The Dynamics of Groundwater Flow and Salinity Transport in Unconfined Coastal Aquifers

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INTRODUCTION

Organization of the thesis

Chapter 1: Introduction
Chapter 2: Theoretical framework
Chapter 3: Descriptive study site (Taniyagi beach, Okura Beach)
Chapter 4: Methods of field measurement, data acquisition and data processing
Chapter 5: Descriptive study site (Taniyagi beach, Okura Beach)
Chapter 6: Dynamics of fresh-saline groundwater interactions
Chapter 7: Conclusions

The 2001 Okura Beach tragedy

The Okura Beach tragedy calls for a thorough study of the geo-hydrodynamical performances of nourished sandy beaches.

1. Groundwater table variations due to diurnal and semidiurnal tidal changes.
2. Long-term variations of groundwater table in unconfined aquifer.
3. Unsteady groundwater responses to extreme events such as typhoon-induced storm surges.
5. The dynamics of fresh-saline groundwater interactions.

Deeper understanding:

Purposes

Outcome:

Deeper understanding of the coastal groundwater environments that include the performance of shallow-penetrated coastal wells in low-laying coastal area where freshwater are invaluable resources for potable water or for agricultural purposes.

THEORETICAL FRAMEWORK

1D analysis of tidally induced groundwater level fluctuation

The transfer coefficient $C$:

$C = \frac{k}{m Volkswagen}$ (Unconfined aquifer)

$C = \frac{k}{m \gamma_r}$ (Confined aquifer)

Essential aspects: Amplitude decay and phase lag with increasing distance $x$ from shoreline.
Fig. 5.23 Patterns of amplitude decay in wave- or tidally induced groundwater level fluctuations in unconfined or confined aquifers.

Fig. 2.9(b) Location of phreatic surface is part of the solution

The three sets of primary unknowns:
- Displacement increments $\Delta U_j$
- Pore air pressures $u_a (J)$
- Pore water pressures $u_w (J)

Solving Eqs. I and II $\sigma_{ij} = \sigma_{ij} - u_n \delta_{ij}
\delta = u_d - u_w$

Solving Eq. III $K \{ u_w \} = \{ R \}$

Fig. 2.9 Location of phreatic surface is part of the solution

Governing equations for saturated/unsaturated groundwater flows

Equilibrium equations for saturated-unsaturated porous media
$$\frac{\partial \sigma_{ij}}{\partial x_j} + h_j = 0 \quad h_j : \text{body force; } u_a, \text{pore air pressure}$$

Mass conservation equations

Pore air:
$$\frac{\partial u_a}{\partial t} + \frac{\partial (u_a u_a)}{\partial x_j} = - \frac{\partial}{\partial x_j} \left( \frac{u_a}{\rho_a} \frac{\partial p_a}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \frac{u_a}{\rho_a} \frac{\partial p_d}{\partial x_j} \right)$$

Pore water:
$$\frac{\partial u_w}{\partial t} + \frac{\partial (u_w u_w)}{\partial x_j} = - \frac{\partial}{\partial x_j} \left( \frac{u_w}{\rho_w} \frac{\partial p_w}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \frac{u_w}{\rho_w} \frac{\partial p_d}{\partial x_j} \right)$$

Validating of 2D groundwater flow model

Experimental results from Uno (1970)

120 elements (21 cm x 2.5 cm)

Fig. 2.4

Fig. 2.8

The present FE analysis is in reasonable agreement with the experimental performance by Uno (1970) and with the Dupuit-Forchheimer quasi-static solution.
Sharp-interface approach using Ghyben-Herzberg assumption

\[ h = \frac{\rho_f - \rho_s}{\rho_f \cdot \rho_s} \cdot z \]

Glover solution for freshwater-seawater interactions

The aquifer is homogeneous, confined at the top and unbounded at the bottom.

\[ \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left( \frac{\rho f - \rho_s}{\rho_f \cdot \rho_s} \right) \]

Darcy’s law for density-dependent groundwater flow

\[ \nu = \frac{1}{\kappa} \left( \frac{\partial}{\partial x} \left( \rho f - \rho_s \right) \right) \]

Mass conservation for density-dependent groundwater flow

\[ \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left( \frac{\rho f - \rho_s}{\rho_f \cdot \rho_s} \right) \]

Relation between salinity and density

\[ \frac{\partial s}{\partial t} = \frac{\partial}{\partial x} \left( \frac{\rho f - \rho_s}{\rho_f \cdot \rho_s} \right) \]

Mass conservation for saline transport

\[ \frac{\partial C}{\partial t} + \frac{\partial}{\partial x} \left( \frac{\rho f - \rho_s}{\rho_f \cdot \rho_s} \right) C = \frac{\partial}{\partial x} \left( \frac{\partial C}{\partial x} \right) \]

Advection-dispersion equations for density-dependent flow

Erosion history of Toban coast

Extensive beach nourishment project has been performed since 1992
THE FIELD STUDY SITE SELECTED

Taniyagi Beach in Toban coast

Study area: Nourished sandy beach with gently sloping shore platform and extends in front of the sea cliff of Pleistocene soil.

Fig. 3.6

FIELD MEASUREMENTS AND DATA ACQUISITION METHODS

Field measurements

<table>
<thead>
<tr>
<th>Meteorological</th>
<th>Geo-hydrological</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Air temperature</td>
<td>1. Soil suction</td>
</tr>
<tr>
<td>2. Humidity</td>
<td>2. Soil moisture</td>
</tr>
<tr>
<td>3. Rainfall intensity</td>
<td>3. Groundwater level</td>
</tr>
<tr>
<td>4. Wind direction and wind velocity</td>
<td>4. Groundwater salinity</td>
</tr>
<tr>
<td>5. Atmospheric pressure</td>
<td>5. Groundwater temperature</td>
</tr>
<tr>
<td>7. Radiation balance</td>
<td>7. Tide level at nearby Fujis point</td>
</tr>
</tbody>
</table>

(Azuma et al., 2005)

Geological settings

Cross-shore profile of the study area with representative boring logs and SPT test results

1. Well-defined unconfined aquifer above stiff clay layer
2. The unconfined aquifer includes the nourished sand layer about 3m thick.

Fig. 3.15

Tide level measurement

Groundwater level measurement

Grain-size distributions of the samples taken from Br. No 2 at Taniyagi Beach compare with the Okura sand.

Fig. 3.18

Grain diameter (mm)

Fig. 4.5

Fig. 4.8
A total of six electric tensiometers (UNSUCs) were installed at soil depths of 0.2m, 0.5m, 0.8m, 1.2m, 1.6m and 2.0m from the sand surface.

Soil suction $s = u_a - u_w$

Suction measurement

Fig. 4.8

Principle of suction measurement

UNSUC for single-level measurement

TIDALLY INDUCED GROUNDWATER FLUCTUATIONS

Evolution of water-level fluctuations over a representative one-year period on Taniyagi Beach

Fig. 5.1

1. Moving average method
   To resolve the trend components (seasonal effects) of the time-series data.

2. Fourier transform technique
   To resolve the fluctuation components of de-trended time-series data.

Important observations:
1. Correspondence between tidal and groundwater fluctuations.
2. Amplitudes decreasing with increasing distance $x$ from the shoreline.

Fig. 4.9

Salinity measurement

Electro-magnetic inductance type EC sensors:
- No direct contact with saltwater needed.
- Built-in data logger.
   → Permitting continuous EC measurements.

Fig. 4.10

Fig. 4.11

Data acquisition methods

Off-line (stand-alone) equipped with built-up data logger ten-minute intervals

On-site data retrieval

On-line (cabled) Campbell CR-10-X (data logger) one-minute intervals

Remote data acquisition

Trend components of tides and groundwater fluctuations

Findings:
1. The tide level is highest in summer and is lowest in winter
   → Seasonal variation

2. The slow groundwater-level variations are in phase with evolution of tide level

3. The inland groundwater levels are well above the tide level
   → Freshwater discharge

Fig. 5.2

(a) Monthly precipitation and (b) the trend components of the tide and groundwater-level fluctuations at the three wells (GW, H17-4 and H17-3) on Taniyagi Beach

Trend components of tides and groundwater fluctuations

The net groundwater head was positive in the first three years, implying fresh groundwater discharge to the sea.
K1: Luni-solar declination diurnal (T=23.9h)
O1: Lunar declination diurnal (T=25.8h)
M2: Principal lunar semidiurnal (T=12.4h)
S2: Solar declination semidiurnal (T=12.0h)

**Harmonic components of tidal fluctuations**

**Dominant tidal components:**
- K1: Luni-solar declination diurnal (T=23.9h)
- O1: Lunar declination diurnal (T=25.8h)
- M2: Principal lunar semidiurnal (T=12.4h)
- S2: Solar declination semidiurnal (T=12.0h)

Fig. 5.3

*Amplitudes of dominant tidal components at Fuji port (Present Study) are compatible with the field performance in the Seto Inland Sea reported by Fujiwara (1981).*

**Characteristics of tidally-induced groundwater responses**

**The transfer coefficient of aquifer C can be determined from a full-scale “field experiment” using the tidal response technique.**

<table>
<thead>
<tr>
<th>Component</th>
<th>Diurnal component</th>
<th>Semi-diurnal component</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ</td>
<td>0.032 m⁻¹</td>
<td>0.048 m⁻¹</td>
</tr>
<tr>
<td>C</td>
<td>0.0356 m²/s</td>
<td>0.0332 m²/s</td>
</tr>
<tr>
<td>C_{AVG}</td>
<td></td>
<td>0.0335 m²/s</td>
</tr>
</tbody>
</table>

Tidal response technique is effective and reliable for estimating aquifer parameters in the coastal region.

**Amplitudes decay and increasing time lag with increasing distance x from the shoreline.**

**Event-accentuated groundwater-level response**

**The field performances**

(a) Time histories of atmospheric pressure and (b) Hourly wind vectors, both were recorded on Taniyagi Beach

**Tidal variations and groundwater fluctuations at well GW**

**The tide peaked at 01:40 on 7 September 2005, exhibiting a storm surge of 0.84m.**

**The groundwater fluctuations in well GW peaked at 05:36, with 4-hour lag in response.**

**The rise of groundwater-level at GW (=0.88m) was very close to the storm surge.**
Groundwater level responses to a storm surge

**Fig. 5.10**

**Performance of suction measurements**

**Effects of precipitation only visible at shallow depths**

The UNSUC -2.0m (T.P.+1.17m) recorded a negative suction (equivalent to a positive water-pressure head 0.14m) → Submergence of the UNSUC

Groundwater level measured by UNSUC -2.0m → 1.17m + 0.14m = 1.31m

The event-accentuated rise in the groundwater level was independently supported by suction measurement at T.P.+1.17m

**Storm surge effect on groundwater-level fluctuations: 2D FE Analysis**

**Finite element mesh and parameters**

- 

Case I - Bottom: impermeable  
  - Landward: permeable  
  - Top: impermeable  
  - Seaward: permeable

Case II - Bottom: impermeable  
  - Landward: impermeable  
  - Top: impermeable  
  - Seaward: permeable

**DYNAMICS OF FRESH-SALINE GROUNDWATER INTERACTION**

Tide effects on tempo-spatial structure of aquifer salinity

Investigating the extent of saltwater intrusion at various depths as influenced by tidal fluctuations:  
- Deeper understanding of groundwater-seawater flow interactions which may include seawater circulation.

Approach:  
High-resolution field measurements of groundwater salinity changes and groundwater fluctuations in the observation wells together with tidal variations.
Tide effects on tempo-spatial structure of aquifer salinity

Main findings:

• Strong correlation between EC variations and tidal fluctuations.
• Constant peaks and troughs at \(x = 23.1\) m indicate mixing of fresh groundwater & seawater.

Performance of continuous EC measurements in two observation wells

Fig. 6.3

Main findings:

1. Fresh groundwater body at above T.P.-2m or so at \(x = 34.1\) m.
2. Low EC values at low tide suggesting the accentuated fresh groundwater discharge to the sea.

Fig. 6.5

Main findings:

1. Time difference between the two highest peaks (or two lowest troughs) → Period of diurnal fluctuation
2. Effect of seawater intrusion → Deeper location, longer effect
3. Time response of circulated seawater (only appear at H19-3) → Deeper location, faster response

Performance of intensive EC measurements in cross-shore array

Fig. 6.9

Layout of instruments used during intensive field measurements (18 May – 3 June 2009)
Findings:
1. Availability of fresh groundwater body at shallow depth at \( x = 23.1 \) m and \( x = 34.1 \) m.
2. EC values dynamically change with tide at deeper depths.

EC systematically decreases with increasing distance landwards.

Performance of intensive EC measurements in cross-shore array

Average values of groundwater EC in cross-shore array at three depths of measurement.

EC seawater = 4.615 S/m

Fig. 6.12

Performance of intensive EC measurements in cross-shore array

Performance of fresh groundwater discharge into sea

Observed long-term performance of precipitation and water level fluctuations

Important observations:
1. Groundwater fluctuations consistently follow the pattern of tidal fluctuations.
2. The tidal and groundwater levels are high in summers and low in winters.
3. Tide levels are higher than groundwater levels in the first five months in year 2009.

Performance of intensive EC measurements in cross-shore array

Fresh-saline groundwater interaction

High Tide: Maximum saltwater penetration. Saltwater pushes the freshwater further inland. Heavier saltwater move underneath the lighter freshwater.

Falling Tide: Fresh groundwater flows seaward. Upward seawater flow at \( x = 23.1 \) m.

Low Tide: Minimum seawater intrusion. Fresh groundwater discharges at maximum.

Rising Tide: Saltwater starts to intrude and reaches maximum state at following high tide.

Stages of maximum and minimum seawater intrusion

Findings:
- Depth to the F/S interface decreases as the shoreline is approached.
- Thickness of the diffusion zone = 1.2 m.
- Freshwater pushes salt water to the sea.
- Thicker diffusion zone.

Net groundwater head and normalized fresh groundwater discharge

Fresh groundwater discharge amounts to \( Q/k = 0.01 \) m on average for the first three years.
Assessment of fresh groundwater discharge $Q$ to the sea

**Fig. 6.22**

Obtained using tidal response technique

$C = 0.0335 \text{m}^2/\text{s}$

$Q \times C = Q_{	ext{discharge}}$ (n=0.4; d=8m)

$Q_{	ext{discharge}} = 1.45 \text{m}^3/\text{day per running meter}$

**CONCLUSIONS**

1. The measured performances of the tide and groundwater level fluctuations in the three observation wells on a cross-shore array over a representative one-year period show the consistent positive correlations between them.
2. The trend components of tide and groundwater level fluctuations can be resolved by taking a moving average over the time-series data. The identified trend components indicate that the inland groundwater heads are systematically higher than the tidal level, revealing the occurrence of fresh groundwater discharge toward the sea.
3. The Fourier spectral analyses of the de-trended tidal data permitted the identification of the four dominant harmonic components, $K_1$, $O_1$, $M_2$, and $S_2$. The amplitudes of the dominant tidal components at Fujie port are compatible with the field performance in the Seto Inland Sea reported by Fujiwara (1981).
4. The application of Fourier analyses facilitated the evaluation of the amplitude decay and time lag of groundwater responses to each of the dominant tidal components, in a manner compatible with the theoretical predictions. The tidal-response procedure thus proves to be a reliable one, facilitating the identification of the aquifer transfer coefficient ($C$) under field conditions.

Seasonal evolution of freshwater-saline water interface

**Fig. 6.23**

The predicted depth $h$ to S/F from June-December 2008 approximates to the observed depth 4.2m from EC measurements

**CONCLUSIONS (Contd.)**

1. The continuous measurements of tide and groundwater level variations captured the event-accentuated groundwater responses during typhoon-induced storm surge on 6 September 2005. The storm surge induced a rapid rise of the groundwater table by 0.88m. The event-accentuated rise in the groundwater level was independently supported by the sharp drop in the soil suction measurement at elevation T.P.+1.17m.
2. The groundwater fluctuations predicted using 2D FE analyses reproduce nicely the measured performance of groundwater fluctuations during the passage of typhoon 0514 and suggests that the hydraulic linkage between the sea cliff and frontal sand beach manifests "hanging springwater".

What happened when the net groundwater head $\zeta$ was negative in value?

**Observed performance during the early five months in year 2009**

- When $\zeta > 0$ — The exit remains open.
- When $\zeta < 0$ — The width of the outlet reduces to zero, eventually permitting the freshwater body to sustain.

**CONCLUSIONS (Contd.)**

1. The dynamics of saltwater-freshwater interaction was captured in term of the intensive field measurements. At high tide the saltwater-freshwater interface moves landward and takes the stage of maximum seawater intrusion. In the following low tidal stage, the interface was pushed back to the sea by enhanced fresh groundwater flow. The thickness of the dispersion zone is found to be 1.2m at the stage of maximum seawater intrusion and it becomes wider at the stage of minimum seawater intrusion under low tide.
2. The long-term observations of groundwater conditions permitted the normalized fresh groundwater discharge ($Q/k$) to be determined at 0.01m on average.
3. The sharp-interface approach to estimating the configuration of saline water-freshwater interface is applicable to the situation when the net groundwater head inland is positive in value. This methodology, in combination with the tidal response method for determining the aquifer constant $C$, permitted an estimate of the fresh groundwater discharge to the sea on Taniyagi Beach; namely, $Q = 1.45 \text{ m}^3/\text{day per running meter}$ of the beach.
4. The long-term field observations reveal that once a body of fresh groundwater is developed, it can withstand subsequent, continued exposures to tidal forcing as long as the hydrological conditions in the hinterland are maintained.