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**CNRS**

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**Centre d'expertise des risques,  
de l'environnement, des  
mobilités et de l'aménagement**

Activity Report 2014

## **Project-Team ANGE**

Numerical Analysis, Geophysics and Ecology

IN COLLABORATION WITH: Laboratoire Jacques-Louis Lions

RESEARCH CENTER  
**Paris - Rocquencourt**

THEME  
**Earth, Environmental and Energy  
Sciences**



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## Project-Team ANGE

**Keywords:** Geophysics, Modeling, Numerical Methods, Simulation, Bioenergy

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### 1. Members

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### 2. Overall Objectives

#### 2.1. Presentation

Among all aspects of geosciences, we mainly focus on gravity driven flows arising in many situations such as

- hazardous flows (flooding, rogue waves, landslides...),
- sustainable energies (hydrodynamics-biology coupling, biofuel production, marine energies...),
- risk management and land-use planning (morphodynamic evolutions, early warning systems...)

There exists a strong demand from scientists and engineers in fluid mechanics for models and numerical tools able to simulate not only the water depth and the velocity field but also the distribution and evolution of external quantities such as pollutants or biological species and the interaction between flows and structures (seashores, erosion processes...). The key point of the researches carried out within ANGE is to answer this demand by the development of efficient, robust and validated models and numerical tools.

## 2.2. Scientific challenges

Due to the variety of applications with a wide range of spatial scales, reduced-size models like the shallow water equations are generally required. From the modelling point of view, the main issue is to describe the behaviour of the flow with a reduced-size model taking into account several physical processes such as non-hydrostatic terms, biological species evolution, topography and structure interactions within the flow. The mathematical analysis of the resulting model do not enter the field of hyperbolic equations anymore and new strategies have to be proposed. Last but not least, efficient numerical resolutions of reduced-size models requires particular attention due to the different time scales of the processes and in order to recover physical properties such as positivity, conservativity, entropy dissipation and equilibria.

## 3. Research Program

### 3.1. Overview

The research activities carried out within the ANGE team strongly couple the development of methodological tools with applications to real-life problems and the transfer of numerical codes. The main purpose is to obtain new models adapted to the physical phenomena at stake, identify the main properties that reflect the physical sense of the models (uniqueness, conservativity, entropy dissipation, ...) and propose effective numerical methods to estimate their solution in complex configurations (multi-dimensional, unstructured meshes, well-balanced, ...).

The difficulties arising in gravity driven flow studies are threefold.

- Models and equations encountered in fluid mechanics (typically the free surface Navier-Stokes equations) are complex to analyze and solve.
- The underlying phenomena often take place over large domains with very heterogeneous length scales (size of the domain, mean depth, wave length,...) and distinct time scales, *e.g.* coastal erosion, propagation of a tsunami,...
- These problems are multi-physics with strong couplings and nonlinearities.

### 3.2. Modelling and analysis

Hazardous flows are complex physical phenomena that can hardly be represented by shallow water type systems of partial differential equations (PDEs). In this domain, the research program is devoted to the derivation and analysis of reduced complexity models compared to the Navier-Stokes equations, but relaxing the shallow water assumptions. The main purpose is then to obtain models well-adapted to the physical phenomena at stake.

Even if the resulting models do not strictly belong to the family of hyperbolic systems, they exhibit hyperbolic features: the analysis and discretization techniques we intend to develop have connections with those used for hyperbolic conservation laws. It is worth noticing that the need for robust and efficient numerical procedures is reinforced by the smallness of dissipative effects in geophysical models which therefore generate singular solutions and instabilities.

On the one hand, the derivation of the Saint-Venant system from the Navier-Stokes equations is based on two approximations, so-called shallow water assumptions, namely

- the horizontal fluid velocity is well approximated by its mean value along the vertical direction,
- the pressure is hydrostatic or equivalently the vertical acceleration of the fluid can be neglected compared to the gravitational effects.

As a consequence the objective is to get rid of these two assumptions, one after the other, in order to obtain models accurately approximating the incompressible Euler or Navier-Stokes equations.

On the other hand, many applications require the coupling with non-hydrodynamic equations, as in the case of micro-algae production or erosion processes. These new equations comprise non-hyperbolic features and must rely on a special analysis.

### 3.2.1. Multilayer approach

As for the first shallow water assumption, *multi-layer* systems were proposed describing the flow as a superposition of Saint-Venant type systems [21], [24], [25]. Even if this approach has provided interesting results, layers are considered separate and non-miscible fluids, which imply strong limitation. That is why we proposed a slightly different approach [22], [23] based on Galerkin type decomposition along the vertical axis of all variables and leading, both for the model and its discretization, to more accurate results.

A kinetic representation of our multilayer model allows to derive robust numerical schemes endowed with properties such as: consistency, conservativity, positivity, preservation of equilibria,... It is one of the major achievements of the team but it needs to be analyzed and extended in several directions namely:

- The convergence of the multilayer system towards the hydrostatic Euler system as the number of layers goes to infinity is a critical point. It is not fully satisfactory to have only formal estimates of the convergence and sharp estimates would enable to guess the optimal number of layers.
- The introduction of several source terms due for instance to Coriolis forces or extra terms from changes of coordinates seems necessary. Their inclusion should lead to substantial modifications of the numerical scheme.
- Its hyperbolicity has not yet been proved and conversely the possible loss of hyperbolicity cannot be characterized. Similarly, the hyperbolic feature is essential in the propagation and generation of waves.

### 3.2.2. Non-hydrostatic models

The hydrostatic assumption consists in neglecting the vertical acceleration of the fluid. It is considered valid for a large class of geophysical flows but is restrictive in various situations where the dispersive effects (like wave propagation) cannot be neglected. For instance, when a wave reaches the coast, bathymetry variations give a vertical acceleration to the fluid that strongly modifies the wave characteristics and especially its height.

When processing an asymptotic expansion (w.r.t. the aspect ratio for shallow water flows) into the Navier-Stokes equations, we obtain at the leading order the Saint-Venant system. Going one step further leads to a vertically averaged version of the Euler/Navier-Stokes equations integrating the non-hydrostatic terms. This model has several advantages:

- it admits an energy balance law (that is not the case for most dispersive models available in the literature),
- it reduces to the Saint-Venant system when the non-hydrostatic pressure term vanishes,
- it consists in a set of conservation laws with source terms,
- it does not contain high order derivatives.

### 3.2.3. Multi-physics modelling

The coupling of hydrodynamic equations with other equations in order to model interactions between complex systems represents an important part of the team research. More precisely, three multi-physics systems are investigated. More details about the industrial impact of these studies are presented in the following section.

- To estimate the risk for infrastructures in coastal zone or close to a river, the resolution of the shallow water equations with moving bathymetry is necessary. The first step consisted in the study of an equation largely used in engineering science: The Exner equation. The analysis enabled to exhibit drawbacks of the coupled model such as the lack of energy conservation or the strong variations of the solution from small perturbations. A new formulation is proposed to avoid these drawbacks. The new model consists in a coupling between conservation laws and an elliptic equation, like the system Euler/Poisson, suggesting to use well-known strategies for the analysis and the numerical resolution. In addition, the new formulation is derived from classical complex rheology models and allowed physical phenomena such as threshold laws.
- Interaction between flows and floating structures is the challenge at the scale of the shallow water equations. This study needs a better understanding of the energy exchanges between the flow and the structure. The mathematical model of floating structures is very hard to solve numerically due to the non-penetration condition at the interface between the flow and the structure. It leads to infinite potential wave speeds that could not be solved with classical free surface numerical scheme. A relaxation model was derived to overcome this difficulty. It represents the interaction with the floating structure with a free surface model-type.
- If the interactions between hydrodynamics and biology phenomena are known through laboratory experiments, it is more difficult to predict the evolution, especially for the biological quantities, in a real and heterogeneous system. The objective is to model and reproduce the hydrodynamics modifications due to forcing term variations (in time and space). We are typically interested in phenomena such as eutrophication, development of harmful bacteria (cyanobacteria) and upwelling phenomena.

## 3.3. Numerical analysis

### 3.3.1. Non-hydrostatic scheme

The main challenge in the study of the non-hydrostatic model is to design a robust and efficient numerical scheme endowed with properties such as: positivity, wet/dry interfaces treatment, consistency. It has to be noticed that even if the non-hydrostatic model looks like an extension of the Saint-Venant system, most of the known techniques used in the hydrostatic case are not efficient as we recover strong difficulties encountered in incompressible fluid mechanics due to the extra pressure term. These difficulties are reinforced by the absence of viscous/dissipative terms.

### 3.3.2. Space decomposition and adaptive scheme

In the quest for a better balance between accuracy and efficiency, a strategy consists in the adaptation of models. Indeed, the systems of partial differential equations we consider result from a hierarchy of simplifying assumptions. However, some of these hypotheses may turn out to be irrelevant locally. The adaptation of models thus consists in determining areas where a simplified model (*e.g.* shallow water type) is valid and where it is not. In the latter case, we may go back to the “parent” model (*e.g.* Euler) in the corresponding area. This implies to know how to handle the coupling between the aforementioned models from both theoretical and numerical points of view. In particular, the numerical treatment of transmission conditions is a key point. It requires the estimation of characteristic values (Riemann invariant) which have to be determined according to the regime (torrential or fluvial).



### 3.3.3. Asymptotic-Preserving scheme for source terms

The hydrodynamic models comprise advection and sources terms. The conservation of the balance between the source terms, typically viscosity and friction, has a significant impact since the overall flow is generally a perturbation around one equilibrium. The design of numerical schemes able to preserve such balances is a challenge from both theoretical and industrial points of view. The concept of Asymptotic-Preserving (AP) methods is of great interest in order to overcome these issues.

Another difficulty occurs when a term, typically related to the pressure, becomes very large compared to the order of magnitude of the velocity. At this regime, namely the so-called *low Froude* (shallow water) or *low Mach* (Euler) regimes, the difference between the speed of the potential waves and the physical velocity makes classical numerical schemes not efficient: firstly because of the error of truncation which is inversely proportional to the small parameters, secondly because of the time step governed by the largest speed of the potential wave. AP methods made a breakthrough in the numerical resolution of asymptotic perturbations of partial-differential equations concerning the first point. The second one can be fixed using partially implicit scheme.

### 3.3.4. Multi-physics models

Coupling problems also arise within the fluid when it contains pollutants, density variations or biological species. For most situations, the interactions are small enough to use a splitting strategy and the classical numerical scheme for each sub-model, whether it be hydrodynamic or non-hydrodynamic.

The sediment transport raises interesting issues from a numerical aspect. This is an example of coupling between the flow and another phenomenon, namely the deformation of the bottom of the basin that can be carried out either by bed load where the sediment has its own velocity or suspended load in which the particles are mostly driven by the flow. This phenomenon involves different time scales and nonlinear retroactions; hence the need for accurate mechanical models and very robust numerical methods. In collaboration with industrial partners (EDF-LNHE), the team already works on the improvement of numerical methods for existing (mostly empirical) models but our aim is also to propose new (quite) simple models that contain important features and satisfy some basic mechanical requirements. The extension of our 3D models to the transport of weighted particles can also be here of great interest.

### 3.3.5. Data assimilation

Data assimilation consists in a coupling between a model and observation measurements. Developing robust data assimilation methods for hyperbolic-type conservation laws is a challenging subject. These PDEs indeed show no dissipation effects and the input of additional information in the model equations may introduce errors that propagate and create shocks. We have recently proposed a new approach based on the kinetic description of the conservation law. Hence, data assimilation is carried out at the kinetic level, using a Luenberger observer. Assimilation then resumes to the handling of a BGK type equation. The advantage of this framework is that we deal with a single “linear” equation instead of a nonlinear system and it is easy to recover the macroscopic variables. We are able to prove the convergence of the model towards the data in case of complete observations in space and time.

This work is done in collaboration with the M3DISIM Inria project-team. M. Doumic and B. Perthame (MAMBA) also participate.

## 4. Application Domains

### 4.1. Overview

Sustainable development and environment preservation have a growing importance and scientists have to address difficult issues such as: management of water resources, renewable energy production, biogeochemistry of oceans, resilience of society w.r.t. hazardous flows,...

As mentioned above, the main issue is to propose models of reduced complexity, suitable for scientific computing and endowed with stability properties (continuous and/or discrete). In addition, models and their numerical approximations have to be confronted with experimental data, as analytical solutions are hardly accessible for these problems/models. A. Mangeney (IPGP) and N. Goutal (EDF) may provide useful data.

## 4.2. Geophysical flows

Reduced models like the shallow water equations are particularly well-adapted to the modelling of geophysical flows since they are characterized by large time or/and space scales. For long time simulations, the preservation of equilibria is essential as global solutions are a perturbation around them. The analysis and the numerical preservation of non-trivial equilibria, more precisely when the velocity does not vanish, are still a challenge. In the fields of oceanography and meteorology, the numerical preservation of the so-called geostrophic quasi-steady state, which is the balance between the gravity and the Coriolis forces, can significantly improve the forecasts. In addition, the data assimilation is required to improve the simulations and correct the dissipative effect of the numerical scheme.

The sediment transport modelling is of major interest in terms of applications, in particular to estimate the sustainability of facilities with silt or scour, such as canals and bridges. Dredging or filling-up operations are costly and generally not efficient in long term. The objective is to determine a configuration almost stable with the facilities. In addition, it is also important to determine the impact of major events like emptying dam. It is aimed at evacuating the sediments in the dam reservoir and requires a large discharge. However, the downstream impact should be measured in terms of turbidity, river morphology and flood.

## 4.3. Hydrological disasters

It is a violent, sudden and destructive flow. Between 1996 and 2005, nearly 80% of natural disasters in the world have meteorological or hydrological origins. The main interest of their study is to predict the areas in which they may occur most probably and to prevent the damages by means of suitable amenities. In France, floods are the most recurring natural disasters and produce the worse damages. In addition, it can be a cause or a consequence of a dam break. The large surface they cover and the long period they can last requires the use of reduced models like the shallow water equations. In urban areas, the flow can be largely impacted by the debris, in particular cars, and required fluid/structure interactions to be well understood. Moreover, underground flows, in particular in sewer, can accelerate and amplify the flow. To take them into account, the model and the numerical resolution should be able to treat the transition between free surface and underground flows.

Tsunamis are another hydrological disaster largely studied. Even if the propagation of the wave is globally well described by the shallow water model in oceans, it is not the case close to the epicenter and in the coastal zone where the bathymetry leads a vertical accretion and produce substantial dispersive effects. The non-hydrostatic terms have to be considered and an efficient numerical resolution should be induced.

Whereas the viscous effects can often be neglected in water flows, they have to be taken into account in situations such as avalanches, debris flows, pyroclastic flows, erosion processes,...*i.e.* when the fluid rheology becomes more complex. Gravity driven granular flows consist of solid particles commonly mixed with an interstitial lighter fluid (liquid or gas) that may interact with the grains and decrease the intensity of their contacts, thus reducing energy dissipation and favoring propagation. Examples include subaerial or subaqueous rock avalanches (*e.g.* landslides).

## 4.4. Biodiversity and culture

Nowadays, simulations of the hydrodynamic regime of a river, a lake or an estuary, are not restricted to the determination of the water depth and the fluid velocity. They have to predict the distribution and evolution of external quantities such as pollutants, biological species or sediment concentration.

The potential of micro-algae as a source of biofuel and as a technological solution for CO<sub>2</sub> fixation is the subject of intense academic and industrial research. Large-scale production of micro-algae has potential for biofuel applications owing to the high productivity that can be attained in high-rate raceway ponds. One of the key challenges in the production of micro-algae is to maximize algae growth with respect to the exogenous energy that must be used (paddlewheel, pumps,...). There is a large number of parameters that need to be optimized (characteristics of the biological species, raceway shape, stirring provided by the paddlewheel). Consequently our strategy is to develop efficient models and numerical tools to reproduce the flow induced by the paddlewheel and the evolution of the biological species within this flow. Here, mathematical models can greatly help us reduce experimental costs. Owing to the high heterogeneity of raceways due to gradients of temperature, light intensity and nutrient availability through water height, we cannot use depth-averaged models. We adopt instead more accurate multilayer models that have recently been proposed. However, it is clear that many complex physical phenomena have to be added to our model, such as the effect of sunlight on water temperature and density, evaporation and external forcing.

Many problems previously mentioned also arise in larger scale systems like lakes. Hydrodynamics of lakes is mainly governed by geophysical forcing terms: wind, temperature variations,...

## 4.5. Sustainable energy

One of the booming lines of business is the field of renewable and decarbonated energies. In particular in the marine realm, several processes have been proposed in order to produce electricity thanks to the recovering of wave, tidal and current energies. We may mention water-turbines, buoys turning variations of the water height into electricity or turbines motioned by currents. Although these processes produce an amount of energy which is less substantial than in thermal or nuclear power plants, they have smaller dimensions and can be set up more easily.

The fluid energy has a kinetic and potential part. The buoys use the potential energy whereas the turbines (hydrolian) are activated by currents. To become economically relevant, these systems need to be optimized in order to improve their productivity. While for the construction of a harbour, the goal is to minimize swell, in our framework we intend to maximize the wave energy.

This is a complex and original issue which requires a fine model of energy exchanges and efficient numerical tools. In a second step, the optimisation of parameters that can be changed in real-life, such as bottom bathymetry and buoy shape, must be studied. Eventually, physical experiments will be necessary for the validation.

# 5. New Software and Platforms

## 5.1. FRESHKISS

Although the Saint-Venant system is the cornerstone of flow modelling in geosciences, this does not mean that the transfer of the efficient dedicated simulation tools is achieved in the geoscience community.

ANGE collaborates with scientists, laboratories and companies that are interested in scientific advances which makes the valuation and the transfer of results easier.

ANGE aims at developing robust and efficient numerical tools. For the simulation of the free surface Navier-Stokes equations, numerical tools have been developed namely FRESHKISS2D<sup>1</sup> and FRESHKISS3D. These tools are used by several scientists typically in the BIOCORE Inria project-team, at EDF and in public research laboratories.

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<sup>1</sup>FRESHKISS: FREe Surface Hydrodynamics using KInetic SchemeS

FRESHKISS3D is a numerical code solving the 3D hydrostatic and incompressible Navier-Stokes equations with variable density. This code was initially dedicated to research activities within the team but we now aim at turning it into a numerical tool being used by non-mathematicians. Indeed, there is a demand in research laboratories and companies to use this tool. A young engineer (R. Hamouda) has been hired (ADT In@lgae funded by Inria) and its assignment is to improve/enrich the code and to make it user-friendly. Notice that FRESHKISS3D is used for teaching (master students in geosciences) at university Denis Diderot Paris 7 and IGP.

## 5.2. TSUNAMATHS

TSUNAMATHS is an educational platform aiming at simulating historical tsunamis. Real data and mathematical explanations are provided to enable people to better understand the overall process of tsunamis. It is available on the Internet:

[http://ange.raoufhamouda.com/tsunami/en\\_animation.htm](http://ange.raoufhamouda.com/tsunami/en_animation.htm)

It was presented in the framework of the 2013 UNESCO year of “Mathematics of Planet Earth” and then exhibited at the ICM 2014 session (see § 9.3).

## 6. New Results

### 6.1. Highlights of the Year

In 2014, ANGE status turned from Inria team to Inria project-team. Afterwards, M. Parisot was recruited by Inria as a junior researcher.

### 6.2. Analysis of models in fluid mechanics

#### 6.2.1. *Well-posedness of multilayer Shallow Water-type equations*

**Participants:** Emmanuel Audusse, Bernard Di Martino, Ethem Nayir, Yohan Penel.

The hyperbolicity of some 2-layer Shallow Water equations had been proven in [26], [23], there are many open theoretical investigations to lead about these systems. In particular, E. Nayir proved the local well-posedness of the model derived in [23] for periodic boundary conditions. Next steps will consist in extending this preliminary result to the whole space and proving the global existence of strong solutions. The existence of weak solutions will be studied from B. Di Martino’s work. The hyperbolicity for  $N$  layers must also be investigated.

As for numerical aspects, the use of FRESHKISS3D will provide qualitative assessments for modelling issues (viscous tensor, source terms, variable density, interfacial velocities). It will also yield comparisons with theoretical results, in particular when the number of layers goes to infinity.

#### 6.2.2. *Non-hydrostatic models*

**Participants:** Dena Kazerani, Jacques Sainte-Marie, Nicolas Seguin.

Together with Corentin Audiard from Univ. Pierre et Marie Curie, we investigated the structure of general non hydrostatic models for shallow water flows. This includes the Green–Naghdi equations and the model proposed by Bristeau *et al.* in [13]. D. Kazerani proved that such systems possess a symmetric structure based on the existence of an energy. The main difference with the well-known hyperbolic case is due to the presence of differential operators instead of matrices.

### 6.3. Modelling of complex flows

#### 6.3.1. *Dynamics of sedimentary river beds with stochastic fluctuations*

**Participants:** Emmanuel Audusse, Philippe Ung.

We studied in [9] the behaviour of the solution of the Saint-Venant–Exner equations when a stochastic term is introduced in the model through the sediment flux. A first investigation was done considering periodic boundary conditions and the next part of this study is devoted to the case when physical ones are imposed. Our goal is to investigate the possibility to bring out a characteristic long time behaviour and to establish a relation between the injected noise and the physical parameters involved in the model. This work was achieved in collaboration with Sébastien Boyaval from Lab. Hydraulique Saint-Venant.

### 6.3.2. *Non-hydrostatic effects*

**Participants:** Nora Aïssiouene, Marie-Odile Bristeau, Edwige Godlewski, Dena Kazerani, Anne Mangeney, Jacques Sainte-Marie, Nicolas Seguin.

The objective is to derive a model corresponding to a depth averaged version of the incompressible Euler equations with free surface and to develop a robust numerical method for the resolution of the model.

Concerning the modelling aspect, a non-hydrostatic shallow water-type model approximating the incompressible Euler and Navier-Stokes systems with free surface was developed and published in [13]. The closure relations are obtained by a minimal energy constraint instead of an asymptotic expansion. The model slightly differs from the well-known Green-Naghdi model and is confronted with stationary and analytical solutions of the Euler system corresponding to rotational flows.

The numerical approximation relies on a projection-correction type scheme. The hyperbolic part of the system is approximated using a kinetic finite volume solver and the correction step implies to solve an elliptic problem involving the non-hydrostatic part of the pressure.

In one dimension, the resolution of the incompressibility problem leads to solve a mixed problem where the pressure and the velocity are defined in compatible approximation spaces. This step uses a variational formulation of the shallow water version of the incompressibility condition.

This numerical scheme satisfies classical properties (positivity, well-balancing and consistency) and a discrete entropy inequality. Several numerical experiments are performed to confirm the relevance of our approach.

This approach will allow us to extend the numerical method in higher dimensions and to treat particular difficult cases occurring in specific geophysical situations (dry/wet interfaces).

### 6.3.3. *Plasticity in Shallow Water equations*

**Participant:** Nicolas Seguin.

In collaboration with Bruno Després and Clément Mifsud from Univ. Pierre et Marie Curie, we proposed in [20] a new definition of solutions for hyperbolic Friedrichs' systems in bounded domains, which follows the idea of Lions' dissipative solutions and Otto's boundary formulation for conservation laws. We proved in the classical settings existence and uniqueness. The goal of this project is to be able to incorporate nonlinear effects of plasticity in models of elasticity or overflowing in channels for shallow water flows, by adding entropy compatible constraints.

### 6.3.4. *Management of marine energies*

**Participants:** Cindy Guichard, Martin Parisot, Jacques Sainte-Marie, Julien Salomon.

The purpose of this project is to model floating devices (like buoys) in the context of recovering energy from water resources (seas and oceans). If the free surface flow can be handled by means of the Saint-Venant equations, the area under the buoys requires a different modelling (for example equivalence with springs) as the surface is constrained. The Archimedes' principle is also involved. Some preliminary numerical results were obtained thanks to the FRESHKISS3D code.

To go further, the optimisation of the overall process is also under consideration. Indeed, to maximise the amount of recovered energy, the bathymetry, the shape of the buoy, the number of buoys are critical parameters which must be modelled in view of industrial applications. Optimal control methods are applied to determine the best configuration depending on the devices: optimisation of the kinetic energy for water-turbines or of the potential energy for buoys.

## 6.4. Accurate simulations of fluid flows

### 6.4.1. A numerical scheme for the Saint-Venant–Exner equations

**Participants:** Emmanuel Audusse, Philippe Ung.

After having established a Godunov-type method based on the design of a three-wave Approximate Riemann Solver for the Saint-Venant equations [10], we extended this approach to the Saint-Venant–Exner equations for modelling the sediment transport. The coupled aspect between the hydraulic and the morphodynamic parts is only located on the evaluation of the wave velocities. Under this assumption, the proposed scheme can be interpreted as a hybrid method between the splitting and non-splitting methods and it also raises the issue of the choice between the two previous approaches.

These results were proven in collaboration with Christophe Chalons from Univ. Versailles–Saint-Quentin.

### 6.4.2. Simulations of fluid/particules interactions

**Participant:** Nicolas Seguin.

In collaboration with Nina Aguillon and Frédéric Lagoutière from Univ. Paris-Sud, we proved in [7] the convergence of finite volume schemes for a simplified model of fluid-particle interaction. The mesh follows the particle which appears in the model as a pointwise contribution. The numerical scheme is based on local well-balanced fluxes, which permits to obtain compactness and convergence.

### 6.4.3. Hydrostatic reconstruction

**Participants:** Emmanuel Audusse, Marie-Odile Bristeau, Jacques Sainte-Marie.

The hydrostatic reconstruction is a general and efficient method to handle source terms that uses an arbitrary solver for the homogeneous problem and leads to a consistent, well-balanced, positive scheme satisfying a semi-discrete entropy inequality.

In [8], we proved with Francois Bouchut from Univ. Marne-la-Vallée that the hydrostatic reconstruction coupled to the classical kinetic solver satisfies a fully discrete entropy inequality which involves an error term but the latter goes to zero strongly with the mesh size.

### 6.4.4. A numerical scheme for multilayer shallow-water model for all Froude regimes

**Participant:** Martin Parisot.

The aim of this work in collaboration with Jean-Paul Vila from INSA/IMT is to propose an efficient numerical resolution to simulate stratified non-miscible fluids. The strategy should be consistent for all regime especially with the so-called low-Froude regime particularly relevant for applications. The proposed scheme is entropy-satisfying, well-balanced and asymptotic preserving. In addition the stability of the scheme is ensured for large time scale. More precisely, it does not depend on the gravity waves, which are very restrictive for the targeted applications, such as oceanology and meteorology. Further work using the strategy for sustainable energies is in progress.

### 6.4.5. Adaptation of the Godunov scheme to the low Froude regime

**Participants:** Emmanuel Audusse, Do Minh Hieu, Yohan Penel.

Standard numerical schemes designed for the simulation of fluid flows are known to fail when the Mach number becomes too small. Similar behaviours are observed for geophysical flows when the Froude number decreases. Do Minh Hieu is interested in the numerical simulation of the Shallow Water equations including some Coriolis forces. He investigated several corrections of the standard Godunov schemes in 1D to preserve the kernel of spatial operators involved in the aforementioned equations and blamed for being responsible of the loss of accuracy. He now intends to perform the same analysis in 2D under the supervision of E. Audusse, S. Dellacherie (from CEA), P. Omnès (from CEA) and Y. Penel.

## 6.5. Software development and assessments

### 6.5.1. Improvements in the *FRESHKISS3D* code

**Participants:** Marie-Odile Bristeau, David Froger, Raouf Hamouda, Jacques Sainte-Marie.

Several tasks have been achieved in the FRESHKISS3D software:

- FreshKiss3D has been improved to take into account the second order in space for the 3D cases.
- The solver now includes the second order in time.
- The numerical validation using 3D numerical analytical solutions has been achieved.
- Numerous simulations have been driven by industrial contracts:
  - Simulations of fluid hydrodynamics in lagoons for optimizing the geometric field to ensure a high level of agitation for a low energy consumption (SAUR)
  - Simulations of fluid hydrodynamics in lagoons showing the vertical distribution of velocity and how to use it for optimizing micro-algae production (Salinalgue)
- Tsunamis simulations leading to the module TsunaMaths, web interface showing some historical tsunamis.
- Geometric implementations of FRESHKISS3D have been improved.
- Unit tests are being made automatically as the source code is modified.
- A user interface has been created using Python.
- The parallelization of FRESHKISS3D with MPI is under development.

## 7. Bilateral Contracts and Grants with Industry

### 7.1. Bilateral Contracts with Industry

- SAUR (company which manages water supplies): ANGE was involved in a 24.000 euro–contract with the Inria project-team BIOCORE (Sophia-Antipolis). This project relies on the optimisation of hydrodynamics in a lagoon in order to depollute it.
- ADEME (national agency for environment and resource management): ANGE participated to a study upon the contribution of algae in the production of energy in France till 2030.
- La Compagnie du Vent (subsidiary of GDF-Suez): in the framework of the “Salinalgue” project aiming at reducing greenhouse gas emission, ANGE and BIOCORE carried out a study upon microalgae production (10.000 euros for each team).

### 7.2. Grants with Industry

The PhD thesis of P. Ung is granted by CNRS, by AMIES (French agency for mathematics in interaction with companies and the society), by EDF and by GeoHyd (now a part of ANTEA–group) whose mission is the management of integrated natural resources. The PhD comprises simulations of concrete cases by means of the EDF software Telemac.

## 8. Partnerships and Cooperations

### 8.1. Regional Initiatives

#### 8.1.1. *Instabilities in Hydrodynamics (2011–2015)*

**Participant:** Nicolas Seguin.

The Emergence project (Ville de Paris and FSMP) “Instabilities in Hydrodynamics” is related to theoretical, applied, and numerical mathematics for the study of hydrodynamical turbulence phenomena.

### 8.1.2. *Plasticity of geophysical flows and seismic emissions (2013–2016)*

**Participant:** Anne Mangeney.

This project is funded by Sorbonne Paris Cité (80.000 euros) and is a collaboration between IPGP and Univ. Paris 13.

### 8.1.3. *LRC Manon (2010–2014 and 2014–2018)*

**Participants:** Edwige Godlewski, Yohan Penel, Nicolas Seguin.

CEA and Laboratory Jacques-Louis Lions launched a collaboration in order to carry out studies about complex fluids (modelling, numerical simulations and optimisation), in particular about compressible two-phase flows. This includes the derivation of strategies for model coupling, for instance in the case of an asymptotic hierarchy of models. This collaboration was recently renewed for another 4-year partnership.

## 8.2. National Initiatives

### 8.2.1. *ANR MIMOSA (2014–2017)*

**Participants:** Nora Aïssiouene, Marie-Odile Bristeau, Anne Mangeney, Jacques Sainte-Marie.

Program: ANR Défi 1 “Gestion sobre des ressources et adaptation au changement climatique”

Project acronym: MIMOSA

Project title: Microseism MOdeling and Seismic Applications

Coordinator: Eleonore Stutzmann (IPGP)

Seismic noise is recorded by broadband seismometers in the absence of earthquakes. It is generated by the atmosphere-ocean system with different mechanisms in the different frequency bands. Even though some mechanisms have been known for decades, an integrated understanding of the noise in the broadband period band 1-300sec is still missing. Using novel theoretical, numerical and signal processing methods, this project will provide a unified understanding of the noise sources and quantitative models for broadband noise. Conversely, we will be able to interpret seismic noise in terms of ocean wave properties. This first analysis step will lead to the identification and characterization of source events, which we will use to improve noise tomography, and seismic monitoring.

### 8.2.2. *ANR LANDQUAKES (2012–2016)*

Program: ANR Blanc “Mathématiques et interactions”

Project acronym: LANDQUAKES

Project title: Modélisation des glissements de terrain et des ondes sismiques générées pour détecter et comprendre les instabilités gravitaires

Coordinator: Anne Mangeney

Within the ANR domain “Mathematics and Interfaces”, this ANR project (between Univ. Paris-Est – LAMA, Univ. Denis Diderot Paris 7 – IPGP, Univ. Nantes – LPGN, Univ. Strasbourg EOST, 180.000 euros) deals with the mathematical and numerical modelling of landslides and generated seismic waves.

A. Mangeney is also involved in the CARIB ANR program (2014–2017) entitled “Comprendre les processus de construction et de destruction des volcans de l’Arc des Petites Antilles”.

### 8.2.3. *GdR EGRIN (2013–2017)*

**Participants:** Anne Mangeney, Jacques Sainte-Marie.



EGRIN stands for Gravity-driven flows and natural hazards. J. Sainte-Marie is the head of the scientific committee of this CNRS research group and A. Mangeney is a member of the committee. The scientific goals of this project are the modelling, analysis and simulation of complex fluids by means of reduced-complexity models in the framework of geophysical flows.

#### 8.2.4. ADT Inlgae, Inria Project Lab “Algae in Silico”

**Participants:** Marie-Odile Bristeau, Raouf Hamouda, Jacques Sainte-Marie.

In the framework of the ADT Inlgae (2013–2014), we developed in collaboration with the BIOCORE Inria project-team a simulation tool for microalgae culture. It led to the recruitment of R. Hamouda as a young engineer.

An Inria Project Lab “Algae in Silico” is planned in collaboration with BIOCORE. It concerns microalgae culture for biofuel production and the aim is to provide an integrated platform for numerical simulation “from genes to industrial processes”.

#### 8.2.5. ANR project HJnet (2013–2015)

**Participant:** Edwige Godlewski.

This research project consists in studying Hamilton-Jacobi equations on networks, and more generally on heterogeneous structures. This theoretical problem has several potential applications, in particular to traffic flow theory.

#### 8.2.6. Statistical Inference for Structure Health Monitoring (I4S)

**Participant:** Nicolas Seguin.

The I4S team results from a collaboration between Ifsttar and Inria. N. Seguin is funded by this team. His work consists in providing efficient numerical tools to take into account the impact of the flows around the structures. The most challenging part of this project concerns the off-shore wind turbines and the understanding of the ice formation on the structure.

#### 8.2.7. Hydraulics for environment and sustainable development (HED<sup>2</sup>)

The scientific group (GIS in French), which includes Inria, brings together scientists and engineers involved in hydraulics, risk management and sustainable development. ANGE belongs to this group. On the one hand, the team can be provided with experimental measurements (erosion, long waves, fluid structure interactions,...) thanks to this collaboration; on the other hand, the GIS can favor the transfer of numerical tools and scientific results.

### 8.3. European Initiatives

#### 8.3.1. ERC Consolidator Grant (2013–2018)

**Participant:** Anne Mangeney.

The project SLIDEQUAKES about detection and understanding of landslides by observing and modelling gravitational flows and generated earthquakes has been funded by the European Research Council (2.000.000 euros).

### 8.4. International Initiatives

#### 8.4.1. Inria International Partners

##### 8.4.1.1. Informal International Partners

The team has developed strong relations with researchers from Spanish universities, in particular with Carlos Pares (Malaga), Enrique Fernandez-Nieto and Tomas Chacon Rebollo (Sevilla). They have an expertise in complex flows, including variable density flows, erosion, non-hydrostatic effects, ...

## 9. Dissemination

### 9.1. Promoting Scientific Activities

#### 9.1.1. Scientific events organisation

##### 9.1.1.1. Member of the organizing committee

N. Seguin was a member of the organizing committee of “**Mathematical Hydrodynamics 2014**” which took place in Paris in June.

As a member of EGRIN, A. Mangeney co-organised the 2<sup>nd</sup> summer school which took place at domaine de Chalès from June, 30. to July, 3.

#### 9.1.2. Involvement in the mathematical community

E. Godlewski is a member of the board of AMIES.

A. Mangeney is a member of the scientific committees of the Institut de Physique du Globe de Paris (Univ. Paris 7), of Observatory of Côte d’Azur, of the Bureau de Recherches Géologiques et Minières and of the CNRS Institut National des Sciences de l’Univers “Natural Hazards”.

Y. Penel is a member of the commission Popularisation of the French society for Applied and Industrial Mathematics (SMAI).

#### 9.1.3. Journal

##### 9.1.3.1. Reviewer

Member	Journal	Others
E. Godlewski	Numerische Mathematik, Computational and Applied Mathematics, ESAIM:M2AN, Journal of Difference Equations	
A. Mangeney	Physics of Fluids, Proceedings of the Royal Society A, Landslides, Journal of Geophysical Research, Journal of Fluid Mechanics, Earth Surface processes and Landforms and Bulletin of Volcanology	
Y. Penel	Journal of Scientific Computing	

## 9.2. Teaching - Supervision - Juries

### 9.2.1. Teaching

Master’s degree (M2) : A. Mangeney and J. Sainte-Marie, Dynamique des Ecoulements gravitaires et tsunamis, 40 hours (lectures and programming classes), Univ. Paris Diderot Paris 7

Master’s degree (M2) : E. Godlewski and J. Sainte-Marie, Models and numerical methods for free surface flows, 20 hours (lectures), Univ. Pierre et Marie Curie Paris 6

Master’s degree (M2) : E. Godlewski, Numerical methods for nonstationary PDEs, 18 hours (example and example classes), Univ. Pierre et Marie Curie Paris 6

Master’s degree (M2) : C. Guichard, Numerical methods for nonstationary PDEs, 18 hours (example and example classes), Univ. Pierre et Marie Curie Paris 6

Master’s degree (M1) : A. Mangeney, Géologie de l’Environnement, 31 hours (lectures and programming classes), Univ. Paris Diderot Paris 7

Master’s degree (M1) : N. Seguin, Mathematics, Numerical Analysis and Algorithmics, 72 hours (lectures, example and programming classes), Univ. Nantes

Engineering school (2nd year) : Y. Penel, Numerical Analysis applied to financial issues, 15 hours (lectures), EFREI

Bachelor's degree (L3) : C. Guichard, Numerical linear algebra, 72 hours (example and programming classes), Univ. Pierre et Marie Curie Paris 6

Engineering school (1st year) : Y. Penel, Partial Differential Equations, 15 hours (example classes), École Centrale Paris

Bachelor's degree (L2 and L3) : C. Guichard, Introduction to Scilab, 36 hours (programming classes), Univ. Pierre et Marie Curie Paris 6

Bachelor's degree (L2)] : Y. Penel, Integration in 2 and 3 dimensions, 24 hours (lectures), Univ. Pierre et Marie Curie Paris 6

Bachelor's degree (L1) : N. Seguin, Mathematics for Biology and Chemistry, 50 hours (example classes), Univ. Nantes

Bachelor's degree (L1) : N. Aïssiouene, Calculus, 48 hours (example classes), Univ. Pierre et Marie Curie Paris 6

E. Godlewski is the head of the "Mathematics for Industry" M.Sc. program of Univ. Pierre et Marie Curie Paris 6. We mention that E. Audusse is the deputy director of the "Applied Mathematics and Scientific Computing" program of the SupGalilee engineering school.

### 9.2.2. Supervision

PostDoc in progress : Vivien Desveaux, *Méthodes d'assimilation de données dans le cadre de la surveillance des agressions biologiques et chimiques*, supervised by J. Sainte-Marie (in collaboration with M. Boulakia), from Nov. 2014

PhD in progress : Nora Aïssiouene, *Derivation and analysis of a non-hydrostatic Shallow water type model*, Univ. Pierre et Marie Curie Paris 6 (Inria grant), supervised by E. Godlewski and J. Sainte-Marie, from Nov. 2013

PhD in progress : Tim Borikov, *Physical processes at play in Martian landslides*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with D. Mège), from 2012

PhD in progress : Do Minh Hieu, *Analyse mathématique et schémas volumes finis pour la simulation des écoulements quasi-géostrophiques à bas nombre de Froude*, Univ. Paris 13, supervised by E. Audusse and Y. Penel (in collaboration with S. Dellacherie and P. Omnes), from Oct. 2014

PhD in progress : Maxime Farin, *Analysis of the seismic signal generated by laboratory granular flows*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with R. Toussaint and J. de Rosny), from 2011

PhD in progress : Dena Kazerani, *Simulation et modélisation de problèmes à frontière libre*, Univ. Pierre et Marie Curie Paris 6, supervised by N. Seguin (in collaboration with P. Frey and C. Audiard), from Oct. 2013

PhD in progress : Jannes Kinscher, *Analysis of seismicity in quarries*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with P. Bernard and I. Contrucci), from 2011

PhD in progress : Clément Mifsud, *Analyse et approximation des systèmes de Friedrichs : application à la modélisation de l'élastoplasticité*, Univ. Pierre et Marie Curie Paris 6, supervised by N. Seguin (in collaboration with J.-F. Babadjian and B. Després), from Oct. 2013

PhD in progress : Laurent Moretti, *Modelling of seismic waves generated by landslides*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with Y. Capdeville), from 2010

PhD in progress : Ethem Nayir, *Approximation multi-vitesse des équations de Navier-Stokes hydrostatiques: Analyse mathématique et simulations numériques*, Univ. Pierre et Marie Curie Paris 6, supervised by E. Audusse, Y. Penel and J. Sainte-Marie, from Oct. 2014

PhD in progress : Amandine Sergeant-Boy, *Detection and characterisation of seismic sources generated by glaciers: numerical modelling and analysis of seismic waves*, Institut de Physique du Globe (Univ. Paris 7), supervised by A. Mangeney (in collaboration with J.-P. Montagner, E. Stutzmann and O. Castelnaud), from 2013

PhD in progress : Philippe Ung, *Simulation, modélisation et analyse numérique pour le transport sédimentaire*, Univ. Orléans (EDF-CNRS grant), supervised by E. Audusse and Y. Penel (in collaboration with S. Cordier), from Nov. 2012

M2 internship : Chen Cheng, *Modélisation numérique de l'érosion en rivière : un schéma de relaxation pour le modèle de Saint-Venant Exner*, ENSTA, supervised by E. Audusse, Spring 2014

M2 internship : Do Minh Hieu, *Numerical Analysis For Quasi Geostrophic Flows*, Univ. Paris 13, supervised by E. Audusse and Y. Penel (in collaboration with S. Dellacherie and P. Omnes), Spring 2014

M2 internship : Antoine Haddon, *Interprétation cinétique et schémas à grands pas de temps pour le système de Saint-Venant*, Univ. Pierre et Marie Curie Paris 6, supervised by E. Audusse, Y. Penel and J. Sainte-Marie, Summer 2014

M2 internship : Ethem Nayir, *Analyse mathématique d'un modèle hyperbolique pour les écoulements à surface libre*, Univ. Pierre et Marie Curie Paris 6, supervised by E. Audusse and Y. Penel, Summer 2014

### 9.2.3. Juries

22/01/14, PhD : J. Sainte-Marie (referee) : David Benoit (Univ. Paris-Est, *Divers problèmes théoriques et numériques liés à la simulation de fluides non newtoniens*)

09/10/14, HdR : A. Mangeney : Frédéric Cappa (Univ. Nice, *Le rôle des fluides dans la mécanique des failles et des glissements de terrain*)

17/10/14, PhD : N. Seguin (referee) : Arnaud Duran, (Univ. Montpellier 2, *Numerical simulation of depth-averaged flow models: a class of Finite Volume and discontinuous Galerkin approaches*)

09/12/14, PhD : E. Godlewski (president) : Mathieu Girardin (Univ. Pierre et Marie Curie Paris 6, *Méthodes numériques tout-régime et préservant l'asymptotique de type Lagrange-Projection. Application aux écoulements diphasiques en régime bas Mach*)

09/12/14, PhD : A. Mangeney : Nadège Langet (IPG Strasbourg), *Détection et caractérisation massives de phénomènes sismologiques pour la surveillance d'événements traditionnels et la recherche systématique de phénomènes rares*)

## 9.3. Popularisation

2014 : E. Audusse intervened in a secondary school (Pontault Combault) for "Maths en Jeans".

2014 : P. Ung presented his PhD topic in a high school (Lycée Duhamel Du Monceau, Pithiviers). This intervention was an initiative of "Centre-Science" (Orléans) in the context of a doctoral training.

26-28/11/14 : M. Parisot and Y. Penel ran the stand of the French mathematics community (SFdF, SMAI, SMF) at the Onisep part of the European exhibition for Education.

12/12/2014 : E. Audusse gave a talk at Bobigny for Mathematic Park entitled "Maths and Natural Hazards".

Alongside these events, the web platform TsunaMaths developed by E. Audusse, R. Hamouda and J. Sainte-Marie was presented at the exhibition on the occasion of "Mathematics of Planet Earth" (December 2012-December 2013) at the Deutsches Technikmuseum (Berlin). It was also a part of the Nims-Imaginary exhibition at Seoul (Aug. 13-20, 2014) on the occasion of ICM2014.

## 10. Bibliography

### Publications of the year

#### Articles in International Peer-Reviewed Journals

- [1] M. BERNARD, S. DELLACHERIE, G. FACCANONI, B. GREC, Y. PENEL. *Study of a low Mach nuclear core model for two-phase flows with phase transition I: stiffened gas law*, in "ESAIM: Mathematical Modelling and Numerical Analysis", 2014, vol. 48, pp. 1639-1679 [DOI : 10.1051/M2AN/2014015], <https://hal.archives-ouvertes.fr/hal-00747616>
- [2] F. BOUCHUT, E. D. FERNANDEZ-NIETO, A. MANGENEY, G. NARBONA-REINA. *A two-phase shallow debris flow model with energy balance*, in "ESAIM: Mathematical Modelling and Numerical Analysis", January 2015, vol. 49, n<sup>o</sup> 1, pp. 101 - 140, <https://hal-ujpec-upem.archives-ouvertes.fr/hal-00860871>
- [3] S. DELLACHERIE, G. FACCANONI, B. GREC, E. NAYIR, Y. PENEL. *2D numerical simulation of a low Mach nuclear core model with stiffened gas using FreeFem++*, in "ESAIM: Proceedings", 2014, vol. 45, pp. 138-147 [DOI : 10.1051/PROC/201445014], <https://hal.archives-ouvertes.fr/hal-00942569>
- [4] M. PARISOT, J.-P. VILA. *Numerical scheme for multilayer shallow-water model in the low-Froude number regime*, in "Comptes Rendus de l'Academie des Sciences. Serie 1, Mathematique", 2014, vol. 352, pp. 953 - 957 [DOI : 10.1016/J.CRMA.2014.09.020], <https://hal.inria.fr/hal-01079843>
- [5] B. PERTHAME, N. SEGUIN, M. TOURNUS. *A simple derivation of BV bounds for inhomogeneous relaxation systems*, in "Communications in Mathematical Sciences", 2014, vol. 13, n<sup>o</sup> 2, pp. 577-586, <https://hal.archives-ouvertes.fr/hal-00974269>

#### International Conferences with Proceedings

- [6] P. HARTMANN, D. DEMORY, C. COMBE, R. HAMOUDA, J. SAINTE-MARIE, M.-O. BRISTEAU, A.-C. BOULANGER, B. SIALVE, J.-P. STEYER, S. RABOUILLE, A. SCIANDRA, O. BERNARD. *Growth Rate Estimation of Algae in Raceway Ponds: A Novel Approach*, in "19th IFAC World Congress", Cape Town, South Africa, August 2014 [DOI : 10.3182/20140824-6-ZA-1003.02408], <https://hal.inria.fr/hal-01097313>

#### Other Publications

- [7] N. AGUILLON, F. LAGOUTIÈRE, N. SEGUIN. *Convergence of finite volumes schemes for the coupling between the inviscid Burgers equation and a particle*, October 2014, <https://hal.inria.fr/hal-01077311>
- [8] E. AUDUSSE, F. BOUCHUT, M.-O. BRISTEAU, J. SAINTE-MARIE. *Kinetic entropy inequality and hydrostatic reconstruction scheme for the Saint-Venant system*, September 2014, <https://hal.inria.fr/hal-01063577>
- [9] E. AUDUSSE, S. BOYAVAL, N. GOUTAL, M. JODEAU, P. UNG. *Numerical Simulation of the Dynamics of Sedimentary River Beds with a Stochastic Exner Equation*, December 2014, <https://hal.archives-ouvertes.fr/hal-01102335>
- [10] E. AUDUSSE, C. CHALONS, P. UNG. *A simple well-balanced and positive numerical scheme for the shallow-water system*, January 2015, <https://hal.archives-ouvertes.fr/hal-01083364>

- [11] F. BOUCHUT, I. IONESCU, A. MANGENEY. *A shallow model including static-flowing transition for viscoplastic Drucker-Prager materials*, November 2014, <https://hal-upec-upem.archives-ouvertes.fr/hal-01081213>
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- [16] D. KAZERANI. *The symmetric structure of the Green-Naghdi type equations*, October 2014, <https://hal.archives-ouvertes.fr/hal-01074488>
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- [20] C. MIFSUD, B. DESPRÉS, N. SEGUIN. *Dissipative formulation of initial boundary value problems for Friedrichs' systems*, October 2014, <https://hal.archives-ouvertes.fr/hal-01074542>

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