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# Studies on seepage law considering stratigraphic dips

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A B S T R A C T

Currently, water injection is widely used for oil field developments. For reservoirs with complex geological structures, large stratigraphic dip angles, low porosities and extra-low permeabilities, the effect of water injection is not satisfying. This paper establishes a modified radial flow formula on the dip angle, and uses the plane radial seepage theory to get formation pressure distributions and a production formula in tilted strata. For injectors with their threshold pressures greater than their formation in-situ pressures, the effective radius for waterflooding is derived for a given injection pressure and then it is used to evaluate waterflooding effect and well pattern suitability, and guide the oilfield production. This method can also be applied to other waterflooding oilfields with similar geological conditions.



## 1. Introduction

In some reservoirs with complex geological structures, large stratigraphic dips, low porosities and extra-low permeabilities, their water absorption capacity is poor due to low reservoir matrix porosity and permeability. With production of crude oil, their formation energy gradually depletes. In order to maintain their reservoir pressures, we often implement network regulation for the purpose of water injection. However, waterflooding is often successful [1]. The bottom-hole pressures of injectors increase with waterflooding development; the required pump pressures thus increase. It's believed that, the reasons of injection pressure increase is in part due to the extra-low permeability and porosity, and in part related to the large reservoir dip angles. Without considering the effects of dip angles, only using the plane radial seepage theory [2] will have significant deviation to guide the production.

Many progresses on effects of stratigraphic dip have been made in recent years. Noaman [3] proposed a mathematical model which was developed to predict waterflood performance in communicating stratified reservoirs with a dip angle. Pu et al. [4] studied effect of seepage on creep of overlying strata in filling mining process. Vervoort [5] presented an overview of typical rock mechanics problems in an inclined shafts and adits of South African collieries. And in his paper, the geological and geotechnical conditions, tunnel design and supporting systems are described and compared. Zhao [6] introduced in detail the experimental method and results of two phase gas-liquid seepage in rock fractures, and the complex permeability of two phase fluid changes regularly with the gas saturations and 3D stresses.

Kerzner [7] presented a new method for dipmeter computation which was based on formalizing and implementing some of the rules of optical dipmeter correlation, Applications of this method result in a precise definition of dip information at both structural and stratigraphic levels. Salim [8] studied the Stratigraphic dip patterns from high-resolution microresistivity images, which could indicate the paleocurrent direction of sediments transported by water and the associated depositional environment such as sand-filled stream channels and flood planes. This information then was successfully used in the prediction of sand body orientation trends. Chen and Zhan [9] proposed a new technique that could be used to extract

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structural and stratigraphic information from seismic data automatically and quickly. Parvaneh [10] introduced a new algorithm for seismic image flattening. The algorithm transfers seismic data to a new coordinate system and consists of two steps. First, local slopes of seismic events are estimated by plane-wave-destruction, then this information is spread along the seismic data; and horizons are picked by predictive painting algorithm. Bigelow's [11] integration of data from a larger areal extent provides a more conclusive evidence in defining the geometry, depositional trends, and lithostratigraphy of an inclined reservoir. Charles [12] provided a method which was used to geosteer horizontal wellbores. It compares a log track in the horizontal well lateral, usually a gamma ray log, to the same type of log in a nearby vertical well (the pilot or template well). In this process, the log from the horizontal wellbore is squeezed and/or inverted until the characteristics in the new well matches that in the template well. Squeezing is necessary because relatively small stratigraphic intervals in the template well will be traversed over much larger distances in a horizontal well.

However, until now, the studies on stratigraphic dips are mainly related to seismic and geology, the studies on the seepage law of stratigraphic dip are rarely reported. What impacts will the dip angle have on fluid flow? It has significantly impacts on waterflood in such reservoirs. This paper uses the basic plane radial seepage theory and carries on the dip angle calibration, and establishes a formula to predict formation pressure distributions and well productions in tilted strata.

## 2. Differential equations in tilted strata

In reservoirs with large stratigraphic dips, low porosities and extra-low permeabilities, waterflood is often unsuccessful, this paper focuses on the problem of oil wells without successful waterflooding, establishes a homogeneous formation model based on following assumption [13,14]:

(1) In a round, equal thickness, tilted, and homogeneous stratum, there is a perfect well at the center, the formation edge has sufficient fluid supply. The supply edge radius in horizontal projection plane is $R_e$, the formation pressure converting to the well point level is $P_e$. Oil wells radius is $R_w$, bottom-hole flowing pressure is $P_w$, and the formation thickness is $h$.

(2) Under the hydraulic drive mode, the reservoir has a single phase, homogeneous, and incompressible fluid flow ruled by Darcy's law. For tilted strata, we take the following related parameters (Fig. 1):

$\alpha$—stratigraphic dip;

$\alpha'$—apparent dip between well point and any point of strata;

$\beta$—azimuth calculated from the formation tendency with respect to the well point (origin);

The relationship between the above three parameters are:

$$\begin{aligned} \alpha' &= \frac{2\alpha}{\pi}\left(\frac{\pi}{2}-\beta\right) \quad 0 \le \beta < \pi \\ \alpha' &= \frac{2\alpha}{\pi}\left(\beta-\frac{3\pi}{2}\right) \quad \pi \le \beta < 2\pi \end{aligned} \tag{1}$$

With the above assumptions:

$$\frac{\partial P}{\partial z} = \rho g \tag{2}$$

Derivative of equation (2):

$$\frac{\partial^2 P}{\partial z^2} = 0 \tag{3}$$

Since the fluid is incompressible and has a steady-state flow, therefore:

$$\frac{\partial P}{\partial t} = 0 \tag{4}$$

The basic seepage differential equation:

$$\frac{\partial^2 P}{\partial z^2} + \frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = \frac{\partial P}{\eta \partial t} \tag{5}$$

Substituting equations (3) and (4) into (5):

$$\frac{\partial^2 P}{\partial x^2} + \frac{\partial^2 P}{\partial y^2} = 0 \tag{6}$$

Consistent with the differential equation of the plane radial flow, the fluid is also a radial flow in the tilted strata, and the coordinate transformation of equation (6) is expressed in the polar coordinates as:

$$\frac{d^2 P}{dR^2} + \frac{dP}{RdR} = 0 \tag{7}$$

## 3. Seepage model

When water injection starts, the reservoir intake will start only when injecting pressure reaches a certain threshold pressure, which depends on stratigraphic attributes and is not affected by the dip angle. Different injectors have different threshold pressures. The threshold pressures of some wells are lower than their formation pressures, while others are greater than their formation pressures [15].

Based on the seepage differential equation obtained with the assumption of 1, we will discuss two cases of injection wells in tilted strata in the next step.

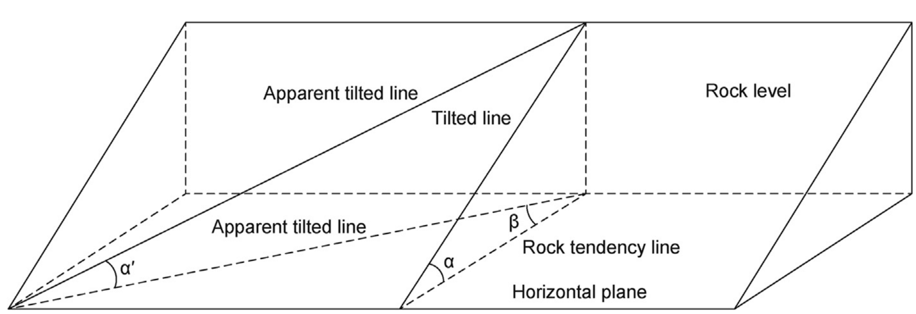


**Fig. 1.** Relationship between the true dip and the apparent dip.