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Research article

POROSITY AND LONGITUDINAL DISPERSION INFLUENCES ON TRANSPORT OF GALLIONELLA IN ALLUVIUM DEPOSITION, PORT HARCOURT METROPOLIS, NIGER DELTA OF NIGERIA

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Abstract

Alluvium deposition were monitored and observed to generate predominant deposited contaminant in the deltaic formation, the specie of microbes are known to be gallionella, the migration process were observed through other investigation that were not able to generate results in the study area. Further study were imperative to be carried out to find better solution to the problem, base on these condition, modeling approach were found fit to solve the pressing problem of contaminant in the study area, applying the concept will developed better solution that can engineer out the contaminant, these application were developed through the system to produced the governing equation, the derived solution generated model at different phase base on the behaviour of the microbes, the study were able to develop models that can solved various stage of the transport in the study area.

Keywords: porosity, longitudinal dispersion, gallionella and alluvium deposition

1. Introduction

The problem of solute dispersion during underground water movement has attracted interest from the early days of this century. Since the early experiments of Slichter (1905) and particularly since the analysis of dispersion during solute transport in capillary tubes, developed by Taylor (1953) and Aris (1956, 1959), a lot of work has been done on the description of the principles of solute transport in porous media of inert particles and in packed bed reactors (see Bear, 1972; Dullien, 1979 Delgado, 2007). Flow velocities and hydrodynamic dispersion coefficients are key parameters for description of fluid and solute transport in porous media. Dispersion topic has interested a vast

scientific community, namely hydrology and contaminant studies, and for some time now it is treated at length in books on flow through porous media (e.g. Delleur, 1999; Fetter, 1999; Sahimi, 1995; Grathwohl, 1998; Bear and Verruijt, 1987; Marsily, 1986; Koch and Brady, 1985; Scheidegger, 1974; Bear, 1972; Fried and Combarnous, 1971 Delgado,2007). studies may be as much as four or six orders of magnitude greater than the corresponding laboratory measured values which commonly are found to range between 0.1 and 10 mm (Freeze and Cherry, 1979). Ratios of aL/aT of 5:1 to 100:1 have been reported in literature (Bear and Verruijt, 1987). Some of most referred works were developed by Fried and Combarnous (1971) and Bear and Verruijt (1987, p. 166); the authors showed the existence of five dispersion regimes, in unconsolidated porous media. Sahimi (1995) and marsily (1986) analyse the data compiled by Fried and Combarnous (1971) to characterize longitudinal dispersion in five dispersion regimes and transverse dispersion in four dispersion regimes and a holdup dispersion. *Gallionella ferruginea* is a bean-shaped bacterium that thrives in iron-bearing waters, were it may produce a
twisted stalk. The cells are difficult to observe because they are usually mixed with a large amount of iron precipitates and stalks (Kucera & Wolfe, 1957; Wolfe, 1964). The bacterium is laborious to culture - it grows to
2 x lo6 cells ml-l in a liquid enrichment medium with inorganic salts and gradients of carbon dioxide, oxygen,
ferrous iron and sulphide (Hanert, 1989). The majority of the work performed on *G. ferruginea* consists of case studies reporting the occurrence of *G. ferruginea* in natural groundwater (e.g. Barbic *et al.*, 1974; Cullimore & McCann, 1977 ; Hannert, 1970,1974 ; Hirsch & Pankratz, 1970; Hasselbarth & Ludeman, 1972; Ivarson & Sojak, 1978; Pedersen & Hallbeck, 1985; Ridgeway *et al.*, 1981; Wheatley, 1988). **A** recent study concentrated on the ultrastructure of *G. ferruginea* (Lutters & Hanert, 1989), but most investigations, and also experiments done *in vitro*, have focused on the stalks (e.g. Balashova, 1967; Hanert, 1967; 1973; Mardanyan & Balashova, 1971 ; Vatter & Wolfe, 1957). Studies that concentrate on the stalk-forming cells might overlook other phases in the growth cycle. There is still much information lacking on the metabolism of this organism, and on the mechanism behind stalk formation

2. Theoretical background

Several past years, modeling solute migrations in porous formation like deltaic environment remains the key issue in area of soil and water engineering, thus other discipline including environmental sciences. This is due to anthropogenic chemical substances that often penetrate the soil subsoil, the migration of these substances and microbes has been the frequent contaminant in deltaic formations, especially phreatic beds that generate ground water, it has pose serious threat base on the migration of these contaminant in the study area. It has been observed that advection dispersion has been the most common method of modeling the environmental and ground water. It is obvious that advection is the most common method of modeling solute transport in subsurface porous media in deltaic environment, but this study we are monitoring the effect of longitudinal dispersion and porosity influences of gallionella in alluvium deposition Groundwater molecules are moving at different rates, some are faster than the average linear velocity, while some are slower. There are three causes for this phenomenon: friction on pore walls, variations in pore sizes, and variations in path length. As groundwater moves through the pores, it will move faster at the center of the pore than along the walls due to friction. In cases where different size pores exist, groundwater

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will move through larger pores faster. Groundwater molecules have tortuous flow paths and some will travel longer pathways than others. Because the invading solute-containing water is not all moving at the same rate, mixing occurs along the flow path. This mixing is termed mechanical dispersion. The mixing that occurs along the direction of fluid flow is termed longitudinal dispersion, whereas the mixing that occur normal to the direction of fluid flow is termed transverse dispersion. Transverse dispersion is thought to be the result of the split of flow paths to the side. Due to hydrodynamic dispersion, the concentration of a solute will decrease over distance. Generally speaking, the solute will spread more in the direction of groundwater flow than in the direction normal to the groundwater flow, because longitudinal dispersivity is typically 10 times higher than transverse dispersivity.

3. Governing equation

$$\frac{1+fP_b K_d}{\theta}\frac{\partial C}{\partial t} = D\frac{\partial^2 C_1}{\partial x^2} - V\frac{\partial C}{\partial x} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

The governing equation developed lots of variables in the equation were the structure of soil at various state were considered in the system, the expression here showcase the behaviour of gallionella in the study location, the expression also integrated dispersion under the influences of velocity of flow at higher rate that developed negative impact on the migration of gallionella in alluvium formation, the developed system that generated the governing equation also defined the stage of decay phase on the deposition of the microbes, the governing equation will be derived to monitor the system in various ways of the transport process in alluvium formation, the structure of the formation will be thoroughly express it impact on the migration of the microbes in various strata.

Nomenclature

C	=	Bacterial Concentration (cell/m^3)
S_k	=	Bacterial concentration on kinetic adsorption (cell/g)
P_b	=	Bulk Density (g/m^2)
K_d	=	Partitioning coefficient of bacteria (m^3/g)
θ	=	Porosity (m^3/m^3)
D	=	Longitudinal Dispersion coefficient (m^2/sec)
X	=	Co-ordinate parallel to the flow (m)
V	=	Pore velocity (m/sec)
α	=	First order mass transfer coefficient (sec^{-1})
μ_{sk}	=	First order bacterial deposition coefficient (sec^{-1})

Applying physical splitting techniques on equation (1) we have

$$D\frac{\partial^2 C_1}{\partial x^2} = D\frac{\partial^2 C_1}{\partial x^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

$$\left.\begin{aligned} &x = 0 \\ &C_{(o)} = C_o \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

$$\left.\frac{\partial C_1}{\partial x}\right|_{x = 0} = 0$$

$$\frac{1+fP_bK_d}{\theta}\frac{\partial C_2}{\partial t} = V\frac{\partial C_2}{\partial x} - \frac{\alpha P_b}{\theta} 1-f\,K_d C - S_k \quad \ldots\ldots\ldots\ldots\ldots \quad (4)$$

$$\left.\begin{aligned} & t = 0 \\ & x = 0 \\ & C_{(o)} = 0 \\ & \left.\frac{\partial C_2}{\partial t}\right|_{t = 0,\ B} \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

$$D\frac{\partial^2 C_3}{\partial x^2} = -V\frac{\partial C_3}{\partial x} - \frac{\alpha P_b}{\theta} 1-f\,K_d \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

$$\left.\begin{aligned} & x = 0 \\ & C_{(o)} = 0 \end{aligned}\right\} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (7)$$

Applying direct integration on (2)

$$\frac{1+fP_bK_d}{\theta}\frac{\partial C}{\partial t} = DC + K_1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (8)$$

Again, integrate equation (8) directly, yields

$$\frac{1+fP_bK_d}{\theta} = DCx + K_1x + K_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (9)$$

Subject to equation (3), we have

$$\frac{1+fP_bK_d}{\theta}Co = K_2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

And subjecting equation (8) to (3)

At $\left.\frac{\partial C_1}{\partial t}\right|_{x = 0,\ C_{(o)} = C_o} = 0$

There the tendency of limitation by determining the boundary conditions in the transport system of the gallionella in soil at various strata, these developed system considered this phase on the derived solution, by establishing boundary values in the migration process , several microbes also need to be monitored with boundary conditions establishments, but it depend on the structure of the formation and types of achievement the researcher need. The establishment of boundary condition is imperative to determine the microbes limit on the transport process in the study location.

Yield

$O = DCo\ K_2$

$$\Rightarrow \quad K_1 = -DC_o \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

So that, we put (10) and (11) into (9), we have

$$\frac{1+fP_bK_d}{\theta}C_1 - DC_1x - DCox + \frac{1+fP_bK_d}{\theta}C_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

$$\frac{1+fP_bK_d}{\theta}C_1 - DC_1x = \frac{1+fP_bK_d}{\theta}C_o - DCox \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

$$\Rightarrow \quad C_1(1+fP_bK_d - Dx) = Co(1+fP_bK_d - Dx)$$

$$\Rightarrow \quad C_1 = Co \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (14)$$

The derived solution at these stage were able to determined the initial base of the contaminant, these are through the application of these concepts that generated the initial concentration from the derivation state in [14]. The behaviour of the system are affected by the parameters reaction in the migration process of the soil, this determine the rate of concentration at initial state.

Hence equation (14), entails that at any given distance, x, we have constant concentration of the contaminant in the system In most system it may experiences homogeneous deposition, this implies that under normal condition, if the strata deposit uniformity in structural disintegration in there formations, there the tendency of homogeneous setting base on the uniformity of formation characteristics generating constant concentration in the strata, therefore the transport system may definitely observed this condition as it is integrated in the derived solution.

$$\frac{1+fP_bK_d}{\theta}\frac{\partial C_2}{\partial t} = V\frac{\partial C_2}{\partial x}\ \frac{\alpha P_b}{\theta}\ 1-f\ K_dC - S_k \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

We approach this system by using the Bernoulli's method of separation of variables

$$C_2 = XT \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

$$\frac{\partial C_2}{\partial t} = XT^1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (16)$$

$$\frac{\partial C_2}{\partial x} = X^1T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

Put (16) and (17) into (15), so that we have

$$\frac{1+fP_bK_d}{\theta}XT^1 = V\frac{\alpha P_b}{\theta}V\ 1-f\ K_dC - S_kX^1T \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (18)$$

i.e. $1+fP_bK_d\dfrac{T^1}{T} = V\dfrac{\alpha P_b}{\theta}V\ 1-f\ K_dC - S_k\dfrac{X^1}{X} = -\lambda^2 \quad \ldots\ldots\ldots\ldots \quad (19)$

Hence $\frac{1+fP_bK_d}{\theta}\frac{T^1}{T} + \lambda^2 = 0$ ………………………… (20)

That is,

$$\frac{X^1 + \lambda^2}{\frac{1+fP_bK_d}{\theta}} x = 0 \quad \text{…………………………} \quad (21)$$

$$1 - fK_d\, C - S_k\, T^1 + \lambda^2 T = 0 \quad \text{…………………………} \quad (22)$$

From (21), $X = \frac{A\,Cos\,\lambda}{\frac{1+fP_bK_d}{\theta}}t + \frac{B\,Sin\,\lambda}{\frac{1+fP_bK_d}{\theta}}x$ ………………………… (23)

And (16) gives

$$\boxed{T = C\,\ell^{\frac{-\lambda^2}{Vd\frac{P_b}{\theta}V1 - fK_dC - Sk}t}} \quad \text{…………………………} \quad (24)$$

By substituting (23) and (24) into (15), we get

$$\boxed{C_2 = \left(\frac{A\,Cos\,\lambda}{\frac{1+fP_bK_d}{\theta}}x + \frac{B\,Sin\,\lambda}{\frac{1+fP_bK_d}{\theta}}x\right) C\,\ell^{\frac{-\lambda^2}{Vd\frac{P_b}{\theta}V1 - fK_dC - Sk}t}} \quad (25)$$

The behaviour of the gallionella deposition were considered at this stage to determined is stationary phase, this are normal in some microbial transport process due other challenges that it may experiences in the formation, the structure of the soil will definitely vary and on the process of migration thus the microbes experiences stationary phase. Other impact on these stage of the transport are the velocity and permeability at lower degree base on the stratum deposition, these are some of the challenges that developed stationary phase on the migration process expressed in [25]

Subject equation (25) to conditions in (5), so that we have

$$C_o = AC \quad \text{…………………………………} \quad (26)$$

Therefore, equation (26) become

$$C_2 = C_o \ell^{\frac{-\lambda^2}{Vd\frac{P_b}{\theta}V1-fK_dC-Sk}t} \; Cos \frac{\lambda}{\frac{1+fP_bK_d}{\theta}} x \quad \ldots\ldots\ldots\ldots \quad (27)$$

Again, at

$$\left.\frac{\partial C_2}{\partial t}\right|_{x=0,\,B} = 0,\; t = 0$$

Equation (27) becomes

$$\frac{\partial C_2}{\partial t} = \frac{\frac{\lambda^2}{1+fP_bK_d}}{\theta} C_o \ell^{\frac{\lambda^2}{Vd\frac{P_b}{\theta}V1-fK_dC-Sk}t} \; Cos \frac{\frac{Sin\,\lambda}{1+fP_bK_d}}{\theta} x \quad \ldots\ldots\ldots \quad (28)$$

$$\frac{\frac{C_o\;\lambda}{1+fP_bK_d}}{\theta} \neq 0 \quad \text{Considering NKP}$$

This is the substrate utilization for microbial growth (population),

The expressing here shows that in most transport system of microbes' experiences increment of microbial growth there is the tendency of microbial increase in the depositions that slight micronutrient are found in the formation, therefore the there need to consider this condition in the system as it expressed in derived solution, gallionella behaviour on it migration process may experience similar condition, unless the microbes are affected other factors in the deposition of the soil.

$$0 = \frac{\frac{-C_o\;\lambda}{\sqrt{1+fP_bK_d}}}{\theta} \; \frac{\frac{Sin\;\lambda}{\sqrt{1+fP_bK_d}}}{\theta} B \quad \ldots\ldots\ldots\ldots \quad (29)$$

$$\Rightarrow \frac{\frac{C_o\;\lambda}{\sqrt{1+fP_bK_d}}}{\theta} = \frac{n\pi}{2},\; n = 1, 2, 3 \quad \ldots\ldots\ldots\ldots \quad (30)$$

$$\Rightarrow \lambda = \frac{\frac{n\pi\sqrt{1+fP_bK_d}}{\theta}}{2} \quad \ldots\ldots\ldots\ldots \quad (31)$$

So that equation (27) becomes

$$C_2 = C_o \ell^{\frac{-n^2\pi^2\frac{P_b}{\theta}1-fK_dC-Sk}{2Vd\frac{P_b}{\theta}1-fK_dC-Sk}t} \; Cos \frac{\frac{n\pi\sqrt{1+fP_bK_d}}{\theta}}{\frac{2\sqrt{1+fP_bK_d}}{\theta}} x \quad \ldots\ldots\ldots\ldots \quad (32)$$

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$$\therefore \Rightarrow \quad C_2 = C_o \ell^{\frac{-n^2\pi^2 \frac{P_b}{\theta} 1 - fK_d C - Sk}{2Vd \frac{P_b}{\theta} 1 - fK_d C - Sk} t} \quad Cos \frac{n\pi}{2} x \qquad \text{.......................................} \qquad (33)$$

The migration stage may experiences growth on the process, therefore it is imperative that the derived solution considered the sources of the growth rate as the derived model are expressed in [33], the deposition of substrate are defined in this phase to be the principal actor on the gallionella deposition, therefore, increase in population of gallionella were considered in the system as it express in the developed model considering substrate deposition.

Now, we consider equation (6) which is the steady-flow state of the system

$$\frac{\partial C_3}{\partial x^2} = \frac{V\partial C_3}{\partial x} - d \frac{P_b}{\theta} 1 - fK_d$$

Applying Bernoulli's method, we have

$$C_3 = XT \qquad \text{.......................................} \qquad (34)$$

$$\frac{\partial^2 C_3}{\partial x^2} = X^{11} T \qquad \text{.......................................} \qquad (35$$

$$\frac{\partial C_3}{\partial x} = X^1 T \qquad \text{.......................................} \qquad (36)$$

Put (35) and (36) into (6), so that we have

$$DX^{11} T = Vd \frac{P_b}{\theta} 1 - fK_d C - Sk \, X^1 T \qquad \text{.......................................} \qquad (37)$$

That is,

$$\frac{DX^{11}}{X} = -Vd \frac{P_b}{\theta} 1 - fK_d C - Sk \frac{X^1}{X} = \varphi \qquad \text{.......................................} \qquad (38)$$

$$\frac{DX^{11}}{X} = \varphi \qquad \text{.......................................} \qquad (39)$$

$$-Vd \frac{P_b}{\theta} 1 - fK_d C - Sk \frac{X^1}{X} = \varphi \qquad \text{.......................................} \qquad (40)$$

That is $X = A\ell^{\frac{\varphi}{D} x}$ .... (41)

And

$$T = B\ell^{\frac{-\varphi}{D} t} \qquad \text{.......................................} \qquad (42)$$

Put (41) and (42) into (34), gives

$$C_3 = A\ell^{\frac{\varphi}{Vd\frac{P_b}{\theta}1-fK_dC-Sk}x} \bullet B\ell^{\frac{-\varphi}{Vd\frac{P_b}{\theta}1-fK_dC-Sk}x} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (43)$$

$$C_3 = AB\ell^{(t-x)\frac{\varphi}{Vd\frac{P_b}{\theta}1-fK_dC-Sk}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (44)$$

Subject equation (44) to (7), yield

$$C_3 = (0) = C_o \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (45)$$

So that equation (45), becomes

$$C_3 = C_o\,\ell^{(t-x)\frac{\varphi}{Vd\frac{P_b}{\theta}1-fK_dC-Sk}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (46)$$

Now assuming that at the steady state flow, there is no NKP for substrate utilization, our concentration here is zero, so that equation (46) become

$$C_3 = 0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (47)$$

Therefore, solution of the system is of the form

$$`C_3 = C_1 + C_2 + C_3 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (48)$$

We now substitute (14), (33) and (47) into (48), so that we have the model

$$C = C_o + C_o\,\ell^{\frac{-n^2\pi^2\frac{1+P_bK_d}{\theta}}{2Vd\frac{P_b}{\theta}1-fK_dC-Sk}t} \; Cos\,\frac{n\pi}{2}x \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (49)$$

The expression considering when the microbes did not experiences substrate, there the tendency of degradation, if it is not apply adaptation in the formation where it could not found substrate, such phase were considered on the derived process as is expressed on the developed model at [49], the rate of migration can observed through the behaviuor influenced by some predominant formation characteristics in the study area.

$$\boxed{C = C_o\,1 + \ell^{\frac{-n^2\pi^2\frac{P_b}{\theta}1-fK_dC-Sk}{2Vd\frac{P_b}{\theta}1-fK_dC-Sk}t} \; Cos\,\frac{n\pi}{2}x} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (50)$$

The developed model at [50] were generated base on the integrated models at various stage of the transport system, the study were able to monitor the deposition of gallionella in various phase under its behaviour in the study location, the nature of the soil in the area where observed through some investigation carried in the past, there result where not able to generate solution to the challenging problem, this call for other concept that generated developing of mathematical modeling applications. The developed equation look at various stages in the system considered it to produce the final model for the study.

4. Conclusion

The behaviour of gallionella in alluvium deposition has been thorough analyzed in the study location, this was possible through other investigations carried that generate limitation of previous results in the past, the study were able to monitor the migration process in various dimensions, the structures of the soil were also considered to be the principal determinant of the migration process of gallionella base on the behaviour of it transport process, these conditions were integrated in the derived solution to generate the models at various phase, the study were able to monitor the formation characteristics influences as it consider in most part of the formations. Experts will definitely fine these conceptual frameworks useful in monitoring and evaluation of gallionella deposition in alluvilm formations.

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