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Numerical modeling of leachate migration in compacted tropical laterite soil

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Abstract. To protect groundwater from leachate contamination in sanitary landfill involve the use of hydraulic barriers i.e. liners and covers. Nonetheless, can these barriers continue to impede the migration of leachate over a long period? A full-scale experiment would be prohibitively costly and time consuming. The only feasible recourse therefore is to construct a model, which reasonably portray the behaviour of the full-scale system and simulate the relevant physical parameters and describes the overall significant characteristics of the transport phenomena. This research investigates the long-term performance of compacted tropical laterite soil liners at various gradations against leachate migration in sanitary landfills using numerical modeling. Series of laboratory experimentation were carried out using three different laterite soil gradations (30%, 40% and 50% with respect to fines content) compacted at optimum moisture content using British Standard light energy. Leachate was poured on the compacted soil in an acrylic column and its migration was monitored using Digital Image Technique (DIT). Subsequently, PetraSim computer software a graphical interface used to solve problems related to contaminant transport was applied to predict the velocity of leachate migration. The predicted velocity values for 30%, 40% and 50% fines are 4.5×10^{-7} m/s, 7×10^{-9} m/s, and 8×10^{-10} m/s, respectively. This shows that the laterite soil with 50% fines content is more compatible with the leachate and can be used as soil liner. The outcome of this research would enable designers to use non-destructive method to monitor and predict leachate migration in compacted soil liners to simulate leachate migration in waste containment applications.

1. Introduction

Computer models are essential to analyze subsurface flow and contamination problems because the models are designed to incorporate hydrologic parameters that an analytical model cannot incorporate. A great quantity of input data for the model must be gathered from a literature review, field investigations, and laboratory studies [1]. Nowadays, some of the most developed and used groundwater modeling softwares are Groundwater Modeling System (GMS), Tough2, Groundwater Vistas (GV) and Visual MODFLOW [2].

Computer modeling approach of groundwater flows and transport systems has become imperative. These models provide a systematic background for understanding the mechanisms of groundwater systems and the procedures that effect their quality. Progressively, models are an integral part of water resources assessment, protection and restoration studies, and provide essential and cost-effective support for planning and screening of alternative policies, regulations, and engineering designs affecting groundwater [3].

There are many different groundwater modeling codes available, each with its own capabilities, operational characteristics, and limitations. If modeling is considered for a project, it is important to determine if a particular code is appropriate for that project, or if a code exists that can perform the simulations required in the project. Systematic and comprehensive description of a code features based on an informative classification provides the necessary basis for efficient selection of a groundwater modeling code for a particular project or for the determination that no such code exists [3]. Therefore, model selection involves selection of the type of processes to be studied and included in the mathematical statement. Different solution techniques are available to solve the chosen mathematical model. Analytical solutions are usually possible only for simple geometries, homogeneous aquifers, and simple boundary conditions [4].

This research adopts the non-invasive technique using digital image analysis to capture successive migration of leachate through compacted laterite soil in the laboratory. The use of photographic technique to capture the migration of liquids in soil in the last few years, especially the noninvasive imaging techniques has increased, bringing with it a more accurate characterization and hence understanding of transport system. Researches that applied non-invasive imaging techniques produced precise depiction and improved understanding of the multiphase system. Recently, image analysis techniques were used to investigate the migration of fluids within soils [5]. The application of digital image technique is usually used for double-porosity soil [5-13].

A non-invasive digital image technique using Matlab processing code and Surfer software generate 2D contour plots. The velocities of the leachate are then computed from the generated 2D contour plots. To further analyze the future migration of leachate into the compacted laterite soil, a numerical model was deployed using PetraSim. PetraSim is a graphical interface for the Tough2 family of simulators used to solve problems related to geothermal systems, carbon sequestration, contaminant transport and more. PetraSim makes the power of Tough2 accessible to modelers through an interactive environment that includes mesh generation, parameter definition, and display of results [14].

2. Material and Method

2.1. Material

A reddish laterite soil was used in this study and was extracted using the method of disturbed sampling from Skudai campus (Johor) which is located at latitude 1º33'39"N and longitude 103º38'44"E of Universiti Teknologi Malaysia (UTM). The soil is classified as MV according to the British Standard classification [15]. Laboratory tests were conducted to determine the index properties of the laterite soil in accordance with British Standard as shown in Table 1.

Table 1. Index properties of natural laterite soil.

Property	**Value**
Natural Moisture Content, %	34
Liquid Limit, %	76
Plastic Limit, %	42
Plasticity Index, %	34
Free Swell Index, %	31
BS Classification	MV
Specific Gravity	2.7
OMC, %	28
MDD, Mg/m^3	1.35

2.2. Method

Three different grading sizes (i.e. gravel, sand and fines) were gotten from sieved natural laterite soil samples and then reconstituted into different gradations. The following gradations were investigated:

1. Natural laterite soil with 30% fines, 40% sand and 30% gravel contents by weight of dry soil denoted as L1.
2. Reconstituted laterite soil with 40% fines, 40% sand and 20% gravel contents by weight of dry soil denoted as L2.
3. Reconstituted laterite soil with 50% fines, 40% sand and 10% gravel contents by weight of dry soil denoted as L3.

Reasons for selecting these gradations are as follow: First, the higher the fines content the lower the hydraulic conductivity [16]. Likewise, laterite soils with 20% to 30% fines content might not be used as liner or hydraulic barriers because their hydraulic conductivities are higher than the minimum requirement of 1×10^{-9} m/s [17-18]. So reconstituted soil with different fines content are used in this research for validation. Second, adequate amount of sand will result in volumetric shrinkage of less than or equal to 4% and low potential for desiccation cracks [17, 19]. Third, the percentage of gravel content should be $\leq 30\%$ because high amount of gravel leads to high hydraulic conductivity and the likelihood that pockets of gravel (segregation of gravel) can occur during construction [20-21].

2.2.1. Physical Modeling Method. In this research, a non-invasive technique was applied using digital image technique that captures successive migration of leachate through compacted laterite soil in the laboratory to simulates the leachate transportation in actual landfill. The captured digital images were fed through an image processing code using Matlab software to convert them to hue-saturation-intensity (HSI) format. Surfer software then read the HSI to generate a 2D contour plot. Velocity of the leachate was then computed from the generate 2D contour plot. To validate and further analyze the future migration of leachate into the compacted laterite soil, say 50 years, a numerical model was deployed using PetaSim. Therefore, the analysis used in the PetraSim was based on the DIT results. Among these three different gradations, L3 (50% fines) provides the recommended hydraulic conductivity after a month monitoring which can be used as soil liner in waste containment applications. Hence, most of the investigation mainly rely on L3. Nevertheless, comparisons were made between the different gradations to check their long-time performance.

2.2.2. Numerical Modeling Method. The development of a model required an input data, data needed to characterize a flow system include hydrogeologic parameters and constitutive relations of the permeable medium, thermophysical properties of the fluids, initial and boundary conditions of the flow system, and sinks and sources [22]. The computer model adopted in this study is the PetraSim, a new interactive, cross-platform, pre and post-processor that can be used to create models and display simulation results through time [23-24]. PetraSim as a graphical user interface allows modelers to run simulations entirely within the software from grid creations to result displays. It helps users create different dimensional grids, apply complex boundary and initial conditions, and assign wells for injecting and extracting fluids or heats [25]. In the PetraSim, a new file was created choosing the simulator mode in Tough mode using the equation of state (EOS) in the saturated/unsaturated flow to simulate the laboratory experiment. An inserted model boundary condition i.e. minimum and maximum XYZ of 100 mm in all directions with respect to the soil sample acrylic column. The next step taken was to create a regular mesh as it is rectangular simulating the grids used in the physical model. In the global properties, analysis chosen for the software to be run was Tough2. Material properties such as material name, colour, density, porosity, and permeability were applied based on the experimental results. The wet heat conductivity also referred to as specific heat is the amount of heat required to change the temperature of an object by a certain degree, while thermal conductivity is the property of a material to conduct heat. These heat values were selected for the laterite soil in accordance with [26-28]. The Corey's curve was selected as the Brooks and Corey equation was used to calculate the unsaturated hydraulic conductivity of the laterite soil [29]. The solution control which allows for selecting the start and end time of the project was selected to predict for 50 years in this study. The software was run to do the simulation and plot the graph as presented in the results and discussion.

3. Discussion of Results

The results of the numerical analysis using PetraSim are presented accordingly.

3.1. Prediction of Leachate Migration

PetraSim create models and display simulation results through time. The prediction of leachate migration was carried out to evaluate the velocity (v) parameter over some presumed time.
According to Holtz, Kovacs,Sheahan [30], flow in most soils is so slow that can be considered as laminar. Thus, an expression of Darcy's law is written as;

$$v = ki \tag{1}$$

Where;
v = velocity
k = hydraulic conductivity
i = hydraulic gradient

Hydraulic gradients found in the field are too low to be realistic for completing laboratory test in a reasonable time period [31]. At low hydraulic gradients some organics may not permeate a water saturated soil. At higher gradients, the macropores and other discontinuities that develop in the soil result in larger hydraulic conductivities [31]. According to USEPA [32], the leachate height in a landfill must not exceed 300 mm. For a soil liner 900 mm thick, hydraulic gradient will be around 1. Therefore, when the hydraulic gradient equals to 1, then velocity is equals to hydraulic conductivity as expressed in equation 2.

$$v = k \tag{2}$$

3.1.1. Calibration of PetraSim. In order to determine the precision of the PetraSim software, it was calibrated based on physical model experimental data (i.e. digital image analysis) to assess the benefits of model conformity. The calibration was carried out for L3 as it provides the recommended hydraulic conductivity amongst the gradations. Nevertheless, comparisons were made between the different gradation to check their long-term performance. The velocity of 1.38 x 10-8 m/s for day one taken from DIT was used to simulate for one week and four weeks velocities in PetraSim as shown in Figure 1 and Figure 2, respectively. From Figure 1, the velocity steadily decreases from 1.38 x 10-8 m/s to 4.5 x 10-9 m/s in the PetraSim from the first day to seven days as compared to 4.98 x 10-9 m/s in digital image technique. Figure 2 shows a decrease in velocity from 1.38 x 10-8 m/s to 1.2 x 10-9 m/s in the PetraSim from the first day to four weeks as compared to 1.24 x 10-9 m/s in digital image technique. As realized from the velocity values, the difference between the actual (DIT) and simulated (PetraSim) are quite negligible which shows that there is design conformity as presented in the calibration curve in Figure 3. The pattern of migration of Figures 1 is laminar i.e. the energy or head loss increases linearly with increasing velocity. The migration pattern in Figure 2 started linear then after one week becomes curvilinear, because of friction, energy is lost at a much greater rate and the relationship is nonlinear (turbulent) (Holtz et al., 2011).

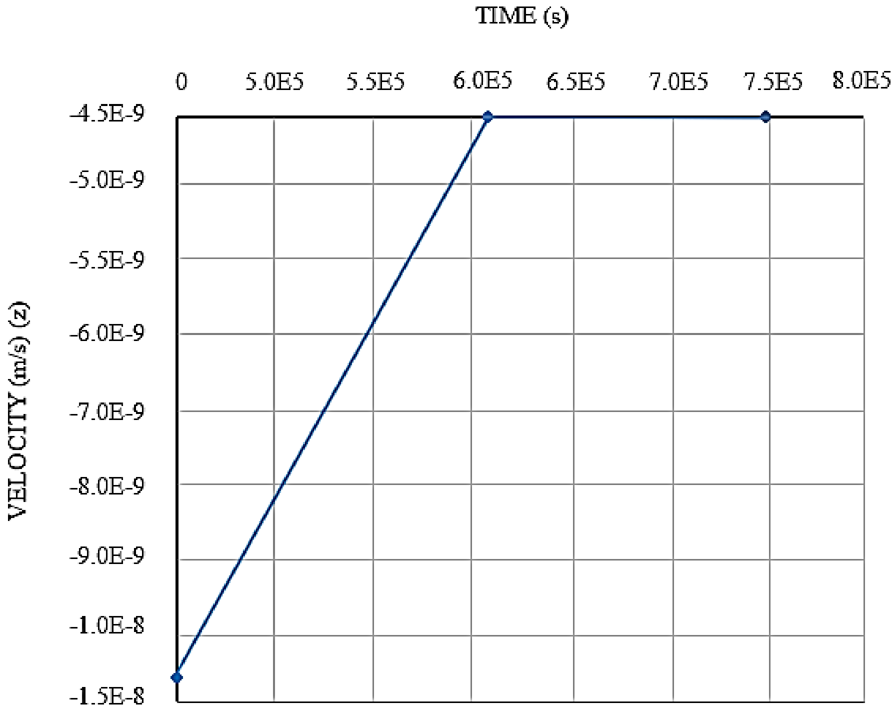

Figure 1. Velocity versus time graph for 7 days.

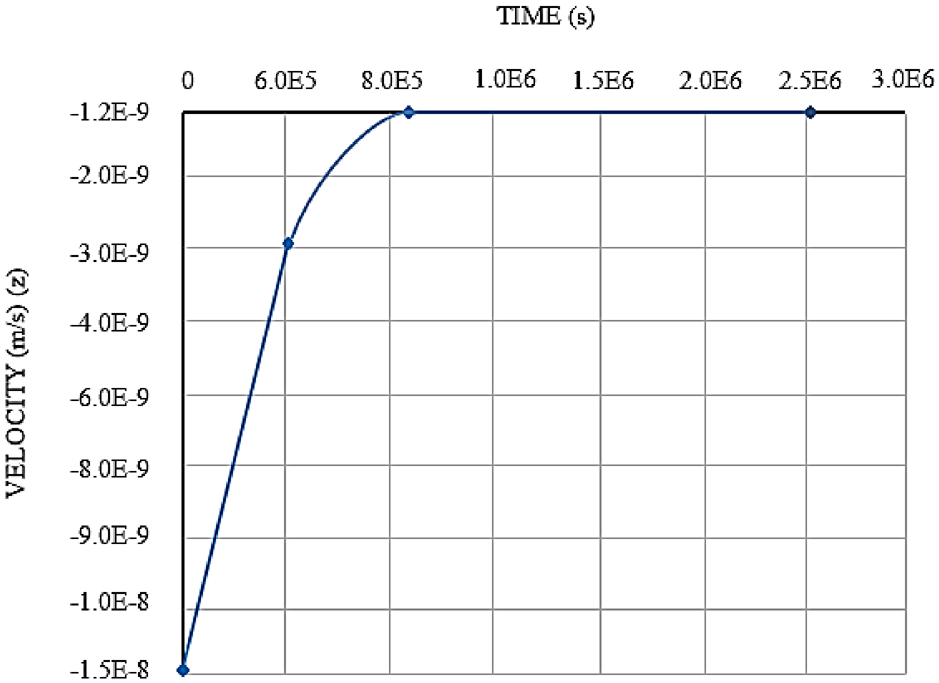

Figure 2. Velocity versus time graph for 28 days.

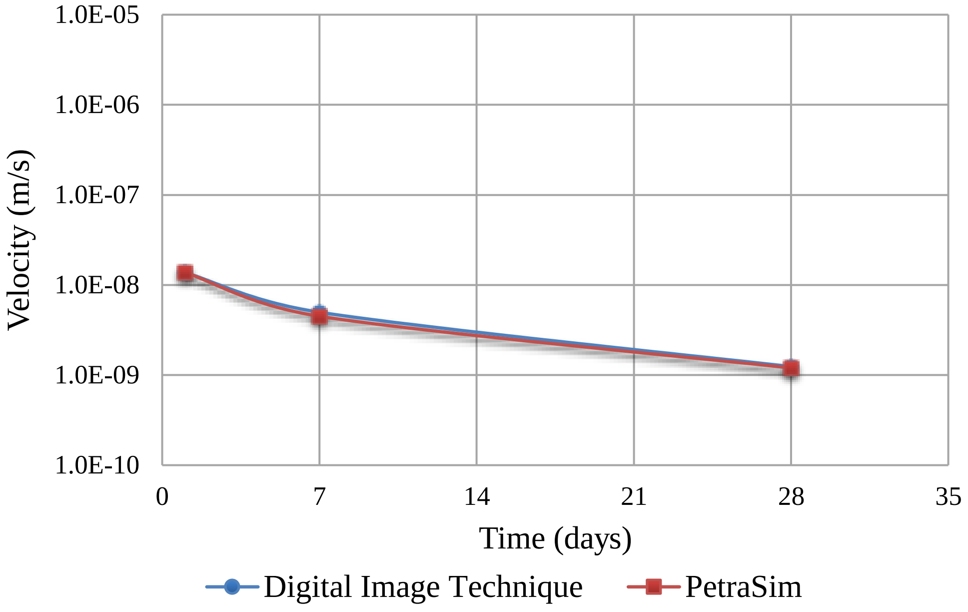

Figure 3. Calibration curve of velocity versus time.

Therefore, the distances migrated by the leachate in the laterite soil sample at 7 days and 28 days are approximately 2.7 mm and 2.9 mm, respectively. These are in close line with the digital image analysis that shows the distance migrated by the leachate in the soil sample in 7 days and 28 days was 3 mm for both as the migration stops after 7 days. In the DIT, migration became constant after 7 days, while in the PetraSim migration continue after 7 days until 28 days covering 2 mm between this period which necessitates projection over longer period or life span of the waste containment system. The minimum thickness of a compacted soil liner in municipal solid waste landfill is 600 mm with a hydraulic conductivity of no more than 1 x 10^{9} m/s [33]. Therefore, it is paramount to justify the distance covered by the leachate over the lifespan of 50 years in order to check if the leachate would travel more than 600 mm. Table 2 presents the comparison of results between calibration of DIT and PetraSim.

Table 2. Calibration parameters for DIT and PetraSim.

	Digital Image Technique	**PetraSim**
v (m/s) for 7 days	4.98 x 10^{-9}	4.5 x 10^{-9}
v (m/s) for 28 days	1.24 x 10^{-9}	1.2 x 10^{-9}
d (m) for 7 days	3	2.7
d (m) for 28 days	3	2.9

3.1.2. Simulation using PetraSim. To predict the velocity for 50 years, a simulation of 1.2 x 10^{-9} m/s velocity parameter that was calibrated based on physical model experimental data of 28 days was used. From the time-velocity graphs in Figure 4 using PetraSim, the velocity decreases from 1.2 x 10^{-9} m/s to 6 x 10^{-10} m/s in 28 days to 50 years respectively. The leachate migration over the period of 50 years will travel approximately 39 mm which is within the safety zone as the distance did not exceed the 600 mm.

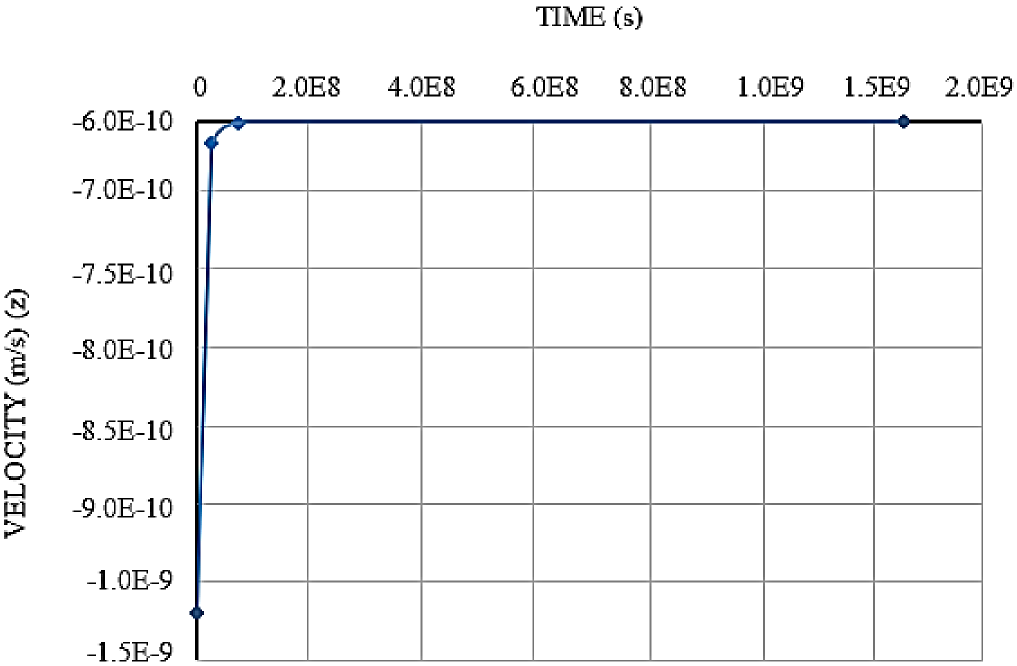

Figure 4. Velocity versus Time graph for 50 years.

Furthermore, the saturated hydraulic conductivities of the laterite soil at three different gradations of L1, L2 and L3 at *OMCs* are used to predict 50 years hydraulic conductivities of 2.5 x 10^{-6} m/s, 3.78 x 10^{-8} m/s, and 2.44 x 10^{-9} m/s, respectively. This is because the saturated hydraulic conductivity is considered as it is more critical (with higher values) and to make comparison between the different soil gradations. The 50 years velocities predicted for L1, L2 and L3 using PetraSim software are 4.5 x 10^{-7} m/s, 7 x 10^{-9} m/s, and 8 x 10^{-10} m/s respectively as presented in Figures 5, 6 and 7. The results showed a decrease in the velocity over 50 years because of compaction, most of the pores in the soil are rendered ineffective (i.e. non-interconnected) thereby resulting in difficulty for the leachate to move further. The decrease in velocity could also be due to susceptibility of the laterite soil particles to swelling, resulting in its rearrangement and reorientation making it more difficult for the leachate to pass through. According to Amadi [34], it is required for soil barrier materials to have high swelling potential to achieve low hydraulic conductivity and to fill voids and fractures to achieve an improved impermeable zone around the landfill. The laterite soil used has a free swelling index of 31% which shows that it possesses moderately high self-sealing abilities when in contact with leachate [35]. From these predicted values, L3 provides the lowest velocity of 8 x 10^{-10} m/s as presented in Figure 7 because of the higher fines content. Generally, the higher the fines content, the lower the hydraulic conductivity, thus slower leachate migration [20, 31].

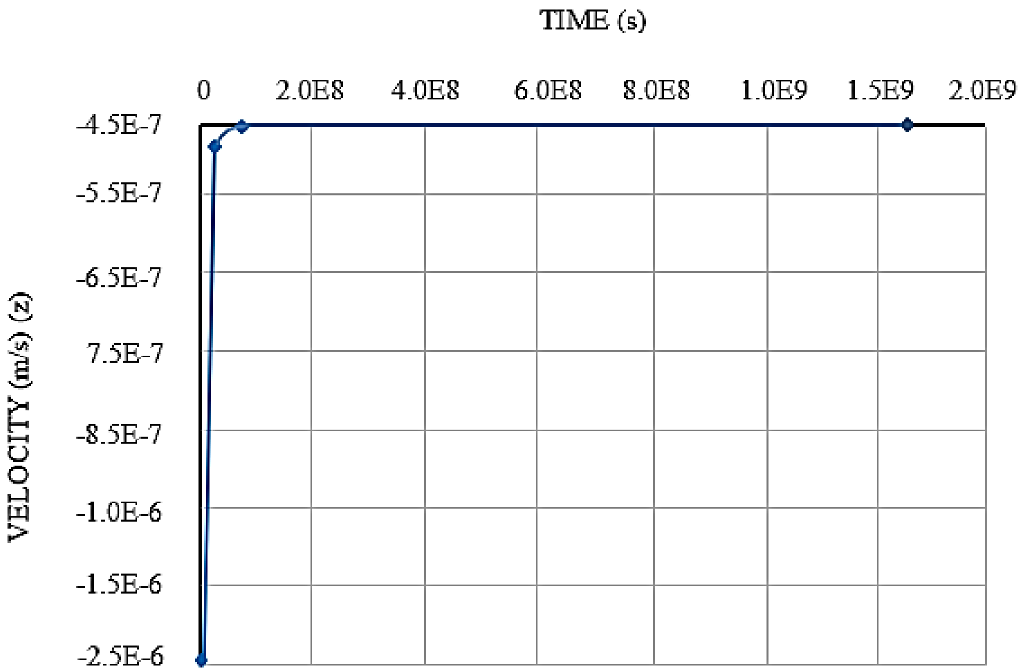

Figure 5. Velocity versus time graph of L1 for 50 years.

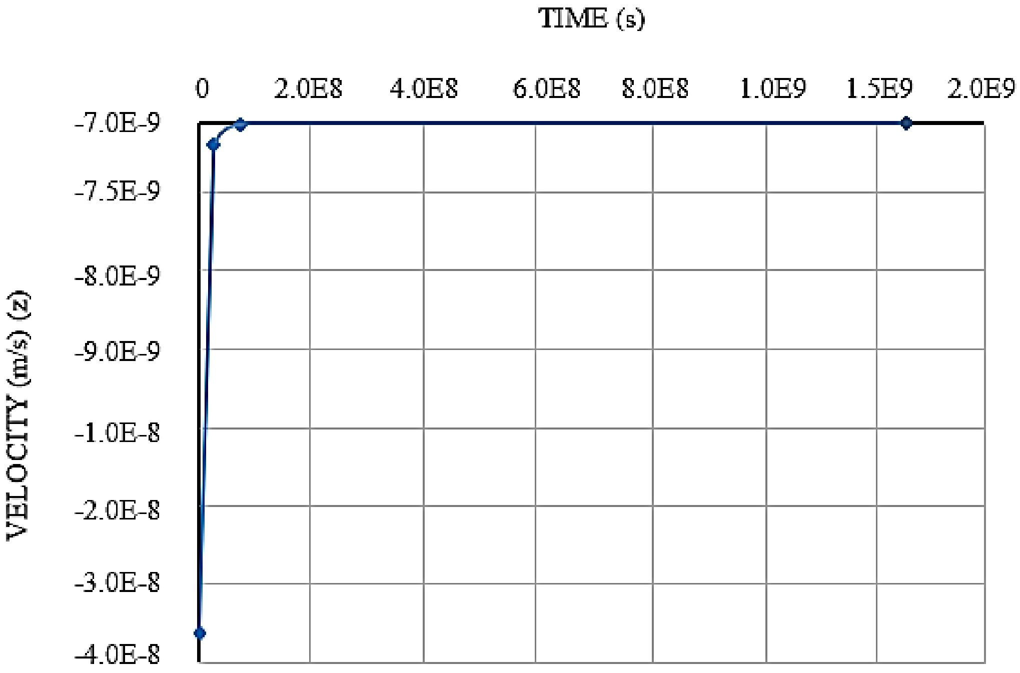

Figure 6. Velocity versus time graph of L2 for 50 years.

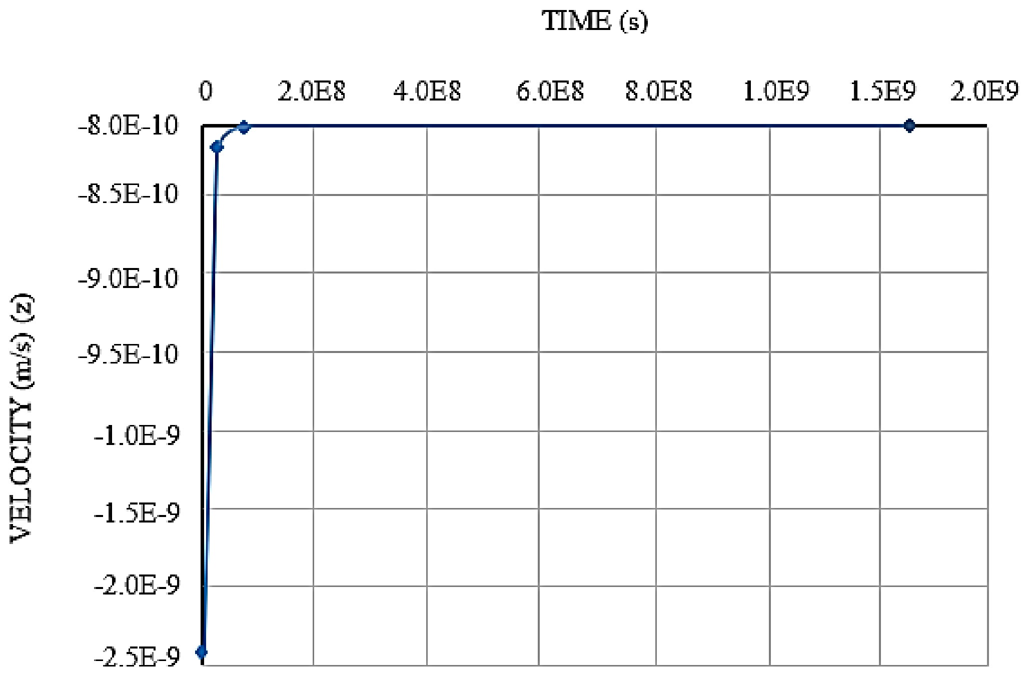

Figure 7. Velocity versus time graph of L3 for 50 years.

Additionally, comparison was carried out to check if the laterite soil liners at the three different gradations (L1, L2 and L3) can withstand the longtime permeation of leachate estimated over 50 years lifespan of the sanitary landfill. Figure 8 shows that the measured velocities from the laboratory experiment and the predicted velocities using PetraSim in which L3 (50% fines) guarantees the safe containment of the leachate in 50 years compared to L1 (30%) and L2 (40%). Soils with inadequate fines typically have too little silt- and clay-sized material to produce suitably low hydraulic conductivity [36]. Data from Benson, Zhai,Wang [37], suggest that a minimum of 50% fines might be an appropriate requirement for many soils. According to USEPA [36], field inspectors should check the soil to make sure the percentage of fines meets or exceeds the minimum stated in the construction specifications and should be particularly watchful for soils with less than 50% fines.

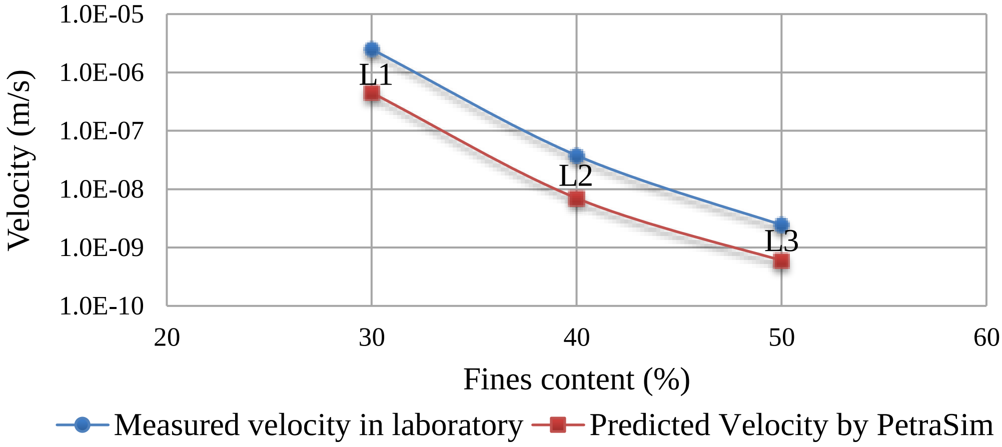

Figure 8. Velocity versus fines content for 50 years.

4. Conclusions

A full-scale experiment would be prohibitively costly and time consuming. The only feasible recourse therefore is to construct a model, which reasonably portray the behaviour of the full-scale system and simulate the relevant physical parameters and describes the overall significant characteristics of the transport phenomena. In this research, laboratory experiments were conducted on compacted laterite soil at different gradations. The digital image processing technique using Matlab routine and Surfer software were applied to observe the leachate migration behaviour in the soil column physical model. The results of the laboratory experiments determined through the observation of leachate percolation into the test samples were compared and the rate of permeation calculated. It was observed that the rate of migration of leachate decreased when the fines content is increased. The 50 years velocities predicted for L1, L2 and L3 using PetraSim software are 4.5×10^{-7} m/s, 7×10^{-9} m/s, and 8×10^{-10} m/s respectively. The numerical projection reveals that L3 is the most compatible with the leachate and can impede its flow with time. Therefore, laterite soil with 50% fines content provides the recommended hydraulic conductivity which can be used as hydraulic barriers in waste containment applications.

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