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RESEARCH ARTICLE

Hydrogeological-geotechnical Characterization and Analysis for Construction of a Subsurface Reservoir at a Coastal Site in the Nakdong Deltaic Plain, Busan, South Korea

Pham Huy Giao[1*] **Namsik Park**[2*]

1. Department of Geological Engineering, PetroVietnam University (PVU), Baria-Vung Tau, 790000, Vietnam
2. Department of Civil Engineering, Dong-A University, Busan, 49315, Korea

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ABSTRACT

Store and recover clean groundwater from a man-made subsurface reservoir is useful for the development of coastal cities. A full-scale pilot field test of managed aquifer recharge (MAR) schemes were conducted in the Nakdong River plain, Korea. The process involved constructing a hydrogeological-geotechnical model based on investigation data, including the target aquifer that was located between 30 and 67 meters deep. The subsurface response to water pumping was analyzed, and this led to the creation of charts to determine the maximum allowable injection pressure and maximum recharge rate. For two factors of safety of 1.5 and 2.0, the maximum injection head rise was estimated to be 9.7 meters and 7.25 meters, respectively, corresponding to recharge rates of 5,000 and 3,800 m^3/d. One-dimensional FE consolidation analyses were conducted for different groundwater drawdowns (2, 5, 10 and 15 m) and the results showed a good match with the monitored settlement and rebound for the 2-meter drawdown case. The study concluded that the injection rate could potentially be much higher than what was tested, which would increase the capacity of the subsurface reservoir. The lessons learned from this study are useful for similar coastal sites in terms of the application of MAR technology.

1. Introduction

Artificial recharge is a process where water is injected into the ground [1], while Aquifer Storage Recovery (ASR) is a more comprehensive concept of water management that involves the storage of water in an aquifer through wells and the recovery of water when it is needed. Managed aquifer recharge (MAR) is a term conceived by the British hydrogeologist Ian Gale for an increasingly impor-

*Corresponding Author:
Pham Huy Giao,
Department of Geological Engineering, PetroVietnam University (PVU), Baria-Vung Tau, 790000, Vietnam;
Email: giaoph@pvu.edu.vn
Namsik Park,
Department of Civil Engineering, Dong-A University, Busan, 49315, Korea;
Email: nspark@dau.ac.kr

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tant water management strategy, alongside demand management, to help maintain, enhance and secure stressed groundwater systems and improve water quality. The term Managed Aquifer Recharge (MAR) is commonly used nowadays to reflect the continuing advancement in recharge technology [2,3]. As reported by Dilon et al. [4], by the end of the last decade "*MAR has reached about 10 km^3/year or 2.4% of groundwater extraction in countries reporting MAR (or approximately 1.0% of global groundwater extraction)*". Typical examples of stressed groundwater systems are found in most Middle East and North Africa (MENA) countries where groundwater extraction exceeds its renewability by 6% to 100% [5], where the potential application of MAR is seriously investigated.

The success of many MAR projects depends on the ability to construct a suitable subsurface reservoir. This can be achieved by injecting fresh surface water into an underground confined aquifer, which can be commonly found at the estuary of a large river, such as in the Nakdong deltaic plain in Busan, Korea. The main operating facilities of the MAR system include injection wells and pumping wells, which can be dual or separate. During normal operation, water is injected through the injection wells and pumped from the pumping wells simultaneously. The flow of water through the aquifer is expected to enhance the water quality. In emergency situations, such as drought, flood, or accidents, an injection can be stopped to protect the subsurface reservoir, but pumping can still be maintained for a prolonged period. A subsurface reservoir that uses a confined aquifer can be a viable alternative to more conventional water supply schemes.

It is important to understand the geotechnical and hydrogeological characteristics of the subsurface to ensure the success of a subsurface reservoir. This includes knowledge of the deformation of the soil layer, particularly the lower-permeability layer overlying a confined aquifer. This understanding can help to prevent subsidence caused by groundwater pumping, which is a common problem in many Asian cities where water demand is high due to rapid population growth, urban expansion, and industrial development [6-10]. It is crucial to have a comprehensive understanding of the subsurface behavior in response to pumping and storage activities to design and operate a subsurface reservoir effectively.

A field experiment on the subsurface reservoir was set up and conducted at a coastal site in the Nakdong River plain from June 2013 to the end of 2018. A substantial amount of field data was collected. The primary objective of this study is to propose an integrated geotechnical-hydrogeological model, which can be used to conduct groundwater and consolidation analyses and simulate and predict the responses of the artificially-injected and stored reservoir to the discharge-recharge operation. Another objective of this study is to construct charts to aid in determining the maximum injection pressure and recharge rate.

2. Testing and Monitoring

2.1 Study Location

The construction site of a subsurface reservoir in the Nakdong plain is shown in Figure 1. It is located on the left floodplain of the Nakdong River, and its shape is approximately square, with a side length of 400 meters.

2.2 Monitoring

The plan view of the field instrumentation is depicted in Figure 2. It includes 12 red-colored injection wells labeled OIW1-9 and NIW1-3, 8 blue-colored pumping wells labeled W1-8, 10 purple triangle-shaped vibrating wire piezometers designated PW1-10 to monitor pore water pressure, 14 blue rhomb-shaped extensometers labeled SE1-14 to monitor settlements, and 5 black rectangular-shaped surface settlement plates labeled SP1-5. The study site has been divided into five monitoring areas, each equipped with specific extensometers and piezometers. The mon-

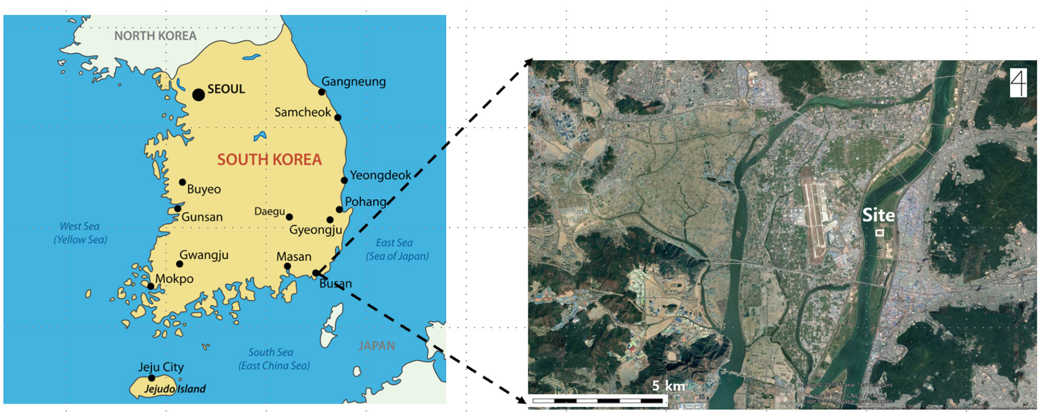


Figure 1. The location of the MAR testing site in the Nakdong River plain, Busan, South Korea [11].

itoring areas are designated as Area A (SE1-4, PW1-2, PW9-10), Area B (SE5-8, PW3-4), Area C (SE9-12, PW5-6), and Area D (SE13-14, PW7-8). The type and location of geotechnical sensors are detailed in Table 1.

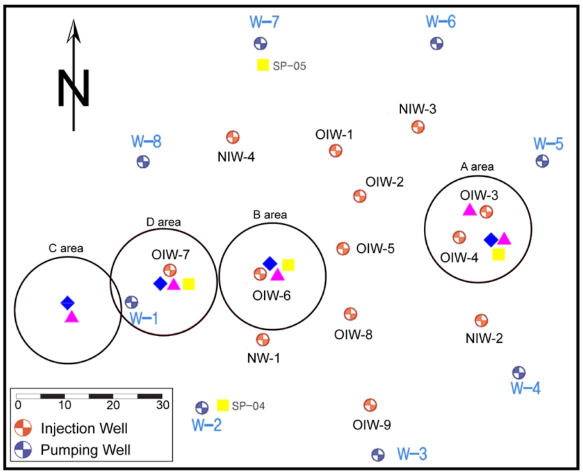


Figure 2. Layout of field monitoring instrumentations (modified after DAU, 2017 [11]).

The subsoil profile and the vertical instrumentation layout of each monitoring area are shown in Figure 3.

Additionally, observation wells were installed to monitor groundwater flow. Three wells were placed in the upper sand layer and thirteen wells in the target aquifer. These wells were situated within a 125-meter circular area. However, they were not included in Figure 2 to prevent symbol overcrowding, as the focus of this manuscript is geotechnical.

Table 1. Geotechnical sensors and locations.

Equipment	Symbol (Notation)	Location and Sensors
Piezometer-vibrating wire type (PW)	Triangle	A area: PW-1, -2, -9, -10
		B area: PW-3, -4
		C area: PW-5, -6
		D area: PW-7, -8
Settlement Extensometer (SE)	Diamond	A area: SE-1, -2, -3, -4
		B area: SE-5, -6, -7, -8
		C area: SE-9, -10, -11, -12
		D area: SE-13, -14
Settlement Plate (SP)	Square	A area: SP-1
		B area: SP-2
		D area: SP-3
		Other: SP-4, -5

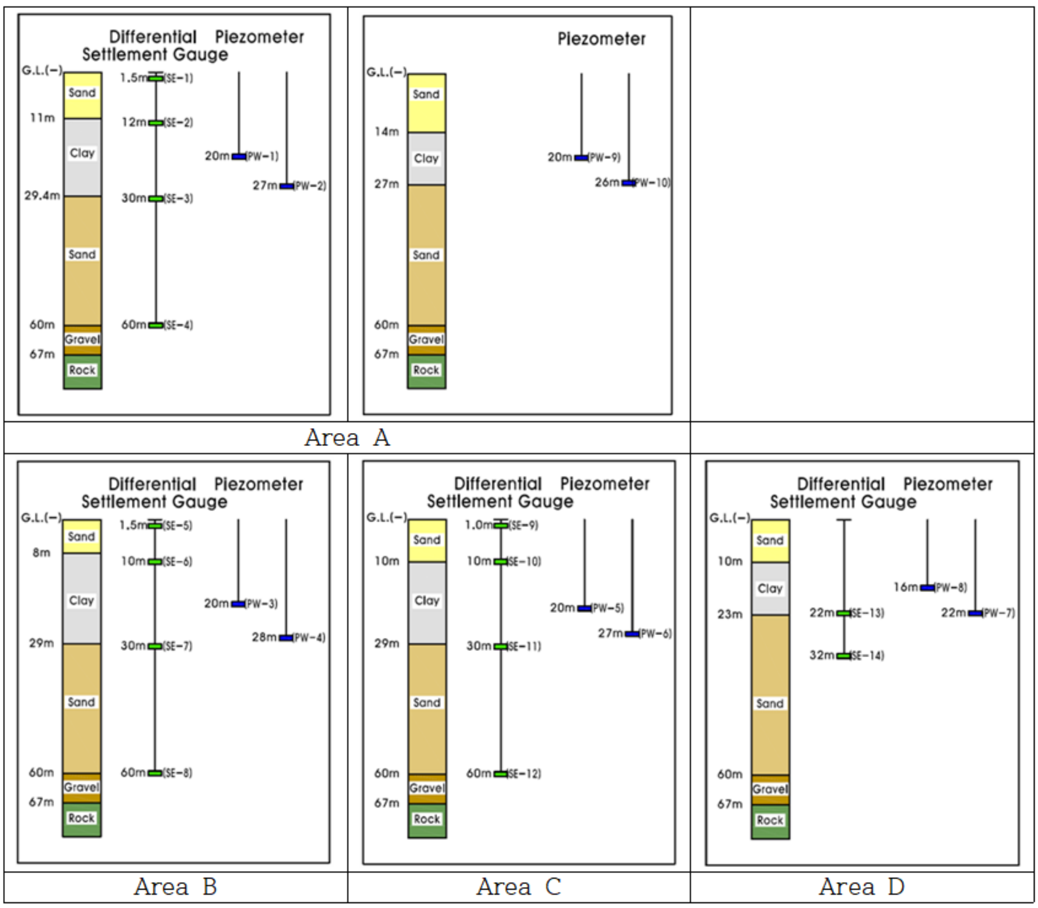


Figure 3. Subsoil profile and field instrumentations layouts at five monitoring areas [11].

3. The Hydro-geotechnical Model for the MAR Testing Site

3.1 Subsurface Model

Three investigative boreholes were drilled at locations OW2, OW5, and OW6, reaching a depth of 60 meters. Soil samples were collected from these boreholes for laboratory testing, as indicated in Table 2a. A standard penetration test (SPT) was also performed in the same three boreholes at 1-meter intervals, excluding the sampling positions.

The soil layers' geotechnical index properties were tested, as shown in Table 2a. The results of the normal and constant rate of strain (CRS) consolidation tests are presented in Table 2b. A hydro-geotechnical model was created for the subsurface at the MAR testing site, as depicted in Figure 4. This model shows a compressible clay layer from 10 to 30 meters deep, which is composed of a normally-consolidated (NC) clay with an over-consolidation ratio (OCR) ranging from 1.0 to 1.1. This clay layer is known as Busan marine soft clay that was well investigated by Chung et al. [12] and it functions as a confining aquitard, sandwiched between the top unconfined aquifer located from 1 to 10 meters deep and the underlying confined aquifer of gravelly sand located from 30 to 67 meters deep, where the subsurface reservoir is intended to be constructed.

The hydrogeological condition of the confined aquifer is a crucial factor in determining the results of the MAR experiment. In this experiment, parameters that represent the area are more valuable than those at specific points. Aquifer-wide hydraulic conductivity and specific storage were assessed based on three sets of injection-recovery tests. For each test, a different combination of wells was chosen, involving a total of three injection wells and eight monitoring wells.

The durations and injection rates of the tests ranged from five to fourteen days and from approximately 200 m^3/d to 260 m^3/d, respectively. The distances between the injection and observation wells were from 8.0 m to 71.4 m. In each test, water was injected through one or two wells, and hydraulic heads were measured at three or four wells. The hydraulic conductivity and specific storage were determined using a numerical groundwater flow model and a genetic algorithm. The aquifer-wide hydrau-

Table 2a. Basic geotechnical parameters of the clay layer overlying the target aquifer at the study site.

Borehole	Sample Depth (m)	NSPT	#200 sieve (%)	Gs	W (%)	LL (%)	PL (%)	PI	Soil Type
OW2	15	11-2	90.05	2.67	52	42.85	29.35	13.50	ML
	16		68.40	2.60	52	39.99	29.00	11.00	ML
	18		88.52	2.68	45	55.86	37.85	18.01	MH
OW5	15	0-7	94.64	2.63	60	47.97	26.99	20.98	CL
	17		87.63	2.61	55	45.11	28.47	16.64	ML
	18		97.71	2.63	53	49.95	32.74	18.39	ML
OW6	20	11-12	82.56	2.63	53	47.31	32.63	14.68	ML
	21		85.58	2.66	42	36.21	26.59	9.62	ML

Table 2b. Results of consolidation tests.

Consolidation Test	Borehole	Sample Depth (m)	C_r	C_c	P_c (kPa)	σ_0 (kPa)	OCR
Standard	OW2	18	0.068	0.59	157.6	145.2	1.09
	OW5	19	0.078	0.78	142.8	139.2	1.03
	OW6	22	0.058	0.42	161.5	164.8	0.98
CRS	OW2	18	0.052	0.56	160.0	145.2	1.10
	OW5	19	0.068	0.76	158.0	139.2	1.14
	OW6	22	0.060	0.51	165.0	181.7	0.91

lic conductivity and specific storage were determined to be 17.8 m/d and 4.25×10^{-4} m^{-1}, respectively. The details of the injection tests are outside the scope of this manuscript and will be reported elsewhere.

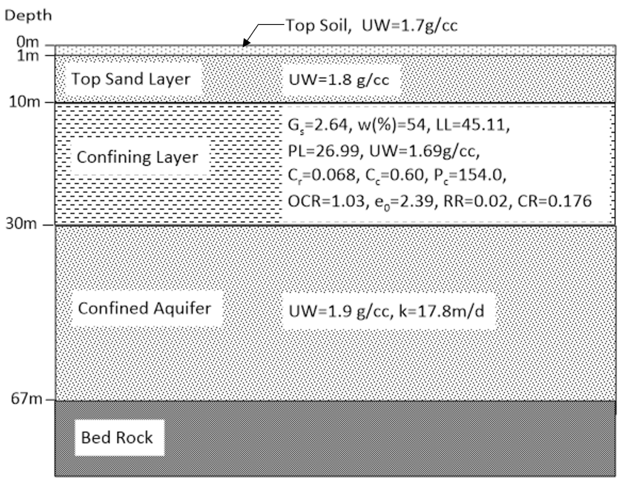


Figure 4. The hydro-geotechnical model of the MAR testing site.

3.2 Calculation of Maximum Injection Pressure (P_{max}) and Maximum Recharge Rate (Q_{max})

The permissible injection pressure is an important design parameter for an artificial recharge well as it determines the safe injection rate and helps prevent boiling. If the injection pressure is higher than a permissible criterion vertical cracks can be developed at the injection depth level and propagated up to the ground surface, damaging the recharge site. Such a phenomenon is commonly referred to as boiling. The permissible injection pressure is basically controlled by the horizontal effective stress at the depth level immediately above the screen or gravel pack.

The procedure to estimate the permissible injection pressure involves calculating the vertical effective stress, determining the coefficient of lateral pressure at rest ($K_0 = 0.4$), calculating the horizontal effective stress ($\sigma'_H = K_0 . \sigma'_V$), determining the maximum injection pressure (P_{max}) and corresponding head rise (dh_{max}), and finally determining the maximum recharge rate (Q_{max}) with a factor of safety considered. The charts in Figure 5 and Figure 6 provide a visual representation of these calculations and help in determining the maximum recharge rate (Q_{max}).

For this MAR study site, the depth to the top of the gravel pack is 45 m, where the vertical and horizontal effective stresses are 36.2 t/m^2 and 14.5 t/m^2, considering the coefficient of later pressure at rest equal to 0.4 (see Figure 5). For FS = 1.5, $dh_{max,p} = dh_{max,cal}/FS$ = 14.5 m/1.5 = 9.7 m. Based on the chart in Figure 6, for dh_{max} = 9.7 m, the corresponding maximum injection rate is 5000 m^3/d. For FS = 2.0, $dh_{max,p} = dh_{max,cal}/FS$ = 14.5 m/2.0 = 7.25 m. Based on the chart in Figure 6, for dh_{max} = 7.25 m, the corresponding maximum injection rate is 3800 m^3/d. It is important to note that these values are just estimates and actual values may vary based on the site-specific conditions and the design of the artificial recharge well. The detailed calculations are shown below:

$$FS = dh_{max,cal}/dh_{max,p} \quad (1)$$

Thus, if FS =1.5 => $dh_{max,p}$ = 14.5/1.5 = 9.7 m => Q = 5,000 m^3/d.

Thus, if FS =2.0 => $dh_{max,p}$ = 14.5/2.0 = 7.25 m => Q = 3,800 m^3/d.

where: FS is the factor of safety, $dh_{max,p}$ is the maximum head rise to be used in practice, $dh_{max,cal}$ is the maximum head rise calculated using the chart in Figure 5, Q is the recharge rate.

It's important to consider the actual conditions and limitations of the injection facilities when deciding on the injection rate for an artificial recharge experiment. The actual injection rate of 1500 m^3/d applied in this experiment was smaller than the geotechnically permissible injection rate due to the limitations of the injection facilities such as injection wells, pumps, and pipes as shown by the calculation results presented earlier. The injection wells were designed with 100 mm PVC pipes and lengths of screens varying between 10 m and 15 m starting from 15 m to 20 m below the bottom of the clay layer.

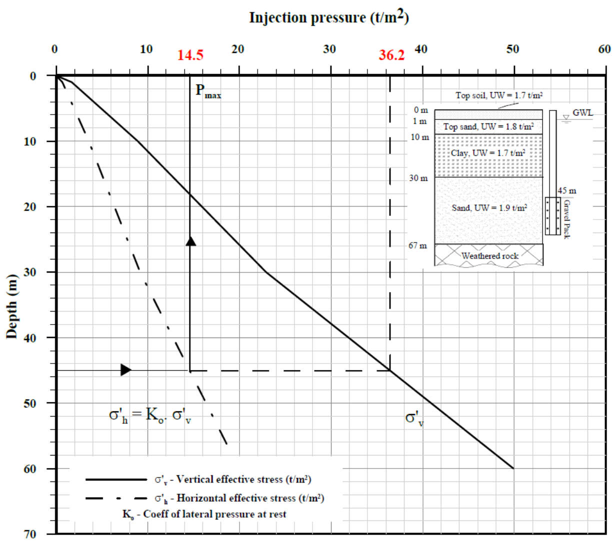


Figure 5. Chart to determine the maximum injection pressure (P_{max}) for the MAR testing site.

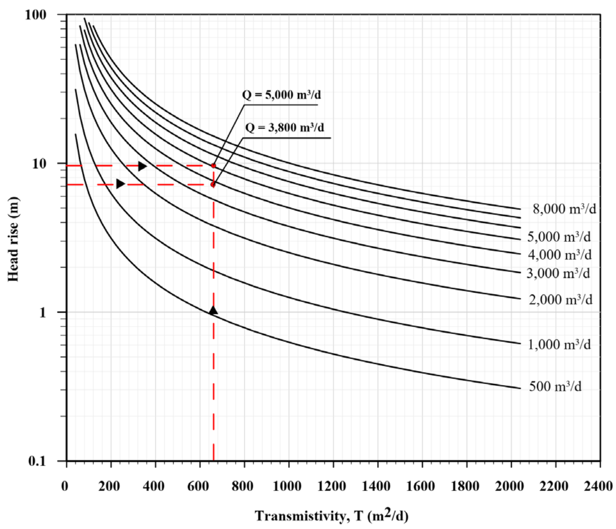


Figure 6. Chart to determine the maximum injection rate for the study MAR testing site.

4. Consolidation Analysis

4.1 FEM Formulation of 1D Consolidation Equation

The consolidation analysis could be done using the 1D FEM code of consolidation analysis named the TZP program to calculate the groundwater drawdown-induced settlement and/or injection-induced rebound of the subsoil [6,8,10]. The 1-D consolidation analysis starts from the following consolidation equation:

$$C_v \frac{\partial^2 u}{\partial z^2} = \frac{\partial u}{\partial t} \quad (2)$$

where C_v is the coefficient of consolidation, u is the rate of dissipation of pore pressure in the clay layer, and u = dh/γ_w, with dh being the head change and γ_w being the unit weight of water. In one-dimensional finite element (1D FEM) consolidation analysis, linear elements are employed instead of quadrilateral elements. Applying Galerkin's procedure on Equation (2) one can get the following weak form:

$$\int_{\Omega^e} C_v \frac{\partial N_k}{\partial z}\frac{\partial N_l}{\partial z} u_k d\Omega^e + C_v N_l \frac{\partial N_k}{\partial z} u_k \Big|_{R^e} - \int_{\Omega^e} N_k N_l \frac{\partial u_k}{\partial t} d\Omega^e = 0 \quad (3)$$

The second term in Equation (3) is the flux term, which is usually considered zero in the case of a 1D consolidation model. Thus, Equation (3) is reduced to:

$$\int_{\Omega^e} C_v \frac{\partial N_k}{\partial z}\frac{\partial N_l}{\partial z} u_k d\Omega^e - \int_{\Omega^e} N_k N_l \frac{\partial u_k}{\partial t} d\Omega^e = 0 \quad (4)$$

And FEM global matrix equation of 1D consolidation will be:

$$[KT]u + \left[BS \frac{\partial u}{\partial t}\right] = 0 \quad (5)$$

4.2 Settlement Calculation

To calculate the consolidation settlement of a compressible (clay) layer adjacent to a pumped aquifer using the TZP program, the layer is divided into smaller sub-layers, for each of which the incremental settlement can be calculated by the following relationship:

$$dS_i = h_i . \left[RR_i . \log \frac{\sigma'_p(i)}{\sigma'_v(i)} + CR_i . \log \frac{\sigma'_v(i) + \Delta\sigma_v(i) \pm \Delta u(i)}{\sigma'_P(i)} \right] \quad (6a)$$

$$S_c = \sum_{i=1}^{N} dS_i \quad (6b)$$

where: S_c is the total settlement of the entire compressible layer;

dS_i is the incremental settlement of the sub-layer i;

h_i, RR and CR are thickness, recompression ratio and compression ratio, respectively;

$\sigma'_p(i)$ is the maximum past pressure, usually determined from the oedometer test;

$\sigma'_v(i)$ is the vertical effective stress (effective overburden);

$\Delta\sigma'_v(i)$ is the change in vertical effective stress due to a surcharge loading on the surface;

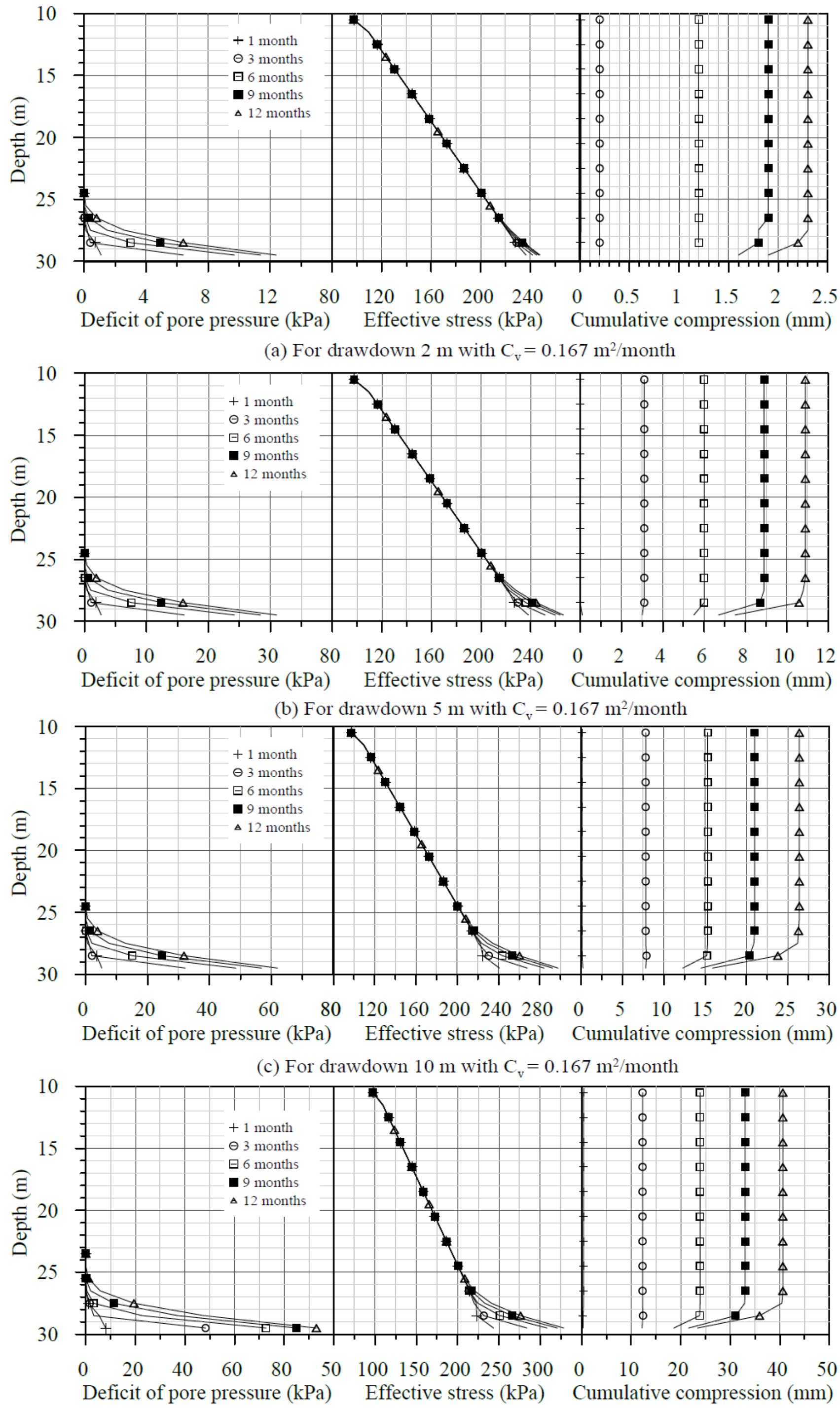
$\Delta u(i)$ is the change in vertical effective stress due to pore pressure change (plus sign for deficit pore pressure due to pumping; while minus sign for excess pore pressure due to artificial recharge or natural recovery).

A number of consolidation analyses were performed to evaluate the impact of various hypothetical drawdowns of 2.0 m, 5.0 m, 10.0 m, and 15.0 m of the aquifer underlying the clay layer, which has properties as shown in Table 3. The results of the 1-year consolidation analysis, conducted over 12 months, are depicted in Figure 7. The long-term results, up to 25 years, can be seen in Figure 8. It can be observed that for drawdowns of 2.0 m or 5.0 m, the subsidence of the ground surface at the MAR reservoir site is still relatively small, with magnitudes of only a few millimeters, particularly during the first year of operation. However, as per the FEM consolidation analysis results shown in Figure 8, after 25 years of operation, cumulative subsidence may reach 25 cm and 33 cm for a drawdown of 10.0 m and 15.0 m, respectively. Comparison of the calculated settlement and the monitored ground deformation is shown in Figure 9.

Table 3. Geotechnical properties of clay layers used in 1D FEM consolidation analysis.

Layer	Depth Interval (m)	Thickness (m)	UW (kN/m^3)	C_v (m^2/y)	C_c	C_s	CR	RR	OCR
Clay	10–30	20 m	16.90	2.0	0.6	0.068	0.176	0.02	1.05

Note: C_c (compression index), C_s (recompression index), C_v (vertical consolidation coefficient), CR (compression ratio), RR (recompression ratio), and OCR (over consolidation ratio).



(a) For drawdown 2 m with C_v = 0.167 m^2/month

(b) For drawdown 5 m with C_v = 0.167 m^2/month

(c) For drawdown 10 m with C_v = 0.167 m^2/month

(d) For drawdown 15 m with C_v = 0.167 m^2/month

Figure 7. Results of 1-year consolidation analysis for the clay layer located from 10 to 30-m deep with C_v = 2 m^2/y and different drawdowns: (a) 2.0 m; (b) 5.0 m; (c) 10.0 m; (d) 15.0 m.

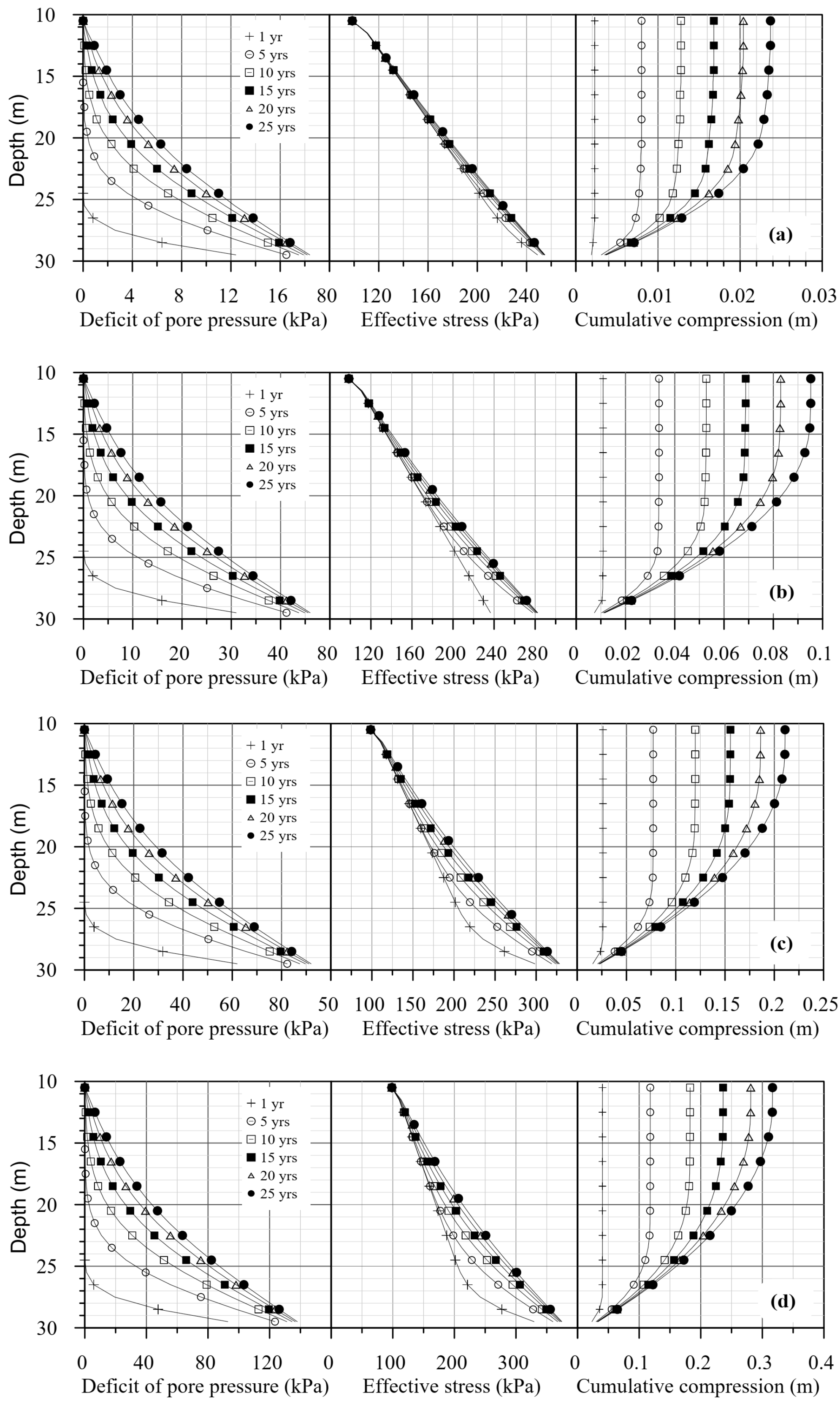


Figure 8. Results of 25-year consolidation analysis for the clay layer located from 10 to 30-m deep with $C_v = 2\ m^2/y$ and different drawdowns: (a) 2.0 m; (b) 5.0 m; (c) 10.0 m; (d) 15.0 m.

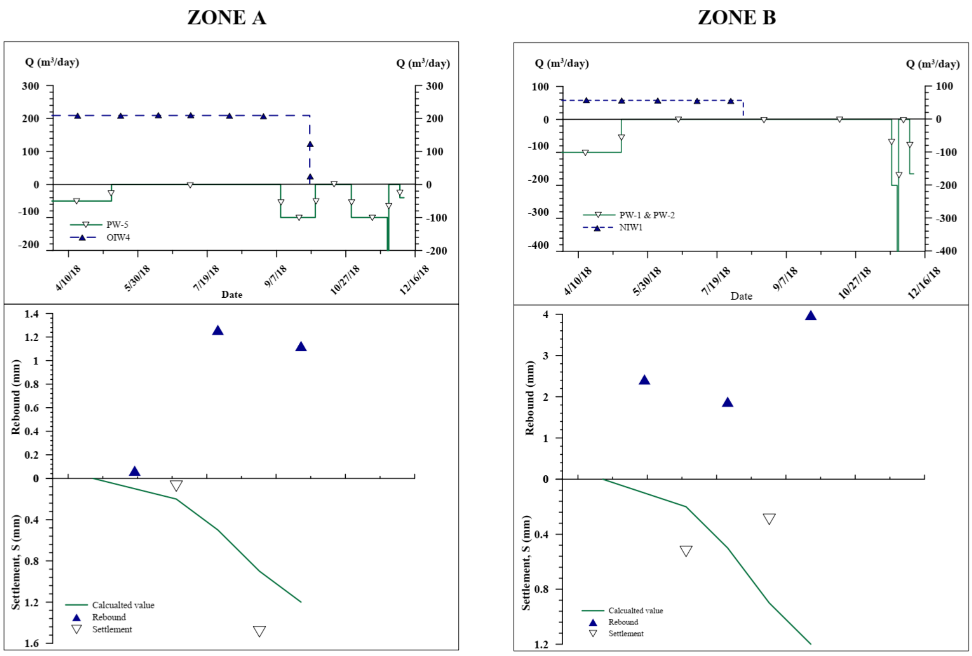


Figure 9. Comparison of the calculated settlement and monitored ground deformation.

As the consolidation analyses were performed with significantly higher pumping and injection rates than what was used in the pilot test (less than 500 m^3/d), it is expected that there will be no significant environmental impact caused by subsidence during the MAR test.

5. Results and Discussion

The results of the geotechnical and hydrogeological investigation conducted during field experiments at the experimental site of a subsurface reservoir in the coastal area of the Nakdong River plain led to the construction of a hydro-geotechnical model of the subsoil. The confined aquifer, where the subsurface reservoir was built, is located between 30 to 67 meters deep. In 2017 and 2018, a series of pumping and injection tests were conducted, and the pore pressure at the settlement monitoring data was obtained, demonstrating the smooth operation of the MAR test. To assess whether the constructed subsurface reservoir was fully utilized, post-experiment groundwater and consolidation analyses were carried out using the hydro-geotechnical model developed in this study. These results were used to create charts that determined the maximum allowable injection pressure and maximum recharge rate for the MAR test site in this study. The maximum injection head rise was theoretically calculated to be 14.5 meters. By considering two cases of a factor of safety (FS = 1.5 and 2.0), the maximum injection head rise was estimated to be 9.7 and 7.25 meters, corresponding to recharge rates of 5,000 m^3/d and 3,800 m^3/d, respectively.

6. Conclusions

A full-scale pilot field test of managed aquifer recharge (MAR) schemes, was successfully conducted in the Nakdong River plain, Korea as the first step of constructing a subsurface reservoir to store and supply clean water for a coastal area in the Nakdong plain, Busan, Korea. The following conclusions were drawn, and namely:

1) A hydrogeological-geotechnical model was successfully constructed based on the investigation data of the target aquifer which was located between 30 and 67 meters deep.

2) Based on the newly constructed subsurface model and geotechnical testing results a chart was created to determine the maximum injection pressure (P_{max}) and the maximum recharge rate (Q_{max}) for different scenarios of water injection into the subsurface reservoir in the future.

3) A 1D FEM consolidation code was revisited and employed to calculate the subsoil deformation, i.e., settlement or rebound due to pumping out or injection activities, respectively.

4) There is potential to increase the capacity of this subsurface reservoir in the future. The lessons learned from this pilot MAR test are expected to be useful for the construction of subsurface reservoirs at other coastal sites.

Author Contributions

Both authors contribute equally to this research article. P.H.G.: FEM geotechnical analysis, model development, manuscript writing, editing, revising. N.P.: funding, data acquisition, project management, manuscript editing, revising.

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Conflict of Interest

There is no conflict of interest.

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