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CATS – A process-based model for turbulent turbidite systems at the reservoir scale

Vanessa Teles *, Benoît Chauveau, Philippe Joseph, Pierre Weill [1], Fakher Maktouf [2]

IFP Énergies nouvelles, 1-4, avenue de Bois-Préau, 92852 Rueil-Malmaison cedex, France

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ABSTRACT

The Cellular Automata for Turbidite systems (CATS) model is intended to simulate the fine architecture and facies distribution of turbidite reservoirs with a multi-event and process-based approach. The main processes of low-density turbulent turbidity flow are modeled: downslope sediment-laden flow, entrainment of ambient water, erosion and deposition of several distinct lithologies. This numerical model, derived from (Salles, 2006; Salles et al., 2007), proposes a new approach based on the Rouse concentration profile to consider the flow capacity to carry the sediment load in suspension. In CATS, the flow distribution on a given topography is modeled with local rules between neighboring cells (cellular automata) based on potential and kinetic energy balance and diffusion concepts. Input parameters are the initial flow parameters and a 3D topography at depositional time. An overview of CATS capabilities in different contexts is presented and discussed.

1. Introduction

Several recent oil discoveries are set in deep-marine reservoirs, and these are commonly composed of turbidite sandstones with very good reservoir properties, but also with a very high degree of heterogeneity. These reservoirs are usually formed by the stacking of deposits related to several hundreds of individual turbidity flow events. There is a wide range of gravity flow types and several classifications have been proposed in the literature according to flow characteristics such as rheology or density (Mulder and Alexander, 2001; Mulder and Cochonat, 1996; Shanmugam, 2000), sedimentary facies of deposits (Mutti and Ricci Lucchi, 1975; Pickering et al., 1989) or sediment transport processes (Lowe, 1979; Middleton and Hampton, 1973; Stow et al., 1996). The relationship between processes and resulting architectures are still subject to debate (Mulder, 2011; Shanmugam, 2012), particularly because direct observations and characterization of turbidity currents are difficult in reality. They are the scene of several complex physical processes interacting in a nonlinear way. Even in recent cases such as turbidity currents monitored in Monterey Canyon (Xu et al., 2004, 2013), and the 1929 Grand Banks event (Piper et al., 1999) or the 1979 Nice event (Migeon et al., 2001; Mulder et al., 2012), where cable breaks provide constrains on timing and associated deposits can be studied, there is debate on the flow regime, transport and deposition processes.

Most of these reservoirs lie in deep-offshore locations where data are scarce. To better understand their internal

* Corresponding author.
E-mail address: vanessa.teles@ifpen.fr (V. Teles).
[1] Now at Université de Caen Normandie, CNRS, Morphodynamique continentale et côtière (M2C), 24, rue des Tilleuls, 14000 Caen, France.
[2] Now at GEOREX, 7C, place du Dôme, immeuble Élysée-La Défense, 92056 Paris-La Défense cedex, France.

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architecture and sediment distribution, one approach is to study the processes, which led to their formation. Numerical modeling is one way to study these systems and to link the modeled processes to the associated deposits and resulting architecture. All parameters can be easily controlled and sensitivity analysis can be carried out. The difficulty lies in modeling the different processes and their interactions correctly when there is still debate on the acting processes themselves and on the different proposed formulations. The most detailed flow models (Basani et al., 2014; Meiburg et al., 2015; Rouzairol et al., 2012) implement 3D Navier–Stokes equations and are able to reproduce the full complexity of turbulent flow. But, these detailed numerical simulations require huge running times, even with highly parallelized powerful computing machines. The most common approximation of the Navier–Stokes equations is the Saint-Venant system of equations (e.g., Parker et al., 1986; Zeng and Lowe, 1997) in which the flow parameters are depth-averaged. Even with this approximated approach, the application of these models to a whole turbidite reservoir, resulting from the stacking of many flow event deposits, remains a challenge. Furthermore, since flow parameters vary from one event to the other and are difficult to infer from field data, it is difficult to constrain the model with accurate parameters. The applications of such process-based models follow a trial-and-error approach that requires several simulations and thus high computation time.

To overcome these problems, an alternative approach is to use simplified models mimicking the flow with enough realism to reproduce detailed description of reservoir architecture and heterogeneity of deep-offshore fields and with low computation times in order to generate multi-event simulations. To this purpose, the Cellular Automata for Turbidite Systems (CATS) model was developed at IFPEN. CATS is a multi-lithology process-based model for turbulent turbidity currents and their associated sedimentary processes. An overview of CATS capabilities in different contexts is presented and discussed in this paper.

2. Model description

2.1. CATS: a model for low-density turbidity currents

Among gravity flows, turbidity currents are usually defined as submarine sediment-laden flows in which the transport is mainly supported by the flow turbulence, with a distinction between high-density and low-density turbidity currents (Middleton and Southard, 1984; Mulder and Alexander, 2001). The CATS model has been developed for low-density turbidity currents where sediments are transported essentially in suspension by the fluid and where interactions between particles can be neglected. Mulder and Alexander (2001) give a maximum threshold of 9% of volumetric sediment concentration for low-density turbidity currents above which interactions between particles become non-negligible (Bagnold, 1962). In such a context, the main processes to be modeled are sediment-laden gravity-driven flow of turbulent dilute sediment suspensions, ambient water entrainment into the flow and sedimentary processes such as erosion and deposition.

2.2. Cellular Automata principles

This model is based on cellular automata (CA) concepts (Salles, 2006):

- the space is partitioned into identical cells composing a regular mesh. Each cell is an automaton and bears the local physical properties of the flow and of the seafloor;
- the chosen modeled processes are implemented through local laws either as *local interactions* between neighboring cells through mass and energy transfers; or as *internal transformations* of physical and energetic properties in each cell, which can be performed independently from the neighbors' state.

In the CATS model, flow distribution driven by gravity and by kinetic energy is considered as local interactions between adjacent cells. Sediment erosion, deposition and water entrainment of ambient water are internal transformations essentially based on empirical laws.

2.3. The flow model

2.3.1. Definition of the flow

The flow is described by a thickness (h) representing the turbiditic sediment-laden flow thickness, by volumetric mean concentrations ($C_{\text{sed}i}$) of different chosen discrete lithologies, and by a scalar velocity U (in m/s) computed from the kinetic energy balance in the system. It means that there is no vector velocity that could drive the fluxes and could define their direction. The ambient fluid is not explicitly modeled. Sediments are defined in as many discrete classes of particle types (grain-size and composition, referred to as "lithology") as needed to describe the sedimentary system. Secondary variables such as particle settling velocity are computed following empirical laws (Dietrich, 1982; Soulsby, 1997). Others, such as critical erosion/deposition shear stress $\left((\tau_{\text{cr}}^{\text{E}})_i/(\tau_{\text{cr}}^{\text{D}})_i\right)$ can be adjusted by the user to model different sediment behaviors and change their erodibility or depositional capabilities. The seabed is described by a given topography (cell altitudes) and proportions of the different sediments.

2.3.2. Flow distribution: a local algorithm

The CATS model is inspired by the cellular automata approach first developed by Di Gregorio et al. (1994, 1997, 1999) for subaerial landslides where the flow distribution is computed through the local algorithm of "minimization of height differences". Salles (2006) and Salles et al. (2007) adapted this algorithm for submarine turbidity currents. The algorithm seeks the equilibrium of energies between neighboring cells, considering both potential and kinetic energies, in order to take into account both gravitational and inertial effects. They are represented respectively through the flow thickness at the cell elevation and through the run-up height (hr). The latter was first defined by Rottman et al. (1985) as the height that can be reached by the flow when its kinetic energy is transformed to an