Journal of Petroleum Science and Engineering 160 (2018) 531–536

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

journal homepage: www.elsevier.com/locate/petrol

Modeling of shear stress distribution on mud surface in the subsea sand-mud alternate layer

Takero Yoshida[a,1], Paul E. Brumby[a,2], Hiroyuki Oyama[a], Georgios Fytianos[a], Toru Sato[a,*], Ryosuke Sakaizawa[a], Tatsuya Fuji[b], Jiro Nagao[c], Norio Tenma[d], Hideo Narita[c]

[a] Department of Ocean Technology, Policy, and Environment, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8563, Japan
[b] Department of System Innovation, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku 113-8656, Japan
[c] Research Institute of Energy Frontier, Department of Energy and Environment, National Institute of Advanced Industrial Science and Technology (AIST), 2-17 Tsukisamu-Higashi, Toyohira, Sapporo 062-8517, Japan
[d] Research Institute of Energy Frontier, Department of Energy and Environment, National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba West, 16-1 Onogawa, Tsukuba 305-8569, Japan

ARTICLE INFO

Keywords:
Sand-mud alternate layer
Mud surface erosion
Sandy porous media
Shear stress distribution
Lattice Boltzmann method
Gamma distribution function

ABSTRACT

This study aims at showing that the shear stress distribution on a flat surface in the porous media can be expressed by just one probability density function. It is known that methane hydrate exists in the sand layers off Kii Peninsula in Japan within the turbidite sand-mud alternate strata. One of the concerns about gas production from methane hydrate is mud erosion and consequent reservoir clog caused by skin formation. The erosion rate of mud particles depends on the shear stress distribution on the surface of the mud layer in the alternates. The distribution of shear stress should depend on the flow and reservoir properties. Being able to predict the total mass of the eroded mud in advance would definitely be convenient. The objective of this paper is to propose a mathematical model of shear stress distribution on a flat interface between sand and mud layers, because it is believed that the maximum mud-erosion rate is given at the very beginning of the gas production when the mud surface is almost flat. To obtain the shear stress distribution on a flat surface, we conducted pore-scale numerical simulations using computational domains including numerically generated sand-mud beds. Interestingly, we found that the histograms of the shear stresses fit just one curve by means of proper non-dimensionalization. These consistent histograms of the non-dimensional shear stress were then matched with a Gamma distribution function, to develop a mathematical model. This new finding may make possible to predict the maximum rate of mud erosion if we know water flow velocity and reservoir properties, such as porosity and permeability.

1. Introduction

To produce gas from methane hydrate in the subsea sand-mud alternate layers, depressurization is considered a feasible method (Yamamoto, 2014)). During the production of gas, methane gas and water dissociated by depressurization migrate through the sand-mud alternates. If the flow is too fast, the surface of the mud layer may be eroded, possibly resulting in reservoir clog (Yamamoto, 2008). This process is schematically depicted in Fig. 1. As shown in Fig. 1, mud erosion is likely to occur on the surface of mud layers, caused by water flow through the pore space of sand layers.

Yoshida et al. (2016) conducted numerical simulations of mud erosion using a pore-scale computational domain and concluded that mud erosion rate has a peak only at the beginning of the production when the mud surface is almost flat and decreases to almost zero within 10 days. It is, therefore, convenient if we can predict the maximum mud erosion rate at a particular subsea site in advance.

This study aims at trying to show that shear stress distribution on the mud surface in sand-mud alternate layers can be expressed by a simple mathematical model. To obtain shear stress distribution on the flat mud surface in the pore-scale sand layer, a lattice Boltzmann method (LBM) of Yoshida et al. (2016) was adopted. The modeling approach follows. (1) Numerical simulations were conducted in order to draw histograms of shear stress distribution acting on flat mud surface for various pore

* Corresponding author.
E-mail address: sato-t@k.u-tokyo.ac.jp (T. Sato).
[1] Current address: Institute of Industrial Science, The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa 277-8574, Japan.
[2] Current address: Department of Mechanical Engineering, Keio University, 3-14-1 Hiyoshi, Kohoku-ku, Yokohama 223-8522, Japan.

https://doi.org/10.1016/j.petrol.2017.10.090
Received 26 February 2017; Received in revised form 13 August 2017; Accepted 30 October 2017
Available online 2 November 2017
0920-4105/

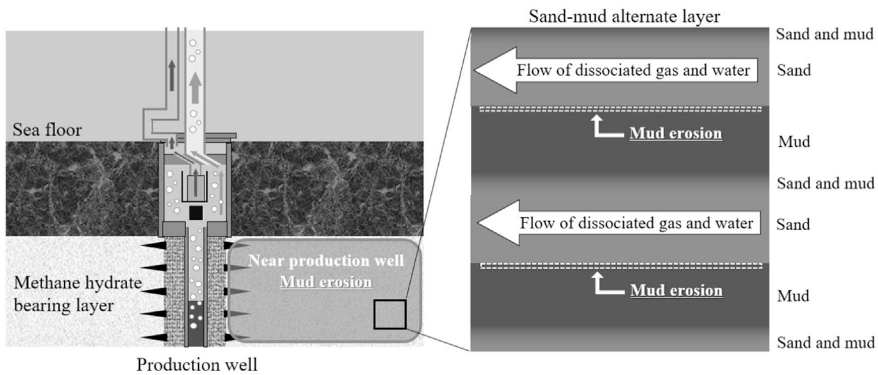

Fig. 1. Schematic image of the erosion of mud surface, caused by water flow, in sand-mud alternate layers.

spaces with different porosities and specific surface areas. (2) Non-dimensionalization of shear stress was then applied in order to develop a kind of universal shear stress distribution. (3) Then, we showed that this non-dimensional distribution can be expressed using the Gamma probability function. Using this model, the initial and the maximum rate of mud erosion can be estimated.

Here, the main assumptions we made were (a) that the shear stress distributions on a flat surface in the sandy porous media were analyzed to estimate the maximum erosion rate, and (b) that the mathematical model that can fit the non-dimensional shear stress distribution is the Gamma function.

2. Materials and methods

2.1. Generation of computational domains

A numerical method for packing sand grains into a pore-scale computational domain to achieve a required porosity has been developed by Sugita et al. (2012). The data of sand grain shapes was obtained using tomography images of sands of methane-hydrate-bearing layers off Kii Peninsula. We generated 30 sand patterns for each porosity: that is 0.40, 0.42, 0.44, 0.46, 0.48, or 0.50, based on the data of the hydrate-bearing sand layer off Kii Peninsula, Japan (Suzuki et al., 2015a, 2015b). The edge length of the domain is 200 μm and the number of sand grains in a domain is 6. A periodic condition is implemented at the boundaries of the domain. The errors in porosity of the generated sand patterns were within ±0.001. The domain is divided into 80 × 80 × 80 grids. Fig. 2 displays examples of the generated computational domains.

2.2. Numerical simulation of pore-scale fluid flow

The numerical simulation method is the same as that of Yoshida et al. (2016) and is also briefly explained here. It should be noted that this numerical method was already validated by comparing with the theoretical solution of the Poiseuille flow and with the eroded mass of mud measured by Oyama et al. (2016).

Water flows in pore space are computed using the LBM code originally developed by Sugita et al. (2012) and modified by Sato et al. (2012) and Yoshida et al. (2016). The code adopts the three-dimensional (3D) fifteen-velocity model of Qian et al. (1992). Here, the particle distribution function f_i is given by

$$\frac{\partial f_i}{\partial t} + c_i \cdot \nabla f_i = -\frac{1}{\tau}\left(f_i - f_i^{eq}\right), \tag{1}$$

where c_i is the directions of the particle velocity towards i, and τ is the relaxation time. The local equilibrium distribution function, f_i^{eq}, in non-dimension, is written as

$$f_i^{eq} = \rho w_i \left\{1 + 3c_i \cdot \mathbf{u} + \frac{9}{2}(c_i \cdot \mathbf{u})^2 - \frac{3}{2}\mathbf{u} \cdot \mathbf{u}\right\}, \tag{2}$$

where w_i is the weighting factor. The non-dimensional fluid density ρ and velocity $\mathbf{u}$ are expressed as

$$\rho = \sum_i f_i, \tag{3}$$

$$\mathbf{u} = \sum_i c_i f_i. \tag{4}$$

To obtain real velocity, lattice speed c (m/s), expressed as the following equation, is multiplied by (4).

$$c = \frac{\Delta x}{\Delta t}, \tag{5}$$

where Δx (m) is the lattice constant, Δt (s) is the time step. In order to satisfy the Navier–Stokes equation, the relaxation time τ is tuned by

$$\nu = \frac{1}{3}\left(\tau - \frac{1}{2}\right)c^2 \Delta t, \tag{6}$$

where ν (m^2/s) is the kinetic viscosity of water.

For replicating fluid flows, the following equations are calculated as the collision and streaming processes:

$$f_i(x + c_i\Delta t, t + \Delta t) = f_i(x, t) - \frac{1}{\tau}\left[f_i(x, t) - f_i^{eq}(x, t)\right], \tag{7}$$

$$f_i(x + c_i\Delta t, t + \Delta t) = f_i(x, t). \tag{8}$$

We used a bounce-back boundary condition presented by Bouzidi et al. (2001) for solid boundaries with curved surfaces.

2.3. Calculation of shear stress

The momentum-exchange method (Ladd, 1994; Mei et al., 2002) is an efficient way to calculate forces acting on solid surfaces in an LBM. The

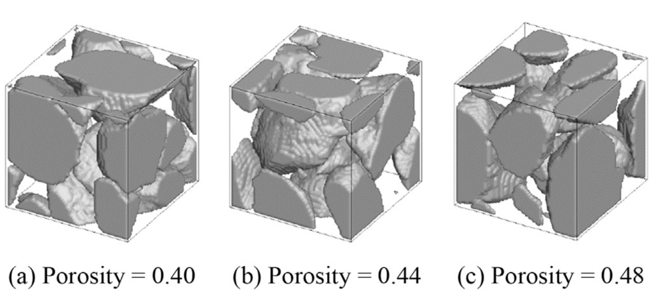

Fig. 2. Examples of pore-scale computational domains with different porosities.