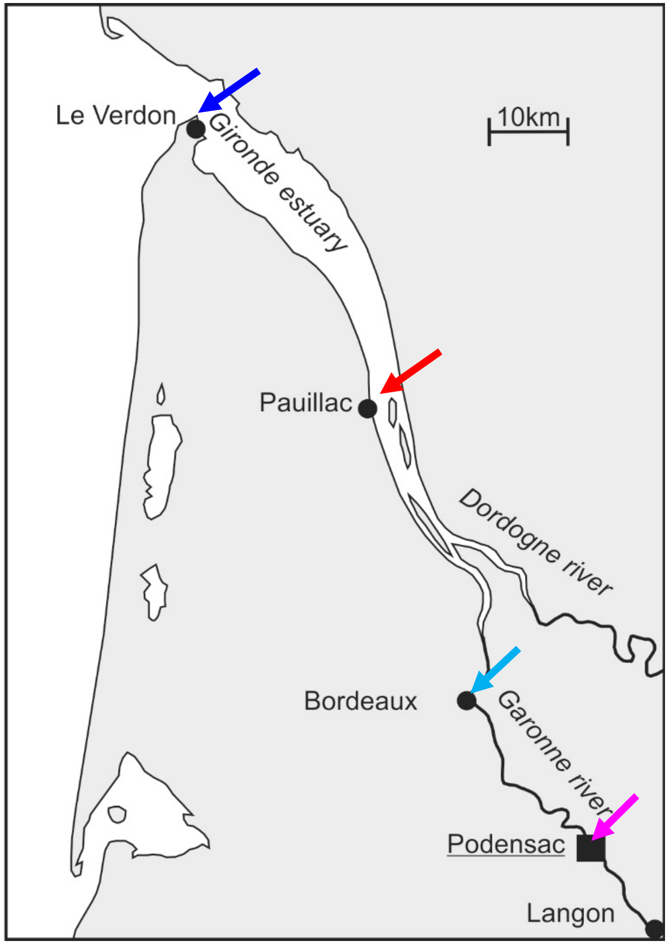
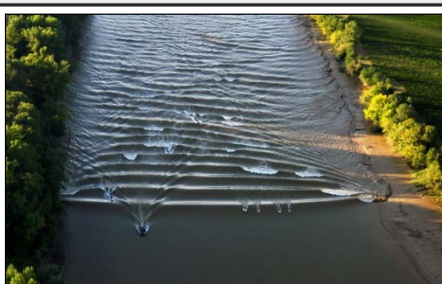
Dynamique des ressauts de marée et mascarets en milieu estuarien

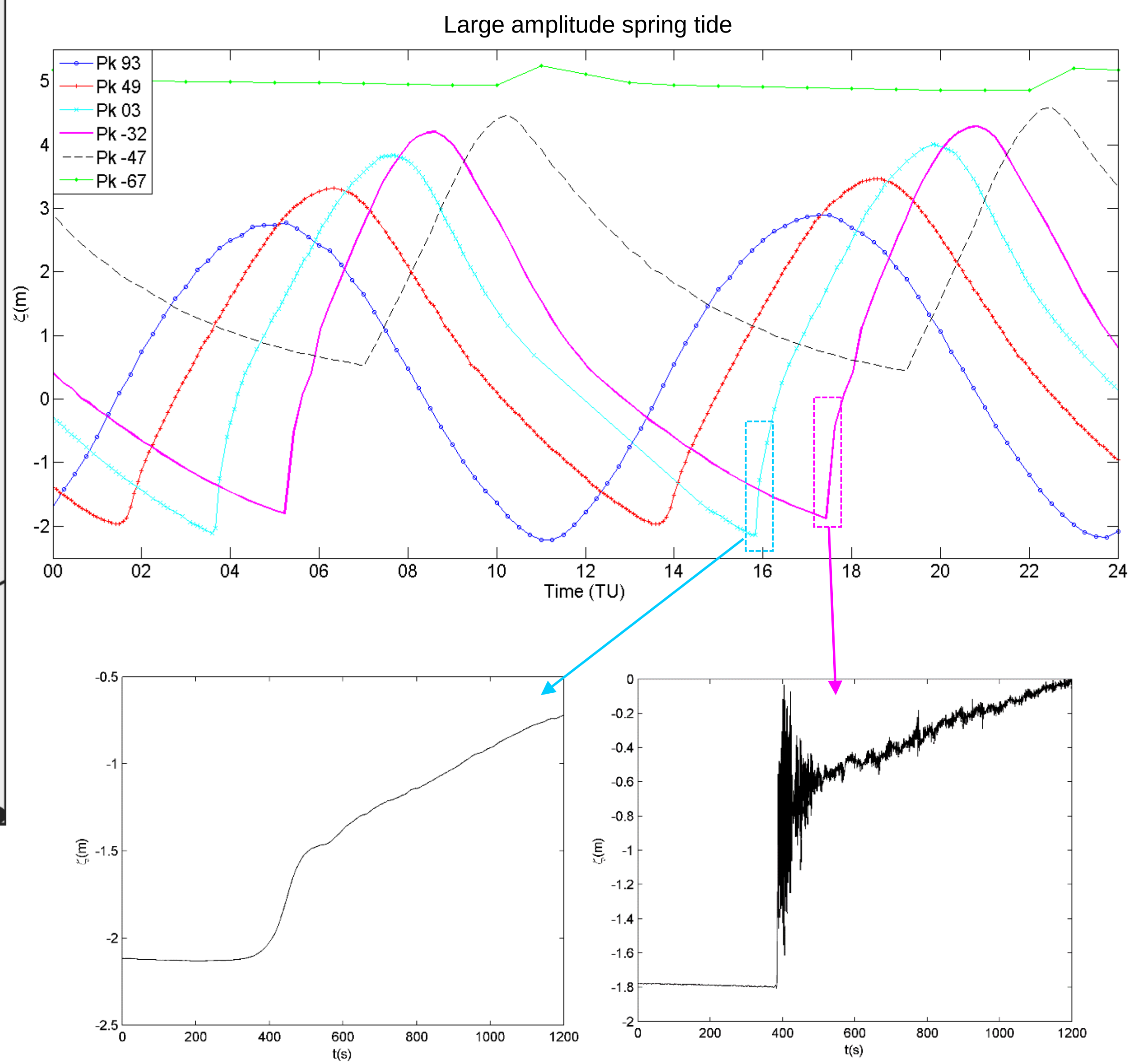
Philippe Bonneton

EPOC, METHYS team, Bordeaux Univ., CNRS

Exemple de ressaut de marée



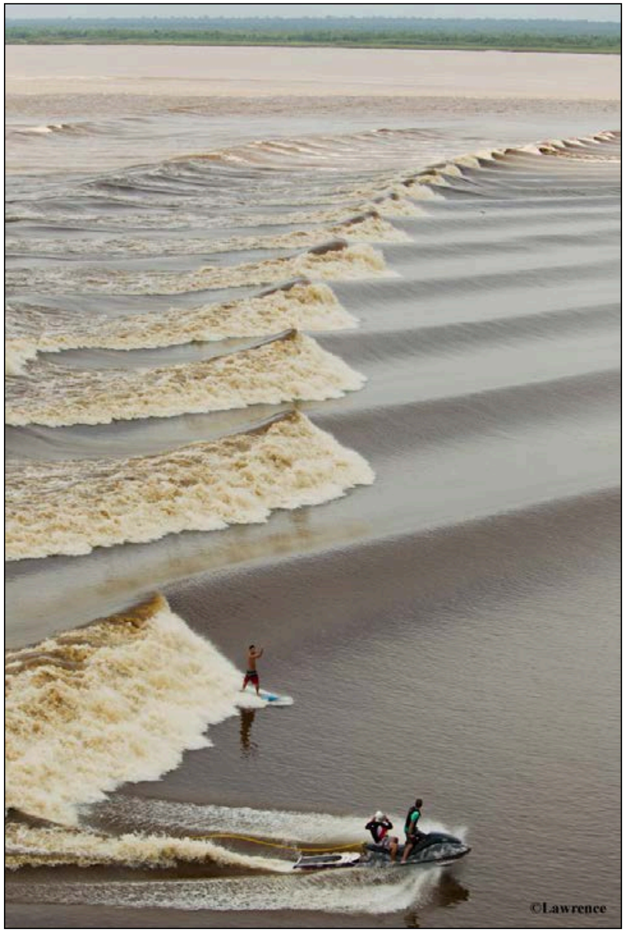




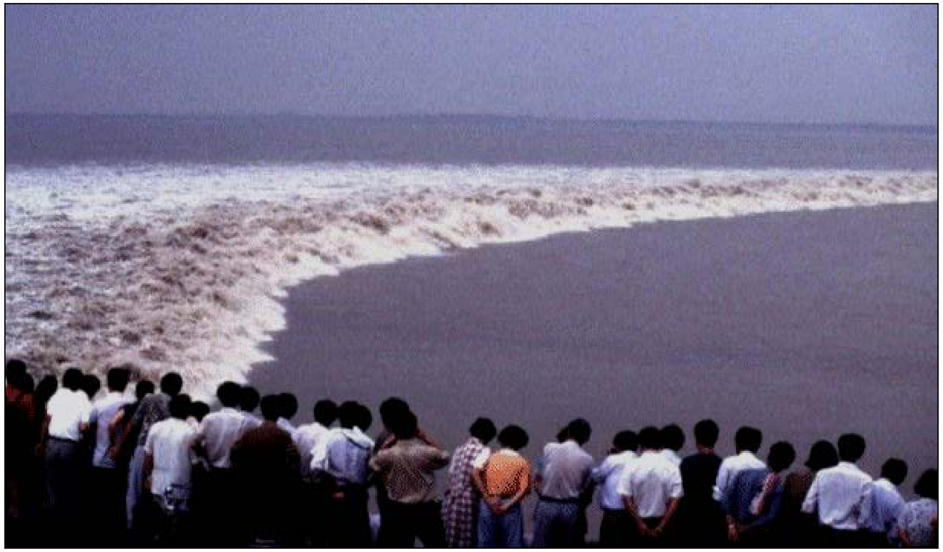
Bonneton et al. JGR 2015

Severn River - England

Amazon River – Brazil (Pororoca)



Kampar River – Sumatra (Bono)



Qiantang River – China

un phénomène intense, mais fragile, qui a disparu dans de nombreux estuaires

Phénomène ondulatoire spectaculaire mal connu

→ observations in situ qualitatives (visuelles)

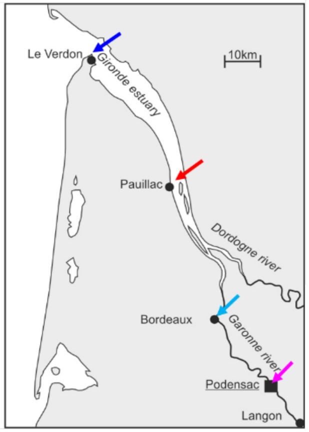
e.g. *Bartsch-Winkler and Lynch 1988, Chanson 2012*

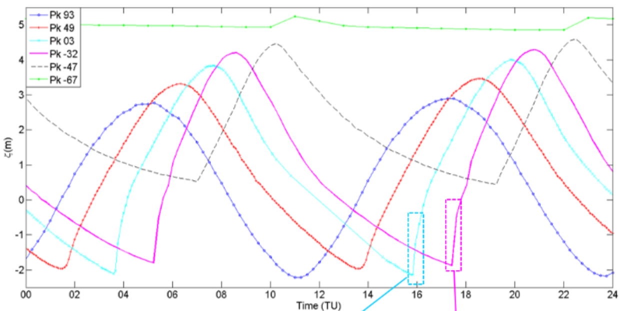
Analyse détaillée de la dynamique des ressauts de marée

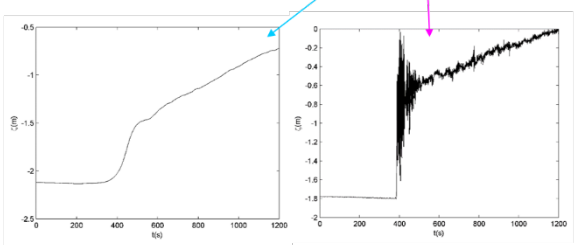
→ campagnes de mesures intensives (Gironde/Garonne et Seine)

→ modélisation numérique (équations de Serre / Green Naghdi)

Travaux sur les ressauts de marée







Grande échelle

Transformation de la marée et mécanisme de formation des RM

- Bonneton, P., Filippini, A.G., Arpaia, L., Bonneton, N. and Ricchiuto, M 2016. Conditions for tidal bore formation in convergent alluvial estuaries. *Estuarine, Coastal and Shelf Science.* **172**, 121-127
- Filippini, A.G., Arpaia, L., Bonneton, P., and Ricchiuto, M. 2018. Modeling analysis of tidal bore formation in convergent estuaries. *Eur. J. Mech. B Fluids*.

Petite échelle

Dynamique haute fréquence des RM

- Bonneton, N., Bonneton, P., Parisot, J-P., Sottolichio, A. and Detandt G. 2012. Tidal bore and Mascaret - example of Garonne and Seine Rivers. *Comptes Rendus Geosciences*, **344**, 508-515.
- Bonneton, P., Bonneton, N., Parisot, J-P. and Castelle, B. 2015. Tidal bore dynamics in funnel-shaped estuaries. *J. Geophys. Res.: Ocean*, **120**(2), 923-941.
- Chassagne R., Filippini A., Ricchiuto M. and Bonneton P. 2018. Dispersive-like bores in channels with sloping banks. In preparation

Exposé

- **field measurements**

→ *Bonneton N., Castelle B., Detandt G., Parisot J-P., Sottolichio A. (EPOC, METHYS team, Bordeaux)*

→ *Frappart F., Roussel N., Darrozes J. (OMP, Toulouse)*

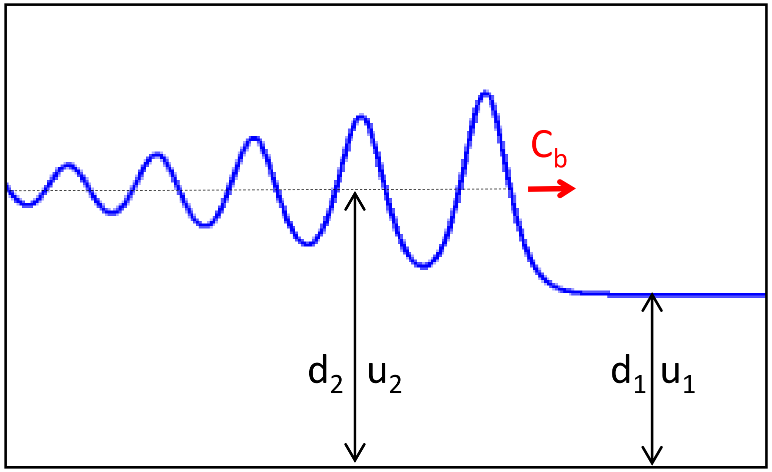
→ *Martins K. (Bath University)*

- **long wave modeling**

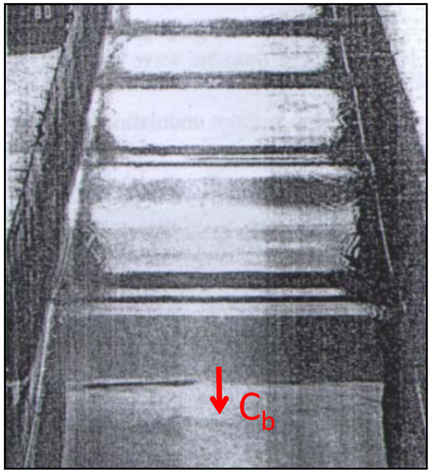
→ *Ricchuito M., Arpaia L., Filippini A. (INRIA, Bordeaux), Chassagne R. (LEGI)*

Plan

Analogie entre les ressauts de marée ondulants et les ondes de Favre

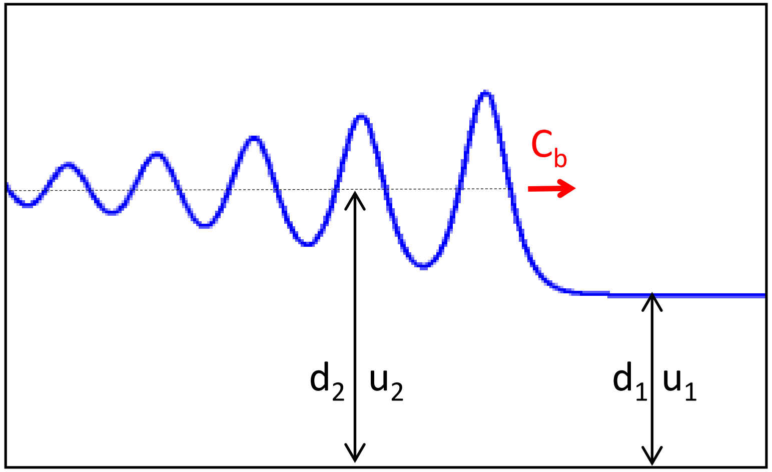


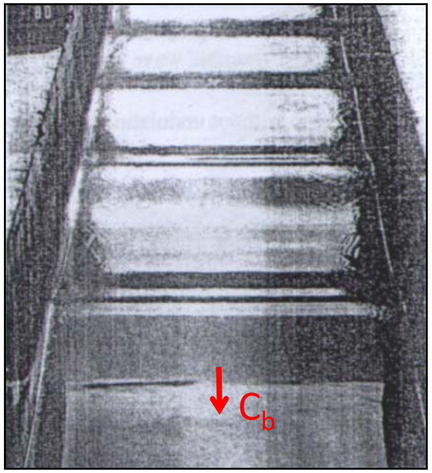
Ressaut en translation ondulant 2D



Expérience de Treske 1994

Ondes de Favre





- **Mathematical and physical theories**:

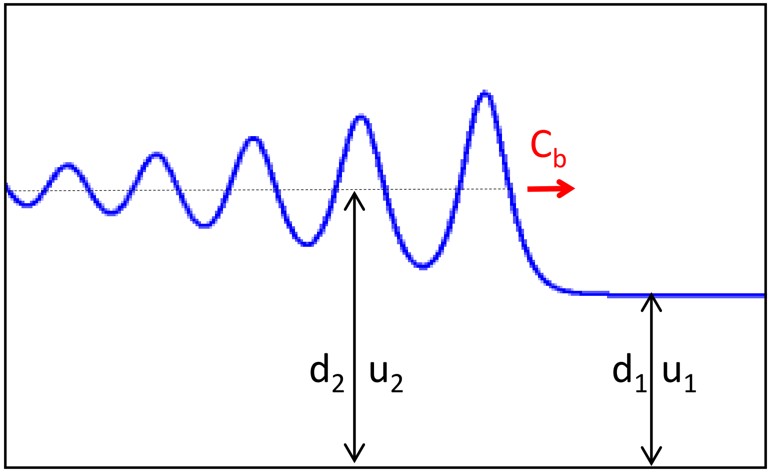
Rayleigh 1914, Lemoine 1948, Serre 1954, Benjamin and Lighthill 1954, Johnson 1970, Gurevich and Pitaevskii 1973, El et al. 2006 and many others …

- **Laboratory experiments**:

Favre 1935, Sandover and Zienkiewics 1957, Bennet & Cunge 1971, Treske 1994, Chanson 1996 & 2009, Soares Frazao and Zech 2002, Simon 2013, Furgerot 2014, David et al. 2014, and many others …

- **Numerical simulations**:

Peregrine 1966, Wei et al. 1995, Soares Frazao and Zech 2002, Lubin et al. 2010, Pan & Lu 2011, Tissier et al. 2011, Simon 2013, Filippini et al. 2018, and many others …



conditions de saut pour le ressaut moyen

$$\boxed{\begin{aligned} c_b - u_1 &= -\left(\frac{gd_2}{2d_1}(d_2+d_1)\right)^{\frac{1}{2}} \\ c_b - u_2 &= -\left(\frac{gd_1}{2d_2}(d_2+d_1)\right)^{\frac{1}{2}} \end{aligned}}$$

$$\boxed{C_\phi + u_2 = C_b}$$

$$C_\phi = \left(\frac{g}{k}\tanh(kd_2)\right)^{1/2}$$

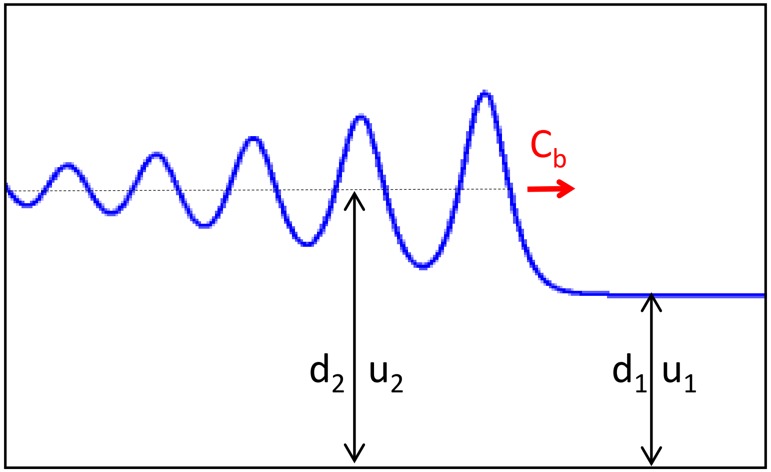
$$\boxed{\frac{\lambda}{d_1} = f(F_r)}$$

$$F_r = \frac{C_b - u_1}{gd_1}$$

$$\frac{\lambda}{d_1} \simeq \frac{\sqrt{2}\pi}{\sqrt{3}}(F_r - 1)^{-1/2}$$

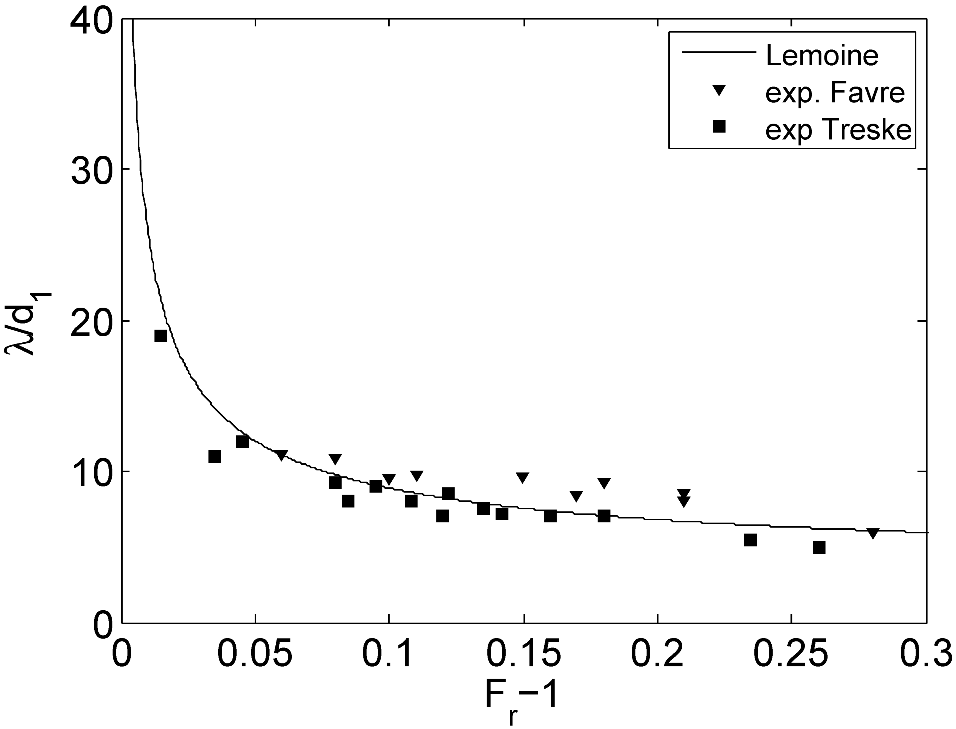
Ondes de Favre

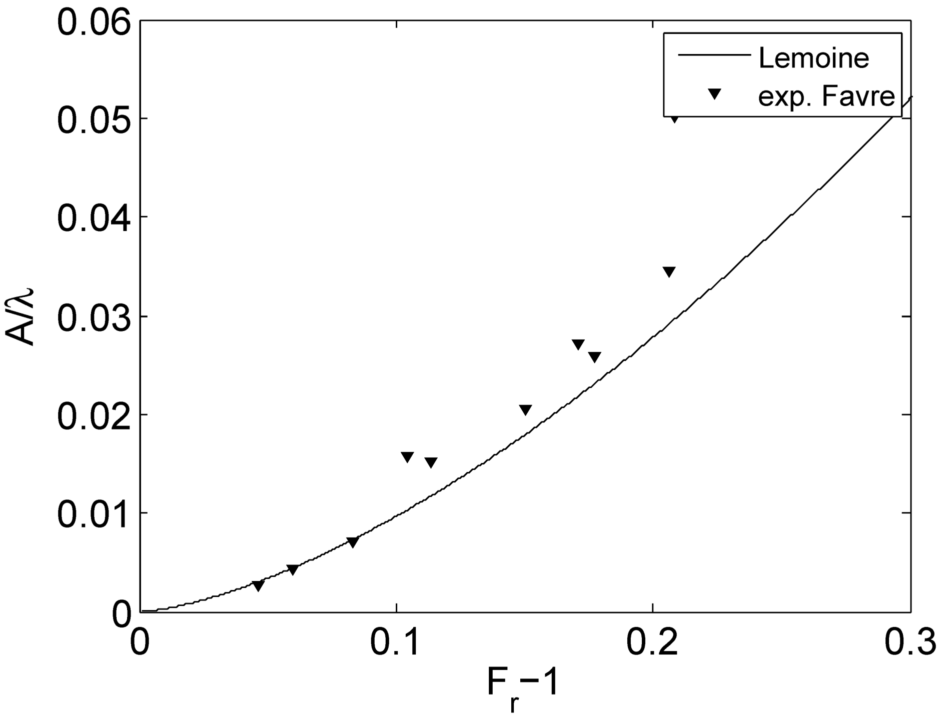
Approche de Lemoine



$$\frac{\lambda}{d_1} \simeq \frac{\sqrt{2}\pi}{\sqrt{3}}(F_r - 1)^{-1/2}$$

$$\frac{A}{\lambda} \simeq \frac{4}{3\sqrt{2}\pi}(F_r - 1)^{3/2}$$





Ondes de Favre : onde 2D $\longrightarrow$ canaux rectangulaires

Ressauts de marée

$\longrightarrow$ **influence très grande de la pente des berges**

Plan

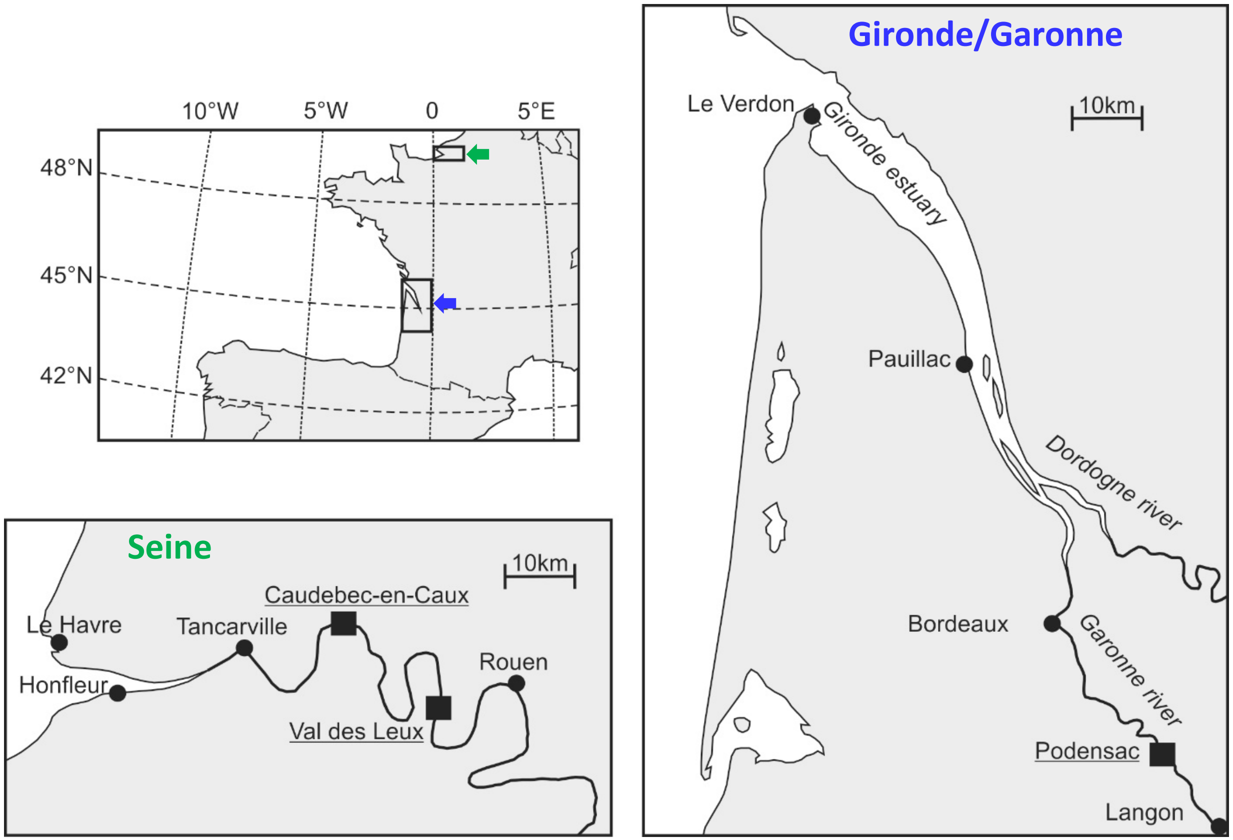
I. Introduction

II. Ondes de Favre

III. Observations in situ

IV. Ressaut de marée de faible cambrure

V. Conclusion and perspectives

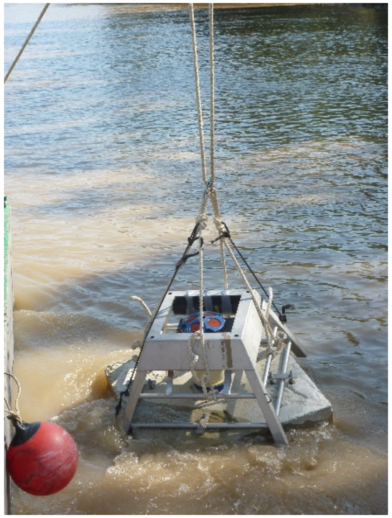


- Plus de 200 marées observées sur le système estuarien Gironde/Garonne

  → très large gamme de marnage et débit fluvial

- Mesures complémentaires sur la Seine

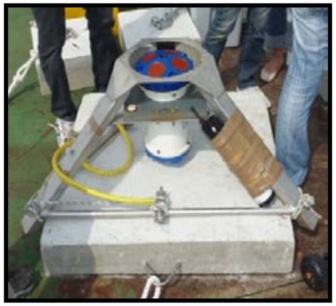
Podensac field site (Gironde/Garonne)

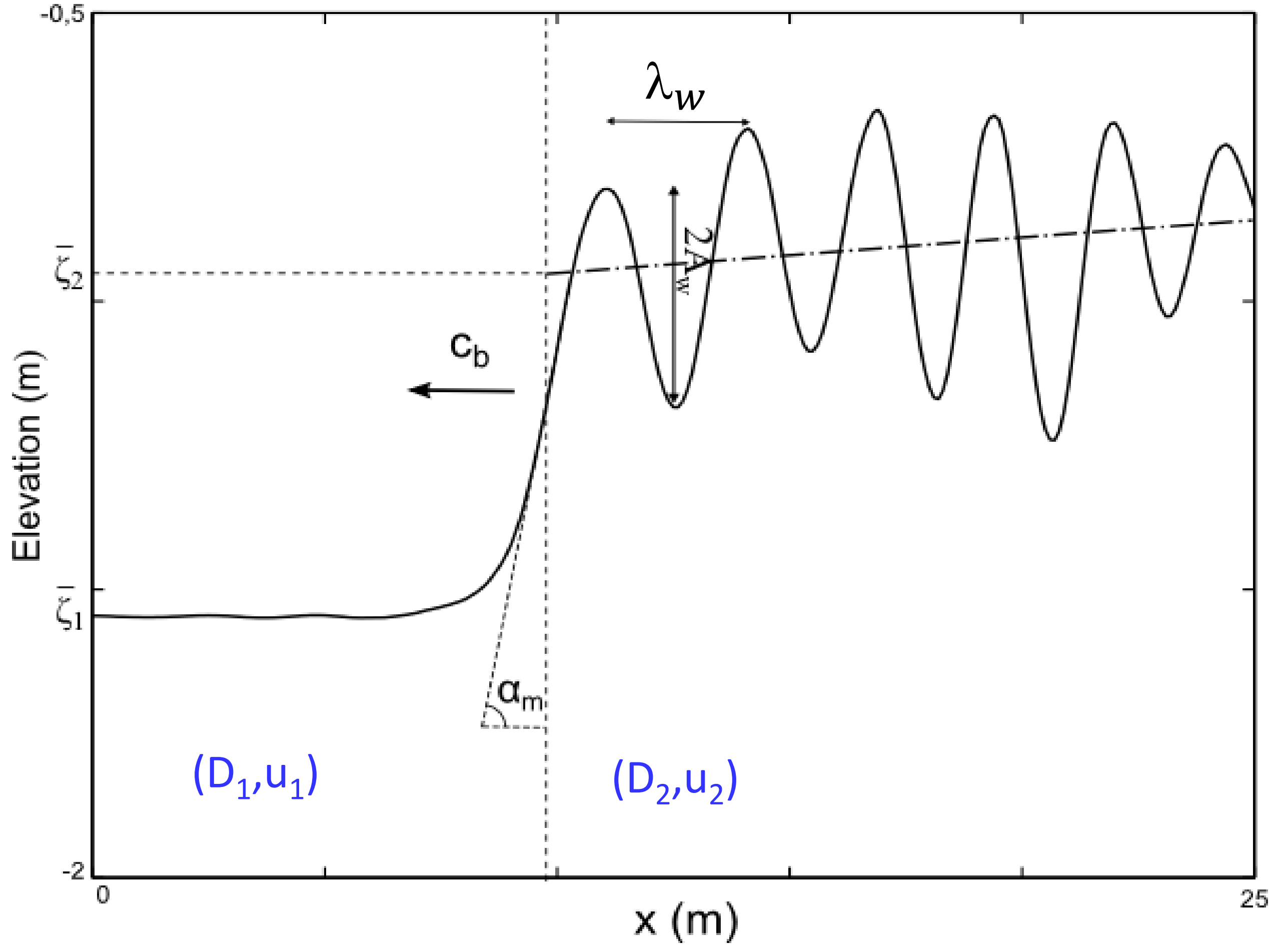


High-frequency measurements

Pressure sensors
(10 Hz)

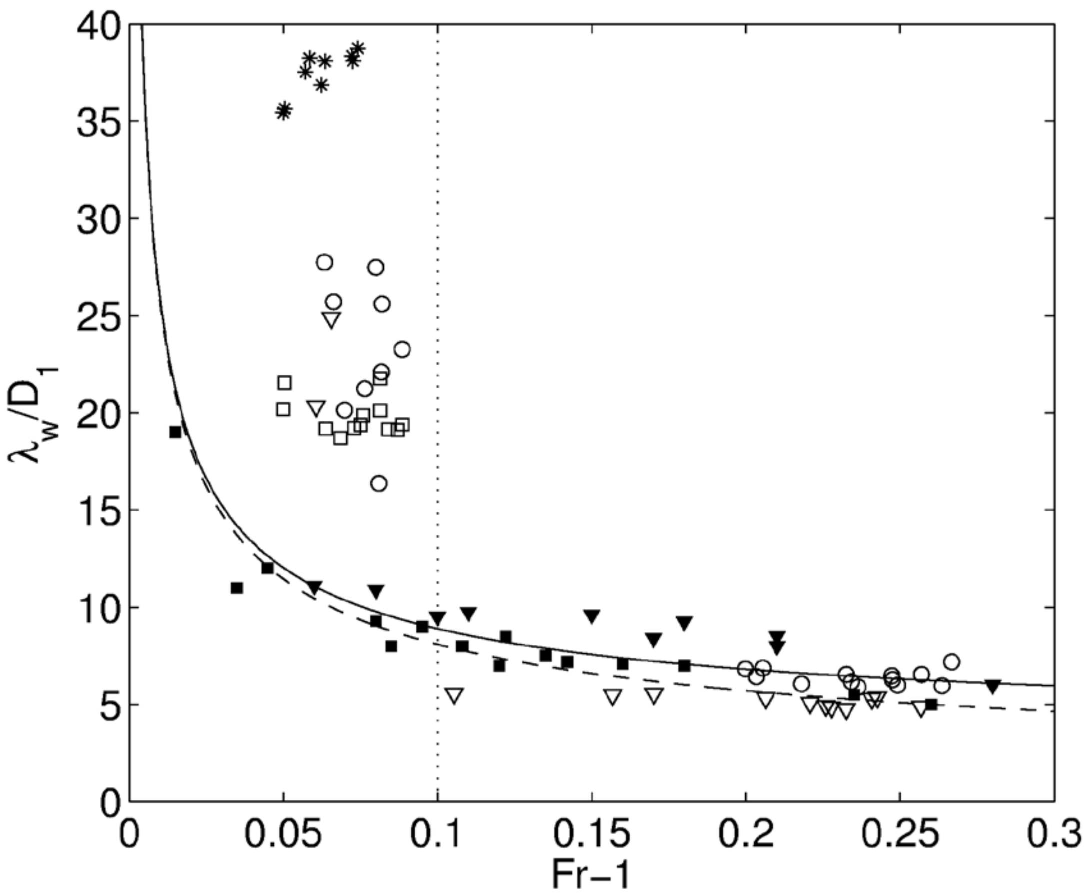
Acoustic Doppler current profilers
(2-8 Hz)

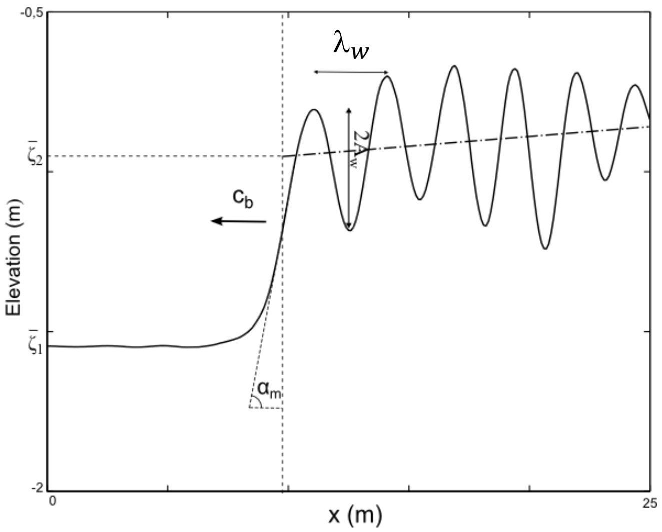




λ_w, A_w, α_m : mesurés dans l'axe de la rivière

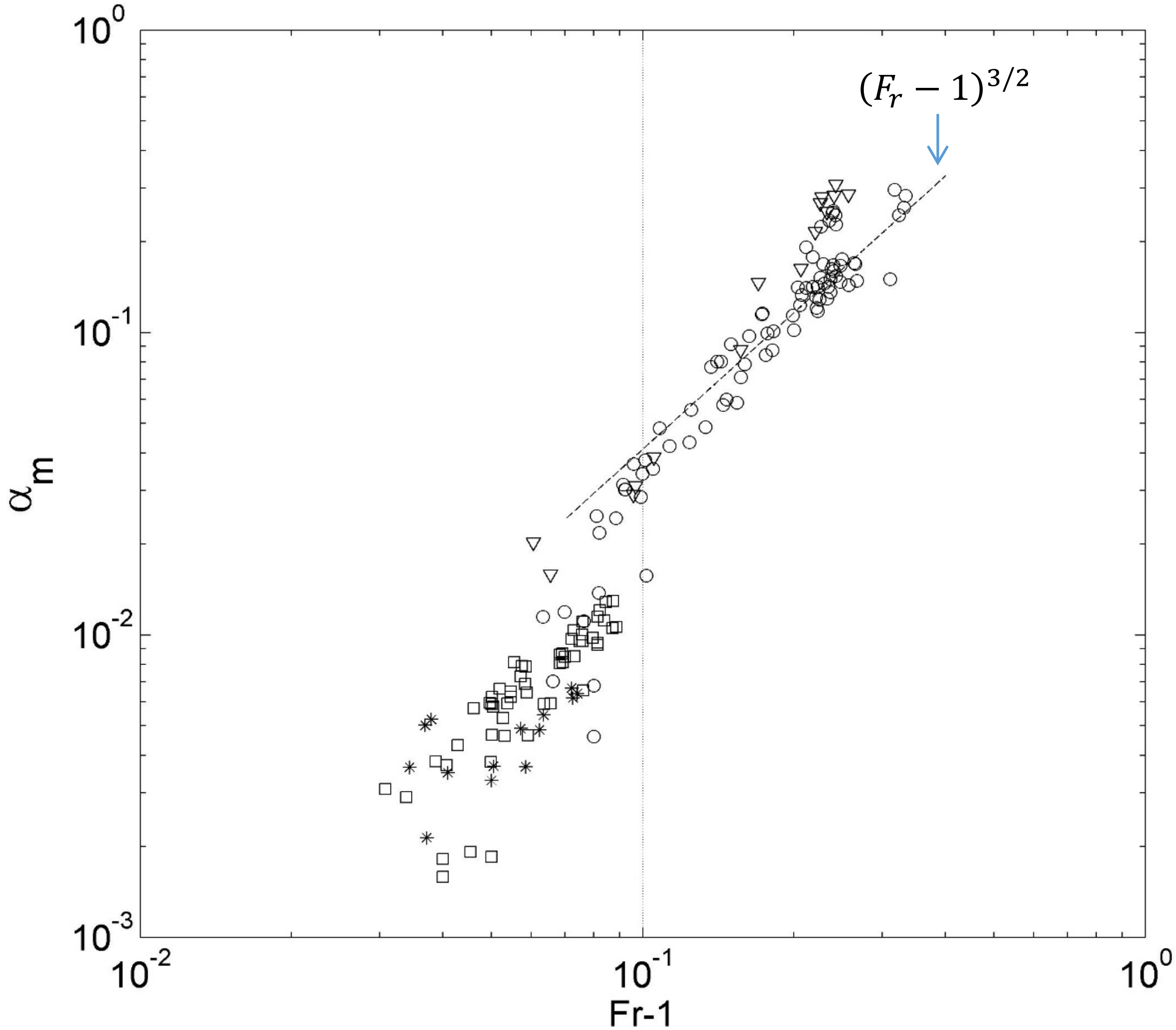
Structure des ondes secondaires



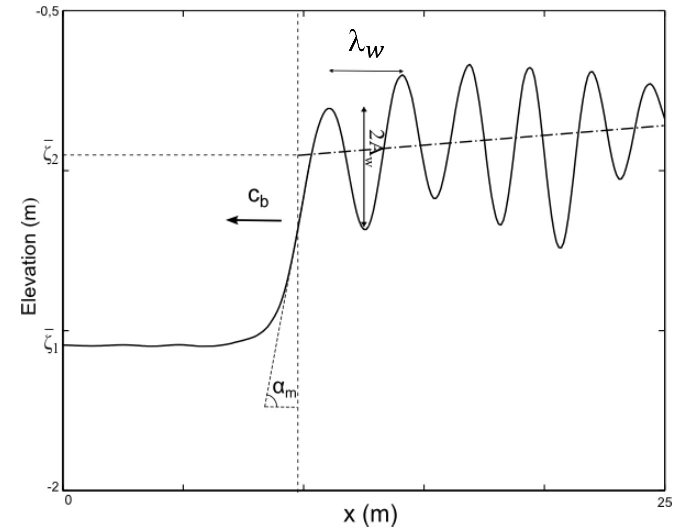


$$\frac{\lambda_w}{D_1} = \frac{\pi}{\sqrt{3}}(F_r - 1)^{-1/2}$$

Transition at Fr=F$_T$ (F$_T$≈1.1)



secondary wave



$\rightarrow$ **Transition at Fr=F$_T$** (F$_T$≈1.1)

Low steepness
secondary wave regime
$\rightarrow$ **not readily visually observable**

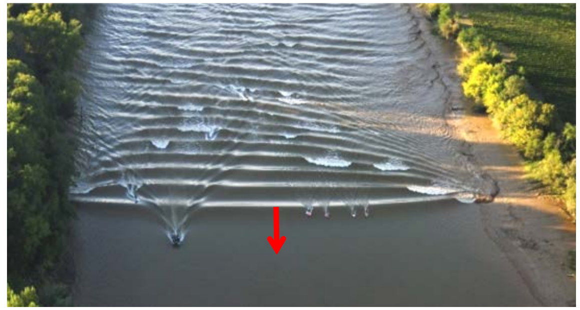
high steepness
secondary wave regime
$\rightarrow$ ***mascaret***

Observations in situ

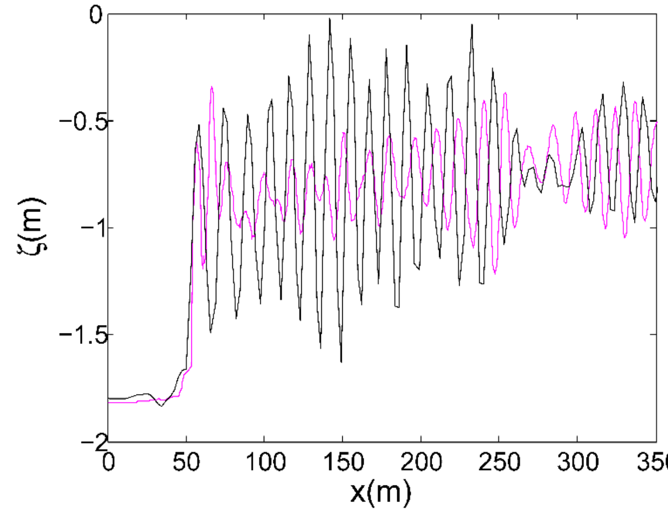
Structure des ondes secondaires

$F_B > F > F_T$

high-steepness regime

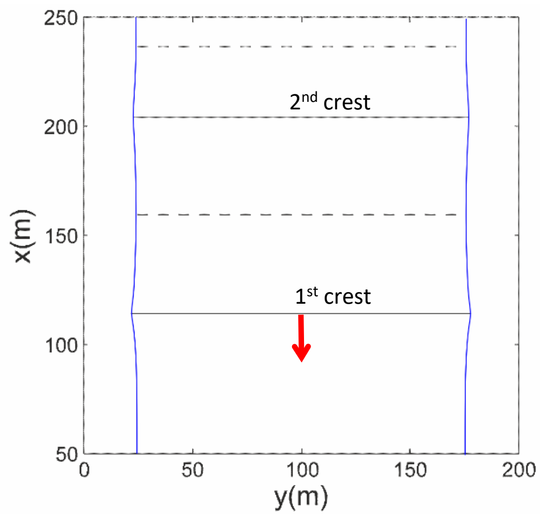


2D phase structure $\phi(x,y)$

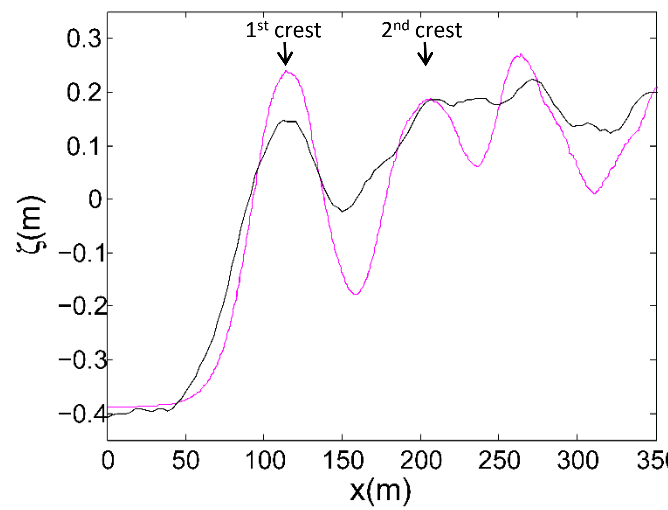


$F_T > F > 1$

low-steepness regime



quasi-1D phase structure $\phi(x)$



Bores on trapezoidal channels

Treske (1994)

$F_B>F>F_T$

high-steepness regime

2D phase structure $\phi(x,y)$

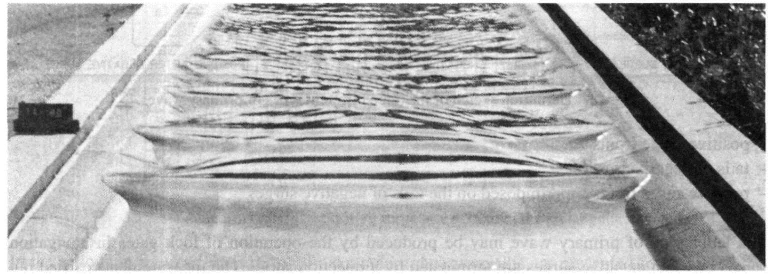


Fig. 11. Undular bore at Froude ~ 1.12.

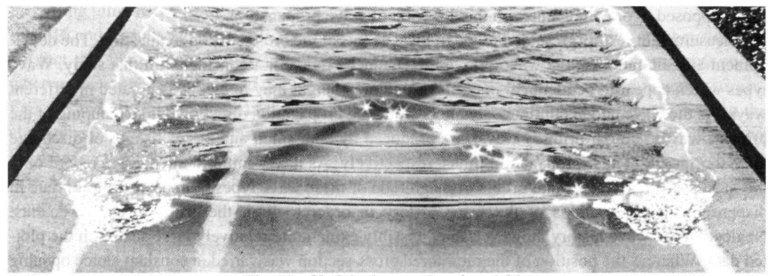


Fig. 12. Undular bore at Froude ~ 1.24.

$F_T>F>1$

low-steepness regime

1D phase structure $\phi(x)$

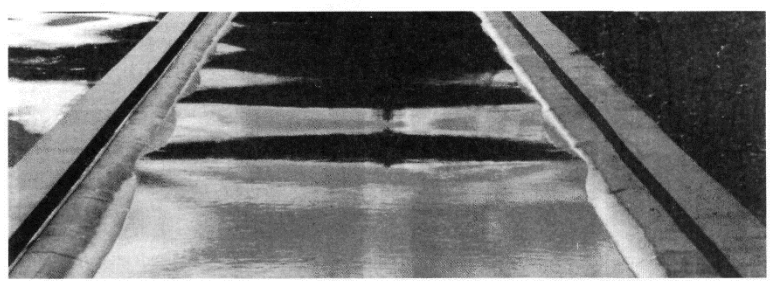


Fig. 9. Undular bore at Froude ~ 1.06.

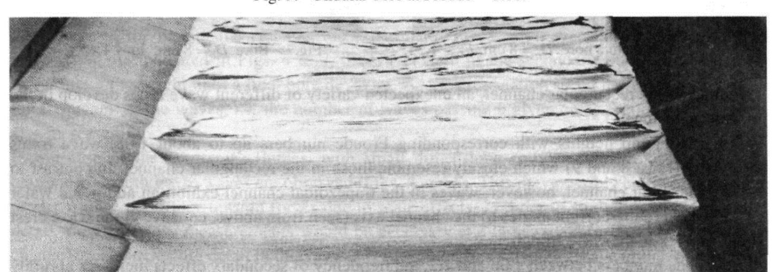


Fig. 10. Undular bore at Froude ~ 1.10.

Plan

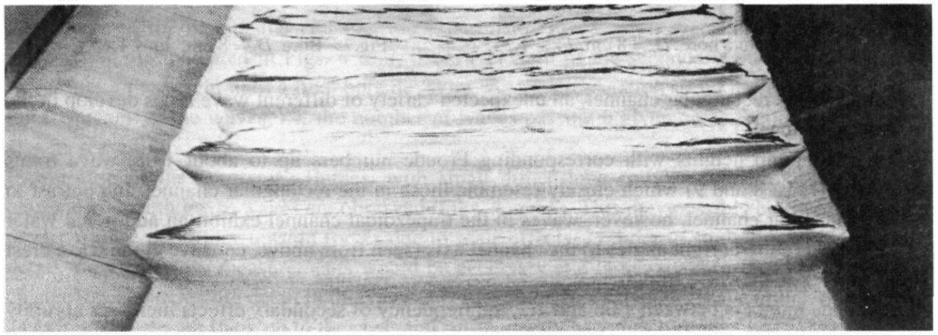
I. Introduction

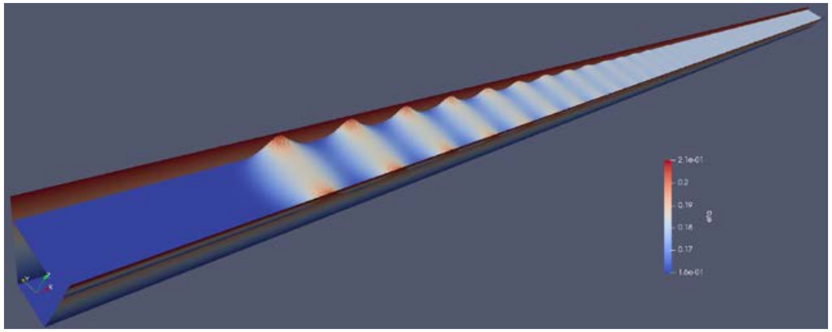
II. Ondes de Favre

III. Observations in situ

IV. Ressaut de marée de faible cambrure

V. Conclusion and perspectives

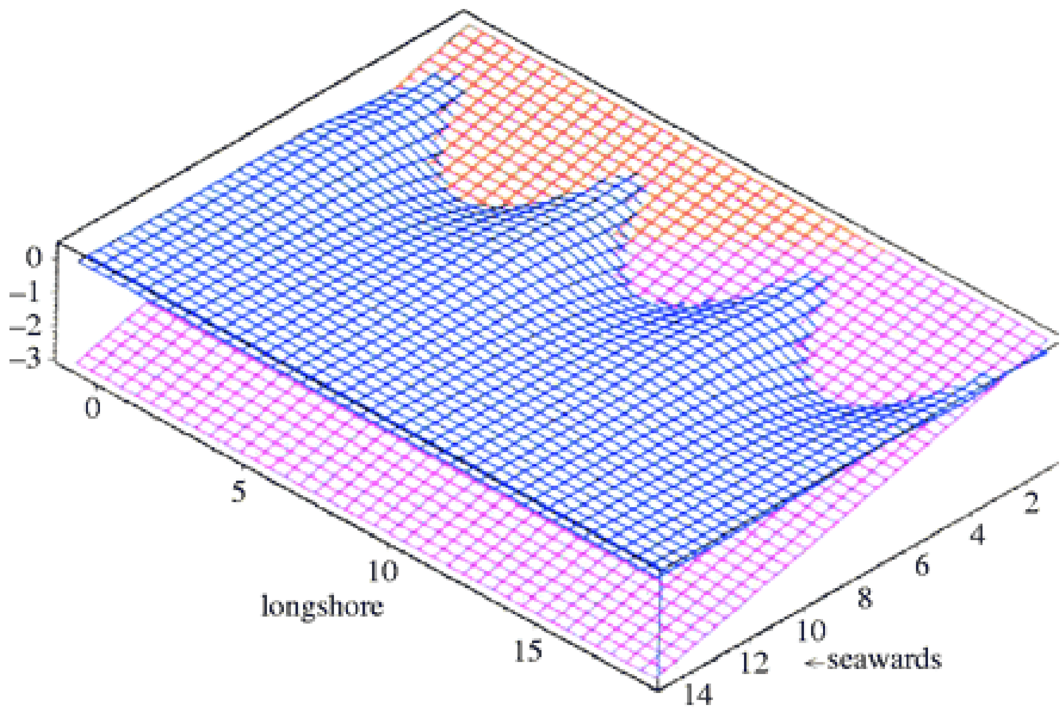




Chassagne R., Filippini A., Ricchiuto M. and Bonneton P. 2018. Dispersive-like bores in channels with sloping banks. In preparation

analogies avec les ondes de coin (edge waves)?

→ ondes longues (infragravitaires, tsunamis, ...) piégées par réfraction



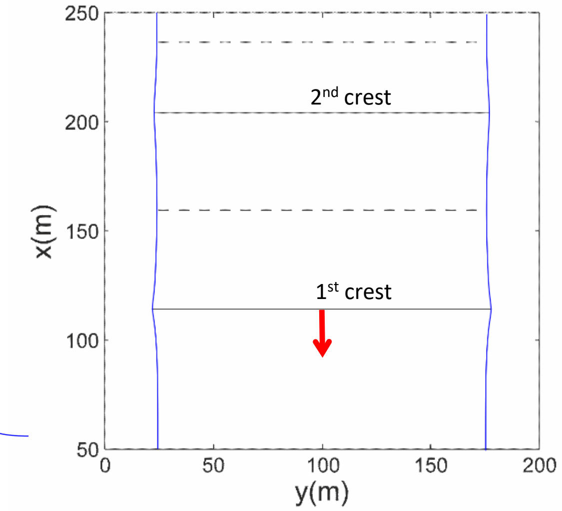
Johnson (2007)

- propagation parallèlement à la plage
- structure de phase 1D
- décroissance de l'amplitude vers le large

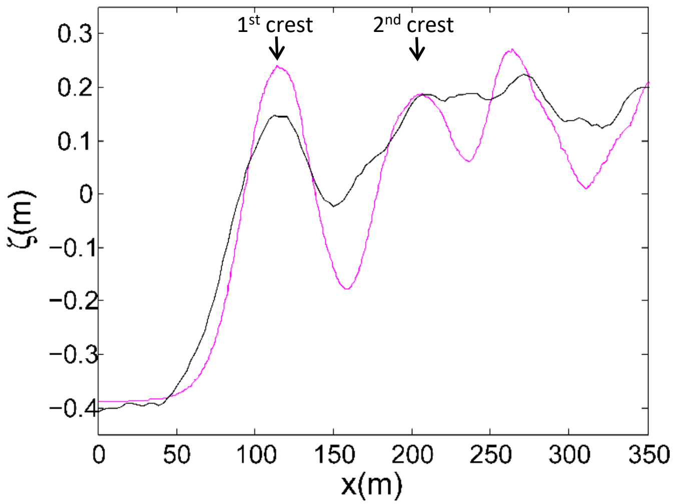
- ondes longues décrites par les équations hyperboliques de Saint Venant 2D
- comportement similaire à des ondes dispersives 1D

$\underline{F_T > F > 1}$

low-steepness regime

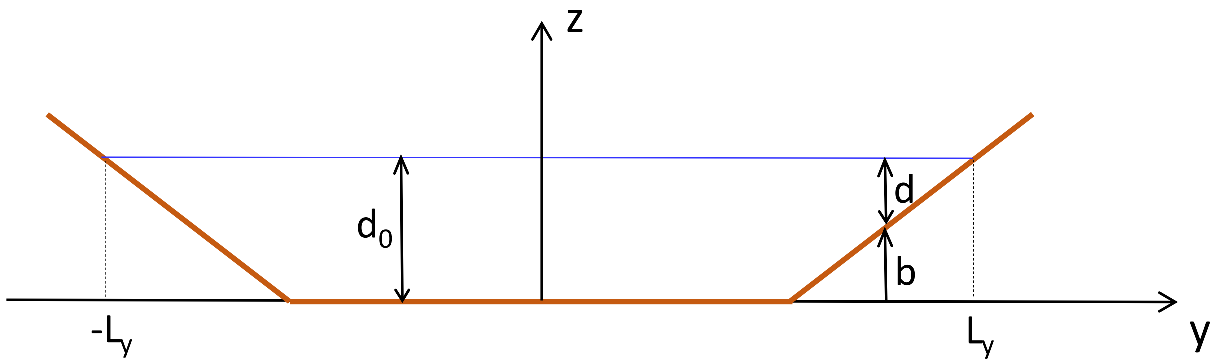


quasi-1D phase structure $\phi(x)$



intégration des équations de SV 2D le long de la section de la rivière

$\rightarrow$ équation d'onde 1D pour $\bar{\zeta}(x,t)$



$d(y)=d_0-b(y)$

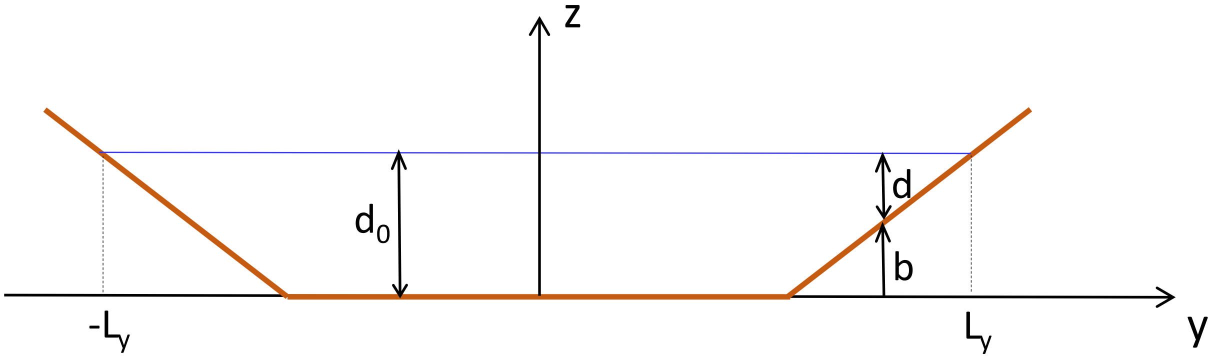
$h(x,y,t)=d(y)+\zeta(x,y,t)$

Equations de Saint Venant linéarisées 2D

$$\begin{aligned}
\frac{\partial \zeta}{\partial t} + d\frac{\partial u}{\partial x} + \frac{\partial dv}{\partial y} &= 0\\
\frac{\partial u}{\partial t} + g\frac{\partial \zeta}{\partial x} &= 0\\
\frac{\partial v}{\partial t} + g\frac{\partial \zeta}{\partial y} &= 0
\end{aligned}$$

$$\boxed{\frac{\partial^2 \zeta}{\partial t^2} - C^2\Delta\zeta - g\frac{\partial d}{\partial y}\frac{\partial \zeta}{\partial y} = 0,}$$

with $C = \sqrt{gd}$.



$d(y)=d_0-b(y)$

$h(x,y,t)=d(y)+\zeta(x,y,t)$

$$\overline{(\cdot)} = \frac{1}{2L_y}\int_{-L_y}^{L_y}(\cdot)dy$$

$$\frac{\partial^2\bar{\zeta}}{\partial t^2} - \overline{gd\frac{\partial^2\zeta}{\partial x^2}} = 0,$$

$$\boxed{\frac{\partial^2\bar{\zeta}}{\partial t^2} - C_m^2\frac{\partial^2\bar{\zeta}}{\partial x^2} - \overline{g(d-\bar{d})\frac{\partial^2\zeta}{\partial x^2}} = 0,}$$

with $C_m = \sqrt{g\bar{d}}$.

adimensionnement des équations

$$x' = \frac{x}{L_x}, \quad y' = \frac{y}{L_y}, \quad d' = \frac{d}{\bar{d}}, \quad \zeta' = \frac{\zeta}{A}$$

$$t' = \frac{t}{L_x/C_m}, \quad u' = \frac{u}{AC_m/\bar{d}}, \quad v' = \frac{v}{AC_m/\bar{d}}$$

$$\begin{aligned}
\delta\frac{\partial\zeta}{\partial t} + \delta d\frac{\partial u}{\partial x} + \frac{\partial dv}{\partial y} &= 0\\
\frac{\partial u}{\partial t} + \frac{\partial\zeta}{\partial x} &= 0\\
\delta\frac{\partial v}{\partial t} + \frac{\partial\zeta}{\partial y} &= 0
\end{aligned}$$

$$\frac{\partial^2\bar{\zeta}}{\partial t^2} - \overline{d\frac{\partial^2\zeta}{\partial x^2}} = 0$$

$$\boxed{\delta = \frac{L_y}{L_x} \ll 1}$$

$$\zeta = \sum_{i \geq 0} \delta^i \zeta_i$$

Ordre O(1)

$$\boxed{\begin{aligned} \frac{\partial d v_0}{\partial y} &= 0 \\ \frac{\partial u_0}{\partial t} + \frac{\partial \zeta_0}{\partial x} &= 0 \\ \frac{\partial \zeta_0}{\partial y} &= 0 \end{aligned}} \longrightarrow \boxed{\begin{aligned} v_0 &= 0 \\ u_0 &= \bar{u}_0 \\ \zeta_0 &= \bar{\zeta}_0 \end{aligned}}$$

$$\boxed{\frac{\partial^2 \bar{\zeta}_0}{\partial t^2} - \frac{\partial^2 \bar{\zeta}_0}{\partial x^2} = 0}$$

Ordre O(δ)

$$\begin{aligned} \frac{\partial d v_1}{\partial y} &= -\frac{\partial \zeta_0}{\partial t} - d\frac{\partial u_0}{\partial x} \\ \frac{\partial u_1}{\partial t} + \frac{\partial \zeta_1}{\partial x} &= 0 \\ \frac{\partial \zeta_1}{\partial y} &= 0 \end{aligned}$$

$\rightarrow$

$$\begin{aligned} v_1 &= -\frac{y+1}{d}\frac{\partial \bar{\zeta}_0}{\partial t} - \frac{D}{d}\frac{\partial \bar{u}_0}{\partial x} \\ u_1 &= \bar{u}_1 \\ \zeta_1 &= \bar{\zeta}_1 \end{aligned}$$

$$D = \int_{-1}^{y} d(s)ds$$

$$\boxed{\frac{\partial^2 \bar{\zeta}_1}{\partial t^2} - \frac{\partial^2 \bar{\zeta}_1}{\partial x^2} = 0}$$

Ordre O(δ²)

$$\boxed{\begin{aligned} \frac{\partial d v_2}{\partial y} &= -\frac{\partial \zeta_1}{\partial t} - d\frac{\partial u_1}{\partial x} \\ \frac{\partial u_2}{\partial t} + \frac{\partial \zeta_2}{\partial x} &= 0 \\ \frac{\partial \zeta_2}{\partial y} &= -\frac{\partial v_1}{\partial t} \end{aligned}} \longrightarrow \boxed{\zeta_2 = \bar{\zeta}_2 + (K(y) - \bar{K})\frac{\partial^2 \bar{\zeta}_0}{\partial x^2}}$$

$$K = \int_{-1}^{y} \frac{(y + 1 - D)}{d} ds$$

Ordre O(δ²)

$$\boxed{\begin{aligned} \frac{\partial d v_2}{\partial y} &= -\frac{\partial \zeta_1}{\partial t} - d\frac{\partial u_1}{\partial x} \\ \frac{\partial u_2}{\partial t} + \frac{\partial \zeta_2}{\partial x} &= 0 \\ \frac{\partial \zeta_2}{\partial y} &= -\frac{\partial v_1}{\partial t} \end{aligned}}$$

$$\longrightarrow \quad \boxed{\zeta_2 = \bar{\zeta}_2 + (K(y) - \bar{K})\frac{\partial^2 \bar{\zeta}_0}{\partial x^2}}$$

$$K = \int_{-1}^{y} \frac{(y+1-D)}{d}\, ds$$

$$\boxed{\zeta = \zeta_0 + \delta\zeta_1 + \delta^2\zeta_2 = \bar{\zeta} + \delta^2(K(y) - \bar{K})\frac{\partial^2 \bar{\zeta}}{\partial x^2} + O(\delta^3)}$$

$$\boxed{\frac{\partial^2 \bar{\zeta}}{\partial t^2} - \frac{\partial^2 \bar{\zeta}}{\partial x^2} - \delta^2 \chi \frac{\partial^4 \bar{\zeta}}{\partial x^4} = 0}$$

$$\chi = \overline{d(K(y) - \bar{K})}$$

$$\boxed{\frac{\partial^2 \bar{\zeta}}{\partial t^2} - \frac{\partial^2 \bar{\zeta}}{\partial x^2} - \delta^2 \chi \frac{\partial^4 \bar{\zeta}}{\partial x^4} = 0}$$

$$\bar{\zeta} = A \exp(i(kx - \omega t))$$

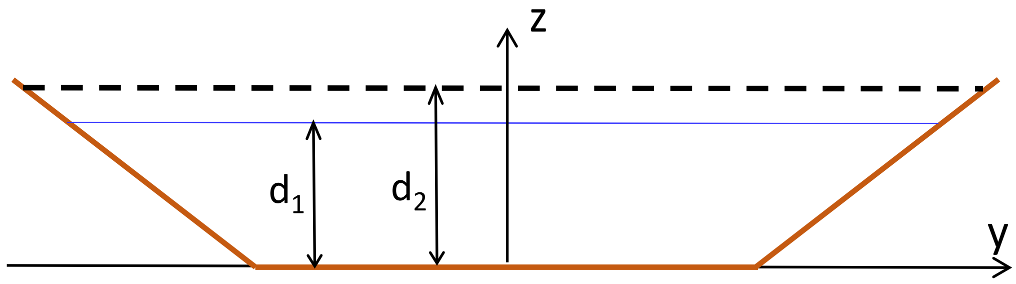
$$C_\phi^2 = \frac{\omega^2}{k^2} = 1 - \delta^2 \chi k^2$$

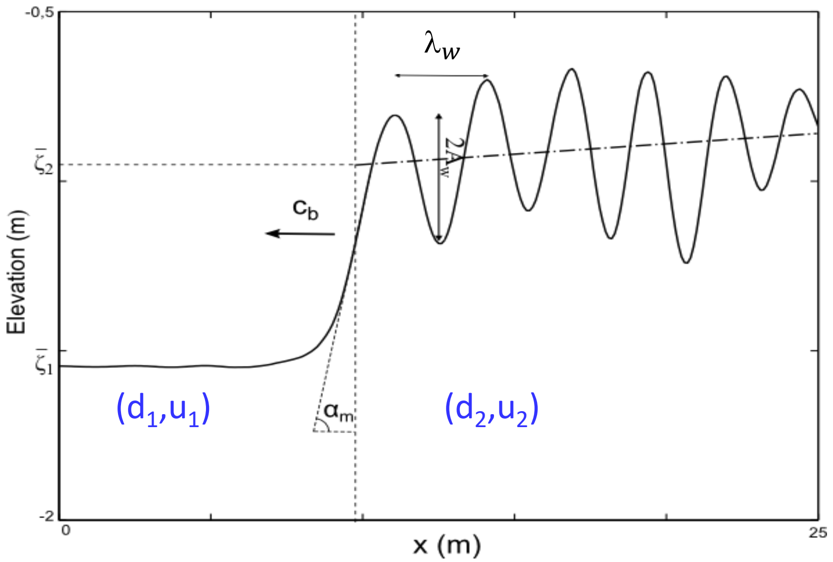
$$\boxed{C_\phi = C_m \left(1 - \chi k^2\right)^{1/2}}$$

$$C_m = \sqrt{g \bar{d}}$$

Ressauts de marée à faible cambrure

Approche « à la Lemoine »





$$\boxed{C_\phi + u_2 = C_b}$$

$$C_\phi = C_m \left(1 - \chi k^2\right)^{1/2}$$

$$\boxed{\lambda = 2\pi\chi^{1/2}\left(1 - \frac{(C_b - u_2)^2}{g\bar{d}_2}\right)^{1/2}}$$

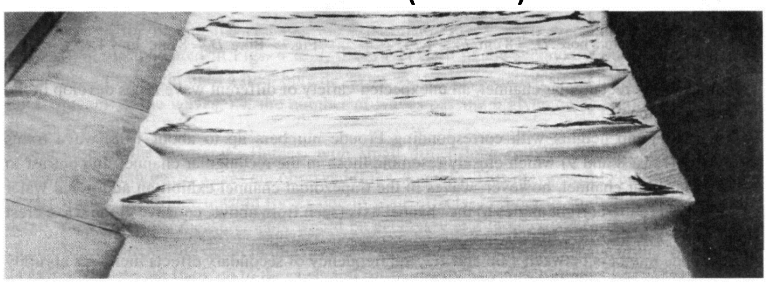
Conditions de saut pour le ressaut moyen

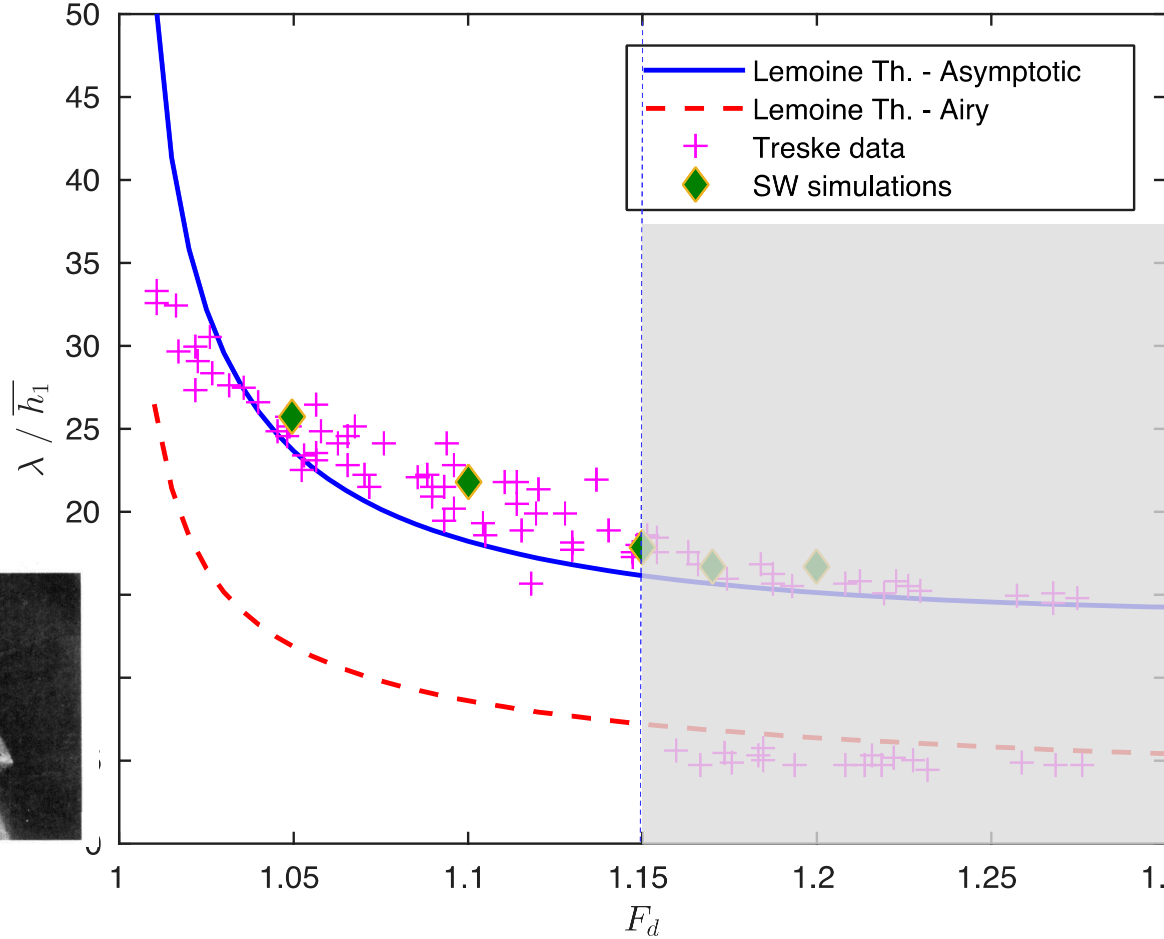
$$\boxed{\begin{aligned} C_b - u_1 &= \sqrt{g\,\frac{\mathcal{A}_2}{\mathcal{A}_1}\,\frac{\mathcal{K}_2 - \mathcal{K}_1}{\mathcal{A}_2 - \mathcal{A}_1}} \\ C_b - u_2 &= \sqrt{g\,\frac{\mathcal{A}_1}{\mathcal{A}_2}\,\frac{\mathcal{K}_2 - \mathcal{K}_1}{\mathcal{A}_2 - \mathcal{A}_1}} \end{aligned}}$$

$$\mathcal{K} = \int \mathcal{A}\,dh$$

Ressauts de marée à faible cambrure | Approche « à la Lemoine »

Treske (1994)



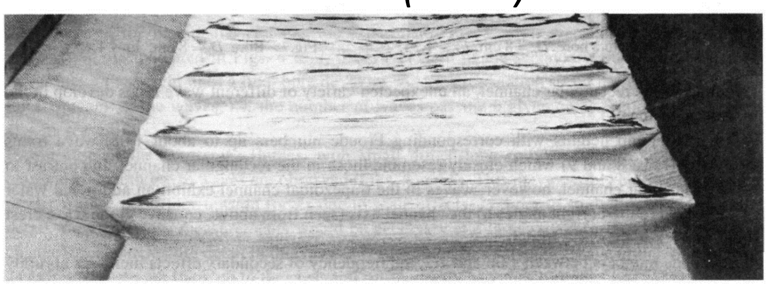


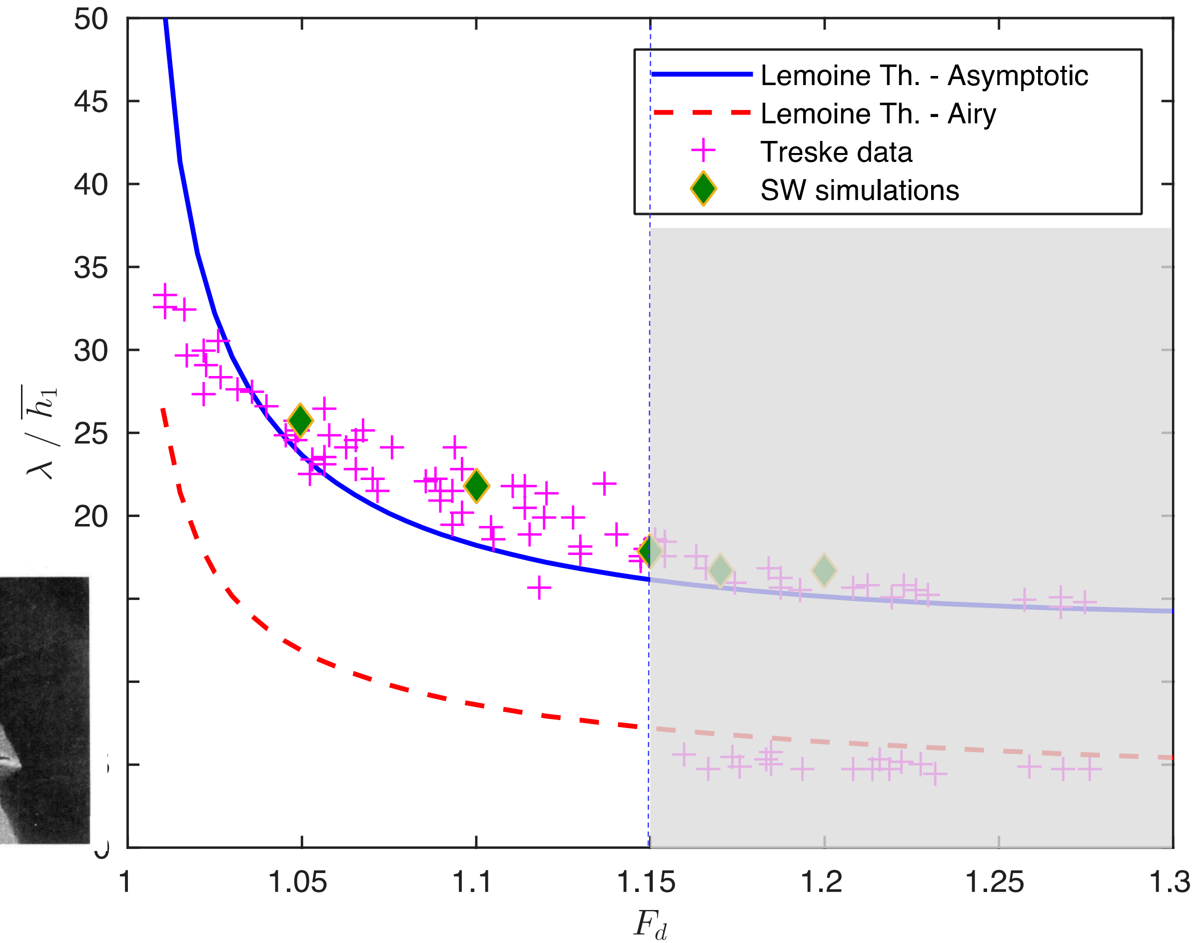
Transition at $Fr=F_T$

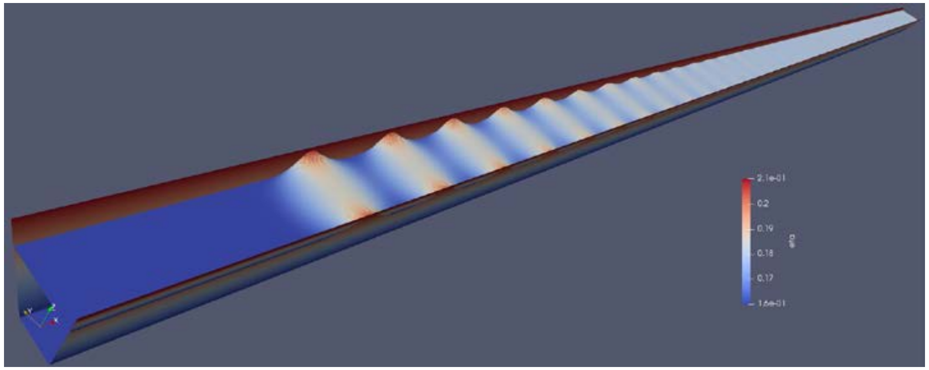
Low steepness
secondary wave regime

Approche « à la Lemoine »

Treske (1994)







Conclusion et perspectives

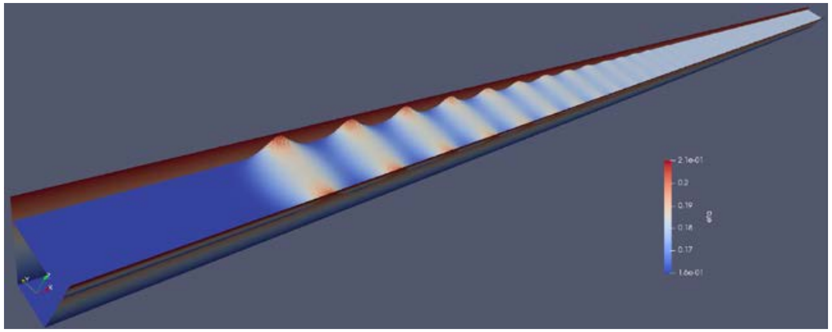
- Identification d'un nouveau régime d'écoulement pour les ressauts de marée ondulants

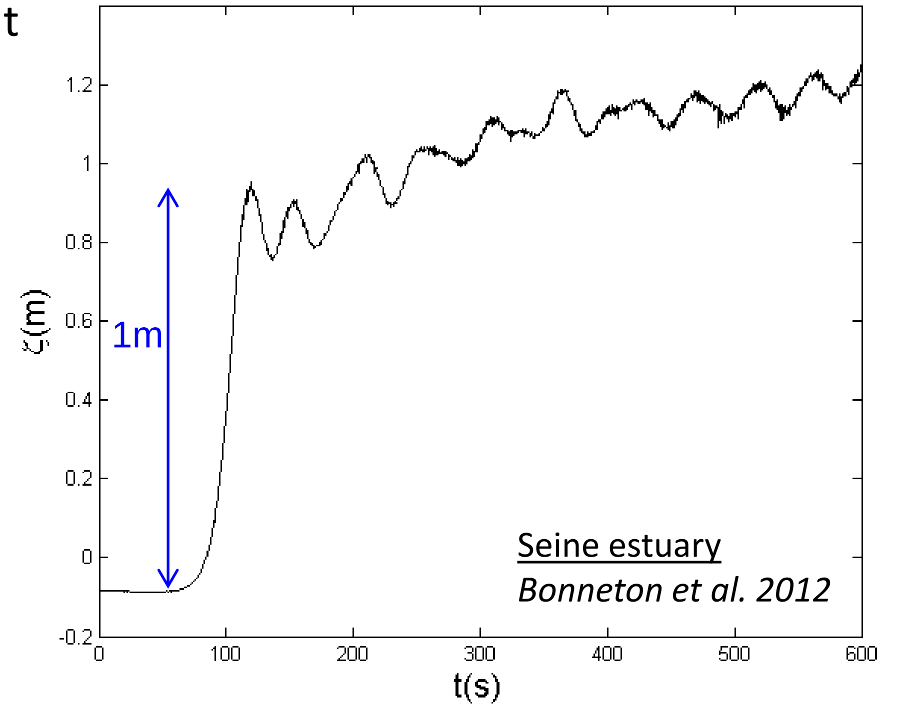
  $\rightarrow$ RM à faible cambrure

- Dynamique contrôlée par la réfraction sur les berges

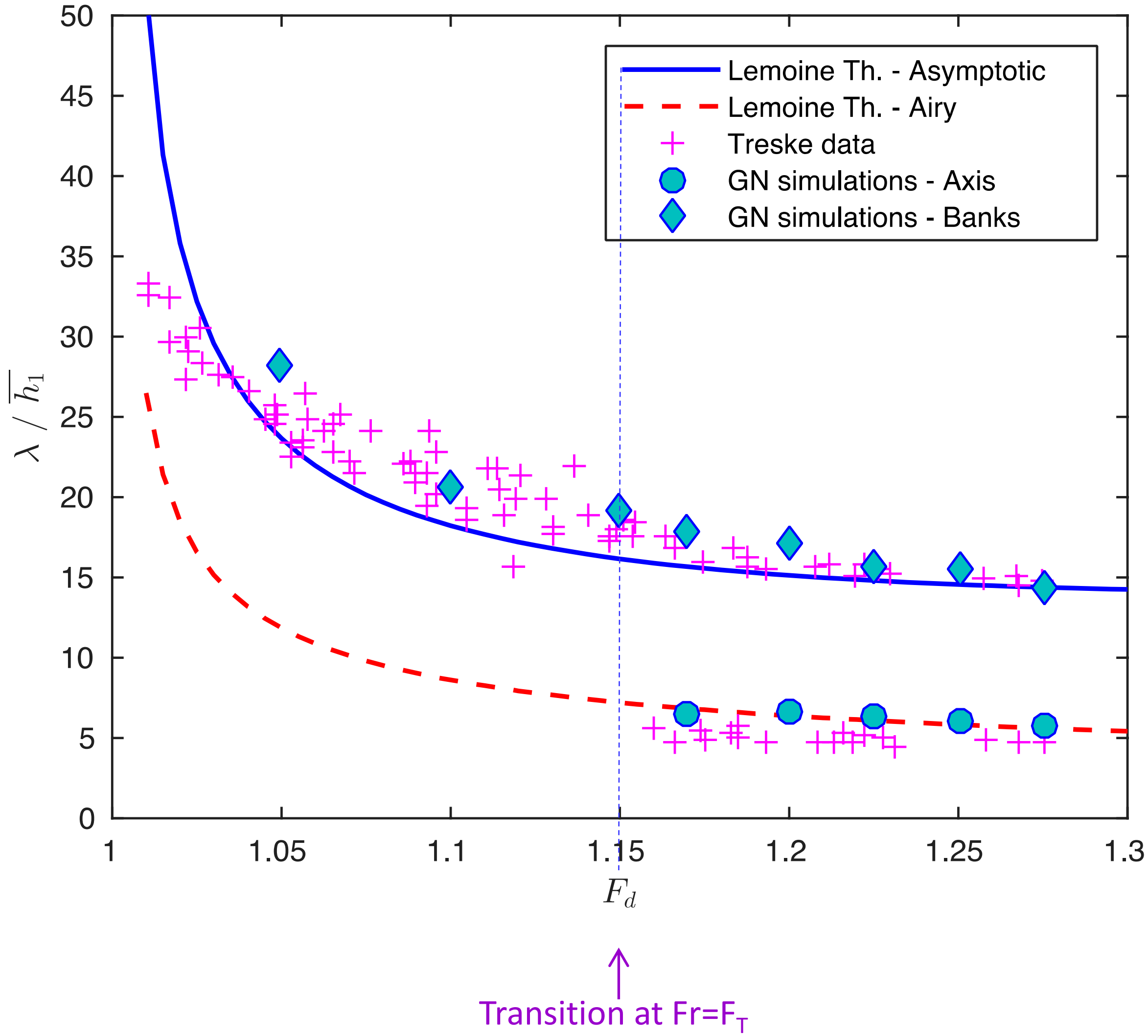
  $\rightarrow$ équation d'onde 1D de nature dispersive

$$\boxed{\frac{\partial^2 \bar{\zeta}}{\partial t^2} - \frac{\partial^2 \bar{\zeta}}{\partial x^2} - \delta^2 \chi \frac{\partial^4 \bar{\zeta}}{\partial x^4} = 0}$$





Conclusion et perspectives



Simulations numériques
Serre-Green Naghdi
Chassagne et al. 2018

- **Quels mécanismes contrôlent la transition à F=F_T ?**

Merci de votre attention