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Point-to-point connectivity prediction in porous media using percolation theory

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HIGHLIGHTS

- Reservoir connectivity and its uncertainty evaluated for 2D areal models.
- Connectivity between points is much lower than that between lines.
- The exponent and percolation threshold for point-to-point connectivity is obtained.
- Point-to-point connectivity obeys the finite size scaling law.

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ABSTRACT

The connectivity between two points in porous media is important for evaluating hydrocarbon recovery in underground reservoirs or toxic migration in waste disposal. For example, the connectivity between a producer and an injector in a hydrocarbon reservoir impact the fluid dispersion throughout the system. The conventional approach, flow simulation, is computationally very expensive and time consuming. Alternative method employs percolation theory. Classical percolation approach investigates the connectivity between two lines (representing the wells) in 2D cross sectional models whereas we look for the connectivity between two points (representing the wells) in 2D aerial models. In this study, site percolation is used to determine the fraction of permeable regions connected between two cells at various occupancy probabilities and system sizes. The master curves of mean connectivity and its uncertainty are then generated by finite size scaling. The results help to predict well-to-well connectivity without need to any further simulation.

1. Introduction

Evaluation of underground reservoir connectivity is of great importance to reservoir forecasting, which is used for decision making in various possible development scenarios. Reservoir performance prediction usually consists of two processes; static property modeling and flow simulation. Geostatistical techniques are used to build static property models based on all available data and geological interpretations. Lack of sufficient data often creates great uncertainties in the generated models. These uncertainties are reflected in the differences between many equi-probable reservoir models. In practice, realizations ranking is needed before any flow simulation due to large computational costs associated with flow simulations [1]. Thus, there is a great interest to produce a much simpler, physically-based method to predict uncertainties in the reservoir performance very quickly, especially for engineering purposes.

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Nomenclature

p	Occupancy probability or net-to-gross ratio
L	Size of the system
$P(p, L)$	Connectivity of finite size system
β	Connectivity exponent
p_c^{∞}	Infinite percolation threshold
$\tilde{p}_c$	Apparent percolation threshold
Δ	Standard deviation of connectivity
F	Universal scaling function of connectivity
R	Universal scaling function of standard deviation of connectivity
ξ	Correlation length
ν	Correlation length exponent

The most common metrics used to describe the spatial distribution of a field are based on two-point statistics, such as covariances, variograms, or spatial entropy [2,3], but they are not able to measure the connectivity [2–4]. Two-point statistical metrics describe only the probability of having a certain value at a certain location knowing the value at another location. Neither the structure of property map nor the connectivity is considered in such metrics [2]. This is the reason why other approaches such as percolation theory or multiple-point geostatistics should be used [2,4].

In this research, we used the percolation theory approach for quantifying well-to-well connectivity and its associated uncertainty. It is emphasized that the well-to-well connectivity is considered as a static property of porous media. Another important property to be evaluated is the well-to-well conductivity which is an indicator of flow connectivity in porous media as used by Knudby and Carrera [3]. The same methodology can be implemented on the backbone (instead of the whole connected cluster) to evaluate this property. This issue is out of the scope of the present work and it will be discussed in the future studies.

Percolation theory deals with phase transition from many disconnected finite clusters to an infinite spanning cluster when the occupancy probability p increases [5]. The assumption of binary system has originally been used by site percolation. The real problems do not satisfy the assumptions used in the percolation theory. Usually the permeability distribution of hydrocarbon reservoirs is not as a binary permeability field (i.e. grid blocks to be either permeable or impermeable) as assumed in the classic percolation theory. The permeability distribution can be characterized by a very broad distribution such as a log-normal distribution. Moreover, in reality the spatial distributions of permeability maps are neither isotropic nor uncorrelated. The greater flexibility can be implemented by using either bond percolation or continuum percolation. However, the intersection with zero dimensional point becomes a challenge in bond percolation. The intersection of the point with a 2D site (in site percolation) or with a 2D object (in continuum percolation) is easily achievable by using some realizations of the model compared with the intersection of the point with a 1D line segment in bond percolation. In this study, without loss of generality we start with site percolation, as it is much easier, and we aim to expand it to continuum media in our future works.

Percolation theory has been applied to both the pore scale [6–8] and the field scale [9–13]. King [9] used an overlapping sandbodies model to study the connectivity and conductivity of reservoirs. Berkowitz [10] applied the percolation theory to characterize the flow behavior of fractured rock systems. Nurafza et al. [11] validated the developed connectivity curves against a realistic field dataset. Masihi et al. [12] developed the connectivity master curves of fractured reservoirs using the percolation theory. Sadeghnejad et al. [13] extended the percolation approach to determine the hydraulic conductivity and breakthrough time.

In previous studies [9–13], percolation theory has been applied for quantifying the connectivity between two lines in 2D cross models where two lines representing completely perforated injection and production wells (Fig. 1-left). This is a classic 2D percolation problem where line-to-line connectivity is studied. However, there are several cases in which the point-to-point connectivity address the connectivity between two wells. Examples are 2D cross models where the wells are partial perforated or 2D aerial models where each well is represented by a point (Fig. 1-right). In such cases, we need to know what fraction of permeable phase is connected between two points. The purpose of this study is to apply percolation concepts to evaluate the point-to-point connectivity and its associated uncertainty in 2D models and compare the results with line-to-line connectivity values.

In reality the reservoirs are three-dimensional, with tens of meters thickness and tens of kilometers aerial extent, so the measure of the line-to-line connectivity in 3D becomes important, as some of the properties have been studied by da Silva et al. [14,15]. However, under some situations, reservoir engineers, for example, simplified the 3D reservoir models into 2D aerial models [16,17]. The assumption of two-dimensional reservoirs may result from laterally continuous heterogeneities that exist in nature [18]. If a reservoir is vertically stratified into separate reservoir compartments, and the stratification thickness is approximately the same as the channel thickness, then the reservoir can be modeled as a 2D sheeted reservoir [18]. Essentially, any impermeable mudstone unit that is continuous across the entire reservoir and forms reservoir compartments on the order of the thickness of the channel deposits can cause two-dimensional connectivity [18].