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A non-monotone conservation law for dune morphodynamics.

Nathaël Alibaud, Pascal Azerad and Damien Isèbe

September 21, 2007

ABSTRACT. We investigate a non-local non linear conservation law, first introduced by A.C. Fowler to describe morphodynamics of dunes, see [5, 6]. A remarkable feature is the violation of the maximum principle, which allows for erosion phenomenon. We prove well-posedness for initial data in L^2 and give explicit counterexample for the maximum principle. We also provide numerical simulations corroborating our theoretical results.

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1 Introduction

We investigate the following Cauchy problem:

$$\begin{cases} \partial_t u(t,x) + \partial_x \left(\frac{u^2}{2}\right)(t,x) + \mathcal{I}[u(t,.)](x) - \partial^2_{xx} u(t,x) = 0 & t \in (0,T), x \in \mathbb{R}, \\ u(0,x) = u_0(x) & x \in \mathbb{R}, \end{cases} \tag{1}$$

where T is any given positive time, $u_0 \in L^2(\mathbb{R})$ and $\mathcal{I}$ is a non-local operator defined as follows: for any Schwartz function $\varphi \in \mathcal{S}(\mathbb{R})$ and any $x \in \mathbb{R}$,

$$\mathcal{I}[\varphi](x) := \int_0^{+\infty} |\zeta|^{-\frac{1}{3}} \varphi''(x-\zeta) d\zeta.$$

Remark 1. *Equation* (1) *can also be written in conservative form*

$$\partial_t u + \partial_x \left(\frac{u^2}{2} + \mathcal{L}[u] - \partial_x u \right) = 0$$

where

$$\mathcal{L}[\varphi](x) := \int_0^{+\infty} |\zeta|^{-\frac{1}{3}} \varphi'(x-\zeta) d\zeta.$$

Equation (1) appears in the work of Fowler [5, 6] on the evolution of *dunes*; the term dunes refers to instabilities in landforms, which occur through the interaction of a turbulent flow with an erodible substrate. Equation (1) is valid for a river flow (from left to the right) over a erodible bottom $u(t,x)$ with slow variation. For more details on the physical background, we refer the reader to [5, 6].

Roughly speaking, $\mathcal{I}[u]$ is a weighted mean of second derivatives of u with the bad sign; hence, this term has a deregularizing effect and the main consequence is probably the fact that (1) does not satisfy the maximum principle (see below for more details). Nevertheless, one can see that the diffusive operator $-\partial^2_{xx}$ controls the instabilities produced by $\mathcal{I}$ and ensures the existence and the uniqueness of a smooth solution for positive times. The starting point to establish these facts is the derivation of a new formula for the operator $\mathcal{I}$, namely (3). This result allows first to show easily that $\mathcal{I} - \partial^2_{xx}$ is a pseudo-differential operator with symbol $\psi_{\mathcal{I}}(\xi) = 4\pi^2\xi^2 - a_{\mathcal{I}}|\xi|^{\frac{4}{3}} + i\, b_{\mathcal{I}}\xi|\xi|^{\frac{1}{3}}$, where $a_{\mathcal{I}}$ and $b_{\mathcal{I}}$ are positive constants (see (4)). The symbol $4\pi^2\xi^2$ corresponds to the diffusive operator $-\partial^2_{xx}$ and $-a_{\mathcal{I}}|\xi|^{\frac{4}{3}} + i\, b_{\mathcal{I}}\xi|\xi|^{\frac{1}{3}}$ is the symbol of the nonlocal operator $\mathcal{I}$. Notice that this last symbol contains a fractional anti-diffusion $-a_{\mathcal{I}}|\xi|^{\frac{4}{3}}$ (recall that this is the symbol of $-(-\partial^2_{xx})^{\frac{4}{6}}$, up to a positive multiplicative constant) and a fractional drift $i\, b_{\mathcal{I}}\xi|\xi|^{\frac{1}{3}}$. Because of the fact that the fractional anti-diffusion is of order $\frac{4}{3}$, the real part of $\psi_{\mathcal{I}}(\xi)$ behaves as ξ^2, up to a positive multiplicative constant, as $\xi \to +\infty$. A consequence is that Equation (1) has a regularizing effect on the initial data: even if u_0 is only L^2, the solution u becomes C^∞ for positive times. The uniqueness of a $L^\infty((0,T);L^2)$ solution is obtained by the use of a mild formulation (see Definition 1) based on Duhamel's formula (12), in which appears the kernel K of $\mathcal{I} - \partial^2_{xx}$. The use of such a formula also allows to prove local-in-time existence with the help of a contracting fixed point theorem. Such an approach is quite classical; we refer the reader, for instance, to the book of Pazy [8] and the references therein on the application of the theory of semigroups of linear operators to partial differential equations. We also refer the reader to the work of Droniou *et al.* in [3] for fractal conservation laws of the form

$$\partial_t u + \partial_x(f(u)) + (-\partial^2_{xx})^{\frac{\lambda}{2}}[u] = 0, \tag{2}$$

where f is locally Lipschitz continuous and $\lambda \in (1,2]$, and to the work of Tadmor [9] on the Kuramoto-Sivashinsky equation:

$$\partial_t u + \frac{1}{2}|\partial_x u|^2 - \partial^2_{xx}u = (-\partial^2_{xx})^2[u].$$

In fact, fractal conservation law (2) is monotone and the global existence of a L^∞ solution is based on the fact that the L^∞ norm of u does not increase. In our case, this is not true and we have to use a classical energy estimate to get a global L^2 estimate. The regularizing effect on the initial data are first proved by a fixed point theorem on the Duhamel's formula to get H^1 regularity in space and next by a bootstrap method to get further regularity. This technique has already been used in [3].

On the other hand, one of our main result is probably the proof of the failure of the maximum principle for (1): more precisely, we exhibit positive dunes which take negative values in finite time, since we establish that the bottom is eroded downstream from the dune. We also give some numerical results that illustrate this fact (for more precision, see Remark 2 and Section 7). The proof of the failure of the maximum principle is based on the integral formula (3). Roughly speaking, this formula means that $\mathcal{I}$ is a Lévy operator with a bad sign, see [2]. Notice that the Kuramoto-Sivashinsky equation is also non-monotone, but no proof of the failure of the maximum principle is given in [9].

The paper is organized as follows. In Section 2, we give the integral and pseudo-differential formula for $\mathcal{I}$; we also establish the properties on the kernel K of $\mathcal{I} - \partial^2_{xx}$ that will be needed. In Section 3, we define the notion of mild solution for (1). Sections 4 and 5 are, respectively, devoted to the proof of the uniqueness and the existence of a mild solution; Section 5 also contains the proof of the regularity of the solution. The proof of the failure of the maximum principle is given in Section 6. Finally, we give in Section 7 some numerical simulations that illustrate the theory of the preceding sections.

Here are our main results.

Theorem 1. *Let $T > 0$ and $u_0 \in L^2(\mathbb{R})$. There exists a unique mild solution $u \in L^\infty((0,T); L^2(\mathbb{R}))$ of* (1) *(see Definition 1). Moreover,*

i) $u \in C^\infty((0,T] \times \mathbb{R})$ *and for all* $t_0 \in (0,T]$, u *and all its derivatives belong to* $C([t_0,T]; L^2(\mathbb{R}))$.

ii) u *satisfies* $\partial_t u + \partial_x(\frac{u^2}{2}) + \mathcal{I}[u] - \partial^2_{xx} u = 0$, *on* $(0,T] \times \mathbb{R}$, *in the classical sense (*$\mathcal{I}[u]$ *being properly defined by* (3) *and* (4)*).*

iii) $u \in C([0,T]; L^2(\mathbb{R}))$ *and* $u(0,.) = u_0$ *almost everywhere (a.e. for short).*

Proposition 1 (L^2-stability). *Let* (u,v) *be solutions to* (1) *with respective* L^2 *initial data* (u_0, v_0), *we have:*

$$||u - v||_{C([0,T];L^2(\mathbb{R}))} \leq C\left(T, M, ||u_0||_{L^2(\mathbb{R})}, ||v_0||_{L^2(\mathbb{R})}\right) ||u_0 - v_0||_{L^2(\mathbb{R})}$$

where $M := \max\left(||u||_{C([0,T];L^2(\mathbb{R}))}, ||v||_{C([0,T];L^2(\mathbb{R}))}\right)$.

Theorem 2 (Failure of the maximum principle). *Assume that* $u_0 \in C^2(\mathbb{R}) \cap H^2(\mathbb{R})$ *is nonnegative and such that there exist* $x_* \in \mathbb{R}$ *with* $u_0(x_*) = u_0'(x_*) = u_0''(x_*) = 0$ *and*

$$\int_{-\infty}^{0} \frac{u_0(x_* + z)}{|z|^{7/3}}\, dz > 0.$$

Then, there exists $t_* > 0$ *with* $u(t_*, x_*) < 0$.

Remark 2. *Hypothesis of the theorem above are satisfied, for instance, for non-negative* $u_0 \in C^2(\mathbb{R}) \cap H^2(\mathbb{R})$ *such that there exists* $x_* \in \mathbb{R}$ *with* $u_0(x_*) = u_0'(x_*) = u_0''(x_*) = 0$ *and*

$$\forall x \leq x_*,\ u_0(x) \geq 0 \quad \textit{and} \quad \exists x_0 < x_* \textit{ s.t. } u_0(x_0) > 0.$$

A simple example of such an initial dune is shown in Figure 1. Observe that the bottom is eroded downstream from the dune (recall that the nonlinear convective term propagates a positive dune from the left to the right).

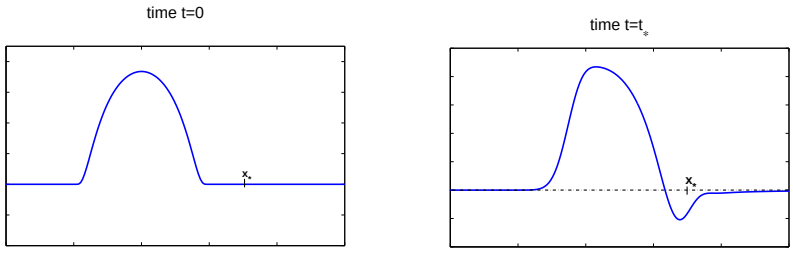

Figure 1: Evolution of a dune, at $t = 0$ and $t = t_*$. We can observe that $u(t_*, x_*) < 0$ and that $\int u(t,x)\, dx$ remains constant.

Notations: In the following, we let $\mathcal{F}$ denote the Fourier transform defined for $f \in L^1(\mathbb{R})$ by: for all $\xi \in \mathbb{R}$,

$$\mathcal{F}f(\xi) := \int_{\mathbb{R}} e^{-2i\,\pi x \xi} f(x) dx.$$

We also let $\mathcal{F}$ define the extension of the preceding operator from L^2 to L^2. In the sequel, we only consider Fourier transform with respect to (w.r.t. for short) the space variable; in order to simplify the presentation, for any $u \in C([0,T];L^2(\mathbb{R}))$, we let $\mathcal{F}u \in C([0,T];L^2(\mathbb{R},\mathbb{C}))$ denote the function

$$t \in [0,T] \to \mathcal{F}(u(t,\cdot)) \in L^2(\mathbb{R},\mathbb{C}).$$

2 Preliminaries

In Subsection 2.1, we give the integral and the pseudo-differential formula for $\mathcal{I}$ and in Subsection 2.2 we give the properties on the kernel of $\mathcal{I} - \partial^2_{xx}$.

2.1 Integral formula for $\mathcal{I}$

Proposition 2. *For all $\varphi \in \mathcal{S}(\mathbb{R})$ and all $x \in \mathbb{R}$,*

$$\mathcal{I}[\varphi](x) = C_{\mathcal{I}} \int_{-\infty}^{0} \frac{\varphi(x+z) - \varphi(x) - \varphi'(x)z}{|z|^{7/3}}\, dz, \tag{3}$$

with $C_{\mathcal{I}} = \frac{4}{9}$.

Proof. The proof is an easy consequence of Taylor-Poisson's formula and Fubini's Theorem; notice that the regularity of φ ensures the validity of the computations that follow. We have:

$$\begin{aligned}
\int_{-\infty}^{0} \frac{\varphi(x+z) - \varphi(x) - \varphi'(x)z}{|z|^{7/3}}\, dz &= \int_{-\infty}^{0} |z|^{-\frac{7}{3}} \left(\int_0^1 (1-\tau)\varphi''(x+\tau z) z^2 d\tau \right) dz, \\
&= \int_0^1 (1-\tau) \left(\int_{-\infty}^{0} |z|^{-\frac{1}{3}} \varphi''(x+\tau z) dz \right) d\tau, \\
&= \int_0^1 (1-\tau)\tau^{-\frac{2}{3}} \left(\int_0^{+\infty} |\zeta|^{-\frac{1}{3}} \varphi''(x-\zeta) d\zeta \right) d\tau,
\end{aligned}$$

thanks to the change of variable $\tau z = -\zeta$. Then,

$$\int_{-\infty}^{0} \frac{\varphi(x+z) - \varphi(x) - \varphi'(x)z}{|z|^{7/3}}\, dz = \int_0^1 (1-\tau)\tau^{-\frac{2}{3}} d\tau\, \mathcal{I}[\varphi](x) = \frac{9}{4}\mathcal{I}[\varphi](x).$$

The proof is now complete. ■

Corollary 1. *There are positive constants $a_{\mathcal{I}}$ and $b_{\mathcal{I}}$ such that for all $\varphi \in \mathcal{S}(\mathbb{R})$ and all $\xi \in \mathbb{R}$,*

$$\mathcal{F}\left(\mathcal{I}[\varphi] - \varphi''\right)(\xi) = \psi_{\mathcal{I}}(\xi)\mathcal{F}\varphi(\xi), \tag{4}$$

where $\psi_{\mathcal{I}}(\xi) = 4\pi^2\xi^2 - a_{\mathcal{I}}|\xi|^{\frac{4}{3}} + i\, b_{\mathcal{I}}\xi|\xi|^{\frac{1}{3}}$.

Proof. We have

$$\mathcal{F}\left(\mathcal{I}[\varphi]\right)(\xi) = C_{\mathcal{I}} \int_{\mathbb{R}} \int_{-\infty}^{0} e^{-2i\pi x\xi} \frac{\varphi(x+z) - \varphi(x) - \varphi'(x)z}{|z|^{7/3}}\, dz dx.$$

Notice that Proposition 2 ensures that for $\varphi \in \mathcal{S}(\mathbb{R})$, $\mathcal{I}[\varphi] \in L^1(\mathbb{R})$ and thus its Fourier transform is well-defined. By Fubini's theorem, we can first integrate w.r.t x to deduce that

$$\mathcal{F}\left(\mathcal{I}[\varphi]\right)(\xi) = C_{\mathcal{I}} \int_{-\infty}^{0} \frac{\mathcal{F}\left(\mathcal{T}_{-z}\varphi\right)(\xi) - \mathcal{F}\varphi(\xi) - \mathcal{F}(\varphi')(\xi)z}{|z|^{7/3}}\, dz,$$

where we let $\mathcal{T}_{-z}\varphi$ denote the (translated) function $x \to \varphi(x+z)$. Classical formulae on Fourier transform imply that $\mathcal{F}\left(\mathcal{I}[\varphi]\right)(\xi) = \psi(\xi)\mathcal{F}\varphi(\xi)$, where

$$\psi(\xi) = C_{\mathcal{I}} \int_{-\infty}^{0} \frac{e^{2i\pi\xi z} - 1 - 2i\pi\xi z}{|z|^{7/3}}\, dz.$$

Simple computations show that

$$\psi(\xi) = C_{\mathcal{I}} \int_{-\infty}^{0} \frac{\cos\left(2\pi\xi z\right) - 1}{|z|^{7/3}}\, dz + i\, C_{\mathcal{I}} \int_{-\infty}^{0} \frac{\sin\left(2\pi\xi z\right) - 2\pi\xi z}{|z|^{7/3}}\, dz.$$

It is immediate that the real part of $\psi(\xi)$ is even, non-positive, non-identically equal to 0 and homogeneous of degree $\frac{4}{3}$ (the last property can be seen by changing the variable by $z' = \xi z$). Moreover, the imaginary part of $\psi(\xi)$ is odd, negative and homogeneous of degree $\frac{4}{3}$ on $\mathbb{R}_*^-$. There then exist positive constants $a_{\mathcal{I}}$ and $b_{\mathcal{I}}$ such that

$$\psi(\xi) = -a_{\mathcal{I}}|\xi|^{\frac{4}{3}} + i\, b_{\mathcal{I}}\xi|\xi|^{\frac{1}{3}}$$

and, in particular, $\mathcal{F}\left(\mathcal{I}[\varphi]\right)(\xi) = \left(-a_{\mathcal{I}}|\xi|^{\frac{4}{3}} + i\, b_{\mathcal{I}}\xi|\xi|^{\frac{1}{3}}\right)\mathcal{F}\varphi(\xi)$. Since $\mathcal{F}(-\varphi'')(\xi) = 4\pi^2\xi^2\mathcal{F}\varphi(\xi)$, the proof of Corollary 1 is complete. ■

Remark 3. *1. Since $\mathcal{I}[\varphi] = \mathbf{1}_{\mathbb{R}_+}|\cdot|^{-\frac{1}{3}} * \varphi''$, we have $\mathcal{F}(\mathcal{I}[\varphi]) = \mathcal{F}(\mathbf{1}_{\mathbb{R}_+}|\cdot|^{-\frac{1}{3}}) \cdot (-4\pi^2|\xi|^2) \cdot \mathcal{F}(\varphi)$. Elementary computations give $\mathcal{F}(\mathbf{1}_{\mathbb{R}_+}|\cdot|^{-\frac{1}{3}}) = \Gamma(\frac{2}{3})\left(\frac{1}{2} - i\,\mathrm{sign}(\xi)\frac{\sqrt{3}}{2}\right)|\xi|^{-\frac{2}{3}}$. Hence $a_{\mathcal{I}} = \Gamma(\frac{2}{3})\frac{1}{2}$ and $b_{\mathcal{I}} = \Gamma(\frac{2}{3})\frac{\sqrt{3}}{2}$.*

2. Let $s \in \mathbb{R}$. If $\varphi \in H^s(\mathbb{R})$, one can also define $\mathcal{I}[\varphi]$ through its Fourier transform by

$$\mathcal{F}(\mathcal{I}[\varphi])(\xi) := -4\pi^2\Gamma(\frac{2}{3})\left(\frac{1}{2} - i\,\mathrm{sign}(\xi)\frac{\sqrt{3}}{2}\right)|\xi|^{\frac{4}{3}} \cdot \mathcal{F}(\varphi)$$

Thus,if $\varphi \in H^s$, we have that $\mathcal{I}[\varphi] \in H^{s-\frac{4}{3}}$ and $||\mathcal{I}[\varphi]||_{H^{s-\frac{4}{3}}} \leq 4\pi^2\Gamma(\frac{2}{3})||\varphi||_{H^s}$. This implies in particular that $\mathcal{I} : H^2(\mathbb{R}) \to C_b(\mathbb{R}) \cap L^2(\mathbb{R})$, since by Sobolev embedding $H^{\frac{2}{3}} \hookrightarrow C_b(\mathbb{R}) \cap L^2(\mathbb{R})$.

3. Corollary 1 implies that $\mathcal{I} - \partial_{xx}^2 : C^2(\mathbb{R}) \cap H^2(\mathbb{R}) \to C(\mathbb{R}) \cap L^2(\mathbb{R})$ with $\mathcal{I}$ which satisfies both formula (3) *and* (4)*.*

2.2 Main properties on the kernel K of $\mathcal{I} - \partial_{xx}^2$

By Corollary 1, we see that the semi-group generated by $\mathcal{I} - \partial_{xx}^2$ is formally given by the convolution with the kernel (defined for $t > 0$ and $x \in \mathbb{R}$)

$$K(t,x) = \mathcal{F}^{-1}(e^{-t\psi_{\mathcal{I}}})(x).$$

Proposition 3. *$K(t,\cdot)$ is a L^1 real valued continuous function.*

Proof. $K(t,\cdot)$ is a L^1 real valued continuous function as inverse Fourier transform of a $W^{2,1}$ function with an even real part and an odd imaginary part. ■

In the sequel, we only consider real valued solution of (1). We expose in Figure 2 the evolution of $K(t,\cdot)$ for different times. Note that $K(t,\cdot)$ is not compactly supported but that $K(t,x) \leq \frac{C(t)}{x^2}$, for $|x| \geq 1$ with $C(t) = \frac{1}{4\pi^2}||\partial^2_{\xi\xi}\mathcal{F}(K(t,.))(\xi)||_{L^1}$

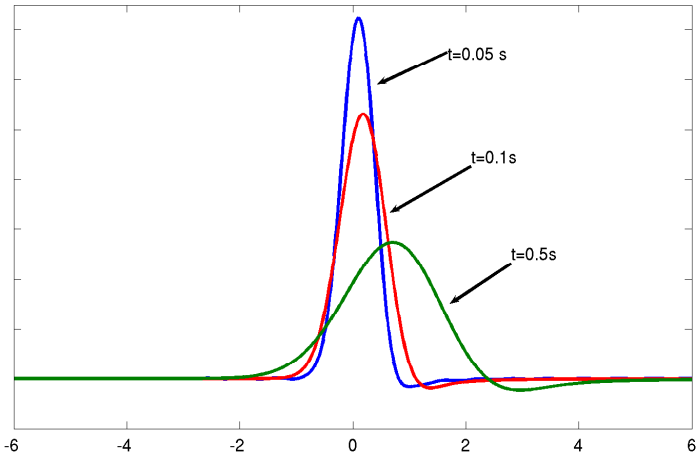

Figure 2: The kernel of $\mathcal{I} - \partial^2_{xx}$ for $t = 0.05, 0.1$ and 0.5 s.

Proposition 4. *The kernel K has a non-zero negative part.*

Proof. Let us assume that K is nonnegative, then

$$|e^{-t\psi_{\mathcal{I}}(\xi)}| \leq ||\mathcal{F}^{-1}(e^{-t\psi_{\mathcal{I}}})||_{L^1(\mathbb{R})} = \int_{\mathbb{R}} |K(t,.)|$$
$$= \int_{\mathbb{R}} K(t,.) = \mathcal{F}\left(\mathcal{F}^{-1}(e^{-t\psi_{\mathcal{I}}})\right)(0) = e^{-t\psi_{\mathcal{I}}(0)} = 1$$

for all $\xi \in \mathbb{R}$; hence, since $|e^{-t\psi_{\mathcal{I}}(\xi)}| = e^{-t(4\pi^2|\xi|^2 - a_{\mathcal{I}}|\xi|^{\frac{4}{3}})} > 1$ for $0 < |\xi| < \frac{a_{\mathcal{I}}^{\frac{3}{2}}}{8\pi^3}$, this gives us a contradiction. ■

The main consequence of this is the failure of the maximum principle for the equation

$$\partial_t u + \mathcal{I}[u] - \partial^2_{xx} u = 0; \tag{5}$$

that is to say, there exists a non-negative initial condition u_0 such that, for some $t > 0$, $u(t,.) := K(t,.) * u_0$ has a non-zero negative part, see section 6 below. Nevertheless, K enjoys many properties similar than those one satisfied by the kernel of the heat equation and that ensure that Equation (5) has

a regularizing effect on the initial condition: if $u_0 \in L^p(\mathbb{R})$ for some $p \in [1, +\infty)$, then u is C^∞ for positive times, see section 5.

Let us precise here the properties that will be needed in this paper. Since $K(t,\cdot) \in L^1(\mathbb{R})$, the family of bounded linear operators $\left\{u_0 \in L^2(\mathbb{R}) \to K(t,\cdot) * u_0 \in L^2(\mathbb{R})\right\}_{t>0}$ is well-defined. Moreover, it is a strongly continuous semi-group of convolution, that is to say:

$$\begin{array}{c} \forall t, s > 0,\ K(s,\cdot) * K(t,\cdot) = K(s+t,\cdot), \\ \forall u_0 \in L^2(\mathbb{R}),\ \lim_{t\to 0} K(t,\cdot) * u_0 = u_0 \text{ in } L^2(\mathbb{R}). \end{array} \tag{6}$$

Next, the kernel K is smooth on $(0, +\infty) \times \mathbb{R}$ and we have:

$$\forall T > 0,\ \exists \mathcal{K}_0 \text{ s.t. } \forall t \in (0,T],\ ||\partial_x K(t,.)||_{L^2(\mathbb{R})} \leq \mathcal{K}_0 t^{-\frac{3}{4}}, \tag{7}$$

$$\forall T > 0,\ \exists \mathcal{K}_1 \text{ s.t. } \forall t \in (0,T],\ ||\partial_x K(t,.)||_{L^1(\mathbb{R})} \leq \mathcal{K}_1 t^{-\frac{1}{2}}, \tag{8}$$

$$\forall t, s > 0,\ K(s,\cdot) * \partial_x K(t,\cdot) = \partial_x K(s+t,\cdot). \tag{9}$$

Proof of these properties. The semi-group property (6) and (9) are immediate consequences of Fourier formula. Let us prove the strong continuity. By Plancherel's formula,

$$\begin{aligned} ||K(t,\cdot) * u_0 - u_0||^2_{L^2(\mathbb{R})} &= ||\mathcal{F}(K(t,\cdot) * u_0) - \mathcal{F}u_0||^2_{L^2(\mathbb{R})} \\ &= ||e^{-t\psi_{\mathcal{I}}}\mathcal{F}u_0 - \mathcal{F}u_0||^2_{L^2(\mathbb{R})} = \int_{\mathbb{R}} |e^{-t\psi_{\mathcal{I}}} - 1|^2 \, |\mathcal{F}u_0|^2. \end{aligned} \tag{10}$$

The function $|e^{-t\psi_{\mathcal{I}}} - 1|^2 \, |\mathcal{F}u_0|^2$ converges pointwise to 0 on $\mathbb{R}$, as $t \to 0$. Recalling that $\min \mathrm{Re}(\psi_{\mathcal{I}})$ is finite, we infer that $|e^{-t\psi_{\mathcal{I}}} - 1|^2 \, |\mathcal{F}u_0|^2 \leq C|\mathcal{F}u_0|^2$ and the dominated convergence theorem implies that the last term of (10) tends to 0 as $t \to 0$. This completes the proof of (6). Let us now prove the estimates on the gradient. The smoothness of K is an immediate consequence of the theorem of derivation under the integral sign applied to the definition of K by Fourier transform. We get in particular:

$$\partial_x K(t,\cdot) = \partial_x \mathcal{F}^{-1}(e^{-t\psi_{\mathcal{I}}}) = \mathcal{F}^{-1}\left(\xi \to 2i\pi\xi e^{-t\psi_{\mathcal{I}}(\xi)}\right).$$

Since the function $\xi \to 2i\pi\xi e^{-t\psi_{\mathcal{I}}(\xi)}$ is L^2, $\partial_x K(t,\cdot)$ is L^2 and we have:

$$||\partial_x K(t,.)||^2_{L^2(\mathbb{R})} = \int_{\mathbb{R}} 4\pi^2\xi^2 |e^{-t\psi_{\mathcal{I}}(\xi)}|^2 d\xi = \int_{\mathbb{R}} 4\pi^2\xi^2 e^{-2t(4\pi^2|\xi|^2 - a_{\mathcal{I}}|\xi|^{\frac{4}{3}})} d\xi.$$

Let us change the variable by $\xi' = t^{\frac{1}{2}}\xi$. We get:

$$\begin{aligned} ||\partial_x K(t,.)||^2_{L^2(\mathbb{R})} &= t^{-\frac{3}{2}} \int_{\mathbb{R}} 4\pi^2 |\xi'|^2 e^{-2(4\pi^2|\xi'|^2 - t^{\frac{1}{3}} a_{\mathcal{I}}|\xi'|^{\frac{4}{3}})} d\xi', \\ &\leq t^{-\frac{3}{2}} \int_{\mathbb{R}} 4\pi^2 |\xi'|^2 e^{-2(4\pi^2|\xi'|^2 - T^{\frac{1}{3}} a_{\mathcal{I}}|\xi'|^{\frac{4}{3}})} d\xi', \end{aligned}$$

for all $t \in (0,T]$. The proof of (7) is now complete. To prove (8), we have to derive a "homogeneity-like" property for K. Easy computations show that

$$\begin{aligned} K(t,x) &= \int_{\mathbb{R}} e^{2i\,\pi x\xi} e^{-t\psi_{\mathcal{I}}(\xi)} d\xi, \\ &= \int_{\mathbb{R}} e^{2i\,\pi x\xi} e^{-t(4\pi^2|\xi|^2 - a_{\mathcal{I}}|\xi|^{\frac{4}{3}} + i\,b_{\mathcal{I}}\xi|\xi|^{\frac{1}{3}})} d\xi, \\ &= t^{-\frac{1}{2}} \int_{\mathbb{R}} e^{2i\,\pi(t^{-\frac{1}{2}}x)\xi'} e^{-(4\pi^2|\xi'|^2 - t^{\frac{1}{3}}a_{\mathcal{I}}|\xi'|^{\frac{4}{3}} + i\,t^{\frac{1}{3}}b_{\mathcal{I}}\xi'|\xi'|^{\frac{1}{3}})} d\xi', \end{aligned}$$

by changing the variable by $\xi' = t^{\frac{1}{2}}\xi$. Then,

$$\begin{aligned} K(t,x) &= t^{-\frac{1}{2}} \int_{\mathbb{R}} e^{2i\,\pi(t^{-\frac{1}{2}}x)\xi'} e^{-(4\pi^2|\xi'|^2 - a_{\mathcal{I}}|\xi'|^{\frac{4}{3}} + i\,b_{\mathcal{I}}\xi'|\xi'|^{\frac{1}{3}})} e^{-(1-t^{\frac{1}{3}})(a_{\mathcal{I}}|\xi'|^{\frac{4}{3}} - i\,b_{\mathcal{I}}\xi'|\xi'|^{\frac{1}{3}})} d\xi', \\ &= t^{-\frac{1}{2}} \int_{\mathbb{R}} e^{2i\,\pi(t^{-\frac{1}{2}}x)\xi'} e^{-\psi_{\mathcal{I}}(\xi')} e^{-(1-t^{\frac{1}{3}})(a_{\mathcal{I}}|\xi'|^{\frac{4}{3}} - i\,b_{\mathcal{I}}\xi'|\xi'|^{\frac{1}{3}})} d\xi'. \end{aligned}$$

For $t < 1$, define $G((1-t^{\frac{1}{3}}),\cdot) := \mathcal{F}^{-1}\left(e^{-(1-t^{\frac{1}{3}})(a_{\mathcal{I}}|\xi'|^{\frac{4}{3}} - i\,b_{\mathcal{I}}\xi'|\xi'|^{\frac{1}{3}})}\right)$. It is readily seen that G is L^1 as inverse Fourier transform of a $W^{2,1}$ function. Moreover, for $t_0 \in (0,1)$ and all $t \in (0,t_0]$,

$$||G((1-t^{\frac{1}{3}}),\cdot)||_{L^1(\mathbb{R})} \leq C \left|\left| e^{-(1-t^{\frac{1}{3}})(a_{\mathcal{I}}|\cdot|^{\frac{4}{3}} - i\,b_{\mathcal{I}}\cdot|\cdot|^{\frac{1}{3}})} \right|\right|_{W^{2,1}(\mathbb{R},\mathbb{C})} \leq C(t_0),$$

where $C(t_0)$ only depends on t_0. Classical formula on Fourier transform then give:

$$K(t,x) = t^{-\frac{1}{2}} \left(K(1,\cdot) * G((1-t^{\frac{1}{3}}),\cdot)\right)(t^{-\frac{1}{2}}x).$$

Observe now that $\partial_x K(1,\cdot) = \mathcal{F}^{-1}\left(\xi \to 2i\,\xi\pi e^{-\psi_{\mathcal{I}}(\xi)}\right)$ is L^1 as inverse Fourier transform of a $W^{2,1}$ function. Then,

$$\partial_x K(t,x) = t^{-1} \left(\partial_x K(1,\cdot) * G((1-t^{\frac{1}{3}}),\cdot)\right)(t^{-\frac{1}{2}}x)$$

is L^1 and its L^1 norm can be computed by the change of variable $x' = t^{-\frac{1}{2}}x$ as follows:

$$||\partial_x K(t,\cdot)||_{L^1(\mathbb{R})} = t^{-\frac{1}{2}}||\partial_x K(1,\cdot) * G((1-t^{\frac{1}{3}}),\cdot)||_{L^1(\mathbb{R})} \leq t^{-\frac{1}{2}}||\partial_x K(1,\cdot)||_{L^1(\mathbb{R})} C(t_0),$$

for any $t \in (0,t_0]$. Since

$$||\partial_x K(t,\cdot)||_{L^1(\mathbb{R})} \leq C||\xi \to 2i\,\xi\pi e^{-t\psi_{\mathcal{I}}(\xi)}||_{W^{2,1}(\mathbb{R},\mathbb{C})} \leq C(t_0,T),$$

for all $t \in [t_0,T]$, the proof of (8) is now complete. ■

Remark 4. *For any $u_0 \in L^2(\mathbb{R})$ and $t > 0$,*

$$||K(t,\cdot) * u_0||_{L^2(\mathbb{R})} \leq e^{\omega_0 t}||u_0||_{L^2(\mathbb{R})}, \tag{11}$$

where $\omega_0 = -\min \mathrm{Re}(\psi_{\mathcal{I}})$.

Proof. This is readily established with Plancherel's formula, like in (10). ■

3 Duhamel's formula

Using Fourier transform and Corollary 1, we formally see that any solution to (1) satisfies Duhamel's formula (12) (see also the proof of Lemma 3, which justifies the computations). This observation is the starting point of the definition of mild solution below.

Definition 1. *Let $T > 0$ and $u_0 \in L^2(\mathbb{R})$. We say that $u \in L^\infty((0,T); L^2(\mathbb{R}))$ is a mild solution to* (1) *if for a.e. $t \in (0,T)$,*

$$u(t,\cdot) = K(t,\cdot) * u_0 - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * u^2(s,\cdot)ds. \tag{12}$$

The following proposition shows that all the terms in (12) are well-defined and that Equation (1) generates a (non-linear) semi-group.

Proposition 5. *Let $T > 0$, $u_0 \in L^2(\mathbb{R})$ and $v \in L^\infty((0,T); L^1(\mathbb{R}))$. Then, the function*

$$u : t \in (0,T] \to K(t,\cdot) * u_0 - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * v(s,\cdot)ds \in L^2(\mathbb{R}), \tag{13}$$

is well-defined and belongs to $C([0,T]; L^2(\mathbb{R}))$ (being extended at $t = 0$ by the value $u(0,.) = u_0$). (Semi-group property) Moreover, for all $t_0 \in (0,T)$ and all $t \in [0, T - t_0]$,

$$u(t_0 + t, .) = K(t,\cdot) * u(t_0,\cdot) - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * v(t_0+s,\cdot)ds.$$

Proof. By (6), it is classical that the function $t \in (0,T] \to K(t,\cdot) * u_0 \in L^2(\mathbb{R})$ is continuous and can be continuously extended by the value $u(0,\cdot) = u_0$ at $t = 0$. What is left to prove is thus the continuity of the function

$$w : t \in [0,T] \to \int_0^t \partial_x K(t-s,\cdot) * v(s,\cdot)ds \in L^2(\mathbb{R}).$$

Let us extend $\partial_x K$ and v for all times the following way:

$$\mathcal{H}(t,\cdot) := \begin{cases} \partial_x K(t,\cdot) & \text{if } t > 0, \\ 0 & \text{if not} \end{cases} \quad \text{and} \quad \mathcal{V}(t,\cdot) := \begin{cases} v(t,\cdot) & \text{if } t \in (0,T), \\ 0 & \text{if not.} \end{cases}$$

Then we have

$$w(t,\cdot) = \int_{\mathbb{R}} \mathcal{H}(t-s,\cdot) * \mathcal{V}(s,\cdot)ds.$$

It is immediate that $\mathcal{V} \in L^\infty(\mathbb{R}; L^1(\mathbb{R}))$. Moreover, (7) implies that

$$||\mathcal{H}(t,\cdot)||_{L^2(\mathbb{R})} \leq \mathbf{1}_{\{0<t<T\}} \mathcal{K}_0 t^{-\frac{3}{4}} \tag{14}$$

and it follows that $\mathcal{H} \in L^1(\mathbb{R}; L^2(\mathbb{R}))$. Young's Inequalities imply that for all $t \in \mathbb{R}$

$$\begin{aligned} \int_{\mathbb{R}} ||\mathcal{H}(t-s,\cdot) * \mathcal{V}(s,\cdot)||_{L^2(\mathbb{R})} ds &\leq \int_{\mathbb{R}} ||\mathcal{H}(t-s,\cdot)||_{L^2(\mathbb{R})} ||\mathcal{V}(s,\cdot)||_{L^1(\mathbb{R})} ds, \\ &\leq ||\mathcal{H}||_{L^1(\mathbb{R};L^2(\mathbb{R}))} \, ||\mathcal{V}||_{L^\infty(\mathbb{R};L^1(\mathbb{R}))}. \end{aligned} \tag{15}$$

This implies, in particular, that the function w is well-defined. Let us now take $t, s \in \mathbb{R}$ and define

$$I := \left|\left| \int_{\mathbb{R}} \mathcal{H}(t-\tau,\cdot) * \mathcal{V}(\tau) d\tau - \int_{\mathbb{R}} \mathcal{H}(s-\tau,\cdot) * \mathcal{V}(\tau) d\tau \right|\right|_{L^2(\mathbb{R})}.$$

We have

$$\begin{aligned} I &\leq \int_{\mathbb{R}} ||(\mathcal{H}(t-\tau,\cdot) - \mathcal{H}(s-\tau,\cdot)) * \mathcal{V}(\tau)||_{L^2(\mathbb{R})}\, d\tau, \\ &\leq \int_{\mathbb{R}} ||\mathcal{H}(t-\tau,\cdot) - \mathcal{H}(s-\tau,\cdot)||_{L^2(\mathbb{R})} ||\mathcal{V}(\tau)||_{L^1(\mathbb{R})} d\tau, \end{aligned}$$

thanks to Young's Inequalities. It follows that

$$I \leq \int_{\mathbb{R}} ||\mathcal{H}(t-\tau,\cdot) - \mathcal{H}(s-\tau,\cdot)||_{L^2(\mathbb{R})} d\tau \; ||\mathcal{V}||_{L^\infty(\mathbb{R};L^1(\mathbb{R}))}.$$

Since the translation are continuous in $L^1(\mathbb{R}; L^2(\mathbb{R}))$, we see that $I \to 0$ as $|t-s| \to 0$. In particular, the function w is continuous and this completes the proof of the continuity of u.

Let us now prove the semi-group property. By (6) and (9), we infer that

$$\begin{aligned} u(t_0+t,\cdot) &= K(t,\cdot) * K(t_0,\cdot) * u_0 - \frac{1}{2}\int_0^{t_0} \partial_x K(t+t_0-s,\cdot) * v(s,\cdot) ds \\ &\qquad -\frac{1}{2}\int_{t_0}^{t+t_0} \partial_x K(t+t_0-s,\cdot) * v(s,\cdot) ds, \\ &= K(t_0,\cdot) * K(t,\cdot) * u_0 - \frac{1}{2}\int_0^{t_0} K(t,\cdot) * \partial_x K(t_0-s,\cdot) * v(s,\cdot) ds \\ &\qquad -\frac{1}{2}\int_0^{t} \partial_x K(t-s',\cdot) * v(t_0+s',\cdot) ds', \end{aligned}$$

thanks to the change of variable $s' = s - t_0$ to compute the last integral term. Then,

$$\begin{aligned} u(t_0+t,\cdot) &= K(t,\cdot) * K(t_0,\cdot) * u_0 - K(t,\cdot) * \frac{1}{2}\int_0^{t_0} \partial_x K(t_0-s,\cdot) * v(s,\cdot) ds \\ &\qquad -\frac{1}{2}\int_0^{t} \partial_x K(t-s',\cdot) * v(t_0+s',\cdot) ds', \\ &= K(t,\cdot) * \left(K(t_0,\cdot) * u_0 - \frac{1}{2}\int_0^{t_0} \partial_x K(t_0-s,\cdot) * v(s,\cdot) ds \right) \\ &\qquad -\frac{1}{2}\int_0^{t} \partial_x K(t-s',\cdot) * v(t_0+s',\cdot) ds', \\ &= K(t,\cdot) * u(t_0,\cdot) - \frac{1}{2}\int_0^{t} \partial_x K(t-s',\cdot) * v(t_0+s',\cdot) ds'. \end{aligned}$$

The proof of the semi group property is now complete. ■

Remark 5. *For $v \in L^\infty((0,T); L^1(\mathbb{R}))$, $u \in C([0,T]; L^2(\mathbb{R}))$ defined in* (13) *satisfies:*

$$||u||_{C([0,T];L^2(\mathbb{R}))} \leq e^{\omega_0 T} ||u_0||_{L^2(\mathbb{R})} + 2\mathcal{K}_0 T^{\frac{1}{4}} ||v||_{L^\infty((0,T);L^1(\mathbb{R}))}. \tag{16}$$

Proof. Indeed, with (14) and (15), we estimate the integral term of (13) and with (11), we estimate the L^2 norm of $K(t,\cdot) * u_0$. ■

4 Uniqueness of a solution

Let us state a lemma that will be needed later.

Lemma 1. *Let $T > 0$, $u_0 \in L^2(\mathbb{R})$. For $i = 1, 2$, let $v_i \in L^\infty((0,T); L^1(\mathbb{R}))$ and define $u_i \in C([0,T]; L^2(\mathbb{R}))$ as in Proposition 5 by*

$$u_i(t,\cdot) := K(t,\cdot) * u_0 - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * v_i(s,\cdot) ds.$$

Then we have the estimate

$$||u_1 - u_2||_{C([0,T];L^2(\mathbb{R}))} \leq 2\mathcal{K}_0 T^{\frac{1}{4}}\, ||v_1 - v_2||_{L^\infty((0,T);L^1(\mathbb{R}))}. \tag{17}$$

Proof. For all $t \in [0,T]$, we have

$$u_1(t,\cdot) - u_2(t,\cdot) = -\frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * (v_1(s,\cdot) - v_2(s,\cdot)) ds.$$

Hence,

$$\begin{aligned} ||u_1(t,\cdot) - u_2(t,\cdot)||_{L^2(\mathbb{R})} &= \frac{1}{2}\left|\left|\int_0^t \partial_x K(t-s,\cdot) * (v_1(s,\cdot) - v_2(s,\cdot)) ds\right|\right|_{L^2(\mathbb{R})}, \\ &\leq \frac{1}{2}\int_0^t ||\partial_x K(t-s,.) * (v_1(s,.) - v_2(s,.))||_{L^2(\mathbb{R})}\, ds. \end{aligned} \tag{18}$$

By (7),

$$\begin{aligned} ||\partial_x K(t-s,.) * (v_1(s,\cdot) - v_2(s,\cdot))||_{L^2(\mathbb{R})} &\leq ||\partial_x K(t-s,\cdot)\,||_{L^2(\mathbb{R})} ||v_1(s,\cdot) - v_2(s,\cdot)||_{L^1(\mathbb{R})} \\ &\leq \mathcal{K}_0 (t-s)^{-\frac{3}{4}} ||v_1(s,\cdot) - v_2(s,\cdot)||_{L^1(\mathbb{R})}. \end{aligned}$$

Inequality (18) then gives

$$\begin{aligned} ||u_1(t,\cdot) - u_2(t,\cdot)||_{L^2(\mathbb{R})} &\leq \frac{\mathcal{K}_0}{2}\int_0^t (t-s)^{-\frac{3}{4}} ds\, ||v_1 - v_2||_{L^\infty((0,t);L^1(\mathbb{R}))}, \\ &= 2\mathcal{K}_0 t^{\frac{1}{4}}\, ||v_1 - v_2||_{L^\infty((0,t);L^1(\mathbb{R}))}. \end{aligned}$$

In particular, for all $s \in [0,t]$

$$||u_1(s,\cdot) - u_2(s,\cdot)||_{L^2(\mathbb{R})} \leq 2\mathcal{K}_0 s^{\frac{1}{4}}\, ||v_1 - v_2||_{L^\infty((0,s);L^1(\mathbb{R}))} \leq 2\mathcal{K}_0 t^{\frac{1}{4}}\, ||v_1 - v_2||_{L^\infty((0,t);L^1(\mathbb{R}))}$$

and we have proved that

$$||u_1 - u_2||_{C([0,t];L^2(\mathbb{R}))} \leq 2\mathcal{K}_0 t^{\frac{1}{4}}\, ||v_1 - v_2||_{L^\infty((0,t);L^1(\mathbb{R}))}. \tag{19}$$

■

Proposition 6. *Let $T > 0$ and $u_0 \in L^2(\mathbb{R})$. There exists at most one $u \in L^\infty((0,T); L^2(\mathbb{R}))$ which is a mild solution to* (1)*.*

Proof. Let $u, v \in L^\infty((0,T);L^2(\mathbb{R}))$ be two mild solutions. Let $t \in [0,T]$. With Lemma 1 applied to $v_1 = u^2$ and $v_2 = v^2$, we get

$$||u-v||_{C([0,t];L^2(\mathbb{R}))} \leq 2\mathcal{K}_0 t^{\frac{1}{4}} \, ||u^2 - v^2||_{L^\infty((0,t);L^1(\mathbb{R}))}. \tag{20}$$

Since $||u^2-v^2||_{L^\infty((0,t);L^1(\mathbb{R}))} \leq M||u-v||_{C([0,t];L^2(\mathbb{R}))}$ with $M = ||u||_{C([0,T],L^2(\mathbb{R}))} + ||v||_{C([0,T],L^2(\mathbb{R}))}$, we get:

$$||u-v||_{C([0,t];L^2(\mathbb{R}))} \leq 2M\mathcal{K}_0 t^{\frac{1}{4}} \, ||u-v||_{C([0,t];L^2(\mathbb{R}))}.$$

We then have established that $u = v$ on $[0,t]$ for any $t \in (0,T]$ such that $t < (2M\mathcal{K}_0)^{-4}$. Notice that since u and v are continuous with values in L^2, $u = v$ on $[0,T_*]$ with $T_* = (2M\mathcal{K}_0)^{-4} > 0$. To prove that $u = v$ on $[0,T]$, let us define $t_0 := \sup\{t \in (0,T] \text{ s.t. } u = v \text{ on } [0,t]\}$ and let us assume that $t_0 \neq T$. The continuity of u and v implies that $u(t_0,\cdot) = v(t_0,\cdot)$. The semi-group property of Proposition 5 thus implies that $u(t_0+\cdot,\cdot)$ and $v(t_0+\cdot,\cdot)$ are mild solutions of (1)with the same initial condition; that is to say $u(t_0+0,\cdot) = v(t_0+0,\cdot)$. The first step of the proof then implies that $u(t_0+\cdot,\cdot) = v(t_0+\cdot,\cdot)$ on $[0, \min\{T_*, T-t_0\}]$; hence, we get a contradiction with the definition of t_0 and we deduce that $t_0 = T$. The proof of the uniqueness is now complete. ■

5 Existence of a regular solution

This section is devoted to the proof of the existence of a solution $u \in C^{1,2}((0,T]\times\mathbb{R})$to (1); that is to say, u is C^2 in space and C^1 in time. We first need the following technical result:

Lemma 2. *Let $u_0 \in L^2(\mathbb{R})$ and $T > 0$. Let $v \in C([0,T];L^1(\mathbb{R})) \cap C((0,T];W^{1,1}(\mathbb{R}))$ that satisfies*

$$\sup_{t\in(0,T]} t^{\frac{1}{2}} ||\partial_x v(t,\cdot)||_{L^1(\mathbb{R})} < +\infty. \tag{21}$$

Let $u \in C([0,T];L^2(\mathbb{R}))$ be the function defined in (13)*. Then, $u \in C((0,T];H^1(\mathbb{R}))$ with*

$$\sup_{t\in(0,T]} t^{\frac{1}{2}} ||\partial_x u(t,\cdot)||_{L^2(\mathbb{R})} \leq \mathcal{K}_1 ||u_0||_{L^2(\mathbb{R})} + \frac{\mathcal{K}_0 I}{2} \, T^{\frac{1}{4}} \sup_{t\in(0,T]} t^{\frac{1}{2}} ||\partial_x v(t,\cdot)||_{L^1(\mathbb{R})}, \tag{22}$$

where I is a constant equal to $\int_0^1 (1-s)^{-\frac{3}{4}} s^{-\frac{1}{2}} ds = B(1/2,1/4)$, B being the beta function.
Moreover, let $v_i \in C([0,T];L^1(\mathbb{R})) \cap C((0,T];W^{1,1}(\mathbb{R}))$ satisfy (21) *and define u_i by* (13) *(with u and v replaced, respectively, by u_i and v_i) for $i = 1,2$. Then,*

$$\sup_{t\in(0,T]} t^{\frac{1}{2}} ||\partial_x (u_1-u_2)(t,\cdot)||_{L^2(\mathbb{R})} \leq \frac{\mathcal{K}_0 I}{2} \, T^{\frac{1}{4}} \sup_{t\in(0,T]} t^{\frac{1}{2}} ||\partial_x (v_1-v_2)(t,\cdot)||_{L^1(\mathbb{R})}. \tag{23}$$

Proof. Recall that Proposition 5 ensures that $u \in C([0,T];L^2(\mathbb{R}))$. It is easy to check that the distribution derivative of u w.r.t. the space variable satisfies: for any $t \in (0,T]$,

$$\partial_x u(t,\cdot) = \partial_x K(t,\cdot) * u_0 - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * \partial_x v(s,\cdot) ds.$$

Let us verify that all the terms are well-defined in L^2. Since $\partial_x K(t,\cdot) \in L^1(\mathbb{R})$, it is obvious that $\partial_x K(t,\cdot) * u_0 \in L^2(\mathbb{R})$. Moreover, define

$$w(t,\cdot) := \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * \partial_x v(s,\cdot) ds.$$

Young's Inequalities and (7) give

$$\begin{aligned}||\partial_x K(t-s,\cdot) * \partial_x v(s,\cdot)||_{L^2(\mathbb{R})} &\leq ||\partial_x K(t-s,\cdot)||_{L^2(\mathbb{R})}||\partial_x v(s,\cdot)||_{L^1(\mathbb{R})},\\ &= ||\partial_x K(t-s,\cdot)||_{L^2(\mathbb{R})} s^{-\frac{1}{2}} s^{\frac{1}{2}}||\partial_x v(s,\cdot)||_{L^1(\mathbb{R})},\\ &\leq \mathcal{K}_0(t-s)^{-\frac{3}{4}}s^{-\frac{1}{2}} \sup_{\tau\in(0,T]} \tau^{\frac{1}{2}}||\partial_x v(\tau,\cdot)||_{L^1(\mathbb{R})}. \qquad (24)\end{aligned}$$

Since $\int_0^t (t-s)^{-\frac{3}{4}}s^{-\frac{1}{2}}\,ds < \infty$, by (21) we deduce that $w(t,\cdot)$ is well-defined in L^2 and thus for all $t \in (0,T]$, $\partial_x u(t,\cdot) \in L^2(\mathbb{R})$. Let us now prove that $\partial_x u$ is continuous on $(0,T]$ with values in L^2. For $\delta > 0$ and $t \in (0,T]$, define

$$w_\delta(t,\cdot) := \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * \left(\mathbf{1}_{\{s>\delta\}}\partial_x v(s,\cdot)\right) ds.$$

Since $\mathbf{1}_{\{s>\delta\}}\partial_x v(s,\cdot) \in L^\infty([0,T];L^1(\mathbb{R}))$, Proposition 5 ensures that w_δ is continuous on $[0,T]$ with values in L^2. Moreover, for any $t_0 \in (0,T]$, $\delta \leq t_0$ and $t \in [t_0,T]$,

$$\begin{aligned}||w(t,\cdot) - w_\delta(t,\cdot)||_{L^2(\mathbb{R})} &\leq \frac{1}{2}\int_0^\delta ||\partial_x K(t-s,\cdot) * \partial_x v(s,\cdot)||_{L^2(\mathbb{R})} ds,\\ &\leq \frac{\mathcal{K}_0}{2}\int_0^\delta (t-s)^{-\frac{3}{4}}s^{-\frac{1}{2}}ds \sup_{s\in(0,T]} s^{\frac{1}{2}}||\partial_x v(s,\cdot)||_{L^1(\mathbb{R})} \quad \text{by (24)},\\ &\leq \frac{\mathcal{K}_0}{2}\int_0^\delta (t_0-s)^{-\frac{3}{4}}s^{-\frac{1}{2}}ds \sup_{s\in(0,T]} s^{\frac{1}{2}}||\partial_x v(s,\cdot)||_{L^1(\mathbb{R})}.\end{aligned}$$

It follows that

$$\sup_{t\in[t_0,T]} ||w(t,\cdot) - w_\delta(t,\cdot)||_{L^2(\mathbb{R})} \leq \frac{\mathcal{K}_0}{2}\int_0^\delta (t_0-s)^{-\frac{3}{4}}s^{-\frac{1}{2}}ds \sup_{s\in(0,T]} s^{\frac{1}{2}}||\partial_x v(s,\cdot)||_{L^1(\mathbb{R})} \to 0,$$

as $\delta \to 0$. We deduce that $w \in C((0,T];L^2(\mathbb{R}))$ as local uniform limit of continuous functions. Moreover,

$$\partial_x K(t,\cdot) * u_0 = \mathcal{F}^{-1}\left(\xi \to 2i\,\pi\xi e^{-t\psi_{\mathcal{I}}(\xi)}\mathcal{F}u_0(\xi)\right).$$

The dominated convergence theorem immediately implies that for any $t_0 > 0$,

$$\int_{\mathbb{R}} 4\pi^2|\xi|^2\left|e^{-t\psi_{\mathcal{I}}(\xi)} - e^{-t_0\psi_{\mathcal{I}}(\xi)}\right|^2 |\mathcal{F}u_0(\xi)|^2 d\xi \to 0, \quad \text{as } t \to t_0.$$

This means that $t > 0 \to \left(\xi \to 2i\,\pi\xi e^{-t\psi_{\mathcal{I}}(\xi)}\mathcal{F}u_0\right) \in L^2(\mathbb{R})$ is continuous and, since $\mathcal{F}$ is an isometry of L^2, we deduce that $t > 0 \to \partial_x K(t,\cdot) * u_0 \in L^2(\mathbb{R})$ is continuous. We then have established that $\partial_x u \in C((0,T];L^2(\mathbb{R}))$. Let us now estimate how the L^2 norm of $\partial_x u$ can explode at $t = 0$. By (24),

$$\begin{aligned}||w(t,\cdot)||_{L^2(\mathbb{R})} \leq \frac{\mathcal{K}_0}{2}\int_0^t (t-s)^{-\frac{3}{4}}s^{-\frac{1}{2}}ds \sup_{\tau\in(0,T]} \tau^{\frac{1}{2}}||\partial_x v(\tau,\cdot)||_{L^1(\mathbb{R})}\\ = \frac{\mathcal{K}_0 I}{2}t^{-\frac{1}{4}} \sup_{\tau\in(0,T]} \tau^{\frac{1}{2}}||\partial_x v(\tau,\cdot)||_{L^1(\mathbb{R})},\end{aligned}$$

where $I = \int_0^1 (1-s')^{-\frac{3}{4}} s'^{-\frac{1}{2}} ds' = B(1/2, 1/4)$; notice that the last integral term has been computed with the help of the change of variable $s' = \frac{s}{t}$. Moreover, (8) and Young's Inequalities imply that

$$||\partial_x K(t,\cdot) * u_0||_{L^2(\mathbb{R})} \leq \mathcal{K}_1 t^{-\frac{1}{2}} ||u_0||_{L^2(\mathbb{R})}.$$

We deduce that for any $t \in (0,T]$,

$$||\partial_x u(t,\cdot)||_{L^2(\mathbb{R})} \leq \mathcal{K}_1 t^{-\frac{1}{2}} ||u_0||_{L^2(\mathbb{R})} + \frac{\mathcal{K}_0 I}{2} t^{-\frac{1}{4}} \sup_{s\in(0,T]} s^{\frac{1}{2}} ||\partial_x v(s,\cdot)||_{L^1(\mathbb{R})},$$

which implies immediately (22).

Let us now prove (23). For any $t \in (0,T]$,

$$\begin{aligned} ||\partial_x (u_1-u_2)(t,\cdot)||_{L^2(\mathbb{R})} &\leq \frac{1}{2}\int_0^t ||\partial_x K(t-s,.) * \partial_x (v_1-v_2)(s,\cdot)||_{L^2(\mathbb{R})} ds, \\ &\leq \frac{\mathcal{K}_0}{2}\int_0^t (t-s)^{-\frac{3}{4}} s^{-\frac{1}{2}} ds \sup_{s\in(0,T]} s^{\frac{1}{2}} ||\partial_x (v_1-v_2)(s,\cdot)||_{L^1(\mathbb{R})}, \\ &= \frac{\mathcal{K}_0 I}{2} t^{-\frac{1}{4}} \sup_{s\in(0,T]} s^{\frac{1}{2}} ||\partial_x (v_1-v_2)(s,\cdot)||_{L^1(\mathbb{R})}, \end{aligned}$$

which implies immediately (23). ■

Remark 6. *Let u_0, T, v and u that satisfy assumptions of Lemma 2. Then, we have established that for any $t \in (0,T]$,*

$$\partial_x u(t,\cdot) = \partial_x K(t,\cdot) * u_0 - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * \partial_x v(s,\cdot) ds.$$

Let us now prove the local-in-time existence of a regular solution.

Proposition 7. *Let $u_0 \in L^2(\mathbb{R})$. There exists $T_* > 0$ that only depends on $||u_0||_{L^2(\mathbb{R})}$ such that* (1) *admits a (unique) mild solution $u \in C([0,T_*]; L^2(\mathbb{R})) \cap C((0,T_*]; H^2(\mathbb{R}))$ on $(0,T_*)$such that*

$$\sup_{t\in(0,T_*]} t^{\frac{1}{2}} ||\partial_x u(t,\cdot)||_{L^2(\mathbb{R})} < +\infty \quad \textit{and} \quad \sup_{t\in(0,T_*]} t||\partial^2_{xx} u(t,\cdot)||_{L^2(\mathbb{R})} < +\infty.$$

Moreover, u belongs to $C^{1,2}((0,T_*]\times\mathbb{R})$ and satisfies the PDE in (1) *in the classical sense.*

Proof. We use a contracting fixed point theorem. For $u \in C([0,T_*]; L^2(\mathbb{R})) \cap C((0,T_*]; H^1(\mathbb{R}))$, define the norm

$$|||u||| := ||u||_{C([0,T_*];L^2(\mathbb{R}))} + \sup_{t\in(0,T_*]} t^{\frac{1}{2}} ||\partial_x u(t,\cdot)||_{L^2(\mathbb{R})}. \tag{25}$$

Define the space

$$X := \left\{ u \in C([0,T_*]; L^2(\mathbb{R})) \cap C((0,T_*]; H^1(\mathbb{R})) \text{ s.t. } u(0,\cdot) = u_0 \text{ and } |||u||| < +\infty \right\}.$$

It is readily seen that X is a complete metric space endowed with the distance induced by the norm $|||\cdot|||$. For $u \in X$, define the function

$$\Theta u : t \in [0,T_*] \to K(t,\cdot) * u_0 - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * u^2(s,\cdot) ds \in L^2(\mathbb{R}). \tag{26}$$

By Proposition 5, $\Theta u \in C([0,T_*];L^2(\mathbb{R}))$ and satisfies $\Theta u(0,\cdot) = u_0$. Define $v := u^2$. We have $\partial_x v = 2u\partial_x u$. Therefore that $v \in C([0,T_*];L^1(\mathbb{R})) \cap C((0,T_*];W^{1,1}(\mathbb{R}))$ and that (21) holds true. By Lemma 2, we deduce that $\Theta u \in X$. Let us take $R > ||u_0||_{L^2(\mathbb{R})} + \mathcal{K}_1||u_0||_{L^2(\mathbb{R})}$ and assume that $|||u||| \leq R$. Since $||u^2||_{L^\infty((0,T_*);L^1(\mathbb{R}))} = ||u||^2_{C([0,T_*];L^2(\mathbb{R}))}$, estimate (16) of Remark 5 implies that

$$\begin{aligned} ||\Theta u||_{C([0,T_*];L^2(\mathbb{R}))} &\leq e^{\omega_0 T_*}||u_0||_{L^2(\mathbb{R})} + 2\mathcal{K}_0 T_*^{\frac{1}{4}}\,||u||^2_{C([0,T_*];L^2(\mathbb{R}))}, \\ &\leq e^{\omega_0 T_*}||u_0||_{L^2(\mathbb{R})} + 2\mathcal{K}_0 T_*^{\frac{1}{4}}\,R^2. \end{aligned} \tag{27}$$

Estimate (22) of Lemma 2, implies that

$$\begin{aligned} \sup_{t\in(0,T_*]} t^{\frac{1}{2}}||\partial_x(\Theta u(t,\cdot))||_{L^2(\mathbb{R})} &\leq \mathcal{K}_1||u_0||_{L^2(\mathbb{R})} + \frac{\mathcal{K}_0 I}{2}\,T_*^{\frac{1}{4}} \sup_{t\in(0,T_*]} t^{\frac{1}{2}}||\partial_x(u^2)(t,\cdot)||_{L^1(\mathbb{R})}, \\ &\leq \mathcal{K}_1||u_0||_{L^2(\mathbb{R})} + \mathcal{K}_0 I\,T_*^{\frac{1}{4}} R^2, \end{aligned}$$

by Cauchy-Schwarz inequality. Adding this inequality with (27), we get:

$$|||\Theta u||| \leq e^{\omega_0 T_*}||u_0||_{L^2(\mathbb{R})} + \mathcal{K}_1||u_0||_{L^2(\mathbb{R})} + (2+I)\,\mathcal{K}_0 T_*^{\frac{1}{4}} R^2.$$

For $T_* \in (0,T]$ sufficiently small such that

$$e^{\omega_0 T_*}||u_0||_{L^2(\mathbb{R})} + \mathcal{K}_1||u_0||_{L^2(\mathbb{R})} + (2+I)\,\mathcal{K}_0 T_*^{\frac{1}{4}} R^2 \leq R, \tag{28}$$

we deduce that $|||\Theta u||| \leq R$. To sum-up, we have established that for any $T_* \in (0,T]$ such that (28) holds true, Θ (defined by (26)) maps $\overline{B}_R$ into itself, where $\overline{B}_R$ denotes the ball of X (endowed with the $|||\cdot|||$ norm) centered at the origin and of radius R. Let us now prove that Θ is a contraction. For $u, v \in \overline{B}_R$, Estimate (17) of Lemma 1 implies that

$$||\Theta u - \Theta v||_{C([0,T_*];L^2(\mathbb{R}))} \leq 4R\mathcal{K}_0 T_*^{\frac{1}{4}}\,||u-v||_{C([0,T_*];L^2(\mathbb{R}))}, \tag{29}$$

where we again used $||u^2 - v^2||_{C([0,T_*];L^1(\mathbb{R}))} \leq (||u||_{C([0,T_*],L^2(\mathbb{R}))} + ||v||_{C([0,T_*],L^2(\mathbb{R}))})||u-v||_{C([0,T_*];L^2(\mathbb{R}))}$. Moreover, Estimate (23) of Lemma 2 implies that

$$\sup_{t\in(0,T_*]} t^{\frac{1}{2}}||\partial_x(\Theta u - \Theta v)(t,\cdot)||_{L^2(\mathbb{R})} \leq \mathcal{K}_0 I T_*^{\frac{1}{4}} \sup_{t\in(0,T_*]} t^{\frac{1}{2}}||(u\partial_x u - v\partial_x v)(t,\cdot)||_{L^1(\mathbb{R})}.$$

Since

$$\begin{aligned} t^{\frac{1}{2}}||(u\partial_x u - v\partial_x v)(t,\cdot)||_{L^1(\mathbb{R})} &\leq t^{\frac{1}{2}}||\partial_x v(t,\cdot)||_{L^2(\mathbb{R})}||(u-v)(t,\cdot)||_{L^2(\mathbb{R})} \\ &\quad + t^{\frac{1}{2}}||u(t,\cdot)||_{L^2(\mathbb{R})}||\partial_x(u-v)(t,\cdot)||_{L^2(\mathbb{R})}, \\ &\leq |||v|||\;||(u-v)(t,\cdot)||_{L^2(\mathbb{R})} \\ &\quad + |||u|||\;t^{\frac{1}{2}}||\partial_x(u-v)(t,\cdot)||_{L^2(\mathbb{R})}, \\ &\leq R|||u-v|||, \end{aligned}$$

we get: $\sup_{t\in(0,T_*]} t^{\frac{1}{2}}||\partial_x(\Theta u - \Theta v)(t,\cdot)||_{L^2(\mathbb{R})} \leq R\mathcal{K}_0 I T_*^{\frac{1}{4}}|||u-v|||$. Adding this inequality with (29), we find that

$$|||\Theta u - \Theta v||| \leq (4+I)R\mathcal{K}_0 T_*^{\frac{1}{4}}|||u-v|||.$$

Consequently, for any $T_* > 0$ sufficiently small such that (28) holds true and $(4+I)R\mathcal{K}_0 T_*^{\frac{1}{4}} < 1$, Θ is a contraction from $\overline{B}_R$ into itself. The Banach fixed point theorem then implies that Θ admits a (unique) fixed point $u \in C([0,T_*];L^2(\mathbb{R})) \cap C((0,T_*];H^1(\mathbb{R}))$ satisfying $\sup_{t\in(0,T_*]} t^{\frac{1}{2}}||\partial_x u(t,\cdot)||_{L^2(\mathbb{R})} < \infty$ which is, of course, a mild solution to (1).

To prove the H^2 regularity of u, we have to use again a contracting fixed point theorem. But, this is now the gradient of the solution which is searched as a fixed point. Let $t_0 \in (0,T_*)$. For any $t \in (0, T_* - t_0]$, define $\overline{u}(t,\cdot) := u(t_0+t,\cdot)$. Let $T_*' \in (0, T_* - t_0]$. We still endow $C([0,T_*'];L^2(\mathbb{R})) \cap C((0,T_*'];H^1(\mathbb{R}))$ with the norm $|||\cdot|||$ defined in (25) with T_* replaced by T_*'. Define the complete metric space

$$X' := \left\{ v \in C([0,T_*'];L^2(\mathbb{R})) \cap C((0,T_*'];H^1(\mathbb{R})) \text{ s.t. } v(0,\cdot) = v_0 \text{ and } |||v||| < +\infty \right\},$$

where $v_0 := \partial_x \overline{u}(0,\cdot)$. For $v \in X'$, define the function

$$\Theta' v : t \in [0,T_*'] \to K(t,\cdot) * v_0 - \int_0^t \partial_x K(t-s,\cdot) * (\overline{u}v)(s,\cdot) ds \in L^2(\mathbb{R}). \tag{30}$$

Arguing as in the first step of the proof, we claim that Proposition 5, Remark 5, Lemmas 1 and 2 imply that Θ' maps X' into itself with: for any $u, v \in X'$,

$$|||\Theta' v||| \le e^{\omega_0 T_*'}||v_0||_{L^2(\mathbb{R})} + \mathcal{K}_1||v_0||_{L^2(\mathbb{R})} + C{T_*'}^{\frac{1}{4}}|||v|||,$$

$$|||\Theta' v - \Theta' w||| \le C{T_*'}^{\frac{1}{4}}|||v-w|||,$$

for some nonnegative constant C that only depends on $\mathcal{K}_0$ and $||\overline{u}||_{C([t_0,T_*];H^1(\mathbb{R}))}$. Let us take R' such that

$$R' > e^{\omega_0 T_*'}||v_0||_{L^2(\mathbb{R})} + \mathcal{K}_1||v_0||_{L^2(\mathbb{R})}.$$

If $T_*' > 0$ satisfies

$$e^{\omega_0 T_*'}||v_0||_{L^2(\mathbb{R})} + \mathcal{K}_1||v_0||_{L^2(\mathbb{R})} + C{T_*'}^{\frac{1}{4}} R' \le R' \quad \text{and} \quad C{T_*'}^{\frac{1}{4}} < 1,$$

then Θ' maps $\overline{B}_{R'}(X')$ into itself and is a contraction. Let v denote its unique fixed point. Observe now that $\Theta' \partial_x \overline{u} = \partial_x \overline{u}$, thanks to Remark 6. But, similar arguments than these ones used to prove the uniqueness of a mild solution in the preceding section allow to show that there exists at most one function $w \in L^\infty((0,T_*');L^2(\mathbb{R}))$ that satisfies $\Theta' w = w$. It follows that $\partial_x \overline{u} = v \in X'$ on $(0,T_*')$; hence, we deduce that $u \in C(t_0, t_0+T_*'];H^2(\mathbb{R}))$. To sum-up, we have proved that for all $t_0 \in (0,T_*]$, there exists $T_*' \in (0, T_* - t_0]$ such that $u \in C((t_0, t_0+T_*'];H^2(\mathbb{R}))$. This completes the proof of the continuity of u on $(0,T_*]$ with values in H^2. The proof of the $C^{1,2}$ regularity is postponed to Lemma 3 in the next section, where it will be useful for the maximum principle failure. ■

We can finally prove the global-in-time existence.

Proposition 8. *Let $u_0 \in L^2(\mathbb{R})$ and $T > 0$. There exists a (unique) mild solution $u \in C([0,T];L^2(\mathbb{R})) \cap C((0,T];H^2(\mathbb{R}))$ to* (1) *such that*

$$\sup_{t\in(0,T]} t^{\frac{1}{2}}||\partial_x u(t,\cdot)||_{L^2(\mathbb{R})} < +\infty \quad \textit{and} \quad \sup_{t\in(0,T]} t||\partial^2_{xx} u(t,\cdot)||_{L^2(\mathbb{R})} < +\infty.$$

Moreover, u belongs to $C^{1,2}((0,T]\times\mathbb{R})$ and satisfies the PDE in (1) *in the classical sense.*

Proof. We have to derive first a L^2 estimate on the local regular solution u constructed in Proposition 7. Multiplying (1) by u and integrating w.r.t. the space variable, we get:

$$\frac{d}{dt}\frac{1}{2}\int_{\mathbb{R}} u^2 dx + \int_{\mathbb{R}} (\mathcal{I}[u] - \partial_{xx}^2 u) u dx = 0. \tag{31}$$

Indeed, the following computations show that the nonlinear term equals 0:

$$\int_{\mathbb{R}} \partial_x \left(\frac{u^2}{2}\right) u dx = -\int_{\mathbb{R}} \frac{u^2}{2} \partial_x u dx = -\frac{1}{2}\int_{\mathbb{R}} u(\partial_x u u) dx = -\frac{1}{2}\int_{\mathbb{R}} u\, \partial_x \left(\frac{u^2}{2}\right) dx.$$

But, Corollary 1 implies that

$$\int_{\mathbb{R}} (\mathcal{I}[u] - \partial_{xx}^2 u) u dx = \int_{\mathbb{R}} \mathcal{F}^{-1}(\psi_{\mathcal{I}} \mathcal{F} u) u dx = \int_{\mathbb{R}} \psi_{\mathcal{I}} |\mathcal{F} u|^2 d\xi = \int_{\mathbb{R}} \mathrm{Re}(\psi_{\mathcal{I}}) |\mathcal{F} u|^2 d\xi,$$

since $\int_{\mathbb{R}} (\mathcal{I}[u] - \partial_{xx}^2 u) u dx$ is real. It follows that,

$$\begin{aligned} \int_{\mathbb{R}} (\mathcal{I}[u] - \partial_{xx}^2 u) u dx &\geq \min \mathrm{Re}(\psi_{\mathcal{I}}) \int_{\mathbb{R}} |\mathcal{F} u|^2 d\xi, \\ &= \min \mathrm{Re}(\psi_{\mathcal{I}}) \int_{\mathbb{R}} u^2 dx, \end{aligned}$$

thanks to Plancherel's Equality. Equation (31) then implies that

$$\frac{d}{dt}\frac{1}{2}\int_{\mathbb{R}} u^2 dx \leq \omega_0 \int_{\mathbb{R}} u^2 dx$$

and by Gronwall's Lemma, we deduce that for all $t \in [0, T_*]$

$$||u(t,\cdot)||_{L^2(\mathbb{R})} \leq e^{\omega_0 t} ||u_0||_{L^2(\mathbb{R})}.$$

Define now

$$t_0 := \sup\{t > 0 \text{ s.t. there exists a (unique) mild sol. to (1) on } (0,t) \text{ that satisfies the regularity of Proposition 8}\}$$

and let us assume that $t_0 < T$ (recall that Proposition 7 ensures that $t_0 > 0$). By Proposition 7, there exists $T_* > 0$ such that for any initial data v_0 that satisfy $||v_0||_{L^2(\mathbb{R})} \leq e^{\omega_0 t_0} ||u_0||_{L^2(\mathbb{R})}$, (1) admits a regular mild solution on $(0, T_*)$ with initial datum v_0. Hence, if we define $v_0 = u(t_0 - T_*/2)$, then (1) admits a mild solution v that satisfies the regularity of Proposition 8. Using the uniqueness and the semi-group property, it is now easy to show that $u(t_0 - T_*/2 + t, \cdot) = v(t, \cdot)$ for all $t \in [0, T_*/2]$ and that the function $\widetilde{u}$ defined by $\widetilde{u} = u$ on $[0, t_0]$ and $\widetilde{u}(t_0 - T_*/2 + t, \cdot) = v(t, \cdot)$ for $t \in [T_*/2, T_*]$ is still a mild solution to (1) that satisfies the regularity of proposition 8. Since the solution $\widetilde{u}$ lives on $[0, t_0 + T_*/2]$, this gives us a contradiction. We conclude that $t_0 \geq T$ and this completes the proof of the global existence of a regular solution. ■

Remark 7. *To sum-up, we have proved Theorem 1 with the $C^{1,2}$ regularity of u. To obtain further regularity, we claim that we can use the same method by arguing by induction.*

Now we prove the L^2-stability stated in Proposition 1.

Proof of Proposition 1 . Let (u, v) be solutions to (1) with respective L^2 initial data (u_0, v_0). let $T > 0$ and $t \in [0, T]$. Substracting

$$u(t,\cdot) = K(t,\cdot) * u_0 - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * u^2(s,\cdot)ds$$

and

$$v(t,.) = K(t,\cdot) * v_0 - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * v^2(s,\cdot)ds$$

we get

$$u(t,\cdot) - v(t,\cdot) = K(t,\cdot) * (u_0 - v_0) - \frac{1}{2}\int_0^t \partial_x K(t-s,\cdot) * (u^2(s,\cdot) - v^2(s,\cdot))ds. \tag{32}$$

Hence, by (11) of Remark 4 and Young inequality

$$||u(t,\cdot)-v(t,\cdot)||_{L^2(\mathbb{R})} \leq e^{\omega_0 T}||u_0-v_0||_{L^2(\mathbb{R})} + \frac{1}{2}\int_0^t ||\partial_x K(t-s,\cdot)||_{L^2(\mathbb{R})}||u^2(s,\cdot)-v^2(s,\cdot)||_{L^1(\mathbb{R})}\, ds.$$

Taking $M = \max\left(||u||_{C([0,T];L^2(\mathbb{R}))}, ||v||_{C([0,T];L^2(\mathbb{R}))}\right)$, we can bound

$$\begin{aligned} ||u(t,\cdot) - v(t,\cdot)||_{L^2(\mathbb{R})} &\leq e^{\omega_0 T}||u_0 - v_0||_{L^2(\mathbb{R})} + M\int_0^t ||\partial_x K(t-s,\cdot)||_{L^2(\mathbb{R})}||u(s,\cdot) - v(s,\cdot)||_{L^2(\mathbb{R})}\, ds \\ &\leq e^{\omega_0 T}||u_0 - v_0||_{L^2(\mathbb{R})} + M\mathcal{K}_0\int_0^t (t-s)^{-\frac{3}{4}}||u(s,\cdot) - v(s,\cdot)||_{L^2(\mathbb{R})}\, ds, \end{aligned}$$

thanks to (7). With lemma 4, the proof is finished. ■

6 Failure of the maximum principle

We now investigate the proof of Theorem 2. We first need a regularity result which ensures that if the initial data is regular then so is the solution up to the time $t = 0$.

Lemma 3. *Let $u_0 \in H^2(\mathbb{R})$ and $T > 0$. Assume that u is a mild solution to* (1) *that satisfies the regularity of Proposition 7. Then, u is in fact $C([0,T]; H^2(\mathbb{R})) \cap C^{1,2}((0,T]\times\mathbb{R})$ and satisfies the PDE in* (1) *in the classical sense. Moreover, if $u_0 \in C^2(\mathbb{R})$, then $u \in C^{1,2}([0,T]\times\mathbb{R})$ and satisfies the PDE up to the time $t = 0$.*

Proof. First, we leave it to the reader to verify that the continuity with values in H^2 up to the time $t = 0$ can be proved again by the use of a contracting fixed point theorem. Note that the regularity of u_0 allows to work in a space of continuous functions with values in H^2 up to the time $t = 0$; more precisely, we argue as in the proof of Proposition 7, but we can directly use the $C([0,T_*]; H^2)$ norm instead of the $|||\cdot|||$ norm defined in (25). Let us now prove that u is a classical solution to (1). Taking the Fourier transform w.r.t. the space variable in (12), we get: for all $t \in [0,T]$,

$$\mathcal{F}(u(t,\cdot)) = e^{-t\psi_{\mathcal{I}}}\mathcal{F}u_0 - \int_0^t i\,\pi\cdot e^{-(t-s)\psi_{\mathcal{I}}}\mathcal{F}(u^2(s,\cdot))ds. \tag{33}$$

Since $u^2 \in C([0,T];L^1(\mathbb{R}))$, we know that $\mathcal{F}(u^2) \in C([0,T];C_b(\mathbb{R},\mathbb{C}))$. For any $\xi \in \mathbb{R}$, the function $t \in [0,T] \to \mathcal{F}(u^2(t,\cdot))(\xi) \in \mathbb{C}$ is thus continuous. Define

$$w(t,\xi) := -\int_0^t i\,\pi\xi e^{-(t-s)\psi_{\mathcal{I}}(\xi)}\mathcal{F}(u^2(s,\cdot))(\xi)ds.$$

Classical results on ODE then imply that w is derivable w.r.t. the time variable with

$$\partial_t w(t,\xi) + \psi_{\mathcal{I}}(\xi)w(t,\xi) = -i\,\pi\xi\mathcal{F}(u^2(t,\cdot))(\xi) = -\mathcal{F}\left(\partial_x\left(\frac{u^2}{2}\right)(t,\cdot)\right)(\xi). \tag{34}$$

Let us prove that all these terms are continuous with values in L^2. First, $u \in C([0,T];H^1(\mathbb{R}))$ therefore $\partial_x(u^2) \in C([0,T];L^2(\mathbb{R}))$ and we deduce that $\mathcal{F}(\partial_x(\frac{u^2}{2}))$ is continuous with values in L^2. Moreover, Equation (33) implies that

$$\psi_{\mathcal{I}}\; w(t,\cdot) = \psi_{\mathcal{I}}\left(\mathcal{F}(u(t,\cdot)) - e^{-t\psi_{\mathcal{I}}}\mathcal{F}u_0\right).$$

Since $u \in C([0,T];L^2(\mathbb{R}))$ and $\psi_{\mathcal{I}}$ behaves at infinity as $|\cdot|^2$, $\psi_{\mathcal{I}}w$ is continuous with values in L^2. All the terms in (33) then are continuous with values in L^2 and this implies $w \in C^1([0,T];L^2(\mathbb{R},\mathbb{C}))$ with

$$\frac{d}{dt}(w(t,\cdot)) + \psi_{\mathcal{I}}\; w(t,\cdot) = -\mathcal{F}\left(\partial_x\left(\frac{u^2}{2}\right)(t,\cdot)\right).$$

Moreover, it is easy to see that $t \in [0,T] \to e^{-t\psi_{\mathcal{I}}}\mathcal{F}u_0 \in L^2(\mathbb{R},\mathbb{C})$ is C^1 with

$$\frac{d}{dt}\left(e^{-t\psi_{\mathcal{I}}}\mathcal{F}u_0\right) + \psi_{\mathcal{I}}e^{-t\psi_{\mathcal{I}}}\mathcal{F}u_0 = 0.$$

From Equation (33), we infer that $\mathcal{F}u$ is C^1 on $[0,T]$ with values in L^2 with

$$\begin{aligned}\frac{d}{dt}(\mathcal{F}(u(t,\cdot))) = -\psi_{\mathcal{I}}w(t,\cdot) - \psi_{\mathcal{I}}e^{-t\psi_{\mathcal{I}}}\mathcal{F}u_0 - \mathcal{F}\left(\partial_x\left(\frac{u^2}{2}\right)(t,\cdot)\right)\\ = -\psi_{\mathcal{I}}\mathcal{F}(u(t,\cdot)) - \mathcal{F}\left((u\partial_x u)(t,\cdot)\right).\end{aligned}$$

Since $\mathcal{F}$ is an isometry of L^2, we deduce that $u \in C^1([0,T];L^2(\mathbb{R}))$ and that

$$\begin{aligned}\frac{d}{dt}(u(t,.)) &= -\partial_x\left(\frac{u^2}{2}\right)(t,\cdot) - \mathcal{F}^{-1}\left(\psi_{\mathcal{I}}\mathcal{F}(u(t,\cdot))\right),\\ &= -\partial_x\left(\frac{u^2}{2}\right)(t,\cdot) - \mathcal{I}[u(t,\cdot)] + \partial^2_{xx}u(t,\cdot),\end{aligned}$$

where we used Corollary 1 to compute the pseudo-differential term. In particular, u satisfies the PDE of (1) in the distribution sense. What is left to prove is the C^2 regularity in space of u. Differentiating (12) two times w.r.t. the space variable, we get: for any $t \in [0,T]$,

$$\partial^2_{xx}u(t,\cdot) = K(t,\cdot) * u_0'' - \int_0^t \partial_x K(t-s,\cdot) * v(s,\cdot)ds. \tag{35}$$

where $v = (\partial_x u)^2 + u\partial^2_{xx}u$. By the Sobolev imbedding $H^2(\mathbb{R}) \hookrightarrow C^1_b(\mathbb{R})$, we know that $v \in C([0,T];L^1(\mathbb{R}) \cap L^2(\mathbb{R}))$. By Lemma 5, we know that for all $x,y \in \mathbb{R}$,

$$|\partial_x K(t-s,\cdot)*v(s,\cdot)(x) - \partial_x K(t-s,\cdot)*v(s,\cdot)(y)| \le ||\partial_x K(t-s)||_{L^2(\mathbb{R})}||\mathcal{T}_{(x-y)}(v(s,\cdot)) - v(s,\cdot)||_{L^2(\mathbb{R})}.$$

By (7), we deduce that for all $t \in [0,T]$ and all $x, y \in \mathbb{R}$,

$$\left| \int_0^t \partial_x K(t-s,\cdot) * v(s,\cdot)(x) ds - \int_0^t \partial_x K(t-s,\cdot) * v(s,\cdot)(y) ds \right|$$
$$\leq \int_0^t \mathcal{K}_0 (t-s)^{-\frac{3}{4}} ||\mathcal{T}_{(x-y)}(v(s,\cdot)) - v(s,\cdot)||_{L^2(\mathbb{R})} ds \leq 4T^{\frac{1}{4}} \sup_{s\in[0,T]} ||\mathcal{T}_{(x-y)}(v(s,\cdot)) - v(s,\cdot)||_{L^2(\mathbb{R})}.$$

By Lemma 6, we deduce that the second term of (35) is continuous w.r.t. the space variable independently of the time variable (equicontinuity w.r.t. the time variable). Moreover, we already know that this term is continuous on $[0,T]$ with values in L^2 (by Proposition 5) and Lemma 7 implies that it is continuous w.r.t. the couple (t,x) on $[0,T] \times \mathbb{R}$. We now leave it to the reader to verify that $(t,x) \to K(t,\cdot) * u_0''(x)$ is continuous on $(0,T] \times \mathbb{R}$ when $u_0 \in H^2(\mathbb{R})$ and continuous on $[0,T] \times \mathbb{R}$ when moreover $u_0 \in C^2(\mathbb{R})$. The proof of Lemma 3 is complete. ■

The proof of Theorem 2 is now an immediate consequence of the integral formula (3).

Proof of Theorem 2. Lemma 3 and Proposition 2 imply that the solution u to (1) is $C^{1,2}$ up to the initial time $t = 0$ and that

$$u_t(0,x_*) + u_0(x_*)u_0'(x_*) + C_{\mathcal{I}} \int_{-\infty}^0 \frac{u_0(x_*+z) - u_0(x_*) - u_0'(x_*)z}{|z|^{7/3}}\, dz - u_0''(x_*) = 0.$$

It follows that

$$u_t(0,x_*) = -C_{\mathcal{I}} \int_{-\infty}^0 \frac{u_0(x_*+z)}{|z|^{7/3}}\, dz < 0.$$

There then exists $t_* > 0$ such that $u(t_*,x_*) < 0$. The proof of Theorem 2 is now complete. ■

7 Numerical simulations

The aim of this part is to show some numerical simulations for (1). An explicit discretization gives results in line with the theoretical study (see Remark 2).

We write (1) with a viscous coefficient $\varepsilon > 0$ as follows:

$$\partial_t u + \partial_x \left(\frac{u^2}{2} + \mathcal{L}[u] \right) - \varepsilon \partial_{xx}^2 u = 0, \tag{36}$$

where for any $\varphi \in \mathcal{S}(\mathbb{R})$ and $x \in \mathbb{R}$,

$$\mathcal{L}[\varphi](x) := \int_0^{+\infty} |\zeta|^{-\frac{1}{3}} \varphi'(x-\zeta) d\zeta.$$

The viscous coefficient is taken sufficiently small, in order to magnify the erosive effect of the non-local term. The new definition of the non-local term ($\mathcal{I}[u] = \partial_x \mathcal{L}[u]$) follows [5], which interpretes $\mathcal{L}[u]$ as a flow. Notice that in [5, 6], the bottom is, in fact, $s(t,x) = u(t, x + q'(1)t)$, where q is the bedload transport of sediments; for the sake of simplicity, we continue to work with u.

To shed light on the effect of the nonlocal term, we compare the evolution of the solution of (36) with the solution of the viscous Burgers equation:

$$\partial_t u + \partial_x \left(\frac{u^2}{2} \right) - \varepsilon \partial_{xx}^2 u = 0. \tag{37}$$

7.1 Maximum principle for the viscous Burgers equation

It is well-known that (37) satisfies the maximum principle: for any initial data $u_0 \in L^\infty(\mathbb{R})$, ess-inf $u_0 \leq u \leq$ ess-sup u_0. As a consequence, (37) cannot take into account erosion phenomena. To simulate the evolution of u, we define a regular discretization of $[0, L]$ with a spatial step Δx such that $L = M\Delta x$, and a discretization of $[0, T]$ with a time step Δt such that $T = N\Delta t$. We let x_i, t_n and u_i^n respectively denote the point $i\Delta x$, the time $n\Delta t$ and the computed solution at the point $(n\Delta t, i\Delta x)$. We use the following explicit centered scheme:

$$u_i^{n+1} = u_i^n + \Delta t \left[-\frac{1}{2} \frac{(u_{i+1}^n)^2 - (u_{i-1}^n)^2}{2\Delta x} + \varepsilon \frac{u_{i+1}^n - 2u_i^n + u_{i-1}^n}{\Delta x^2} \right]. \tag{38}$$

It is well-known that this scheme is stable under the CFL-Peclet condition:

$$\Delta t = \min \left(\frac{\Delta x}{|u|}, \frac{\Delta x^2}{2\varepsilon} \right). \tag{39}$$

To convince the reader, let us simulate the evolution of the well-known following travelling waves of (37) for $\varepsilon = 1$:

$$u(t, x) := \frac{1}{2} \left[1 - \tanh \left(\frac{1}{4} \left(x - \frac{1}{2} t \right) \right) \right].$$

We expose in Figure 3 both analytic and numerical solutions. We observe an error of the order of 10^{-4} between these solutions. Let us now take, as an initial dune, the following small regular perturbation on

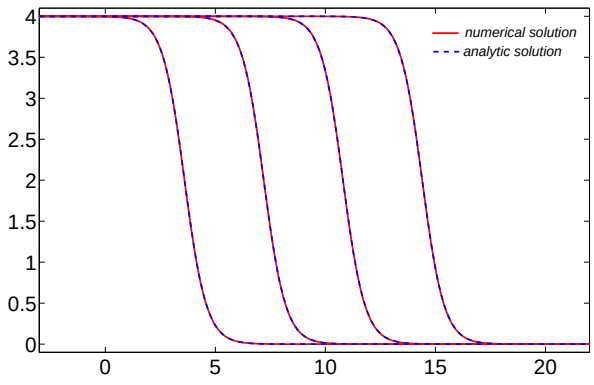

Figure 3: Numerical and analytic travelling waves of the viscous Burgers equation.

the bottom:

$$u_0(x) = \begin{cases} e^{\frac{-1}{1-(x-\frac{L}{2})^2}} & \text{if } \frac{L}{2} - 1 < x < \frac{L}{2} + 1, \\ 0 & \text{otherwise.} \end{cases} \tag{40}$$

We describe its evolution in Figure 4. The dune propagates, but as mentioned above the erosion phenomena are not taken into account since u remains positive (because of the maximum principle).

Remark 8. *Equation* (1) *also admits travelling wave solutions, see [1].*

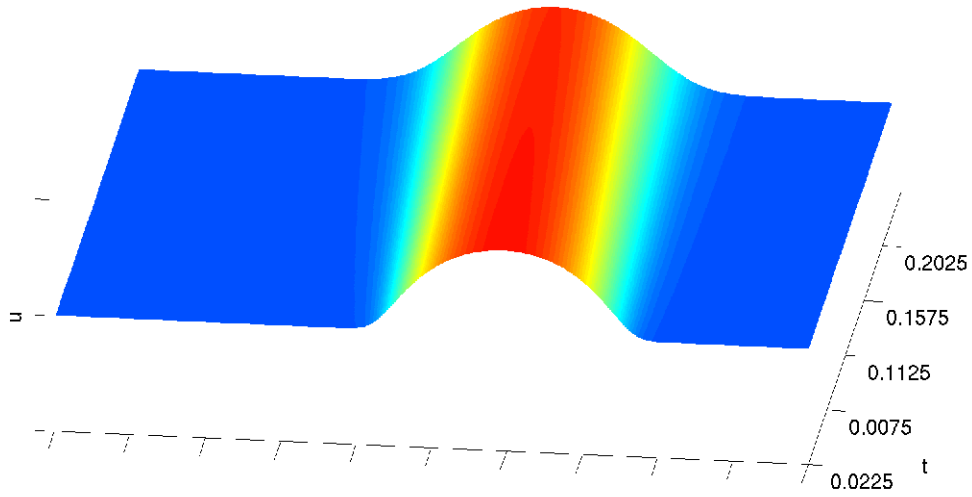

Figure 4: Evolution of the solution of (37) with u_0 defined in (40) ($L = 30$, $M = 4001$ and $\varepsilon = 0.1$).

7.2 Erosive effect of the nonlocal term

Let us return to the study of (36). We add the discretization of the non-local operator $\mathcal{L}$ to the explicit centered scheme (38). It is natural to consider the following discretization:

$$\mathcal{L}[u_i^n] \approx \sum_{j=0}^{+\infty} |j\Delta x|^{-\frac{1}{3}} \frac{u_{i-j+1}^n - u_{i-j-1}^n}{2\Delta x},$$

Instead we will approximate

$$\mathcal{L}[u_i^n] \approx \sum_{j=0}^{i} |j\Delta x|^{-\frac{1}{3}} \frac{u_{i-j+1}^n - u_{i-j-1}^n}{2\Delta x}.$$

This is based on the assumption that for $x \in [0, L]$,

$$\mathcal{L}[u(t,\cdot)](x) \approx \int_0^x |\zeta|^{-\frac{1}{3}} \partial_x u(t, x-\zeta) d\zeta. \tag{41}$$

This fact is not true for general u, but if we assume that the initial profile u_0 satisfies $u_0(x) = 0, \forall x \leq 0$ and semi-discretize in time Equation (36), we get :

$$u(t+\Delta t, x) = u(t,x) + \Delta t \left(-\partial_x (\frac{u^2}{2}) - \partial_x \mathcal{L}[u(t,.)] + \varepsilon \partial_{xx}^2 u \right).$$

We observe that $u(t+\Delta t, x) = 0, \ \forall x \leq 0$ and by induction $u(t_n, x) = 0 \ \forall x \leq 0, \ \forall n$. Now

$$\mathcal{L}[u(t_n,.)] = \int_0^x |\zeta|^{-\frac{1}{3}} \partial_x u(t_n, x-\zeta) d\zeta.$$

Actually, we take $u_0 \in C_c^\infty(\mathbb{R})$ and supp$(u_0) \subset\subset (0, L)$ (see Figure 5). Moreover, Lemma 3 suggests

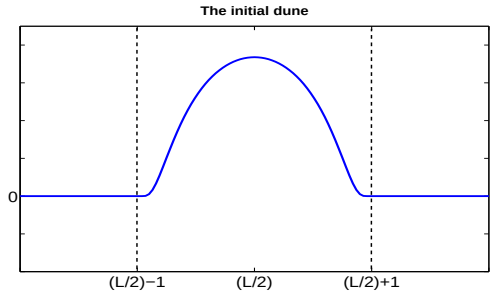

Figure 5: The initial dune defined in (40).

that all the derivatives of u are continuous with values in L^2 w.r.t. the time variable up to the time $t = 0$. It then is natural to expect that (at least for small times) Equation (41) is a good approximation.

We then use the following explicit scheme for (36):

$$u_i^{n+1} = u_i^n + \Delta t \left[-\frac{1}{2} \frac{(u_{i+1}^n)^2 - (u_{i-1}^n)^2}{2\Delta x} - \frac{\mathcal{L}[u_{i+1}^n] - \mathcal{L}[u_{i-1}^n]}{2\Delta x} + \varepsilon \frac{u_{i+1}^n - 2u_i^n + u_{i-1}^n}{\Delta x^2} \right].$$

As far as the stability condition, one can numerically see that (39) is still ensuring stability for small Δx. The evolution of the initial dune (40) is given in Picture 6. As the solutions of the viscous Burgers equation, the dune is propagated downstream but we now observe an erosive process behind the dune: the bottom is eroded downstream from the dune, as shown in Remark 2.

Let us make a final remark. We are aware of that the fact that these numerical simulations are a first crude attempt. To tackle rigorously the non local term would need further study, which will be reported elsewhere.

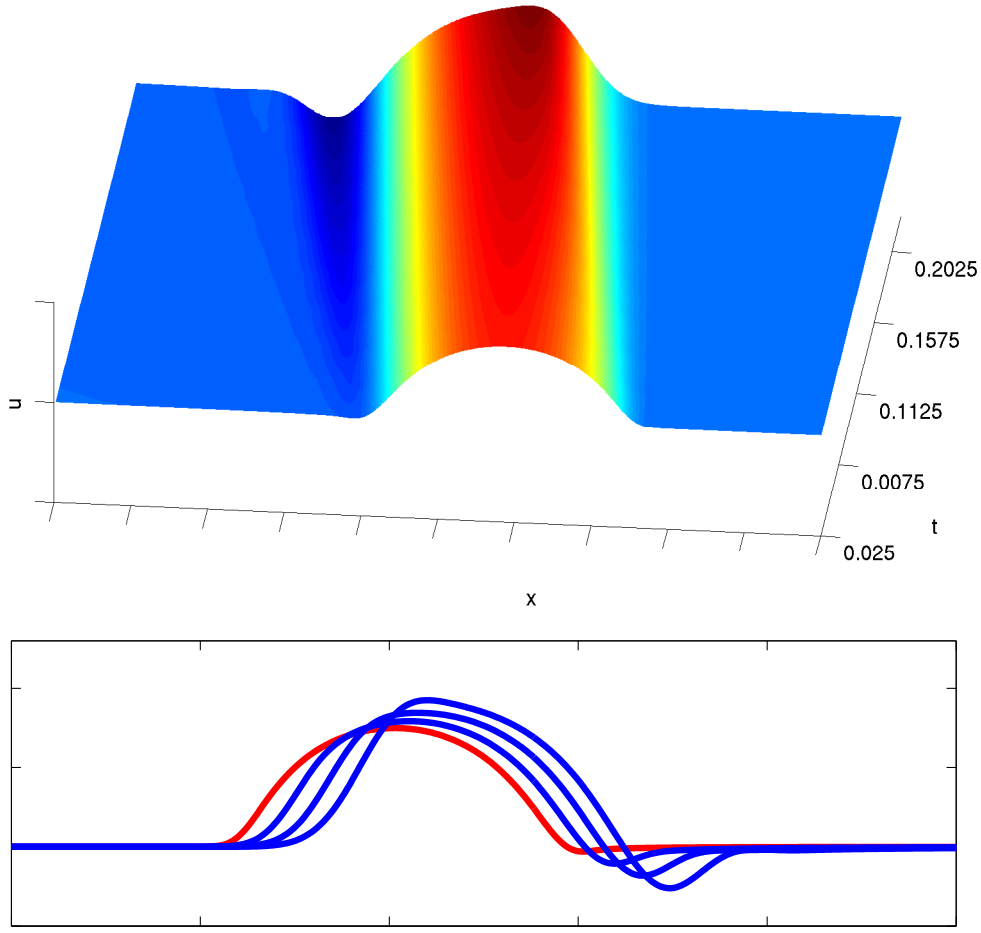

Figure 6: Evolution of an initial dune, by using the non-local model (36) ($L = 30$, $M = 4001$ and $\varepsilon = 0.1$).

A Some technical lemmas.

We first recall a generalization of Gronwall's lemma proved e.g. in [4].

Lemma 4. *Let $g : [0, T] \to \mathbb{R}_+$ be a bounded measurable function and suppose that there are positive constants C, A and $\theta > 0$ such that, for all $t \leq T$,*

$$g(t) \leq A + C \int_0^t (t - s)^{\theta - 1} g(s)\, ds.$$

Then,

$$\sup_{0 \leq t \leq T} g(t) \leq C_T A,$$

where constant C_T does not depend on A.

Lemma 5. *Let $f, g \in L^2(\mathbb{R})$. Then, $f * g \in C(\mathbb{R})$ and for all $x, y \in \mathbb{R}$,*

$$|f * g(x) - f * g(y)| \leq ||\mathcal{T}_{(x-y)} f - f||_{L^2(\mathbb{R})} ||g||_{L^2(\mathbb{R})}.$$

Proof. The result is immediate if f and g are smooth; indeed,

$$\begin{aligned} |f * g(x) - f * g(y)| &= \left| \int_{\mathbb{R}} f(x-z) g(z) dz - \int_{\mathbb{R}} f(y-z) g(z) dz \right|, \\ &\leq \int_{\mathbb{R}} |f(x-z) - f(y-z) g(z)| dz, \\ &\leq ||\mathcal{T}_{(x-y)} f - f||_{L^2(\mathbb{R})} ||g||_{L^2(\mathbb{R})}. \end{aligned}$$

The result for general f and g only L^2, is then obtained by density. ■

Lemma 6. *Let $u \in C([0,T]; L^2(\mathbb{R}))$. Then, $\sup_{t \in [0,T]} ||\mathcal{T}_h(u(t,\cdot)) - u(t,\cdot)||_{L^2(\mathbb{R})} \to 0$, as $h \to 0$.*

Proof. The function u is uniformly continuous with values in L^2 as a continuous function on a compact set $[0,T]$. For any $\varepsilon > 0$, there then exist finite a sequence $0 = t_0 < t_1 < \ldots < t_N = T$ such that for any $t \in [0,T]$, there exists $j \in \{0, \ldots, N-1\}$ with

$$||u(t,\cdot) - u(t_j,\cdot)||_{L^2(\mathbb{R})} \leq \varepsilon.$$

Moreover,

$$\begin{aligned} ||\mathcal{T}_h(u(t,\cdot)) - u(t,\cdot)||_{L^2(\mathbb{R})} \leq\ & ||\mathcal{T}_h(u(t,\cdot)) - \mathcal{T}_h(u(t_j,\cdot))||_{L^2(\mathbb{R})} \\ & + ||\mathcal{T}_h(u(t_j,\cdot)) - u(t_j,\cdot)||_{L^2(\mathbb{R})} + ||u(t_j,\cdot) - u(t,\cdot)||_{L^2(\mathbb{R})}. \end{aligned}$$

Since $||\mathcal{T}_h(u(t,\cdot)) - \mathcal{T}_h(u(t_j,\cdot))||_{L^2(\mathbb{R})} = ||u(t,\cdot) - u(t_j,\cdot)||_{L^2(\mathbb{R})}$, we get:

$$\begin{aligned} ||\mathcal{T}_h(u(t,\cdot)) - u(t,\cdot)||_{L^2(\mathbb{R})} &\leq ||\mathcal{T}_h(u(t_j,\cdot)) - u(t_j,\cdot)||_{L^2(\mathbb{R})} + 2||u(t_j,\cdot) - u(t,\cdot)||_{L^2(\mathbb{R})}, \\ &\leq ||\mathcal{T}_h(u(t_j,\cdot)) - u(t_j,\cdot)||_{L^2(\mathbb{R})} + 2\varepsilon. \end{aligned}$$

By the continuity of the translation in $L^2(\mathbb{R})$, $||\mathcal{T}_h(u(t_j,\cdot)) - u(t_j,\cdot)||_{L^2(\mathbb{R})} \to 0$, as $h \to 0$. Then,

$$\limsup_{h \to 0} ||\mathcal{T}_h(u(t,\cdot)) - u(t,\cdot)||_{L^2(\mathbb{R})} \leq 2\varepsilon.$$

Taking the infimum w.r.t. $\varepsilon > 0$ implies the result. ■

Lemma 7. *Let $u \in C([0,T]; L^2(\mathbb{R}))$ such that u is continuous w.r.t. the variable x uniformly in t. Then, $u \in C([0,T] \times \mathbb{R})$.*

Proof. Let $(t_0, x_0) \in [0,T] \times \mathbb{R}$. Let $\varepsilon > 0$. By the regularity of u w.r.t. the space variable, we know that there exists $\eta > 0$ such that for any $t \in [0,T]$ and all $x, y \in [x_0 - \eta, x_0 + \eta]$,

$$\begin{aligned} |u(t_0,x_0) - u(t,x)| &\leq |u(t_0,x_0) - u(t_0,y)| + |u(t_0,y) - u(t,y)| + |u(t,y) - u(t,x)|, \\ &\leq \varepsilon + |u(t_0,y) - u(t,y)| + \varepsilon. \end{aligned}$$

If we integrate w.r.t. $y \in [x_0 - \eta, x_0 + \eta]$, then we get:

$$2\eta |u(t_0,x_0) - u(t,x)| \leq 4\varepsilon\eta + \int_{x_0-\eta}^{x_0+\eta} |u(t_0,y) - u(t,y)| dy \leq 4\varepsilon\eta (2\eta)^{\frac{1}{2}} ||u(t_0,\cdot) - u(t,\cdot)||_{L^2(\mathbb{R})}.$$

By the continuity of u with values in L^2,

$$\limsup_{(t,x)\to(t_0,x_0)} |u(t_0,x_0) - u(t,x)| \leq 2\varepsilon.$$

Taking the infimum w.r.t. $\varepsilon > 0$ completes the proof. ■

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