Bacterial transport in porous media: New aspects of the mathematical model

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Abstract

Transport of bacteria is an important aspect from scientific, industrial and environmental point of view. In this work, a one-dimensional mathematical model based on linear equilibrium adsorption of bacteria has been developed to predict bacterial transport through porous media. This model is more realistic than existing models because of its coupling both physicochemical and biological phenomena. Two important biological phenomena, the growth and decay of bacterial cells and chemotactic/chemotaxis of bacteria along with physicochemical properties have been adequately incorporated which are quite new aspects in our model. In agreement with experimental study by [D.K. Powelson, R.J. Simpson, C.P. Gerba, J. Environ. Qual. 19 (1990) 396], model simulations indicated that enhancement of breakthrough occurs due to increase in flow velocity, cell concentration, substrate concentration, respectively. It has also been found that chemo tactic has a significant effect on bacterial transport, especially under conditions of considerable substrate gradient and at low pore velocity. The importance of threshold concentration of captured cells (σ_0) on bacterial transport has also been identified which is also a new aspect in our model.

.*Keywords:* Transport model; Porous media; Bacteria; Chemotaxix

1. Introduction

Bacteria can pose serious health hazards if they occur in drinking water wells [1–2]. Historically, groundwater has been assumed to be free of pathogenic viruses, bacteria, and protozoa, but recent surveys indicate that a significant fraction of groundwater supplies are a source of water-borne diseases [3]. If at least four orders of magnitude reduction in virus, bacteria concentration can not be achieved between a potential microorganisms source (e.g. septic tank, leaking sewer line, or sewage infiltration beds, land application of sewage sludge) and a water supply well, the aquifer will be considered "*hydrogeologically sensitive*" [3]. Another major source of bacteria in soils or groundwater aquifers is the controlled application or injection of selected bacteria strains for in situ bioremediation of contaminated sites via bioaugmentation [4] or as biocontrol organisms against certain plant diseases [3]. Therefore, knowledge about transport of bacteria in porous media is necessary for safe disposal of wastewater and for the development of effective bioremediation strategies of contaminated soils and groundwater using introduced bacteria strains [4].

Although the problem has a great practical importance, the mathematical model on bacterial transport phenomena in subsurface environments is very limited. Transport of bacteria in porous media has been an active research area during last two decades [3–23] and it is mainly bounded with small scale batch and column studies. Physical and mathematical model for describing the fate of bacteria in porous media has been developed by few researchers [3,4,8,17,20,23]. Bacterial transport in the subsurface is a complex and interacting process. Because bacterias are living organisms, their trans-

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Nomenclature

C_b	concentration of bacterial cells in suspension in mass per unit volume (kg/m^3)
C_{b0}	initial concentration of bacterial cells in mass per unit volume (kg/m^3)
C_F	concentration of substrate in suspension in mass per unit volume (kg/m^3)
D_b	dispersion coefficient for bacterial cells (m^2/s)
D_F	dispersion coefficient for the substrate (m^2/s)
k_{df}	specific decay rate for freely suspended cells (1/s)
k_{ds}	specific rate for captured cells (1/s)
k_{gf}	specific growth rate for freely suspended cells (1/s)
$k_{g\,max}$	maximum specific growth rate for bacterial cells (1/s)
k_{gs}	specific growth rate for captured cells (1/s)
k_y	detachment rate coefficient for deposited particles (1/s)
k_1	release rate coefficient for sessile cells (1/s)
k_2	captured coefficient for freely suspended cells (1/s)
K_S	Monod constant (kg/m^3)
L	length of the bed (m)
r_c	rate of captured of suspended cells (kg/m^3 s)
r_{df}	rate of decay of freely suspended cells (kg/m^3 s)
r_{ds}	rate of decay of captured cells (kg/m^3 s)
r_F	rate of consumption of substrate (kg/m^3 s)
r_{gs}	rate of growth of captured cells (kg/m^3 s)
r_{gf}	rate of growth of freely suspended cells (kg/m^3 s)
r_r	rate of release of captured cells (kg/m^3 s)
s	cell swimming speed (m/s)
S	mass of bacteria per unit mass of solid particles (kg/kg)
S'	mass of attached bacterial cells per unit volume of water (kg/m^3)
S_F	mass fraction of the substrate adsorbed on to the solid matrix (kg/kg)
S'_{max}	maximum cell retention capacity of the solid particles (kg/m^3)
t	time (s)
t_s	duration of application of bacterial pulse (s)
v_c	chemotactic velocity of bacteria (m/s)
v_g	sedimentation velocity of bacteria (m/s)
v_p	pore water velocity (m/s)
x	distance (m)
$X(C_F)$	chemotactic sensitivity coefficient (m^5/kg s)
Y	yield coefficient

Greek letters

ε	porosity
ρ_b	density of bacteria (kg/m^3)
σ	volume of deposited bacteria per unit volume of bulk soil (m^3/m^3)
σ_0	minimum volume of deposited bacteria per unit volume of bulk soil (m^3/m^3)
σ_x	concentration of sessile cells (fluid volume basis) (kg/m^3)
σ_{x0}	minimal concentration of sessile cells (fluid volume basis) (kg/m^3)

port in the subsurface is more complex than in the case for colloidal solutes transport [24]. Not only are they subject to same physicochemical phenomena as are colloids [24] but they are also a number of strictly biological processes that affect their transport. Several environmental factors controlling bacteria fate in subsurface porous media are captured to and release from the porous medium surfaces, growth and inactivation and advection and dispersion [18]. Experimentally, it has been found that there are several important factors which control the bacteria transport in porous media. These are cell size, shape, hydrophobicity, motility, etc. [22–24], medium characteristics like soil type, grain size, heterogeneity and organic matter content [10,25–26]; water chemistry factors such as pH, and ionic strength [24,26–29]; and flow characteristics, such as flow velocity and bacterial concentration [14,30–31].

Mahler et al. [21] presented the results of an investigation of event-based bacterial contamination of a heterogeneous Karsh aquifer, focusing on the importance of sediment-associated bacterial transport. Camesano and Logan [31] and Camesano et al. [32] developed a filtration based model explicitly accounting for blocking that could be used to predict the effect of influent colloidal solute concentration on the deposition of colloids in porous media. Finally, their model has been used to demonstrate that blocking can results in enhancement in bacteria transport in porous media. Filtration model for bacterial transport has been modified for describing down gradient transport of bacteria in sandy aquifer sediments [20] and they found that adsorption phenomena to be major control of the extent of bacterial movement down gradient [20]. Bales et al. [18] developed a one-dimensional bacterial transport model with first-order kinetic plus an equilibrium mass-transfer term which is adequate to describe the bacteria mass-transfer processes between the soil and water phases of the aquifer. They have been simulated with the advection–dispersion equation coupled with the simple mass transfer equations. Tan et al. [14] developed a model in which they have taken into account maximum retention capacity of the solid surface for the kinetic expression to describe the attachment and detachment of bacteria and its importance on bacterial transport in porous media. Corapcioglu and Hari-

das [8] developed a model for both virus and bacteria considering the environmental factors which affect the transport of both bacteria and virus in soils. They found that the important factors such as bacterial type, rainfall, soil moisture, temperature, soil composition, pH, presence of oxygen, nutrients and availability of organic matter affect the bacterial transport.

Most bacterial transport models incorporate a variety of physical processes such as advection, dispersion, straining and physical filtration. Until recently, approaches to modeling bacterial transport in subsurface environments have drawn heavily on analogies to solute transport that regard the bacteria as nonmotile colloids. Most bioremediation technique depends on the advective–dispersive transport of species to modify metabolism and on the transport of the microbial cells themselves. Cell transport occurs both by convection of aqueous phase organism and by generation of new aqueous phase of microbes through growth. The important processes which can limit the effectiveness of such schemes include cell prediction, cell decay and cell attachment to solid surface. The biological processes affecting bacterial transport should be expressed through growth or decay processes and should include active adhesion or detachment, survival and chemo taxis. The biological nature of these processes presents a challenge for bacterial transport modeling. Microorganism which have the capability to move in the absence of a chemical gradient is known as "Chemotaxis" and those who have capability to move in response to chemical gradient is known as "Chemo tactic". Both random mobility and chemotaxis have cited as potential means of transport of subsurface bacteria [33]. Motile bacteria can respond by moving to a more desirable environment. They move toward increasing concentration of beneficial substances, such as nutrients and away from increasing concentrations of detrimental substances, such as toxins.

In this work, a comprehensive mathematical model for bacterial transport and fate coupling with both physicochemical and biological phenomena such as bacterial growth and decay as well as incorporation of chemotaxis/chemotactic in porous media has been presented which is unique in our developed model. This model is more realistic than the existing models as it describe complete coupling of physicochemical-biological phenomena. This model is based on coupling of microbial and substrate conservation equations, transient conditions, convective transport, etc. Model simulations shows that with the increase of flow velocity, inlet cell concentration, substrate concentration, enhancement of bacterial breakthrough takes place and it is also found that chemotactic played a significant role in bacterial transport, especially under considerable substrate gradient and low pore water velocity. The importance of threshold concentration of captured cells (σ_0) on bacterial transport has also been identified which is also a new aspect in our model. Moreover, model sensitivity on release and capture coefficients of adsorbed cells on breakthrough plots have also been highlighted.

2. Model development

The model has been formulated to study the transport of bacteria through a column packed with a porous medium (sand, soil, etc.) and it is on the similar framework of bacterial transport model developed by Corapcioglu and Haridas [8]. A set of unsteady state mass balance equations are derived based on the following assumptions:

- The bacterial cells are partitioning among the two phases, namely solid matrix and aqueous phase.
- The cells are uniformly suspended in the medium.
- The variation in concentration is significant only in axial direction with water flow.
- The porosity of the bed is constant.

An unsteady state mass balance on plank-tonic cells (cells freely suspended) may be written as:

$$\varepsilon\frac{\partial}{\partial t}(C_\mathrm{b}) = D_\mathrm{b}\varepsilon\frac{\partial^2 C_\mathrm{b}}{\partial x^2} - (v_\mathrm{p}+v_\mathrm{g}+v_\mathrm{c})\varepsilon\frac{\partial C_\mathrm{b}}{\partial x} + (r_\mathrm{r}-r_\mathrm{c}) + (r_\mathrm{gf}-r_\mathrm{df}) \quad (1)$$

where C_b is the concentration of cells in aqueous phase in mass per unit volume of water (kg/m^3), ε is the porosity of the medium, v_c is the chemotactic velocity of bacteria (m/s), v_g is the sedimentation velocity of bacteria (m/s), v_p is the pore water velocity (m/s), D_b is the dispersion coefficient for bacterial cells (m^2/s), r_r is the rate of release of sessile cells (cells adsorbed onto the solid matrix) (kg/m^3 s), r_c is the rate of capture of planktonic cells (kg/m^3 s), r_gf is the rate of growth of plank-tonic cells (kg/m^3 s), and r_df is the rate of decay of planktonic cells (kg/m^3 s).

The simplest form of bacterial chemotaxis is the linear dependence of chemotactic velocity, v_c (m/s) on the substrate concentration gradient [34]:

$$v_\mathrm{c} = X(C_\mathrm{F})\frac{\partial C_\mathrm{F}}{\partial x} \quad (2)$$

where $X(C_\mathrm{F})$ is the chemotactic sensitivity coefficient and is given by:

$$X(C_\mathrm{F}) = vs^2 R_\mathrm{t}\frac{K_\mathrm{d}}{(C_\mathrm{F}+K_\mathrm{d})^2} \quad (3)$$

where s (m/s) is the one-dimentional cell swimming speed, which typically range between 20 and 60 μm/s [35], R_t is the number of receptors on the bacterial cell surface, K_d is the dissociation constant for the receptor–attractant complex, and v is the differential tumbling frequency which represents the fractional change in cell run time per unit temporal change in receptor occupancy.

Considering sedimentation of bacteria negligible due to proximity of density of bacteria to that of water, Eq. (1) becomes

$$\varepsilon\frac{\partial}{\partial t}(C_\mathrm{b}) = D_\mathrm{b}\varepsilon\frac{\partial^2 C_\mathrm{b}}{\partial x^2} - (v_\mathrm{p}+v_\mathrm{c})\varepsilon\frac{\partial C_\mathrm{b}}{\partial x} + (r_\mathrm{r}-r_\mathrm{c}) + (r_\mathrm{gf}-r_\mathrm{df}) \quad (4)$$

An unsteady state mass balance on sessile cells becomes:

$$\frac{\partial}{\partial t}(\rho_b \sigma) = (r_c - r_r) + (r_{gs} - r_{ds}) \tag{5}$$

where σ (m^3/m^3) is volume of captured bacteria in unit volume of bulk soil, r_{gs} (kg/m^3 s) is the rate of growth of sessile cells, r_{ds} (kg/m^3 s) is the rate of decay of sessile cells and ρ_b (kg/m^3) density of bacteria, respectively.

The following relations are used for release and capture of bacterial cells [36]:

$$r_r = k_1 \rho_b (\sigma - \sigma_0) \quad \text{for } \sigma > \sigma_0 \tag{6}$$

$$r_r = 0 \quad \text{for } \sigma < \sigma_0 \tag{7}$$

and

$$r_c = k_2 \varepsilon C_b \tag{8}$$

where k_1 (s^{-1}) is the release rate coefficient for sessile cells, k_2 (s^{-1}) is the capture coefficient for planktonic cells and σ_0 (m^3/m^3) is minimum sessile cell concentration which accounts for cells that are irreversibly captured within the porous medium.

As bacterial growth in a subsurface environment is slow, the Monod equation are used for bacterial growth which is as follows

$$r_{gf} = k_{gf} \varepsilon C_b \tag{9}$$

$$r_{gs} = k_{gs} \rho_b \sigma \tag{10}$$

where k_{gf} (s^{-1}) and k_{gs} (s^{-1}) are specific growth rates for free and captured cells, respectively. We assume that both the specific growth rates are same. Monod equation for the functional relationship between k_g and an essential nutrient concentration C_F can be written

$$k_g = \frac{k_{g\,max} C_F}{K_S + C_F} \tag{11}$$

where $k_{g\,max}$ (s^{-1}) is the maximum specific growth rate and K_S (kg/m^3) is Monod constant for the essential nutrient.

Corapcioglu and Haridas [8] proposed an irreversible first order reaction for death of bacterial cells as:

$$r_{df} = -k_{df} \varepsilon C_b \tag{12}$$

$$r_{ds} = -k_{ds} \rho_b \sigma \tag{13}$$

where k_{df} (s^{-1}) and k_{ds} (s^{-1}) are the specific decay rates for free and captured cells, respectively, and we assume that both rate constants are same.

The substrate, C_F (kg/m^3) that is consumed by the cells at a rate r_F is assumed to be transported by convective dispersion. Thus, the mass conservation equation for C_F in equilibrium with its adsorbed species S_F is written as per Corapcioglu and Haridas [8]

$$\varepsilon \frac{\partial}{\partial t}(C_F) + \frac{\partial}{\partial t}(\rho_s S_F) = D_F \varepsilon \frac{\partial^2 C_F}{\partial x^2} - v_p \varepsilon \frac{\partial C_F}{\partial x} - r_F \tag{14}$$

where C_F (kg/m^3) is the substrate concentration in aqueous phase, S_F (kg/kg) is mass of adsorbed substrate per unit mass of solid matrix; D_F (m^2/s) is the dispersion coefficient for the substrate and ρ_s (kg/m^3) is the bulk density of dry solid matrix.

Considering the presence of a stoichometric ratio, Y, between mass of substrate utilized and cells formed, the net rate of consumption of substrate becomes:

$$r_F = \frac{k_g}{Y}(\varepsilon C_b + \rho_b \sigma) \tag{15}$$

where Y is the Yield coefficient.

Considering linear equilibrium relationship between C_F and S_F, we can write

$$S_F = k_F C_F \tag{16}$$

where k_F (m^3/kg) is the partition coefficient.

The initial and boundary conditions can be written for a packed column of length L as:

$$C_b = 0 \quad x > 0, \quad t = 0 \tag{17}$$

$$\sigma = 0 \quad x > 0, \quad t = 0 \tag{18}$$

$$C_F = 0 \quad x > 0, \quad t = 0 \tag{19}$$

$$C_b = C_{b0} \quad x = 0, \quad t > 0 \tag{20}$$

$$\frac{\partial C_b}{\partial x} = 0 \quad x = L, \quad t > 0 \tag{21}$$

$$C_F = C_{F0} \quad x = 0, \quad t > 0 \tag{22}$$

$$\frac{\partial C_F}{\partial x} = 0 \quad x = L, \quad t > 0 \tag{23}$$

Eqs. (1)–(23) provide a mathematical framework to determine various relevant quantities.

3. Results and discussions

The proposed model for bacterial transport has been applied to simulate the migration of bacterial cells along a finite column. Influent solutions of bacterial cells and nutrient continuously fed through the column. Numerical solution to the set of partial differential equations has been obtained using a fully implicit finite difference scheme. In this method, the entire region of interest is divided into a grid of uniform resolution of the dimensions. The implicit formulations of partial differential equations along with boundary conditions led into sets of ordinary differential equation. The resulting sets of ODEs are solved simultaneously at each time step by using Crank-Nicolson finite difference scheme, which reduced each set of ODEs into sets of algebraic equations with a tridiagonal coefficient matrix which is solved by Gauss elimination technique. Breakthrough curves are presented as percentages of aqueous phase concentration C_b/C_{b0} against pore volume

Table 1
Base values for the model parameters used in simulation [14,35]

Parameter	Value
D_b (m^2/s)	4.0×10^{-6}
D_F (m^2/s)	4.0×10^{-6}
k_d (m^2/s)	1.0×10^{-6}
k_F (m^3/kg)	2.0×10^{-3}
$k_{g\,max}$ (s^{-1})	4.0×10^{-5}
K_S (kg/m^3)	0.2
Y	0.04
ρ_b (kg/m^3)	1000
ρ_S (kg/m^3)	1740
σ_0 (m^3/m^3)	0.02

($tv/L\varepsilon$), where C_{b0} is the influent cell concentration at $x = 0$. The model parameters used in the simulations have been obtained from the published works and are summarized in Table 1.

3.1. Model validation

Fig. 1 shows the comparism between our model predations and experimental data obtained from laboratory column studies performed by Tan et al. [14]. The experiment was carried out by applying bacterial pulse (10^8 cells/ml) at a velocity of 0.2 mm/s at the inlet of a 30 cm column for 1 h, followed by passing deionized water. The bed porosity was 0.38. The values of k_1 and k_2 are taken from the estimation carried out by Tan et al. [14] and all other parameters are taken from Table 1 for our simulation. It is seen that there is reasonable agreement between the experimental data and our model prediction.

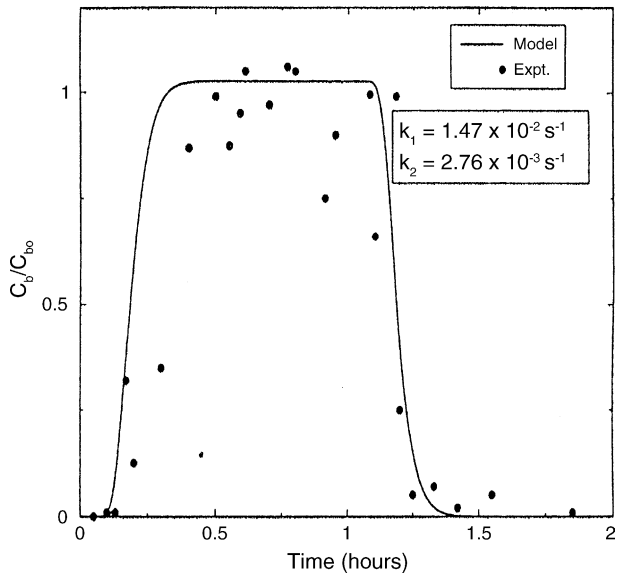

Fig. 1. Comparison between model prediction and experimental data for bacterial breakthrough by Tan et al. [14].

4. Model predictions and discussion

In this section first model simulation results are presented without considering chemotaxis phenomena by varying different parameters such as flow velocity, inlet cell concentration, substrate concentration, etc. so as to investigate the effects of these parameters on bacterial transport and finally effect of chemotaxis on bacterial transport is also highlighted in latter section.

4.1. Effect of velocity on bacterial transport

Fig. 2 represents the effect of flow velocity on aqueous phase bacterial cell concentration. It is clear that with increase in velocity, the breakthrough occurs earlier. This is because at higher velocity, more number of cells are introduced within the same time and saturation of retention capacity occurs much earlier or we can say the threshold adsorption capacity of the captured cells (σ_0) attains much earlier. It may also due to enhancement in the rate of external mass transfer and therefore breakthrough occurs at a much earlier time. Moreover, there is probability in enhancement in the penetration of the cells through the porous medium thereby leading to earlier breakthrough. The enhancement of bacterial transport at higher water flow velocity is also reported experimentally by several other investigators [7,14].

4.2. Effect of inlet cell concentration on bacterial breakthrough

It is presented in Fig. 3 at different inlet cell concentrations (C_{b0}). It shows that bacterial transport is enhanced at higher cell concentration which is also found experimentally by Tan et al. [14] and Lindqvist et al. [37], respectively. This is because of shortage of time in saturation of finite retention sites, i.e. attainment of the threshold concentration of cap-

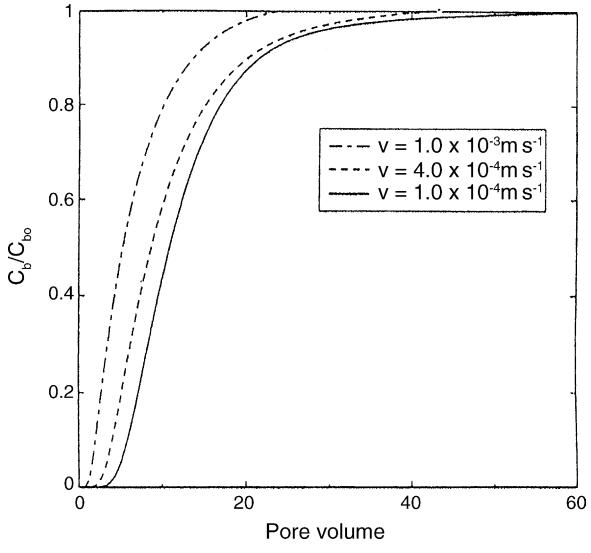

Fig. 2. Effect of flow velocity on bacterial transport.

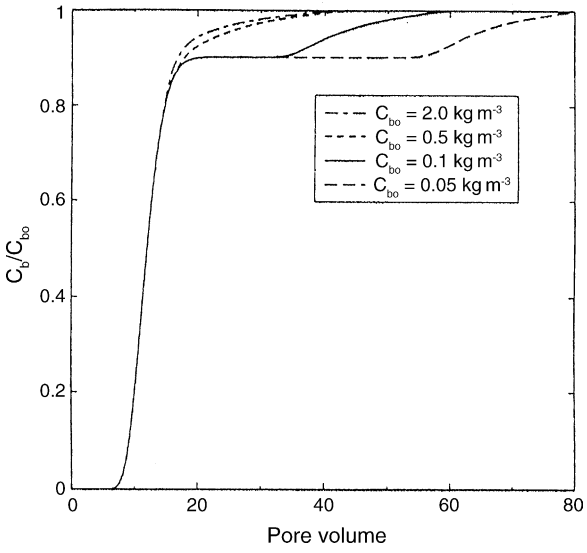

Fig. 3. Effect of inlet cell concentration on bacterial breakthrough.

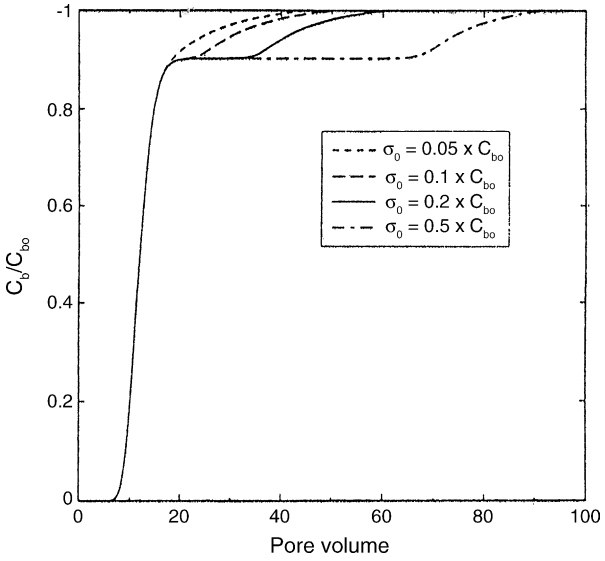

Fig. 4. Effect of threshold captured cell concentration (σ_0) on bacterial breakthrough for an inlet cell concentration (C_{b0}) of 0.1 kg/m^3.

tured cells (σ_0) or newly introduced cells can either move freely or replace already attached cells and hence enhancing the breakthrough.

It is observed from Fig. 3 that at very low values of C_{b0} the breakthrough curves flatten up and remain constant at a value of about 0.9 for quite a long time and then again rises, leading to 1.0 at sufficiently high pore volume. The reason for such behavior might be that for low cell concentrations, once the breakthrough attains a value of 0.9, the concentration of the adsorbed cells become less than the threshold concentration (σ_0), and hence, the desorption of captured cells stops at this point of time. Also during this period, the combined effect of the rates of input and growth of the cells is balanced by the combined effect of the rates of decay of the cells and their adsorption. As a result of these competitive effects, the cell concentration in the suspension remains constant for some time. After that, the concentration of the adsorbed cells goes beyond σ_0 and desorption of the captured cells comes into action once again. Therefore, the combined effect of input, growth and desorption overcomes the net effect of decay and adsorption and the cell concentration in the suspension starts to increase and finally the breakthrough reaches at 1.0. This explanation is further strengthen by the fact that for a constant inlet cell concentration, increase in σ_0, increases the time period over which the breakthrough remains constant as shown in Fig. 4. This is quite obvious that with increase in σ_0, the time for the captured cell concentration to reach σ_0 increases and thereby delaying the commencement of the desorption process. Fig. 4 also shows that when σ_0 is decreased to a very low value (for a given inlet cell concentration), the constancy in breakthrough is not observed which suggests that the captured cell concentration never goes below σ_0 such that the net effect of input, growth and desorption is always greater than the combined effect of decay and adsorption of the cells.

Fig. 5 represents the temporal variation of substrate concentration for different values of C_{b0}. An interesting feature of the substrate concentration plot is that the maximum is attained at an early time and then a gradual decrease to steady state, because of consumption of the substrate by the bacterial cells. Also, the maximum substrates concentration and the steady value increase with decrease in inlet cell concentration because of lesser consumption of the substrate at low cell concentrations.

4.3. Effect of substrate concentration on bacterial breakthrough

Fig. 6 shows that for pore volume as low as 10, the substrate concentration does not have significant effect on bacterial transport. However, at higher pore volume, increased

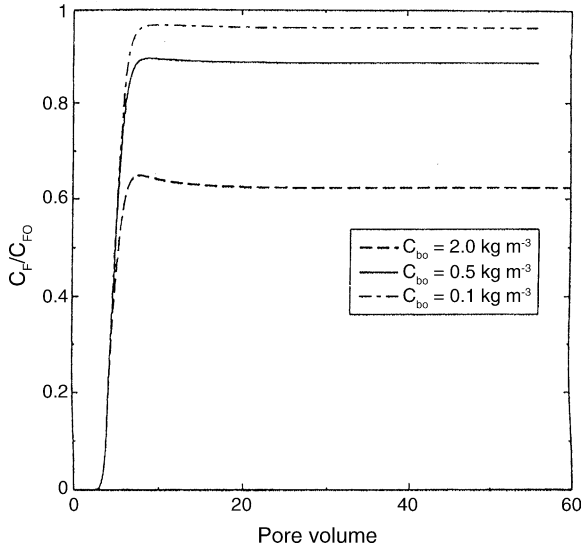

Fig. 5. Temporal variation of substrate concentration for different inlet cell concentrations.

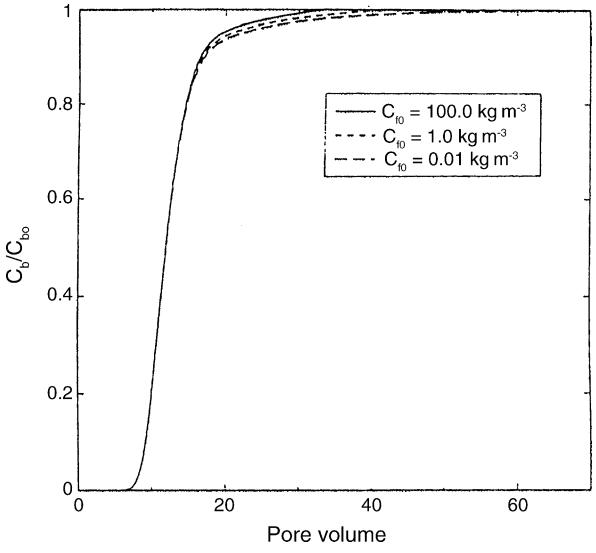

Fig. 6. Effect of substrate concentration on bacterial breakthrough.

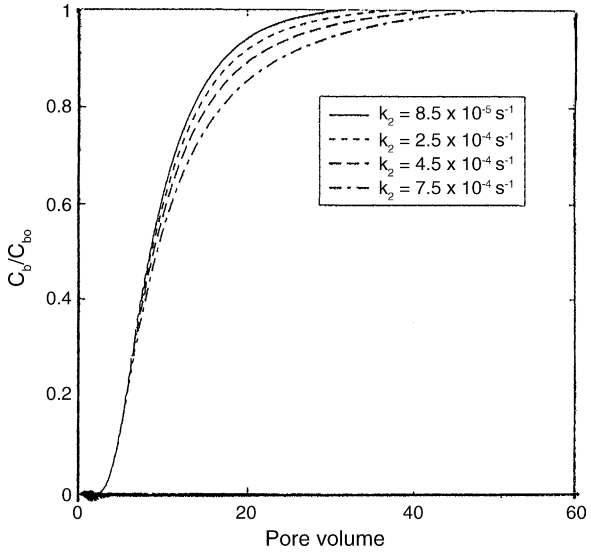

Fig. 8. Sensitivity of the model to capture coefficient (k_2) of adsorbed cells.

substrate concentration weakly enhance bacterial breakthrough. The reason might be that with increase in substrate concentration, the growth of cells increases, which results in increased number of cells being transported down-gradient. At low pore volume, the growth of cells is very low and hence the variation of substrate concentration does not show any significant change in cell transport at pore volume less than 10.

4.4. Effect of release coefficient of captured cells on bacterial breakthrough

This is shown in Fig. 7 for different values of release rate coefficient k_1. It is seen that at low pore volume (less than 15), variation in k_1 does not show any significant changes in cell concentration. However, at pore volume greater than 15, increase in k_1 leads to enhanced breakthrough. This is because at a low pore volume, where the concentration of captured cells is less than the threshold retention capacity (σ_0), there is no release of captured cells from the solid matrix (Eq. (7)). Once the concentration of captured cells goes above σ_0, release of the captured cells from the solid matrix starts and increased k_1 causes faster release of the attached cells, thereby leading to enhanced breakthrough.

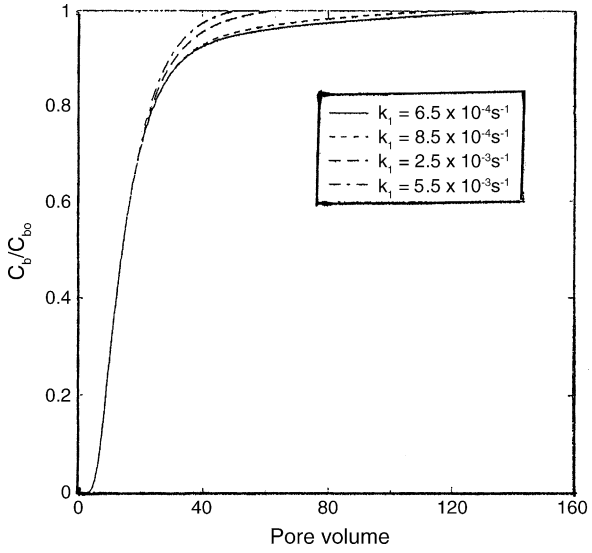

Fig. 7. Sensitivity of the model to release coefficient (k_1) of captured cells.

4.5. Effect of capture coefficient k_2

Fig. 8 presents the sensitivity of the model to capture coefficient (k_2) of the suspended cells. As seen from Fig. 8, C_b variation is quite sensitive to changes in k_2. Initially, changes in k_2 produce insignificant changes in C_b, since, for low values of C_b the rate of capture of the suspended cells onto the solid matrix is very low and changes in k_2 does not show any appreciable change in breakthrough. But once C_b becomes appreciable, the rate of capture is significant and the breakthrough becomes more sensitive to changes in k_2. Also as C_b increases, k_2 shows a more pronounced effect on breakthrough. This is because, as C_b becomes higher the rate of capture of the freely suspended cells also becomes higher and therefore the breakthrough becomes more sensitive to changes in k_2.

5. Model simulation on importance of chemotaxis on bacterial transport

Chemotaxis, infact, can play a significant role on bacterial transport behavior under the conditions of macroscopic substrate gradient. A detailed literature survey revealed that values of vR_t typically range between 50 and 100 s [33–34]. For our model, vR_t is taken as 75 s and cell swimming speed taken as 40 μm/s.

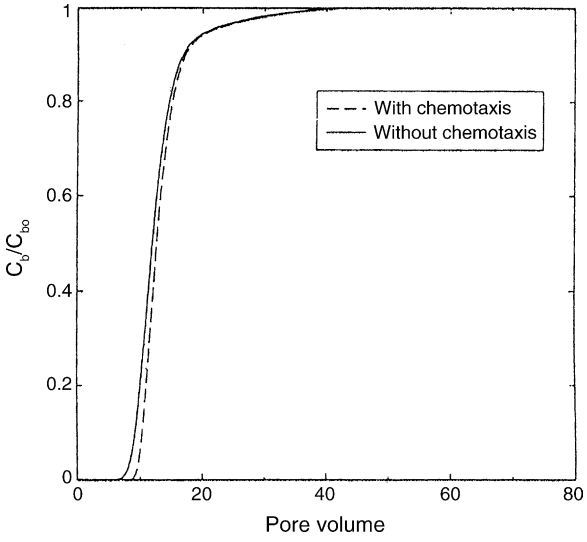

Fig. 9. Comparison between bacterial breakthrough with and without chemotaxis with an inlet cell concentration of 2.0 kg/m^3.

Figs. 9 and 10 shows the comparism between bacterial breakthrough without chemotaxis and the linear model for chemotaxis for two different inlet cell concentrations. It is observed that in presence of chemotaxis, initial breakthrough is retarded. However, at higher pore volume, the two curves merge together, i.e. chemotaxis does not show any change in cell transport. The reason for such behavior might be that at low pore volume, the substrate gradient across the column is very high and bacterial cells tend to bias their movement towards higher substrate concentration because of chemotactic effect. This results in retardation in initial breakthrough. However, since substrate is also transported across the column, at higher pore volume the substrate gradient across the column decreases to a very low value as shown in Fig. 11 such that effect of bacterial chemotaxis on cell movement be-

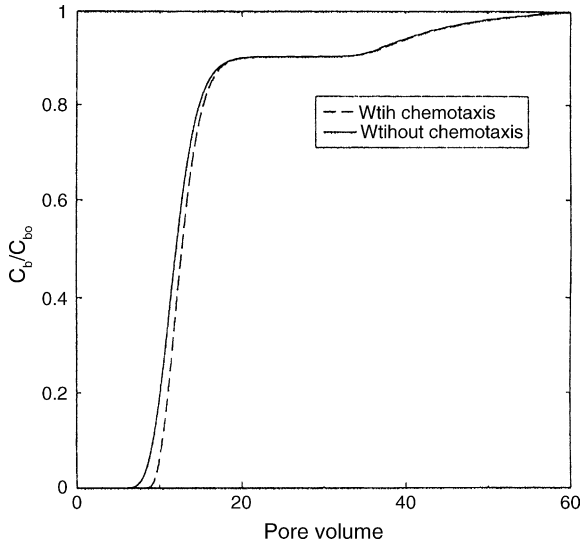

Fig. 10. Comparison between bacterial breakthrough with and without chemotaxis with an inlet cell concentration of 0.1 kg/m^3.

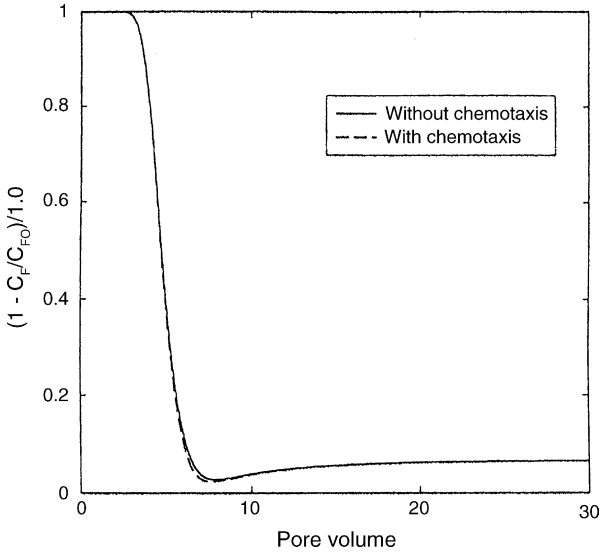

Fig. 11. Temporal variation of dimensionless substrate concentration gradient across the column with and without chemotaxis.

comes insignificant and hence, the breakthrough plot shows no variation from that without chemotaxis.

Fig. 12 presents the breakthrough curves without chemotaxis and linear model for chemotaxis for different velocities. It is seen that, at all velocities, chemotaxis retards the initial breakthrough. At higher pore volume however, bacterial chemotaxis seems to have no effect on cell transport. Fig. 13 shows the effect of cell swimming speed on the chemotactic response of bacteria. It is seen that increasing cell swimming speed results in increase in the chemotactic sensitivity coefficient (Eq. (3)) which in turn, results in more biased movement of the cells towards higher substrate concentration, thereby, leading to retardation in the breakthrough.

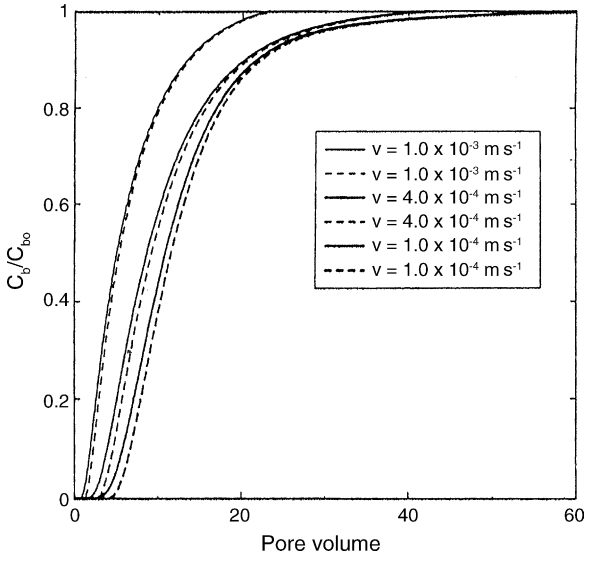

Fig. 12. Comparism between bacterial breakthrough with and without chemo tactic at different velocities (solid line: without chemo tactic, dotted line: with chemo tactic).

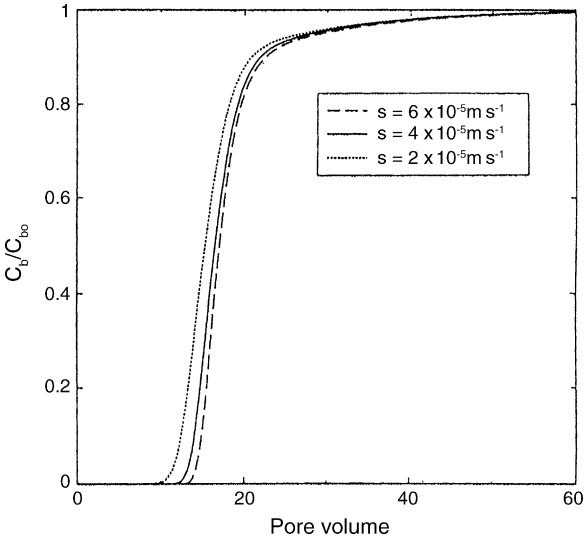

Fig. 13. Effect of cell swimming speed on chemo tactic response of bacteria.

It can be noted from Eq. (1) that the effect of chemotaxis is similar to that of pore velocity. The chemotactic velocity, v_c, is in the direction of increasing concentration of substrate which is opposite to the direction of flow. Hence, v_c is always negative and reduces the net pore velocity. With chemotaxis $(v_p + v_c)$ is always less than v_p and the lowering of pore velocity results in the delayed breakthrough. At low values of v_p, the effect of v_c (chemotaxis) is more significant which in fact is quite agreeing.

It is clear from all these results that chemotaxis does play a significant role in the transport of bacterial cells through porous media, especially under the conditions of higher substrate concentration gradient and low pore velocity. Hence, it is pretty much necessary to consider the effect of chemotaxis on the migration of bacterial cells so as to develop effective strategies for bioremediation of contaminated soils and aquifers using introduced bacterial strains, as well as safe disposal of wastewater.

6. Conclusions

- A one-dimentional bacteria transport model based on linear equilibrium adsorption of bacterial cells, growth and decay of bacteria and chemotaxis/chemotactic of bacteria is developed. Therefore, this model offers a better description of the physics of bacterial transport and fate in subsurface flow.
- Increase in flow velocity led to enhancement of transport breakthrough.
- Increased inlet cell concentration led to faster breakthrough. The threshold concentration of captured cells (σ_0) having a significant effect on bacterial transport. For a given inlet cell concentration, there is a threshold value of σ_0, above which there is retardation in bacterial transport.
- Increase in substrate concentration led to increase in bacterial breakthrough curves.
- The model is very much sensitive to the rate coefficient for capture and release of bacterial cells.
- Chemotaxis played a significant role in bacterial transport, especially under considerable substrate gradient and at low pore velocity.
- This model can be useful in developing effective bioremediation technique as well as to serve as a tool in the long term evaluation of the risk of accumulation of bacteria entering soil and groundwater.

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