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MODELING OF THE WATER BUDGET SYSTEM IN RECLAIMED MAN – MADE ISLAND

by Kuniaki SATO*, Teruyuki FUKUHARA ** and Yukio MIYAMOTO ***

ABSTRACT : The movement of groundwater and the water budget in a reclaimed, man – made island was studied experimentally and theoretically. A set of experiments were carried out using a Hele – Shaw model that incorporated a rainfall simulator and a tidal generator. The analysis of free surface and the salt/fresh water interface was done through the Boundary Integral Equation Method (BIEM). The results showed that the volume of fresh water in the island increases when the rainfall intensity increases, and the propagation velocity and volume decrease along the free surface and at the salt/fresh water interface depending on the characteristics of tidal oscillation as well as rainfall intensity. An application of the BIEM to groundwater analysis in the reclaimed island was proved.

Keywords : Reclaimed man-made island, groundwater movement, water budget, and numerical analysis

1. Introduction

With the increasing demand in recent years for developing reclaimed, man – made coastal islands[1], it is necessary to understand the water budget system to be able to create a harmonious environment for residents and plants. To realize more reasonable designs and plans for these islands, the practices must reflect the hydrogelogical essentials.

The hydrological composition of an artificial reclaimed island is more understandable than that of natural land because reclaimed land is isolated from the complexity of geology and geography. Artificial reclaimed islands are distinctive because (1) the size of the island is limited and it is surrounded by the sea ; (2) the geology of a reclaimed island and its subsurface is simple ; (3) groundwater is not confined and there is a fresh water lens ; and (4) rainfall is the source of the replenishment and the hydrologic cycle.

As is well known, several authors have dealt with the groundwater behavior of the fresh water lens and the salt water intrusion in an ocean island[2]. According to their knowledge, the phenomenon of a fresh water lens is maintained by natural restoration and the underground runoff of fresh water. The salt water intrusion below the lens balances dynamically with the hydrostatic pressure between salt and fresh water (Ghyben – Herzberg approximation). Essentially, the same may be the case with the budget of artificial islands.

On the other hand, many authors have published bibliographies concerning local hydraulics near coastal aquifers since the 1960s[3),4)]. They give us hydraulic fundamentals, such as hydraulic dispersion, salt water wedge, application of Dupuit approximation to unconfined groundwater flows, numerical computation techniques, and others. All of their results are available for comparison to new related work.

This study aims to clarify the mechanism of groundwater motion and water budget in a man – made island through experiments and numerical simulation.

* Hydroscience and Geotechnology Laboratory, Faculty of Engineering, Saitama University, 255 Shimo – ohkubo, Urawa, Saitama, 338 Japan
** Department of Architecture and Civil Engineering, Fukui University, 3 – 9 – 1 Bunkyo, Fukui, 910 Japan
*** Hydroelectric Power Engineering Department, Tokyo Electric Power Services, Ueno Center, 3 – 3 Higashi – Ueno 3 – Chome, Taito – ku, Tokyo, 110 Japan

2. Experimental Apparatus, Procedure, and Conditions

(1) Experimental Apparatus

A water budget system in and around an artificial reclaimed island model is shown in Fig.1. The origin of the hydrological cycle is precipitation, which can be classified into surface runoff, groundwater runoff, evaporation, and infiltration. This is supported by an inherent groundwater balance through fresh water storage relation : $dS_f/dt = I - q_f$ in which S_f is fresh water storage volume in the island ; t is time ; I is net infiltration water volume ; and q_f is runoff volume of fresh water. The storage water volume in the island is affected not only by the net infiltration water volume and runoff water volume, but also by tidal sea water intrusion in a short period. The time rate of storage water volume dS/dt will be divided into two flow domains, i.e., those of salt and of fresh water. With increasing infiltration due to precipitation, the time rate of groundwater storage dS/dt increases since the storage volume S ($= S_f$ + Salt water storage volume S_s) becomes larger. At the same time, the fresh water lens develops over time. In fine weather, groundwater storage decreases due to evaporation. Generally, both the groundwater volume and the fresh water lens develop during rising tides and withdraw during ebbing tides.

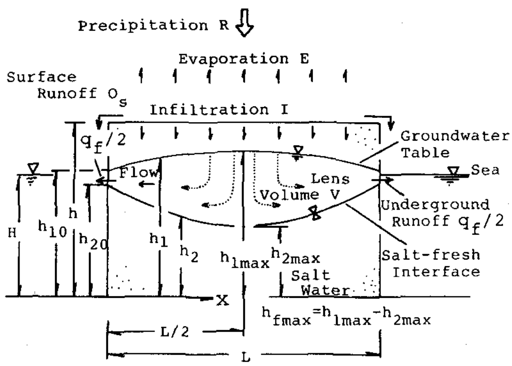


Fig.1 Water Budget System in a Man－made Island

On the basis of characteristics of groundwater mentioned above, an apparatus shown in Fig.2 was designed. The apparatus is mainly composed of (1) vertical Hele－Shaw model, (2) tide generator, and (3) precipitation and evaporation generator. The Hele－Shaw model is 1.30m long and 0.35m high with two reservoirs in each end. The water level oscillation of the tide is created by feeding sea water (viscous oil suspension with fine powder of red oxide of iron for higher density) through the tide generator. The runoff discharge into the two reservoirs is measured by two overflow tubes with funnels that oscillate with the sea water level. The tide generator consists of two tanks for feeding sea water and receiving fresh water, a rotating arm for regulating volume, and a rotating speed reducer for regulating the period of tidal oscillation. The precipitation and evaporation generator has needle pipes and a ponding tank for the required rainfall intensity or evaporation. Putting needle pipes into free surface may realize net infiltration and evaporation is created through suction.

(2) Experimental Procedure and Cases

The procedure depends on three different experiments : (1) the growth of the fresh water lens by infiltration ; (2) fluctuating of the fresh water lens by tidal oscillation with infiltration, and (3) decline of the fresh water lens through evaporation. All experiments had nine sections—three cases in the growth stage, three in the fluctuating stage, and three in the decline stage. The experimental procedure in each process is dependent. The growth of the fresh water lens begins after sea water is supplied to the vertical Hele－Shaw model, and the experiment ends with a fully established lens. Next, tidal oscillation is added. The decline stage is created by putting a set of needle pipes on the free surface of the lens from the sea water.

The runoff volume was measured for all experiments. The change of the moving interface and free surface were taken by a strobocamera.

The experimental conditions and fluid properties are listed in Table－1.

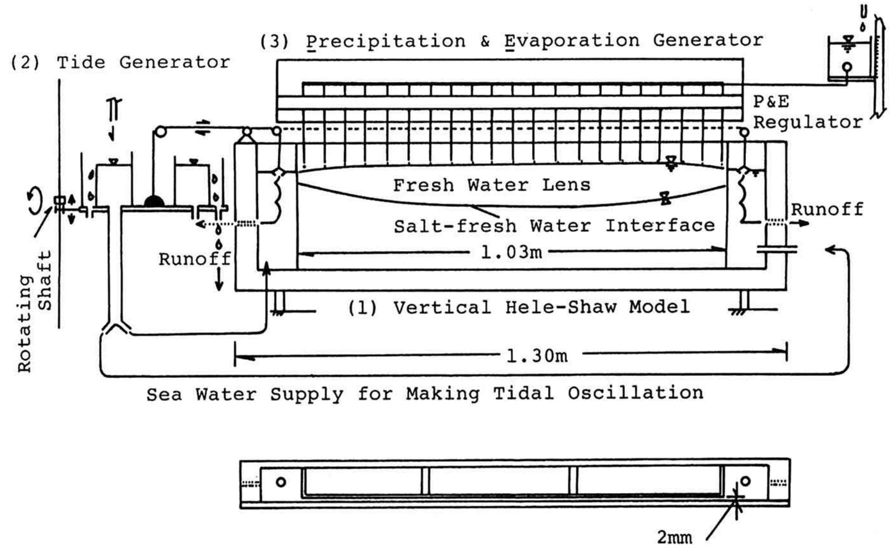


Fig.2 Experimental Apparatus and Its System

Table – 1 Experimental Cases and Fluid Properties

	Depth H (m)	Period T(s)	Amplitude (m)	Rainfall Inten. (mm/h)	Evap. (mm/h)	Density (salt) gr/cm³	Density (fresh) gr/cm³	Viscos. (salt) (m.Pa.s)	Viscos. (fresh) (m.Pa.s)
Exp.-1	0.223	60	0.02	56.0	65.0	0.908	0.886	599.0	302.0
Exp.-2	0.223	240	0.026	65.0	57.0	0.908	0.886	603.0	311.0
Exp.-3	0.223	90	0.007	25.0	34.0	0.908	0.886	612.0	306.0

3. Experimental Results and Numerical Analysis

Fig.3 shows some typical results on the change of the fresh water lens in four different experiments. In Fig.3 (a) the rapid growth of the lens by infiltration replenishment can be observed after 120 minutes. Fig.3 (b) presents several forms of transient interface in the decline process by evaporation. It is recognized that the thinning of the lens begins from both ends of outlet or runoff, and through time the lens remains around the center of the island (see Photo – 1). The fluctuating process of the fresh water lens by tidal oscillation is shown in Fig.3 (c) and (d). Fig.3(c) is an example of a small amplitude tide, and Fig.3 (d) is a larger one. The former reveals that the tide has less influence on the fresh water lens, and it extends inland for a limited distance. On the other hand, the latter shows an abrupt lump of sea water intrusion at both ends of the island during the rising tide (see Photo – 2). During the rising tide, there is no runoff into the sea because the level of the free surface is higher, and the fresh water lens is confined in the island.

We are able to understand the fundamentals and reality of water budget in reclaimed, man – made islands through this set of experimental results.

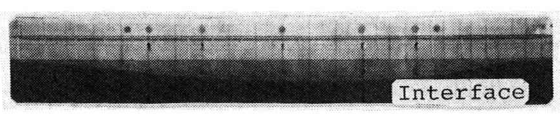
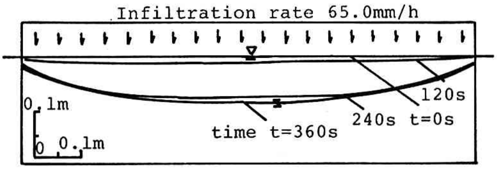
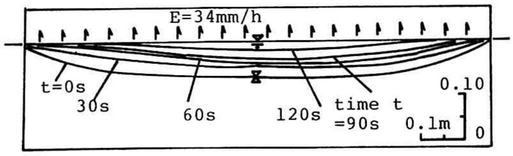


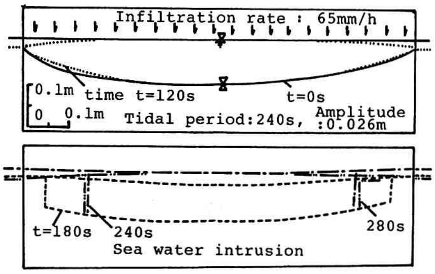
Photo – 1 A Lens Picture in Decay Process (Exp.3, time t = 75min)



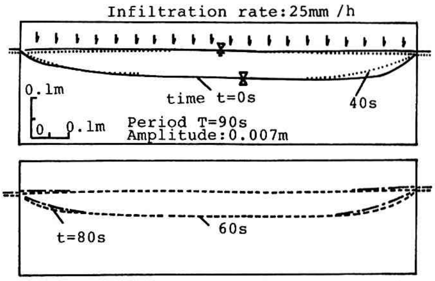
(a) Growth of Fresh Water Lens (Exp.1)



(b) Decay of Fresh Water Lens (Exp.3)

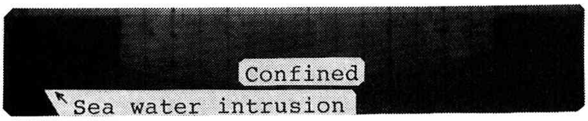


(c) Behavior of Fresh Water Lens with Tide (Exp.3)

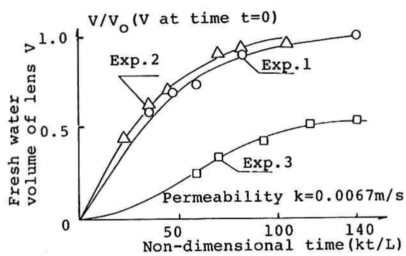


(d) Behavior of Fresh Water Lens with Tide (Exp.2)

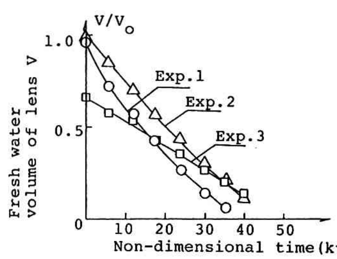
Fig.3 Moving Free Surface and Fresh Water Lens



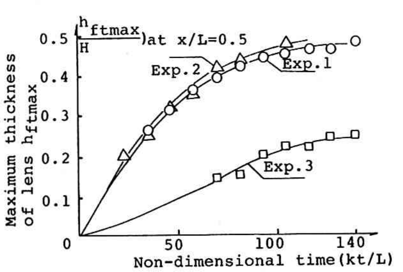
Photo－2 A Picture of Tidal Intrusion (Exp.2, t＝260min)



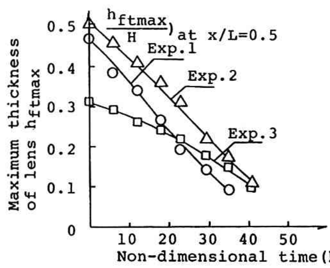
(a) Fresh Water Volume (Infiltration)



(b) Fresh Water Volume (Evaporation)



(c) Maximum Thickness of Lens (Infiltration)



(d) Maximum Thickness of Lens (Evaporation)

Fig.4 Change of Volume and Maximum Thickness of Fresh Water Lens over Time

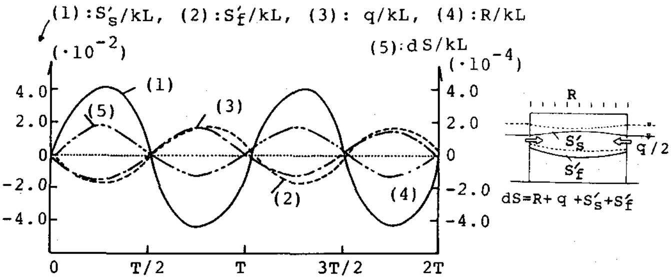


Fig.5 Groundwater Budget (Exp.1)

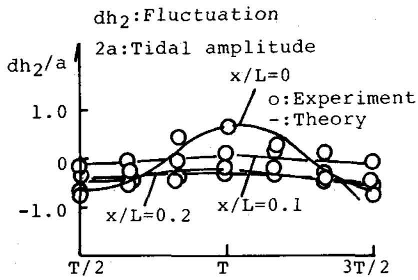


Fig.6 Tidal Variation of Interface at Some Points (Exp.1)

Fig.4 shows some relationships on $V/V_o \sim \tau = kt/L$ and $h_{flmax}/H]_{L/2} \sim \tau = kt/L$ in the infiltration and evaporation processes (V is fresh water volume of lens at time t; V_o is V at $t=0$, h_{flmax} is maximum thickness of lens; H is water depth; K is permeability; L is horizontal length of island; and τ is non-dimensional time). The fresh water volume of the lens increases during the infiltration process and decreases over time through evaporation. V/V_o approaches a constant level during the steady growth of the lens and the runoff into the sea gradually increases during infiltration. On the other hand, the decline of the fresh water lens due to evaporation takes time, and the rate of decline depends on evaporation intensity. The relationships between $h_{flmax}/H]_{L/2}$ and $\tau = kt/L$ have a similar tendency to those of $V/V_o \sim \tau = kt/L$.

In order to examine the groundwater budget in the island, the change over time in net incremental storage volume of water ΔS is shown in Fig.5. A water budget equation is: $\Delta S = R + q + S'_s + S'_f$ in which R is recharge volume in unit time: $q/2$ is underground runoff at island end in unit time; S'_s is incremental volume on free surface, and S'_f is incremental volume on the fresh water lens. Their curves are obtained theoretically from a numerical computation of the BIEM scheme for Exp.1[5]. The application of BIEM to the salt/fresh water interface analysis has been proved by the authors (K.Sato et. al., 1987). According to the computing scheme shown in Fig. 7, the moving free surface and interface profiles are computed by the velocity potential and kinematics conditions. In Fig.5, we can find a time lag in S'_s and S'_f, and a positive increment on the free surface results in a negative increment on the salt/fresh water interface. The theoretical analysis helps us in understanding of the water budget because the measurement of increment volume along the free surface is very difficult.

Fig.6 is useful for examining an interface response resulting from wavy fluctuation of the free surface in the island. These results are obtained by experiments and BIEM's analysis for Exp.1. They show that the tidal oscillation of the sea does not reach very far onto the surface of the lens. In other words, the tide may influence the interface motion around the outside of the island only.

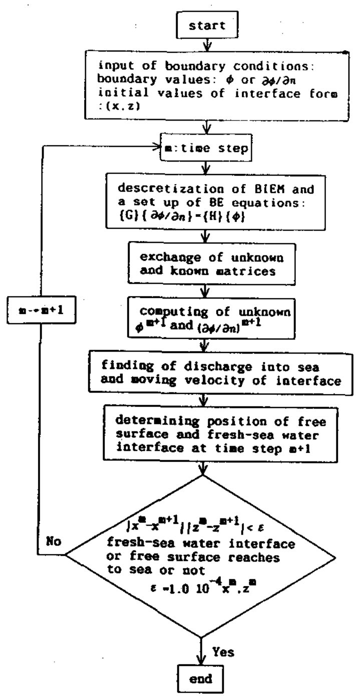


Fig.7 Computing Scheme of BIEM

4. Conclusion

The construction of man-made islands is in progress. A full understanding of groundwater behavior and water budget in and around the island surely contributes to realizing reliability in construction work and the stability of the island as well as controlling the environment. The purpose of the study was to illuminate the water budget system by an artificial reclaimed island model. The experimental results provide a lot of data and prove the numerical approach valid.

The main conclusions of this study are summarized as follows ;

(1) The groundwater movement in the reclaimed island is stimulated by rainfall infiltration, evaporation, and the tide, and the water budget is supported by runoff, tidal sea water intrusion, and the natural restoration of water from the island surface.

(2) The replenishment by precipitation infiltration promotes the growth of the fresh water lens and the decline of the lens volume through evaporation appears from both ends of the island and also propagates to the inside.

(3) An oscillation of the free surface and moving interface between salt and fresh water by the tide rapidly declines in volume because the groundwater is not confined.

(4) An application of BIEM to underground problems in reclaimed islands is proved through this study except some cases in abrupt sea water intrusion.

(5) The Dupuit's assumption with respect to uniformity of unconfined flow does not hold near the outlet for groundwater runoff during a rising tide because the fresh water lens at both ends of the island is disturbed and replaced by new salt water intrusion.

References

1) "Japan Society of Civil Engineers : Man – made Islands." J. Japan society of Civil Engineers, Extra Number, Separate Volume, Vol.78 – 12, 1993, pp. 1 – 127 (in Japanese).

2) J. Bear. *Hydraulics of Groundwater.* McGraw – Hill Book Company, 1979, pp. 379 – 435.

3) J. Bear and A. Verruijt. *Modeling Groundwater Flow and Pollution.* D. Reidel Publishing Company, 1987, pp. 167 – 195.

4) K. Sato, T. Fukuhara and Y. Ito. "Dynamic behavior of groundwater in artificial island." J. the Japanese Society of Soil Mechanics and Foundation Engineering, 34 – 12 (347), No.1649, Dec. 1986, pp. 11 – 16 (in Japanese).

5) K. Sato, T. Fukuhara and Y. Ito. "Prediction of sea water intrusion to underground caverns by means of boundary integral equation method in coastal rock mass." Proc. the Japan Society of Civil Engineers, No.387／II – 8, Nov. 1987, pp. 57 – 66 (in Japanese).