Modelling of Hydro-Mechanical Coupling in Land Uplift Due to Groundwater Recharge

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Abstract. Artificial groundwater recharge is used to increase groundwater in areas with water scarcity. After groundwater recharge, the water table rises, causing ground surface uplift from the increased pore water pressure in an aquifer. To manage groundwater resources effectively, understanding the hydro-mechanical features of aquifers during groundwater withdrawal and recharge is necessary. In practice, an artificial pool can be used to collect surface runoff so that it infiltrates the aquifer and recharges groundwater. Additional studies are required to understand the effect of various parameters on groundwater recharge and ground surface uplift. This study used the finite difference software FLAC 8.0 to examine the influence of the initial degree of saturation and soil type on the rate of groundwater recharge and ground surface uplift in an aquifer. Each aquifer was in an unsaturated state before groundwater recharging; therefore, groundwater recharge analyses were simulated by the two-phase flow in an unsaturated porous media. The results showed that the ground surface uplift was the largest when the initial degree of saturation was 70%, sequentially followed by a saturation of 60 and 50%. The influence of the initial degree of saturation was negligible on the cumulative groundwater recharge volume during the study period. Regarding the influence of soil types on ground surface uplift and the cumulative groundwater recharge volume, the results indicated that the sandy aquifer had the largest cumulative groundwater recharge volume during the study period. However, the ground surface uplift in the sandy aquifer was minimal.

1   Introduction

In recent years, water requirement has increased because of industrial development and population growth. Excessive groundwater withdrawal from aquifers causes groundwater depletion, seawater intrusion, groundwater salinization, and ground settlement. Groundwater recharge is performed to increase groundwater resources. After groundwater recharge, the water table rises resulting in ground surface uplift caused by increased pore water pressure within an aquifer. Although several studies have examined land settlement caused by groundwater withdrawal, only a few have investigated ground surface uplift caused by groundwater recharge, potentially because small-scale ground surface uplift does not cause environmental hazards or damage infrastructure. To manage groundwater resources efficiently, the hydro-mechanical

features of aquifers during groundwater withdrawal and recharge must be identified. In practice, an artificial pool can be used to collect surface runoff so that it infiltrates an aquifer and recharges groundwater. The artificial pool may be used as a stormwater detention pool to reduce flood disasters and recharge groundwater.

Various studies have recently examined ground surface uplift caused by groundwater recharge. Giao et al. (1999) used a finite element method code to calculate the compression and rebound of a multi-aquifer in artificial recharge. Bawden et al. (2001) used global positioning system data with interferometric synthetic aperture radar (InSAR) imagery to examine groundwater withdrawal and recharge and found that it caused long-term subsidence of 12 mm/year. Bell et al. (2008) used the Permanent Scatterer InSAR (PSInSAR) methodology along with data on water level changes to investigate the temporal and spatial patterns of an aquifer in response to groundwater pumping and recharge in the Las Vegas Valley. Teatini et al. (2011) and Gambolati and Teatini (2015) systematically listed the studies related to ground deformation caused by the withdrawal and injection of fluid into geological formations.

Most studies on groundwater recharge have examined the influence of geological conditions and the dimensions of recharge pools on the volume of water that can penetrate an aquifer. Few hydro-mechanical coupling studies have examined ground surface uplift caused by groundwater recharge. The deformation caused by the groundwater recharge of unsaturated soil is more complex because the deformation of an aquifer is associated with effective stress distribution, pore water pressure, and saturation degree of the aquifer. The transient distribution of the degree of saturation during groundwater recharge should be calculated using a seepage analysis of unsaturated soil. The location of the groundwater recharge pool can also be selected after identifying the effect of influencing parameters on ground surface uplift. Therefore, additional studies are required to understand how various parameters affect groundwater recharge.

This study aimed to investigate ground surface uplift caused by groundwater recharge during one rainy season (90 days). Ground surface uplift depends on the material properties of an aquifer and the hydrogeological conditions. Therefore, numerical simulations were used to study the initial degree of saturation and soil type of the aquifer and understand how these influenced ground surface uplift and the cumulative groundwater recharge volume.

2 Two-Phase Flow Model

A two-phase flow model in finite difference software FLAC 8.0 (Itasca Consulting Group 2016) allows numerical modeling of the flow of water and gas through porous media. In the two-phase flow model, void space in porous media is filled with water and gas, which makes the model suitable for simulating and solving the problem of hydro-mechanical coupling in unsaturated soils. The pressure difference between gas and water is called capillary pressure, which is a function of the degree of saturation and can be represented by the van Genuchten model. For conciseness, only the water-related details (but not those related to gas) of the two-phase flow model are presented here. In unsaturated soil, the water transport is described using Darcy's law:

$$q_i = -k_{ij}k_r \frac{\partial}{\partial x_j}(P - \rho g_k x_k), \tag{1}$$

where the tensor k_{ij} is the saturated mobility coefficient, k_r is the relative permeability of water, P is pore pressure, ρ is density of water, and g is gravity acceleration. Relative permeability, k_r, is a function of the degree of saturation by the van Genuchten form (Itasca Consulting Group 2016):

$$k_r = S_e^b \left[1 - \left(1 - S_e^{1/a}\right)^a\right]^2, \tag{2}$$

where a and b are constant parameters and S_e is the effective saturation. In the van Genuchten model, parameter c was required to calculate the relative permeability of gas. The effective saturation is defined as

$$S_e = \frac{S - S_r}{1 - S_r}, \tag{3}$$

where S is the degree of saturation and S_r is the residual degree of saturation.

The capillary pressure P_c can be represented by the van Genuchten form:

$$P_c = P_g - P_w = P_o \left[S_e^{-1/a} - 1\right]^{1-a}, \tag{4}$$

where P_g is the pore pressure of gas, P_w is the pore pressure of water, and parameter P_o depends on the material properties. The constitutive law for water is:

$$n\left[\frac{S}{K_w}\frac{\partial P_w}{\partial t} + \frac{\partial S}{\partial t}\right] = -\left[\frac{\partial q_i}{\partial x_i}\right], \tag{5}$$

where n is porosity, K_w is the water bulk modulus.

In groundwater recharge, the degree of saturation of the unsaturated soil increases because of water infiltration into the soil. The capillary pressure and effective stress of the unsaturated soil decrease in groundwater recharge. The decreased effective stress causes ground surface uplift.

3   Parameter Estimate and Model Verification

In numerical analysis of this study, the two-phase flow model was adapted to perform the coupled fluid-mechanical calculation. Recharge model tests were performed to obtain the values for the two-phase flow model parameters required for numerical analysis and verify the rationality of the analysis. The parameter values of the two-phase flow model for three soils (sand, silt loam, and loam) were selected from the sandbox recharge model test developed by Liu (2001) and cylindrical specimen model tests performed in this study.

3.1   Sandbox Recharge Model Tests

A 10-cm-wide, 180-cm-long, 70-cm-high sandbox was used to conduct the tests by Liu (2001). The sandbox was filled with Ottawa standard sand [average particle size (D_{50}) = 0.35 mm and uniformity coefficient (c_u) = 1.8] layer-by-layer. A trapezoidal pit was then dug into the sand, with upper and lower base lengths of 30 and 10 cm, respectively, and height of 10 cm. The surface of the pit was covered with a layer of impermeable membrane. Water was added to the top of the membrane to fill the pit. Consistent with Pascal's principle, the water was connected to an external water source, so that the water level of the pit remained fixed in the experiments. At the beginning of the test, the impermeable membrane was gradually pulled away, and the wetting front of the sand was recorded by a digital camera. In the numerical simulations, the two-phase flow parameters of the sand were based on the soil-water characteristic curve obtained from Liu's experimental results (Liu 2001). A total of 2200 elements, each approximately 2 cm long, were discretized in a FLAC grid, as shown in Fig. 1. The mechanical boundary conditions corresponded to roller boundaries at the base and sides of the model. The boundaries on the bottom and right side of the model were assumed to be impermeable boundaries. The boundaries on the left side of the model and the surface of pit were assumed to be seepage boundaries. The non-wetting pore pressure was fixed above the water level. The wetting front (experimental results) and flow vector (numerical results) at 60, 600, and 900 s are shown in Fig. 2. The flow vectors (blue arrows in Fig. 2) were close to the wetting front. Therefore, the parameter values of the two-phase flow for the sand as well as the numerical analysis procedure were reasonable. Tables 1 and 2 list the parameter values of the two-phase flow model of the sand.
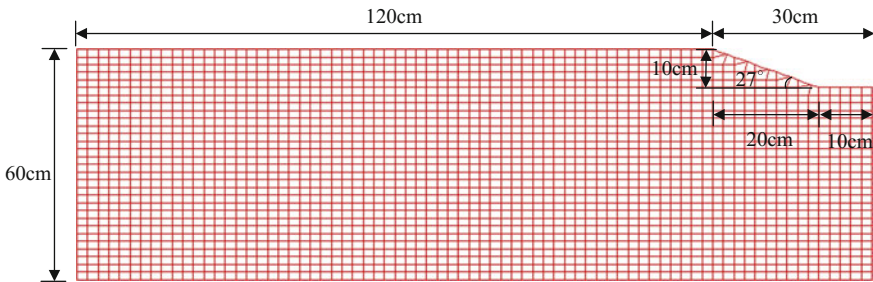

Fig. 1. The FLAC mesh of the sandbox recharge model test

3.2   Cylindrical Specimen Recharge Model Test

For the selection of parameter values of two-phase flow model for loam and silt loam, this study performed the cylindrical specimen recharge model tests and inverse analysis to estimate the optimal parameter values of the two-phase flow model for loam and silt loam soil. The loam (20% sand, 40% clay, and 40% silt) and silt loam (20% sand, 10% clay, and 70% silt) were separately placed into in an acrylic cylindrical mold (approximately 7 cm in diameter and 17 cm in height). The height of the specimens was 16 cm. An external water source was connected to the bottom of the mold so that
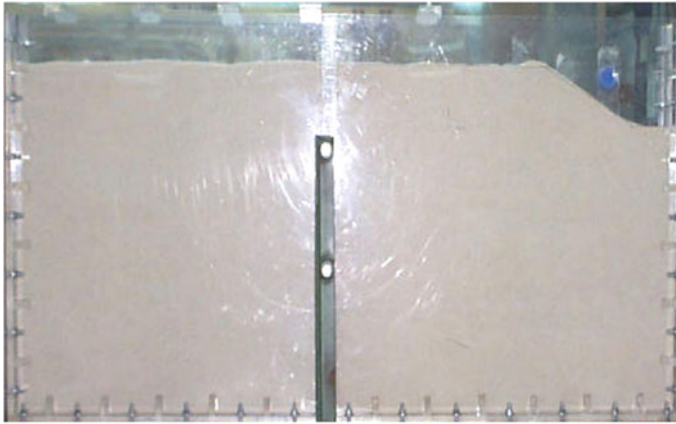
(a) at 0 s
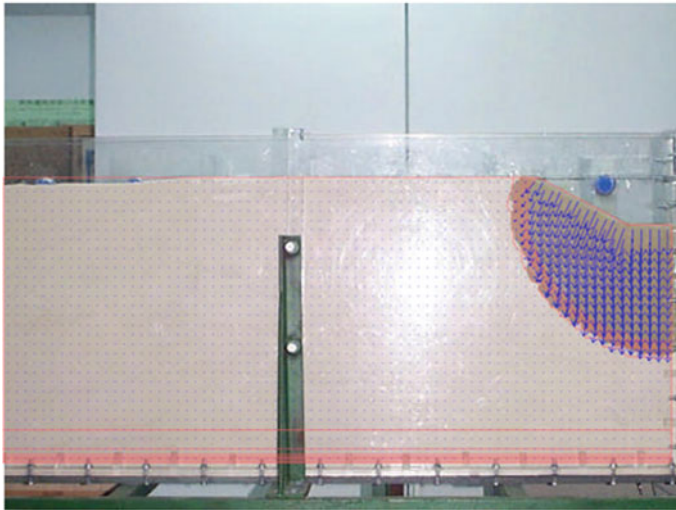
(b) at 60 s

Fig. 2. Comparison of numerical and experimental results in the sandbox recharge model test

the water level of the specimen could be maintained at a 12-cm height. The valve was opened at the beginning of the tests for the water penetrate the specimens from the bottom of the mold. A LVDT was placed on top of the mold to measure the uplift of the specimen. The numerical simulation was performed through axisymmetric analysis; a total of 5600 elements, each 0.1 cm long, were discretized in a FLAC grid, as shown in Fig. 3. The mechanical boundary conditions corresponded to roller boundaries at the base and sides of the model. The boundaries on the sides of the mesh were assumed to be impermeable boundaries. The non-wetting pore pressure was fixed on the top of the model; furthermore, a fixed wetting pore pressure was applied on the bottom of the model. The different parameter values in the two-phase flow model were substituted to
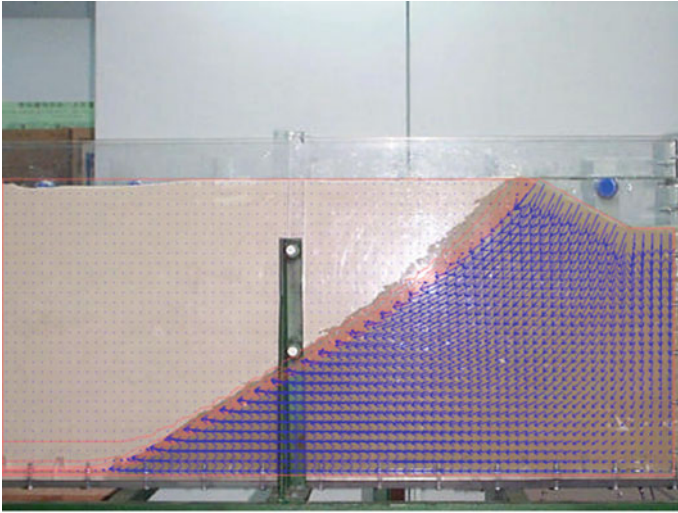
(c) at 600 s
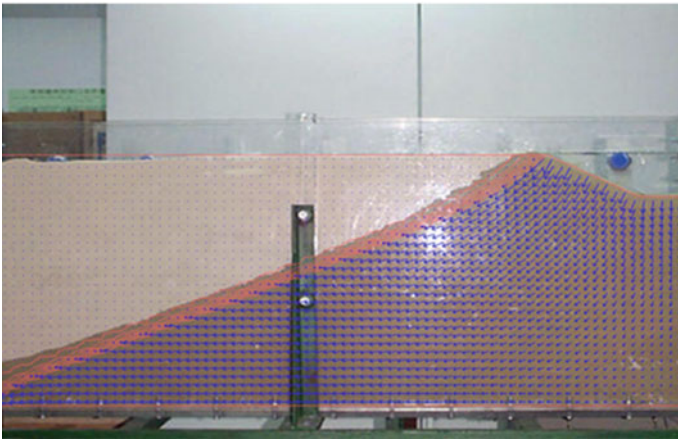
(d) at 900s

Fig. 2. (*continued*)

calculate their corresponding numerical results. By comparing the experimental and numerical results, the optimal parameter values were obtained when the difference between the two results was minimal. The numerical simulation results for the optimal parameter values were compared with the experimental results, as presented in Fig. 4. Tables 1 and 2 list the parameter values of the two-phase flow model of the loam and silt loam soils.
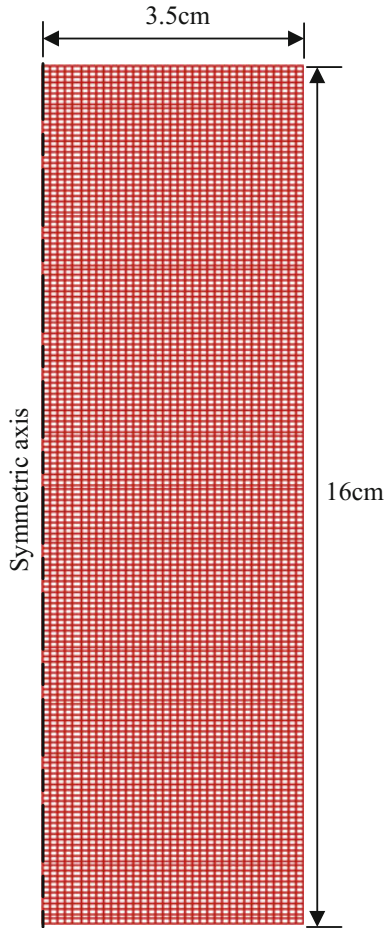
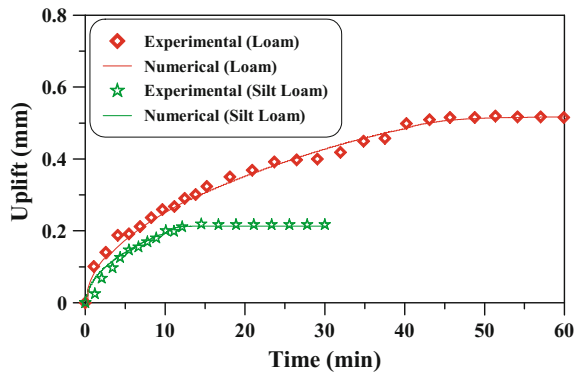**Fig. 3.** The FLAC mesh of the cylindrical specimen recharge model test

Fig. 4. Comparison of numerical and experimental results in the cylindrical specimen recharge model test

Table 1. The material parameters of the aquifers

Aquifer	Density (kg/m^3)	Bulk modulus (MP_a)	Shear modulus (MP_a)	Cohesion (kP_a)	Friction angle (degree)	Saturated permeability (m/s)
Sand	1800	16.6	7.67	–	38	4.8×10^{-4}
Silt loam	1850	12.7	3.91	3.1	26	3.5×10^{-5}
Loam	1826	11.9	3.34	5.2	23	3.7×10^{-6}

Table 2. The van Genuchten parameters of the aquifers

Aquifer	a	b	c	S_r	P_o (kP_a)
Sand	0.66	0.5	0.5	0.2	4.46
Silt loam	0.86	0.5	0.5	0.41	9.81
Loam	0.51	0.5	0.5	0.42	8.53

4 Numerical Model

To study the influence of the groundwater recharge parameters on ground surface uplift, a finite difference program, FLAC 8.0, was used to perform the numerical analyses of groundwater recharge by a recharge pool. The numerical model of the parametric analysis was similar to that of the sandbox recharge model test, and the aquifer model was rectangular, with a length, depth, and element size of 90 m, 20 m, and 0.5 m × 0.5 m, respectively. The initial depth of the water table was 8 m. The recharge pool was trapezoidal, with upper and lower base lengths of 10 and 4 m, respectively, and height of 3 m (Fig. 5). There were 3600 elements in the model. The material properties of soils were assumed to be satisfied to the Mohr-Coulomb model. Two-phase flow model was used to perform the coupled fluid-mechanical calculation. A symmetric numerical model was employed; the right-hand boundary of the model was a symmetrical axis.
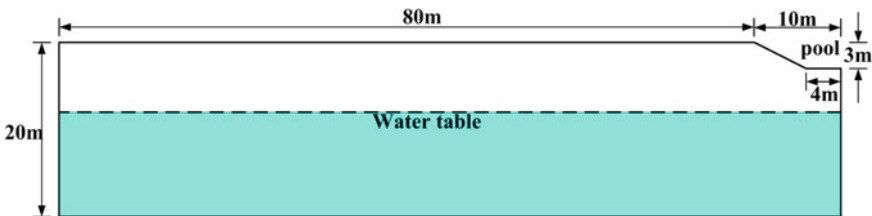

Fig. 5. Configuration of the groundwater recharge pool

The mechanical boundary conditions corresponded to roller boundaries at the base and sides of the model. Below the water table, the fluid-flow boundary condition was the fixed wetting pore pressure. The non-wetting pore pressure was fixed above the

water level. The boundaries on the bottom and left side of the recharge pool were assumed to be seepage boundaries during the groundwater recharge period; furthermore, the non-wetting pore pressure was fixed during the empty pool period. The recharge pool was empty in the beginning. The water level raised to the maximum water level height (3 m) at a rate of 0.2 m/h. A seepage analysis of the groundwater recharge was calculated every time the water level rose by 1 m (three times). The mechanical analysis was performed to calculate the ground surface uplift after every seepage analysis. The time of a groundwater recharge cycle was assumed to be 360 days. The water level in the recharge pool was full for the first 90 days to recharge the groundwater. The groundwater recharge stopped on Day 90. The pool gradually became empty pool after groundwater recharge ceased. The evolution of ground surface uplift was continuously tracked until Day 360.

5 Parametrical Study

5.1 Influence of Various Initial Degrees of Saturation

Figure 6 shows the history curves of the cumulative groundwater recharge volume with different initial degrees of saturation of a sandy aquifer. The simulated groundwater recharge occurred for 90 days. It also illustrates that the cumulative groundwater recharge volume increased with time during the groundwater recharge period. The cumulative groundwater recharge volume remained unchanged when the groundwater recharged ceased. Furthermore, the history curves of the cumulative groundwater recharge volumes for different initial saturations of the sandy aquifer nearly coincided. The initial degree of saturation of the sandy soil had little effect on the history curve of the cumulative groundwater recharge volume.
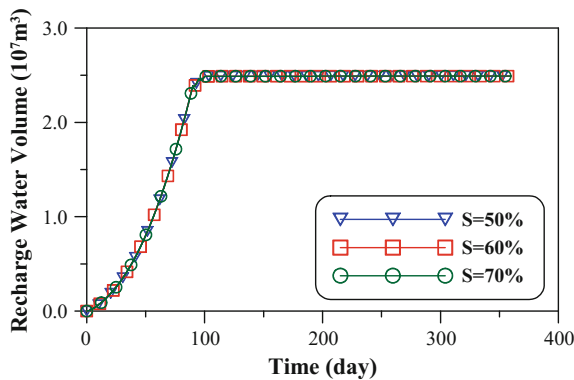

Fig. 6. Influence of initial degree of saturation on the cumulative groundwater recharge volume

Figure 7 illustrates the ground surface uplifts at different locations of the ground surface (the center of the recharge pool was the origin of the coordinate) on Day 90 for the groundwater recharge in the sandy aquifer with a different initial degree of saturation. The ground surface uplift at the end of the 90 days is reflected in the figure

(the water level of the recharge pool was maintained at 3 m). The maximum ground surface uplifts on Day 90 at an initial degree of saturation of 50, 60, and 70% were 0.028, 0.03, and 0.031 m, respectively. Ground surface uplift within 40 m from the recharge pool was obvious; however, the ground surface uplift was relatively low beyond the recharge pool. The ground surface uplift increased slightly during the recharge period when the initial degree of saturation increased for the sandy aquifer.
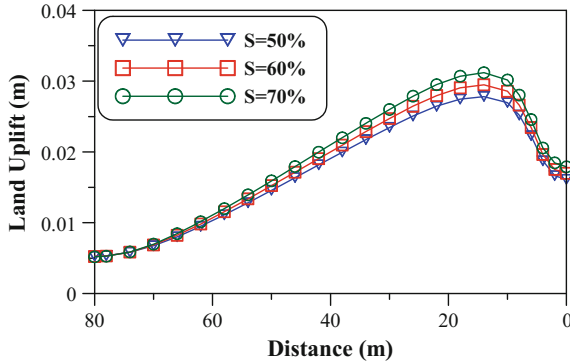

Fig. 7. Influence of initial degree of saturation on ground surface uplift (Day 90)

Figure 8 shows the ground surface uplift history curves at 14 m from the center of the recharge pool (x = 14 m) for different initial degree of saturations of the sandy aquifer during groundwater recharge. The ground surface uplift was the largest when the initial degree of saturation was 70%, sequentially followed by saturations of 60 and 50%. The ground surface uplift related to the water level of the recharge pool. When the water level of the recharge pool increased to the maximum level (3 m), the ground surface uplift also increased. When the water level of the recharge pool remained full, the ground surface uplift remained at a fixed value. Conversely, the ground surface uplift decreased as the water level of the recharge pool fell after the groundwater recharge period. It can be because that the left-side boundary of the mesh grid was assumed to allow water to flow out from the boundary freely. Therefore, when the groundwater recharge ceased, the ground surface gradually returned to its original position.

5.2   Influence of Various Soil Types

Figure 9 illustrates the history curves of the cumulative groundwater recharge volumes for different soil aquifers. The cumulative groundwater recharge volume of the sandy aquifer was the largest, followed by the silt loam aquifer. The loam aquifer had the lowest cumulative groundwater recharge volume, potentially because the cumulative groundwater recharge volume and saturated permeability coefficient of a soil aquifer are related. The permeability coefficient of unsaturated soil is related to the saturated permeability coefficient and the degree of saturation of the soil. When the permeability coefficient of the unsaturated soil aquifer is low, less water infiltrates the soil over a groundwater recharge period.
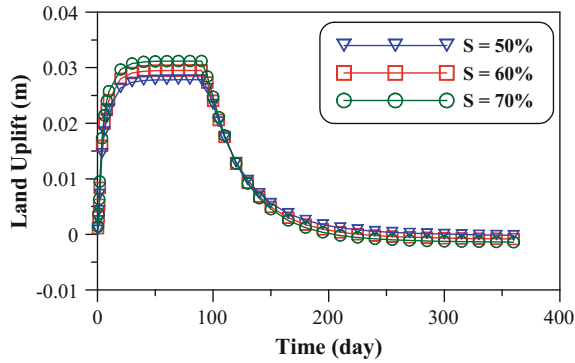
Fig. 8. Influence of initial degree of saturation on the history curve of ground surface uplift (at x = 14 m)
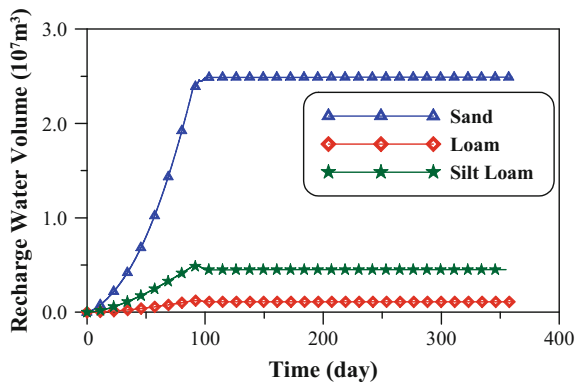

Fig. 9. Influence of soil type on the cumulative groundwater recharge volume

Figure 10 shows the ground surface uplift history curves at 14 m from the center of the recharge pool (x = 14 m) for different soil aquifers during the groundwater recharge period. The ground surface uplift of the silt loam aquifer increased with time during the groundwater recharge period. Ground surface uplift still increased in the silt loam aquifer even after the groundwater recharge period, but decreased after Day 105, probably because of the low permeability coefficient of silt loam. Therefore, groundwater could have been largely retained in the study area. Ground surface settlement occurred in the loam aquifer during the groundwater recharge period because the weight of the pool water was applied at the bottom of the pool. The settlement decreased over time because the pool water infiltrated the loam aquifer causing the soil to swell. The ground surface uplift was detected after Day 95. The lower permeability coefficient of the loam soil, because of its high clay content, resulted in less groundwater uplift in the loam aquifer. Moreover, during the groundwater recharge period, less water infiltrated the loam soil than it did the other soils because of lower permeability; in other words, the rate of ground surface uplift in the loam aquifer was relatively low.
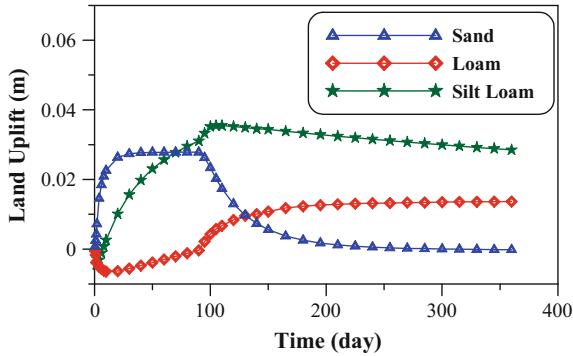
Fig. 10. Influence of soil type on the history curve of ground surface uplift (at x = 14 m)

Figure 11a, b demonstrates the relationship between the ground surface uplift and ground surface position at the end of the groundwater recharge period (Day 90) and that of the groundwater recharge cycle (Day 360), respectively. Figure 11a shows that the ground surface uplifts in the silt loam and sandy aquifers were obvious at the end of the groundwater recharge period (Day 90), particularly near the groundwater recharge pool. The maximum ground surface uplifts in the silt loam aquifer and sandy aquifer were approximately 3.1 and 2.8 cm, respectively. Figure 11b shows that the sandy aquifer had no obvious ground surface uplift at the end of the groundwater recharge cycle (Day 360), potentially because the groundwater flowed out of the study area because of the high permeability of sand. During this time, the groundwater in the silt loam aquifer flowed, but not beyond the study area, because of its low permeability. The zone of influence on ground surface uplift of the silt loam was wider than that of the other two soil types. On Day 360, the surface of the loam aquifer had an obvious uplift near the recharge pool. Other than the unloading effect caused by the empty recharge pool, the water that infiltrated the loam aquifer during the groundwater recharge period flowed to around, increasing the degree of saturation near the recharge pool, resulting in the obvious uplift.
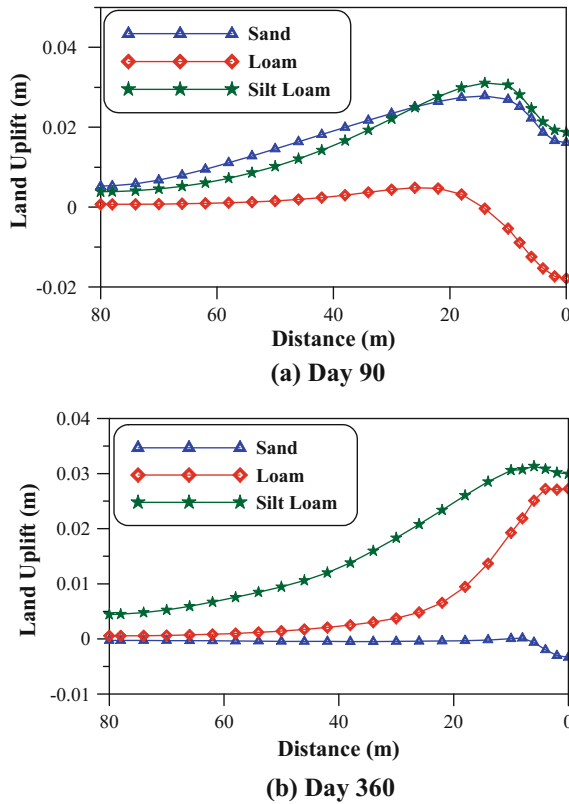
(a) Day 90

(b) Day 360

Fig. 11. Influence of soil type on ground surface uplift

6   Conclusions

By using the finite difference software FLAC 8.0 with a two-phase flow model, a parametrical study was examined ground surface uplift induced by groundwater recharge. The initial degree of saturation and different soil types on ground surface uplift and the cumulative groundwater recharge volume were discussed. The study results are summarized as follows:

1. Compared with the numerical and experimental results, it is clear that the numerical analysis used in this study is rational.
2. The initial degree of saturation had a non-significant effect on the cumulative groundwater recharge volume. When the initial degree of saturation of the aquifer was 70%, the ground surface uplift was the largest, sequentially followed by the initial degree of saturations of 60 and 50%.
3. The sand aquifer had the largest cumulative groundwater recharge volume, followed by the silt loam aquifer. The loam aquifer had the lowest cumulative groundwater recharge volume. At the end of the groundwater recharge period (Day 90), the ground surface uplifts in the silt loam and sandy aquifers were obvious. Because of

the high permeability of sand, the recharged groundwater flowed out of the study area. However, no obvious ground surface uplift in the sandy aquifer were noted at the end of the groundwater recharge cycle (Day 360). Constructing walls within a sandy aquifer to contain the groundwater may prevent the recharged groundwater flow out, it may be able to improve this situation.

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