Effect of Initial Unit Weight and Type of Soil on Water and Nitrate Movement through Saturated- Unsaturated Soils

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Abstract

The effect of initial dry unit weight and type of soil on water and nitrate migration through saturated-unsaturated soil is experimentally investigated using laboratory one-dimensional model (40 mm diameter, 100 mm height) under various head boundary. The results were compared with the numerical results by using packages of finite element name SEEPW and CTRAN of GEOSLOPE software.

The results show that the initial dry unit weight has a significant effect on the transport process of water and contaminant through saturated-unsaturated soils, Nitrate concentration more sensitive than water flow to change in initial dry unit weight due to variation in mechanical dispersion that affected by porosity and void ratio which depended on dry unit weight of soil. Water content and nitrate concentration was highly affected by soil type and water application boundary conditions.

Keywords: Unsaturated soil, One dimension, Nitrate concentration, Initial dry unit weight, GEOSLOPE.

تأثير الكثافة الوزنية الأولية ونوع التربة على حركة الماء والملوثات خلال التربة المشبعة-غير المشبعة

الخلاصة

تمت دراسة تاثير الكثافة الجافة الوزنية الأولية ونوع التربة على أنتقال الماء والملوثات في التربة المشبعة–غير المشبعة بأستخدام موديل مختبري بأتجاه واحد (قطره 40 ملم وأرتفاعه 100 ملم) وتحت ظروف مختلفة من الشروط الحدية للشحنة المسلطة في سطح الترية . النتائج المستحصلة تمت مقارنتها مع النتائج النظرية لنفس الموديل وتحت نفس الشروط الحدية وذلك بأستخدام برنامج GEOSLOPE.

بينت النتائج أن الكثافة الجافة الوزنية الأولية لها تأثير كبير على حركة الماء والملوثاث في التربة المشبعة–غير المشبعة وكان تركيز النترات أكثر حساسية للتغير في الكثافة الجافة الأولية من التغير في المحتوى الرطوبي نتيجة للتغير في الأنتشار الميكانيكي الذي يتأثر بشكل كبير بمسامية التربة ونسبة الفراغات فيها والتي بدورها تتأثر بالكثافة الجافة للتربة. كما بينت النتائج أن المحتوى الرطوبي وتركيز النترات تتأثر بشكل كبير بنوع التربة والشروط الحدية.

الكلمات الدالة: تربة غير مشبعة، أتجاه واحد، تركيز النترات، الكثافة الجافة الوزنية الاولية، برنامج GEOSLOPE.

Introduction

The important of water flow and contaminant migration through saturated –unsaturated soils are recently increased; this case may cause increment damage in soil. The coefficient of permeability can vary 10 orders of magnitude when considering soils that range from gravel to a clay for saturated soils. For unsaturated soils, it is possible for a single soil to have a coefficient of permeability that range 10 orders of magnitude [1]. This has a significant effect when analyzing water and contaminant seepage problems.

Nitrate (NO_3) is one of the major contaminants in ground water which migrate through the vadose zone towards groundwater from areas of high nitrate concentration caused by industrial products and agricultural fertilizer causes a nitrate concentration in many cases greater than the maximum contaminant levels of 10 mg/l of (NO_3-N) or 45 mg/l of (NO_3) set by the US Environmental Protection Agency [2].

Laboratory one dimensional simulation of water and contaminant through saturated-unsaturated soils was used in numerous studies in literature. Wierenga and van Genuchten[3] conducted an unsaturated solute transport by using several small (51 mm in diameter and 300 mm long) and one large column (6000 mm long) packed with the same sandy soil material, Results show that dispersivity was about 50 mm in the large column but only about 10 mm in the small column. The data showed that anions such as chloride or bromide can move considerably faster than noninteracting tracers such as tritium.

Dana and shahrour[4] showed that the soil permeability and capillary pressure and other related parameters, like hysteresis and residual saturation are the key physical parameters toward which experimental work should be oriented. The high effect of soil permeability on solute transport was also observed by Milfont et. al. [5], Bucure et. al. [6]

Lenhart and Saiers[7] showed that the transport of the silica colloids responds to changes in the steady-state volumetric moisture content and for low volumetric moisture depends on the wetting history of the sand pack prior to colloid injection.

Nutzmann et. al.[8] investigated the relationships between water content and relative water velocity fluctuations and water content together with the coefficient of dispersivity in unsaturated porous media. The breakthrough curves (BTCs) of chloride showed that an increase of solute of flow velocity fluctuations for different pathways.

Garg et. al. [2] concluded that strong perching conditions through two field experiments occur in the lateritic vadose zone during the rainy season as well as under constant ponding conditions, which trigger a lateral flow of water in this soil. Nitrate movement under perched water Table conditions is significantly influenced by macropores and lateral flow.

Viotti et. al. [9] used laboratory tests coupled to a semi-pilot test section to derive data for the calibration of a numerical model before using it on defined soils. The sensitivity analysis of the numerical model show that its results are not so much dependent on the classical numerical aspects (time or space increments) but mainly on a set of parameters related to soil structure which must then be derived through a good calibration.

Mantovi et. al.[10] studied water infiltration and nitrate leaching in experimental fields located inside nitrate vulnerable zones of the Emilia-Romagna region (Northern Italy). Results obtained from one of these sites, monitored over a 6-year period demonstrate how nitrogen inputs from slurry cause nitrate accumulation in the surface layer of the soil especially in warm periods (concentrations of up to 300 mg NO_3–N l^{-1} were found in soil water); therefore, soil draining conditions were the dominant variable in controlling leaching even if the soil texture was fine, the shrinking–swelling properties of clay minerals determined fast drainage conditions (related to macroporosity).

Torkzaban et. al.[11] indicating that colloid retention was highly dependent on the suspension ionic strength, water content, and sand grain size. A mathematical model, accounting for time- and depth-dependent straining, produced a reasonably good fit for both the breakthrough curves and final deposition profiles.

Zhuang et. al.[12] demonstrated that decreasing solution surface tension and ionic strength decreased colloid deposition at the solid-liquid interface and increased colloid recovery in the column effluent. The effect of solution surface tension on colloid transport and deposition was greater at lower ionic strength. However, lowering the solution surface tension and ionic strength resulted in a more even distribution of colloids along the column.

The objective of this work is to studying the effect of initial dry unit weight and type of soil on water and nitrate transport through soils under various hydraulic boundary conditions.

Experimental Work

Materials and methods

Materials properties

Two types of soils were used for one dimensional model named S1and S2 which classified as SM and CL-ML respectively according to unified soil classification system (USCS). Sl is artificial soil consist of mixing 70% of sandy soil passing sieve No.10 and 30% of S2 that is a natural soil obtained from Al-Rashedia site in Mosul city. The index properties of two soils are shown in Table 1. The grain size distribution and the standard compaction curves of two soils are shown in Figures (1), (2) respectively. Figure (3) shows the soil water characteristic curves (SWCC) of two soils each at maximum dry unit weight and optimum moisture content, there are three method for obtaining SWCC these are 1-Tensometric plate method (0- 100) kpa, 2- Osmotic membrane method (100-1500) kpa, 3- Saline solution method (2000- 400000) kpa

Experimental apparatus

The one dimensional model is shown in Figure (4). The model consist of a cylindrical plastic tube (4 mm in thickness) with internal diameter of (40) mm and height of (150) mm. The depth of soil column is 100 mm. Two types of head boundary was applied at the surface of soil, these are constant head of 1cm and specified volume of 12.6 cm^3 which represent initial height of contaminated water 1 cm whereas the bottom head boundary was free drainage by using a porous stone below soil column. Three initial dry unit weights for each soil are used to investigate the effect of initial dry unit weight on water and contaminant migration through soil profile for the two types of head boundary. The initial water content was the same for the three type of initial dry unit weight for each soil to neglect the effect of initial water content on water and contaminant transport.

The soil was compacted inside the tube by means of static compaction with a strain rate of 1 mm/min. The samples was taken from the soil by cutting soil sample and take a depth of 1 cm at specified points to measure water content and nitrate concentration. The samples was taken from appoint of 0.5, 2.5, 5.5 and 8.5 cm from top of model for each model. Index properties of used soils are shown in Table (2).

For concentration measurement of nitrate, the samples first mixing with a solution of KCl with a concentration of 74.55 gm/l by using magnetic agitator for a period of 1 hr and then putting in a centrifuge device for a period of 10 min (4500 rpm) to separate the solution. The tests were conducted using Ion chromatographic analysis

Numerical modelling

Finite element package of SEEPW and CTRAN of GEOSLOPE software program was used to perform numerical modelling of water and solute transfer through one dimensional modelling for steady state and transient conditions. The same dimensions of experimental one dimensional model were desicretized by using 20 elements with initial conditions depended on initial water content of each soil (Table 2).

The water flow was established in SEEP/W for saturated and unsaturated conditions. Grain size distribution, volumetric water content and hydraulic conductivity functions were required for each dry unit weight used. Hydraulic conductivity for unsaturated soils was predicted by using van Genuchten method depending on SWCC and saturated coefficient of permeability.. Boundary conditions in SEEP/W was entered as pressure head values for steady state conditions and head function for transient condition at top of soil with free drainage boundary at the bottom of soil body and zero flux boundary at the sides of soil column.

The same one-dimensional mesh was used in SEEP/W are used in CTRAN/W. as data file to analyze contaminant movement depending on results obtained in SEEP/W for water flow. The boundary condition using in CTRAN / W, was concentration (C) at top of soil. The used method for transport of contaminant was advection-dispersion, the dispersivity distance was selected to be 2 mm in the long direction and 1 mm in the perpendicular direction. Effects of adsorption and decay were neglected and the coefficient of diffusion was set to zero for the steady state and transient cases.

Results and Discussion

The results involve studying the effect of initial dry unit weight and soil type on water and contaminant movement through saturated-unsaturated soils experimentally, then comparison the experimental with numerical results were made to ensure that the proposed model is useful to analysis any contaminated area or landfills.

Water flow

For constant head of 1 cm boundary condition, the variation of water content through soil profile at different time intervals are shown in Figures (5), (6), (7) for soil 1 and Figure (8) for soil 2. The Figures shows that the water content for soil 1 with initial dry unit weight 14.5 kN/m^3 approximately reaches the saturated water content at time of 10 min. whereas for dry unit weight 18 kN/m^3 the required time was approximately 3 hr and for dry unit weight 19.82 kN/m^3 the required time is greater than 3 hr. This difference was due to the difference in initial dry unit weight which causes a greater difference in saturated and unsaturated coefficient of permeability (Table 2). This phenomena was also observed for soil 2 with a greater time required for reaching steady state condition due to ability of clayey soils to keeping water in its structure caused by clay mineral compared with sandy soils.

The effect of initial dry unit weight on variation of water content through soil profile was clearly showed in Figures (9 and 10) for soil 1 and 2 respectively.

The comparison between experimental and numerical results considering variation of water content with depth through soil profile are shown in Figures (11), (12) for soil 1 and 2 respectively which shows a good agreement between experimental and numerical methods.

The comparison between two types of used soil was made to investigate the effect of soil type on variation of water content under same boundary conditions. In order to getting clear comparison between soils, the comparison was based on coefficient of permeability which represents the dominant parameter in water flow through soils. Figure (13) shows the variation of water content through soil profile throughout a comparison between soils 1 and 2. The comparison was mad between soil 1 and soil 2 that having closed coefficient of permeability. The figure shows that the values of water content for soil 2 was greater than that for soil 1 for the two comparisons, this variation was attributed to difference of soil structure between clayey soil and sandy soils. This means that the coefficient of permeability is not only control flow of water. The initial suction, saturated water content play a significant rule in variation of water content, these parameters are highly depended on unit weight of soil.

The second case of head boundary used was specified volume of water (12.6 ml) that acts some situation of dissipation of contaminated water from accident or petrol stations in field. The variation of water content through soil profile at different time intervals are shown in Figures (14), (15), (16) for soil 1 and Figure (17) for soil 2. Results shows that the water content reduce from saturated water content at surface and increase at other depth with time for low dry unit weights (14.5 kN/m^3 and 14.16 kN/m^3) due to dissipation of water through soil for this densities whereas at high densities, the variation was equal for constant head through this low times because of low change of head at this time intervals as shown in Figures 18 and 19 for soil 1 and 2 respectively, this means that increasing dry unit weight of soil to maximum dry unit weight reduces dissipation of water under constant head with a high percent at low interval of times which becomes years in field problems. The effect of initial dry unit weight on variation of water content through soil profile is shown in Figures (20 and 21). Water content was increased with dry unit weight in higher depths (8.5 cm) especially at first time; this variation was opposite to variation in constant head condition and to other surface and intermediate depths in specified volume condition. This change was attributed to the high energy of compaction used for high densities causes increasing water content at lower depths compared with surface depths, then water will dissipate with time for low densities faster than that for higher densities to give values of water content equal or greater than values in higher densities.

Nitrate (NO_3) transport

For constant head boundary condition, the variation of nitrate concentration through soil profile for soil 1 and soil 2 are shown in Figures (22 and 23) respectively. The contaminated water with nitrate concentration 2.4 mg/l was used to give an initial concentration at the surface of soil 619 mg/l and 348 mg/l for soil 1 and 2 respectively. Results shows that the nitrate concentration for low dry unit weight (14.5 kN/m^3) was approximately approaches steady state condition which acted by initial concentration along soil profile at time of 3 hours whereas very long time compared with this time was required to reaches this condition for high dry unit weights, this means the soil unit weight and hydraulic conductivity has a greater effect on contaminant transport through soil. Mechanical dispersion arises from velocity variations in the porous media due to friction between the soil particles and the fluid and also due to the curvatures in the flow path, these velocity variations and curvatures in the flow path are highly affected by porosity and void ratio which depended on unit weight of soil. It has been also found that the time of reaching steady state condition for nitrate concentration was greater than that for water flow in spite of that contaminant transport with flowing water under condition of constant head. This difference attributed to the fact that the contaminant transport through soil is complex phenomena and it affected by physical or engineering properties (type of soil, unit weight, hydraulic conductivity) and chemical properties (Interaction between soil and contaminant), this factors causes dilating contaminant transport through soil.

The used method for numerical transport of nitrate was advection-dispersion process which represents the dominant process over other processes for the studied situation. Advection is the movement of the contaminant with the flowing water while dispersion is the apparent mixing and spreading of the contaminant within the flow system, the dispersion process consist of two components, one is the apparent mixing and the other is molecular diffusion. The mixing component called mechanical dispersion whereas molecular diffusion results in the spreading of contaminant due to concentration gradient. The diffusion process was neglected through this research.

The comparison of experimental results with numerical results for constant head condition is shown in Figures 24 and 25 for soil 1 and 2 respectively. Results show a good agreement between experimental and numerical, the difference was appeared in some points because the experimental samples were taken throughout a 1 cm to represent the average value for specified depth.

Conclusions

1- For a same type of soil, as well as head boundary conditions, the initial dry unit weight which causes a greater difference in hydraulic conductivity has a dominant effect on the water content variation through soil profile

2- Nitrate concentration more sensitive than water flow to change in initial dry unit weight, mechanical dispersion are highly affected by porosity and void ratio which depended on unit weight of soil

3- Considering type of soils, water flow was not only controlled by the coefficient of permeability. The initial suction, saturated water content play a significant rule in variation of water content, these parameters are highly depended on unit weight of soil.

4- Nitrate concentration was highly affected by soil type. As well as factors explained in (2), chemical interaction has a clear effect in clayey soils compared with sandy soils.

5-Good agreement between experimental and numerical results were observed for water flow and nitrate concentration , the advection-dispersion model can be used successfully to analysis contaminant transport under industrial products and landfills for near and intermediate time intervals.

References

1- Fredlund, D. G, Xing, H., Huang, S., (1994), "Predicting the Permeability Functions for Unsaturated Soils Using the Soil-Water Characteristic Curve", Canadian Geotechnical Journal, Vol. 31,No. 4, PP. 533-546.

2- Garg, K.K., Jha, M.k., Kar, S., (2005), "Field Investigation of Water Movement and Nitrate Transport under Perched Water Table Conditions", Journal of Biosystems Engineering 92 (1), PP. 69-84, Elsevier Ltd

3- Wierenga, P.J., van Genuchten, M.T., (1989), "Solute Transport Through Small and Unsaturated Soil Column", Journal of Ground Water, Vol. 27, No. 1,P. 35-42.

4- Dana, E., Shahrour, I., (2002), "Hierachary of Physical Phenomena Governing the Contamination of Subsurface Water Sources by Hydrocarbons", The 3rd International Conference on Unsaturated Soils.

Recife, Brazil Edit J.F.T. Juca, et al., PP. 59-64, Balkema Publishers.

5- Milfont, M.L.B., Antonio, A.C.A, Netto, A.M, Carneiro, C.J.G, de Oliveira, C.A.B, (2002), "Modelling NAPL Transport in Unsaturated Soils", The 3rd International Conference on Unsaturated Soils. Recife, Brazil Edit J.F.T. Juca, et al., PP. 65-69, Balkema Publishers.

6- Bucur, C., Ollteanu, M., Pavelescu, M., (2006), "Radionucliide Diffusion in Geological Media", Rom. Journ. Phys., Volume, No. 3-4: pp. 469-478, Bucharest.

7- Lenhart, J.J., Saiers, J.E., (2002), "Transport of Silica Colloids through Unsaturated Porous Media: Experimental Results and Model Comparisons", Journal of Environ. Sci. Technol. 36, PP. 769-777.

8- Nutzmann, G., Maciegewski, S., Joswig, K., (2002), "Estimation of Water Saturation Dependence of Dispersion in Unsaturated Porous Media: Experiments and Modeling Analysis", Journal of Advances in Water Resources 25, PP. 565-576.

9- Viotti, P., Papini, M.P., Stracqualursi, N., Gamba, C., (2005), "Contaminant Transport in an Unsaturated soil: Laboratory Tests and Numerical Simulation Model as Procedure for Parameters Evaluation", Journal of Ecological Modelling 182, PP. 131-148.

10- Mantovi, P., Funmagalli, L., Beretta, G.P., Guermandi, M., (2006), "Nitrate Leaching Through the Unsaturated Zone Following Pig Slurry Applications", Journal of Hydrology 316, PP. 195-212.

11- Torkzaban, S., Bradfored, S.A., van Genuchten, M.T., Walker, S.L., (2008), "Colloid Transport in Unsaturated Porous Media: The Role of Water Content and Ionic Strength on Particle Straining", Journal of Contaminant Hydrology 96, PP. 113-127.

12- Zhuang, J., Goeppert, N., Tu, C., Mccarthy, J., Perfect, E., Mckay, L., (2010), "Colloid Transport with Wetting Fronts: Interactive Effects of Solution Surface Tension and Ionic Strength", Journal of Water Research 44, PP. 1270-1278.

13- ASTM Designation.

14- GEO-SLOP User's Guid, (2002), "Geo-Slope Office for Finite Element Analysis", Ver. 5.

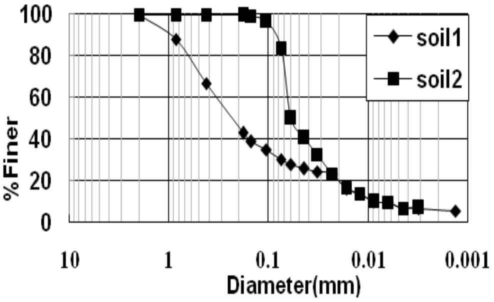


Figure (1): Grain size distribution of used soils

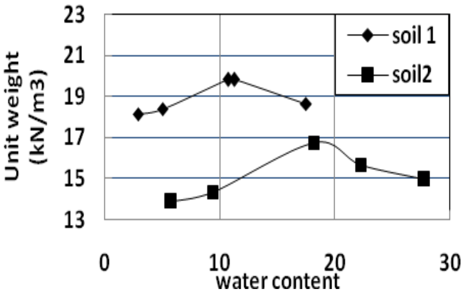


Figure (2): standard compaction curves of used soils

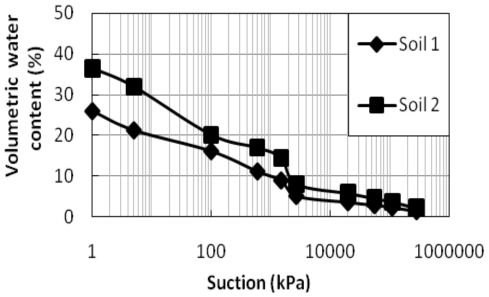


Figure (3): SWCC of used soils

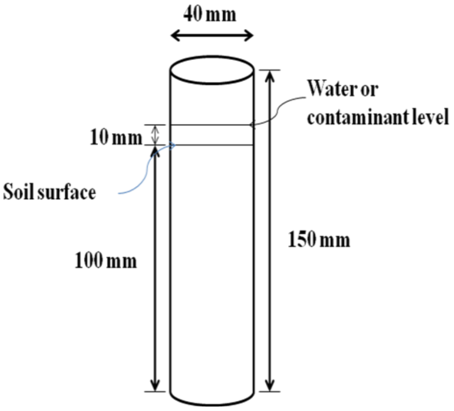
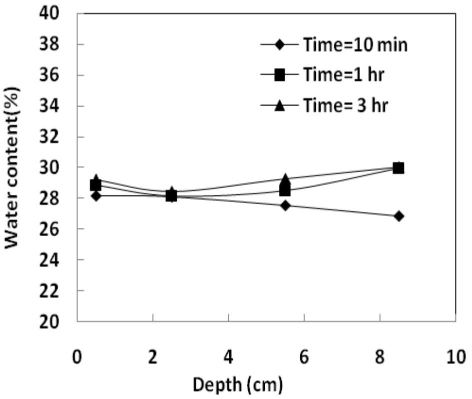


Figure (4): one dimensional model



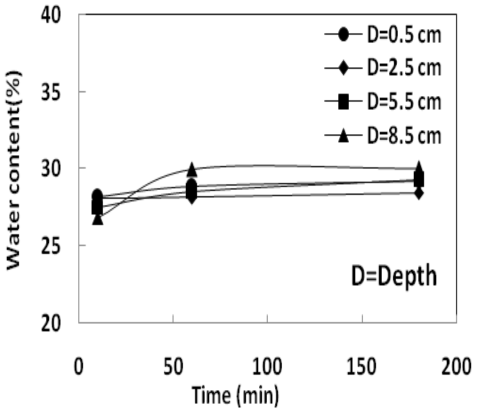


Figure (5): Variation of water content with depth for soil 1
(Dry unit weight = 14.5 kN/m^3)

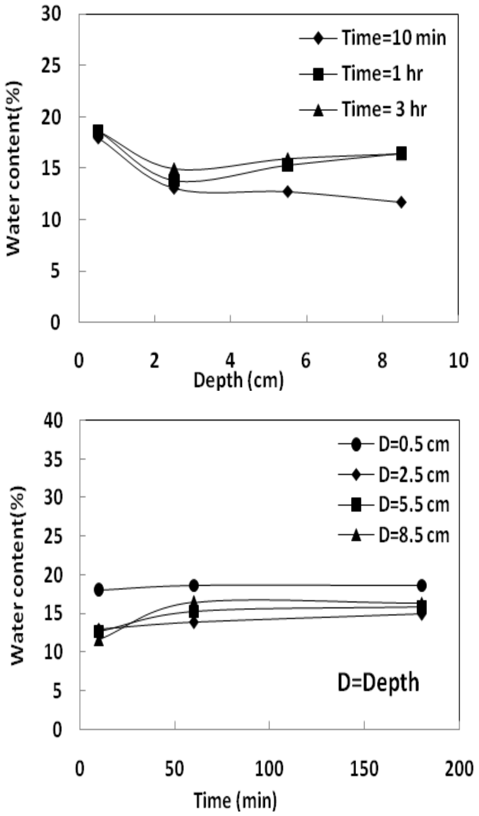


Figure (6): Variation of water content through soil profile for soil 1 (Dry unit weight = 18 kN/m^3)

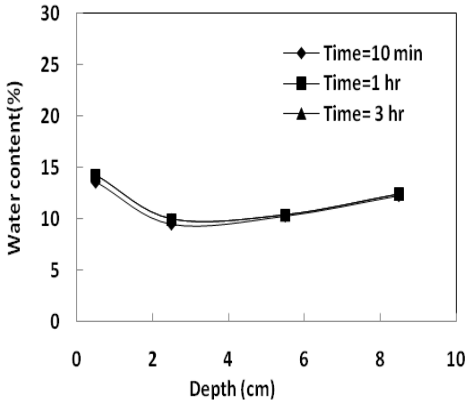
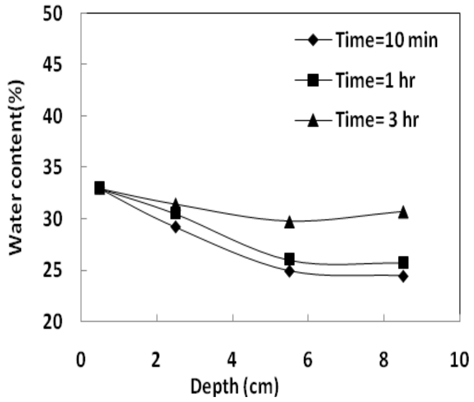
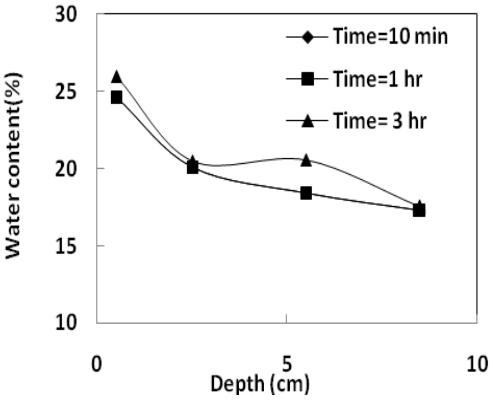


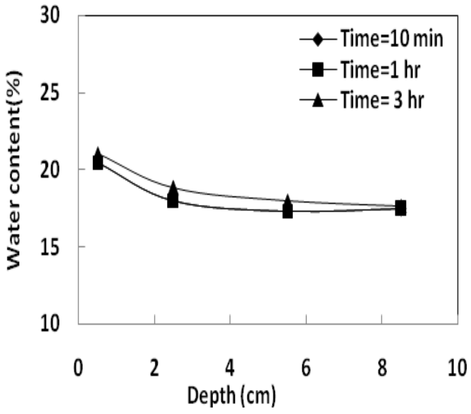
Figure (7): Variation of water content with depth for soil 1 (Dry unit weight = 19.82 kN/m^3)



Dry unit weight = 14.16 kN/m^3



Dry unit weight = 15.96 kN/m^3



Dry unit weight = 16.8 kN/m^3

Figure (8): Variation of water content with depth for soil 2

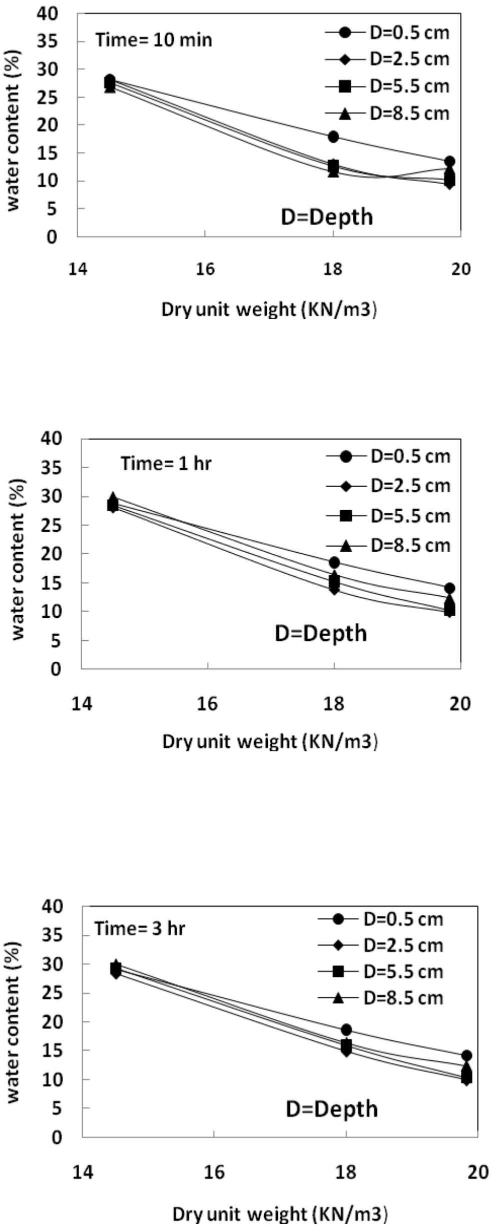


Figure (9): Variation of water content with dry unit weight through soil profile for soil 1

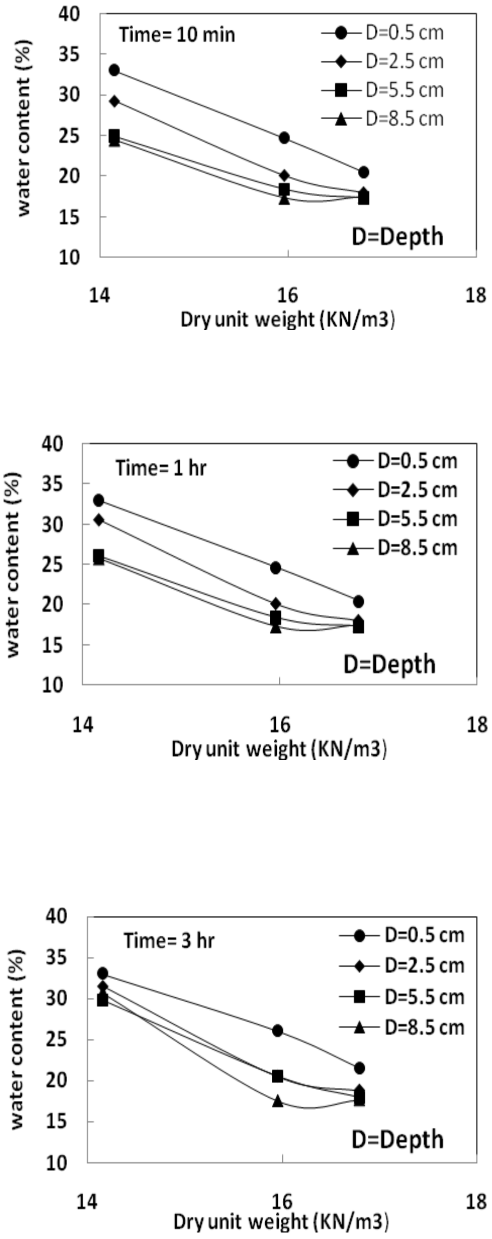
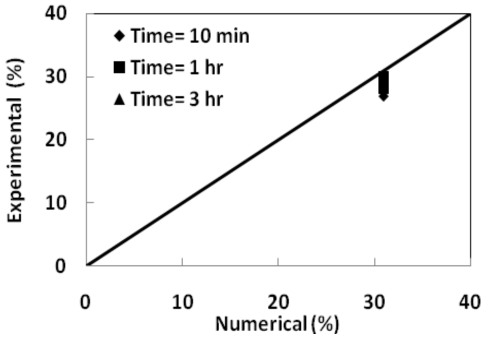
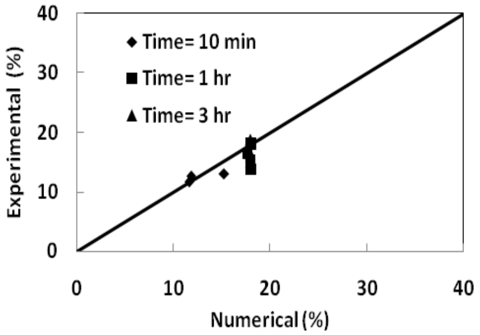


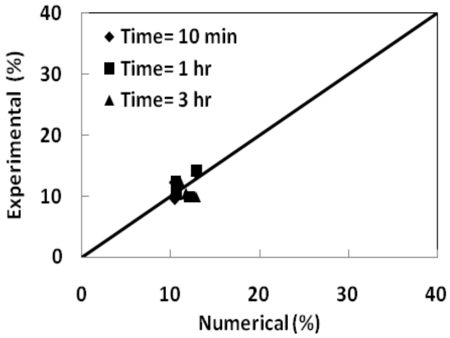
Figure (10): Variation of water content with dry unit weight through soil profile for soil 2



Dry unit weight = 14.5 kN/m^3

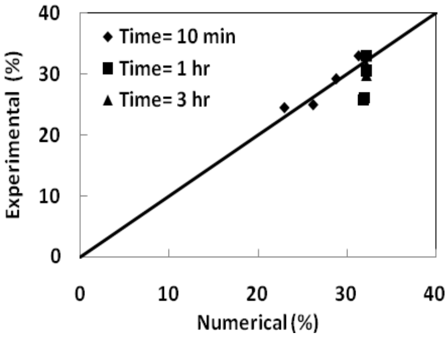


Dry unit weight = 18 kN/m^3

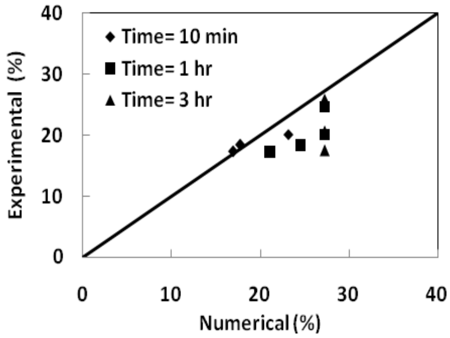


Dry unit weight = 19.82 kN/m^3

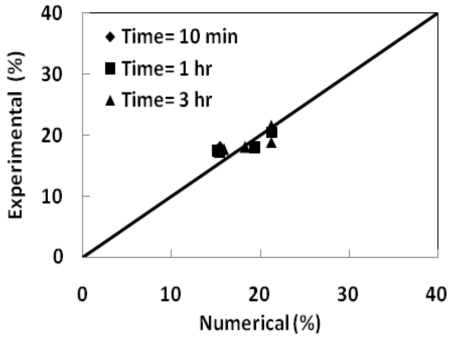
Figure (11): Comparison between experimental with numerical results considering variation of water content with depth for soil 1



Dry unit weight = 14.16 kN/m^3

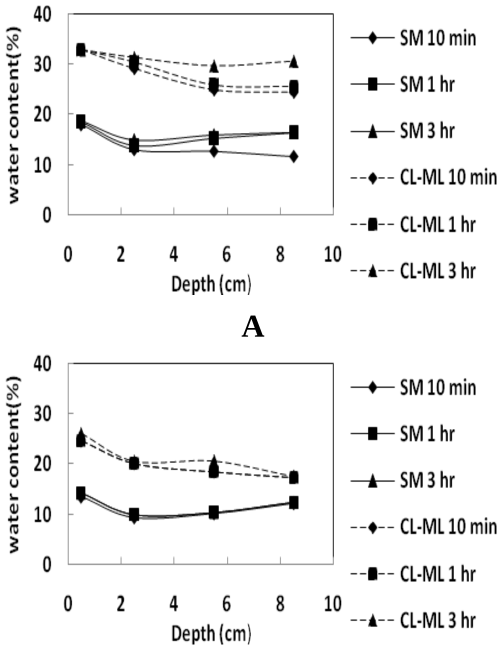


Dry unit weight = 15.96 kN/m^3



Dry unit weight = 16.8 kN/m^3

Figure (12): Comparison between experimental with numerical results considering variation of water content with depth for soil 2



A

B

Figure (13): Variation of water content with depth throughout a comparison between soil 1 and 2 A: S1(γ_d=18 kN/m^3) versus S2 (γ_d=14.16 kN/m^3), B: S1(γ_d=19.82 kN/m^3) versus S2 (γ_d=15.96 kN/m^3)

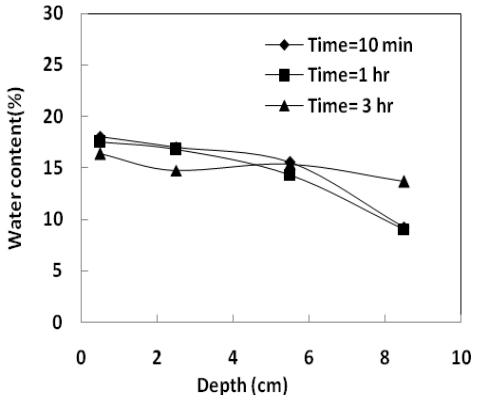


Figure (14): Variation of water content with depth for soil 1 (Dry unit weight = 14.5 kN/m^3)

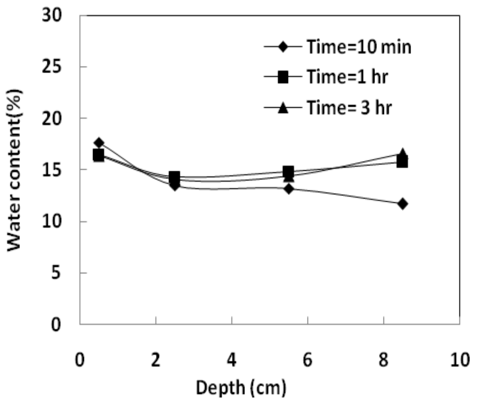


Figure (15): Variation of water content with depth for soil 1 (Dry unit weight = 18 kN/m^3)

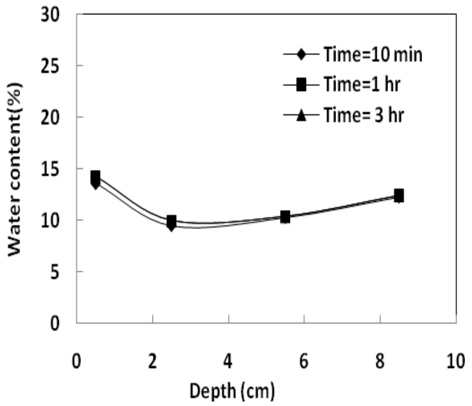
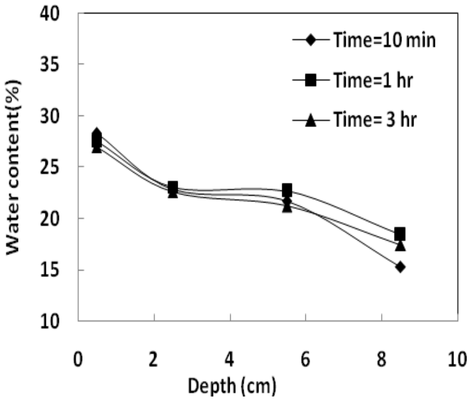
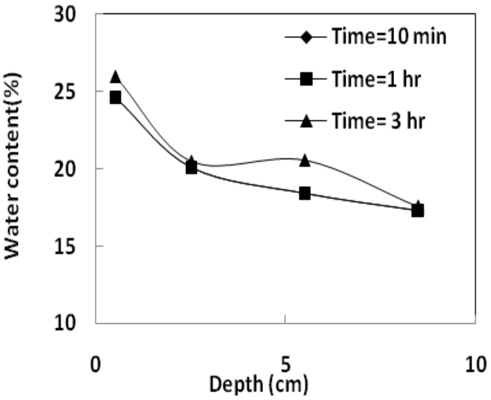


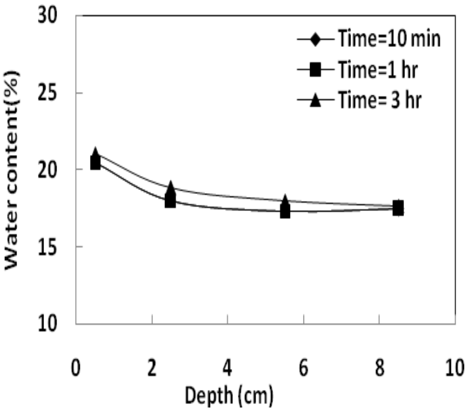
Figure (16): Variation of water content with depth for soil 1 (Dry unit weight = 19.82 kN/m^3)



Dry unit weight = 14.16 kN/m^3



Dry unit weight = 15.96 kN/m^3



Dry unit weight = 16.8 kN/m^3

Figure (17): Variation of water content with depth for soil 2

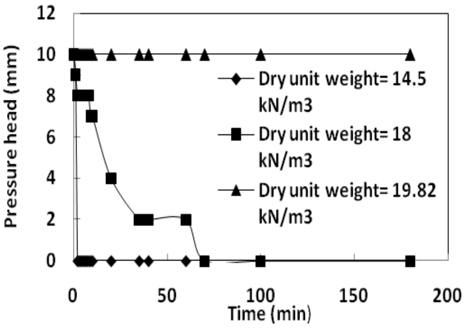


Figure (18) Variation of pressure head with time for specified volume boundary condition for soil 1

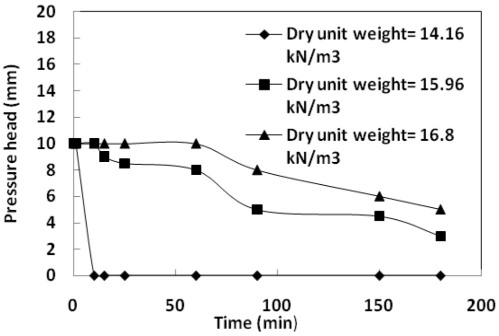


Figure (19) Variation of pressure head with time for specified volume boundary condition for soil 2

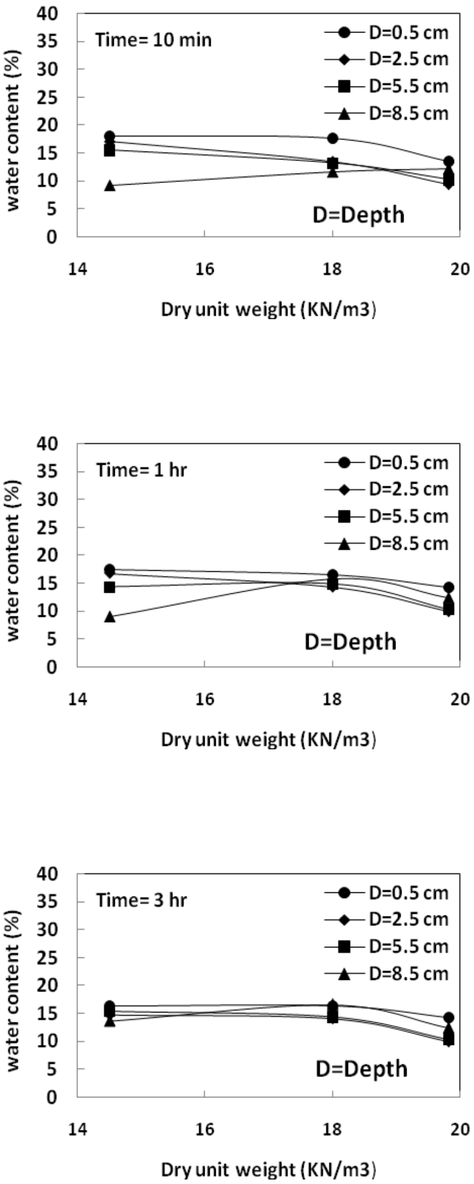


Figure (20): Variation of water content with dry unit weight for soil 1

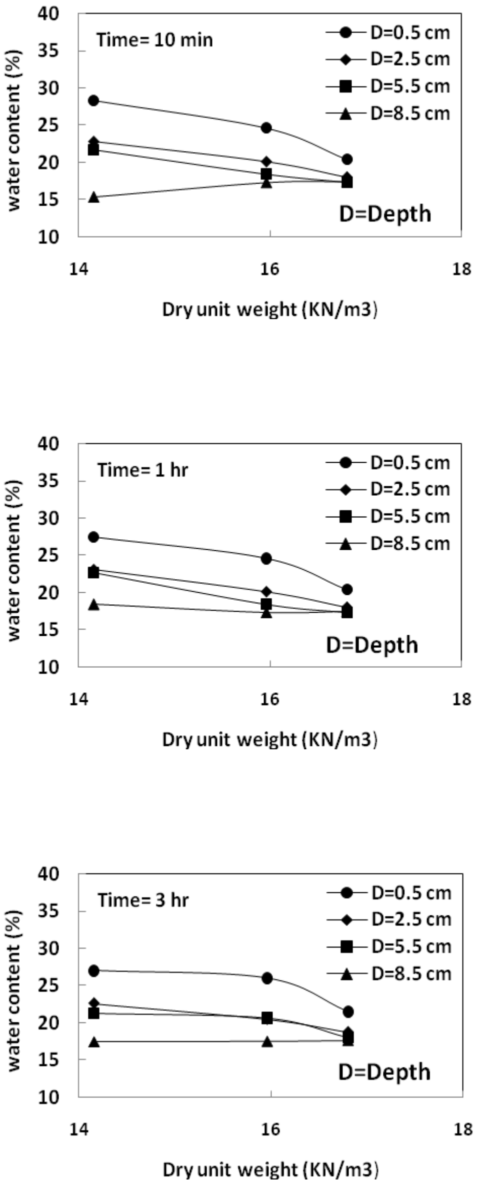
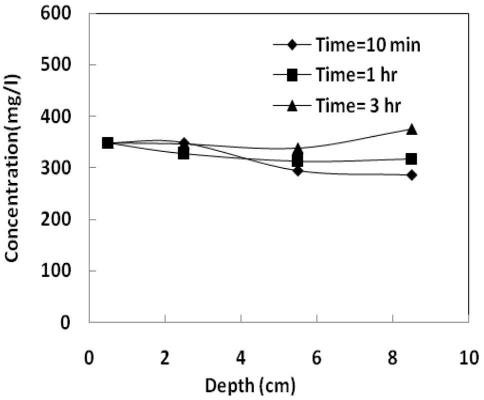
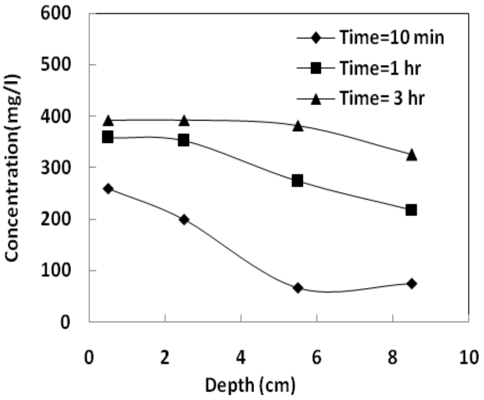


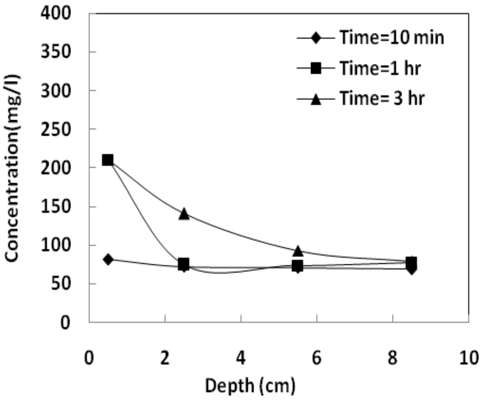
Figure (21): Variation of water content with dry unit weight for soil 2



Dry unit weight = 14.5 kN/m^3

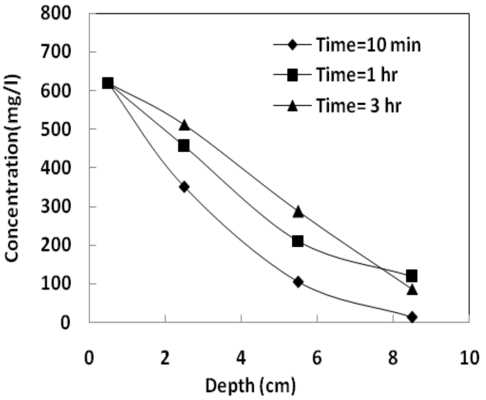


Dry unit weight = 18 kN/m^3

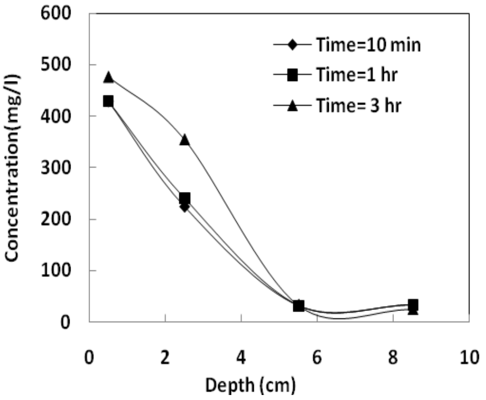


Dry unit weight = 19.82 kN/m^3

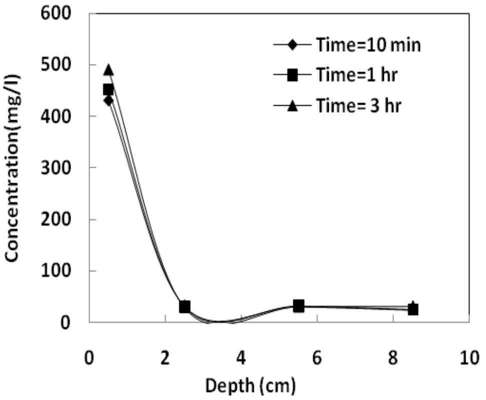
Figure (22): Variation of nitrate concentration with depth for soil 1



Dry unit weight = 14.16kN/m^3

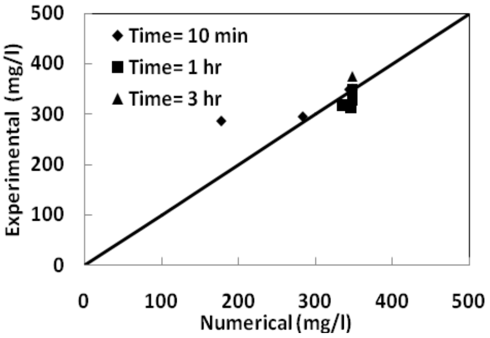


Dry unit weight = 15.96 kN/m^3

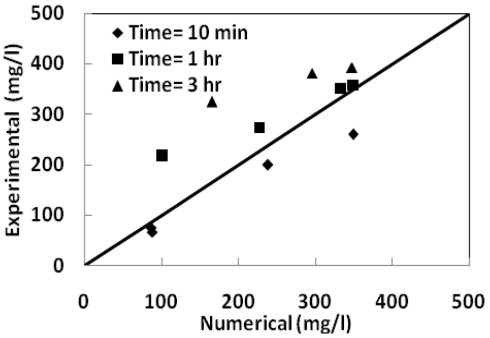


Dry unit weight = 16.8 kN/m^3

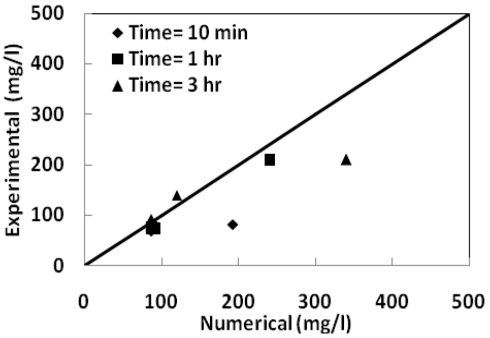
Figure (23): Variation of nitrate concentration with depth for soil 2



Dry unit weight = 14.5 kN/m^3

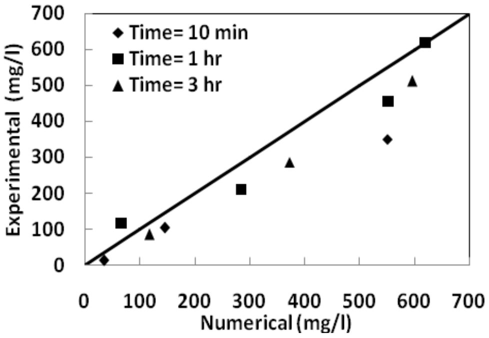


Dry unit weight = 18 kN/m^3

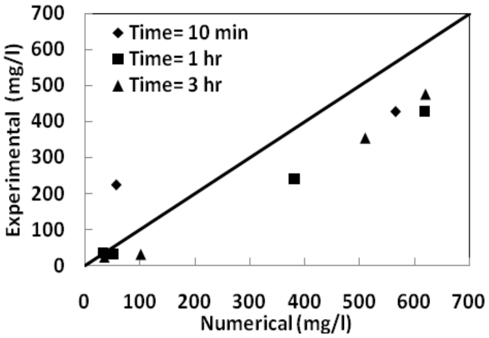


Dry unit weight = 19.82 kN/m^3

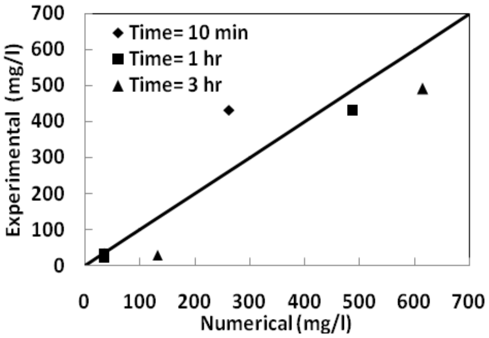
Figure (24): Comparison between experimental with numerical results considering variation of nitrate concentration with depth for soil 1



Dry unit weight = 14.16kN/m^3



Dry unit weight = 15.96 kN/m^3



Dry unit weight = 16.8 kN/m^3

Figure (25): Comparison between experimental with numerical results considering variation of nitrate concentration with depth for soil 1

Table (1): Index properties of used soils

Soil property	**S1**	**S2**
Liquid limite (L.L)	21	30
Plastic limite (PL)	20	23
Plasticity index (PI)	1	7
Soil classification (USCS)	SM	CL-ML
Specific gravity (G_s)	2.723	2.697
Standard Max. Dry unit weight ($\gamma_{drymax.}$) kN/m^3	19.82	16.8
Optimum Moisture Content (ω)	11	19

Table (2): Index properties of soils for numerical modelling

Soil type	**Dry unit weight (kN/m^3)**	**Saturated coefficient of permeability (cm/min)**	**Initial water content (%)**	**Saturated gravimetric water content(%)**	**Saturated volumetric water content**	**Initial pressure head (mm)**
S1 SM	14.5	0.122	10	31	0.457	-500
	18	0.0044	10	18	0.33	-1500
	19.82	$2.67\text{x}10^{-4}$	10	13	0.26	-2500
S2 CL-ML	14.16	0.0033	16.3	32	0.465	-10000
	15.96	$1.905\text{x}10^{-4}$	16.3	24	0.393	-9000
	16.8	$7.7\text{x}10^{-5}$	16.3	21.3	0.365	-9000