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Finite Element Analysis of Phosphate Movement through a Clayey-Sandy Soil by using Geo-Slope Software (CTRAN/W)

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Abstract
A hypothetical 2-D numerical model of a clayey-sandy soil profile had been developed by using Geo-Slope software to analyze the water flow (SEEP/W) and phosphate movement (CTRAN/W) through the sub-surface region of the soil. Results showed that streamlines and equipotential lines are normal to each other and vectors displaying the velocity of the flow direction have the average flow rate of 1.2067 x 10^{-5} ft^3/sec/ft (0.000342 LPS). The Advection-Dispersion Analysis revealed that the adsorption of phosphate on the soil particles is linearly related to the concentration which was represented as contours with different colors. The phosphate concentration after 365 days was 0.93 gm/ft^3 at the toe point of the drain. The overall average velocity for the selected nodal points at head, middle and tail sections were 0.2262, 0.3997, and 0.6834 ft/day, respectively. Only the nodal points present at the tail section reached the free exit drain in between 300-365 days with an average velocity of 0.6855 ft/day. The particles present at the head and middle sections of the land were moving slowly as compared to the tail section. However, results may vary for the other types and texture of soils.
Keywords: Finite Element Method, Sub-Surface Flow, Hydraulic Conductivity, Phosphate Concentration, Contamination, Geo-Slope Software.

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INTRODUCTION

Phosphorus is one of the vital elements essential for growth of plants, animals, and humans. Humans have caused major changes to the universal phosphorus cycle through shipping of phosphorus minerals, and use of phosphorus fertilizer (Naseri *et al.,* 2011). Whenever a grower fertilizes the land with phosphorus it stays where it is placed (Balemi *et al.,* 2012). It is not of environmental concern unless it is moved on soil particles by erosion of the soil itself. Furthermore, Phosphorus movement in saturated / unsaturated soil is very little, even with large amounts of precipitation or irrigation (Singh *et al.,* 2000). This is the basic phosphorus problem due to which the pH of soil becomes alkaline and in some cases a hardpan observed at the subsurface of an agricultural land (Ratnoji *et al.,* 2001).

Various studies showed that the movement of phosphate within the sub-surface region of the soil mainly depends on the permeability of the soil. The movement of chemicals will be more in the course soils like gravel and sandy soils as compared to the fine textured soils like slit and clay (Eltarabily *et al.,* 2015). The movement of these phosphates through different soil regimes can be analyzed by using two techniques, i.e. (i) advection-dispersion analysis and (ii) particle tracking analysis. The advection-dispersion equation is the most effective method for representation of contaminant transport through unsaturated soil. Advection is the method in which solutes moved from one place to another by the bulk motion of groundwater flow while, dispersion is a spreading of contaminant from the path that it would be expected to follow according to the advective hydraulics of the flow system (Simunek *et al.,* 2001). On the other hand, the particle tracking analysis gives awareness about the particles travel time and distances (Eltarabily *et al.,* 2015).

Nowadays, many computer softwares have been developed to simulate the groundwater behavior trend. These software's are worked on a numerical solution method and gives the output in a pictorial form respectively (Geo-Slope, 2007). This study was conducted to check the behavior of the phosphatic fertilizer (DAP) through the clayey-sandy soil by using Geo-Slope software respectively.

MATERIALS AND METHODS

Steps for Model Generation

In order to evaluate the movement of the phosphate fertilizer through the clayey-sandy soil, a hypothetical 2-D numerical model having an overall mesh size of 90ft in length and 24ft in depth was created by using Geo-Slope Software. It has been assumed that the numerical model is comprised of a fallow land nearest to the free drain having mesh dimension of 20ft in length, 24ft in depth respectively. The cross section of trapezoidal canal at the bottom width is 3ft and 1:1 side slope was adopted. To simulate the concentration of phosphate at different interval of time, the agricultural land was divided in to 3 parts (head, middle and tail) for different scenarios respectively. Initially, by using SEEP/W program, the FE mesh was developed (Arshad, 2015). The mesh dimensions for both SEEP/W and CTRAN/W programs were kept constant. The material properties and boundary conditions used during the mesh development were then assigned and calibrated. After all the necessary inputs the mesh was verified and the computation for the flow analysis was carried out accordingly.

Similarly, to analyze the movement of phosphate under a clayey-sandy soil profile, CTRAN/W program was used by adopting the flow system established with SEEP/W program (Eltarabily *et al.,* 2015). After the calibration of geological parameters, the entry and exit locations for the phosphate movement along with the boundary conditions were assigned to the mesh accordingly. The concentration of phosphate having 220 gm/ft^3 (200 kg/acre) was assigned to the mesh with the time-step sequence of 20. The time span of 1 year (365 days) was assigned to the mesh and the longitudinal and transverse dispersivities were set to 6.1ft and 1ft, respectively. The mesh was then verified by the CTRAN/W software and the movement of the phosphate within the soil was carried out accordingly.

RESULTS AND DISCUSSION

By using SEEP/W program, the finite element mesh was composed and consists of triangular, square, rectangular, and trapezoidal types of elements having a unit size of 2.88 ft. The mesh was developed with the help of 311 elements and 352 nodal points respectively (Arshad *et al.,* 2017). According to the given conditions, it has been assumed that the whole soil region is composed of a clayey-sandy soil and having saturated hydraulic conductivity (Ks) of 4.753 x 10^{-7} ft/s. Likewise, CTRAN/W program is used to simulate the movement of phosphate within the soil region. The entry of phosphate and free drain exit location were assigned as boundary conditions for the mesh. Figures 1a and 1b showed the mesh of the domain with and without material properties and boundary conditions.

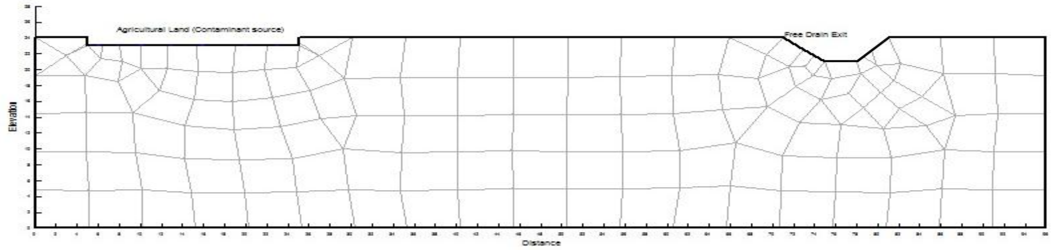

Fig.1(a). The mesh of the domain without material properties and boundary conditions.

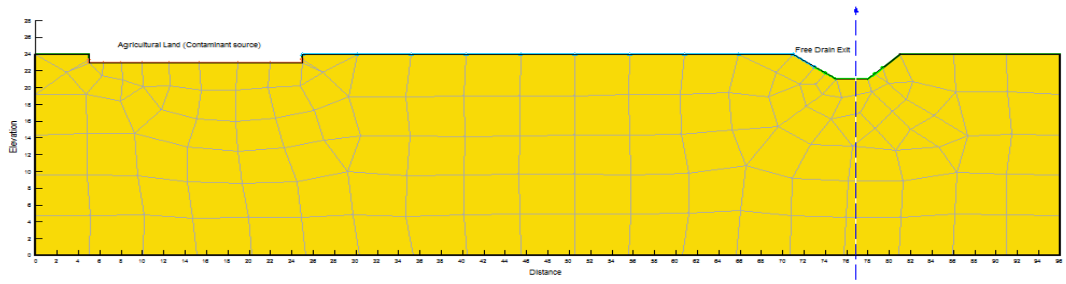

Fig. 1(b). The mesh of the domain with material properties and boundary conditions.

Analysis of Subsurface Flow through Soil Profile by SEEP/W

In the preliminary step, the behavior of the phosphate movement was analyzed by SEEP/W program to acquire the subsurface flow of water through a soil region. The flow-net consist of streamlines, equipotential lines (contours), velocity vectors, and phreatic surface in the subsurface region. According to the simulated results (Fig. 02), streamlines and equipotential lines are following the standard flow and are normal to each other, vectors displaying the velocity of the flow direction, and the average water flow through a subsurface region is of the order 1.2067 x 10^{-5}ft^3/sec/ft (0.000342 LPS), respectively. These results are according to the findings of Arshad et al. (2014), who conducted their research work on a homogeneous earth dam and found the same trend for a subsurface flow.

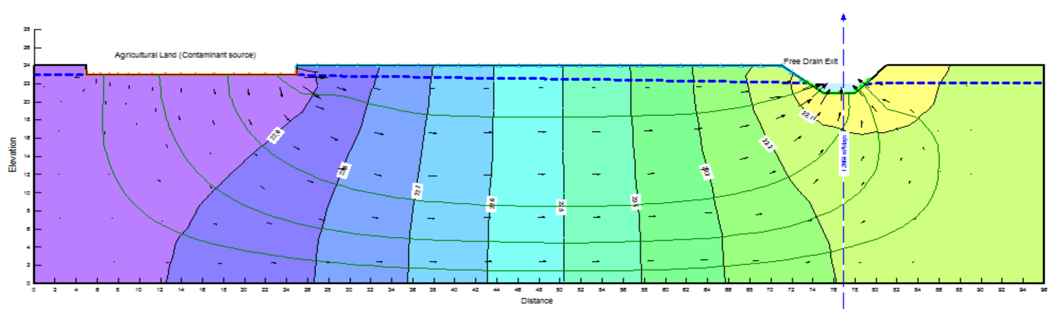

Fig. 2. Simulated results obtained by SEEP/W program showing the sub-surface flow towards the drain.

Analysis of Phosphate Movement through Soil Profile by CTRAN/W

Advection- Dispersion Analysis

The SEEP/W simulated results were adopted by the CTRAN/W program for the phosphate movement analysis within the soil region by using two specific analysis methods, i.e. Advection-Dispersion and Particle Tracking Analysis (PTA) respectively. According to the Advection-Dispersion Analysis the simulated results shows that the adsorption of phosphate on the soil particles is mainly depended to the amount of phosphate fertilizer applied due to which a linear trend observed. Thus, this signifies that the variation of the phosphate concentration is due to the water percolation within the soil which confirms the chemical partitioning between the liquid and solid phases respectively. This means that the chemical partitioning coefficient can be specified as a function of concentration.

Figures 3a - 3g describe the Advection-Dispersion Analysis for the day 50, 100, 150, 200, 250, 300 and 365 days along with a starting concentration of 220 gm/ft^3 (200 kg/acre), respectively. Moreover, the contours represent the different concentration of phosphate for different interval of time; from which the yellow color specifies the maximum concentration while the green color shows the minimum concentration for each case.

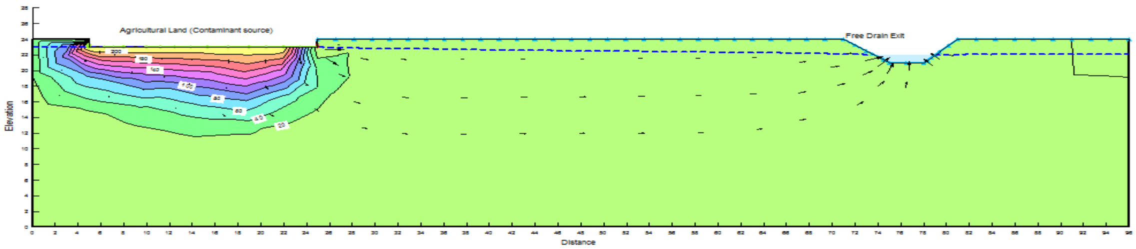

Fig. 3a. Simulated results of Advection-Dispersion Analysis after 50 days.

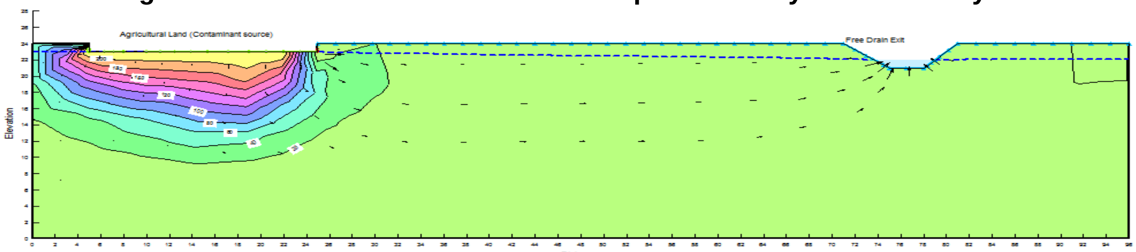

Fig. 3b. Simulated results of Advection-Dispersion Analysis after100 days.

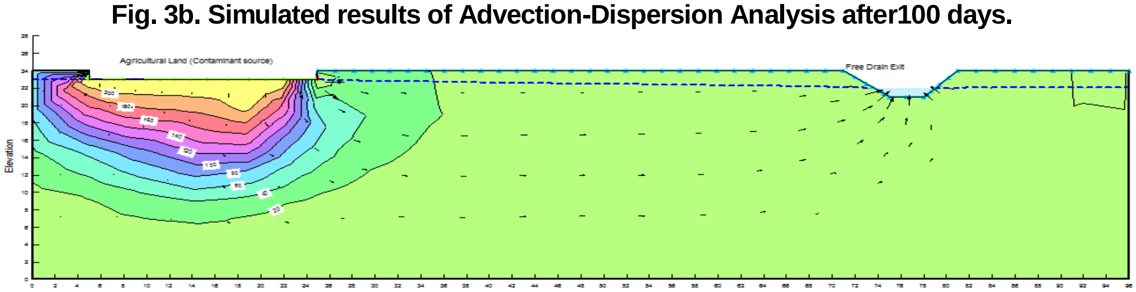

Fig. 3c. Simulated results of Advection-Dispersion Analysis after 150 days.

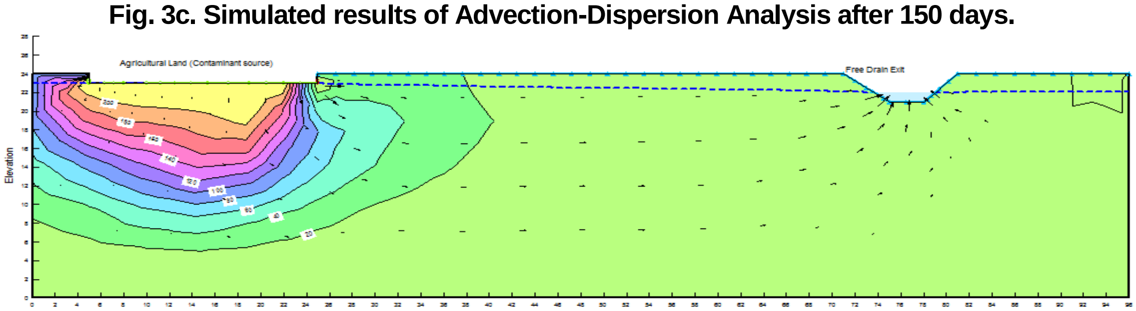

Fig. 3d. Simulated results of Advection-Dispersion Analysis after 200 days.

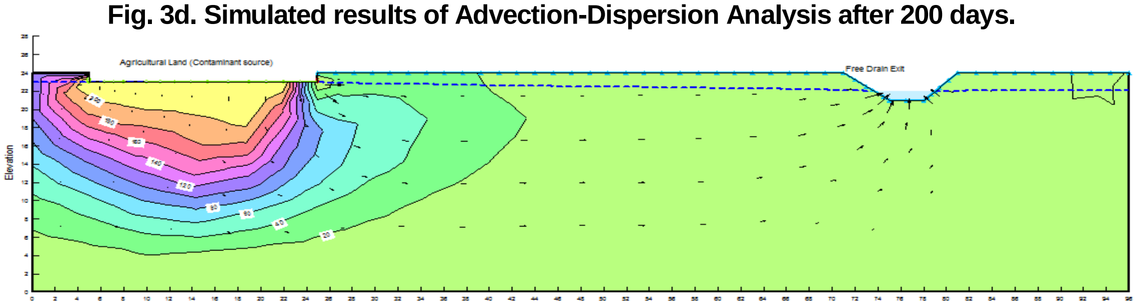

Fig. 3e. Simulated results of Advection-Dispersion Analysis after 250 days.

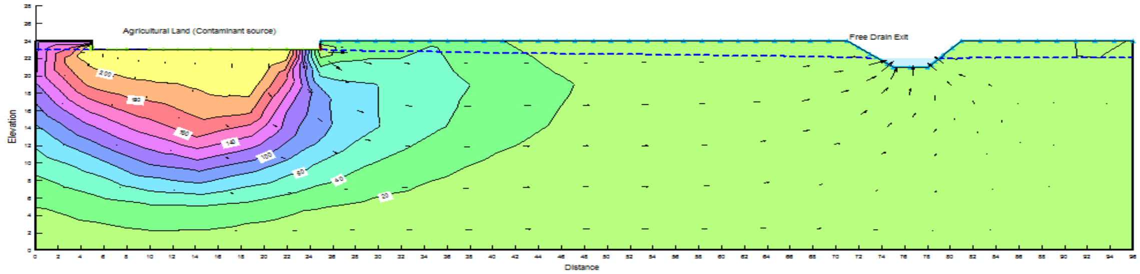

Fig. 3f. Simulated results of Advection-Dispersion Analysis after 300 days.

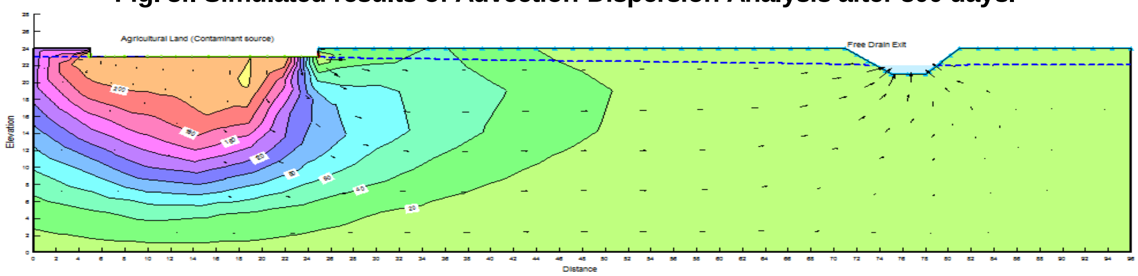

Fig. 3g. Simulated results of Advection-Dispersion Analysis after 365 days.

Results of phosphate concentration showed that phosphate concentration after 365 days was 0.93gm/ft^3 which are an evident that the soil is having a low hydraulic conductivity due to which phosphate particles take an extensive time to reach to the drain. The shape and spread of contours for phosphate concentration showed that the movement of the particles highly depends on the total head and their diffusion and adsorption functions. Similar results were obtained by Eltarabity *et al.* (2015), for a fertilizers movement in a sandy soil by using controlling transport process via vertical barriers. Figures 4a – 4c described the concentration of phosphate at different soil depths of the land at 2ft (head), 10ft (middle), and 18ft (tail) and at different interval of time obtained by CTRAN/W simulations. Table (1–3) described the complete summary of the results.

Table 1. Phosphate Concentration in an agricultural land at a distance of 2ft (head) for different soil depths at different interval of time

S. No.	Soil Depth (ft)	Phosphate Concentration (g/ft^3) at different interval of time (days)							
		50 days	100 days	150 days	200 days	250 days	300 days	365 days	Average
1	22.5	196.22	204.07	206.41	208.45	209.66	210.21	210.98	206.57
2	22.0	179.01	194.70	199.38	203.49	205.89	207.00	208.55	199.72
3	21.5	161.77	185.31	192.33	198.49	202.11	203.78	206.11	192.84
4	21.0	144.91	175.28	184.66	192.97	197.89	200.16	203.36	185.60
5	20.5	129.37	164.09	175.78	186.41	192.80	195.78	199.99	177.75
6	20.0	114.31	153.25	167.19	180.04	187.84	191.50	196.70	170.12

Table 2. Phosphate Concentration in an agricultural land at a distance of 10ft (middle) for different soil depths at different interval of time

S. No.	Soil Depth (ft)	Phosphate Concentration (g/ft^3) at different interval of time (days)							
		50 days	100 days	150 days	200 days	250 days	300 days	365 days	Average
1	22.5	199.67	205.95	207.93	209.67	210.68	211.15	211.79	208.12
2	22.0	185.94	198.49	202.45	205.92	207.97	208.90	210.18	202.84
3	21.5	172.19	191.02	196.97	202.18	205.24	206.64	208.56	197.54
4	21.0	158.43	183.54	191.47	198.42	202.51	204.38	206.95	192.24
5	20.5	144.65	176.06	185.97	194.66	199.77	202.11	205.32	186.93
6	20.0	130.85	168.56	180.46	190.90	197.04	199.84	203.69	181.62

Table 3. Phosphate Concentration in an agricultural land at a distance of 18ft (tail) for different soil depths at different interval of time

S. No.	Soil Depth (ft)	Phosphate Concentration (g/ft^3) at different interval of time (days)							
		50 days	100 days	150 days	200 days	250 days	300 days	365 days	Average
1	22.5	132.80	135.84	136.61	137.24	137.58	137.73	137.93	136.53
2	22.0	123.48	129.52	131.08	132.32	133.01	133.31	133.70	130.92
3	21.5	114.64	123.64	125.95	127.83	128.85	129.30	129.90	125.73
4	21.0	106.26	118.18	121.26	123.75	125.12	125.73	126.53	120.98
5	20.5	98.34	113.14	116.97	120.09	121.81	122.57	123.56	116.64
6	20.0	91.30	108.78	113.44	117.30	119.47	120.43	121.69	113.20

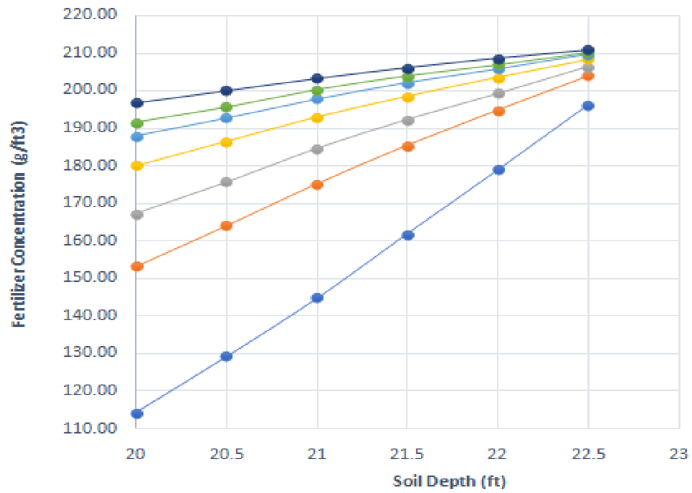

Fig. 4a. Phosphate Concentration vs Soil Depth at a distance of 2ft (head) at different interval of time.

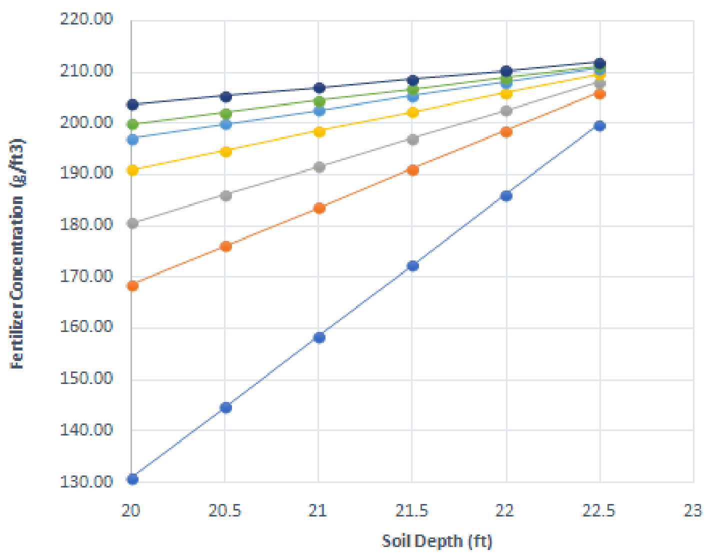

Fig. 4b. Phosphate Concentration vs Soil Depth at a distance of 10ft (middle) at different interval of time

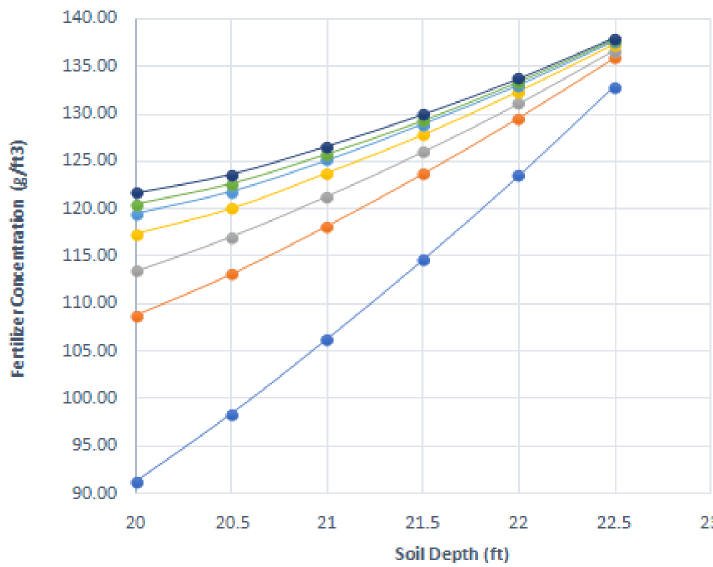

Fig. 4c. Phosphate Concentration vs Soil Depth at a distance of 18ft (tail) at different interval of time.

Particle Tracking Analysis (PTA)

In order to analyze the movement of dissolved solutes (particles) initially a total of six nodal points that were selected from three sections (head, middle, and tail) wherein, two nodal points were assigned per section. From the simulated results, it is observed that the average velocity of the two points at head is about 0.256 ft/day. A decreasing velocity was observed from the 50 days (0.233 ft/day) and on the succeeding days, i.e. 100 days (0.223 ft/day), 150 days (0.213 ft/day), and 200 days (0.209 ft/day), respectively. Consequently, a slight increase in velocity was detected at 250 days (0.224 ft/day) and 300 – 365 days (0.226 ft/day), respectively. Figures 5a–5g describes the particle tracking velocity within the soil which considerably dependent on the flow of water and time respectively.

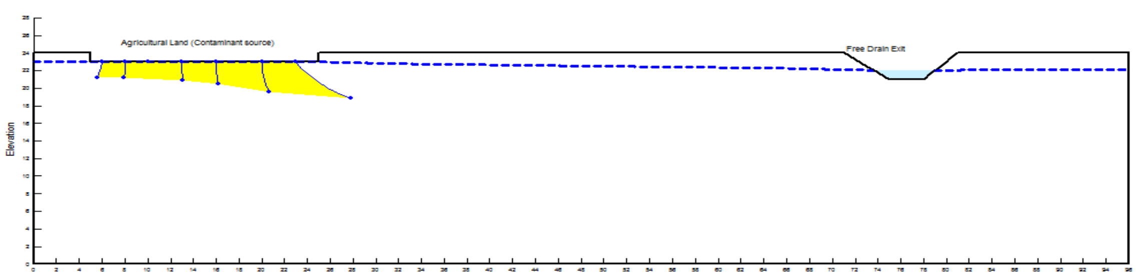

Fig. 5a. Particle tracking analysis after 50 days.

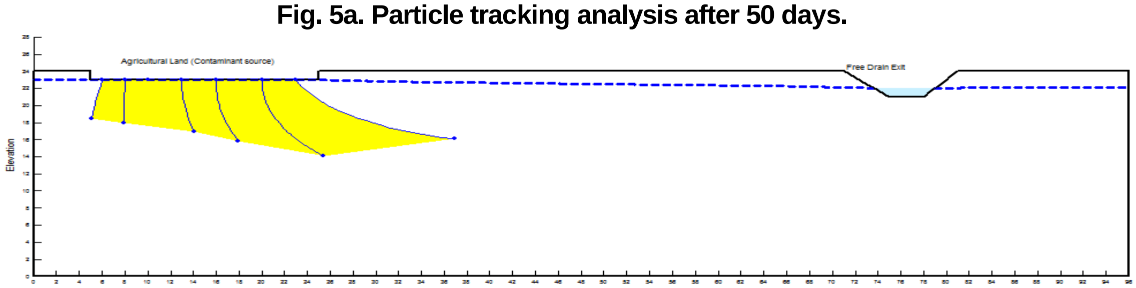

Fig. 5b. Particle tracking analysis after 100 days.

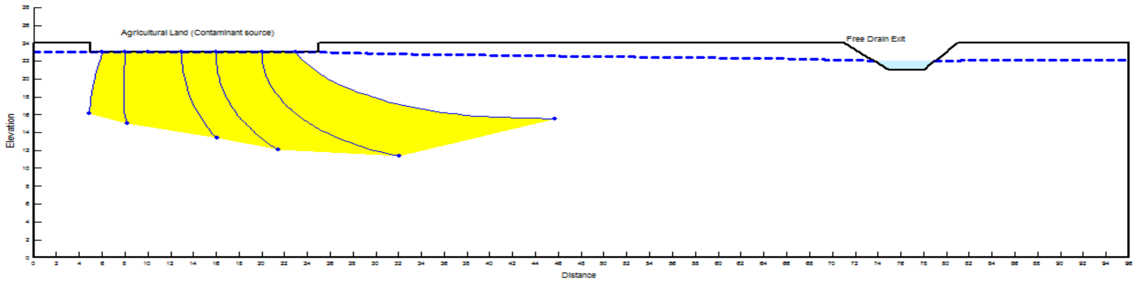

Fig. 5c. Particle tracking analysis after 150 days.

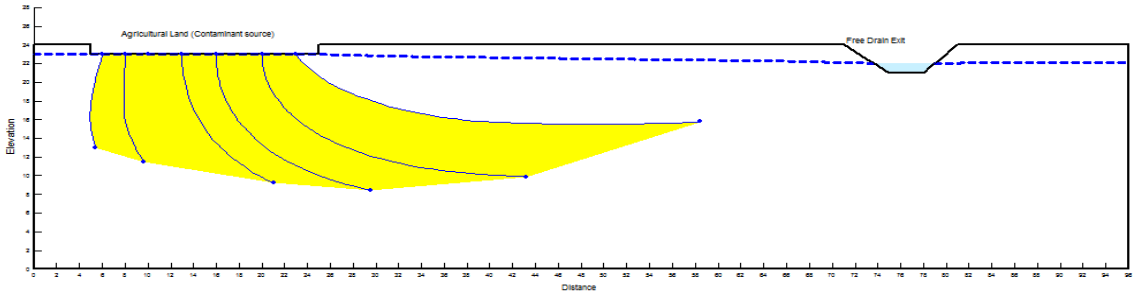

Fig. 5d. Particle tracking analysis after 200 days.

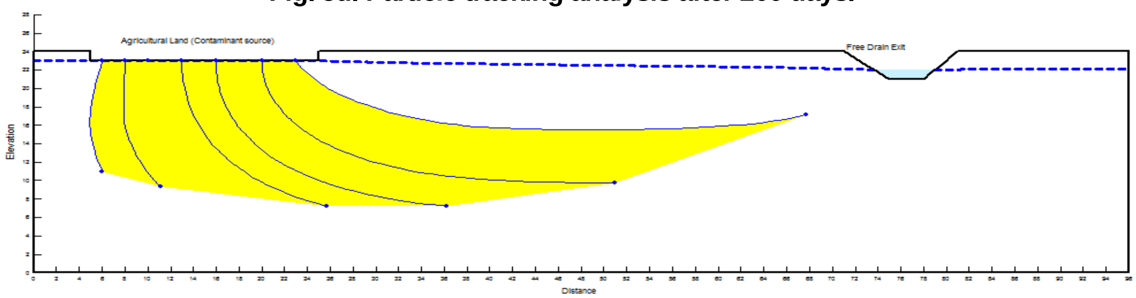

Fig. 5e. Particle tracking analysis after 250 days.

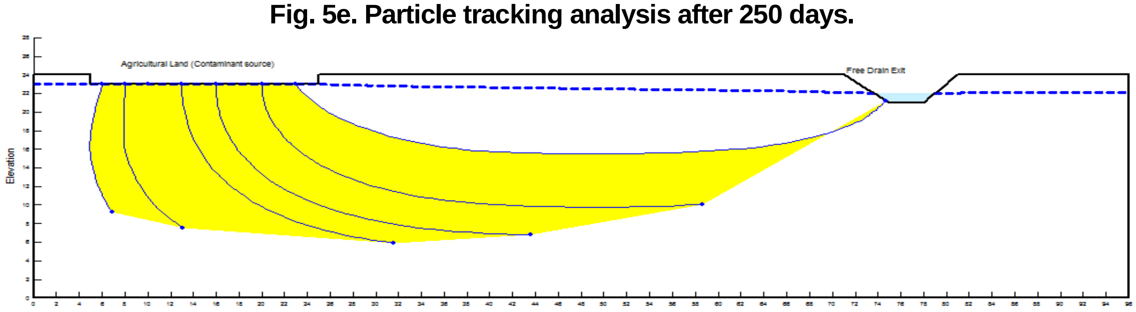

Fig. 5f. Particle tracking analysis after 300 days.

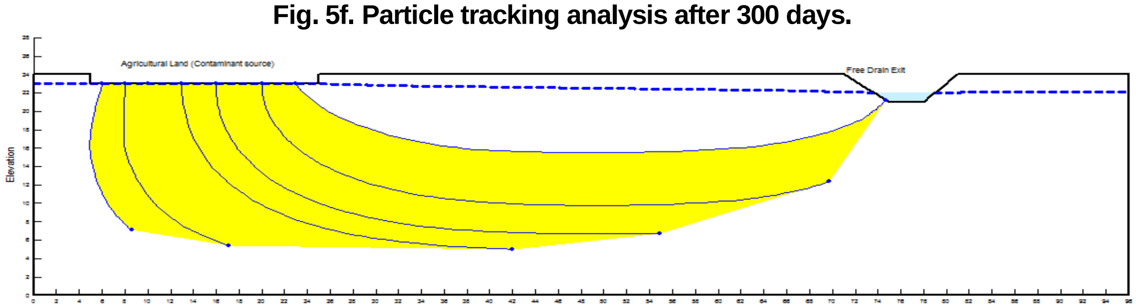

Fig. 5g. Particle tracking analysis after 365 days.

The overall average velocity for the solutes at head, middle, and tail sections was observed as 0.2262 ft/day, 0.3997 ft/day, and 0.6834 ft/day, respectively. However, the solutes present at the tail section reached to the drain in between 300 - 365 days. This may be due to a lesser P-sorption capacity at the tail region. This further implies that the bonding was not strong as compared to the head and middle sections. These results are in agreement with the findings of Arshad (2015), who found that, the particles movement in a sandy loamy clayey soil is slow and due to which the particle movement towards the drain will be slow due to strong bonding between soil and phosphate. The head and middle particles will take more time to reach the free drain while the tail particle will reach early respectively.

CONCLUSION

The study developed a hypothetical 2-D numerical model of a clayey-sandy soil profile using Geo-Slope software, wherein the water flow and phosphate movement were analyzed respectively. Results showed a normal trend for streamlines and equipotential lines. The phreatic surface in the subsurface region has been simulated and this confirms that the flow is proportional to the hydraulic head and conductivity obtaining an average flow rate of the order 0.000342 LPS. The Advection-Dispersion Analysis showed an overall linear trend which indicates that phosphate adsorption mainly dependent on the concentration and which is represented as contours with different colors. Moreover, the phosphate concentration at the drain's exit was observed about 0.93 gm/ft^3 after 365 days. The solutes present at the tail section due to a lesser P-sorption capacity reached the toe of the drain in between 300 - 365 days with an average velocity of 0.6855 ft/day. However, the results may vary for other types and texture of soils.

CONFLICT OF INTEREST

All the authors have declared that no conflict of interest exists.

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