboratory experiments, C_M = 1.7 (C_M = 1.9 for steady flows)
- Use large-scale "dry" experiments,
  - u: impact velocity
  - γ_w: specific weight of lumber
  - σ_f: yield stress of lumber (≈ compressive strength) ~ 20 MPa
  - D: diameter of lumber
  - L: length of lumber

Matsutomi's work



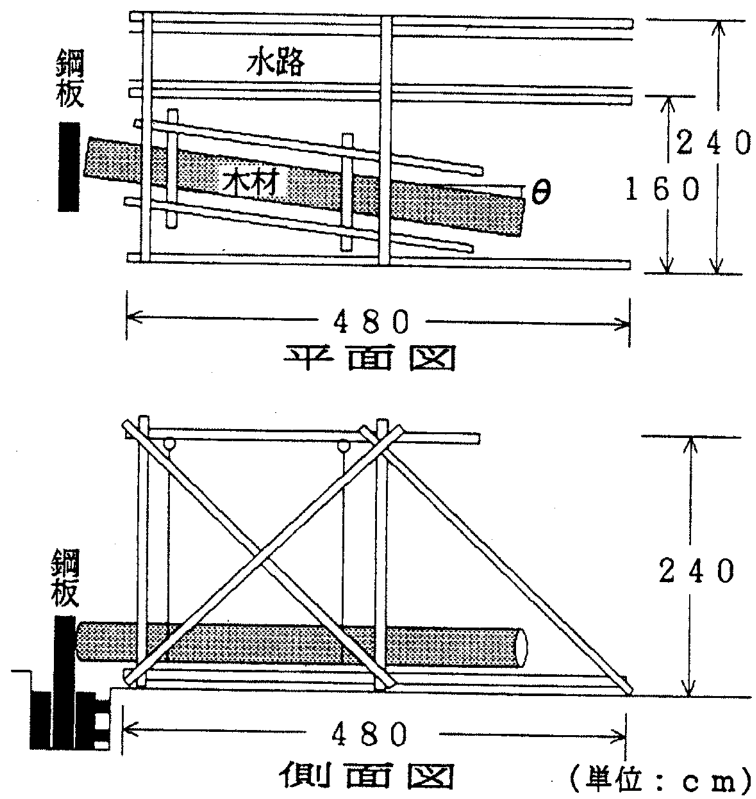
図－1　水路実験装置の概略

表－1　段波とサージの発生条件

	h_1 (cm)	h_0 (cm)
段波	35, 40, 45	1,　2
ｻｰｼﾞ	25　,　40	0

表－2　流木諸元

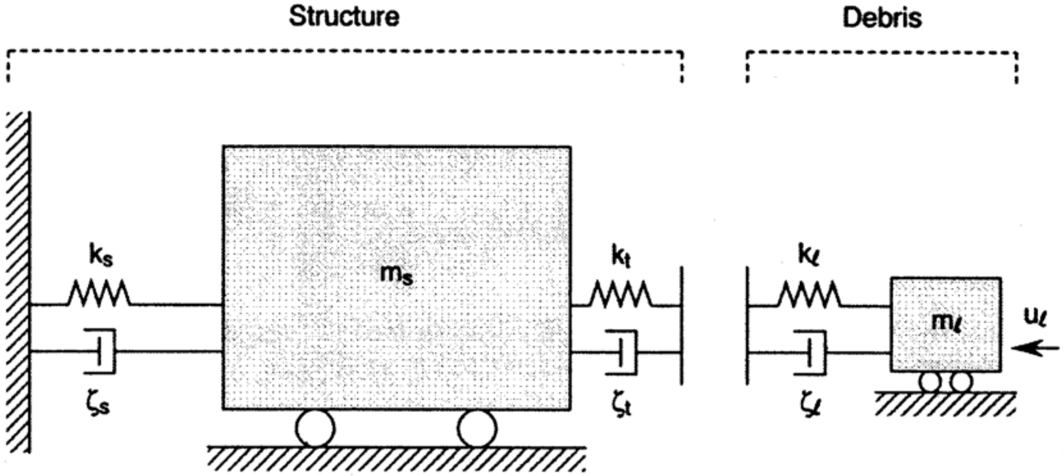
D (cm)	L (cm)	L／D	W (gf)
4.8～12	38.4～160	8,　12,　16	305～8615



図－3　空中での流木衝突実験装置の概略

Haehnel and Daly, 2002

Lumber impact



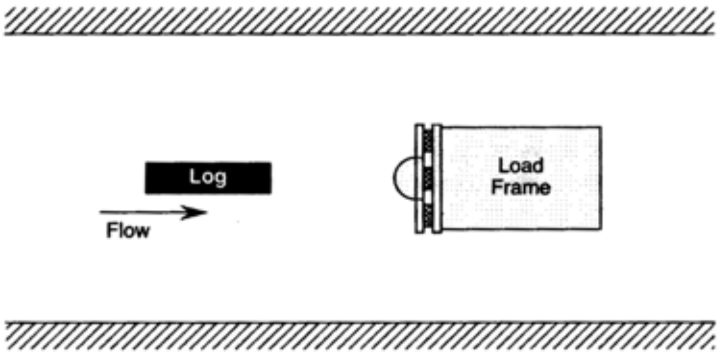
$\zeta \approx 0;\ m_s \gg m_l;\ \ k_s \gg k_t,\ k_l$

$$\frac{1}{\hat{k}} = \frac{1}{k_t} + \frac{1}{k_l}$$

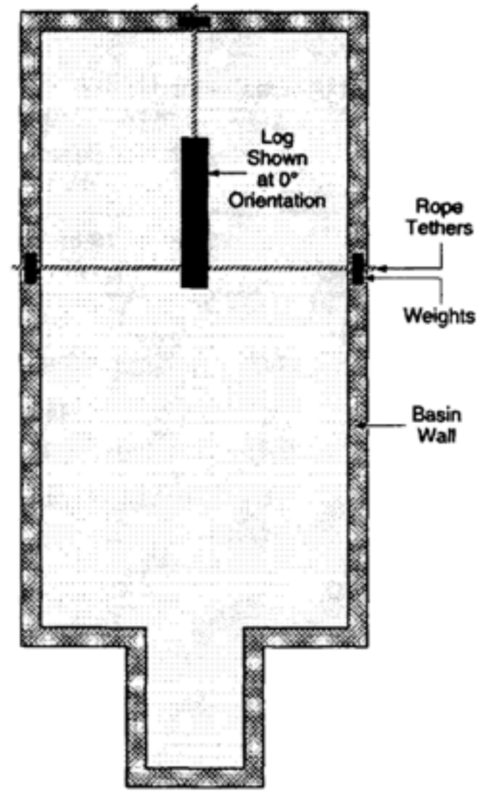
$$m_1\,\ddot{x} + \hat{k}\,x = 0 \quad \Rightarrow \quad x = u\sqrt{m/\hat{k}}\ \sin\left(t\sqrt{\hat{k}/m}\right)$$

$$F = \hat{k}\,x$$

$$\boxed{F_{\max} = Max.\langle \hat{k}\,x \rangle = u\sqrt{\hat{k}\,m}}$$



1.22 x 0.61 x 36.6 m flume.



Plan View

9.1 x 37 x 2.4 m basin

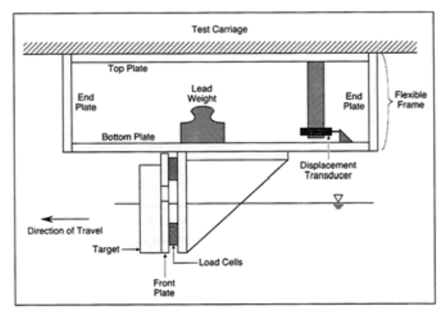


Figure 3. Load frame used in the basin tests.

Experiments by Haehnel & Daly

Haehnel and Daly

Constant Stiffness Approach:

$$\boxed{F_{\max} = Max.\left\langle \hat{k}\, x \right\rangle = u\sqrt{\hat{k}\, m} \approx 1550\, u\sqrt{m}}$$

From their experiments, the effective constant stiffness is **2.4 MN/m** (but no flow in their experiments)

Impulse-Momentum Approach:

$$F_{\max} = \frac{\pi}{2}\frac{u\, m}{\Delta t} \approx 90.9\, u\, m$$

The impulse-momentum approach reduces to the constant stiffness approach by setting

$$\Delta t = \frac{\pi}{2}\sqrt{\frac{m}{\hat{k}}}$$

Work-Energy Approach:

$$F_{\max} = \frac{u^2\, m}{\Delta x} \approx 125\, m\, u^2 + 8000$$

The work-energy approach reduces to the constant stiffness approach by setting

$$\Delta x = u\sqrt{\frac{m}{\hat{k}}}$$

Comments

- Uncertainty may be resulted from the fact that the prediction models are based on the empirical scaled-down (and small) data.

- All of the previous works are for impact of a relatively small water-borne missile, e.g. a lumber log.

- No consideration was made for impact of a large missile such as a ship.

Comments

- Different relations based on the model:
  - **Constant Stiffness Approach** $\Rightarrow$ $F \propto u\sqrt{m}$ $n = 0.50$
  - Impulse-Momentum Approach $\Rightarrow$ $F \propto u\,m$
  - Work-Energy Approach $\Rightarrow$ $F \propto u^2\,m$
  - Ikeno et al. (2003) $\Rightarrow$ $F \propto u^{2.5} m^n$ $n \approx 0.58$
  - Matsutomi (1999) $\Rightarrow$ $F \propto u^{1.2} m^n$ $n \approx 0.66$

Impulse-Momentum Approach: $\Delta t = \frac{\pi}{2}\sqrt{\frac{m}{\hat{k}}}$

Work-Energy Approach: $\Delta x = u\sqrt{\frac{m}{\hat{k}}}$

Summary & Recommendations

- Forces on a building examined for a tsunami shelter.
  - Hydrodynamic force with $C_D = 2$.
  - Surging force may not be important, but if we consider bore formation, this can be taken into account by using $C_D = 3$ instead of 2.

$$\boxed{F_D = \frac{1}{2}\rho C_D b h u^2}$$

  - Impact force can be evaluated by the "modified" constant stiffness approach with an appropriate value of effective stiffness k, and the added mass coefficient C_M (≈ 2). k = 2.4MN/m was recommended for a lumber

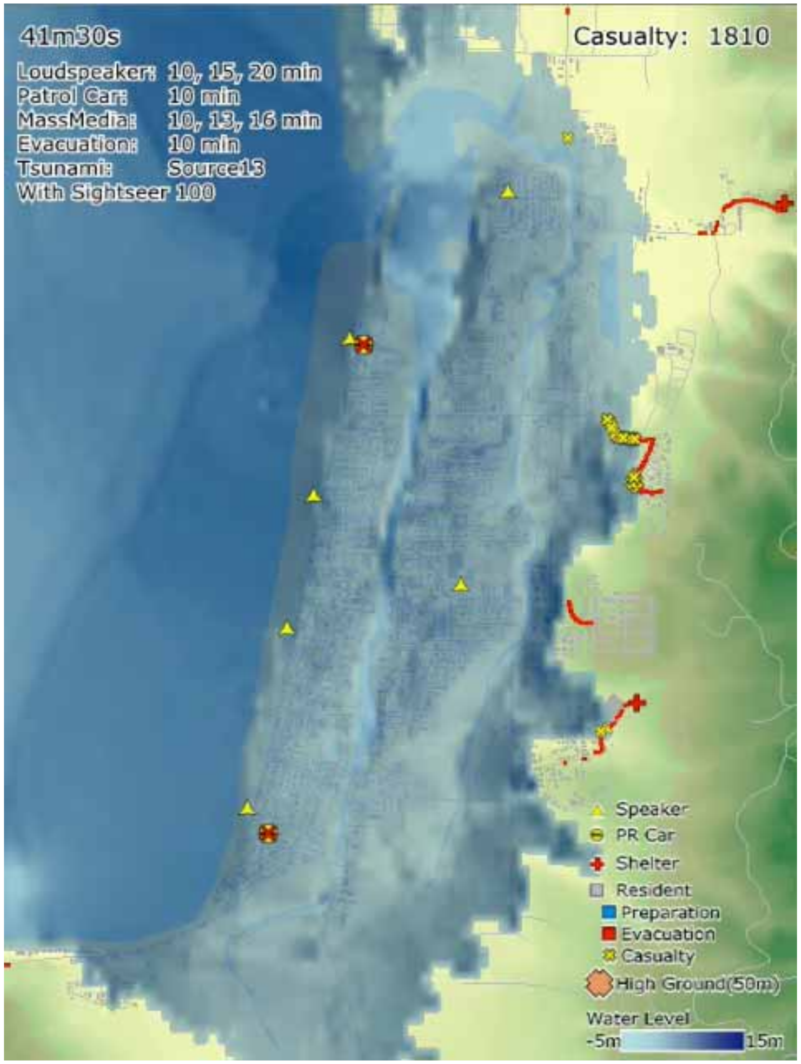
$$\boxed{F_{\max} = C_M u \sqrt{\hat{k} m}}$$

Recommendations - continue

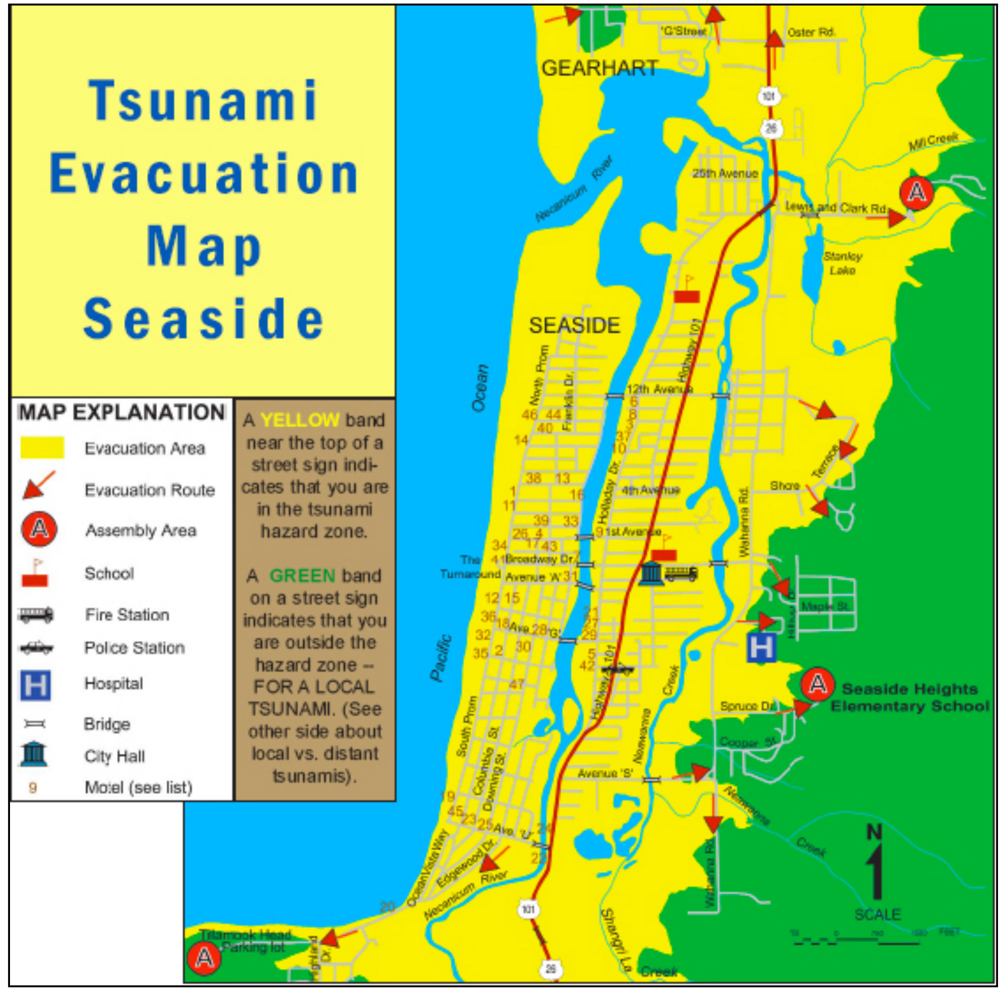
- Need the design values of h, u, hu^2 at the site of interest. Note that: Max (hu^2) $\neq$ Max (h) $\times$ Max (u^2)

  - Obtain the data from detailed numerical simulations with a very fine grid size in the runup zone ($\Delta < 10$ m).

  - As for a guideline, use of the analytical solutions for 1-D runup on a uniformly sloping beach.



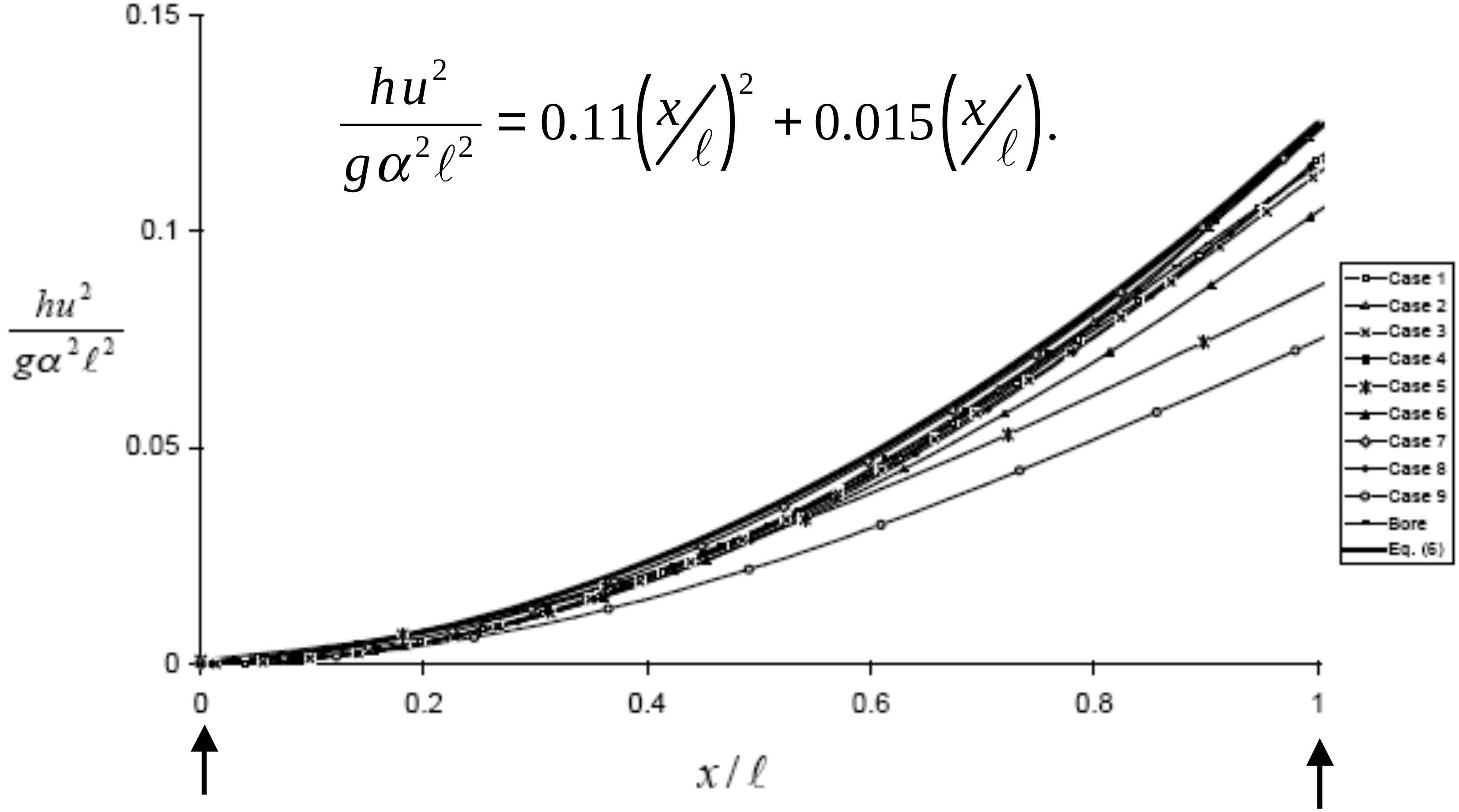
A snap shot of numerical simulation



Available inundation map

Maximum hu^2 distribution in the runup zone

(analytic solution for 1-D runup on a uniformly sloping beach)



$$\frac{hu^2}{g\alpha^2\ell^2} = 0.11\left(x/\ell\right)^2 + 0.015\left(x/\ell\right).$$

Max. inundation

Shore line

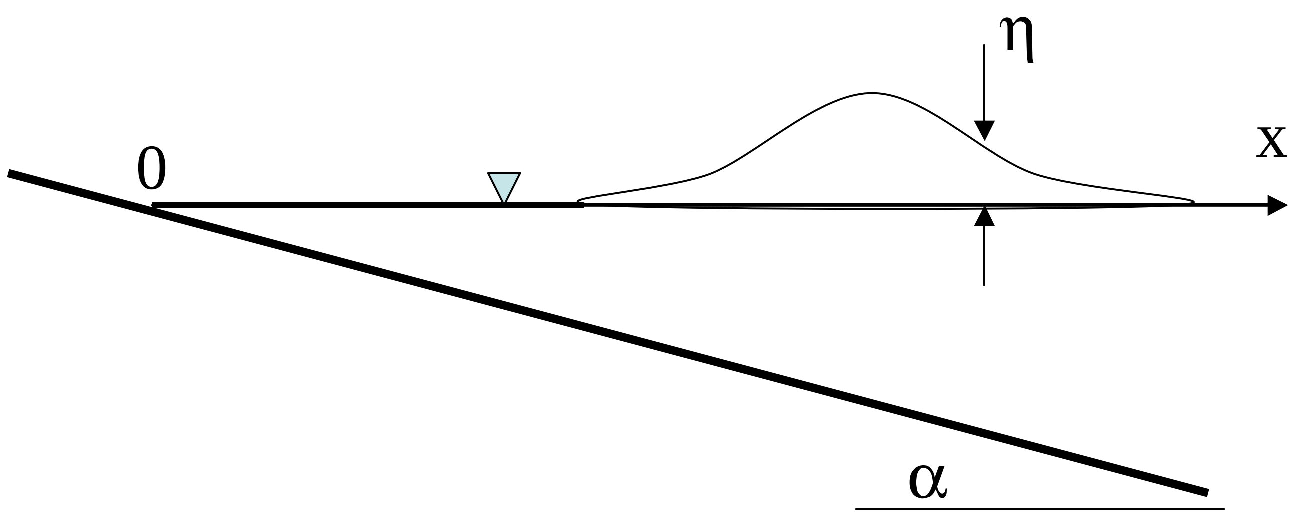
Yeh (2006)

To obtain the design values of h, u, hu^2 at the site of interest

Long-Wave Runup on a Plane Beach

Nonlinear Problem

- Carrier and Greenspan (1958)
- Carrier, Wu, and Yeh (2003) -- Analytic-Numeric Hybrid Approach



The fully nonlinear shallow-water wave

$$\left[u'\left(\alpha x' + \eta'\right)\right]_{x'} + \eta'_{t'} = 0,$$

$$u'_{t'} + u' u'_{x'} + g\eta'_{x'} = 0,$$

Scaling:

$$u' = \sqrt{g\alpha L}\, u; \quad \eta' = \alpha L \eta; \quad x' = L x; \quad t' = \sqrt{L/\alpha g}\; t$$

$$\left[u\left(x + \eta\right)\right]_{x} + \eta_{t} = 0,$$

$$u_t + u u_x + \eta_x = 0.$$

Introducing the distorted coordinates q and λ such that:

$$\lambda = t - u; \quad q = x + \eta$$

The transformation yields:

$$\begin{cases} (q\,u)_q + \left(\eta + \dfrac{u^2}{2}\right)_\lambda = 0, \\ u_\lambda + \left(\eta + \dfrac{u^2}{2}\right)_q = 0. \end{cases}$$

$$\psi = \eta + \frac{u^2}{2} \qquad \sigma = \sqrt{q} = \sqrt{x + \eta}$$

$$4\sigma\psi_{\lambda\lambda} - (\sigma\psi_\sigma)_\sigma = 0 \qquad \text{where} \quad \psi = \eta + \frac{u^2}{2}$$

The same form as the one by Carrier-Greenspan (1958).
For convenience, we introduce the variable φ:

$$\psi = \eta + \frac{u^2}{2} = \varphi_\lambda; \quad u = -\frac{\varphi_\sigma}{2\sigma}; \quad \eta = \varphi_\lambda - \frac{\varphi_\sigma{}^2}{8\sigma^2}$$

$$\boxed{4\sigma\varphi_{\lambda\lambda} - (\sigma\varphi_\sigma)_\sigma = 0}$$

Initial Conditions at $\lambda = t - u = 0$:

$$\varphi(\sigma, 0) = P(\sigma),$$

$$\varphi_\lambda(\sigma, 0) = F(\sigma),$$

$$P(\sigma) = -\int_0^\sigma 2\sigma' u(\sigma', 0)\, d\sigma', \quad \text{and} \quad \mathrm{F}(\sigma) = \eta(\sigma, 0) + \frac{u^2(\sigma, 0)}{2}.$$

Summary

$$4\sigma\varphi_{\lambda\lambda} - (\sigma\varphi_\sigma)_\sigma = 0$$

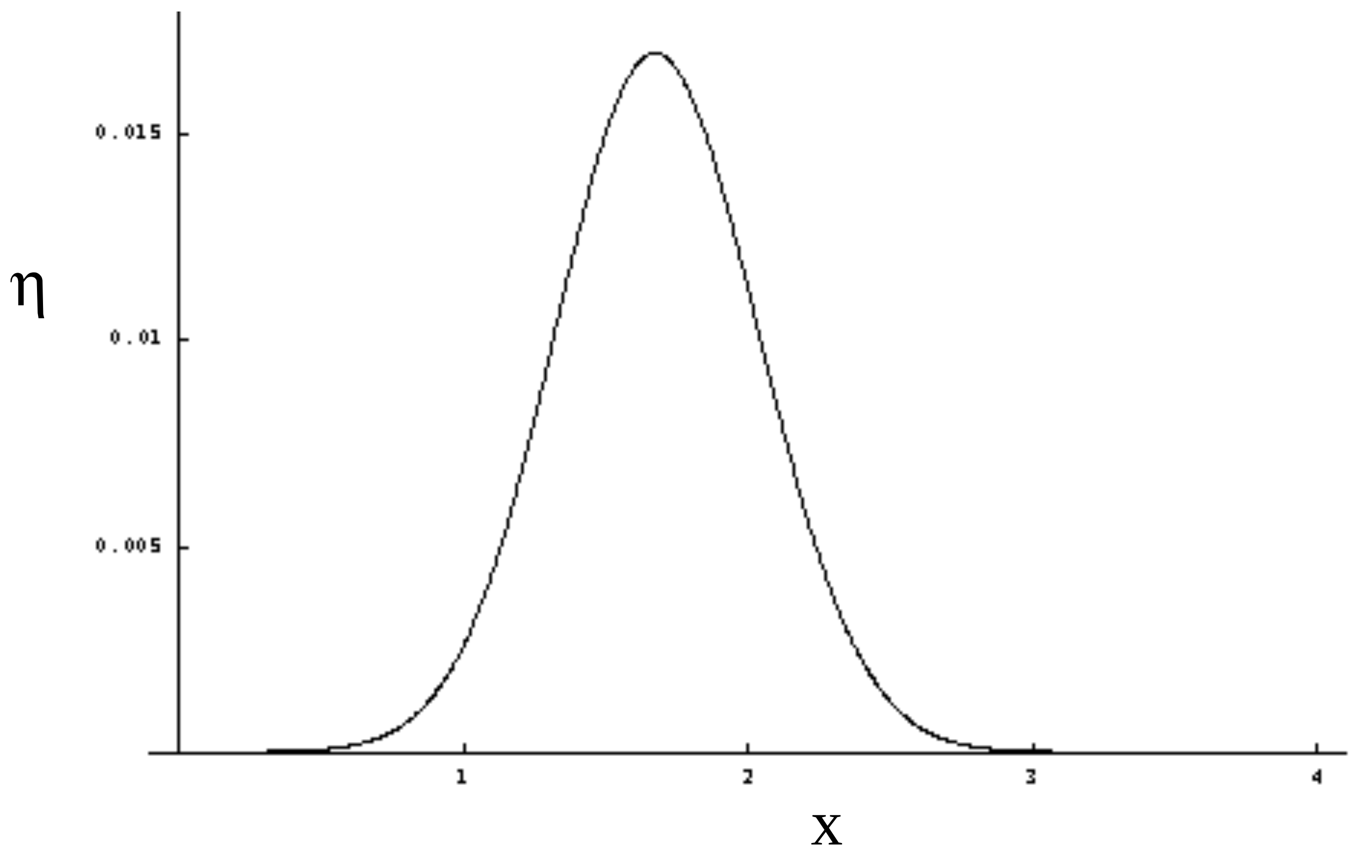
$$\varphi(\sigma,\lambda) = 2\left\{\int_0^\infty F(b)\, G(b,\sigma,\lambda)\, db + \int_0^\infty P(b)\, G_\lambda(b,\sigma,\lambda)\, db\right\}$$

With ICs: $P(\sigma) = -\int_0^\sigma 2\sigma'\, u(\sigma',0)\, d\sigma'$, and $\mathrm{F}(\sigma) = \eta(\sigma,0) + \dfrac{u^2(\sigma,0)}{2}$.

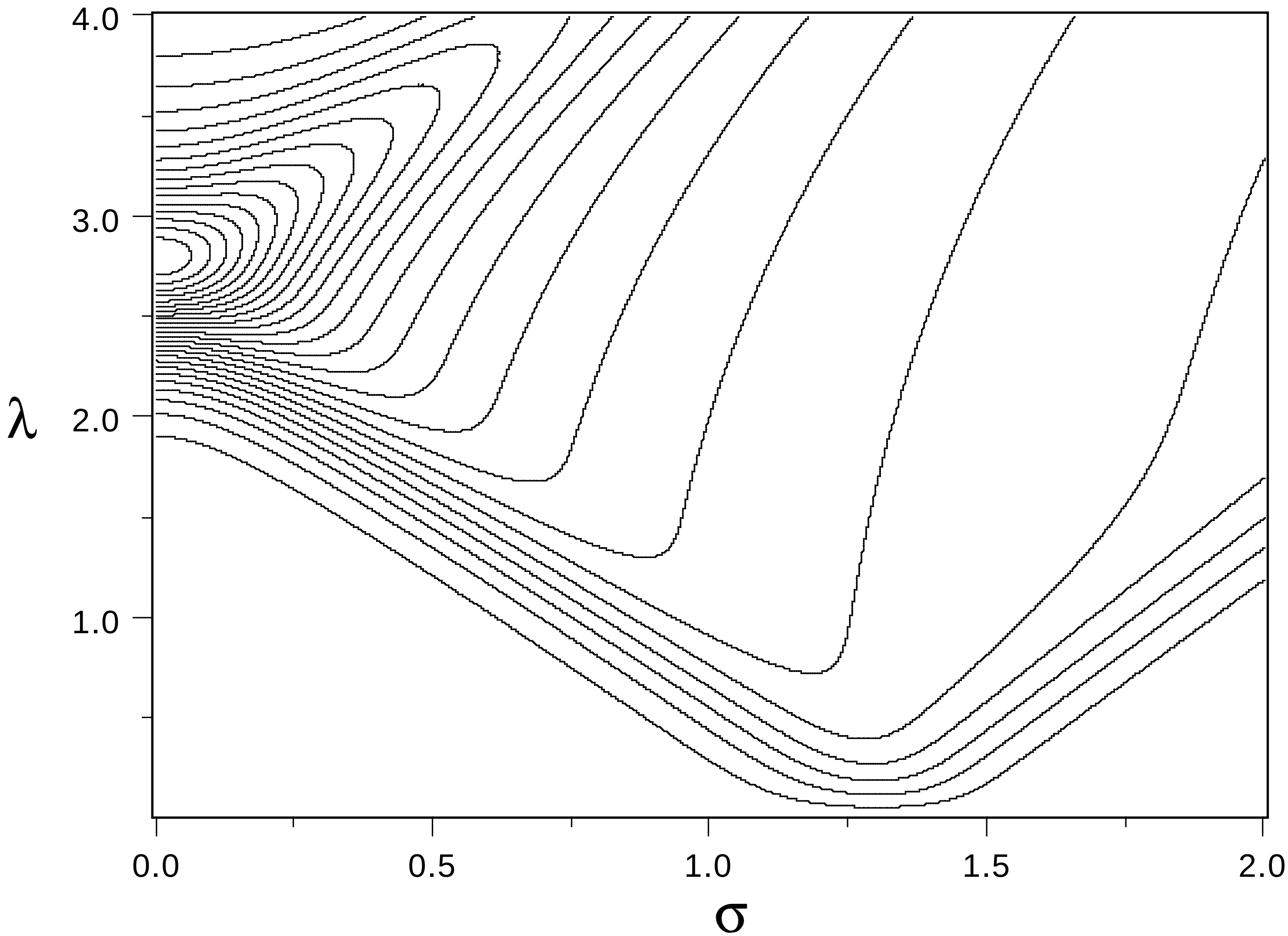
$$\psi = \eta + \frac{u^2}{2} = \varphi_\lambda; \quad u = -\frac{\varphi_\sigma}{2\sigma}; \quad \eta = \varphi_\lambda - \frac{\varphi_\sigma{}^2}{8\sigma^2}$$

$$\lambda = t - u; \quad \sigma = \sqrt{x + \eta}$$

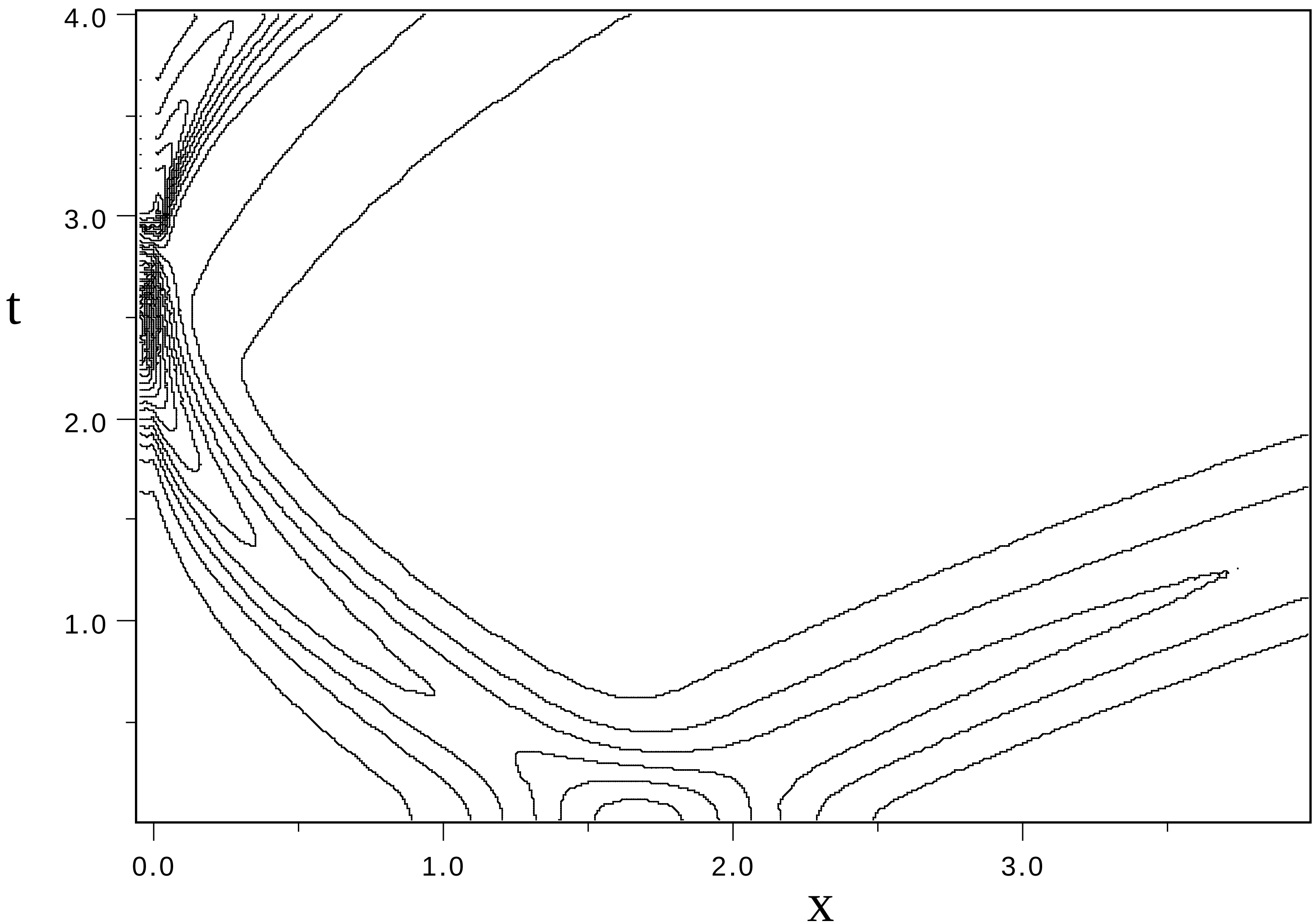
The initial wave form of a Gaussian shape



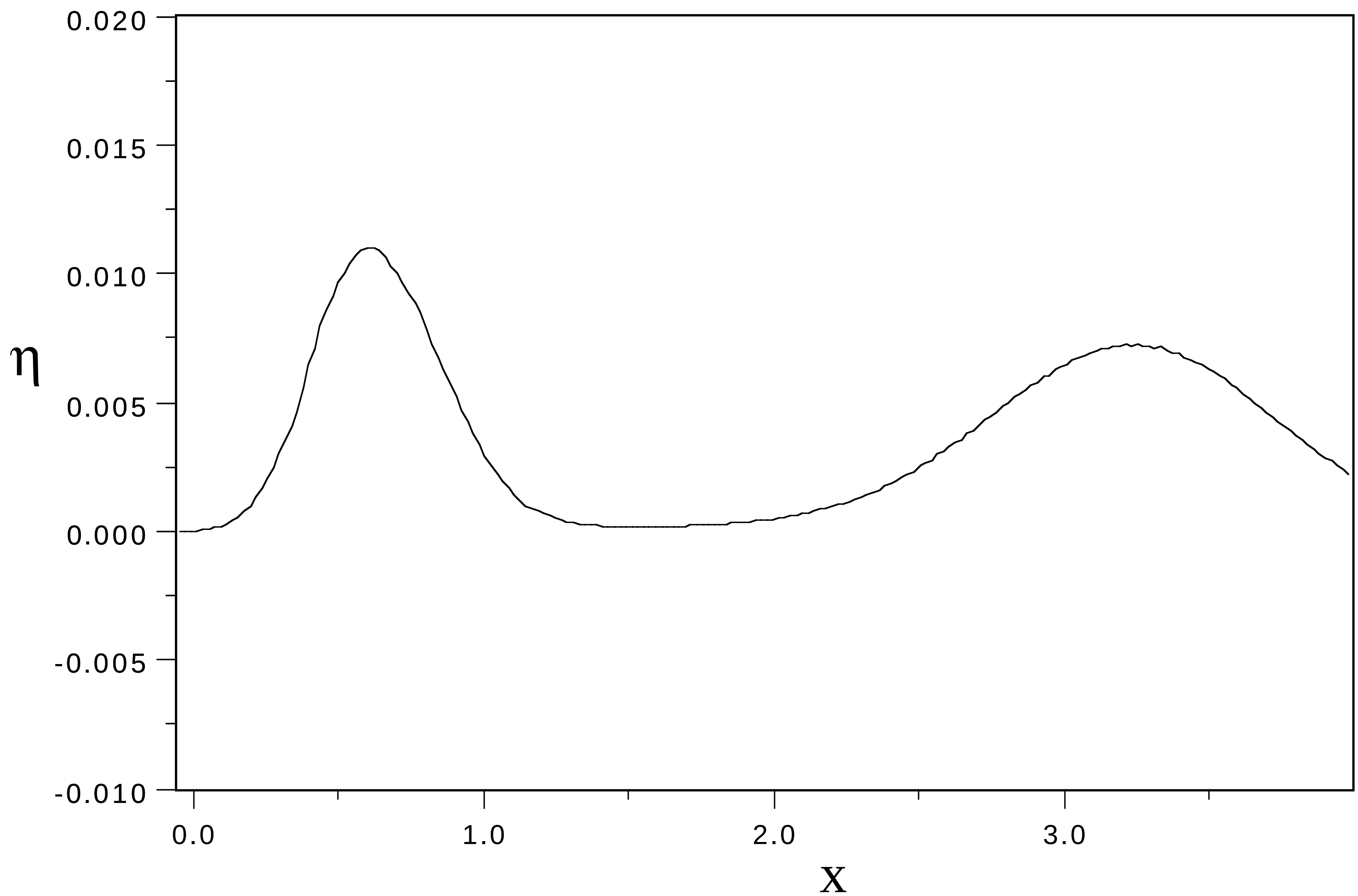
φ (σ, λ) for the Gaussian shaped initial displacement



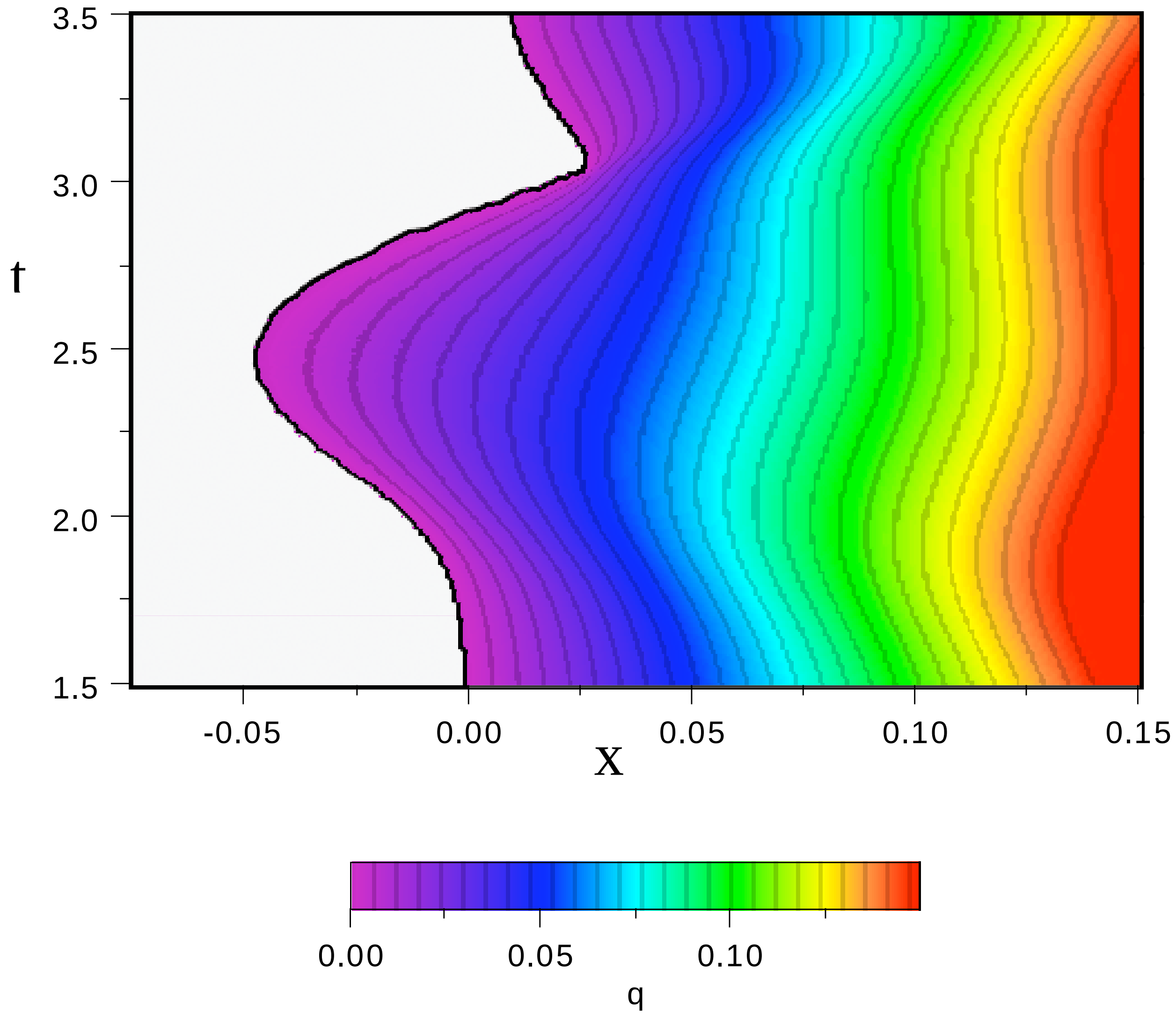
Water-surface plot for the Gaussian shaped initial displacement



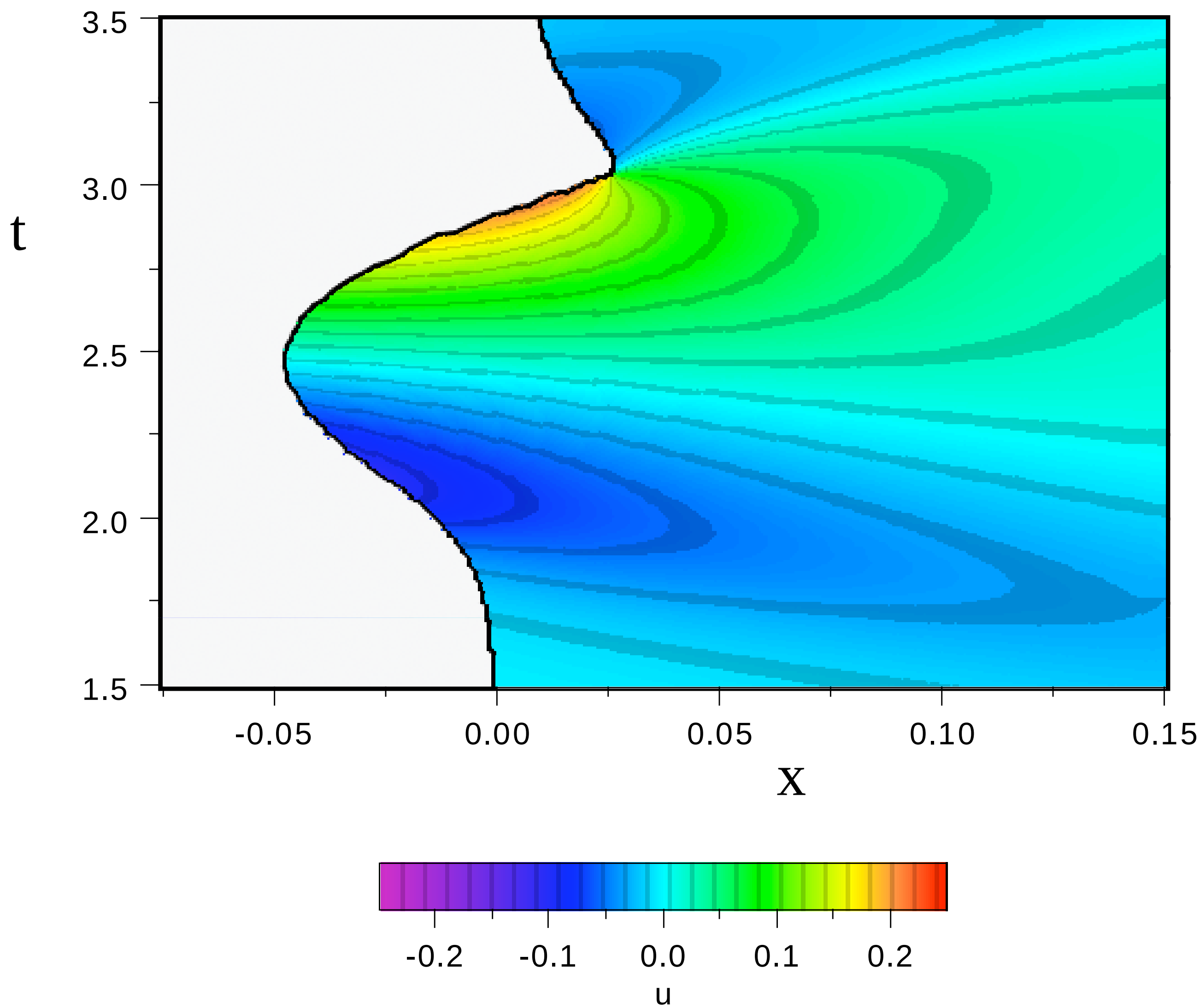
Water-surface profile at t = 1.0



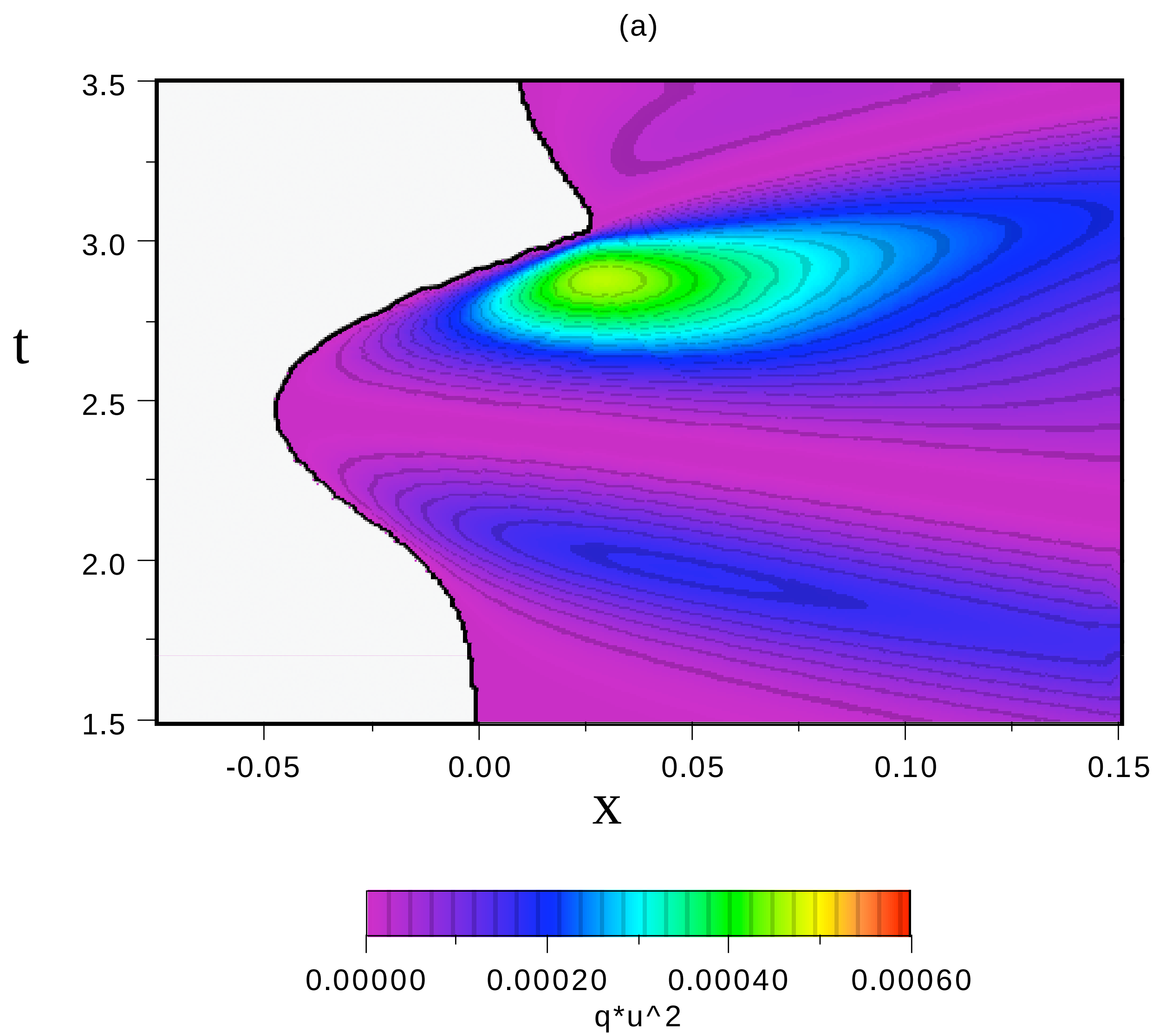
Water-depth variations: q



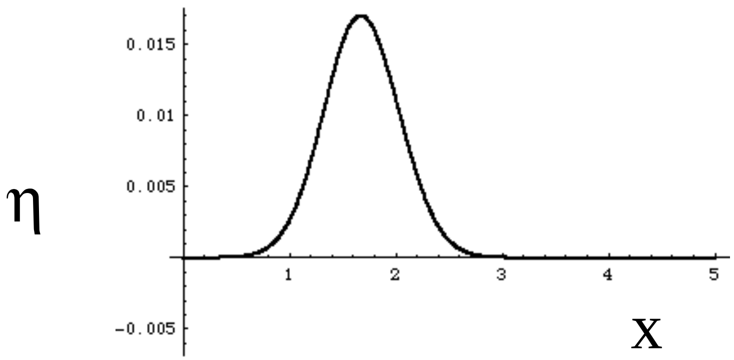
Water velocity: u

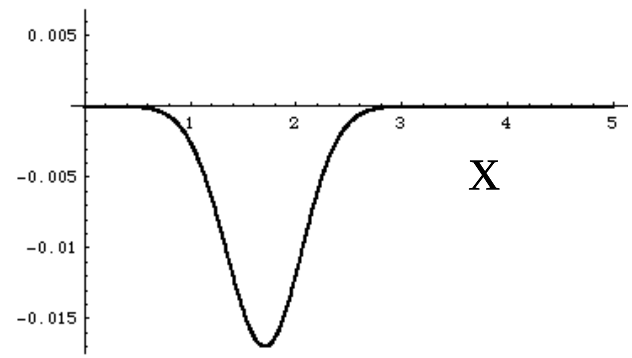


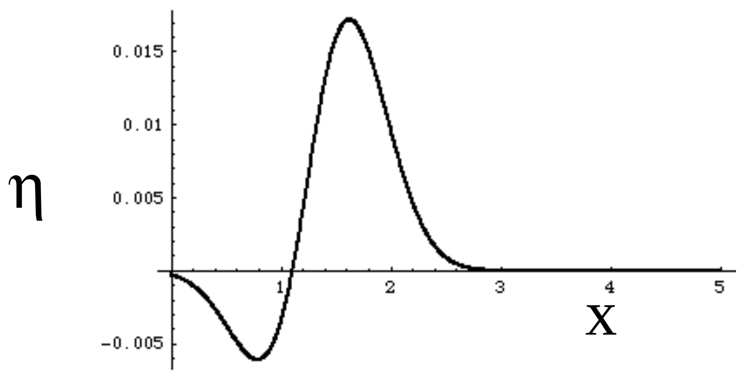
Momentum Flux (Fluid Force) $\propto h\,u^2$

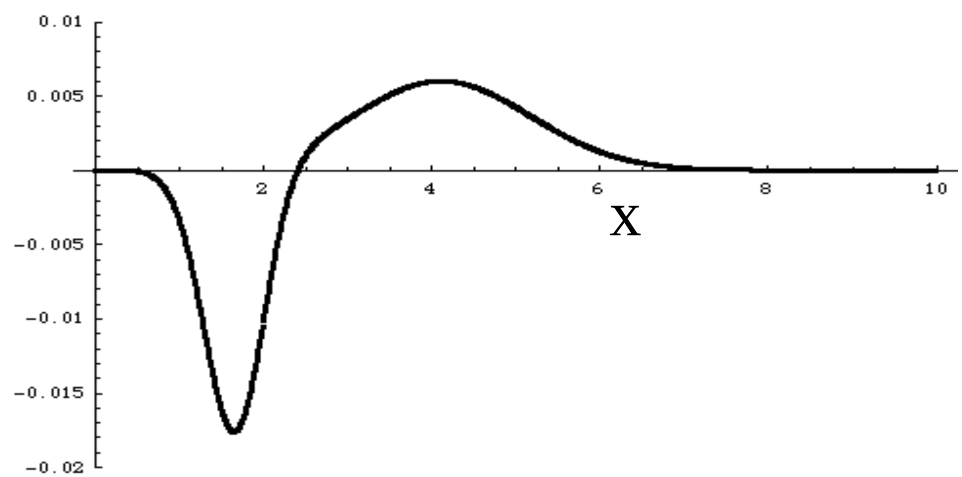


Initial Waveforms

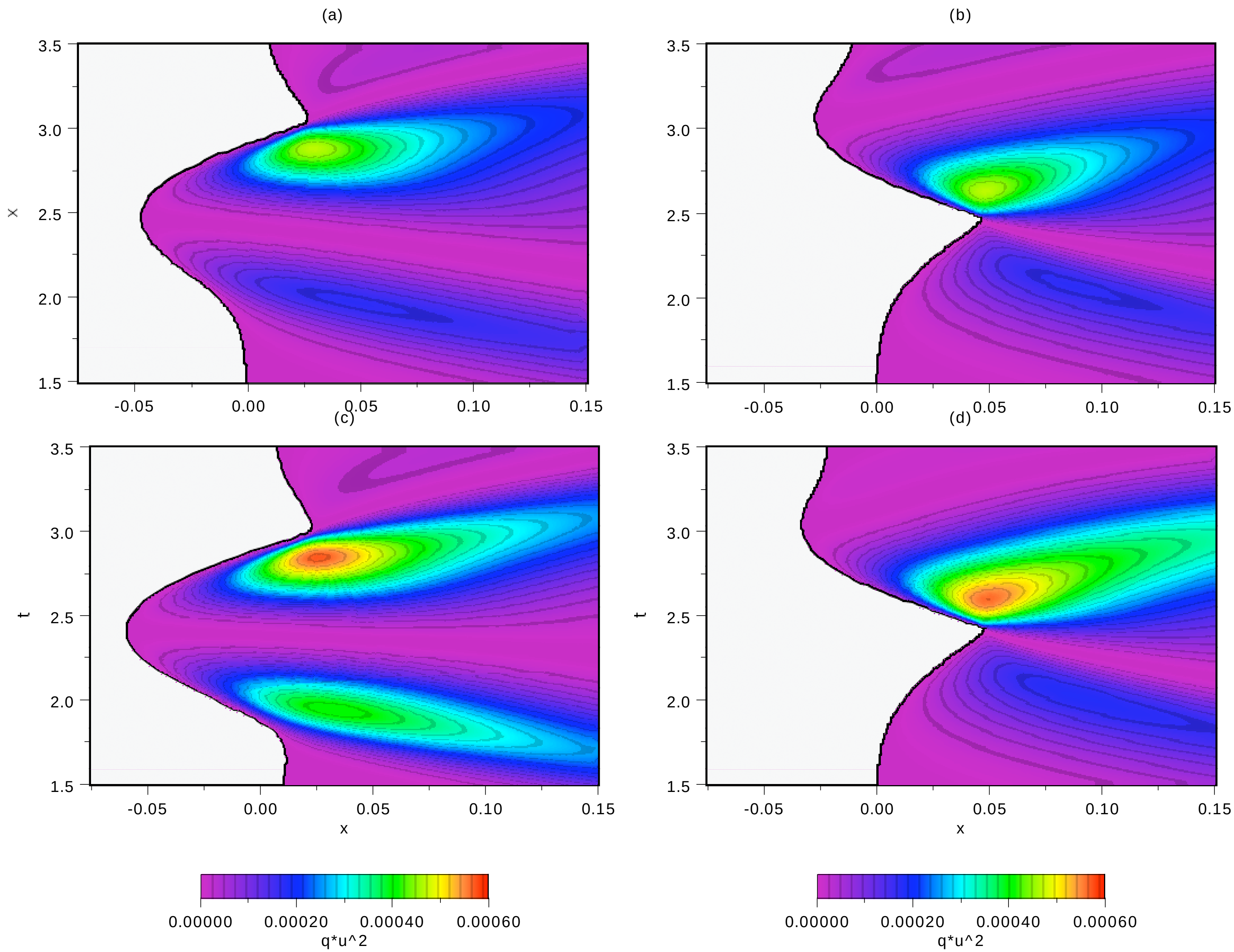




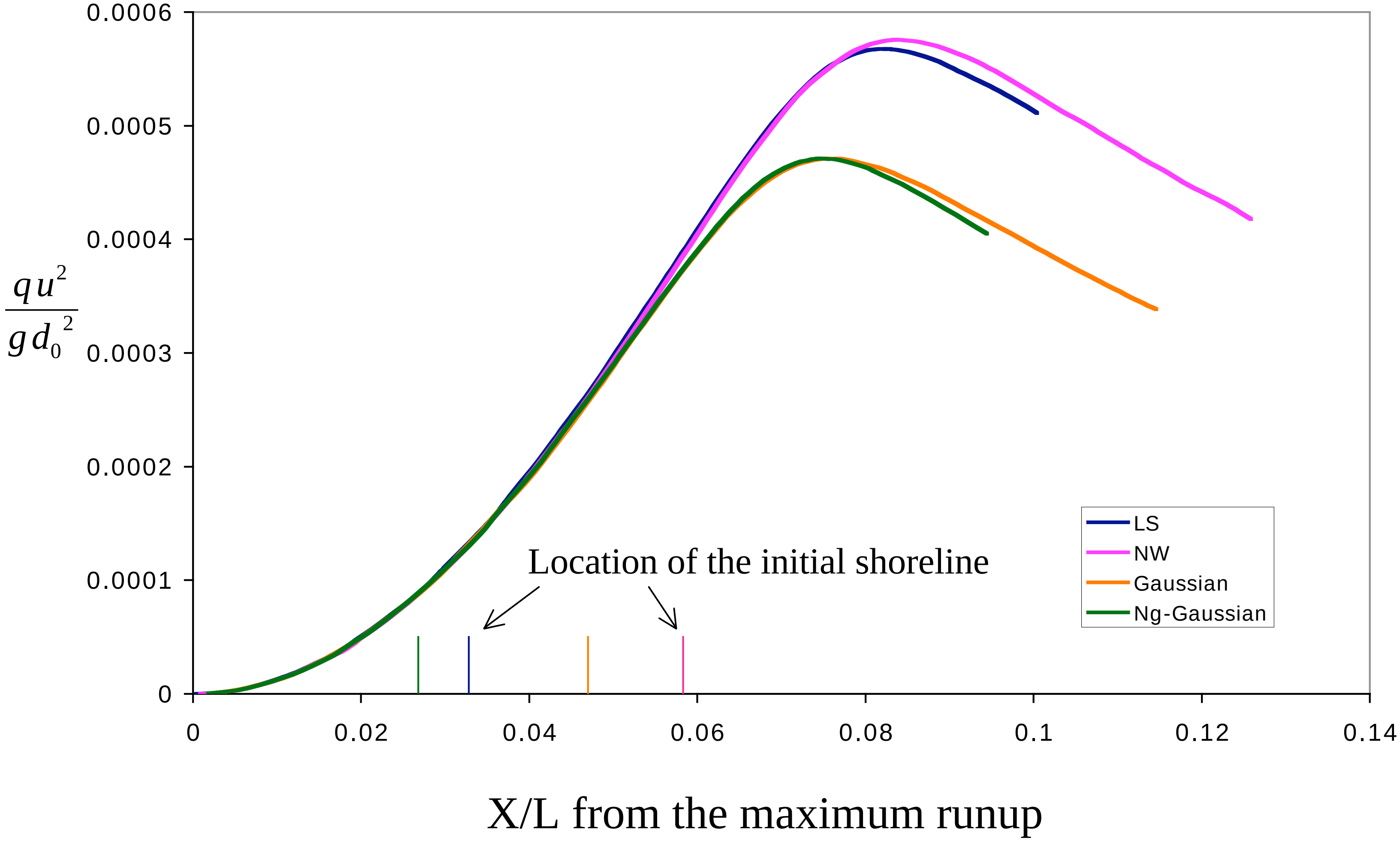




Fluid Forces



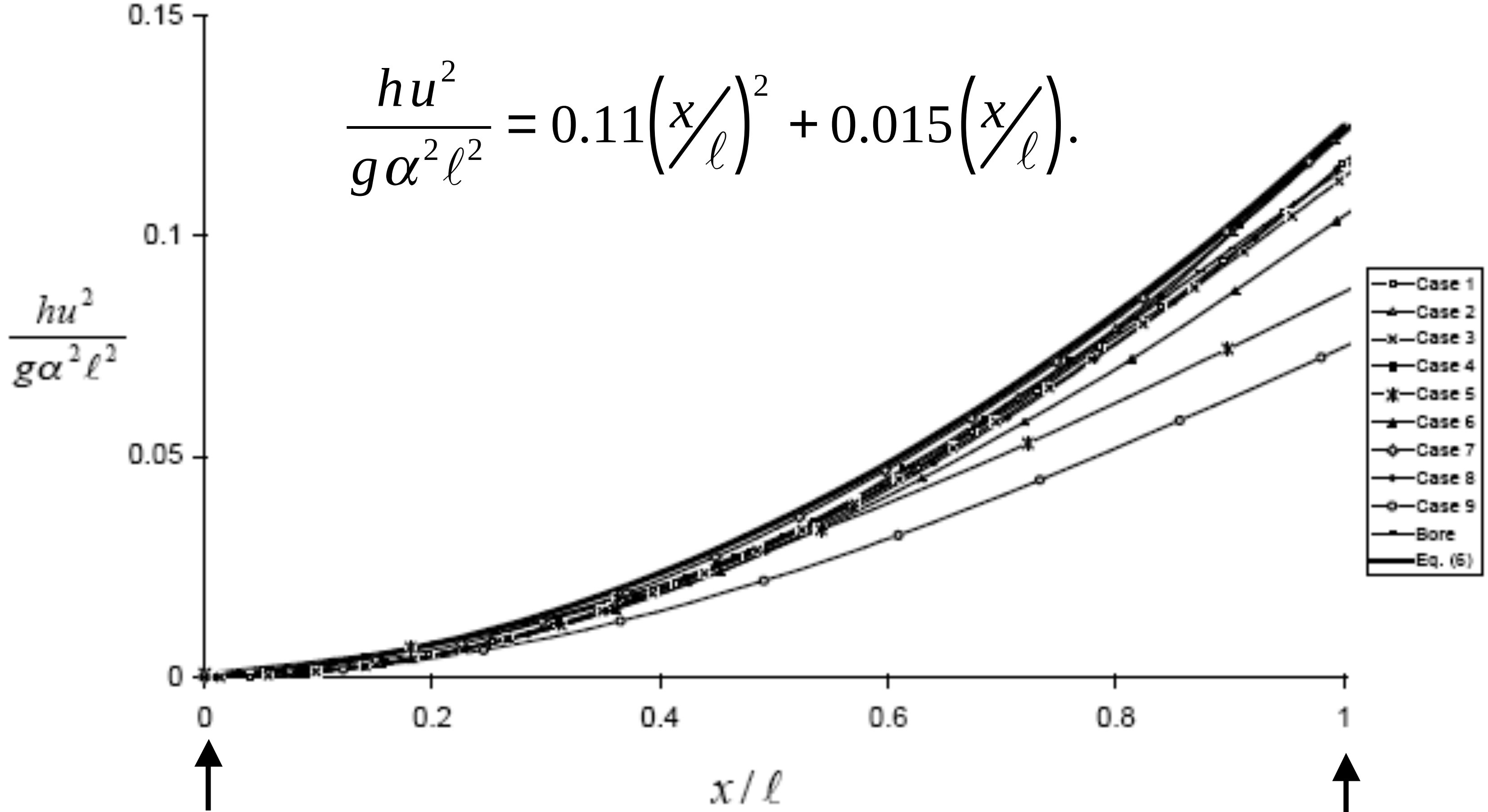
Maximum force distribution from the maximum runup



Maximum hu^2 distribution in the runup zone

(analytic solution for 1-D runup on a uniformly sloping beach)

$$\frac{hu^2}{g\alpha^2\ell^2} = 0.11\left(\frac{x}{\ell}\right)^2 + 0.015\left(\frac{x}{\ell}\right).$$



Max. inundation

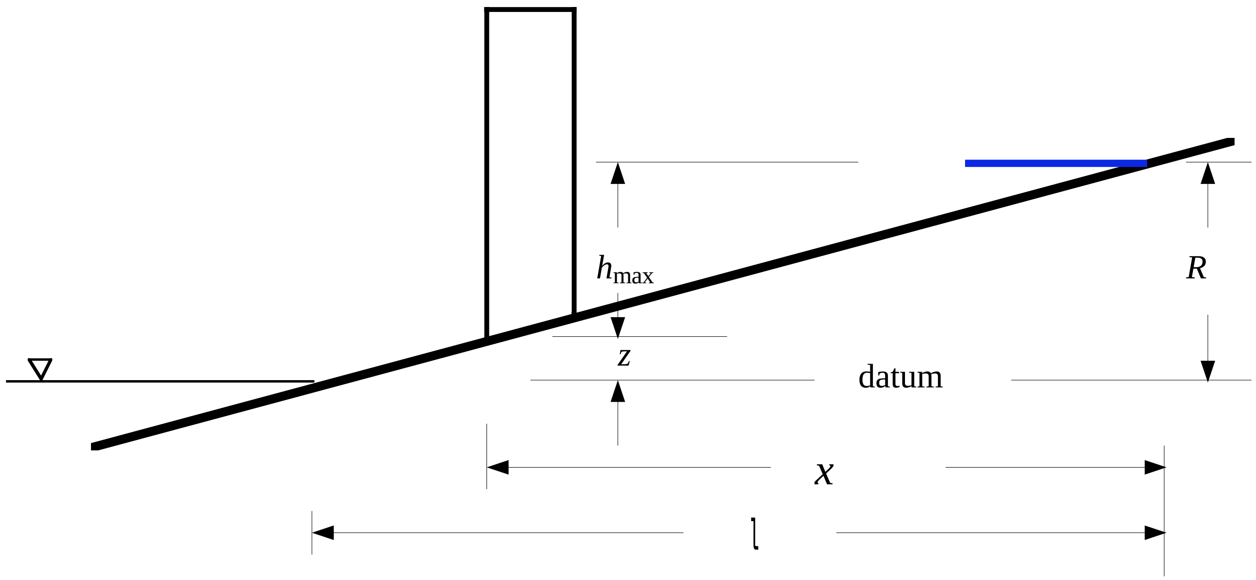
Yeh (2006)

Shore line

Hydrodynamic and Surge Forces

- Hydrodynamic force with C_D = 2.
- Surging force may not be important, but if we consider bore formation, this can be taken into account by using C_D = 3 instead of 2.

$$\boxed{F_D = \frac{1}{2}\rho C_D\, b\, h u^2}$$



$$\frac{hu^2}{g\alpha^2\ell^2} = 0.11\left(x/\ell\right)^2 + 0.015\left(x/\ell\right)$$ based on the distance

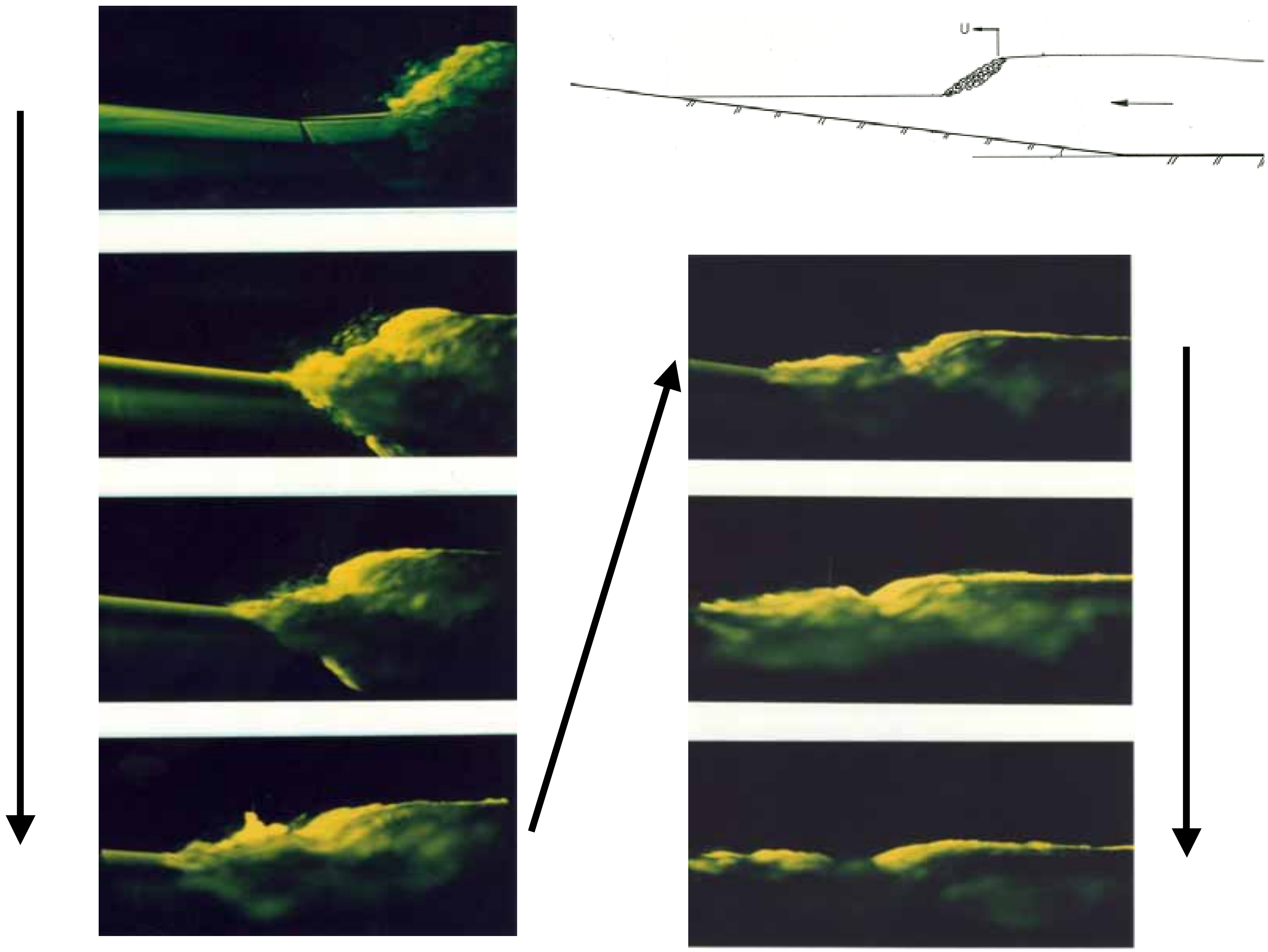
$$\boxed{\frac{hu^2}{gR^2} = 0.125 - 0.235\frac{z}{R} + 0.11\left(\frac{z}{R}\right)^2 \quad \text{based on the elevation}}$$

Impact Force – max. u

- Impact force can be evaluated by the "modified" constant stiffness approach with an appropriate value of effective stiffness k, and the added mass coefficient C_M (≈ 2). k = 2.4MN/m was recommended for a lumber.

$$\boxed{F_I = C_M u \sqrt{\hat{k}\, m}}$$

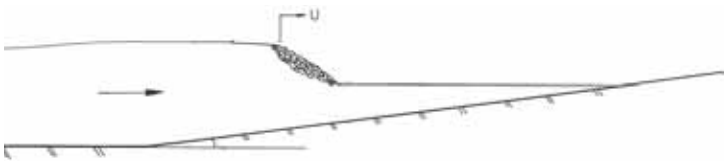
Bore Runup Process



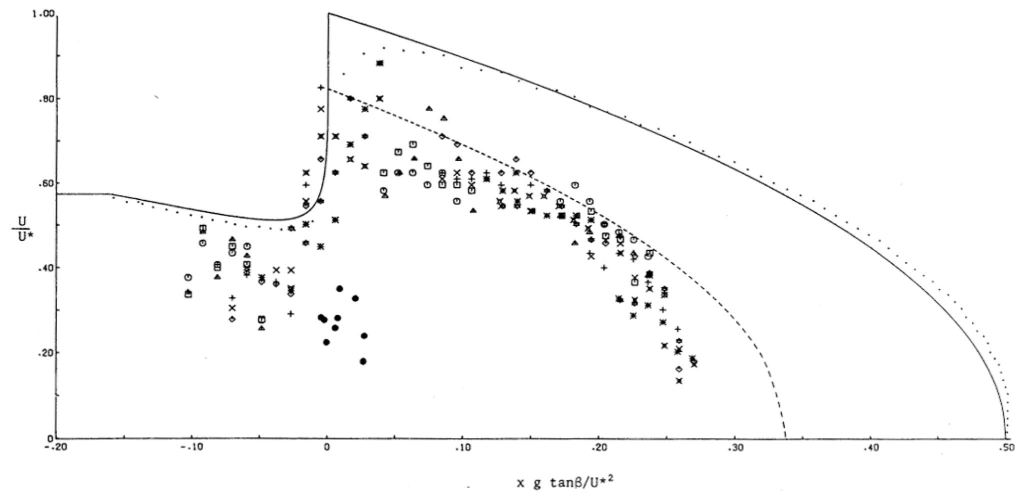
Analytical Solution to Determine u_{max}

Maximum flow-speed *u* distribution in the runup zone:
at the leading tongue of a surge front where the depth *d* = 0.

uniform bore

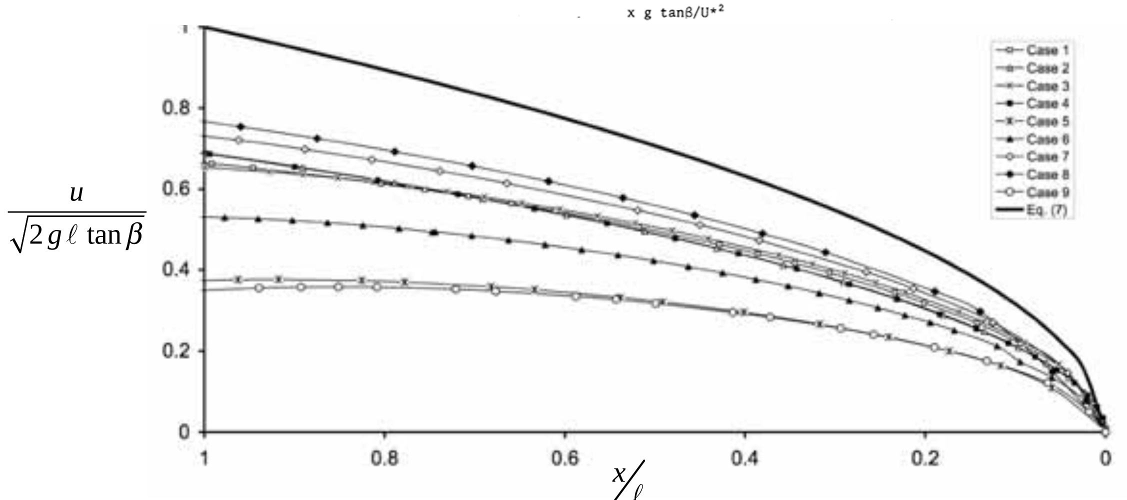


Ho and Meyer (1962)
Yeh et al. (1989)



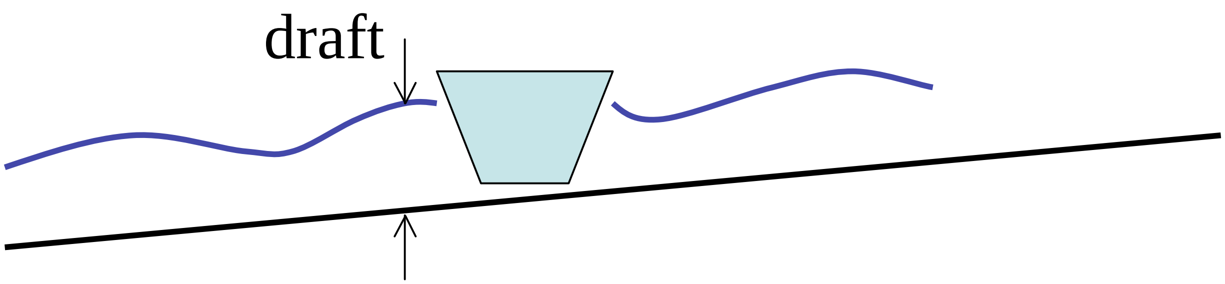
$$u_{\max} = \sqrt{2g\alpha(\ell - x)}$$

$$\boxed{u_{\max} = \sqrt{2gR\left(1 - \frac{z}{R}\right)}}$$



Yeh (2006)

Floating debris with a finite draft



Nagappattinam, India, 2004

Analytical solution to determine u_{max} for a floatable debris with a finite draft

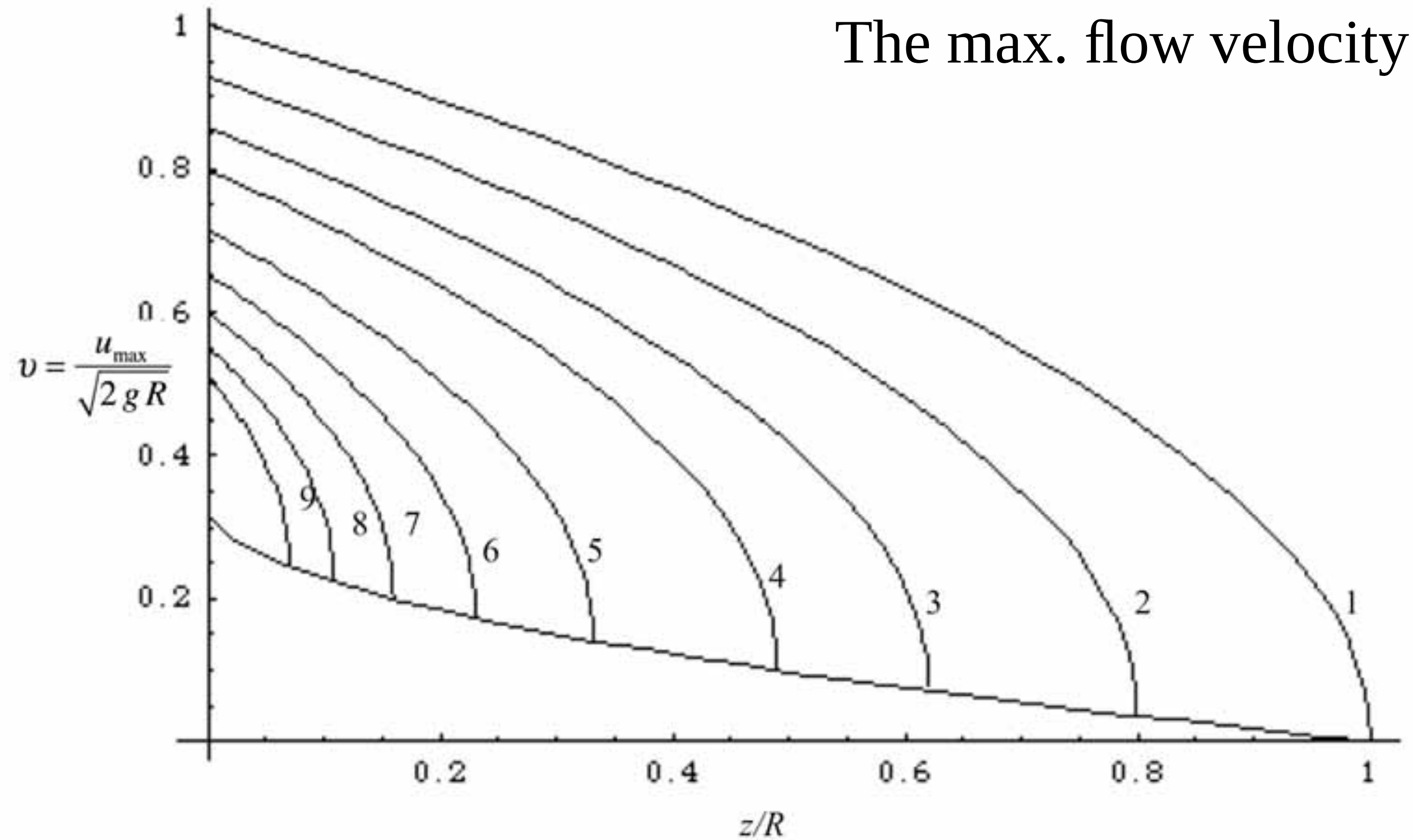
The upper limit of flow-speed *u* for the depth *d*:

d can be the draft of a floating debris.

For bore runup, based on Shen and Meyer (1963), Peregrine and Williams (2001) presented:

$$\begin{cases} \eta = \dfrac{1}{36\tau^2}\left(2\sqrt{2}\,\tau - \tau^2 - 2\zeta\right)^2 \\ \upsilon = \dfrac{1}{3\tau}\left(\tau - \sqrt{2}\,\tau^2 + \sqrt{2}\,\zeta\right) \end{cases}$$

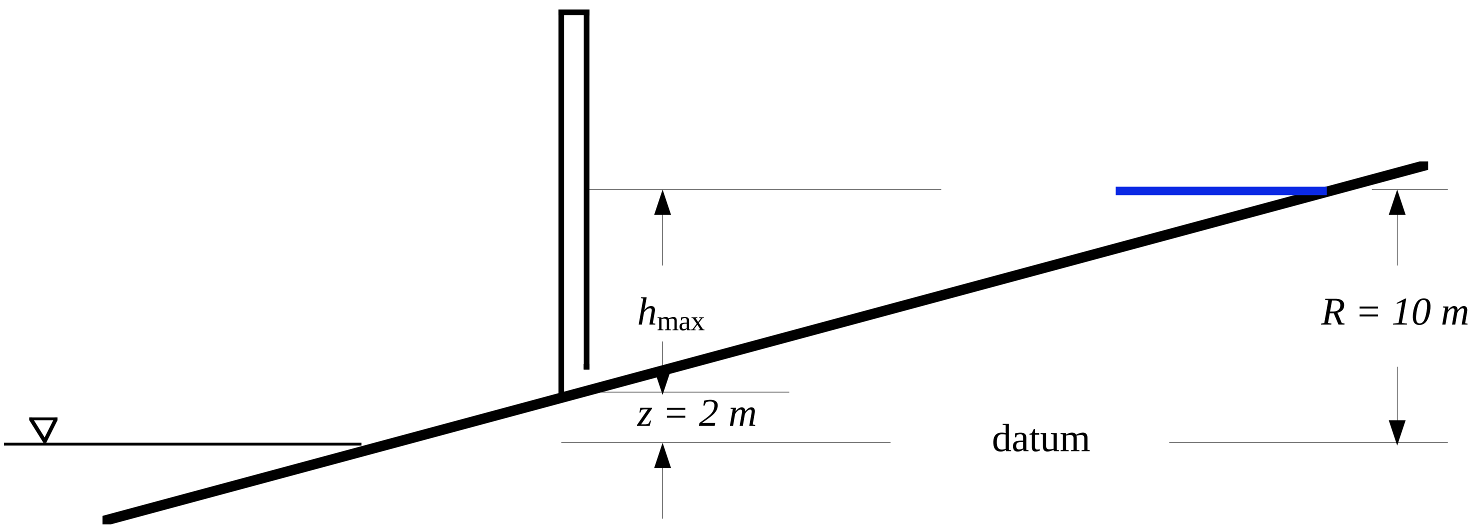
where $\eta = d/R; \quad \upsilon = \dfrac{u}{\sqrt{2gR}}; \quad \tau = t\alpha\sqrt{g/R}; \quad \zeta = z/R$



R = maximum runup elevation.
z = ground elevation
d = flow depth
d/R = (1) 0, (2) 0.0025, (3) 0.01, (4) 0.02, (5) 0.04, (6) 0.06, (7) 0.08, (8) 0.10, and (9) 0.12.

Example

- Maximum runup height $R = 10$ m.
- Beach slope = 1/50 (= 0.02)
- Location of the shelter 100 m from the shoreline ($z = 2$ m), and the shelter breadth $b = 10$ m.
- Drift wood -- mass = 450 kg; effective stiffness $k = 2.4 \times 10^6$ N/m
- Shipping container -- mass = 30,000kg; 12.2m $\times$ 2.44 m $\times$ 2.59m
- $h_{max} = 8$ m
- $\rho = 1025$ kg/m^3 for sea water



Example

- Hydrodynamic and surge forces:

$$\left(h u^2\right)_{\max} = g R^2 \left(0.125 - 0.235 \frac{z}{R} + 0.11\left(\frac{z}{R}\right)^2\right) = 80.8\, m^3/\sec^2$$

$$\begin{aligned} F_d &= \frac{1}{2} \rho\, C_d\, B \left(h u^2\right)_{\max} \\ &= \frac{1}{2}\left(1025\, kg/m^3\right)\left(3.0\right)\left(10\, m\right)\left(80.8\, m^3/\sec^2\right) \\ &= 1240\, kN \end{aligned}$$

- Impact forces (drift wood):

$$u_{\max} = \sqrt{2 g R \left(1 - \frac{z}{R}\right)} = 12.5\, m/\sec.$$

$$\begin{aligned} F_i &= C_m\, u_{\max} \sqrt{k\, m} \\ &= 2.0\left(12.5\, m/\sec\right)\sqrt{\left(2.4\times 10^6\ N/m\right)\left(450\, kg\right)} \\ &= 822\, kN \end{aligned}$$

Example

- Impact force (shipping container):

draft d is: $$d = \frac{W}{\rho A_{box}}$$

$$= \frac{30000\,kg}{\left(1025\,kg/m^3\right)\left(12.2\,m \times 2.44\,m\right)} = 0.98\,m$$

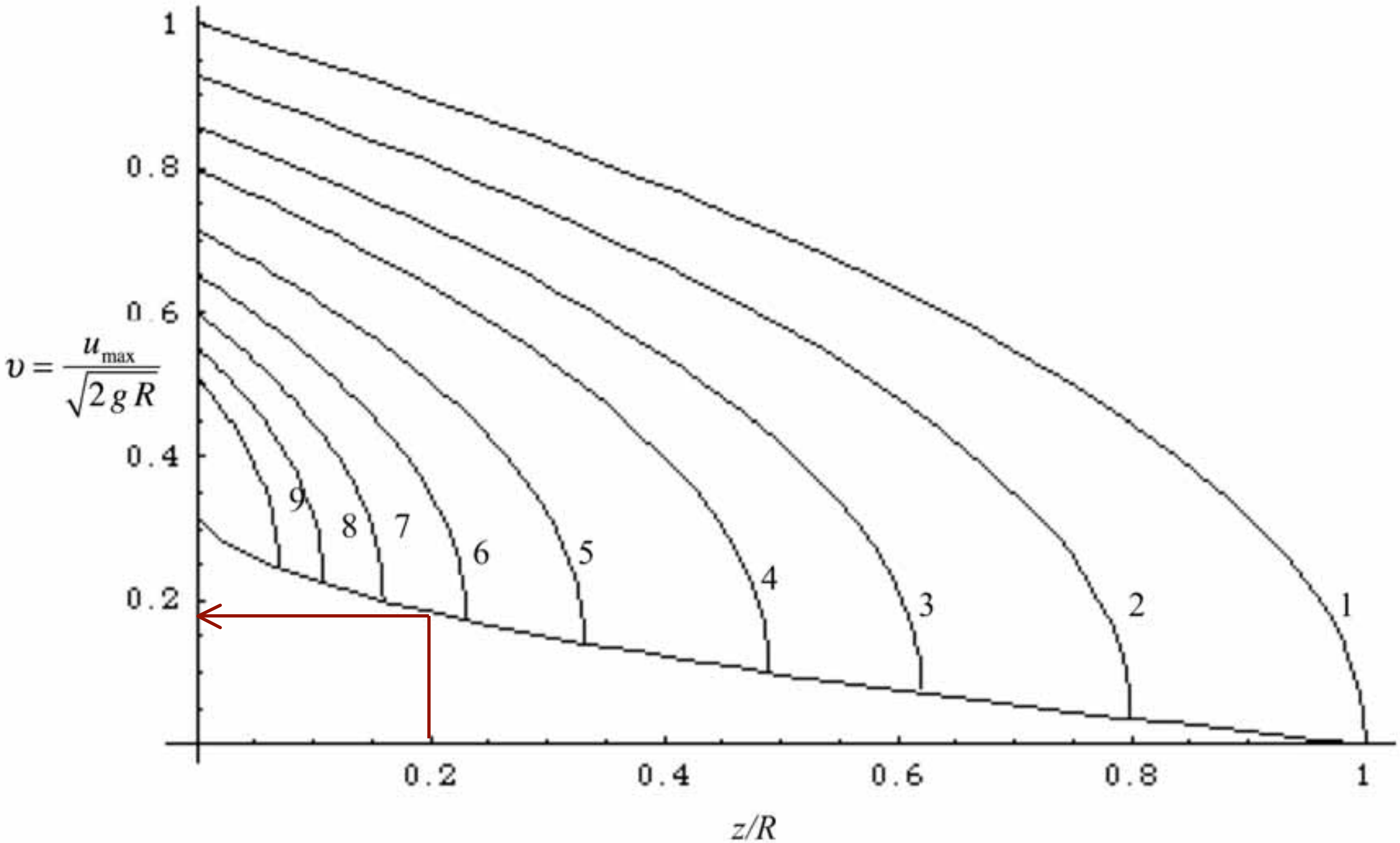
At the location of the shelter site, $\zeta = z/R = 0.2$, and the flow depth, $d/R = 0.098$. The figure shows u_{max} along the limit curve at $\zeta = 0.18$. Hence, the maximum velocity is:

$$u_{\max} = 0.18\sqrt{2\,g\,R} = 2.5\,m/\text{sec}.$$

$$F_i = C_m\, u_{\max}\sqrt{k\,m}$$

$$= 2.0\left(2.5\,m/\text{sec}\right)\sqrt{\left(2.4\times10^6\ N/m\right)\left(30000\,kg\right)}$$

$$= 1340\,kN$$



1) d/R = 0, 2) 0.0025, 3) 0.01, 4) 0.02, 5) 0.04, 6) 0.06, 7) 0.08, 8) 0.10, and 9) 0.12