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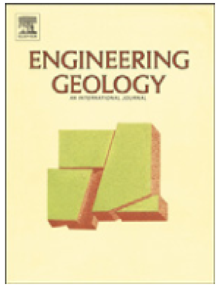

Experimental study on the vertical deformation of sand caused by cyclic withdrawal and recharging of groundwater

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Date : 2024/12/27

- **Land subsidence** is the **lowering or collapsing of the ground surface** caused by natural phenomena or human activities including the exploitation of groundwater resources or changes in drainage caused by the excavation of the underground *(Zheng et al., 2005)*.

- Land subsidence will cause flooding in low-lying areas, sea water invasion in coastal cities and damage of buildings *(Pan and Li, 2012)*. Therefore, **ground vertical deformation (subsidence and rebound)** is an important topic of geotechnical engineering.

- Previous studies have analyzed the relationship between deformation and the change of groundwater level. Various models are also used to simulate land subsidence. Most of the studies **rely on observation data**, and these surveys are cost time and expensive.

- The viscous behavior of clay has been a subject of many studies (*Kutter and Sathialingam, 1992; Fodil et al., 1997; Yin and Zhu, 1999; Yin et al., 2002; Karim et al., 2010)*, while **sand is less often discussed** because sand is usually regarded as a non-viscous material.

Objective :

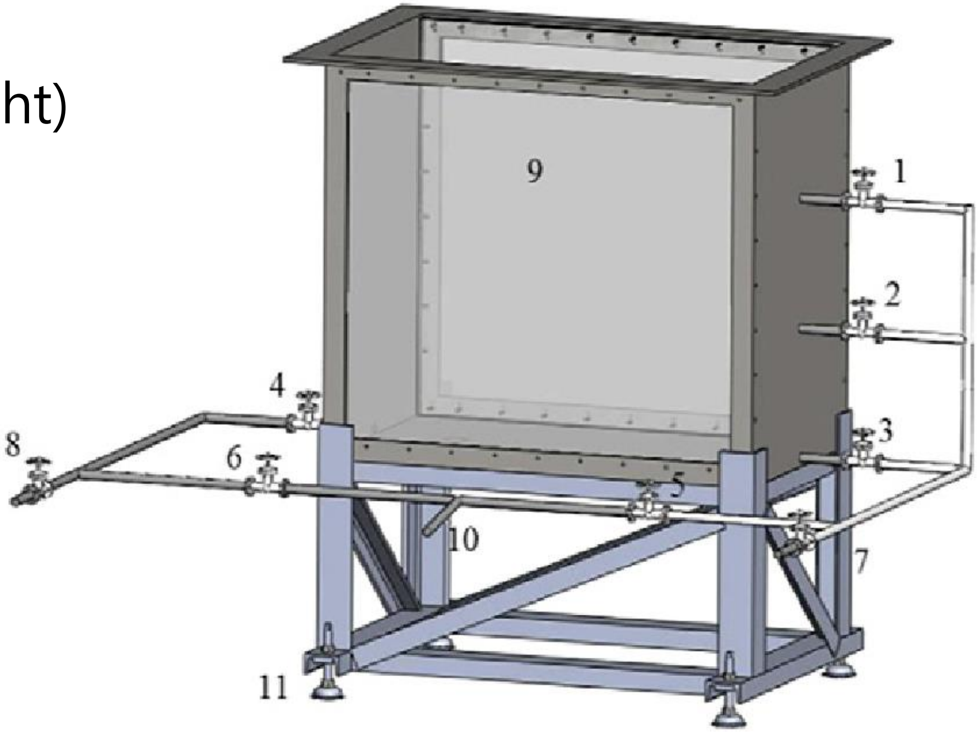
In this study, **a laboratory-scale model test** of **sand** to present a more convenient method to study soil subsidence due to groundwater extraction.

Laboratory model

- Box size :
  1000mm (length) × 600mm (width) × 892mm (height)

- Box making :
  1) The front and back sides were made of **glass** → to observe the experiment and measure the soil deformation (using a ruler fixed to the glass panel)
  2) The lateral and bottom sides were made of **steel plates** → to let the box shell stable

- Valves : Drainage / Water recharge



1,2,3,4	Inlet/Outlet valve	5,6	Inlet valve
7,8	Outlet valve	9	Glass panal
10	Inlet pipe	11	Support frame

Fig. 1. Lateral and front views of the model box and pipes.

Sand sample preparation

- The sand used is standard **Pingtan sand** from Fujian, China. It is a natural **quartz sand** (96% SiO_2), $d_{50} = 0.34mm$(medium sand), mixture of elongated and spherical grains.
- The tests for this study all use the same sand but prepare in three different ways to put the sand into the box, defined as loose sand、medium dense sand、dense sand.

Table 4
Preparation techniques and physical parameters for each sample.

Specimen	Sample preparation technique	Void ratio	Relative density	Density (kg/m^3)
Loose sand	Dry pluviation with a fall height of nearly 0 mm.	0.775	0.222	1489
Medium dense sand	Dry pluviation with a fall height of 400 mm.	0.731	0.356	1527
Dense sand	Combination of dry pluviation (400 mm fall height) with tamping using a hammer of 2.5 kg weight at the sample heights of 250 mm, 500 mm and 700 mm.	0.577	0.824	1676

Experimental steps

- **Saturation process**
  1) After sample preparation, leave the sample for 12 hours in order for the internal forces within the sand to come into balance.
  2) Then add water to the box. After the sand is completely immersed in water, leave it for 24 hours to completely saturate it.
- **Withdrawal test**

  When **water level drops to about 200 mm**, stop withdrawal and leave the sample for 24 hours to stabilize the water level and subsidence.
- **Recharging test**

  When **water level is slightly above the soil surface**, stop recharging and leave the sample for 24 hours to stabilize the water level and subsidence.

Cyclic Withdrawal & Recharging steps to test multiple times.

Water level change and vertical deformation of the soil

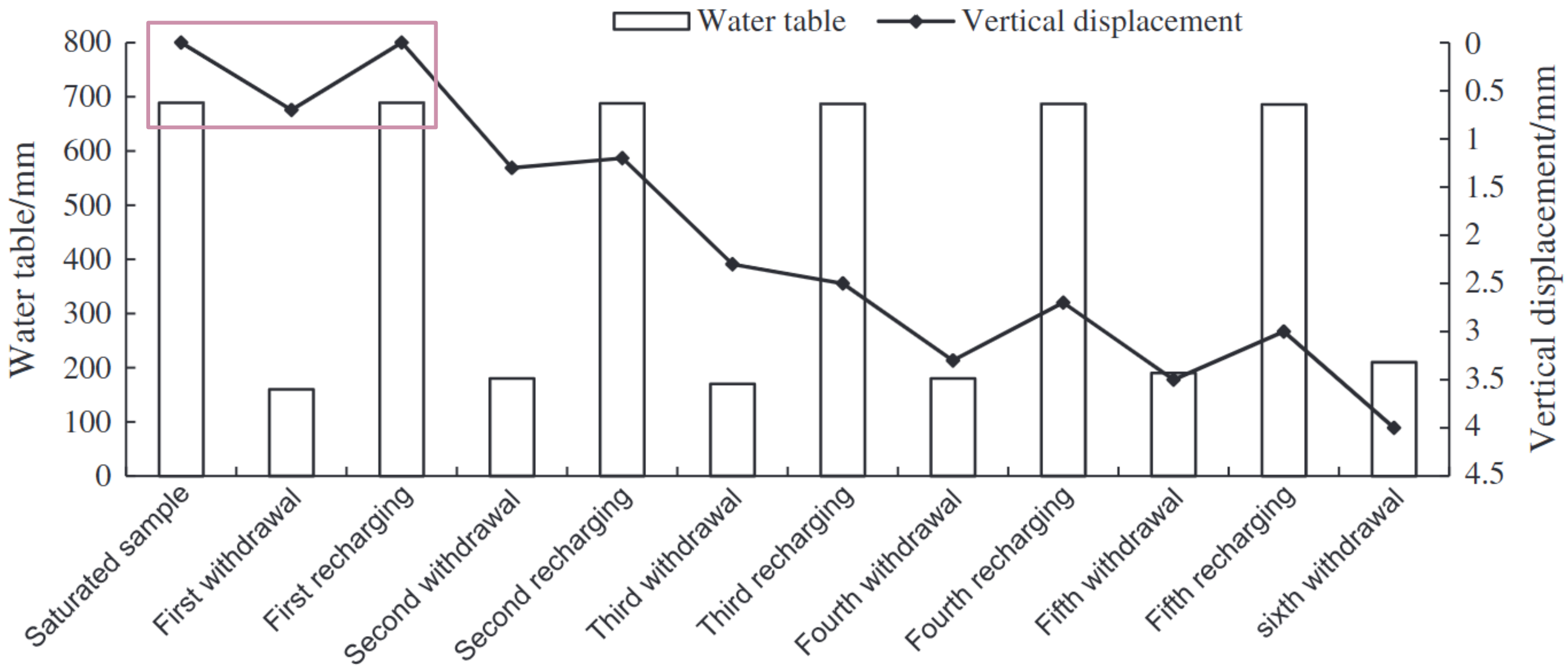
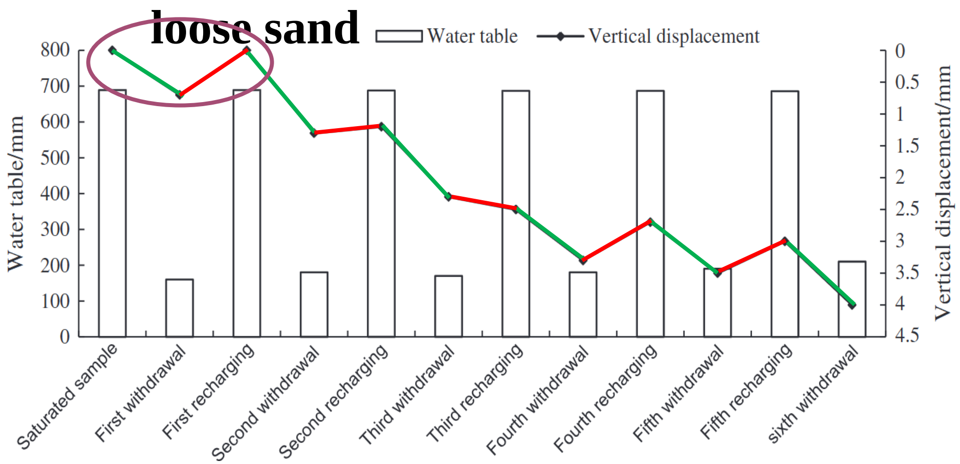


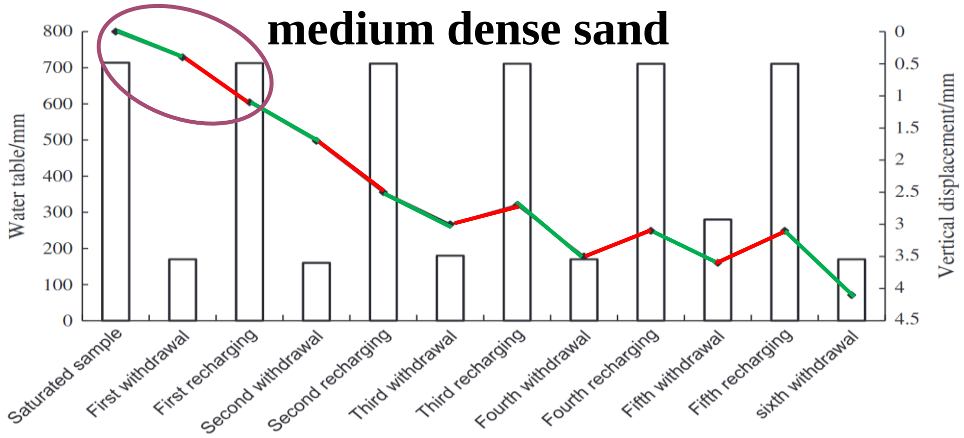
Fig. 2. Variation of water table and vertical deformation for the loose sand.

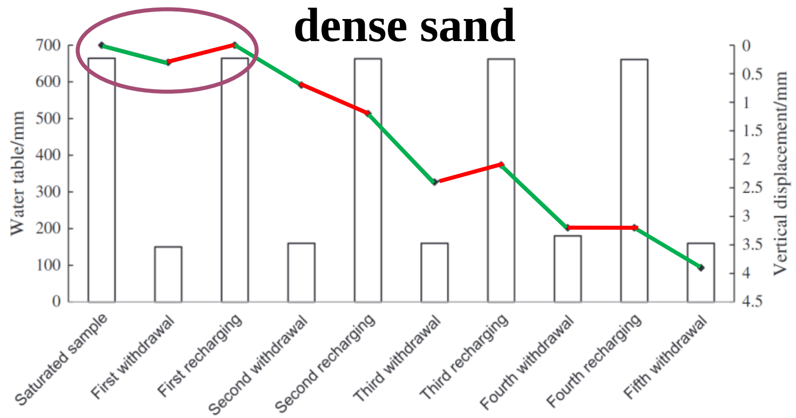
First withdrawal → subsidence

First recharging → rebound

The **total displacement** for the **first cycle is 0 mm**.







- Withdrawal : Lowering water will cause subsidence.
- Recharging : Raising water may reduce subsidence (soil rebound), or make more subsidence.

- First Cycle :
  - Loose sand & Dense sand

    The subsidence value ≈ The rebound value
  - Medium dense sand

    Recharging water tends to increase subsidence

→ This difference in the initial behavior of sand can be explained **based on the initial microstructure of the sand sample**.

Initial microstructure of the sand sample

- **Loose sand**

  Use dry pluviation technique (fall height of nearly 0 mm)

  → Grains cannot be rearranged while falling, so the distribution is more random.

- **Medium dense sand**

  Use dry pluviation technique (fall height of 400 mm)

  → May cause the particles collisions during falling, and to be in the horizontal direction, resulting in higher anisotropy. Particles have less contact in the vertical direction, makes the soil less to rebound when recharging.

- **Dense sand**

  Use dry pluviation technique (fall height of 400 mm) + tamp with a 2.5 kg hammer

  → Tamping the soil may change the deposited direction of particles, in order to fill the available spaces, create more random directions of grains *(Nemat-Nasser and Takahashi, 1984)*.

Sand deformation under withdrawal and recharging conditions

The deformation of the sand can calculate through the **effective stress variation (Δp)** and **strain (ε)** by the material.

$$\gamma' = \gamma - \gamma_w \quad (1)$$

γ : wet (saturated) unit weight of sand
γ' : submerged (effective) unit weight of sand
γ_w : unit weight of water

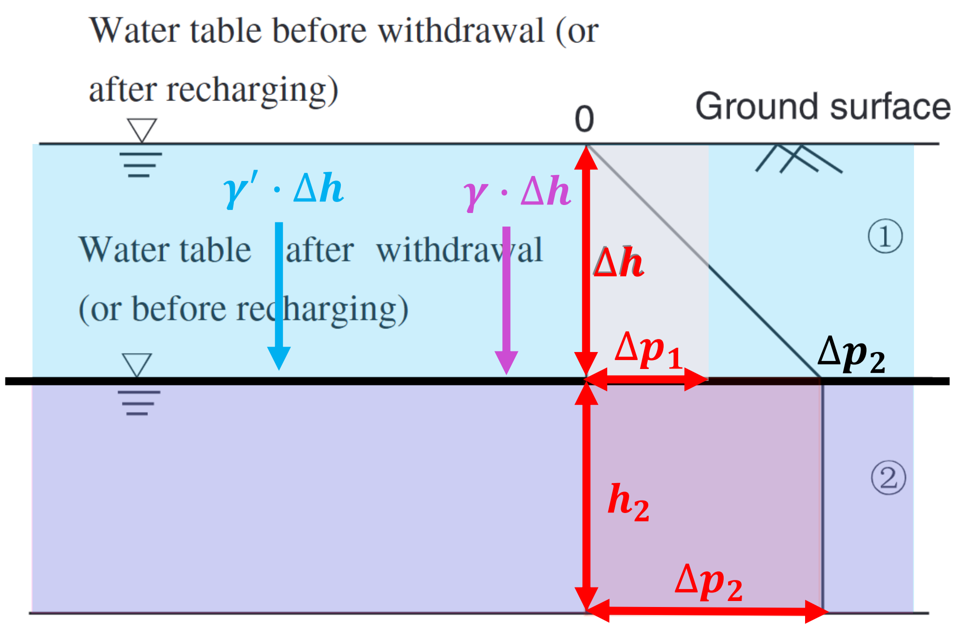


Fig. 5. Sketch of the additional stress distribution.

$$\text{Withdrawal :} \quad \Delta p_2 = \gamma \cdot \Delta h - \gamma' \cdot \Delta h \approx (\gamma_w + \gamma') \cdot \Delta h - \gamma' \cdot \Delta h = \gamma_w \cdot \Delta h \quad (2)$$

$$\text{Recharging :} \quad \Delta p_2 = \gamma' \cdot \Delta h - \gamma \cdot \Delta h \approx \gamma' \cdot \Delta h - (\gamma_w + \gamma') \cdot \Delta h = -\gamma_w \cdot \Delta h. \quad (3)$$

Δp_2 : additional stress due to the change of water table
Δh : the change of water level

$$\Delta p_1 = \Delta p_2 / 2 \quad (4)$$

Δp_1 : average additional stress acting on a sand layer between the initial and final water table

$$\Delta p = (\Delta p_1 \cdot \Delta h + \Delta p_2 \cdot h_2)/(\Delta h + h_2)$$
$$= \begin{cases} \gamma_w \cdot \Delta h \cdot (\Delta h/2 + h_2)/(\Delta h + h_2) & \text{withdrawal} \\ -\gamma_w \cdot \Delta h \cdot (\Delta h/2 + h_2)/(\Delta h + h_2) & \text{recharging} \end{cases} \quad (5)$$

Δp : effective stress variation acting on the sand due to withdrawal
h_2 : the depth of water table after withdrawing water

$$\varepsilon = \Delta l / h \quad (6)$$

Δl : vertical deformation
h : original height of the sand

Withdrawal → pore water pressure ↓ → **effective stress ↑**
Subsidence → **strain ↑**

Recharging → pore water pressure ↑ → **effective stress ↓**
Rebound → **strain ↓**

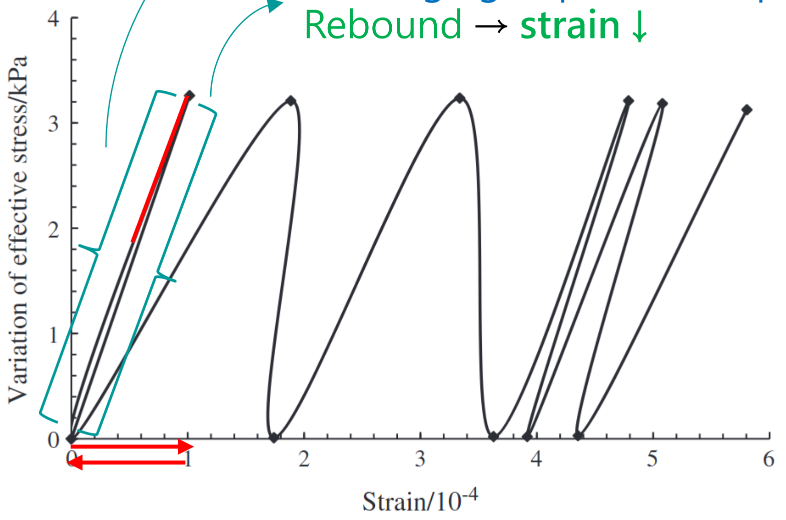


Fig. 6. Stress:strain plot for the loose sand.

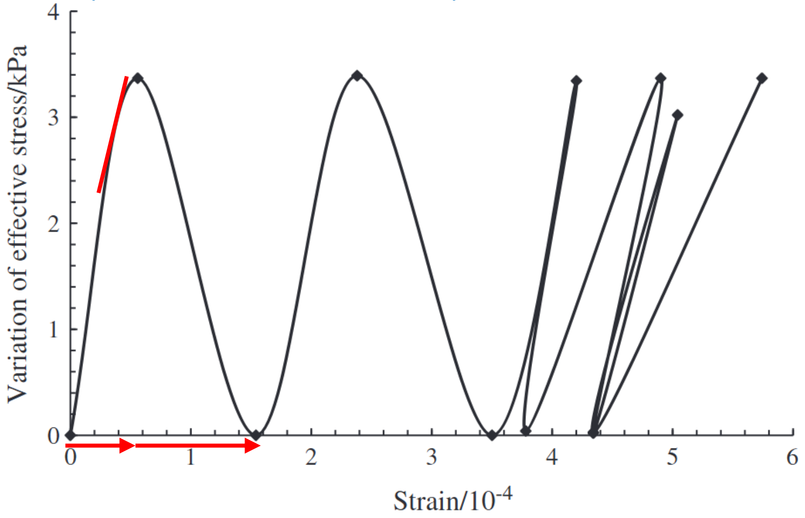


Fig. 7. Stress:strain plot for the medium dense sand.

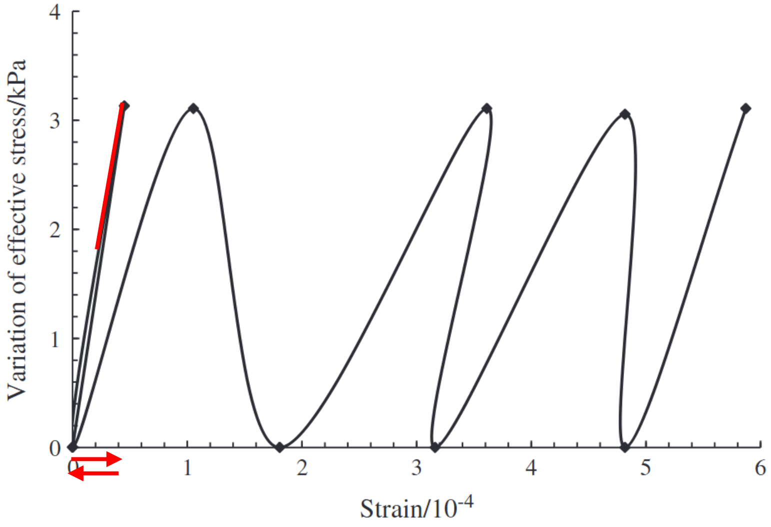


Fig. 8. Stress:strain plot for the dense sand.

	loose sand	**medium dense sand**	**dense sand**
First cycle	Larger strain (about 2) Rebound, elastic deformation	Medium strain (about 1.6) No rebound, plastic deformation	Smaller strain (about 0.8) Rebound, elastic deformation
Compression modulus ($\Delta\sigma/\Delta\varepsilon$)	3.21 MPa	4.81 MPa	6.93 MPa
Second & Third cycles	No rebound or less rebound, plastic deformation (irreversible).		
Third & thereafter cycles	Similar deformation behavior. There is normal subsidence and rebound vibrations. Indicates the initial structure has been destroyed and the density of the sample has been changed.		

- This study conducted an experimental study on the deformation behavior of quartz sand by cyclic withdrawal and recharging of groundwater.

- This study explores the deformation behavior patterns of sand with different initial densities. Future work will focus on research a microstructure effect on the withdrawal and recharging of sands.

- It can be seen from this study that in some cases, water recharging can reduce land subsidence. Therefore, it is important to establish the soil behaviors for which this measure can be used to control land subsidence.

Comments

- No mention of where to measure in the sandbox.
- There is no mention of how many times the experiment was performed, the result of subsidence value is only once or the average of many times.
- The subsidence results showed less than 1 mm, which is a very small value. Only mentions using a camera, but no mention of image analysis method.

Thanks for your listening

Laboratory model

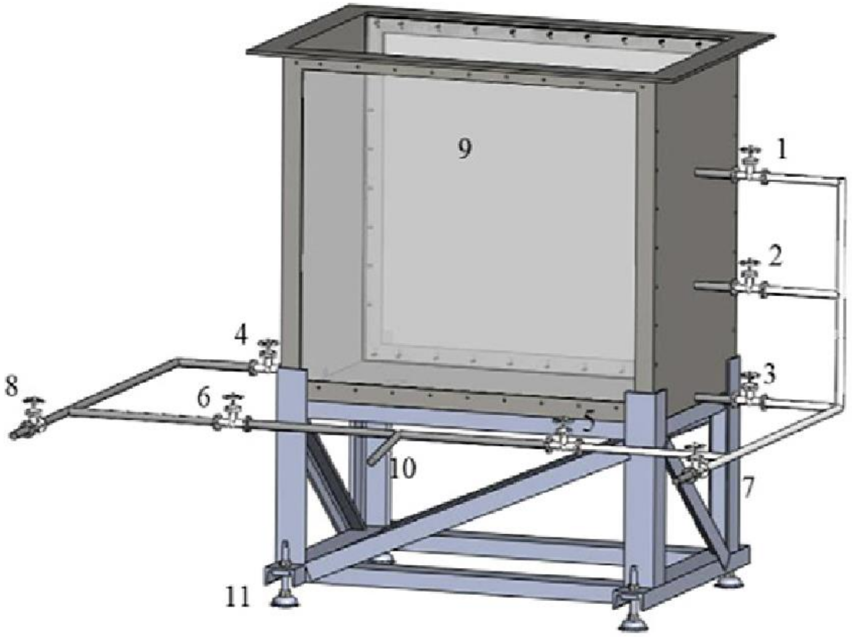


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Fig. 1. Lateral and front views of the model box and pipes.

Valves :

1) Drainage → Open 1~4, 5 and 8. Close 6 and 7. Water flows from 123 to 4.
2) Water recharge → Open 1~4, 6 and 7. Close 5 and 8. Water flows from 4 to 123.

Sand description

Table 1
Particle size distribution for the Pingtan sand.

Particle diameter (mm)	<0.25	0.25–0.45	0.45–0.65	>0.65
Content (%)	6	51 ± 5	40 ± 5	3

Table 2
Particle size distribution characteristic parameters.

d_{50} (mm)	C_u	C_c
0.340	1.542	1.104

d_{50}: median particle size — 0.340: medium sand

C_u: Uniformity Coefficient — Cu < 4：Uniform, small particle size range

C_c: Curvature Coefficient — 1 ≤ Cc ≤ 3 : good distribution and smooth curve

Table 3
Physical indexes.

ρ_{dmax} (g/cm^3)	ρ_{dmin} (g/cm^3)	G_s (g/cm^3)	e_{max}	e_{min}
1.74	1.43	2.643	0.848	0.519

ρ_d : Dry Density　G_s : Specific Gravity　e : Void Ratio

- 最大乾密度 ρdmax=1.74 : 代表土壤在最密狀態下的單位體積質量。此值偏高，說明該砂土的顆粒形狀和排列方式有助於達到高密度。
- 最小乾密度 ρdmin=1.43 : 表示土壤在最鬆散狀態下的單位體積質量。此值與最大乾密度的差異不大，顯示砂土的顆粒形狀和堆積性質偏向均勻。
- 比重 Gs=2.643 : 顆粒的固體比重通常為 2.6~2.7，此值偏向正常範圍，顯示該砂土顆粒是典型的矽質砂（土壤中常見的礦物組成）。
- 最大孔隙比 $e$max=0.848 : 孔隙比代表土壤中孔隙空間的相對大小。此值中等，表明砂土在最鬆散狀態下孔隙較大，但仍在常見砂土範圍內。
- 最小孔隙比 $e$min=0.519 : 當砂土在最緊密排列時的孔隙比。此值偏小，表示該砂土具有良好的壓實性，密度高且穩定。

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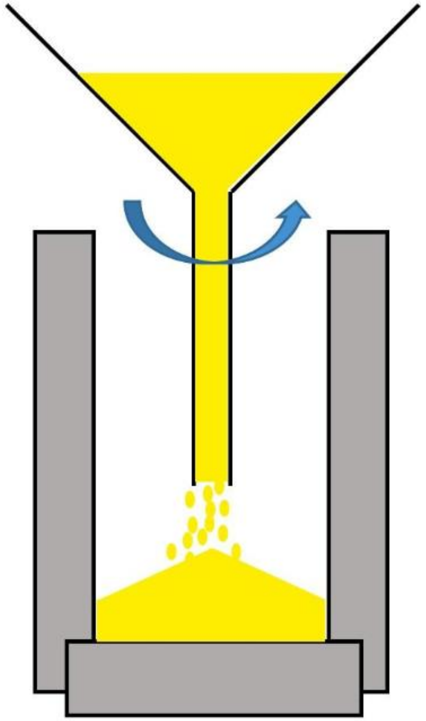
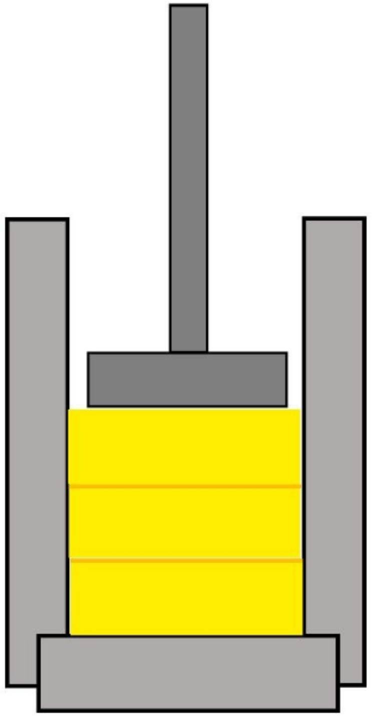


Dry Pluviation



Tamping

Table 5
Subsidence values due to withdrawal and recharging.

	Subsidence value per half cycle (mm)			Cumulative subsidence value (mm)		
	Loose sand	Medium dense sand	Dense sand	Loose sand	Medium dense sand	Dense sand
First withdrawal	0.7	0.4	0.3	0.7	0.4	0.3
First recharging	−0.7	0.7	−0.3	0	1.1	0
Second withdrawal	1.3	0.6	0.7	1.3	1.7	0.7
Second recharging	−0.1	0.8	0.5	1.2	2.5	1.2
Third withdrawal	1.1	0.5	1.2	2.3	3.0	2.4
Third recharging	0.2	−0.3	−0.3	2.5	2.7	2.1
Fourth withdrawal	0.8	0.8	1.1	3.3	3.5	3.2
Fourth recharging	−0.6	−0.4	0	2.7	3.1	3.2
Fifth withdrawal	0.8	0.5	0.7	3.5	3.6	3.9
Fifth recharging	−0.5	−0.5	–	3.0	3.1	–
Sixth withdrawal	1.0	1.0	–	4.0	4.1	–

Note: Negative value means rebound deformation.

- First cycle

Withdrawal : **Loose sand** has larger vertical deformation; **dense sand** has smaller vertical deformation.

Recharging : **Loose sand** and **dense sand** rebound, with more random particle distribution, are more likely to rearrange with the upward movement. **Medium dense sand** has no rebound due to the resistance of the horizontal arrangement of particles.

- Second & Third cycles

The subsidence caused by withdrawal is larger, while the rebound caused by recharging water is smaller.

- For the **medium dense sand**

Soil deformation caused by repeated changes in groundwater levels can destroy the initial microstructure, and it starts to rebound during later recharging.

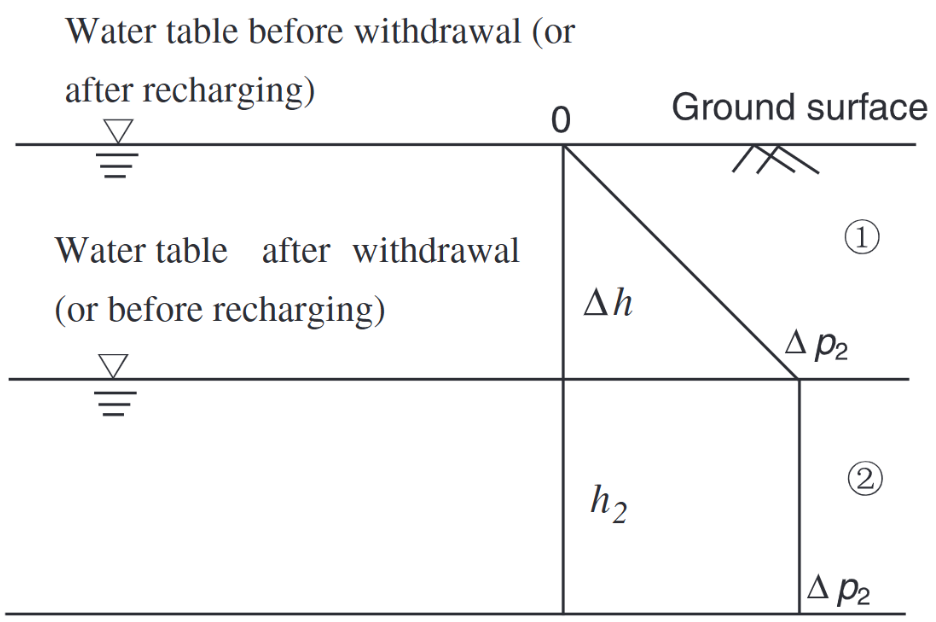


Fig. 5. Sketch of the additional stress distribution.

Δp_1 ?
Since the additional stress acting on the sand layer ① varies with a triangular distribution in depth, i.e. from 0 to Δp2 , hence its average variation can be obtained by taking half of the maximum value Δp_2 .

Strain evolution with the withdrawal–recharging cycles

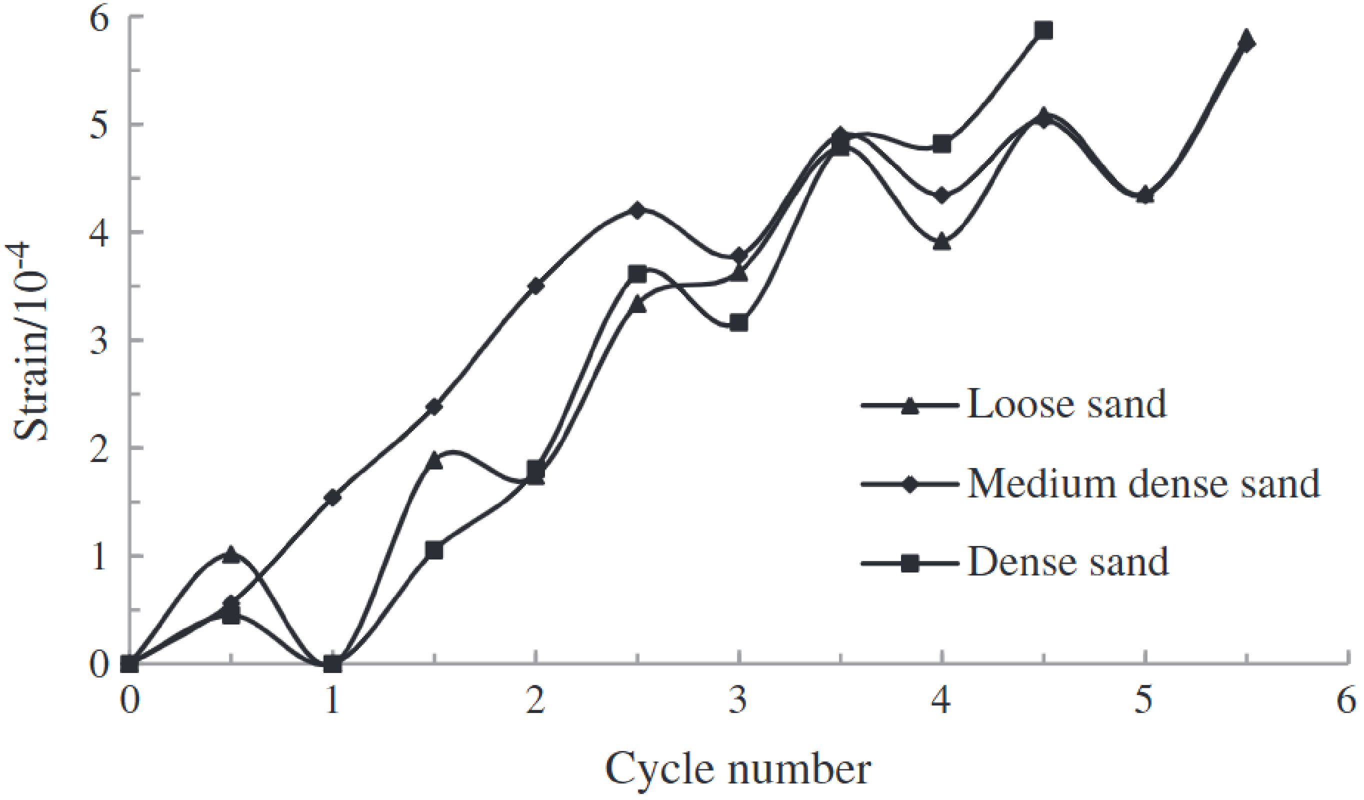


Fig. 9. Strain evolution with the number of cycles.