Dynamics of oil slicks on wavy water surfaces

A. Lukyanov, T. Pryer, H. Hozan & M. Baines

NOC, Liverpool 2025

University of Reading

UNIVERSITY OF BATH

JAZAN UNIVERSITY

Abstract

It is well known that the dynamics of oil spills is a complex phenomenon, it is also well known that water wave activity, including surface waves, make strong impact on oil spills. For example, breaking waves lead to emulsification. In the report, I would like to discuss slightly different aspects of the wave motion effects. In particular, the idea is to rigorously analyse the **‘macroscopic’** effects of wave motion on oil layers – **long waves**. Apparently, such effects should serve as pre-conditioners for the emulsification.

Breaking waves – microphysics beyond the scope

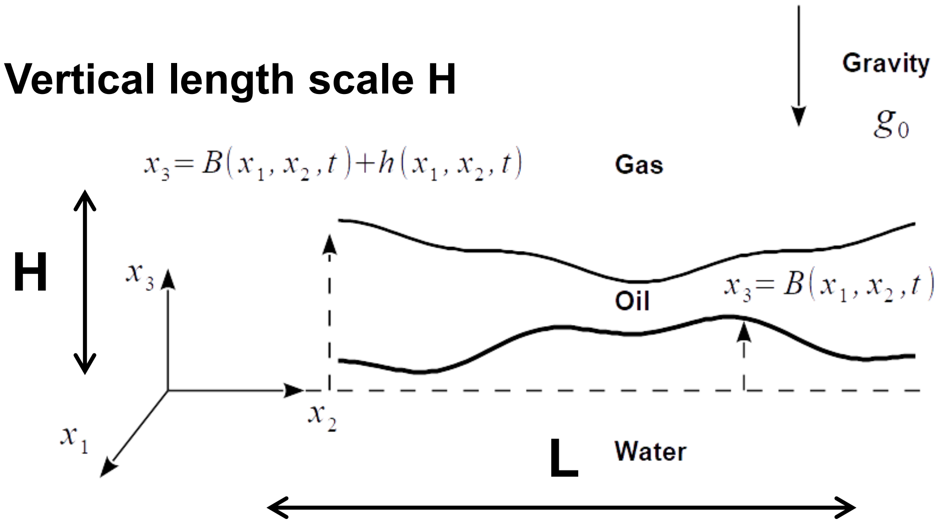
Long waves – macrophysics current study

Summary

- Starting point, **the thin film model** – a non-linear advection-diffusion equation
- **Geometry** of the problem – **isolated** oil spots, oil domains in **semi-confined** settings. **One-dimensional cases** run to identify the effects.
- Oil spot dynamics – no wave present, self-similar behaviour, academic & benchmark
- Oil spot dynamics – impact of surface waves, travelling waves, standing wave, currents can be included, but we have focused on the wave phenomena up to now

Problem formulation

Vertical length scale H



Thin film flow setting

Horizontal length scale L

Non-dimensional number	Role	Range
Bond number $Bo = \frac{\rho g_0 L^2}{\gamma}$	Neglect surface tension γ effects	10^9
Froude number $Fr = \sqrt{\frac{U^2}{g_0 H}}$	Contributes to spreading	> 10
Stokes number $St = \frac{\rho U H^2}{\mu L}$	Neglect **reverse** action of the oil layer	< 0.2
Thin film ratio $\varepsilon = \frac{H}{L}$	**Thin film approximation**	$< 10^{-4}$
Peclet number Pe	Advection & Diffusion	$1 < Pe < 10^3$
Reynolds number $Re = \frac{\rho U H}{\mu} \varepsilon$	Neglect inertial effects	< 0.2

Non-dimensional numbers of the full problem based upon 1 mm < H < 10 mm L=100 m and U=1 m/s

Problem formulation – 1D

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0, \quad q = -\frac{\alpha_g}{3} h^3 \frac{\partial (h+B)}{\partial x} + Vh$$

$$\alpha_g = \frac{\rho g_0 \varepsilon H^2}{\mu U} = \frac{Re}{Fr^2} = \frac{gravity}{viscous}$$

$B(x,t)$ and $V(x,t)$ water-wave elevation and horizontal velocity in the deep-sea approximation **normalised** by H and U, in principle, currents can be added by means of $V_C(x,t)$, but we focus on $V_C = 0$

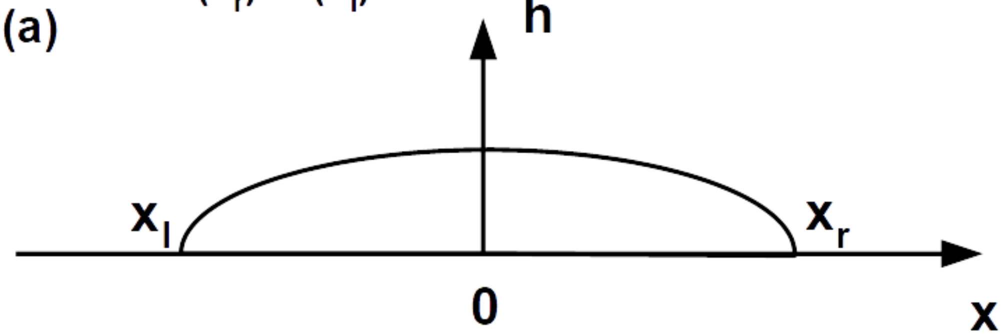
$$B = B_0 \sin(kx - \omega t)\,, V = V_C + \ B_0 \varepsilon \omega \sin(kx - \omega t)$$

$$\omega^2 = \frac{k}{\varepsilon Fr^2}, \qquad Pe = \frac{B_0 \varepsilon \omega}{\alpha_g}$$

Problem formulation, thin film geometry – 1D. (a) – isolated spot, (b) semi-confined geometry

Dirichlet both ends moving
$h(x_r)=h(x_l)=0$

(a)

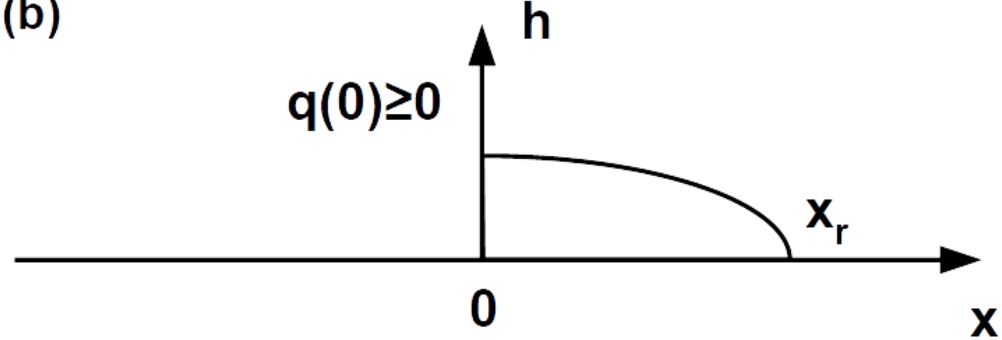


Boundary velocity

$$\frac{dx_{l,r}}{dt} = \frac{q}{h}$$

Neumann & Dirichlet one end moving $h(x_r)=0$

(b)



+ waves

Advection dominant regime $\alpha_g = 2 \cdot 10^{-5}$ – 1D
Isolated oil spot, $\mathrm{H} = 1\mathrm{mm}, Pe \gg 1$

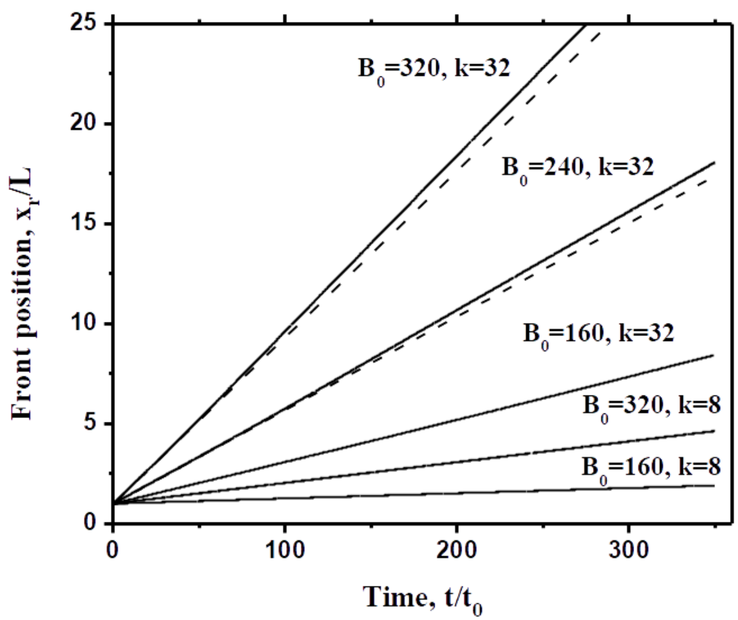
Travelling waves - $B_0 \approx 20\ cm$

Front

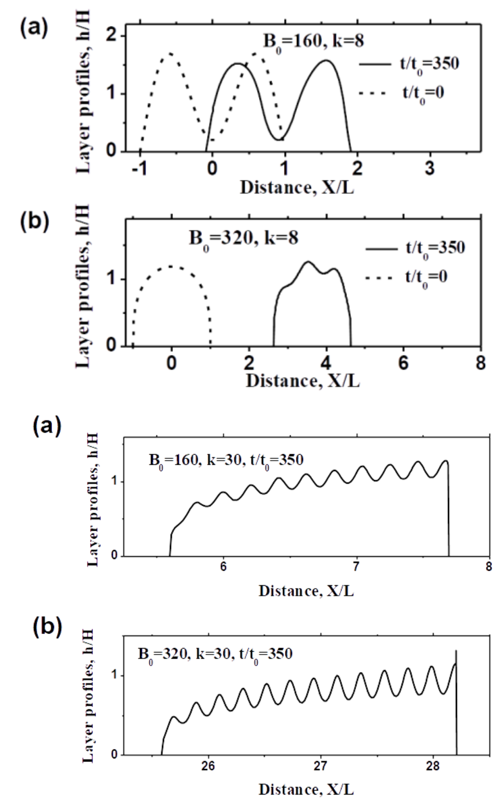
Stokes drift linear

$$\frac{dx}{dt} = B_0 \omega \varepsilon \sin(kx - \omega t) \approx u_s$$

$$u_s = \frac{1}{2} B_0^2 \varepsilon^2 \omega k$$



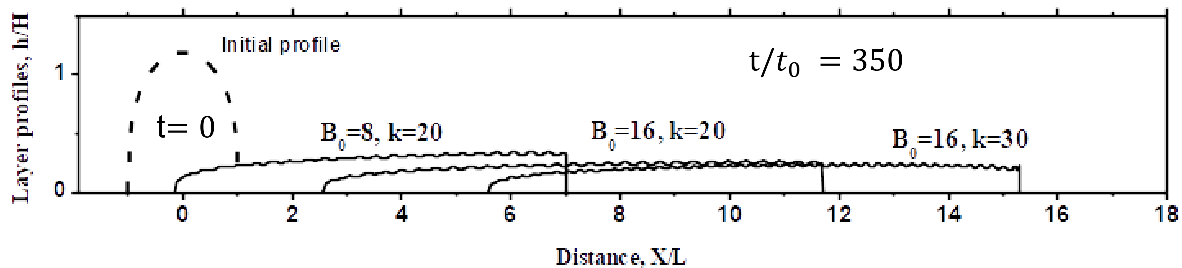
Oil spot profiles h(x)



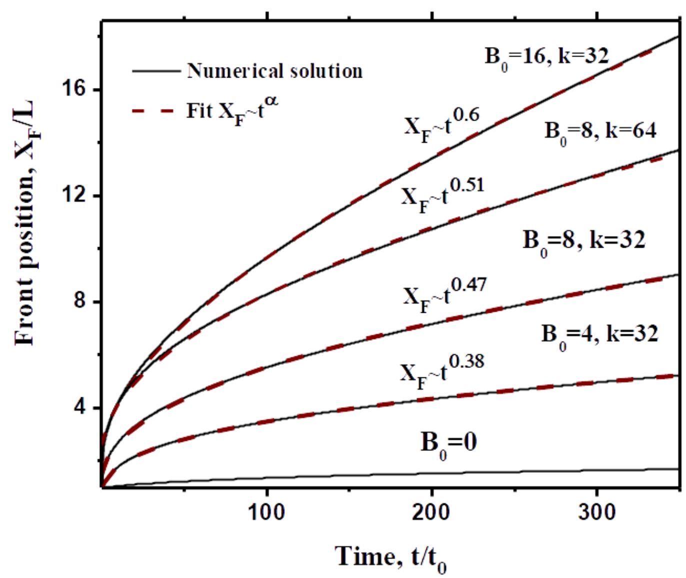
Advection-diffusion regime $\alpha_g = 2 \cdot 10^{-2}$ – 1D

$H = 10\ mm, Pe \approx 1$ travelling waves - $B_0 \approx 20\ cm$

Oil spot profiles h(x)



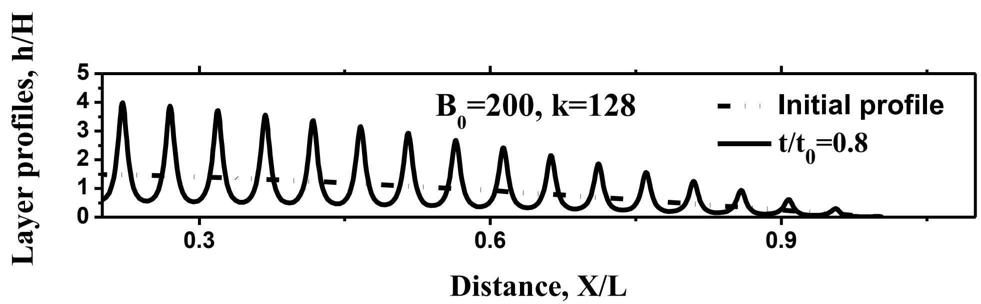
Front motion non-linear

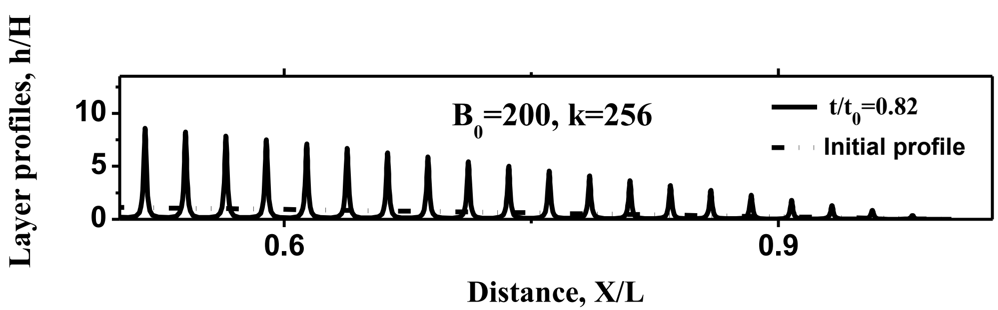


Advection dominant regime $\alpha_g = 2 \cdot 10^{-5}$ – 1D

Standing waves - $B_0 = 20\ cm, Pe \gg 1$

Oil spot profile h(x) with depletions



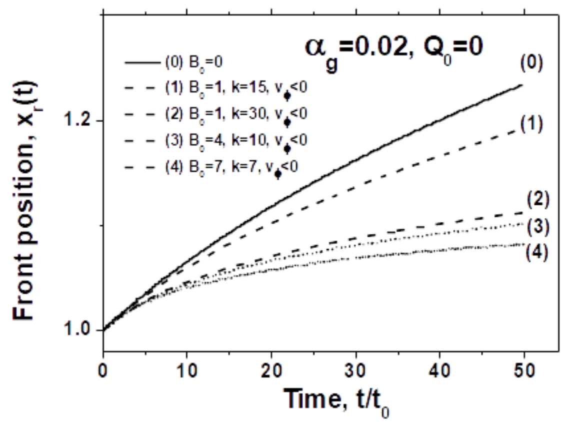


Advection-diffusion regime $\alpha_g = 2 \cdot 10^{-2}$ – 1D.

Semi-confined geometry, but no currents.

Oncoming travelling wave - $B_0 \approx 7\ cm$.

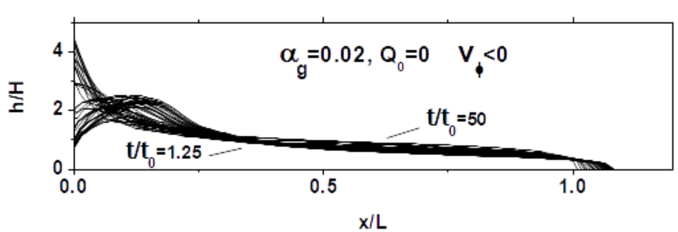
(a)



Front position $x_r(t)$

The suppression of the front motion leading to water-wave induced confinement can be clearly seen

(b)



Oil spot profiles h(x)

Further work ongoing – 2D and **realistic wave spectra, for example Pierson–Moskowitz (PM) spectra, plus realistic currents**

The team A. Lukyanov, T. Pryer

& N. Alsiyali, M. Baines, A. Belozerov, H. Hozan, P. Sweby

Thank you