EGU2020-19014

Observation of gravity fluctuations due to tide-induced groundwater table fluctuations with two superconducting gravimeters

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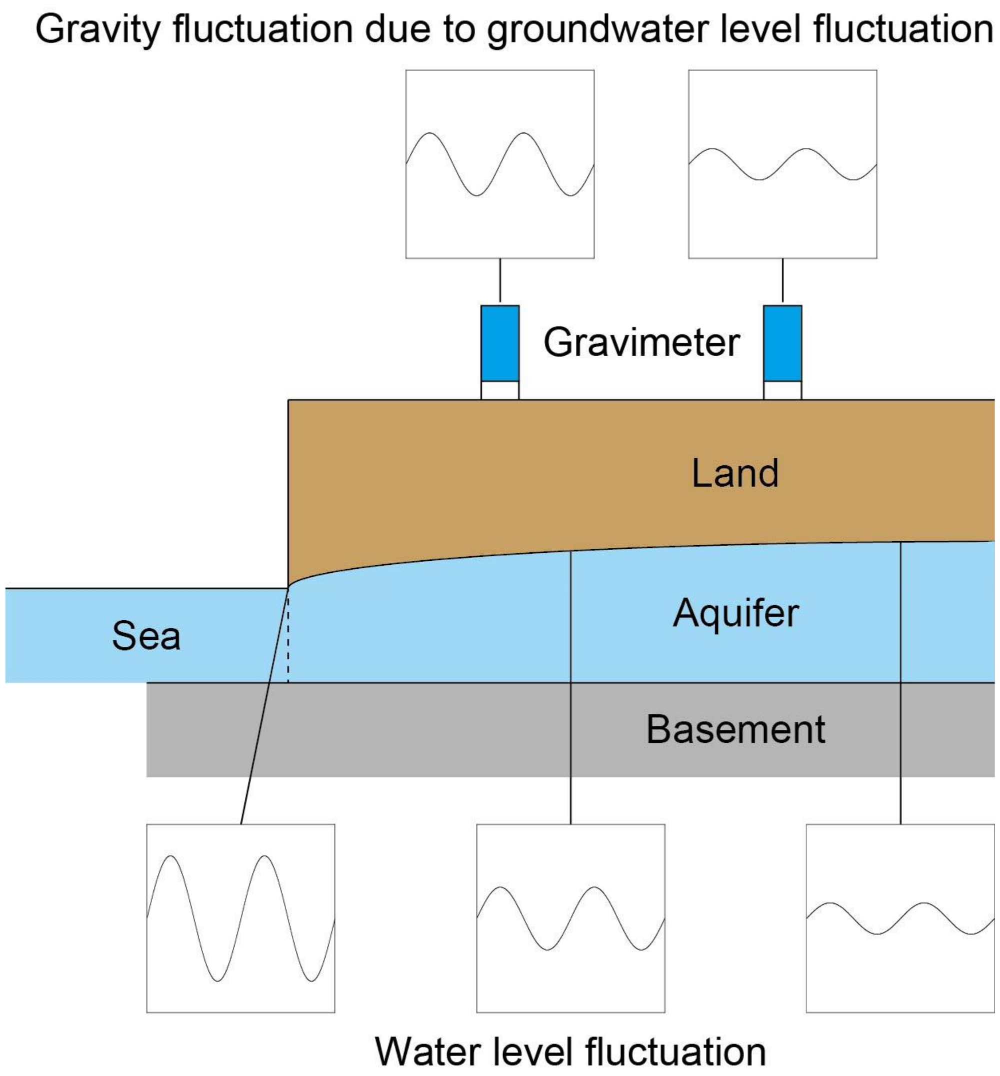
Background

- Analyzing groundwater level response to sea level fluctuation is one method to estimate hydraulic properties of coastal aquifers (e.g., Aichi et al., 2011)
- Gravity data obtained near the sea are expected to include gravity fluctuations due to the tide-induced groundwater level fluctuations (Hagiwara, 1977)
- The amplitude and phase of the gravity fluctuation depend on the distance from the sea
- Common-mode differencing removes signals that affect multiple gravimeters equally and reveals differences in gravity fluctuations due to locally different groundwater level fluctuations
- Gravity data may provide additional information to help estimate aquifer hydraulic properties



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Purpose

- **Investigate whether hydraulic properties of coastal unconfined aquifers can be estimated by analyzing gravity data obtained at multiple locations near the sea**

- **Outline:**
  1. Obtain continuous groundwater level and gravity data near the sea
  2. Determine tidal parameters from the gravity and groundwater level data
  3. Estimate aquifer hydraulic properties from the results of tidal analysis
  4. Compare the hydraulic properties estimated from the gravity and groundwater level data

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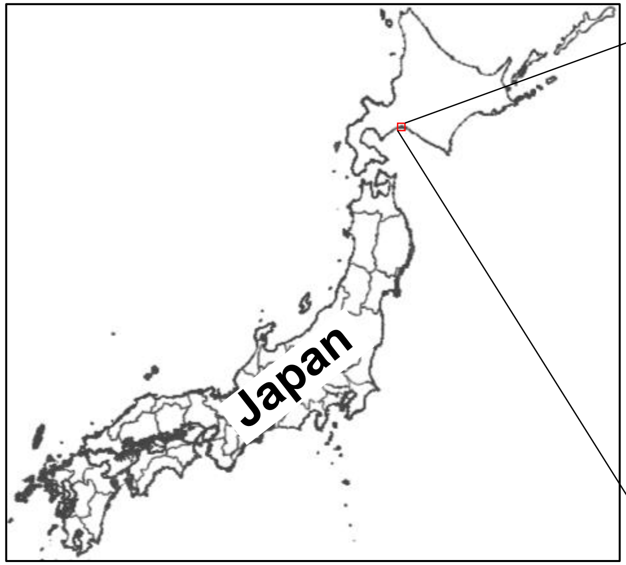
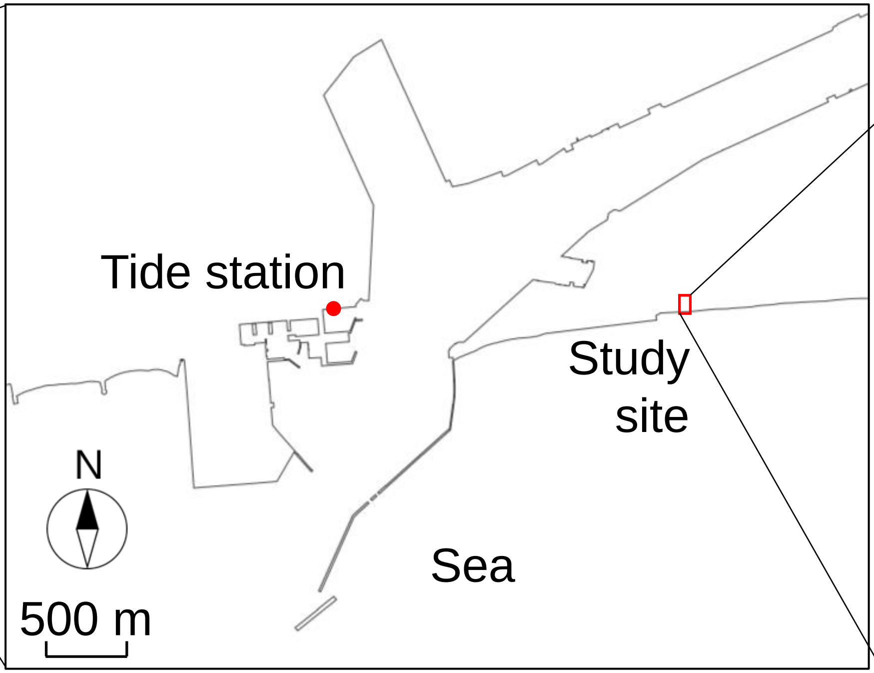
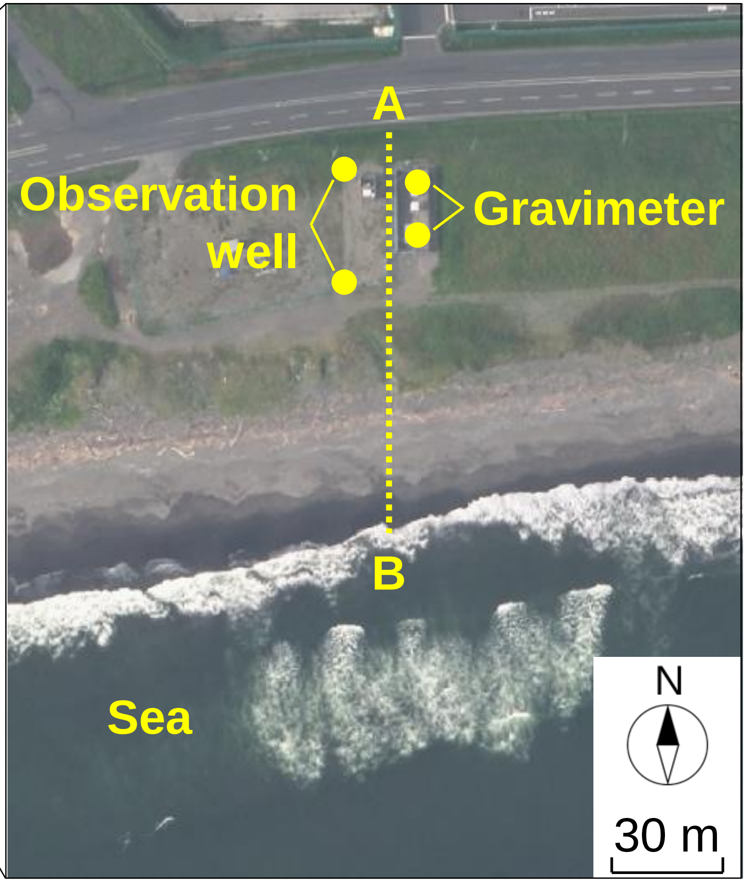
Study area

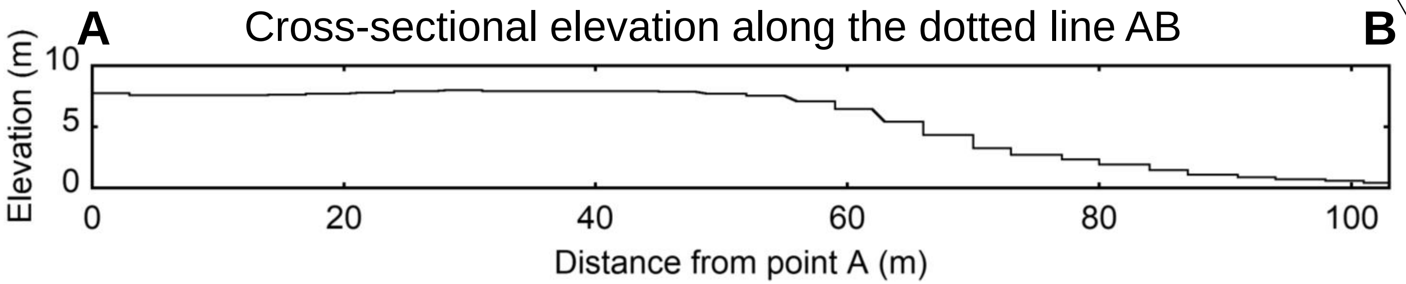




(The tidal station is operated by Hokkaido Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism)



(Maps and elevation data are based on the blank map, aerial photograph, 5-m grid digital elevation model available from the Geospatial Information Authority of Japan (http://www.gsi.go.jp))



Field measurement

Gravity

Superconducting gravimeter (SG)
(iGrav by GWR Instruments, Inc.)

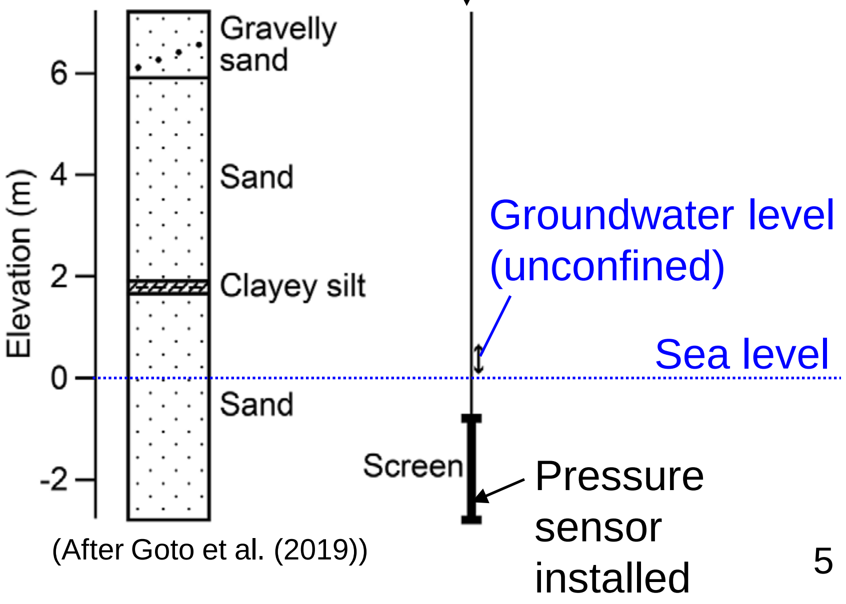
Observation history:

Mar 2015	One SG installed
Jul 2018	Two additional SGs installed
Sep 2018	One old SG removed

- Relative gravimeter that measures changes in gravity
- Continuous recording at 1 s intervals
- 1 nGal (= 1×10^{-11} m/s^2) sensitivity in the frequency domain (Hinderer et al., 2015)

Groundwater level

Observation well
(Both wells have similar design)



(After Goto et al. (2019))

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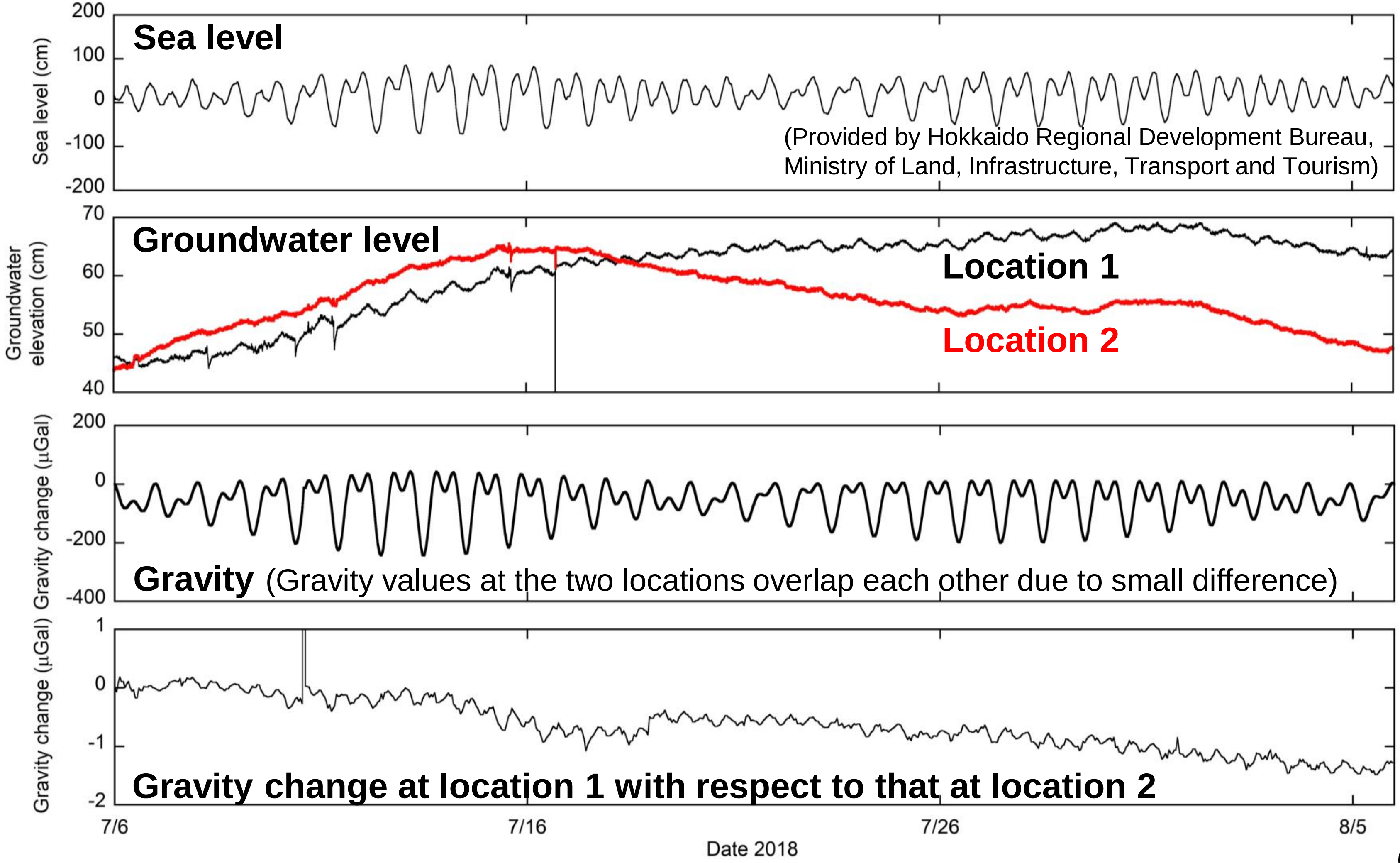
Examples of the measured results

(Based on the aerial photograph available from the Geospatial Information Authority of Japan (http://www.gsi.go.jp))



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Tidal analysis

(Based on the aerial photograph available from the Geospatial Information Authority of Japan (http://www.gsi.go.jp))

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Tidal parameters calculated using BAYTAP-G software (Tamura et al., 1991)
(The units of amplitude of water level and gravity difference are cm and μGal, respectively, and the unit of phase is radian)

	O1 Amp.	P1,S1, K1 Amp.	M2 Amp.	S2,K2 Amp.	O1 Phase	P1,S1 K1 Phase	M2 Phase	S2,K2 Phase
Sea level	18.67	23.02	31.62	14.29	0.56	0.24	1.31	0.58
Groundwater level 1	0.30	0.48	0.36	0.18	-1.11	-0.91	-0.21	-1.55
Groundwater level 2	0.17	0.20	0.11	0.13	-1.73	-1.24	-0.43	-1.82
Gravity difference	0.033	0.034	0.076	0.038	1.65	0.71	1.86	1.55

Groundwater level has a smaller amplitude and a larger phase delay farther from the sea

This preliminary study focuses on the component (P1, S1, K1) which has the largest amplitude in the groundwater level 1

Hydraulic parameter estimation: groundwater level

- Groundwater flow on a 2D cross section perpendicular to the coastline was calculated using the Boussinesq equation assuming isotropy and homogeneity of the aquifer and applying the Dupuit-Forchheimer assumption

- The hydraulic diffusivity that reproduces the amplitude and phase of the component (P1, S1, K1) of the groundwater level 1 was determined respectively

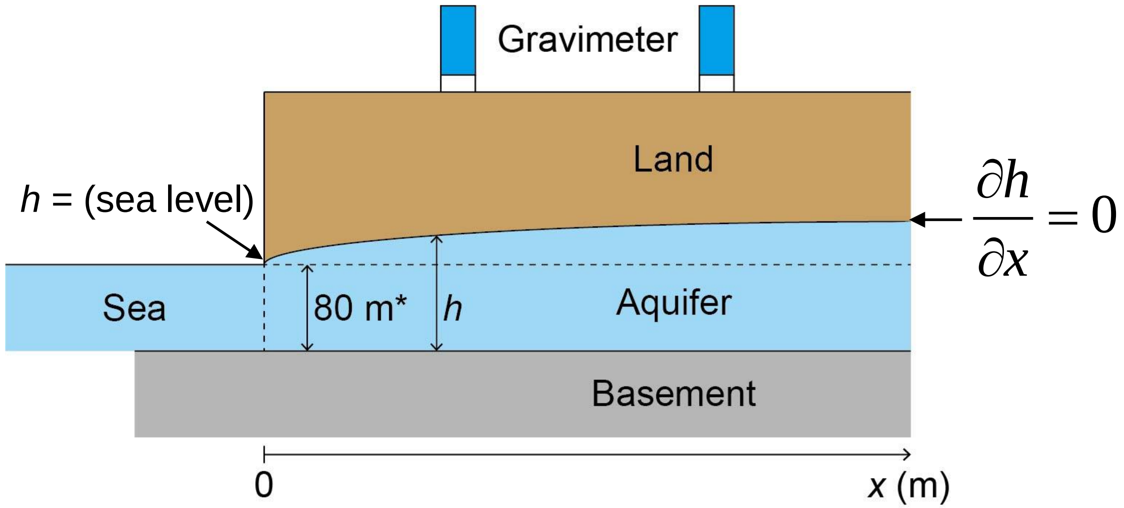
- Determined hydraulic diffusivity:
  - 2.8 × 10^{-3} m^2/s (phase)
  - 1.0 × 10^{-2} m^2/s (amplitude)
  - 1.2 × 10^{-1} m^2/s (phase)

  (Since the phase has a period of 2π, two values close to the value determined from the amplitude were determined)

Boussinesq equation

$$K \frac{\partial}{\partial x}\left(h \frac{\partial h}{\partial x} \right) = n_e \frac{\partial h}{\partial t}$$

K: Hydraulic conductivity
n_e: Effective porosity



* Based on Geological Survey of Hokkaido (1996)

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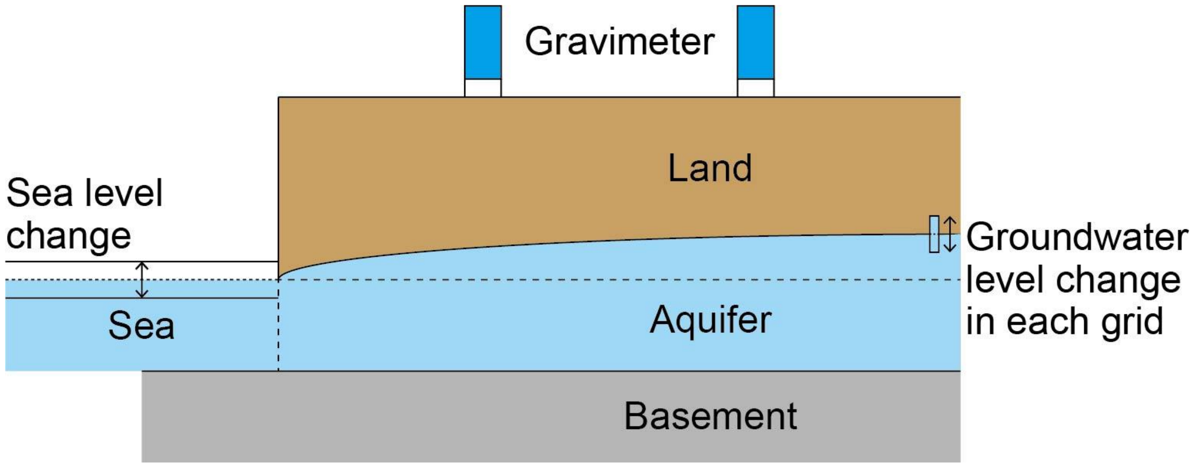
Hydraulic parameter estimation: gravity



- The difference in gravity values measured by each gravimeter was assumed to be the difference in gravity changes due to sea level fluctuations and tidal-induced groundwater level fluctuations
- Gravity fluctuations due to sea level fluctuations and tidal-induced groundwater level fluctuations were calculated using Newton's law of universal gravitation
- K and n_e were determined through a trial and error approach to reproduce the component (S1, P1, K1) of the gravity difference
- Determined parameters:
  - K: 3.8×10^{-5} m/s (Almost typical value for sand)
  - n_e: 0.335 (Almost typical value for sand)
  - Hydraulic diffusivity calculated from the determined K and n_e: 9.1×10^{-3} m^2/s (Consistent with that determined from groundwater level data)

It is suggested that analyzing gravity data obtained at multiple locations near the sea would provide additional information useful in estimating hydraulic properties of coastal unconfined aquifers

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Summary

- Continuous groundwater level and gravity data were obtained using two superconducting gravimeters in a coastal region in Japan
- Differences in gravity obtained at multiple locations near the sea extracted by common-mode differencing included fluctuations with frequencies almost similar to the tidal frequency
- The hydraulic diffusivity of the unconfined aquifer was estimated from gravity and groundwater level data using the Bousinesq equation, and the results were consistent with each other
- It was suggested that gravity data obtained at multiple locations near the sea would provide additional information useful in estimating hydraulic properties of coastal aquifers

- Further study requires evaluation of the uncertainty of the estimation, the applicability of the method to longer-term gravity data, and the sensitivity of parameters to gravity fluctuations

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Acknowledgements:

- This presentation is based on results obtained from a project (JPNP18006) commissioned by the New Energy and Industrial Technology Development Organization (NEDO) and the Ministry of Economy, Trade and Industry (METI) of Japan
- We are grateful to the Tomakomai Port Authority for their permission to use public space and Japan CCS Co., Ltd. for their support in this study

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