Aging, structuration, and creep behavior in sand

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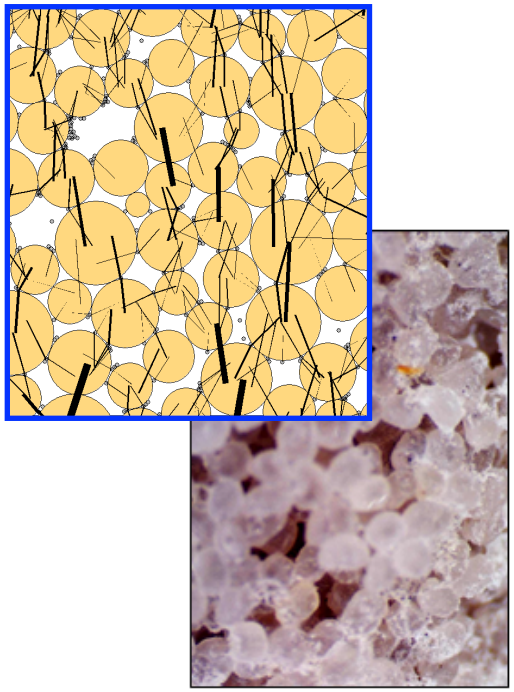
SCIENCE AND TECHNOLOGY

Lab. of Wave-based
Characterizations

Sep 01, 2014

Outline

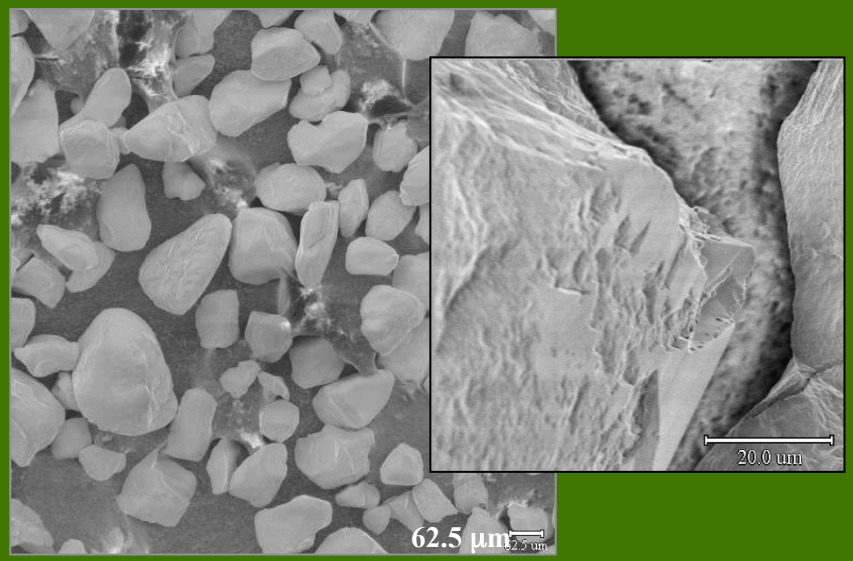
- Introduction
  - What is aging?
  - Omni-aging behavior
  - Proposed mechanisms



- Mechanisms of aging in sand
  - Our hypothesis
  - Numerical and experimental evidence

- Interesting soil behavior related to aging.

Introduction



What is aging?

Everything on the earth has at least one thing in common - everything changes with time.

Schmertmann, 1991

THE MECHANICAL AGING OF SOILS

By John H. Schmertmann,[1] Fellow, ASCE

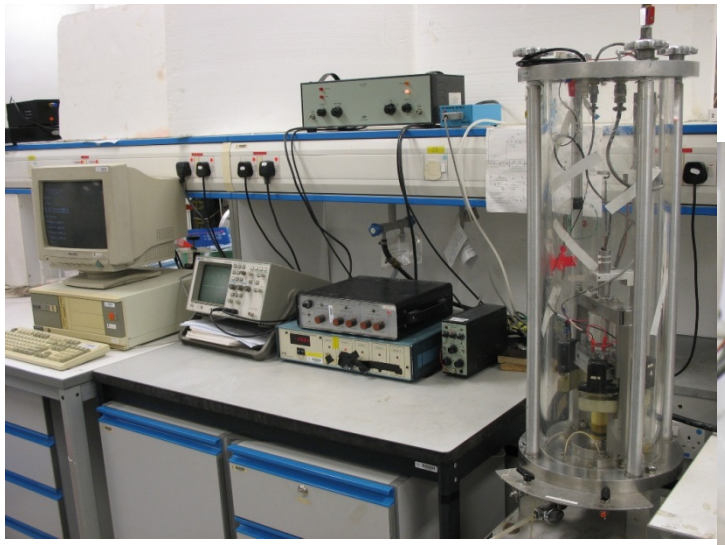
(The Twenty-Fifth Karl Terzaghi Lecture)

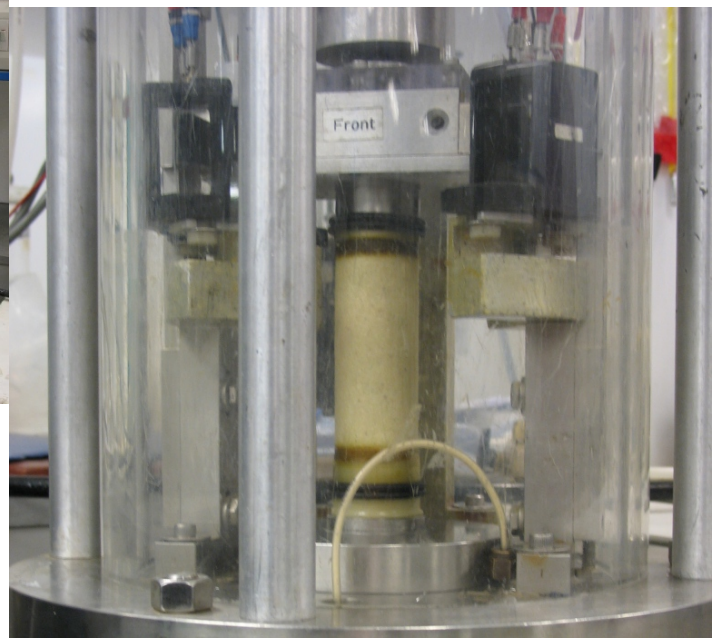
- Aging (creep, structuration):

Time-dependent changes of soil properties

What is Aging (an example)?

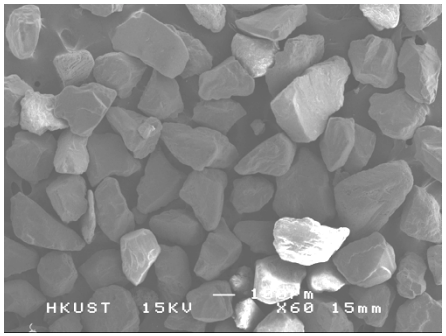
- Resonant column test on dry Toyoura sand.
- **$\sigma' = 35$ kPa, 7 days**
- **G_{max} & D_{min}**



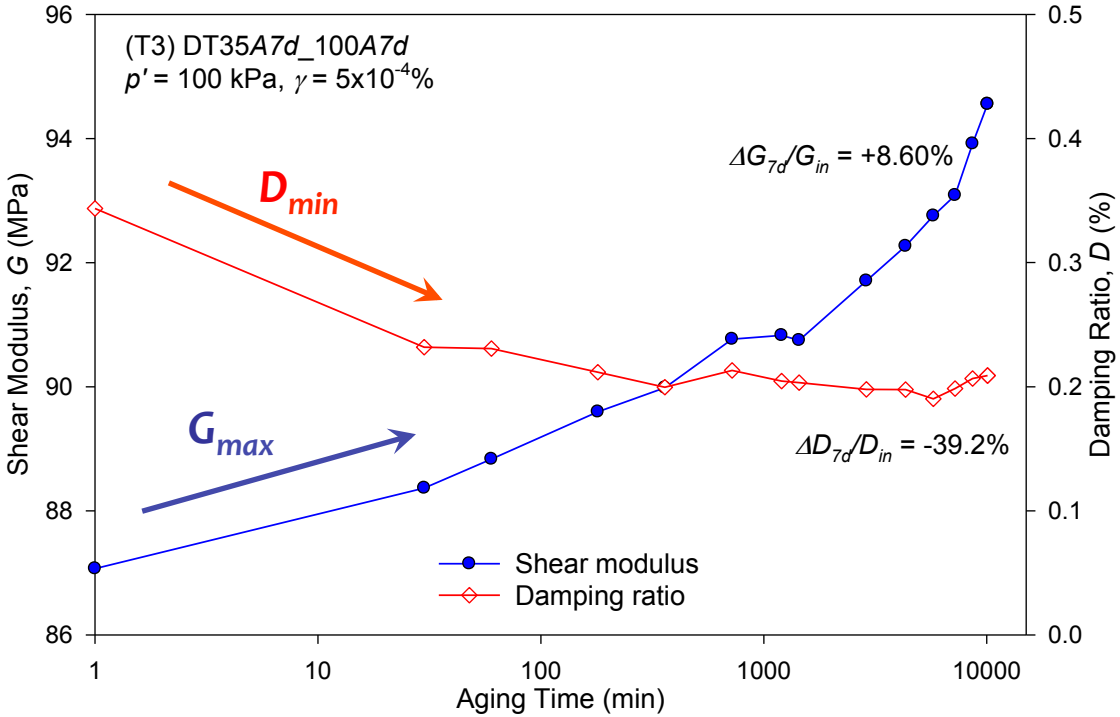


What is Aging (an example)?

- G_{7d}/G_{in} = +8.6%
- D_{7d}/D_{in} = -39.2%
- $\varepsilon_{axial} \approx 10^{-3}\%$ *(minute deformation)*



Why does such a minute deformation can produce significant changes in soil properties?



(Wang and Tsui 2009)

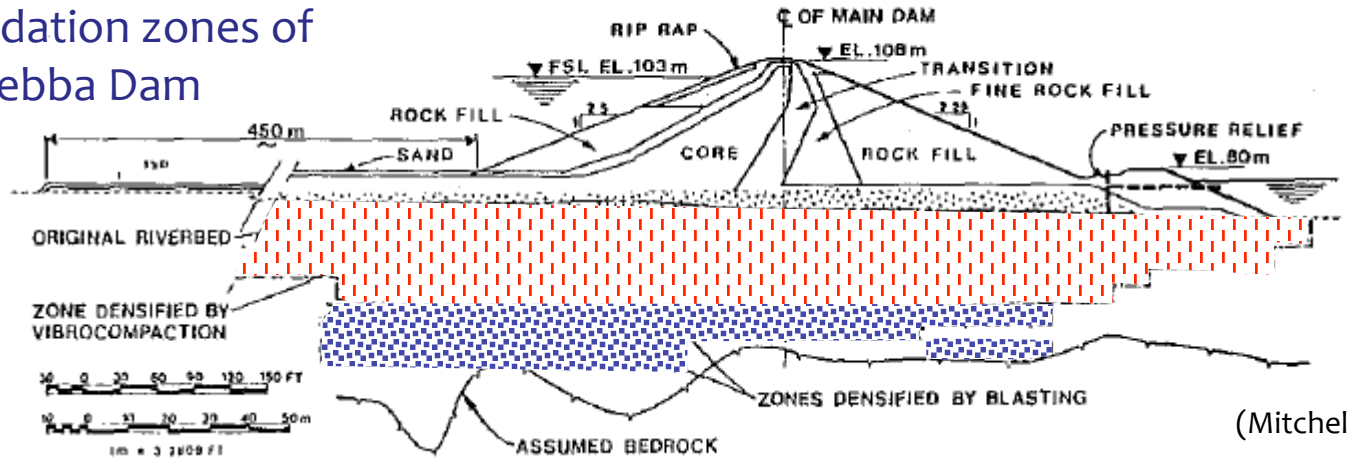
Omni-aging behavior

- **Increasing shear stiffness** (e.g., Afifi and Woods, 1971; Anderson and Stokoe 1978; Baxter and Mitchell 2004)
- **Increasing shear strength** (e.g., Daramola 1980; Tatsouka et al. 2000; Lade 2007)
- **Increasing dilatancy** (e.g., Daramola 1980; Bowman and Soga 2003)

Omni-aging behavior

- **Increasing cone penetration resistance** (e.g., Mitchell and Solymar 1984; Dowding and Hryciw 1986; Thomann and Hryciw 1992; Charlie et al. 1992; Joshi et al. 1995)

Blasting densification at the foundation zones of for Jebba Dam



(Mitchell 1986)

Cone penetration resistance continues to increase after blasting.

PRACTICAL PROBLEMS FROM SURPRISING SOIL BEHAVIOR

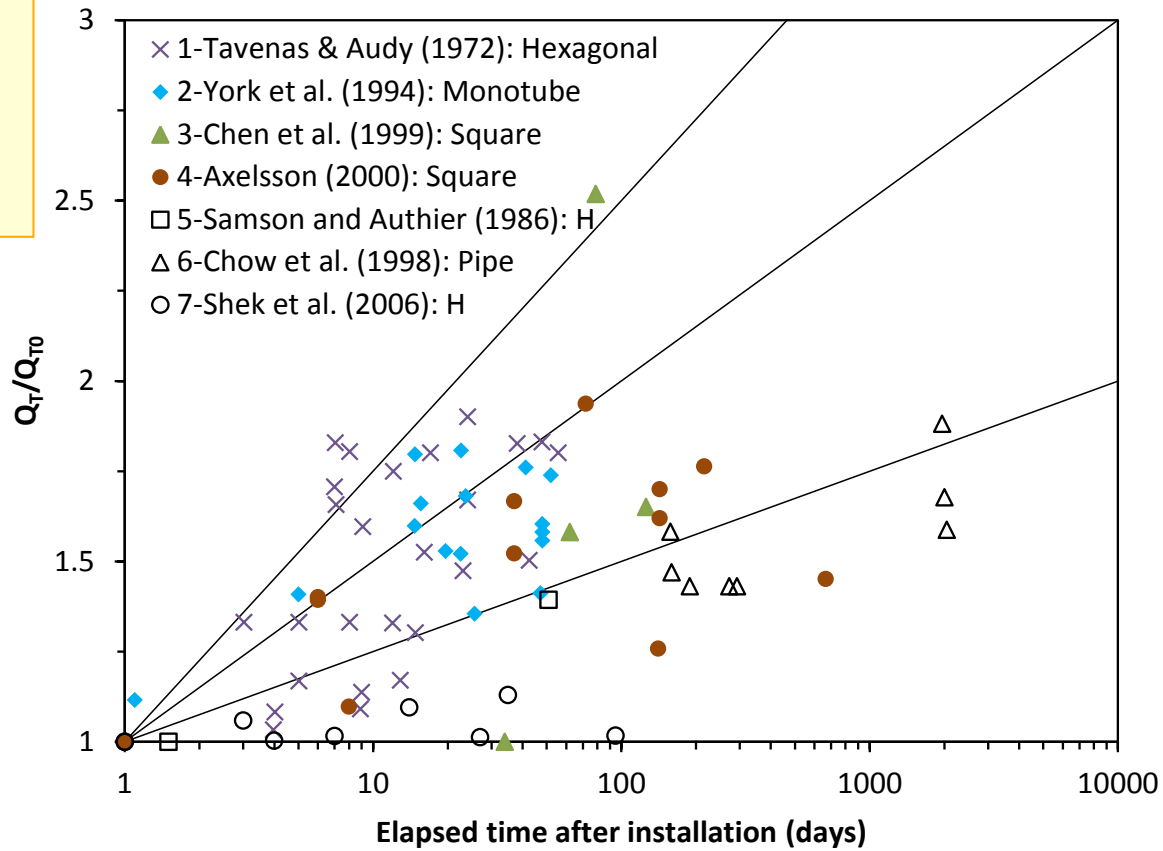
By James K. Mitchell,[1] F. ASCE

(The Twentieth Karl Terzaghi Lecture)

Omni-aging behavior

- **Producing the setup of displacement piles in sand** (e.g., York et al. 1994; Chow et al. 1998; Axelsson 2000; Bowman and Soga 2005; Bullock et al. 2005; Jardine et al. 2006)

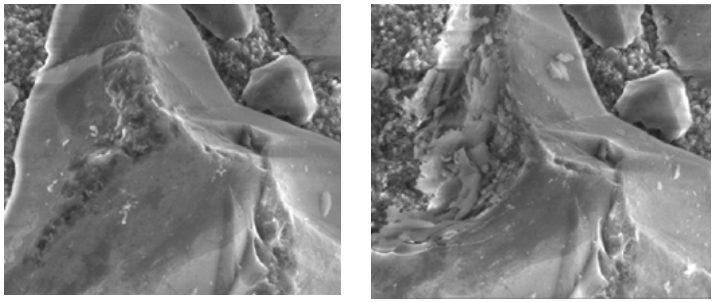
Pile capacity (shaft resistance) continues to increase after installation



summarized by Zhang and Wang(2014)

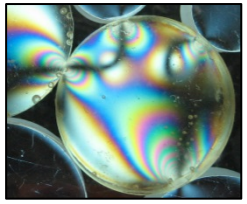
Aging mechanisms

- **Chemical and biological cementation** processes (e.g., Mitchell and Solymar 1984; Mitchell 1986; Mitchell and Soga 2005)
- **Creep processes**, involved particle rearrangement (e.g., Mesri et al. 1990; Schmertmann 1991; Santamarina et al. 2001; Bowman and Soga 2003; Suarez et al. 2014).
- **Static fatigue** at grain contacts (Michalowski et al. 2012; Nadukuru and Michalowski 2014); induced particle crushing (Lade and Karimpour 2010)

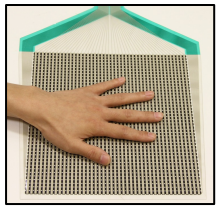


Nadukuru and Michalowski (2014)

Our objectives

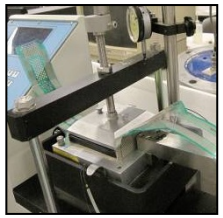


The aging mechanisms ?

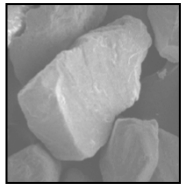


Prove the mechanism
Experimental evidence

Engineering concerns



Simple and plausible explanations



Interesting aging behavior

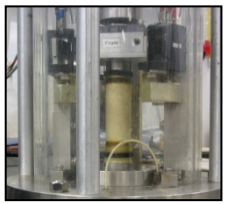
I.
G Stiffness anisotropy

Why are the aging effects not always observable?

unloading/reloading effects

IV.
Structuration
Ko changes
(1-D secondary compression)

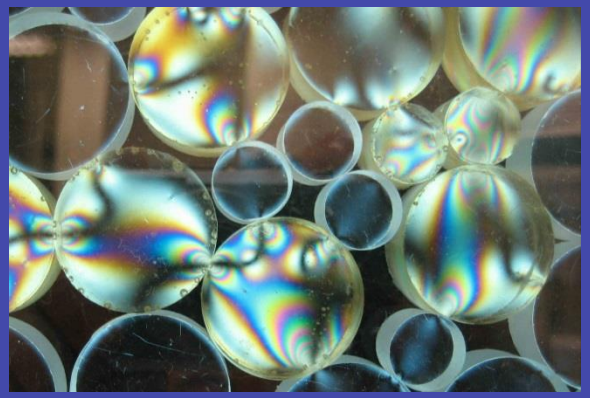
II.
Damping ratio D



V.
Pile setup of displacement pile

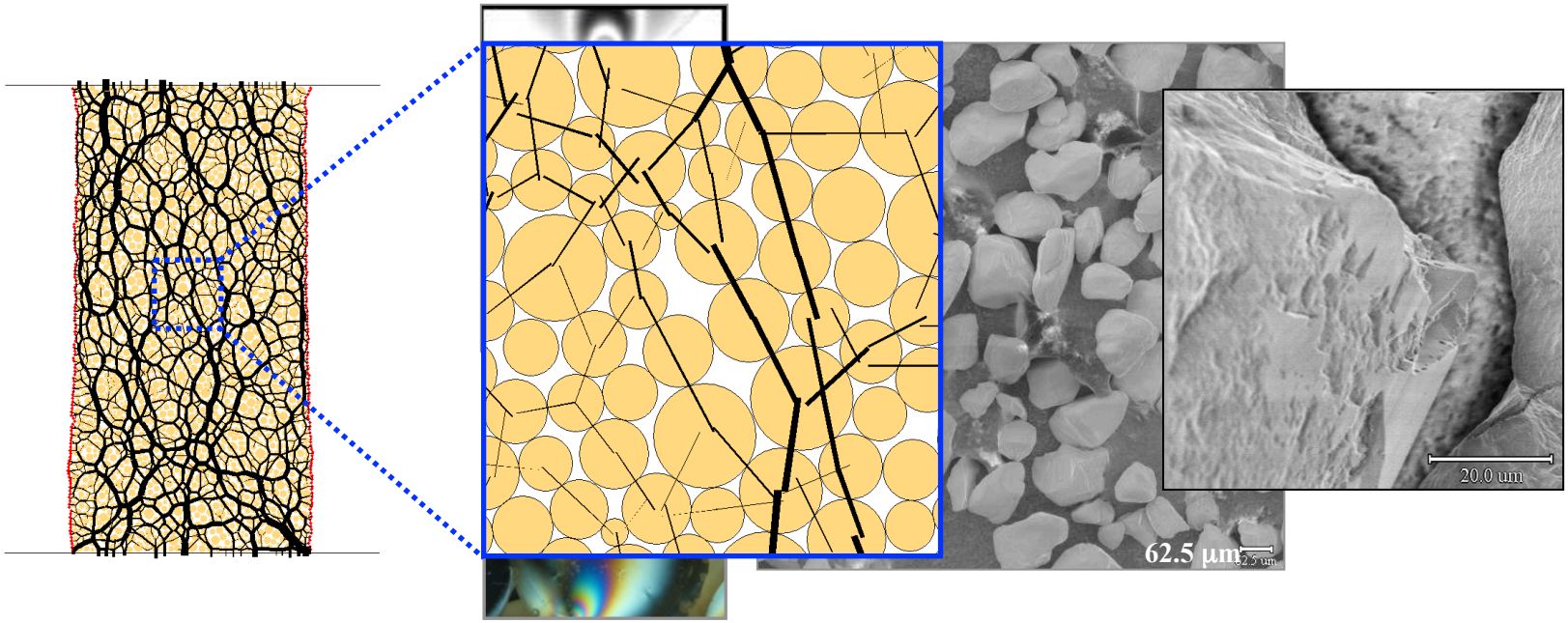
Mechanisms of aging in sand

(Gao et al. 2013)



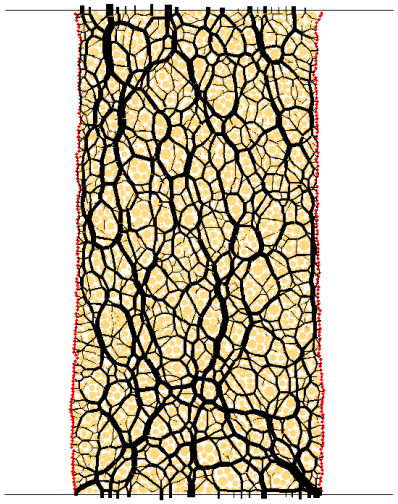
Our hypothesis

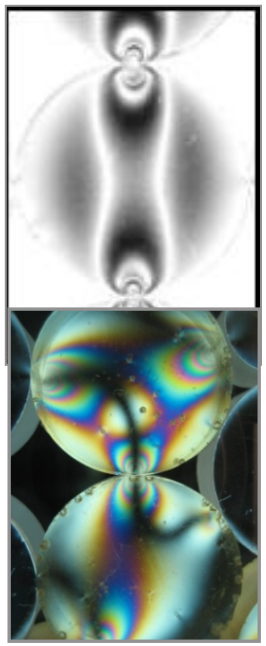
- Interparticle contact normal forces are not uniformly distributed and concentrated at contacts

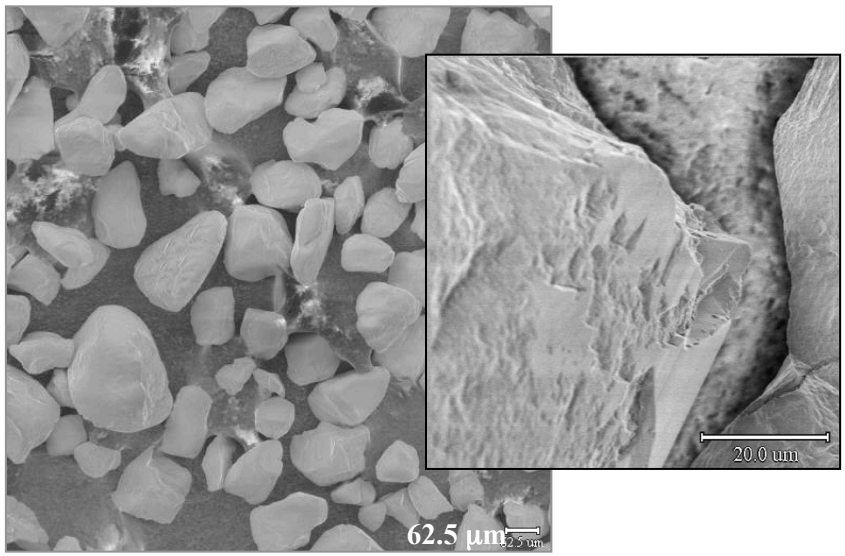


Our hypothesis

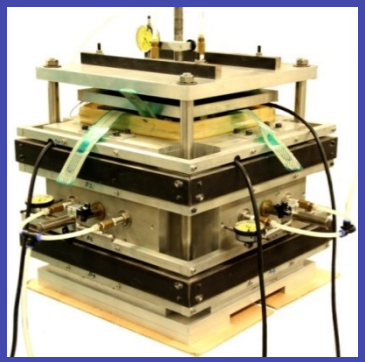
- Homogenization of contact forces (Santamarina et al. 2001; Wang et al. 2008; Gao et al. 2013; Wang and Gao 2013)
  - *Inevitable contact creep during aging*
  - *Contact forces redistribution and homogenization*

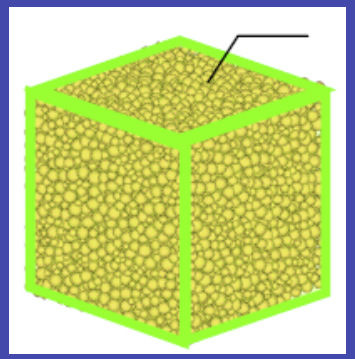






Then, we have to examine and prove this hypothesis……

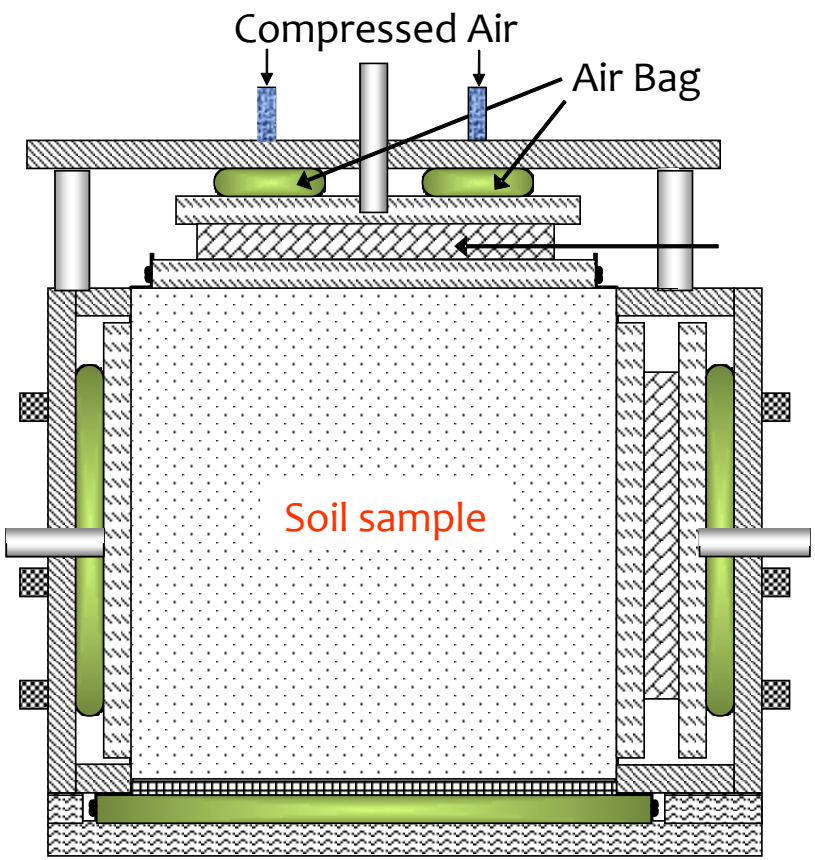




(Gao et al. 2013)

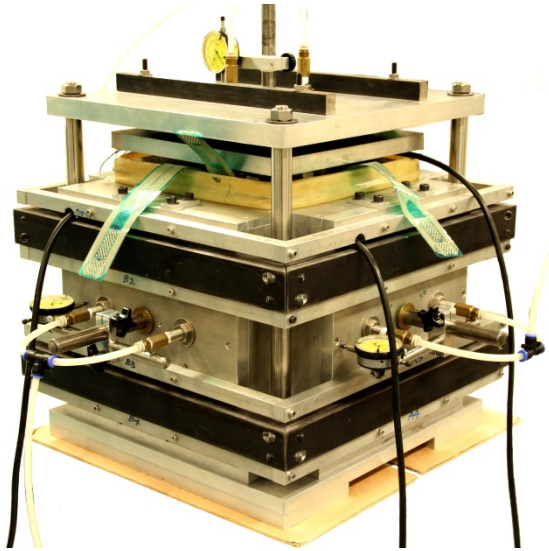
Experimental details

- The true triaxial apparatus



Section view

300 mm × 300 mm × 300 mm

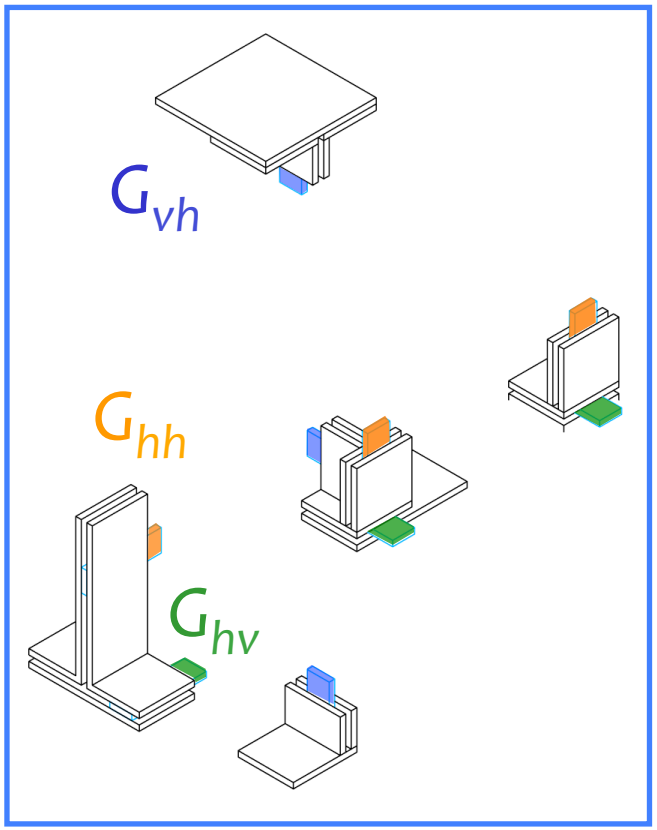


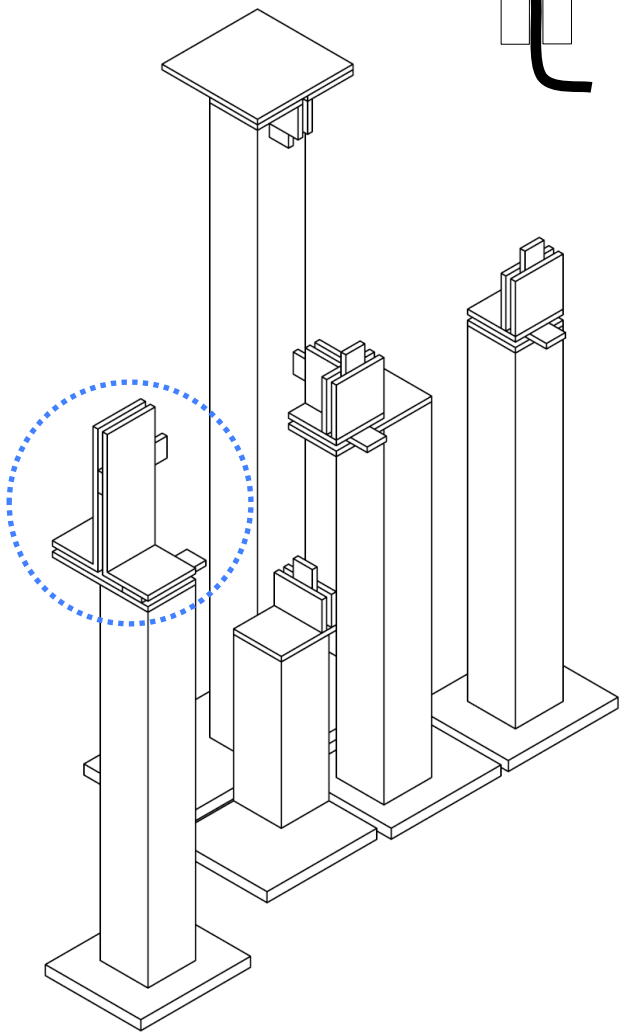
- Independent stress control in x, y, and z directions

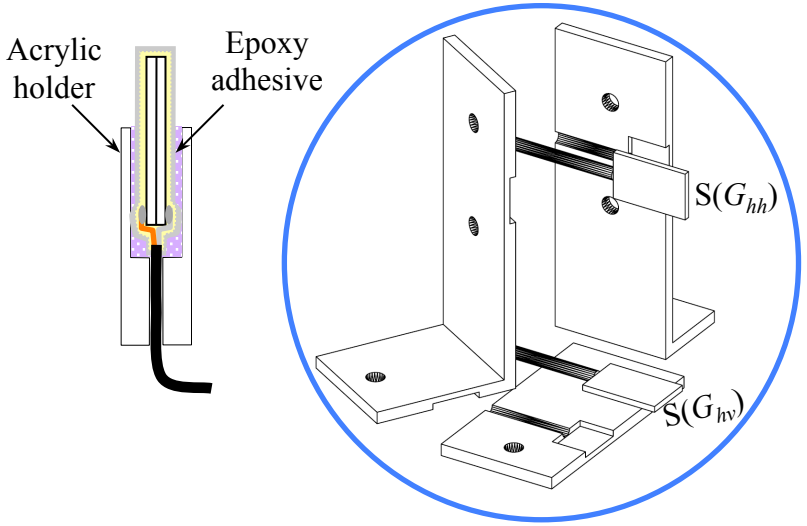
(Compressed air → Air bag)

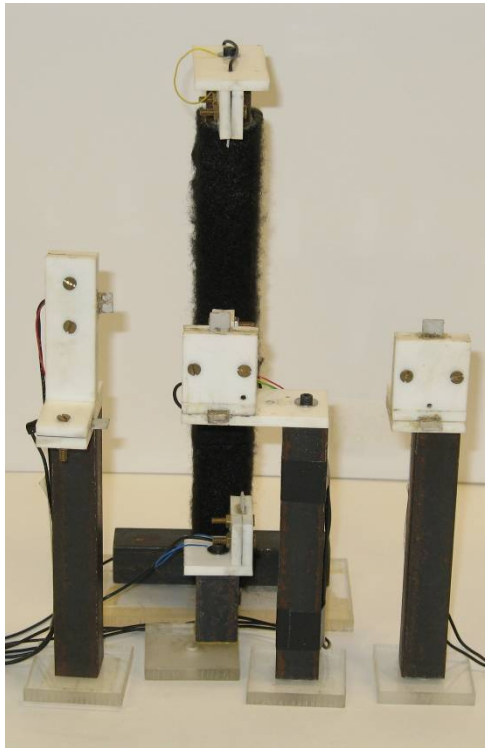
Experimental details

- Bender element system









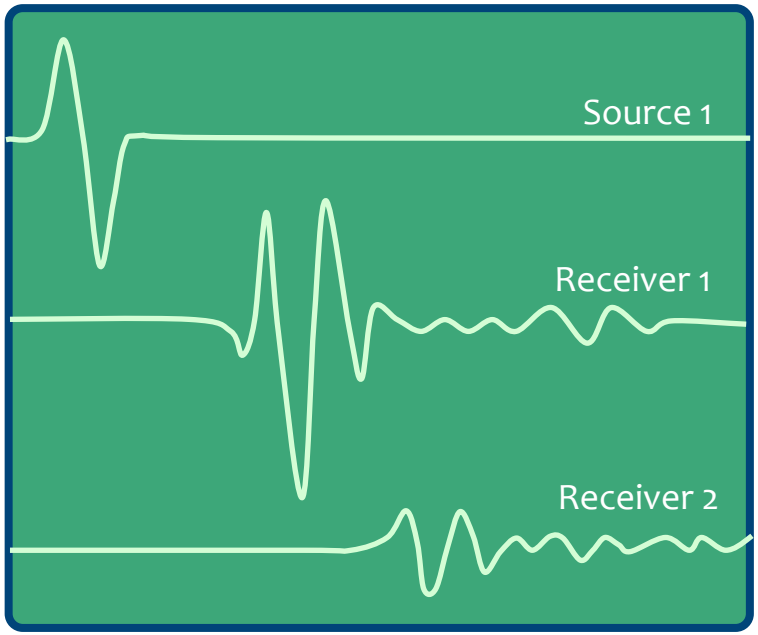
Experimental details

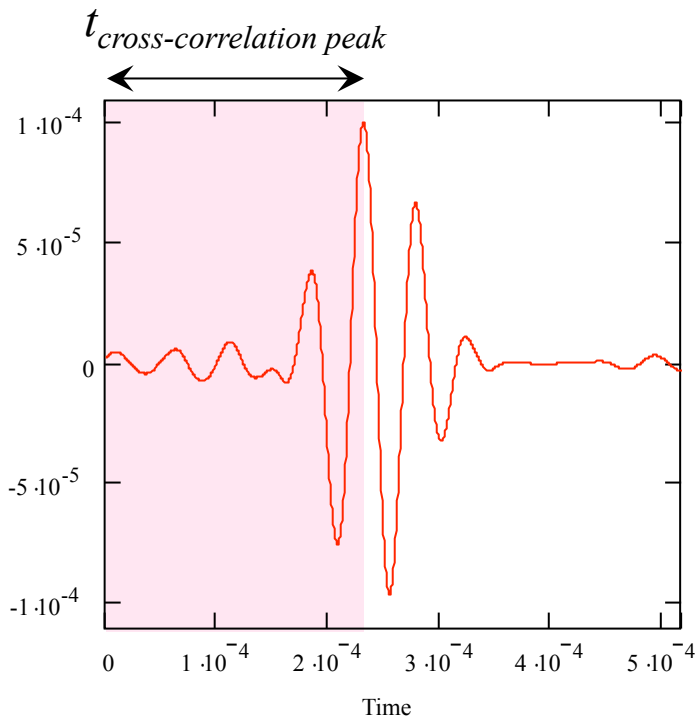
- Determination of shear modulus

Cross-correlation Function

$$cc_k^{\langle p1,p2\rangle} = \sum_i (p1)_i \cdot (p2)_{i+k}$$

$$V_{CCR} = \frac{d}{t_{cross-correlation\_peak}} \rightarrow G_{max} = \rho V_{CCR}^{\ 2}$$



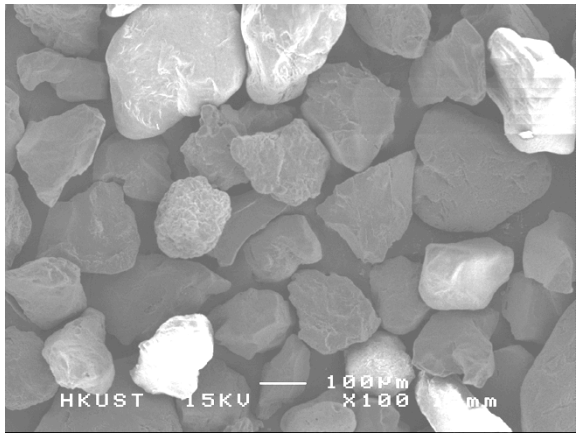


Experimental details

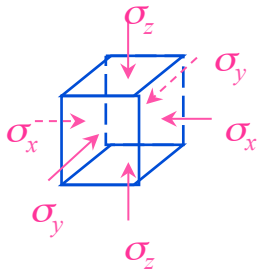
➢ Experimental plans

- Materials

Leighton Buzzard sand (LB)



- Testing plans



Isotropic loading

① 50 kPa → ②200 kPa → ③ 50 kPa

Isotropic unloading

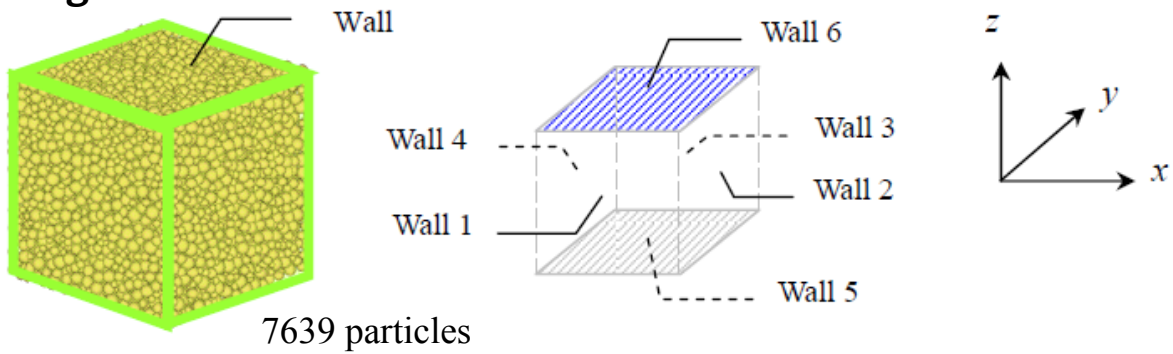
Aging for three days

Details of DEM simulation

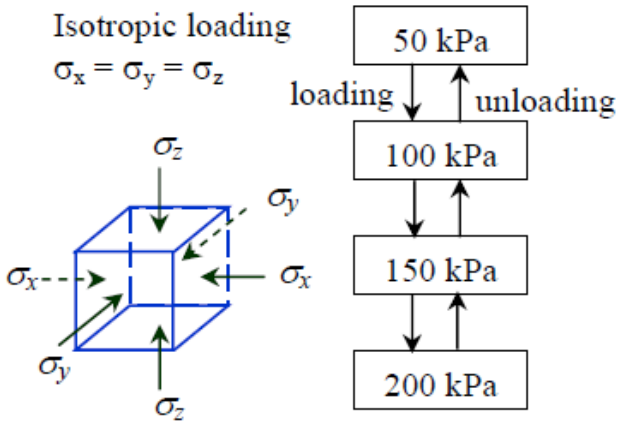
➢ Procedures

3D simulation (PFC3D, Itasca)

(a) Packing



(b) Compression



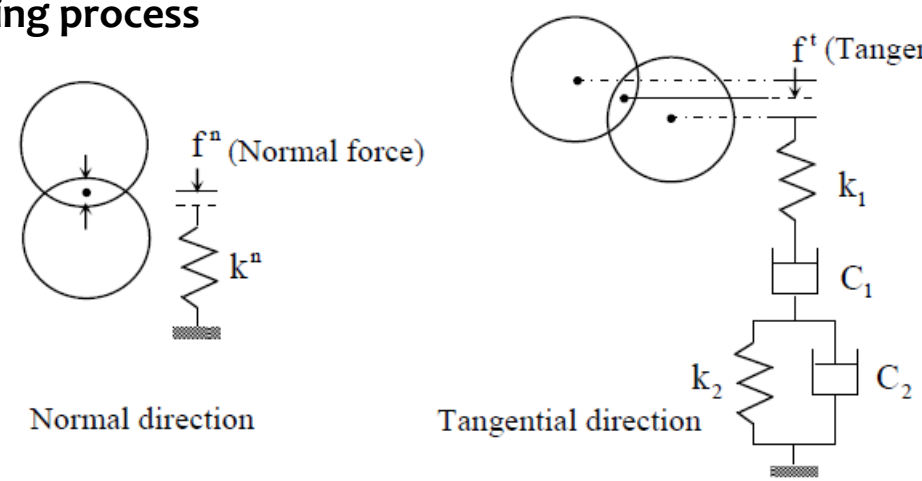
Hertz-Mindlin contact model

Details of DEM simulation

- Procedures

Higher tangential force, higher creep rate.

(c) Aging process

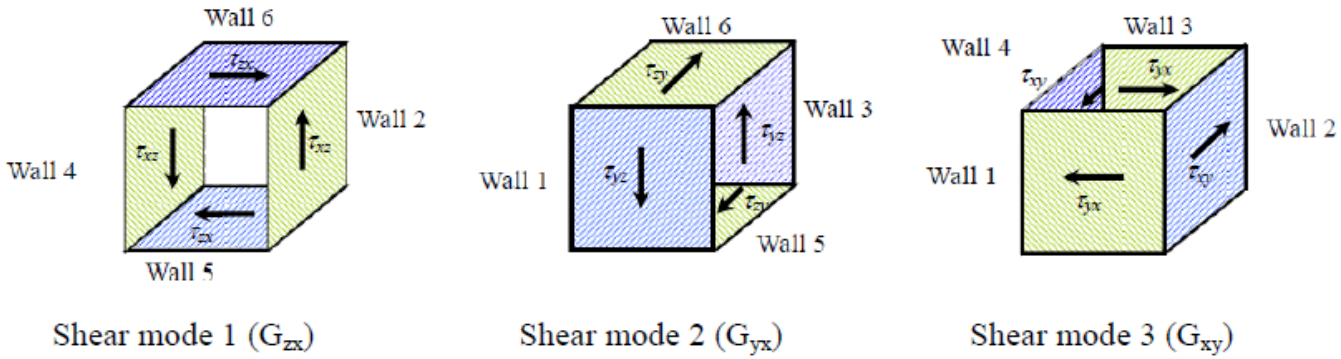


Sliding creep

e.g., Kuhn and Mitchell (1992 & 1993); Collop et al. (2006); Kwok and Bolton (2010)

(d) Shearing test

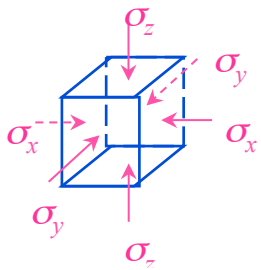
Shear strain: small-strain (~10^{-6}) G_{max}

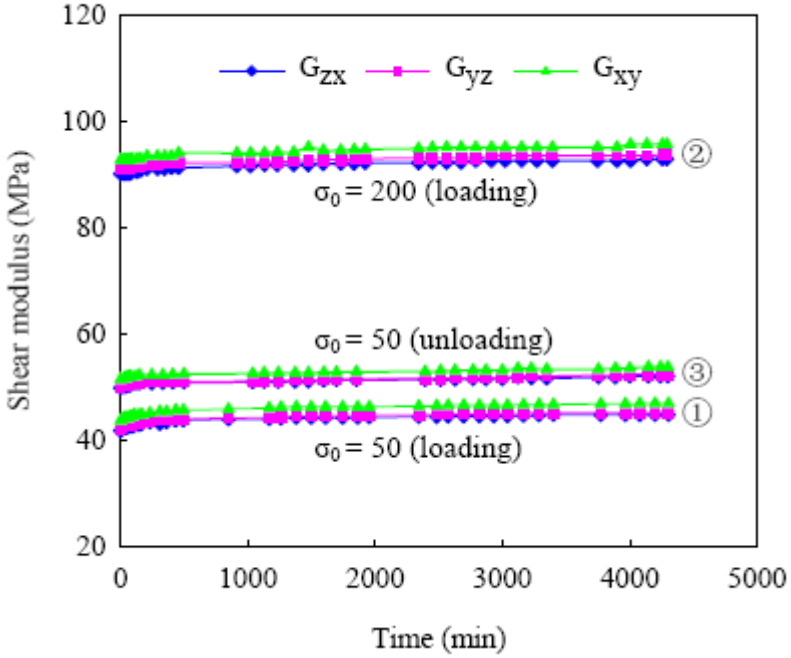


Experimental results

$\sigma_x = \sigma_y = \sigma_z$

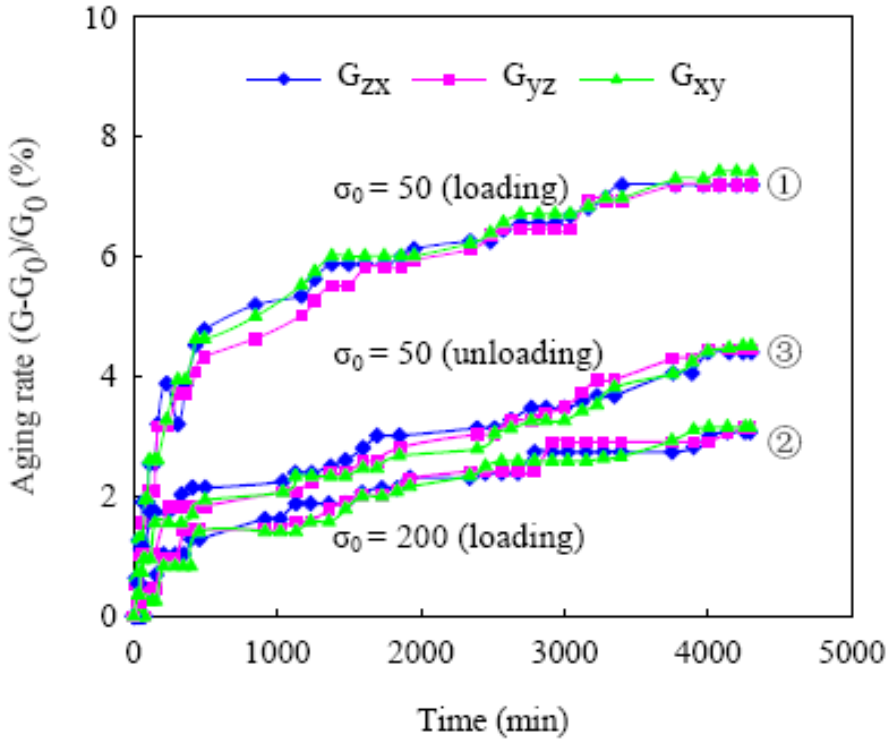
50 kPa→200 kPa→ 50 kPa





Experimental results

Aging rate: $(G- G_o) /G_o \times 100\%$



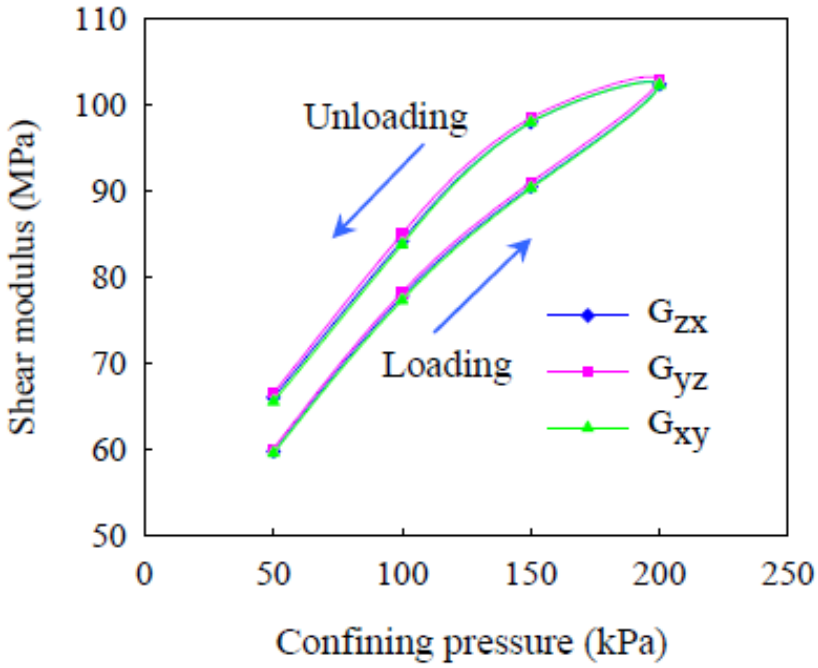
Similar aging rate for three moduli

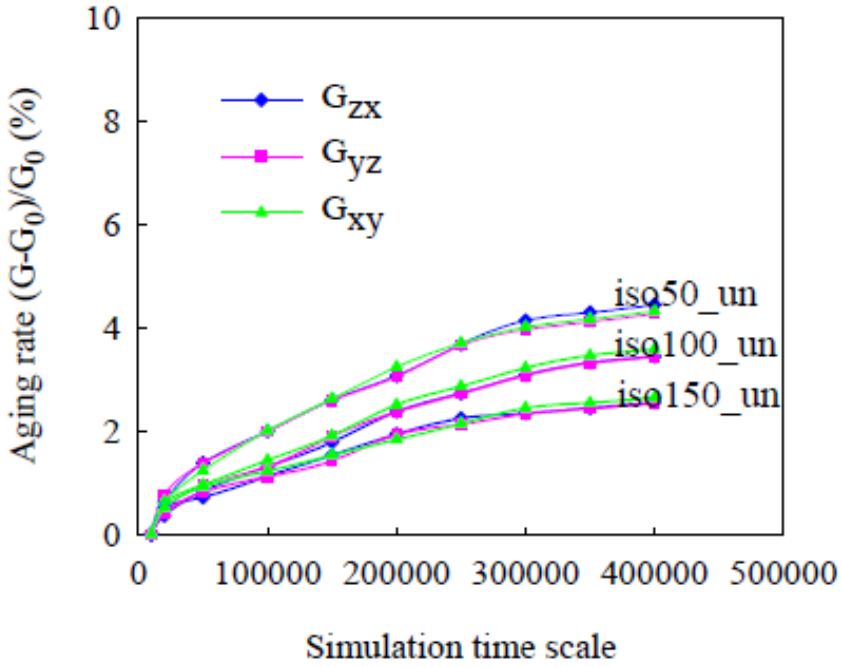
σ_o↑ Aging rate↓

Aging rate↓ on unloading

DEM simulation results

The same behavior was reproduced using DEM simulations.





Unloading: $\sigma_o\downarrow$ Aging rate$\uparrow$

Micromechanical insights – contact normal force

- Strong forces (contacts)

  $F_n / \langle F_n \rangle > 1$, force F_n greater than the mean $\langle F_n \rangle$

- Weak forces (contacts)

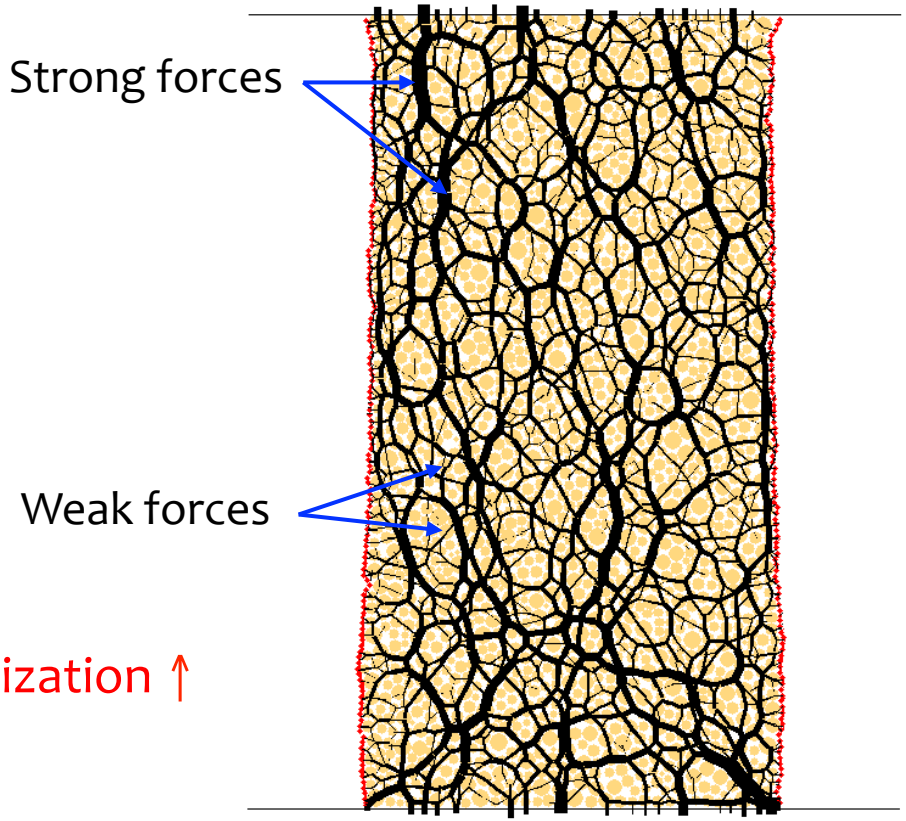
  $F_n / \langle F_n \rangle < 1$, force F_n less than the mean $\langle F_n \rangle$

- **POW**

  The percentage of weak forces

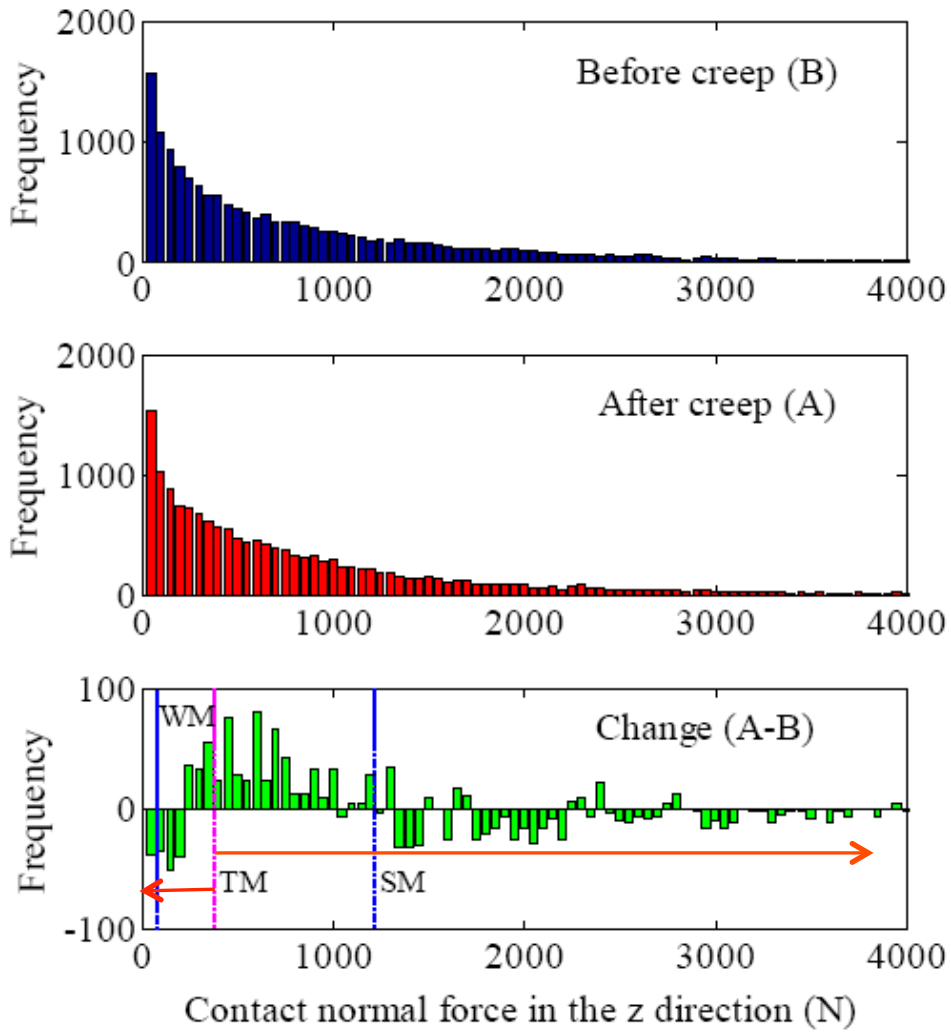
  POW↓

  Degree of contact force homogenization ↑



(After Radjai et al., 1996; 1998)

Micromechanical insights – contact normal force



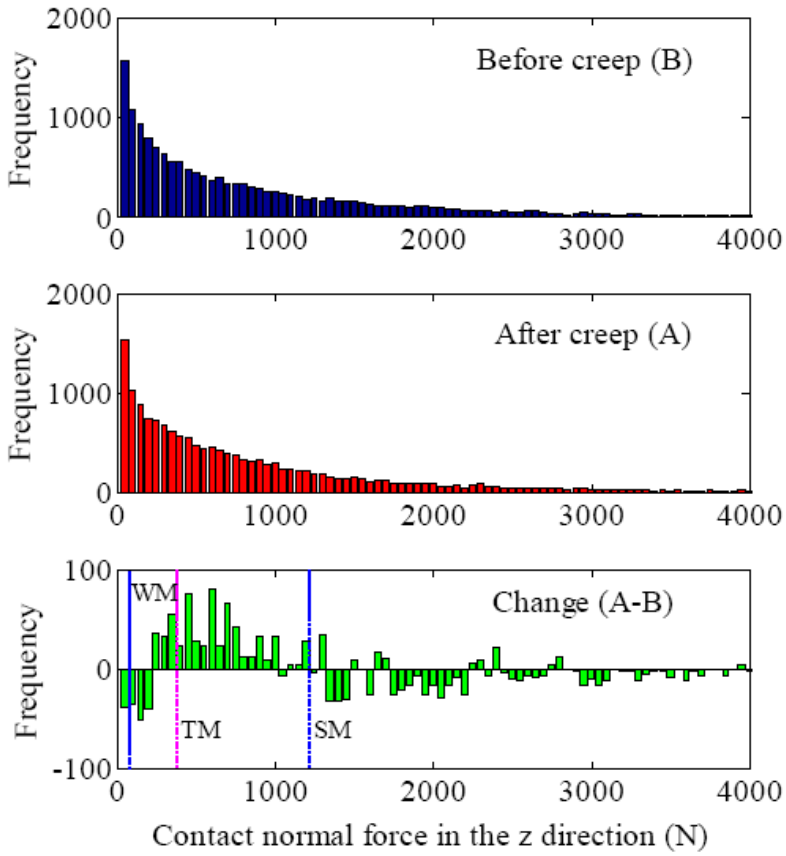
(Mean) Weak forces ↑

(Mean) Strong forces ↓

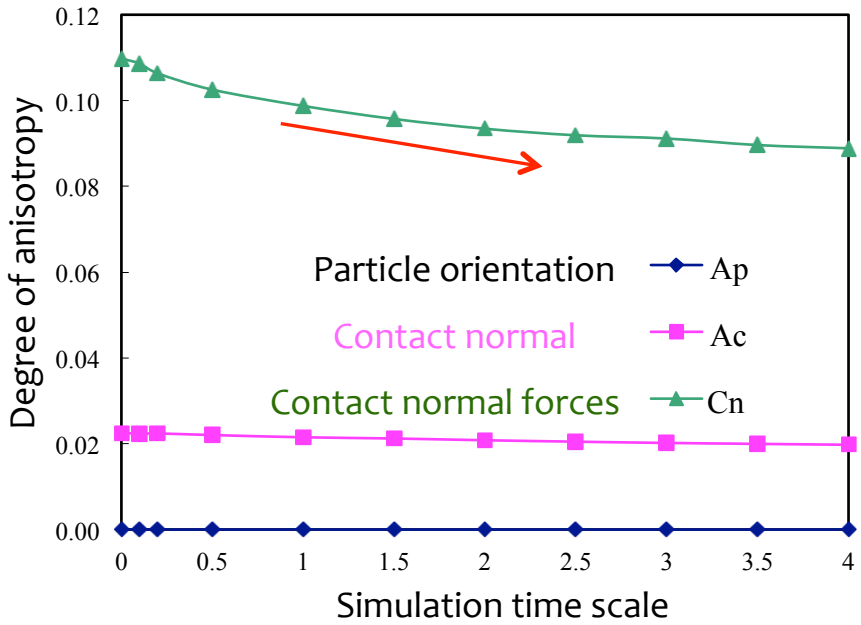
COV ↓

Interparticle contact normal forces become more **homogenized**

Micromechanical insights – contact normal force



Ouadfel and Rothenburg (2001)



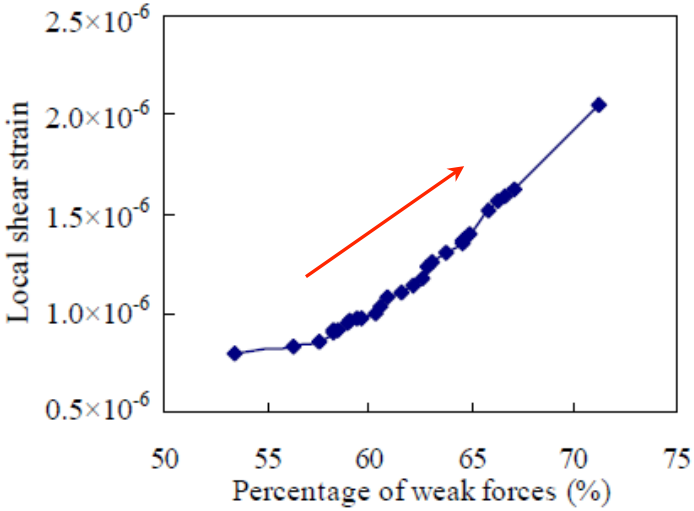
Degree of anisotropy

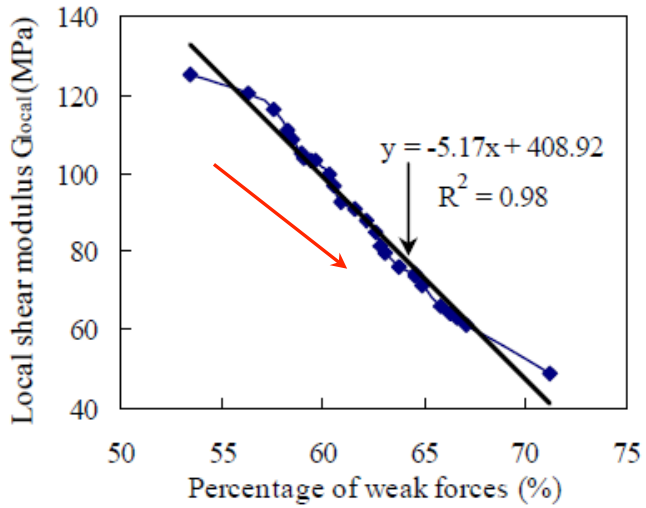
Interparticle contact normal forces become more homogenized

?

Stiffness increase

Discussion

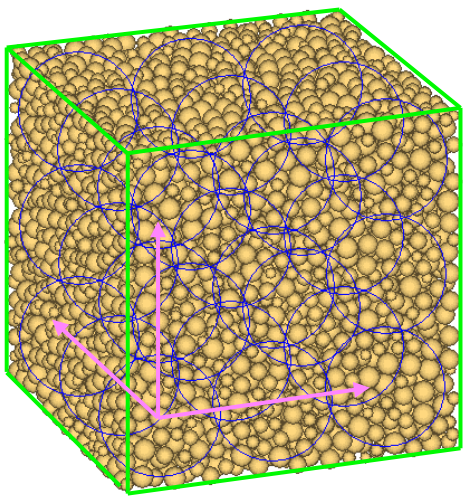


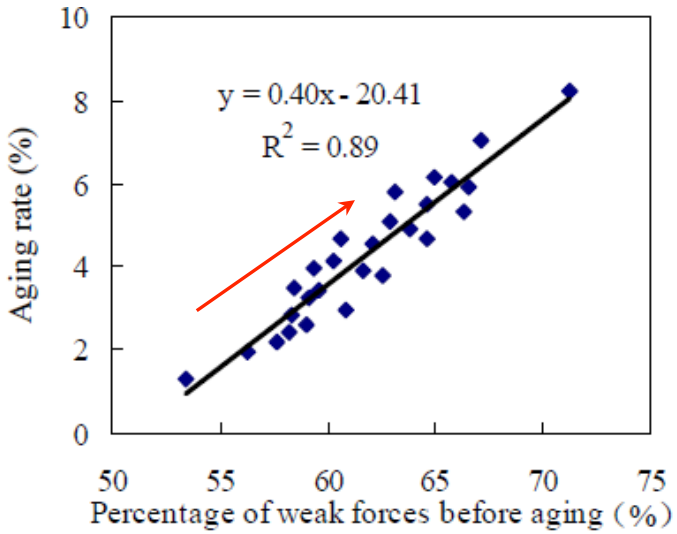


Percentage of weak forces ↑

Local stiffness ↓

27 MS





Aging rate ↑

Discussion

On the unloading path

Denser

POW ↓ (before aging)

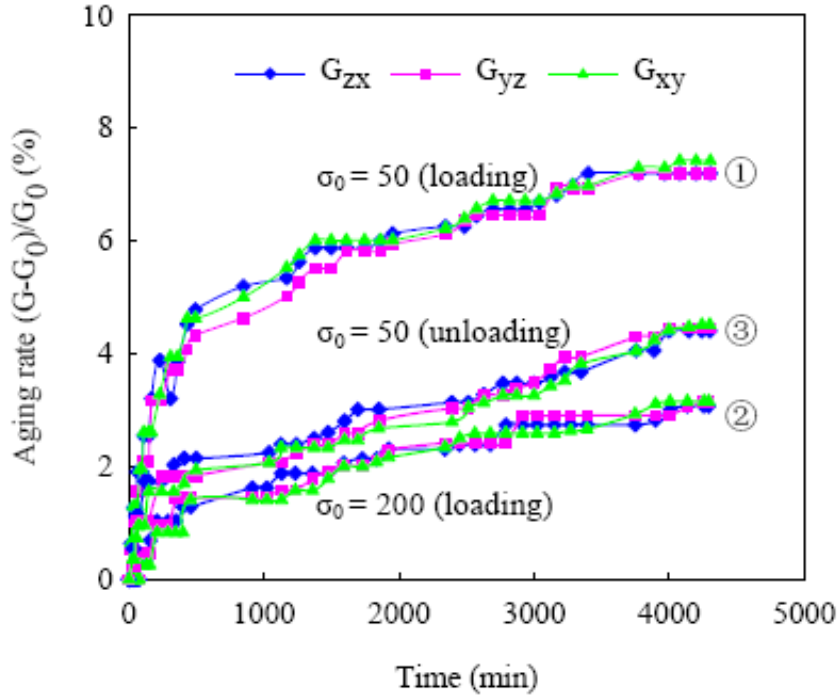
Aging rate↓

Aging rate↓

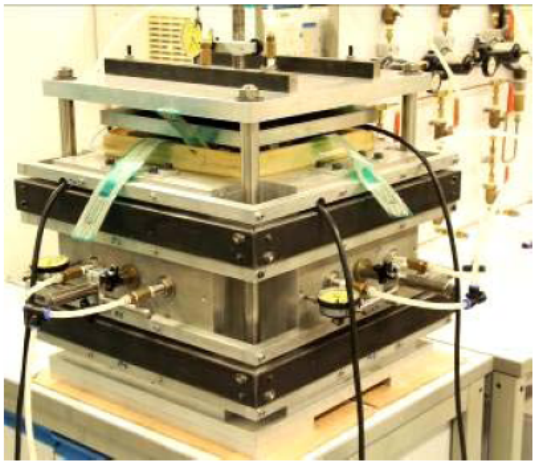
Aging rate: $(G- G_0) /G_0 \times 100\%$

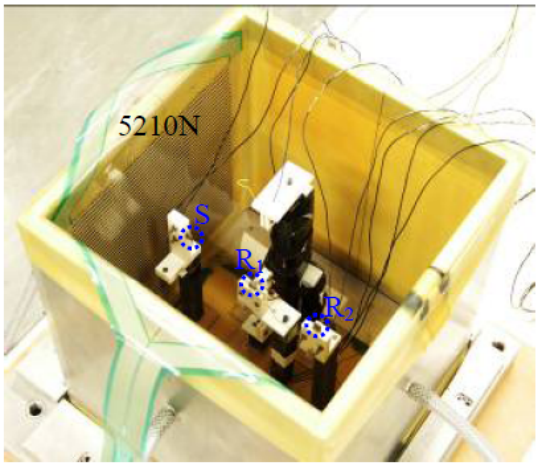
σ_0↑ Aging rate↓

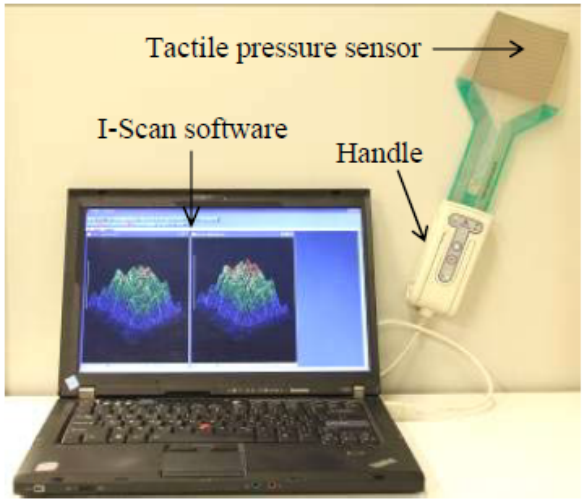
Aging rate↓ on unloading

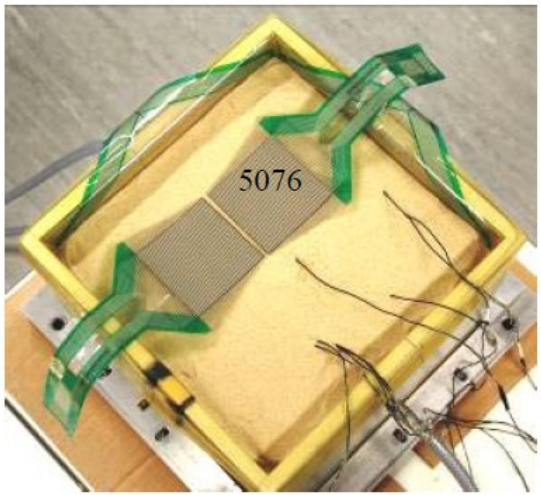


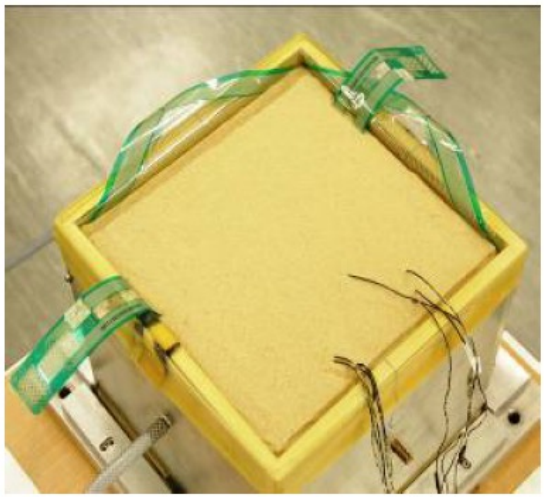
Experimental evidence







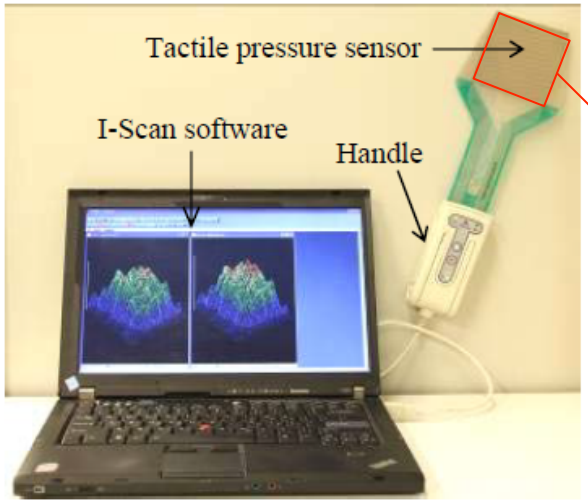


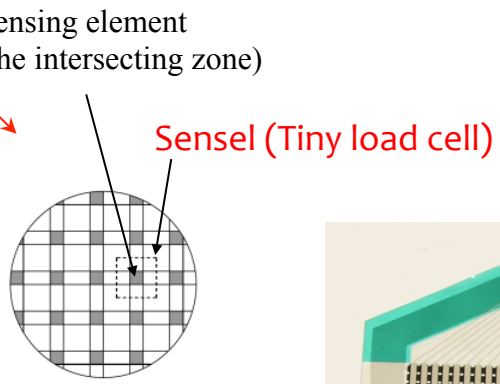


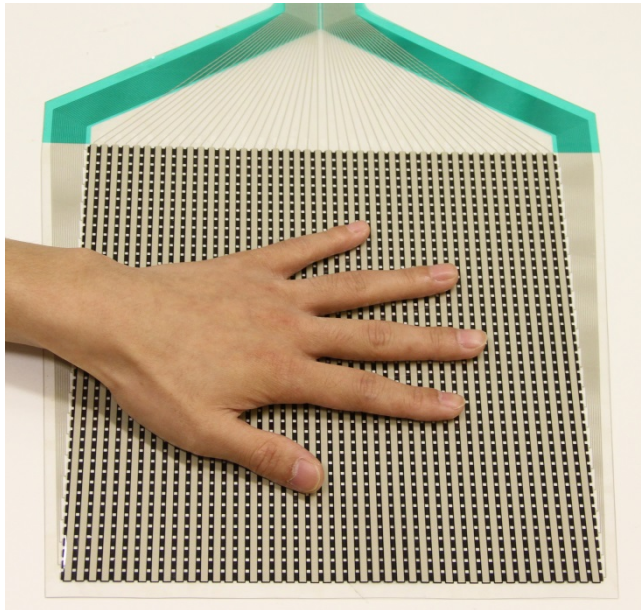
Thin (~0.1 mm) and flexible

Experimental evidence

- Tactile pressures sensor (film-like senor)







1936 sensels

Calibration

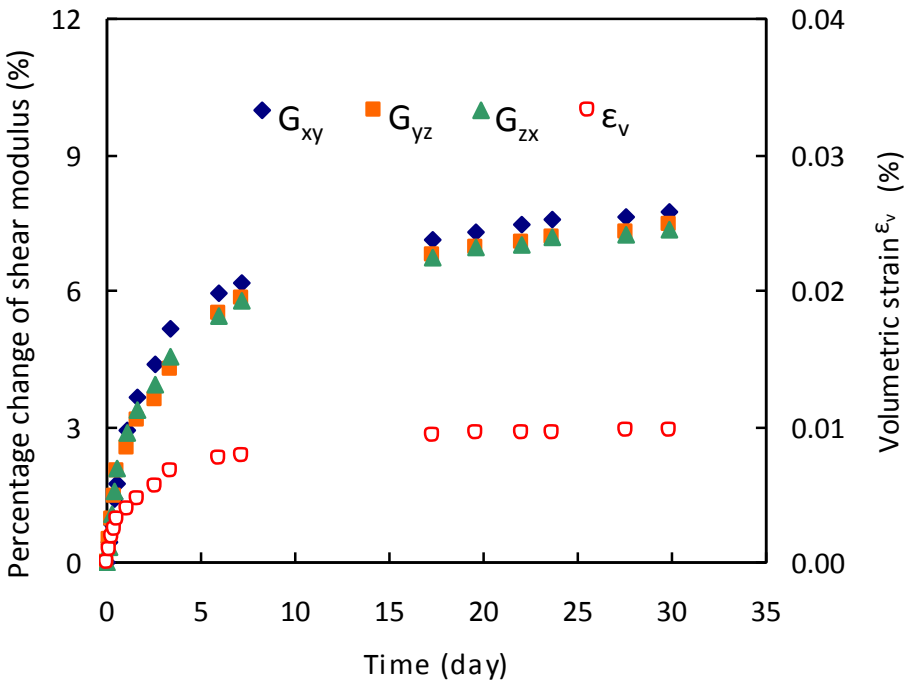
Calibrate for each sensel

Calibrate sensor creep (drift)

(Gao and Wang 2013)

Experimental evidence

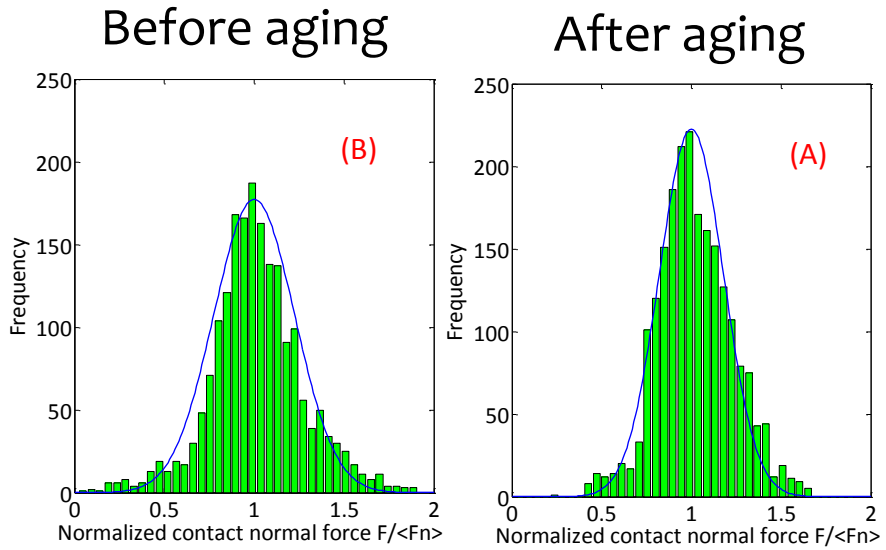
Isotropic loading of 100 kPa for 30 days

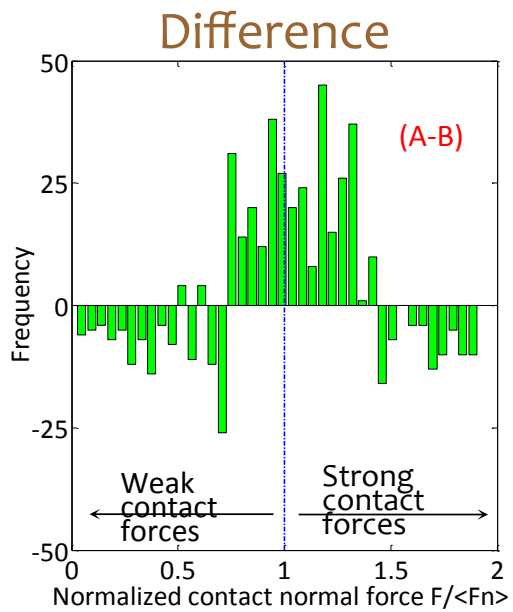


Shear modulus continues to increase with minute volume changes ~0.01%

Experimental evidence

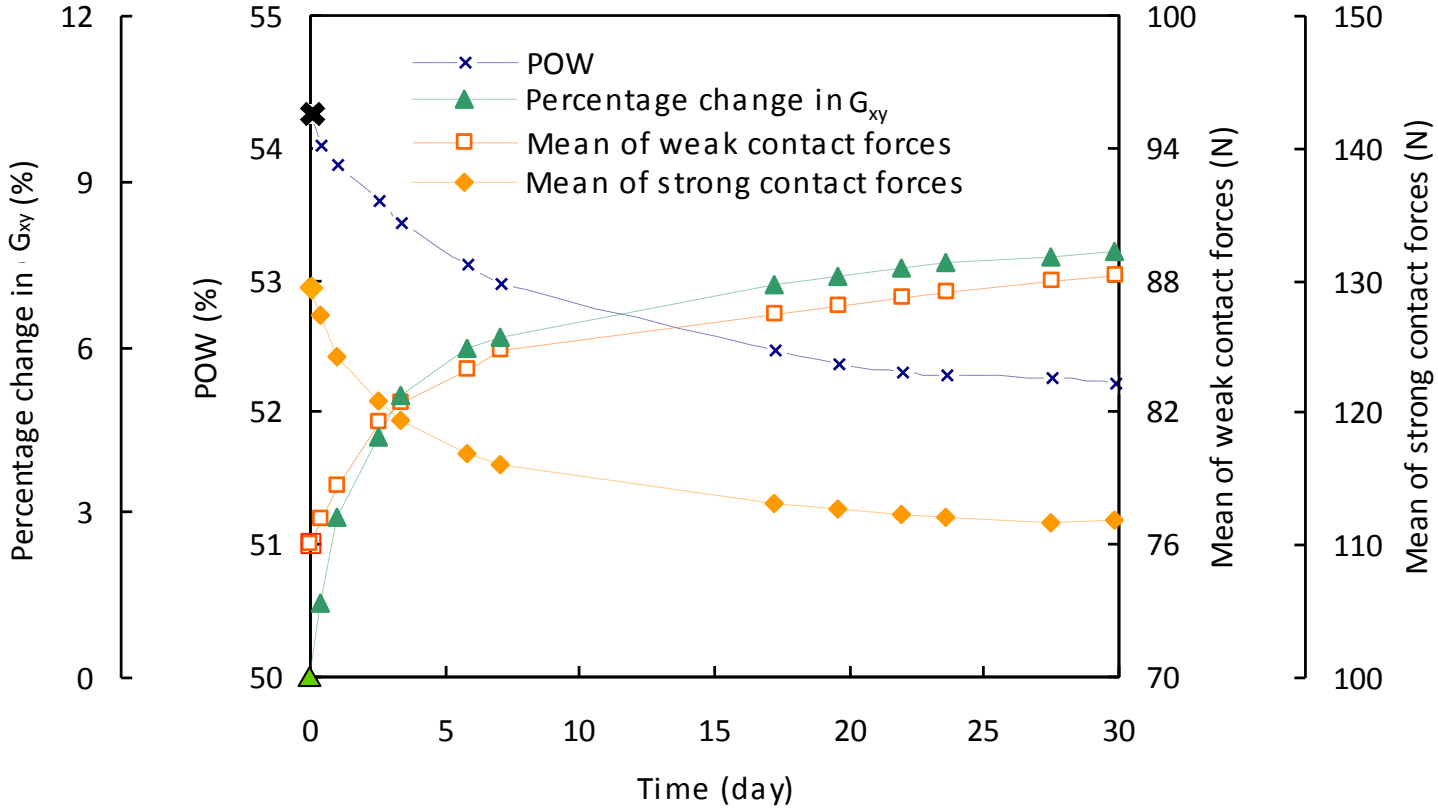
Isotropic loading of 100 kPa





Experimental evidence

Summary



G_{xy} ↑

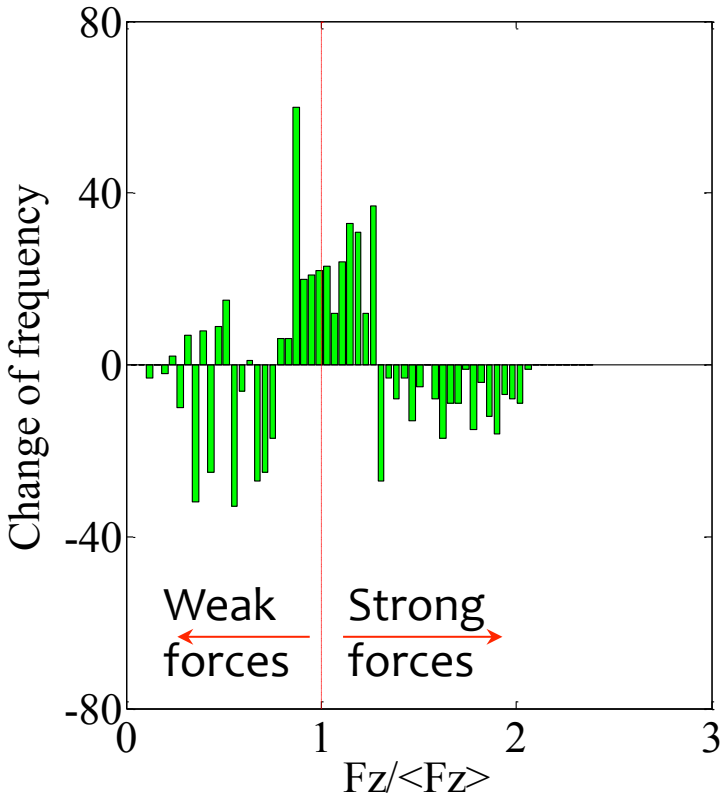
POW ↓

Mean Weak forces ↑

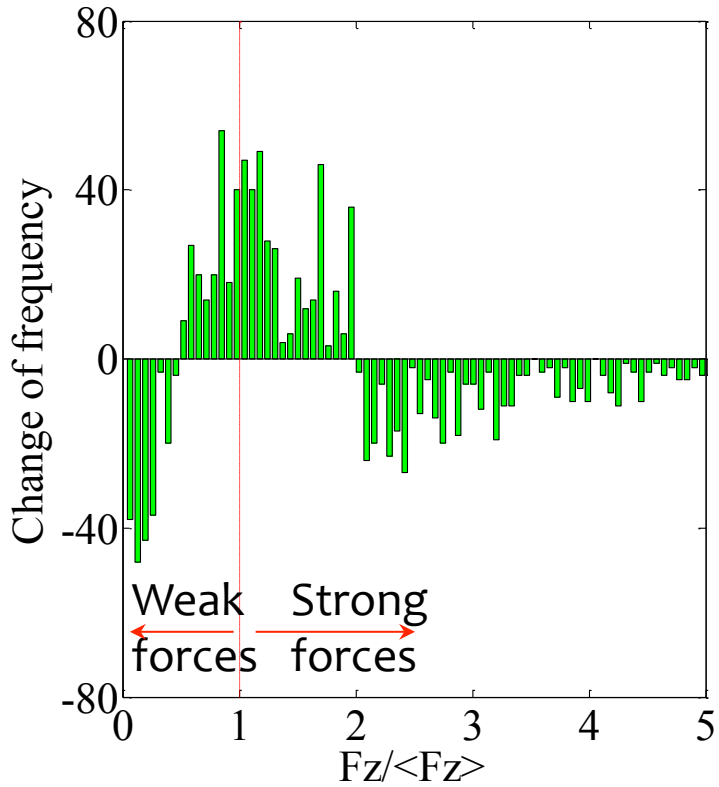
Mean strong forces ↓

Experimental evidence

Experimental result



DEM simulation result

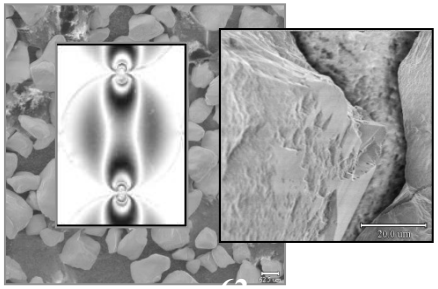


Interparticle contact normal forces become more homogenized

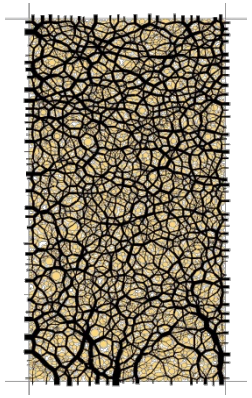
Summary

During aging

Contact creep



Contact forces redistribute

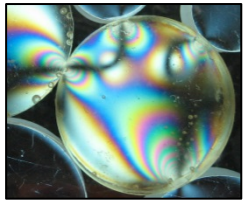


Weak forces increase
Strong forces decrease

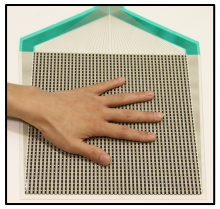
Contact force homogenization

Percentage of weak forces (POW) decreases

Stiffness increase
(other properties changes)



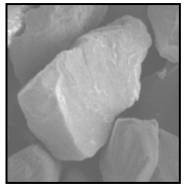
The aging mechanisms ?



Prove the mechanism
Experimental evidence

Simple and plausible explanations

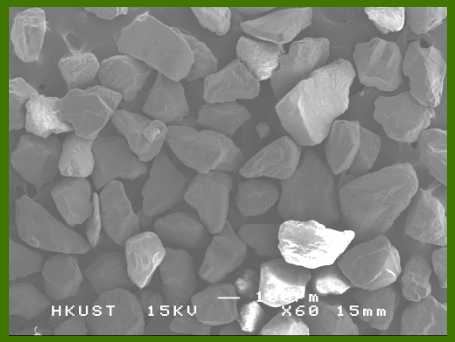
Contact force redistribution & homogenization



Interesting aging behavior

I.
G Stiffness anisotropy

Interesting aging behavior I



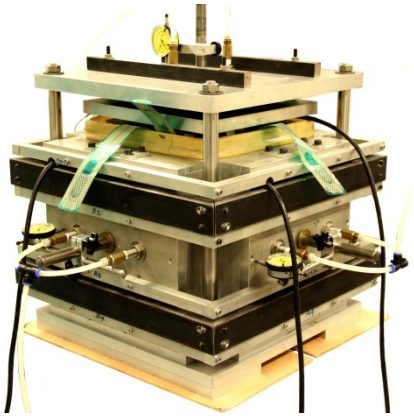
What are aging-induced modulus changes of
sand with inherent fabric anisotropy?

(Wang and Gao 2013)

Experimental details

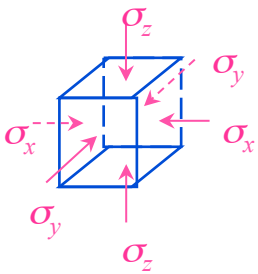
- Testing materials

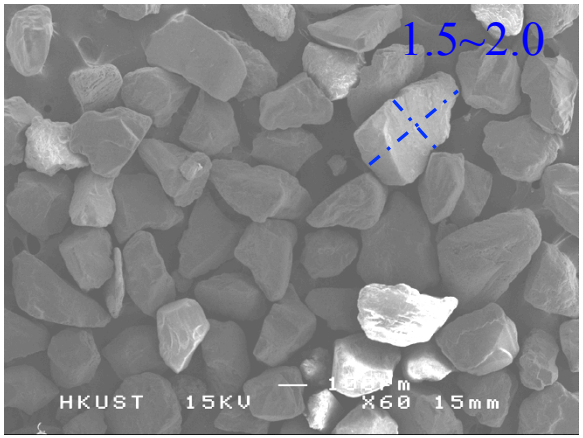
- Testing plans



Toyoura sand

(inherent fabric anisotropy)





Isotropic loading

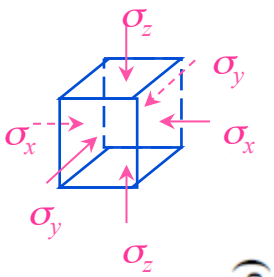
① 50 kPa → ②125 kPa → ③175 kPa

Aging for three days

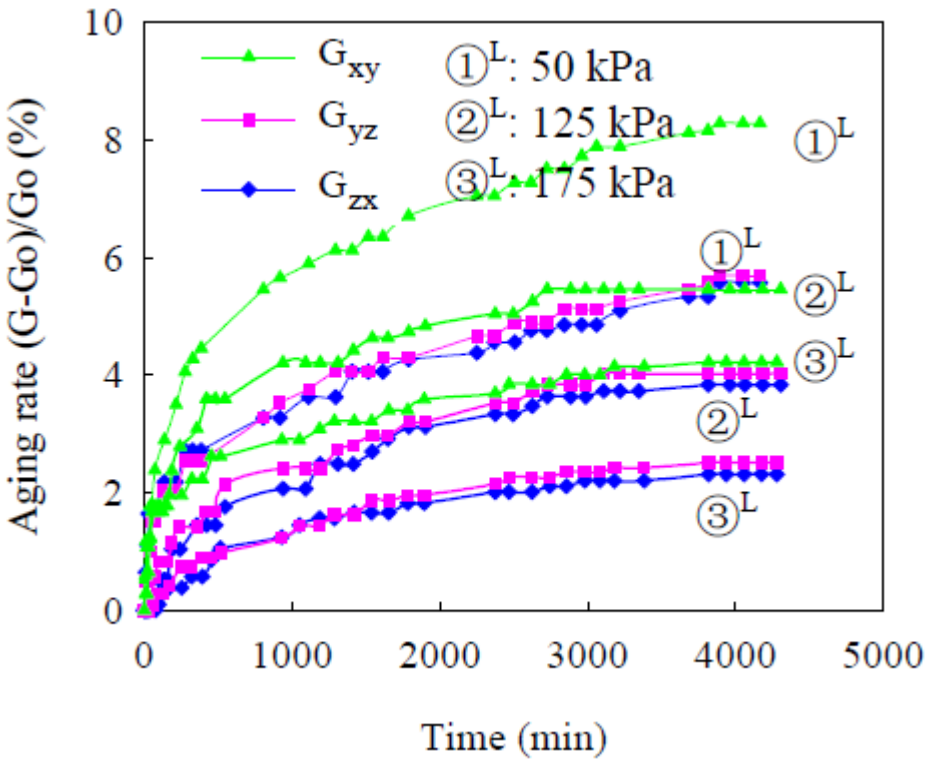
Experimental results

$\sigma_x = \sigma_y = \sigma_z$

50 kPa → 125 kPa → 175 kPa



Aging rate: $(G - G_0)/G_0 \times 100\%$



G↑ with time

$G_{xy} > G_{yz} \approx G_{zx}$ (Fabric-induced stiffness anisotropy)

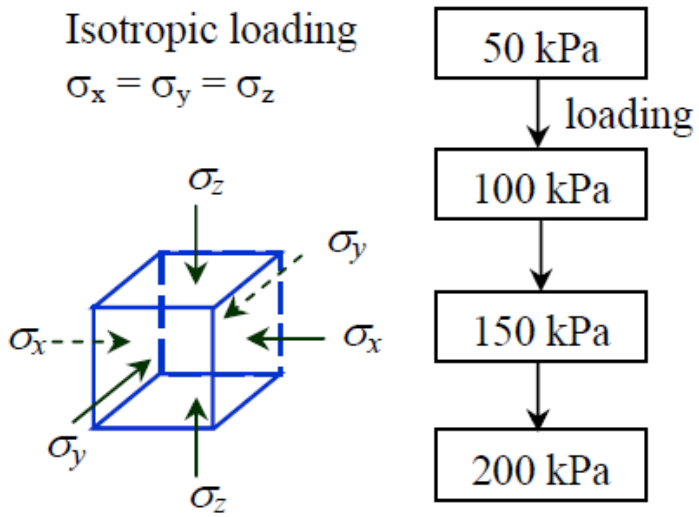
Aging rate

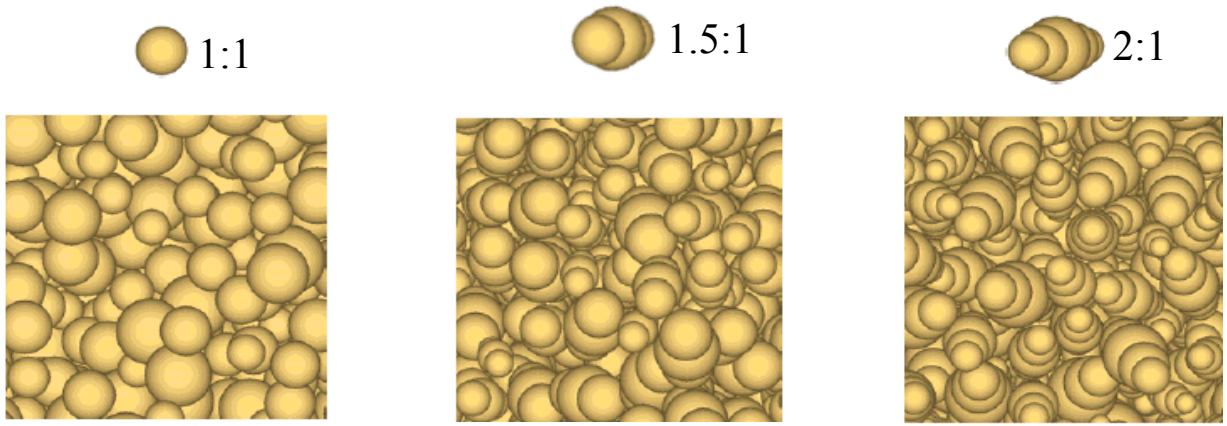
$G_{xy} > G_{yz} \approx G_{zx}$

Stiffness anisotropy ↑

Details of DEM simulation

- Packing
- Compression
- Aging process
- Shearing test



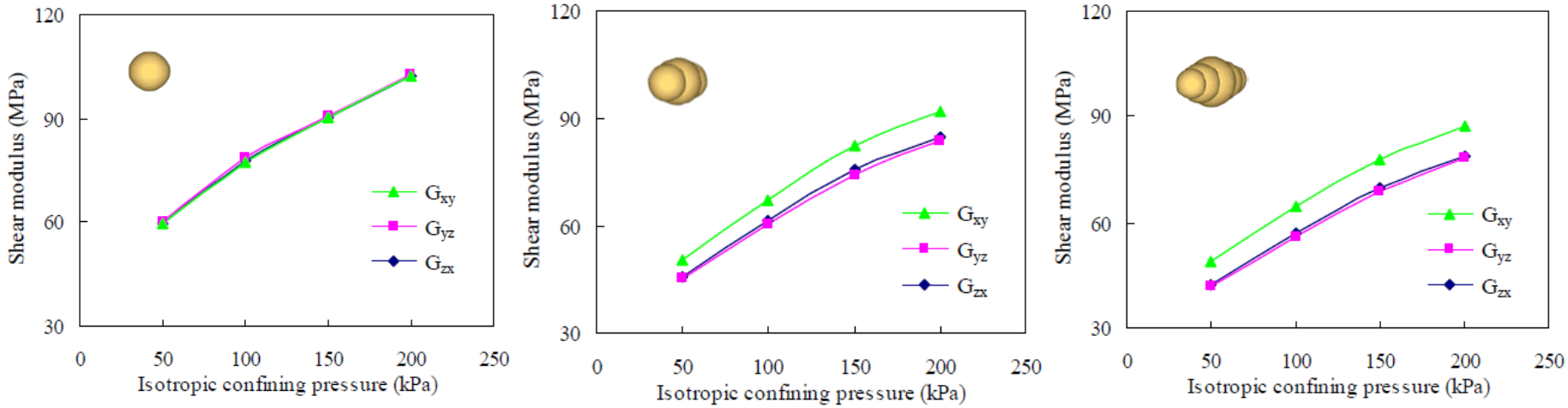


Simulation results

$G_{xy} \approx G_{yz} \approx G_{zx}$

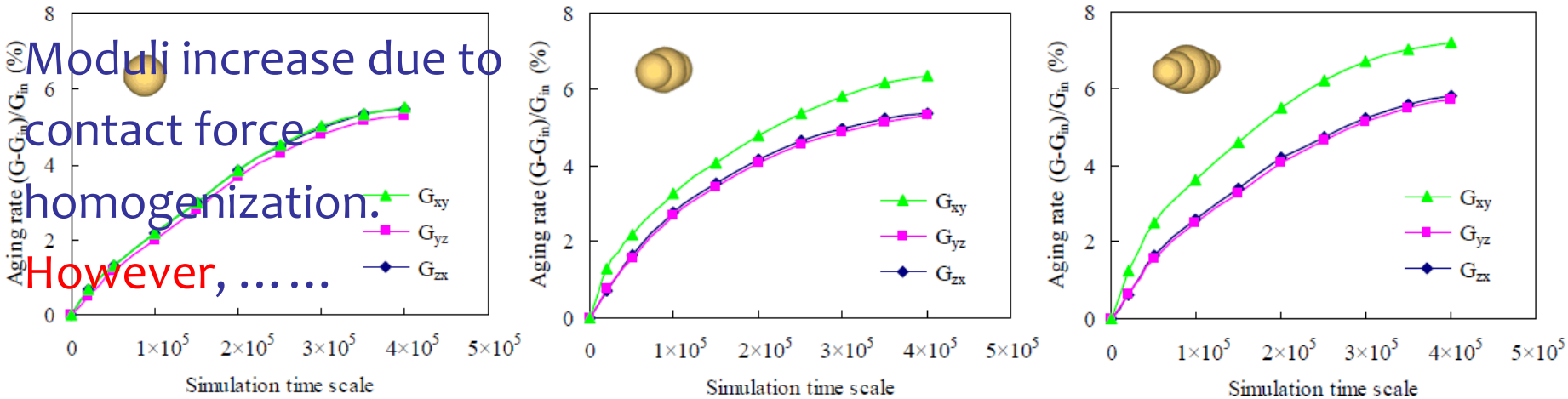
G anisotropy: $G_{xy} > G_{yz} \approx G_{zx}$

G anisotropy increases



Under isotropic loading of 50 kPa

Aging rate: $G_{xy} > G_{yz} \approx G_{zx}$

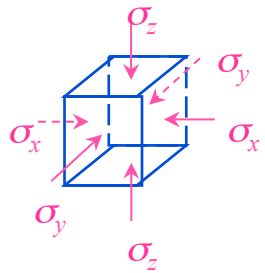


Moduli increase due to contact force homogenization.

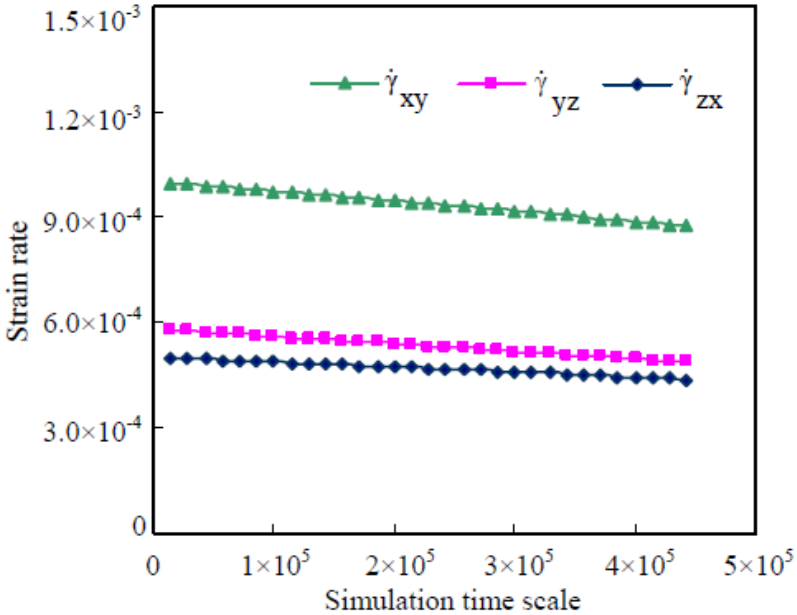
However, ……

Micromechanical insights

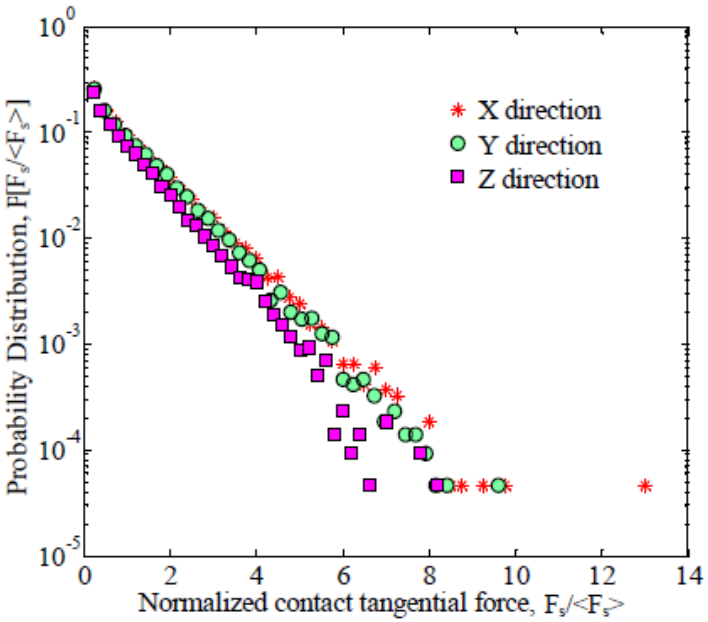
Under isotropic loading of 50 kPa



5-particle clump 



Higher contact normal forces in the X, Y directions



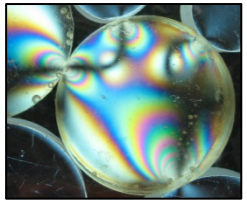
Higher contact tangential forces
Higher contact creep
Greater force redistribution
Aging rate G_{xy} ↑

Summary

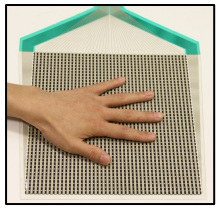
- Larger tangential forces in the x and y directions can induce a higher sliding creep and greater force redistribution in the same direction during aging.

  A higher aging rate for G_{xy} than for G_{yz} (or G_{zx}) is observed.

- Stiffness anisotropy continues to increase during aging.



The aging mechanisms ?

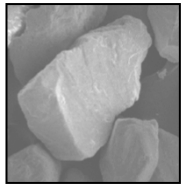


Prove the mechanism
Experimental evidence

Simple and plausible explanations

Contact force redistribution & homogenization

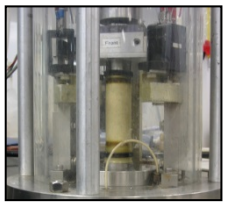
Interesting aging behavior



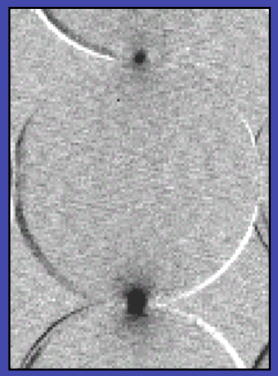
I.
G Stiffness anisotropy

II.
Damping ratio D

III.
Straining, density, and unloading/reloading effects



Interesting aging behavior II & III



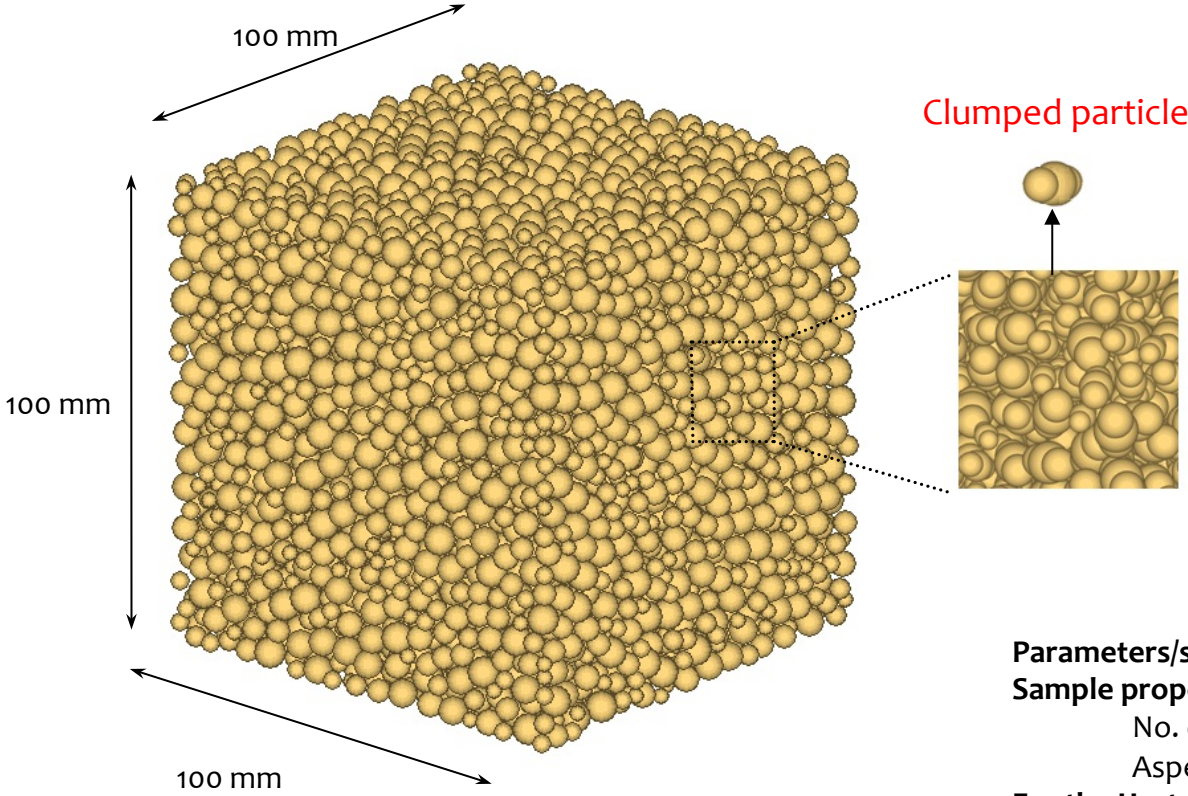
Why are the aging effects more pronounced on the decrease in D_{min}?

Why are aging effects not always observed ?

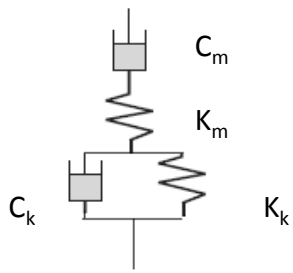
(straining effect)

(Tong and Wang 2014)

DEM simulations of cyclic shear tests

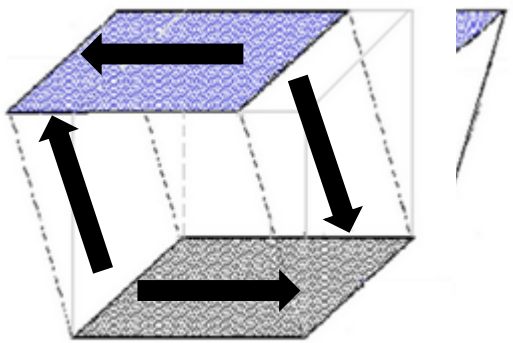


In the shear direction
– Burger's model

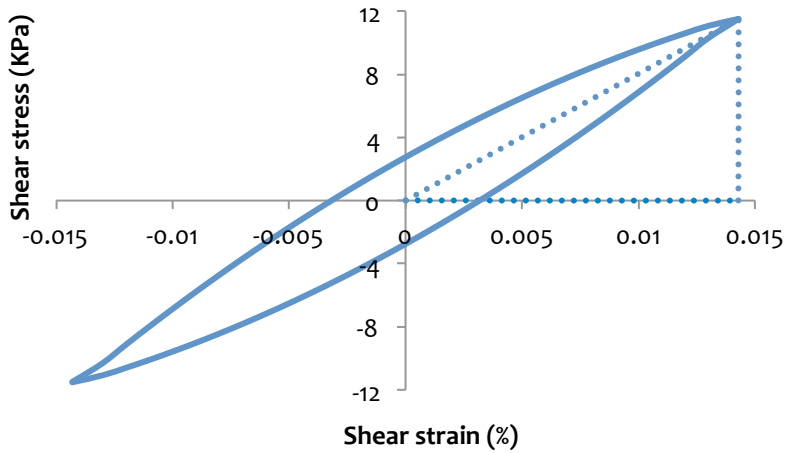


Parameters/sample properties	Values
Sample properties	
No. of particles	32000
Aspect ratio	1.6
For the Hertz-Mindlin contact model	
Poisson's ratio, ν	0.2
Shear modulus, G	3×10^{10} Pa
Friction coefficient, f_s	0.5

DEM simulations of cyclic shear tests



- The shear velocity was very low (~2 ×10^{-7} mm/s)
- The shear strain is controlled in the range of (2 ×10^{-6} ~ 7 ×10^{-4})

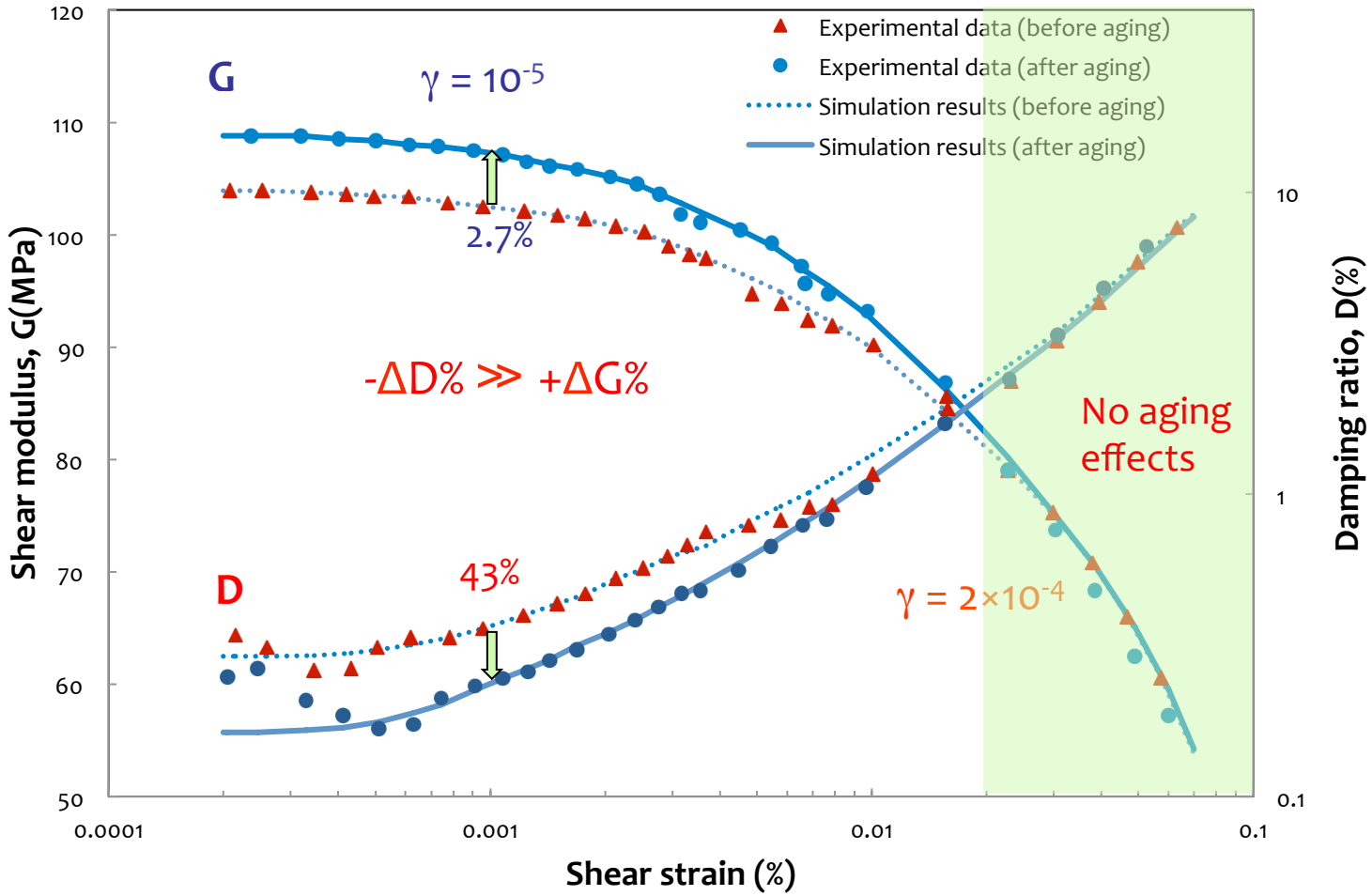


$$D = \frac{W_L}{4\pi W_S} = \frac{W_L}{2G\gamma^2}$$

W_L: Energy dissipated
W_S: Energy stored.

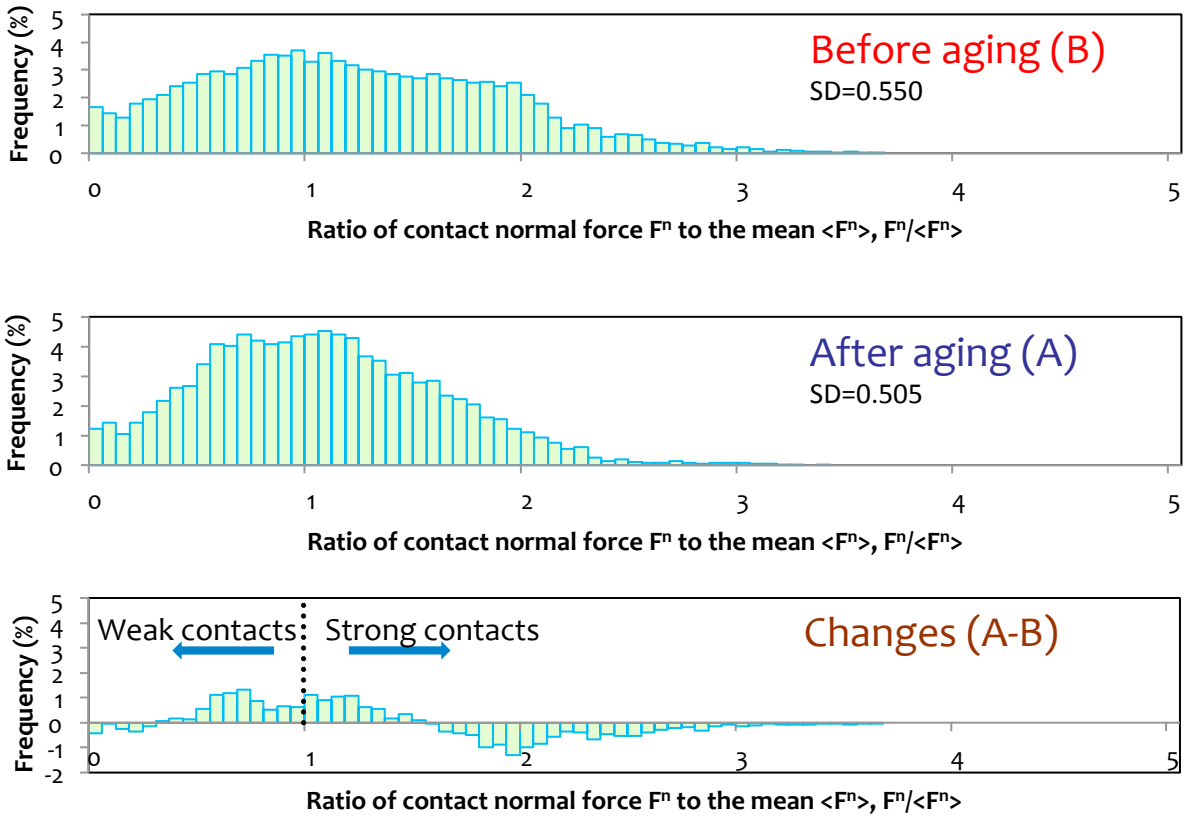
Aging effects on G and D

$$D = \frac{W_L}{4\pi W_S} = \frac{W_L}{2G\gamma^2}$$



Resonant column tests; Toyoura sand subjected to a constant isotropic confining pressure of 100 kPa for 2 days.

Micromechanical insights ($\gamma = 10^{-5}$)

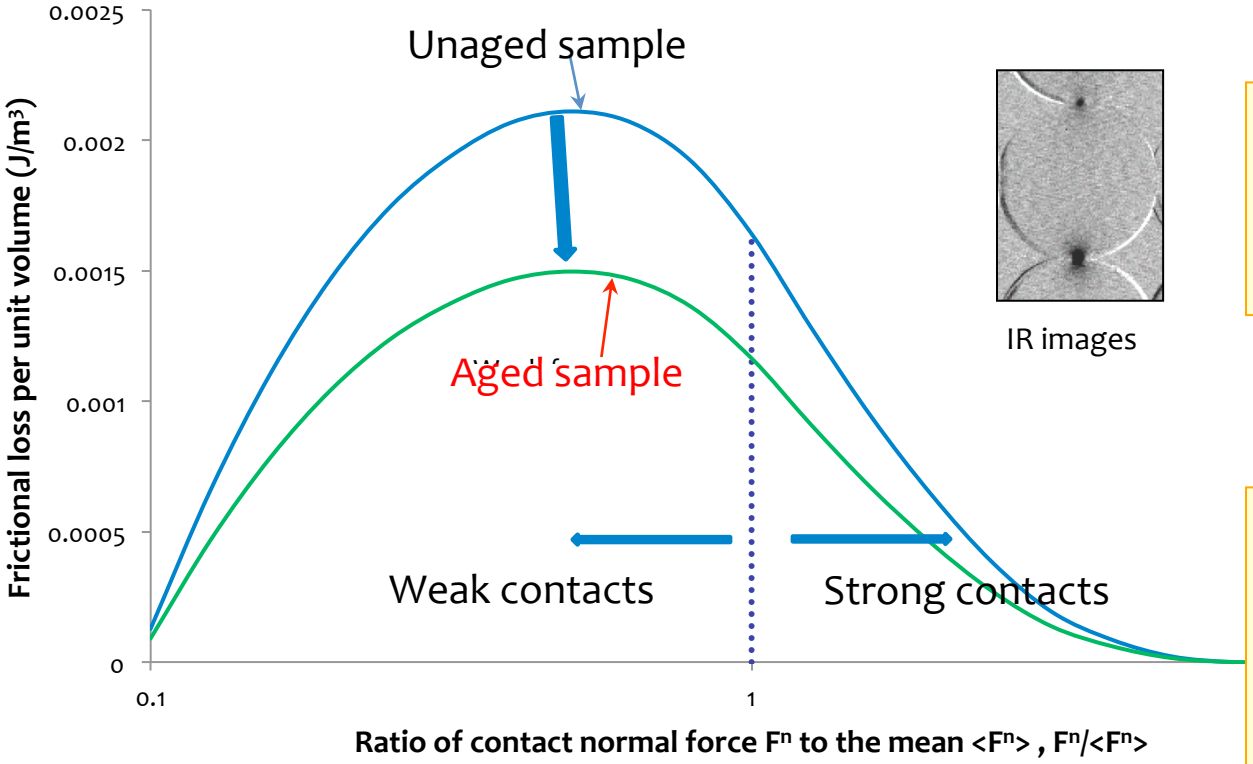


Contact force homogenization

G↑

Micromechanical insights ($\gamma = 10^{-5}$)

$$D = \frac{W_L}{4\pi W_S} = \frac{W_L}{2G\gamma^2}$$



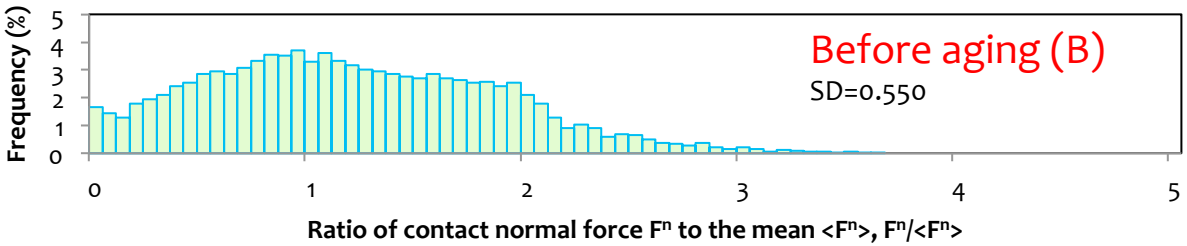
IR images

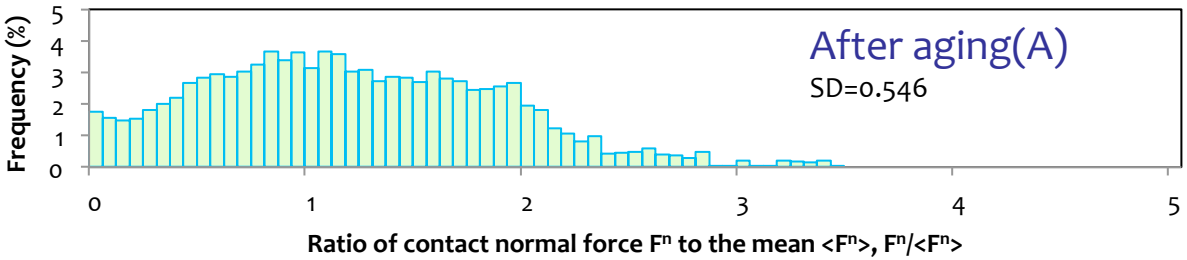
Most particle sliding and energy loss occur at weak contacts (e.g., Radjai et al. 1996; Kuhn 1999)

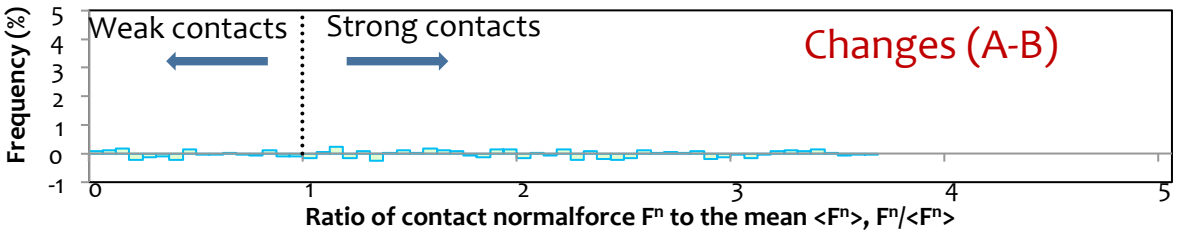
Increasing contact normal forces at the weak contacts can ***significantly reduced energy dissipation***

D ↓

Micromechanical insights ($\gamma = 5 \times 10^{-4}$)





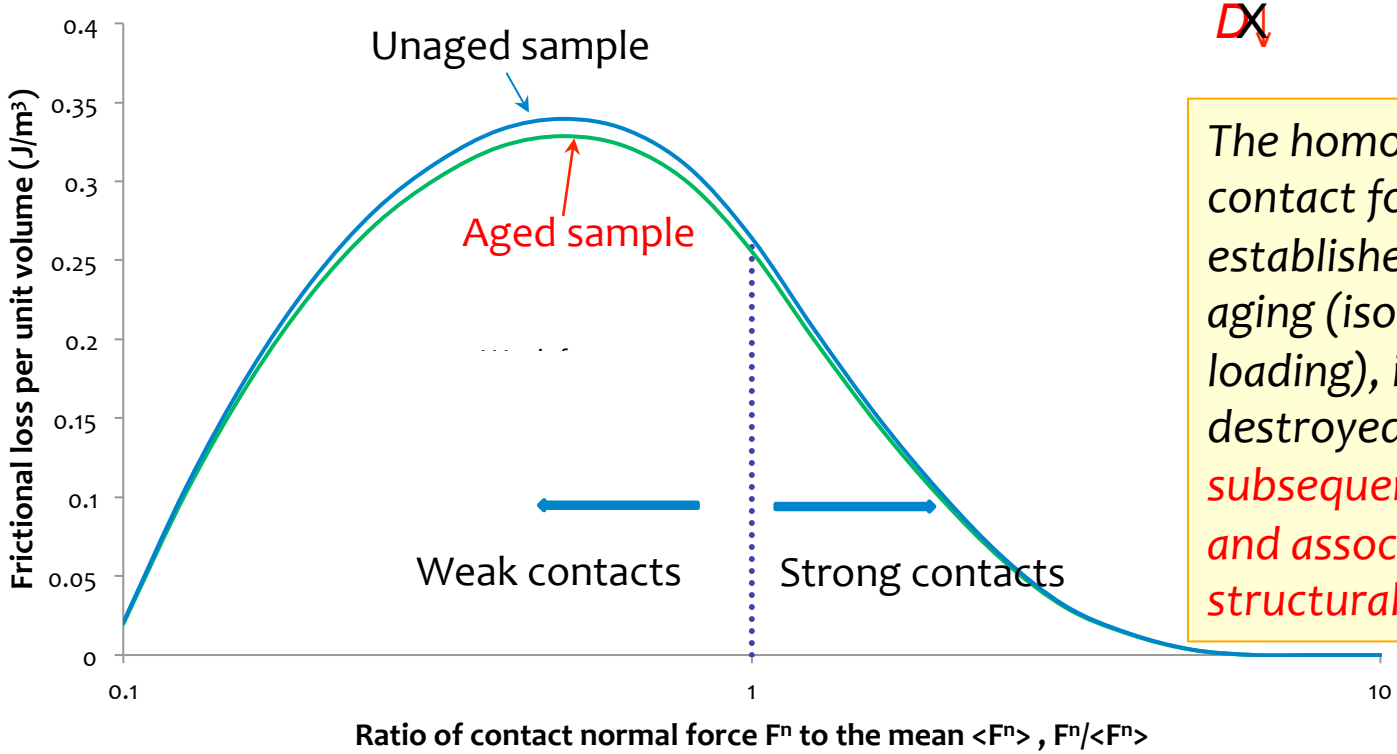


No Contact force homogenization

$\cancel{\gamma}\uparrow$

Results and Discussions ($\gamma = 5 \times 10^{-4}$)

$$D = \frac{W_L}{4\pi W_S} = \frac{W_L}{2G\gamma^2}$$

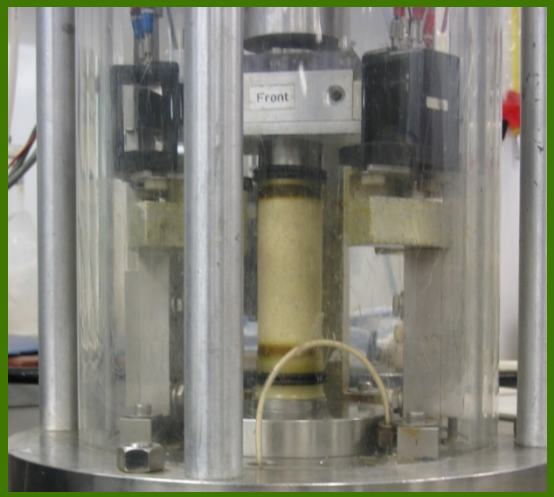


The homogenized contact forces, established during aging (isotropic loading), is gradually destroyed by subsequent shearing and associated structural changes.

Summary

- The aging effects can decrease damping ratios *D* more significantly than they can enhance the shear moduli *G*.

- The contact forces homogenized during aging can be gradually destroyed by subsequent shearing and associated structural changes. This is one of the reasons why aging effects are not always observed.



Interesting aging behavior III

Why are aging effects not always observed (density, unloading/reloading effects)?

(Wang and Tsui 2009)

Effect of packing density on the aging Rate

Summary of the resonant column test (G_{max} and D_{min})

	Aging at 35 kPa		Aging at 100 kPa	
	$\Delta G_f/G_{in}$ (%)	$\Delta D_f/D_{in}$ (%)	$\Delta G_f/G_{in}$ (%)	$\Delta D_f/D_{in}$ (%)
Dense Ottawa	5.5	-6.0	3.6	-8.7
Loose Ottawa	6.0	-7.7	2.4	-16.9
Dense Toyoura	3.9	-17.2	8.6	-39.2
Loose Toyoura	7.1	-23.1	4.8	-17.8

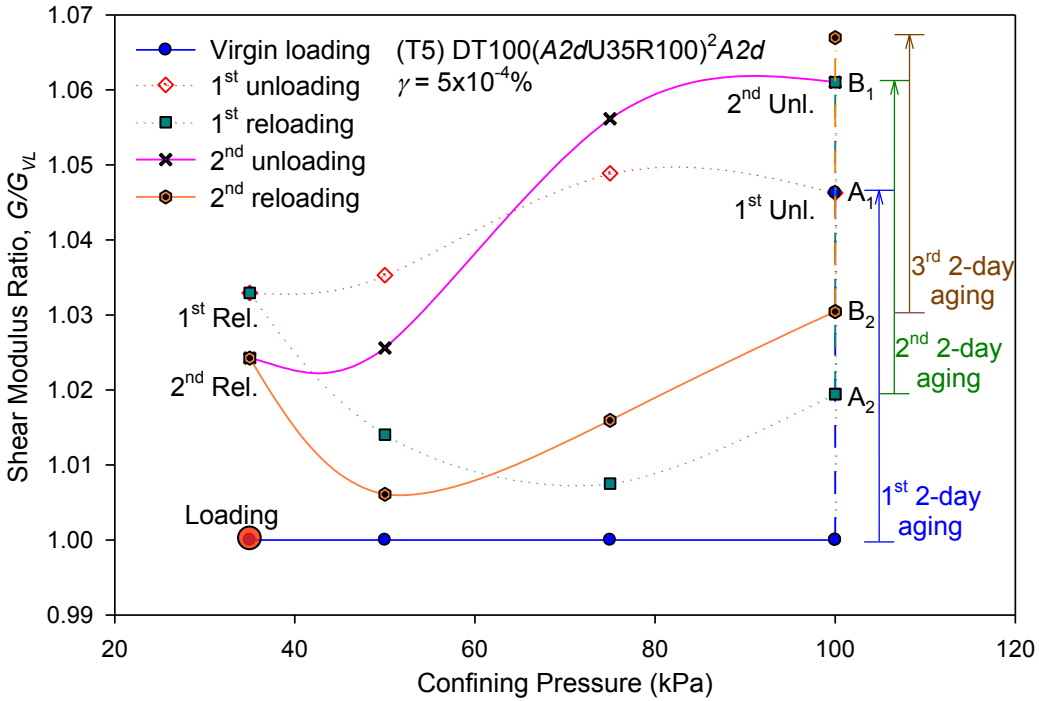
Aging rate: Loose > Dense at 35 kPa

A higher degree of contact forces homogenization in loose sand (as we expect)

Dense > Loose at 100 kPa

Structural instability of loose sand (Bowman and Soga 2003)

Aging behavior after unloading-reloading cycles



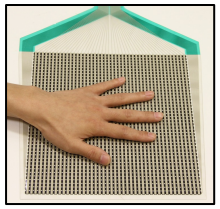
- *Unloading-reloading erases previous aging effects*
- *Sampling effects*

G at different stages is normalized by the virgin-loading value, G_{VL}.

Summary

- Aging effects are density and stress-path dependent.

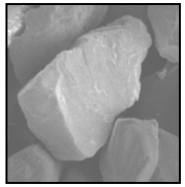
The aging mechanisms ?



Prove the mechanism
Experimental evidence

Simple and plausible explanations

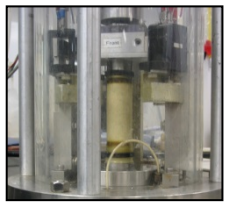
Interesting aging behavior



I.
G Stiffness anisotropy

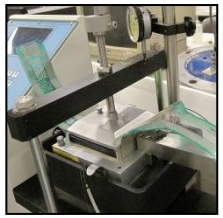
II.
Damping ratio D

III.
Straining, density, and unloading/reloading effects



Contact force redistribution & homogenization

Engineering concerns



IV.
Structuration
Ko changes
(1-D secondary compression)

V.
Pile setup of displacement pile

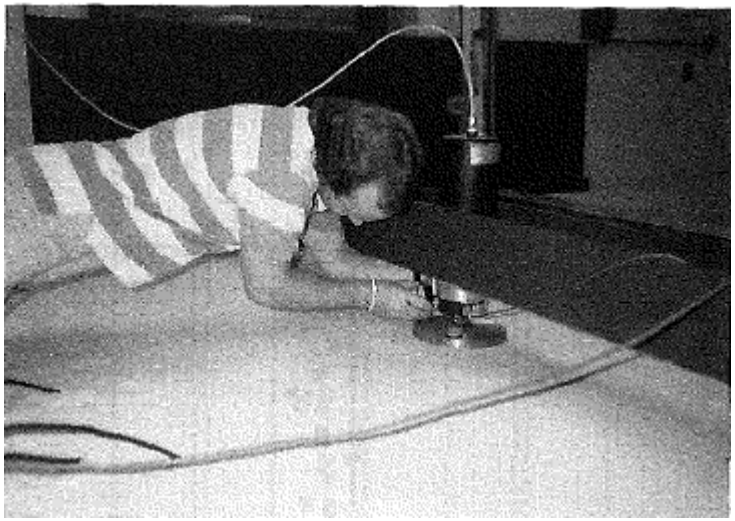
Interesting aging behavior IV

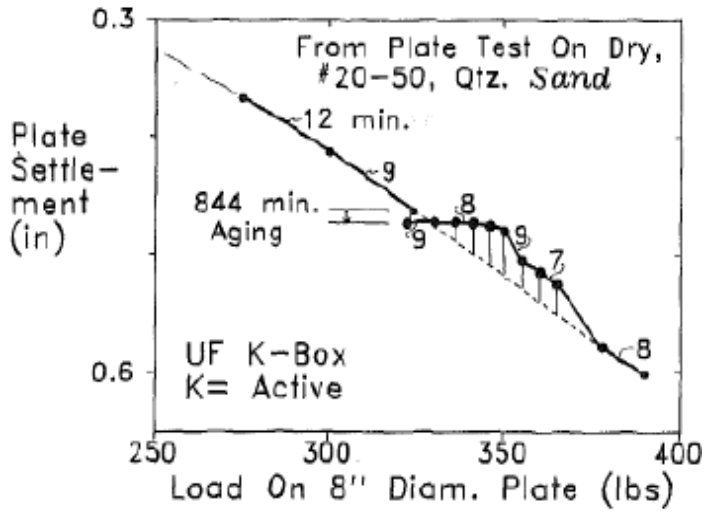
What are structuration mechanisms and K_0 variations during secondary compression and rebound?

(Wang and Gao 2014)

What is structuration?

- Structuration developed during secondary compression can strengthen the soil and then induce a preconsolidation "bump", i.e., a quasi-preconsolidation pressure.

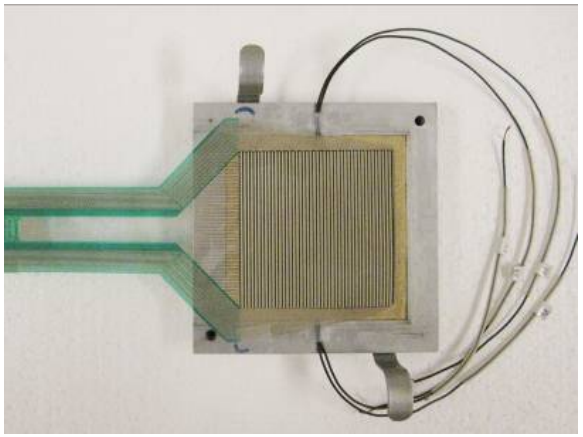


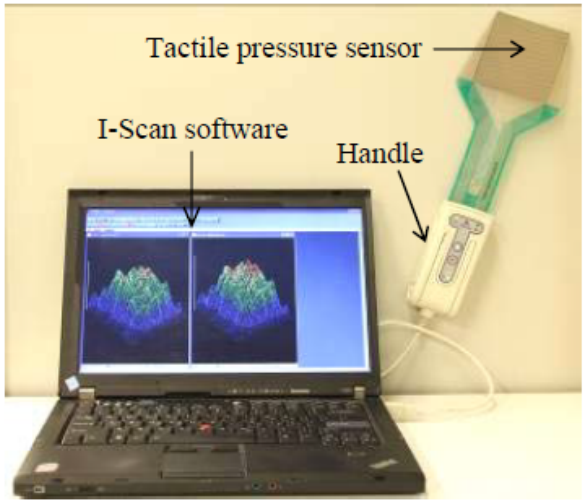


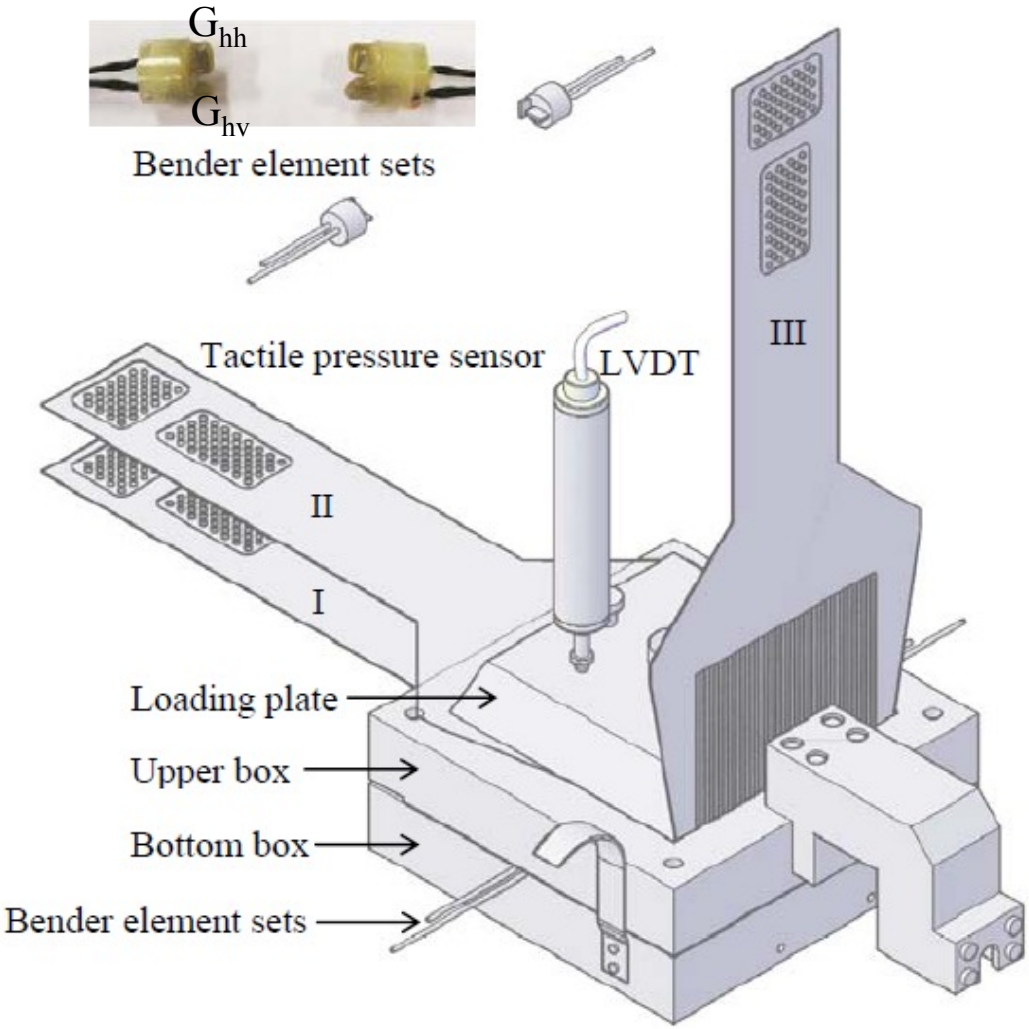
(After Schmertmann, 1991)

"However, another aging test without the preliminary passive-active cycle failed to produce an aging bump for reasons not yet explored." (Schmertmann, 1991)

Experimental details





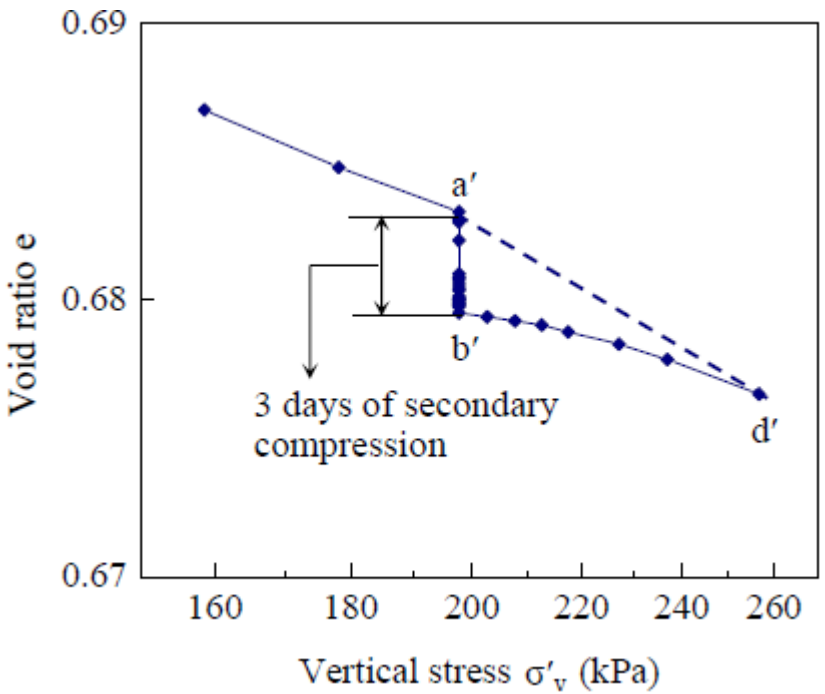


100 mm × 100 mm × 40 mm

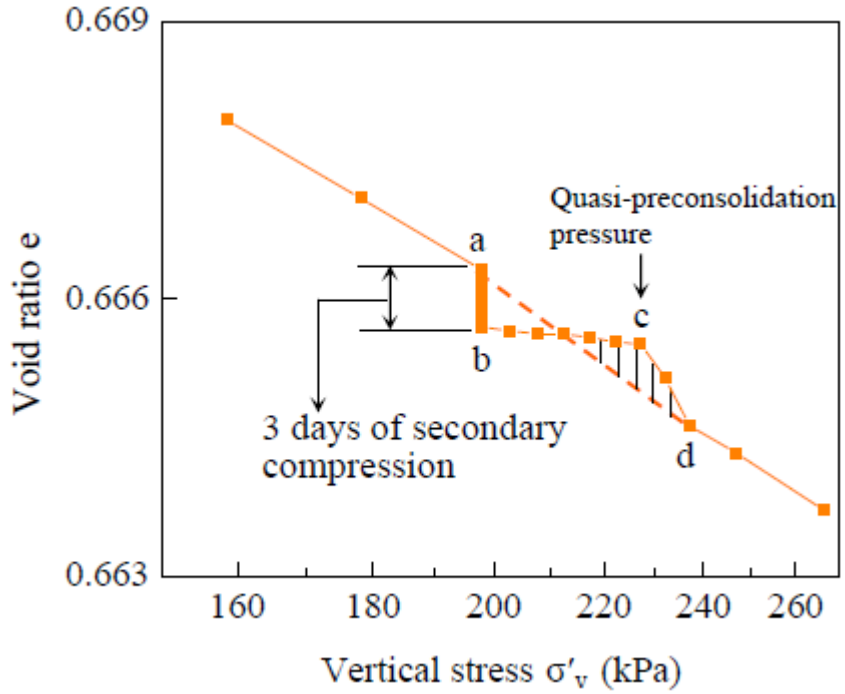
Experimental results

- Void ratio e versus vertical stress σ'_v

For a relative loose packing

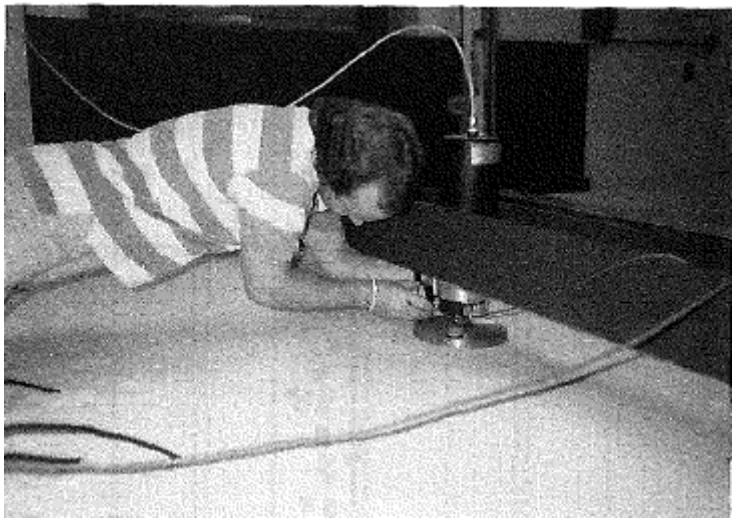


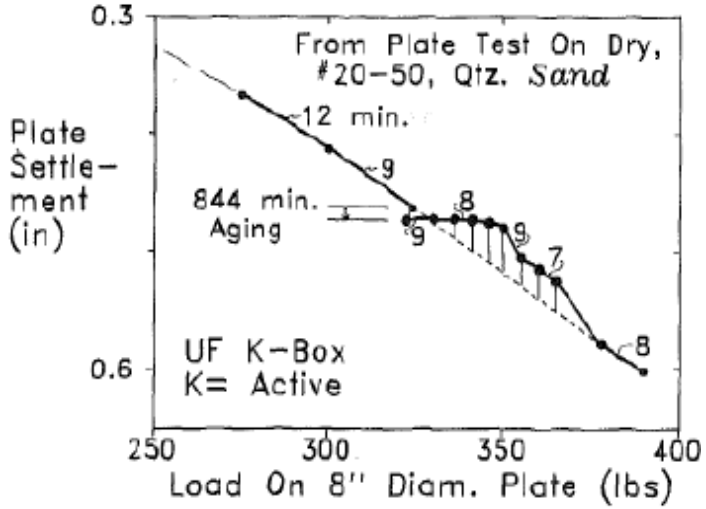
For a relative dense packing)



Greater structure changes involved in the loose sample minimize the structuration (or aging) effects

Experimental results





(After Schmertmann, 1991)

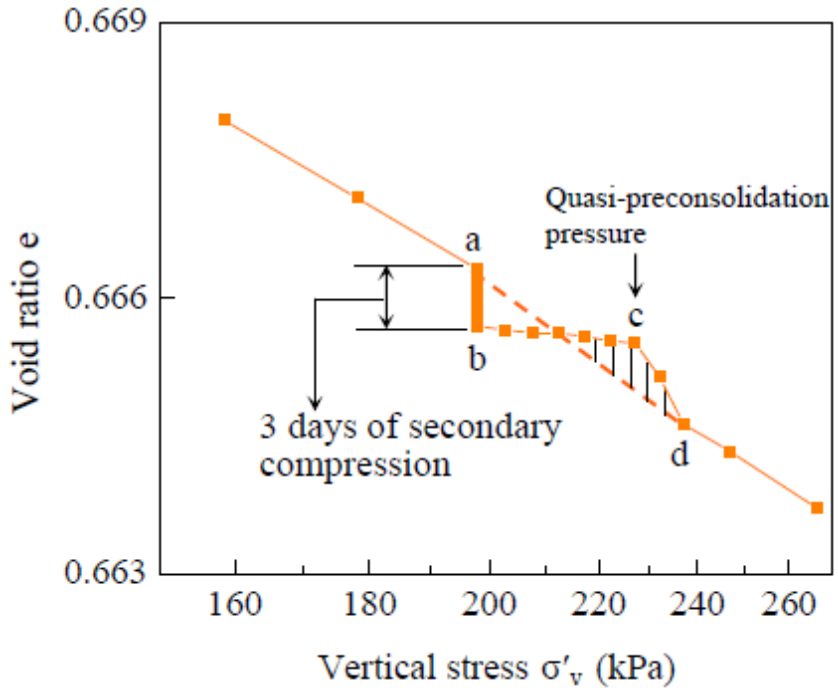
"However, another aging test without the preliminary passive-active cycle failed to produce an aging bump for reasons not yet explored." (Schmertmann, 1991)

After the passive-active cycle, the sample might be densified.

Experimental results

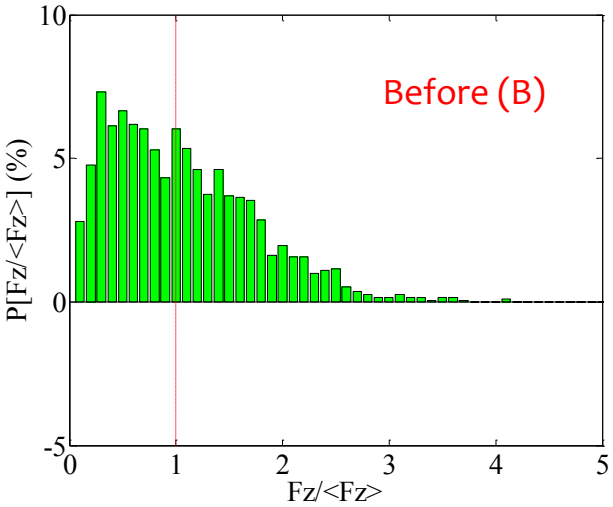
- *Contact normal forces and G* during secondary compression

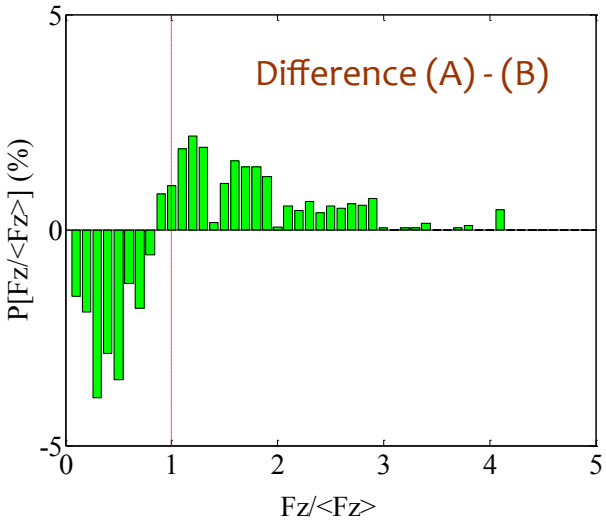
Structuration mechanisms ?

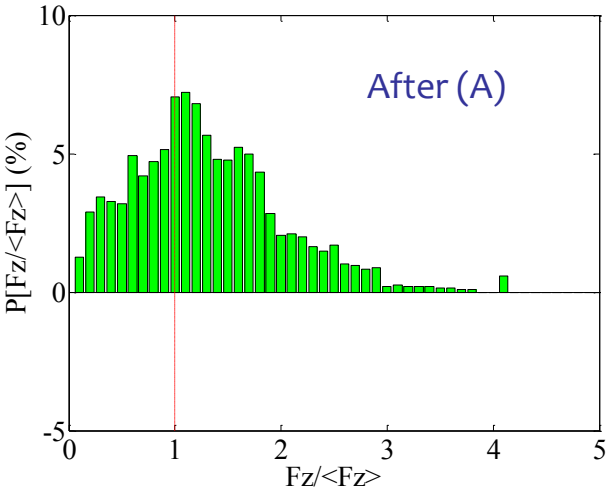


Experimental results

- measured *contact normal forces* during secondary compression



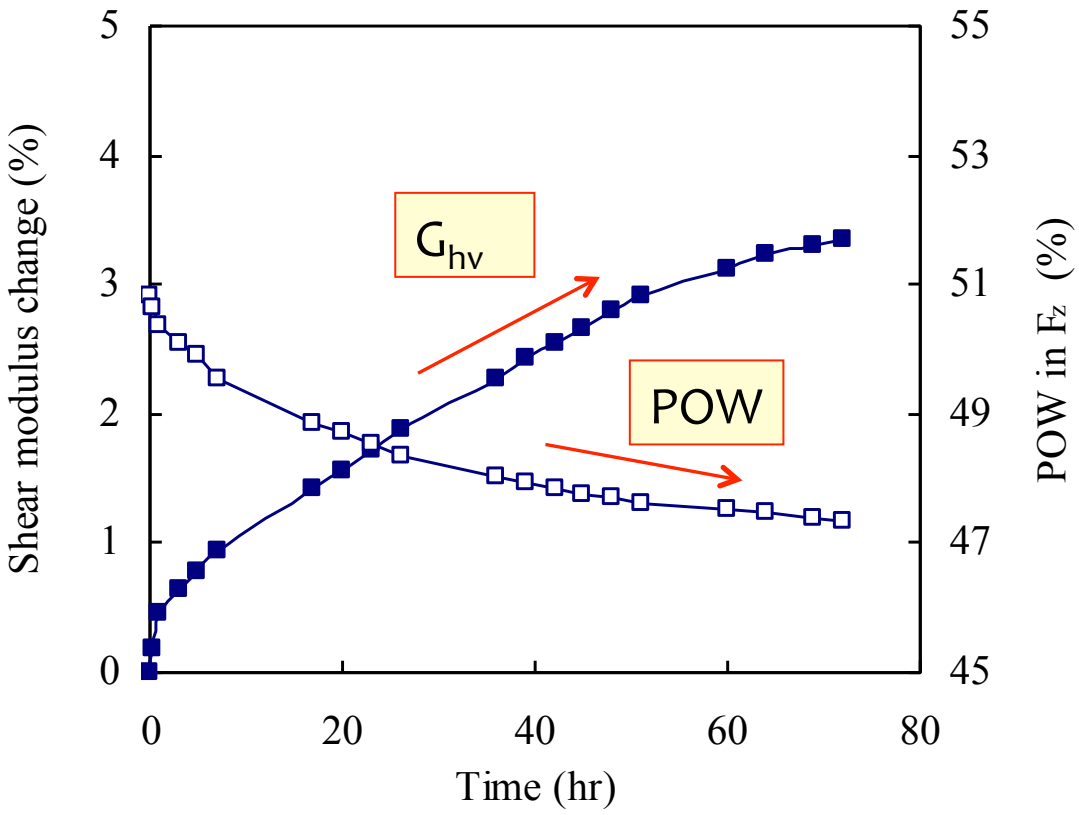




Contact force redistribution leads to increasing weak forces and strengthening the soil structure.

Experimental results

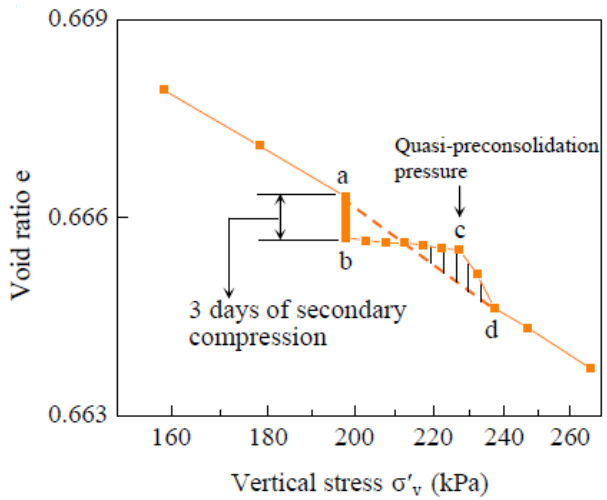
- *Contact normal forces and* G during secondary compression



During the structuration (or aging) process

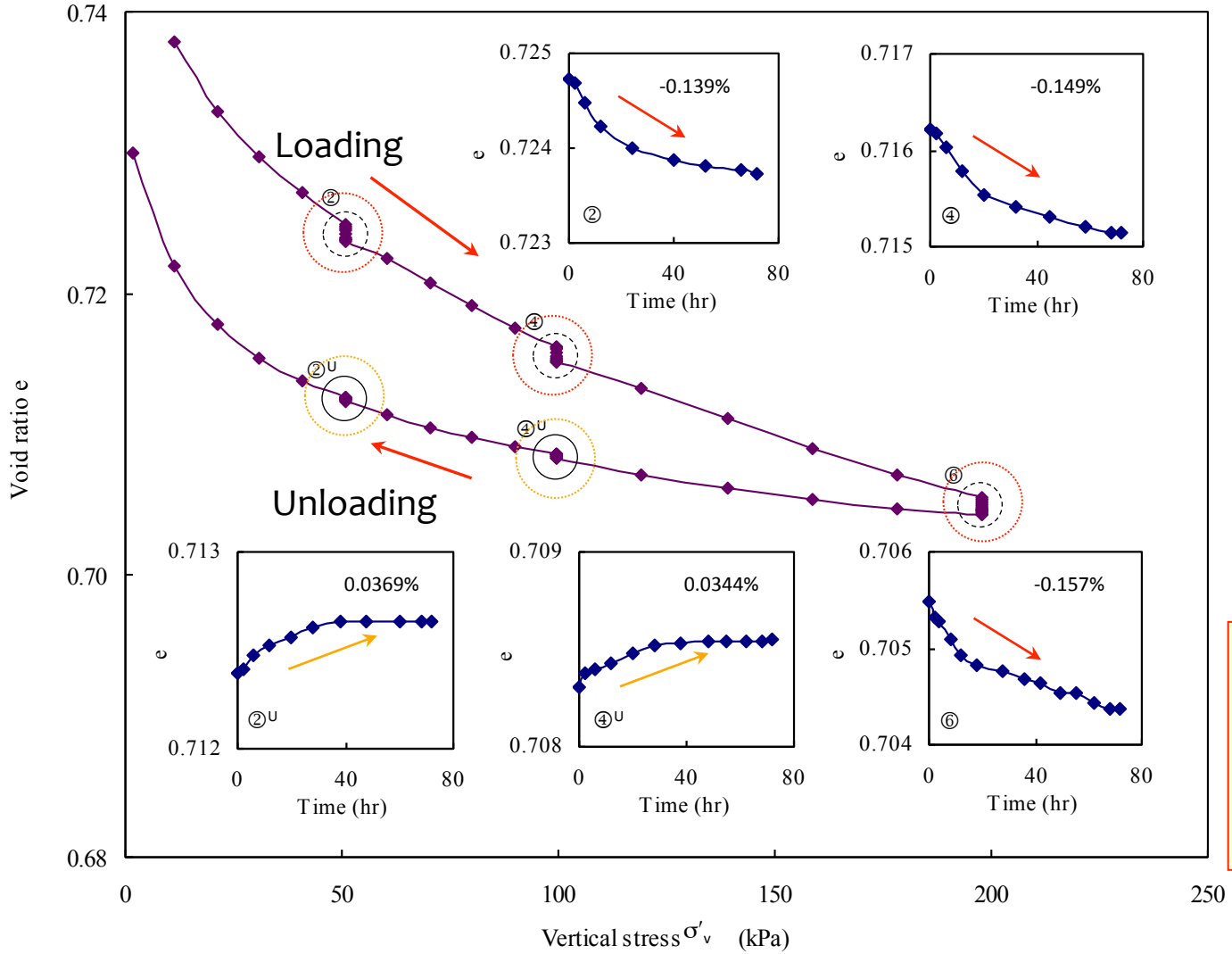
Percentage of weak forces (POW) ↓

Shear modulus G ↑



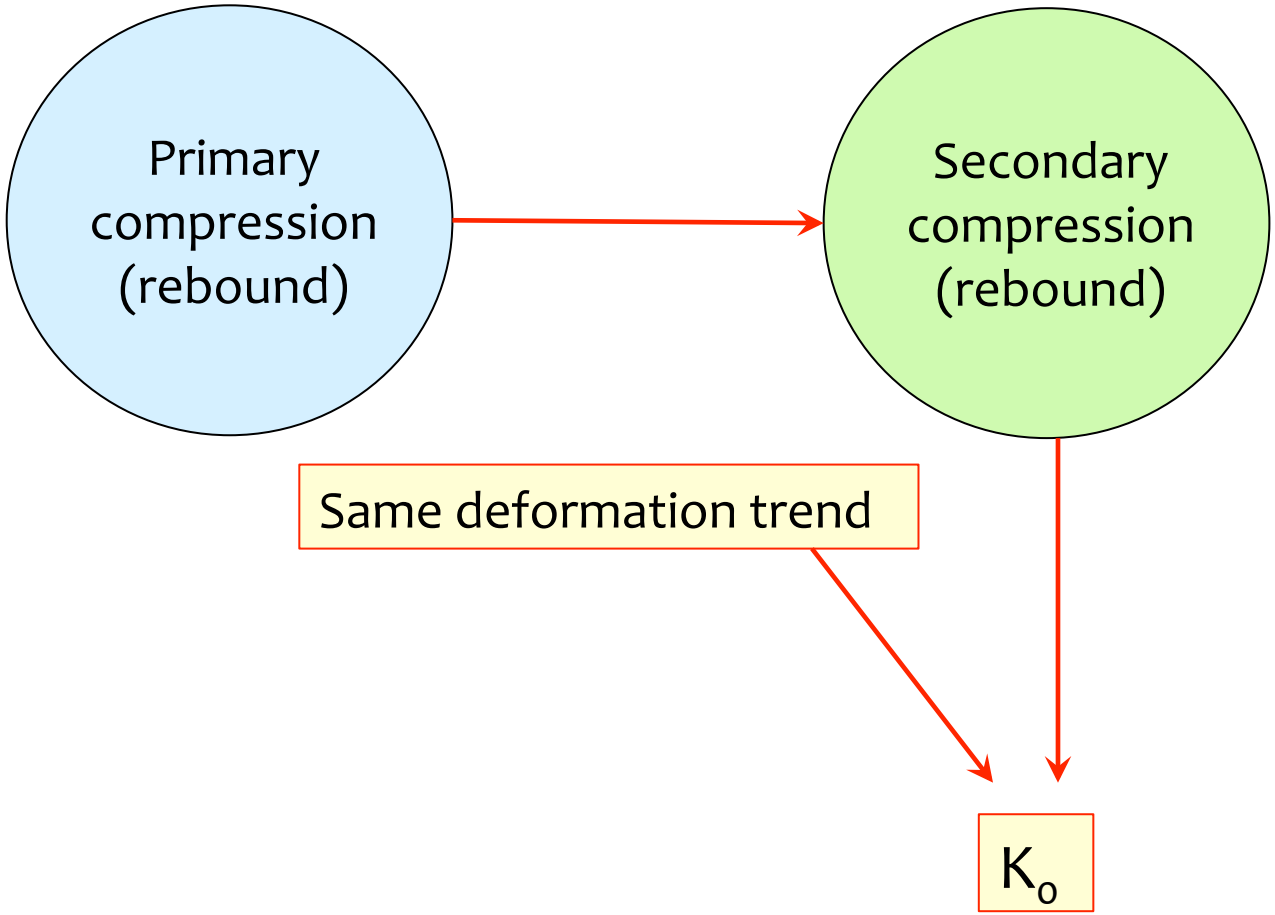
K_o changes

Secondary compression: continuous compression

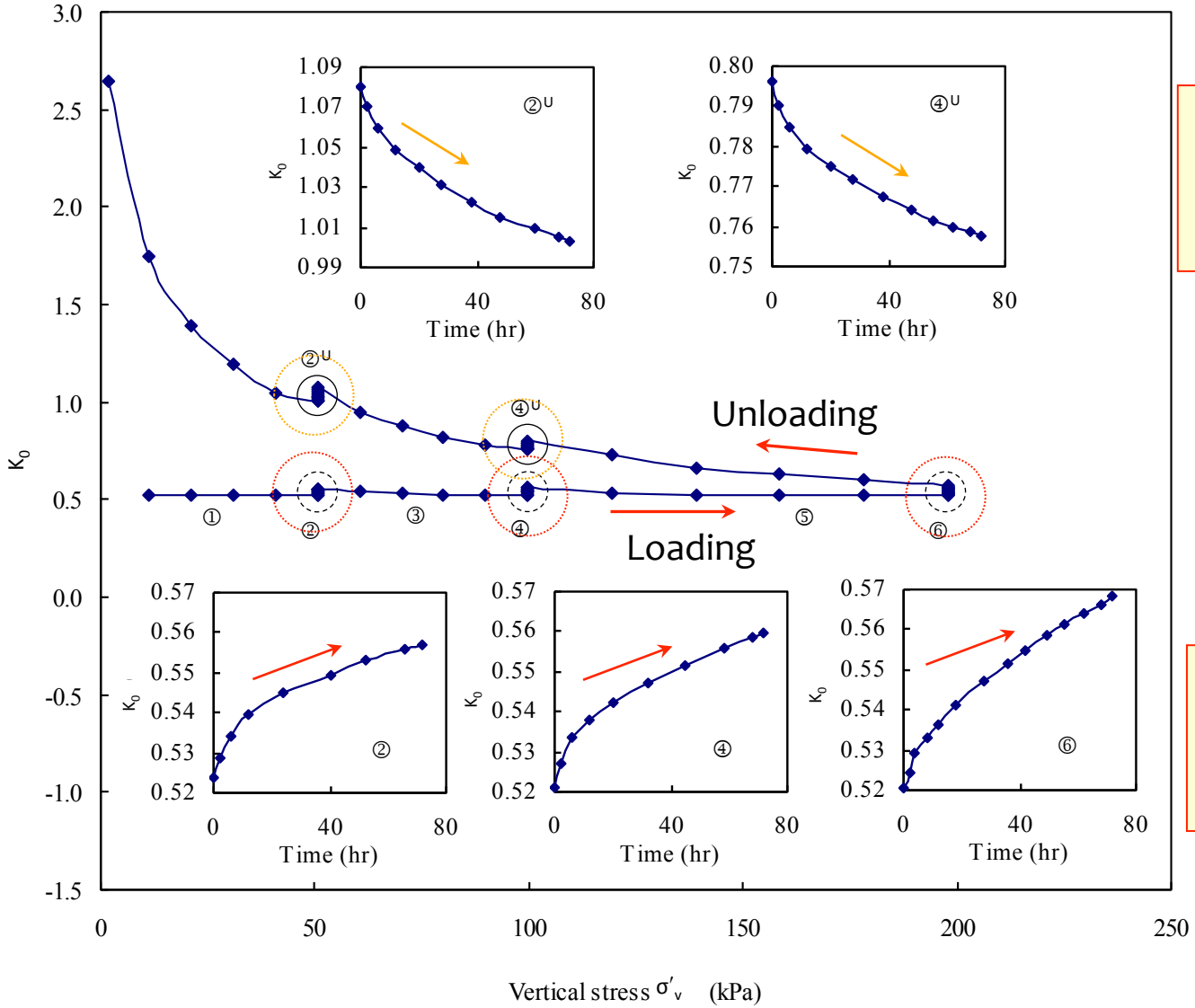


Secondary rebound: continuous expansion

That is,


Primary compression (rebound)
Secondary compression (rebound)
Same deformation trend
K_o

K_o changes



Secondary rebound
$K_o \downarrow$

Secondary compression
$K_o \uparrow$

Summary

- The structuration (or aging effects) developed during secondary compression causes the **contact forces to redistribute and leads to increasing weak forces**. As a result, the soil structure is strengthened.

- **K_o continues to increase during secondary compression** on the loading path. On the unloading path, however, **K_o continues to decrease during secondary rebound.**

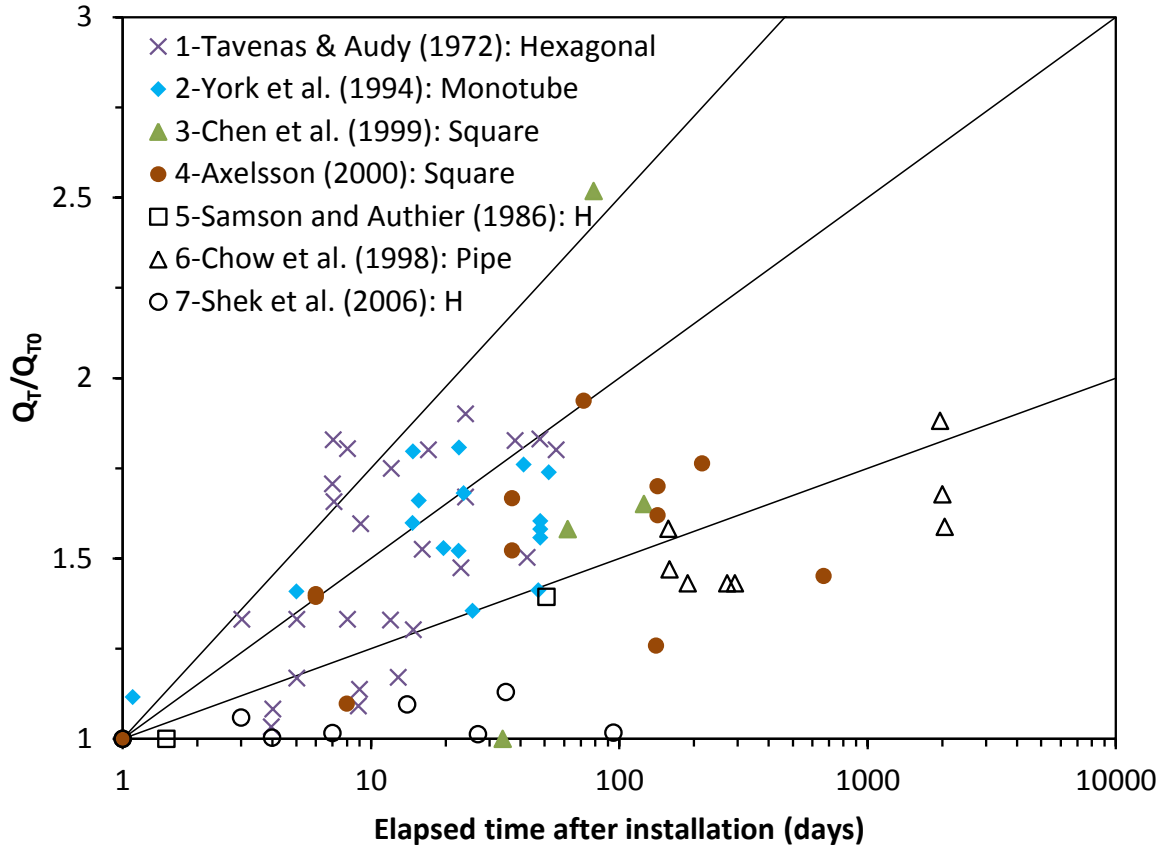
Interesting aging behavior V

What are the aging effects on the driven pile setup in sand ?

(Zhang and Wang 2014)

What is the pile setup?

- Shaft resistance continues to increase after the installation of displacement piles in sand (e.g., York et al. 1994; Chow et al. 1998; Axelsson 2000; White and Bolton 2004; Bowman and Soga 2005; Bullock et al. 2005; White et al. 2005; Jardine et al. 2006)



summarized by Zhang and Wang(2014)

Aging effects on the pile setup

The ultimate shear stress, τ_f, on the shaft (shaft resistance):

$$\tau_f = (\sigma'_{rp} + \Delta\sigma'_{rp})\tan\delta'_f$$ Lehane et al. (1993)

σ_{rp}' is the at-rest radial or lateral effective stress on the pile shaft;
$\Delta\sigma_{rp}'$ is the increase in the radial or lateral effective stress during pile loading;
δ_f' is the interface friction angle at failure.

$$\Delta\sigma'_{rp} = \frac{4\delta h}{D_p} G$$ Cavity expansion theory

Aging effects

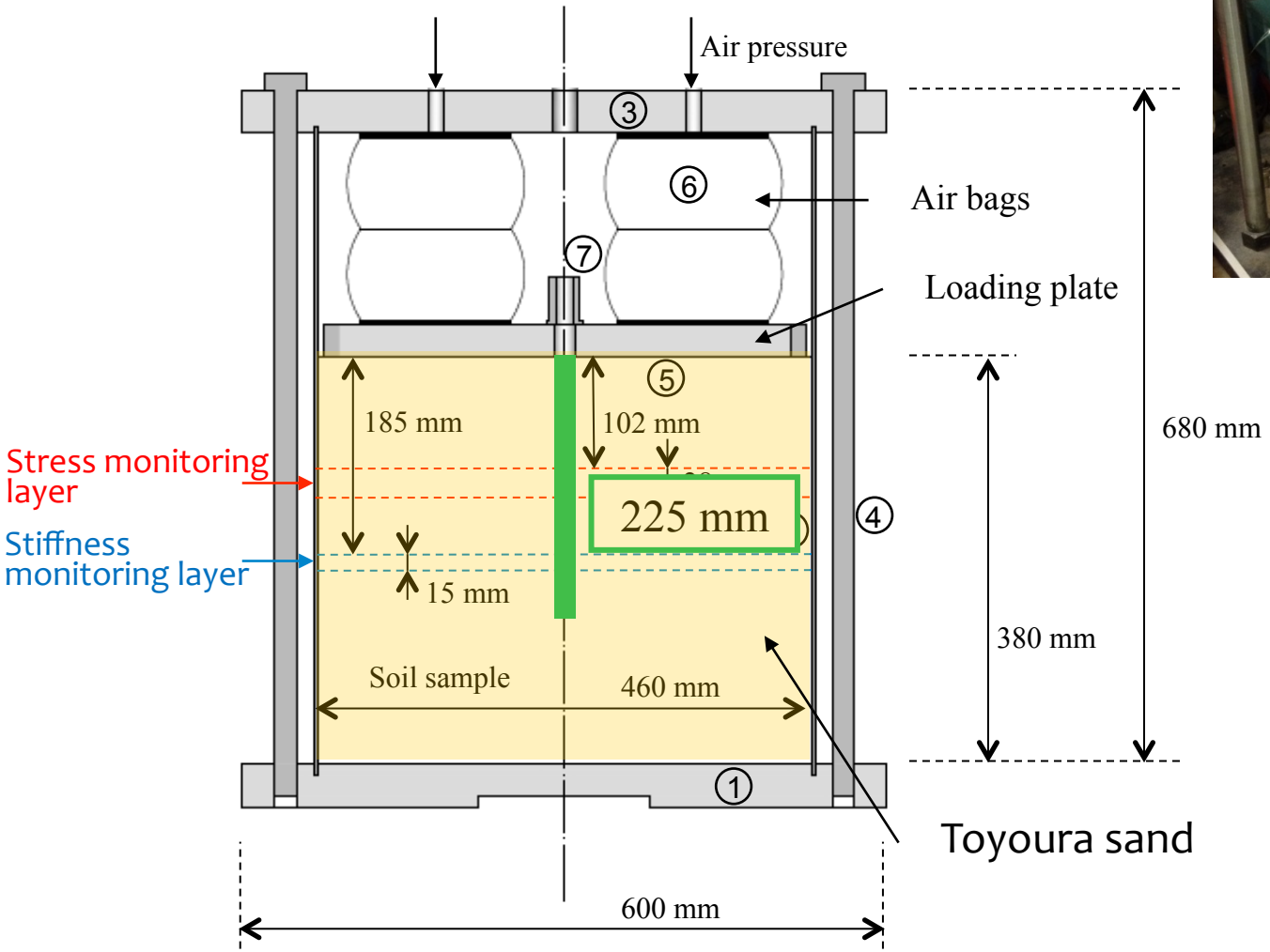
Constrained dilation, δh ↑
Shear modulus, G ↑
$\Delta\sigma'_{rp}$ ↑ τ↑

If the aging effects are the mechanism of pile setup, why is there no pile setup observed in bored piles?

(e.g., Axelsson 2002; Chow et al. 1998)

Experimental details

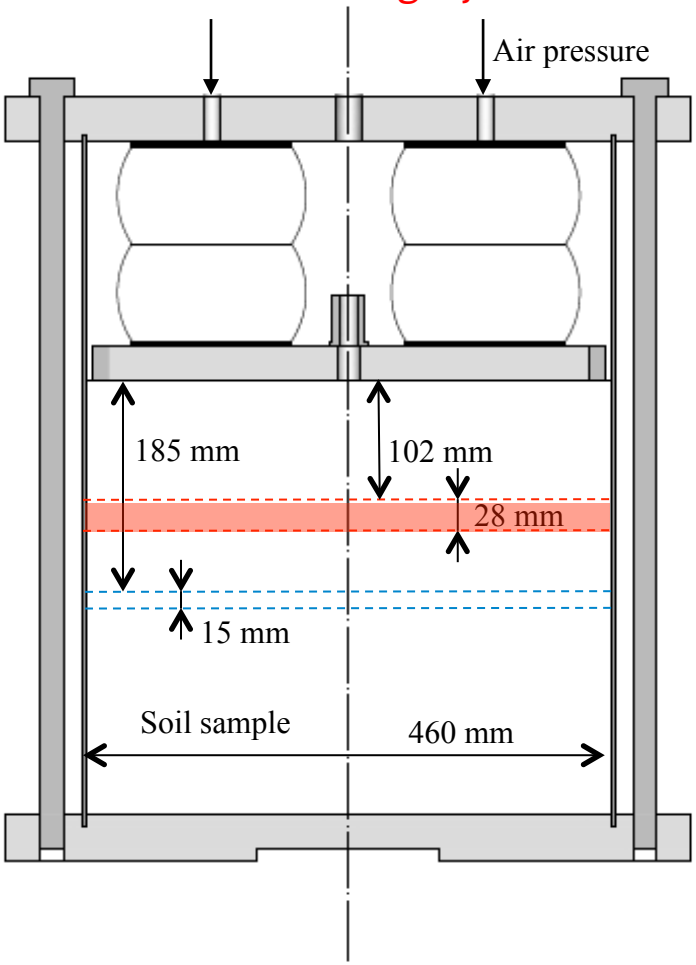
The pressurized chamber

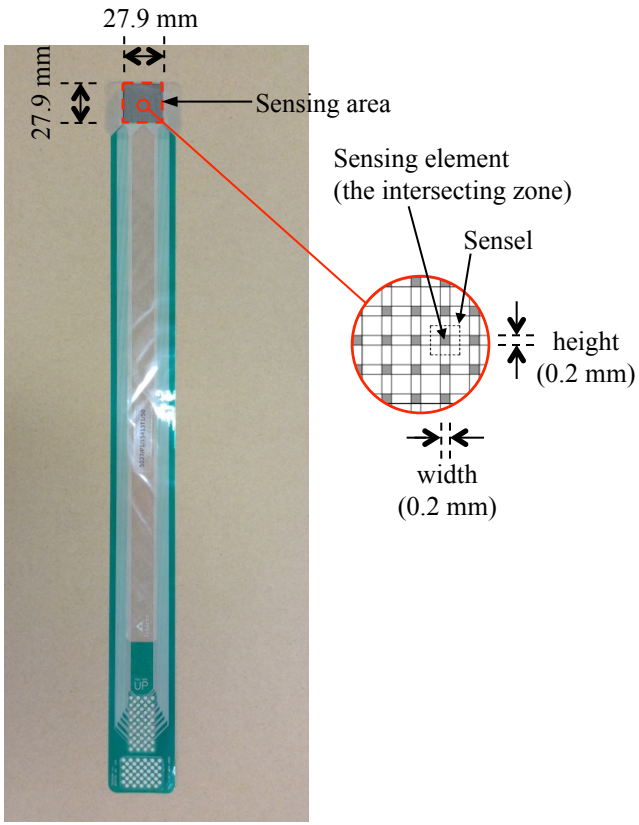


Experimental detail

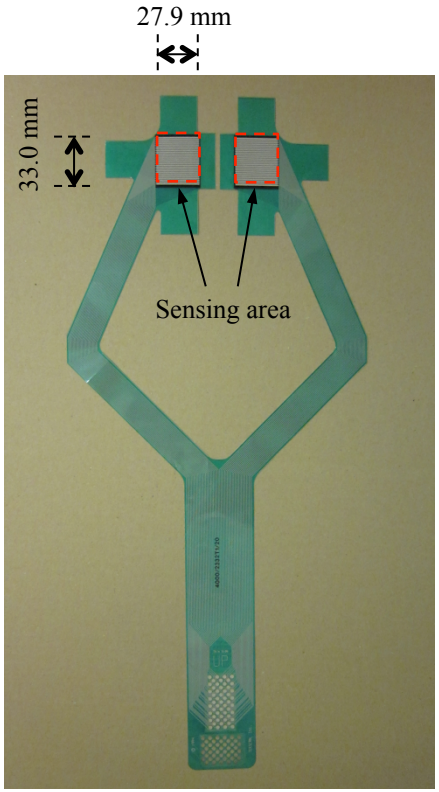
Arrangement of tactile pressure sensors

Stress monitoring layer





Model #5027

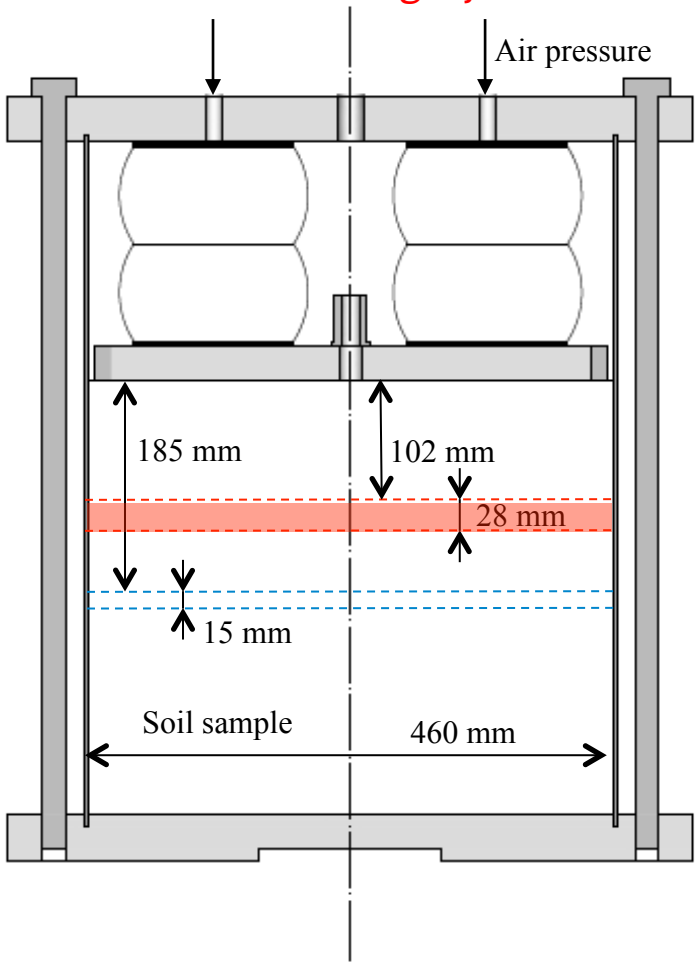


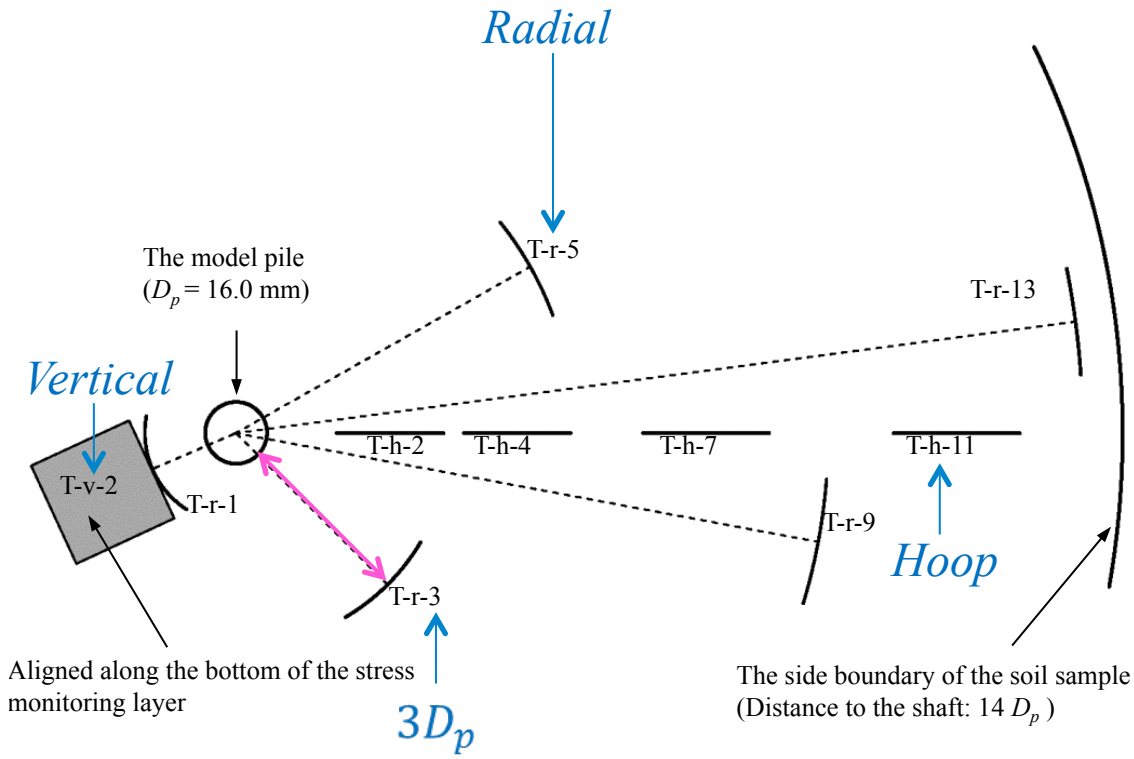
Model #4000

Experimental detail

Arrangement of tactile pressure sensors

Stress monitoring layer

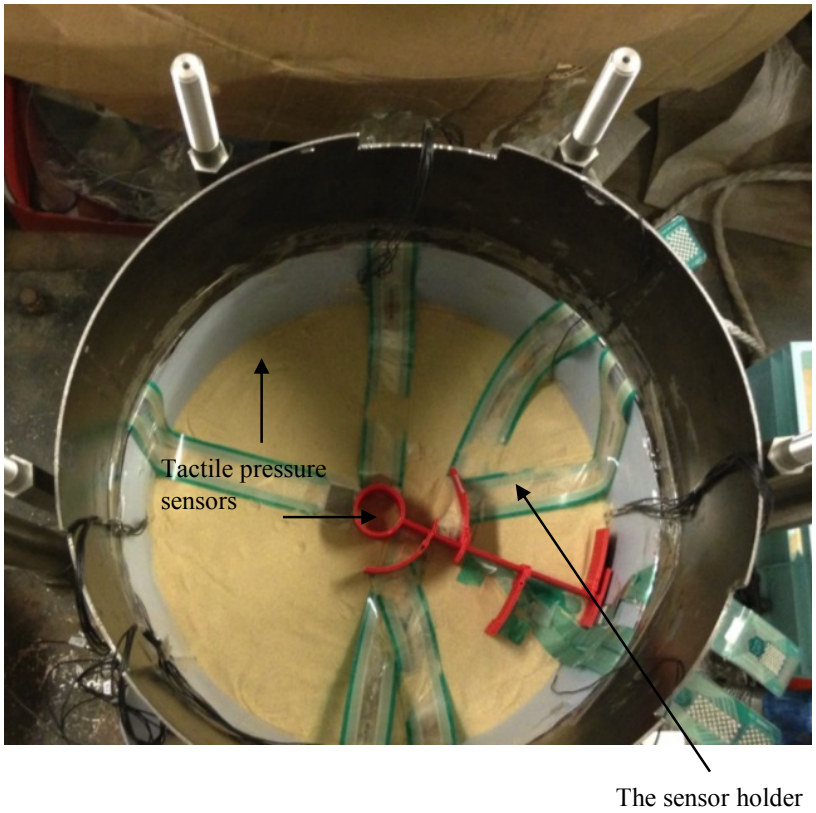


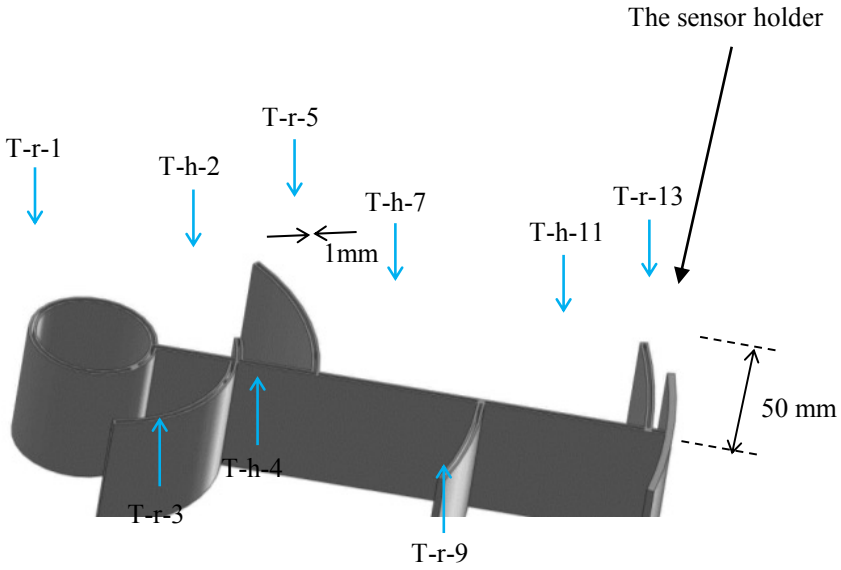


Plan view

Experimental details

Arrangement of tactile pressure sensors



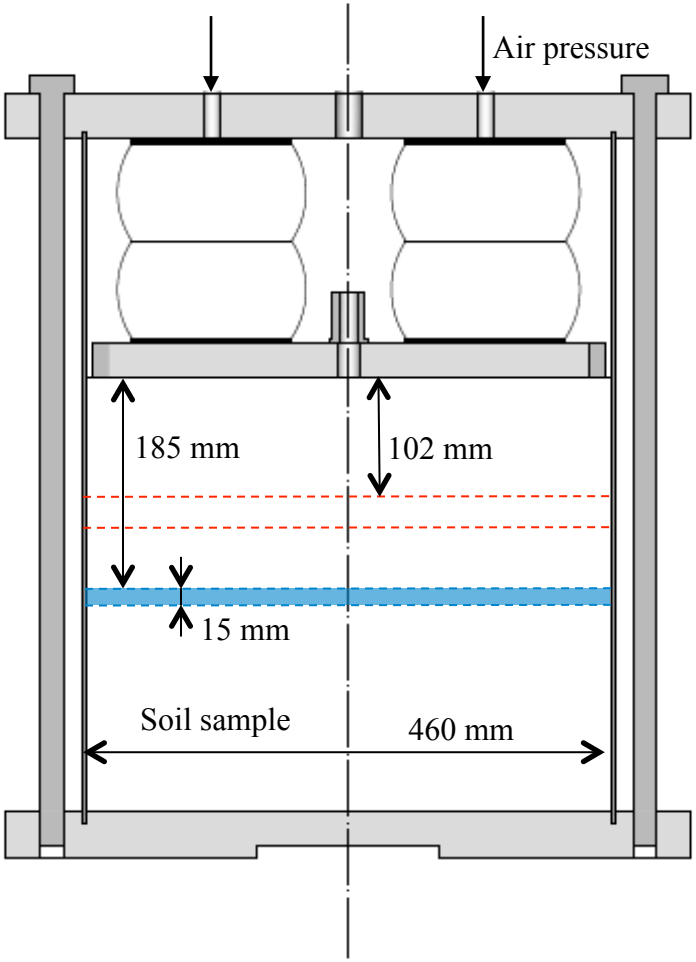


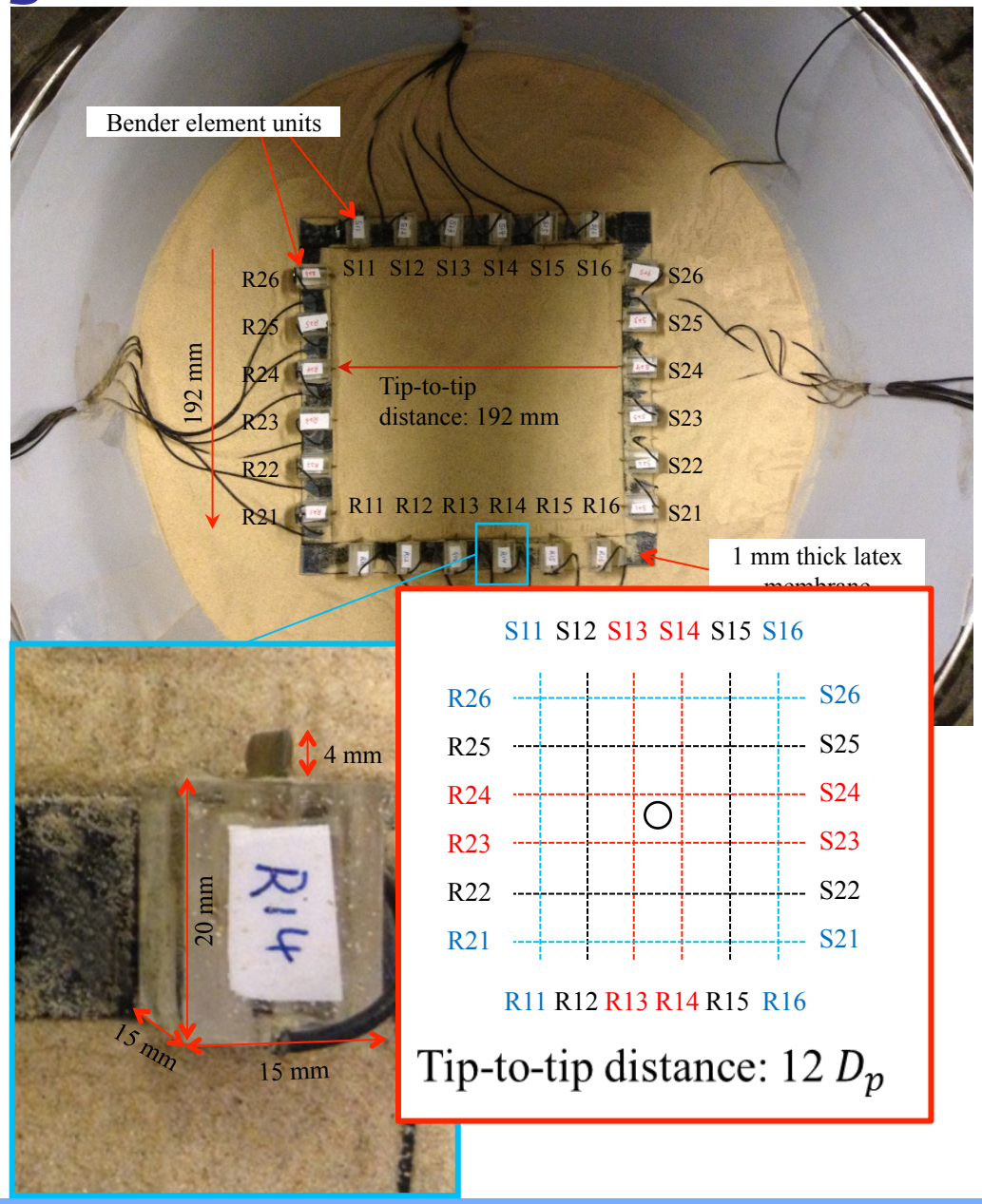
Printed out by 3D printer

Experimental details

Bender elements

Stiffness monitoring layer

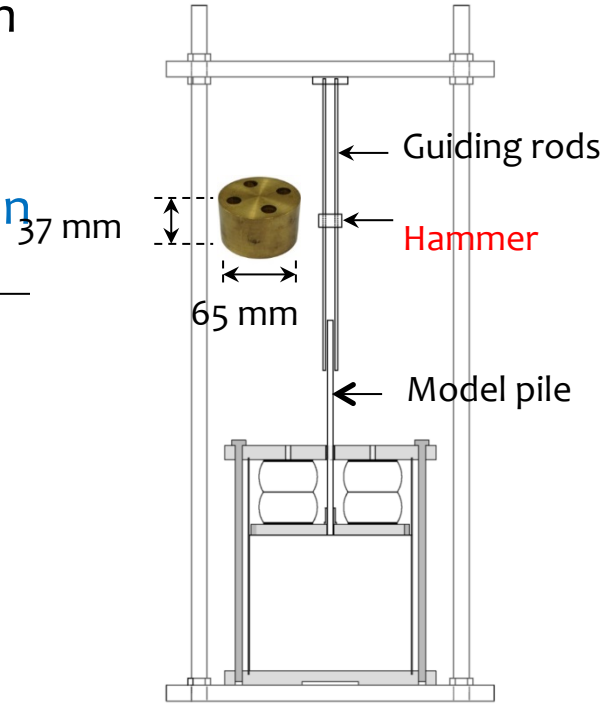




Testing procedures

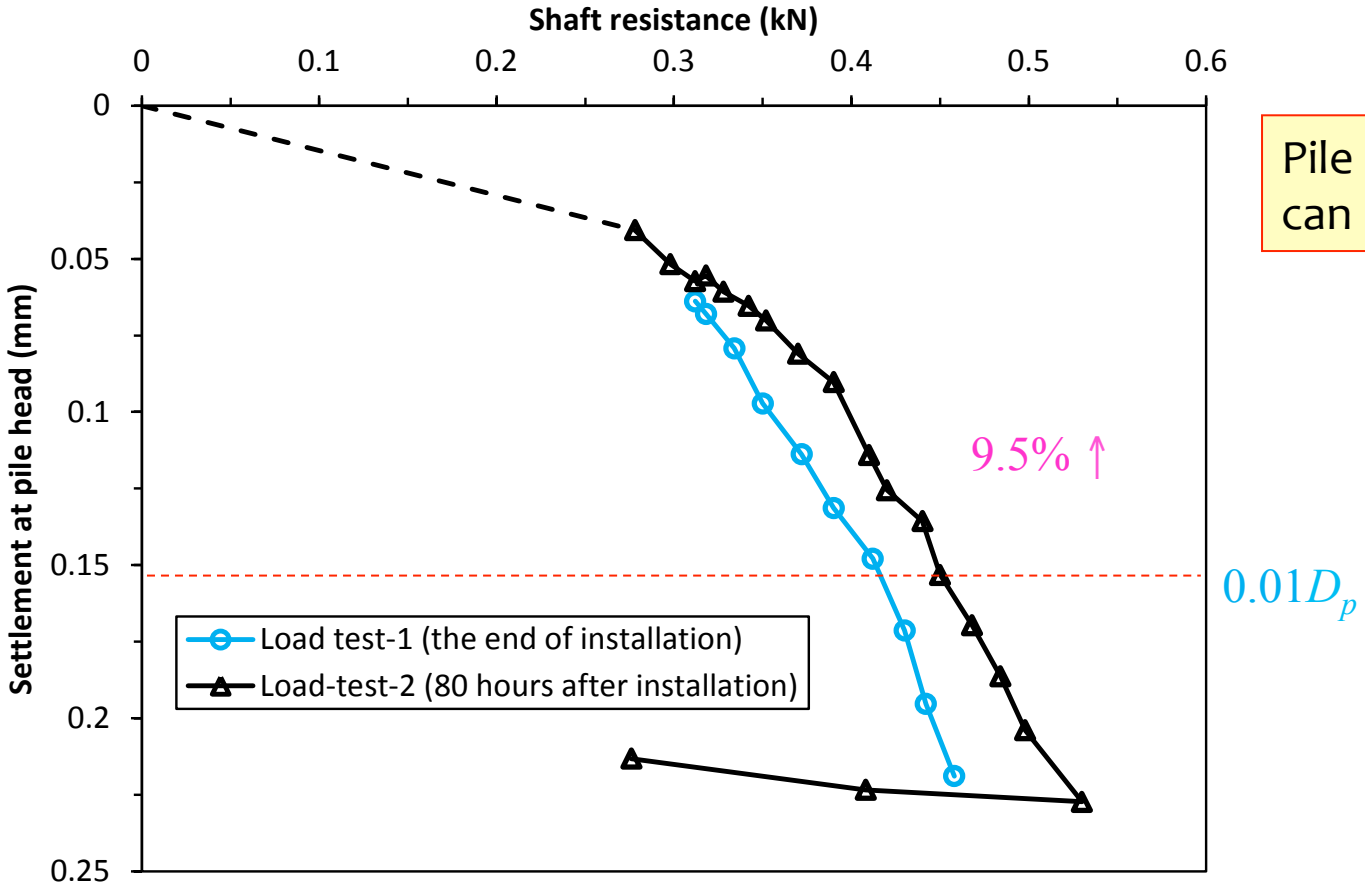
1. Sample preparation using the air pluviation method
2. Compression by 75 kPa for 80 hours
3. Pile installation using the pile driving system
4. The first load test (load test-1)
5. Monitoring the stress and stiffness evolution installation for 80 hours
6. The second load test (load test-2)

The compression period (original aging process)



Experimental results – setup effect

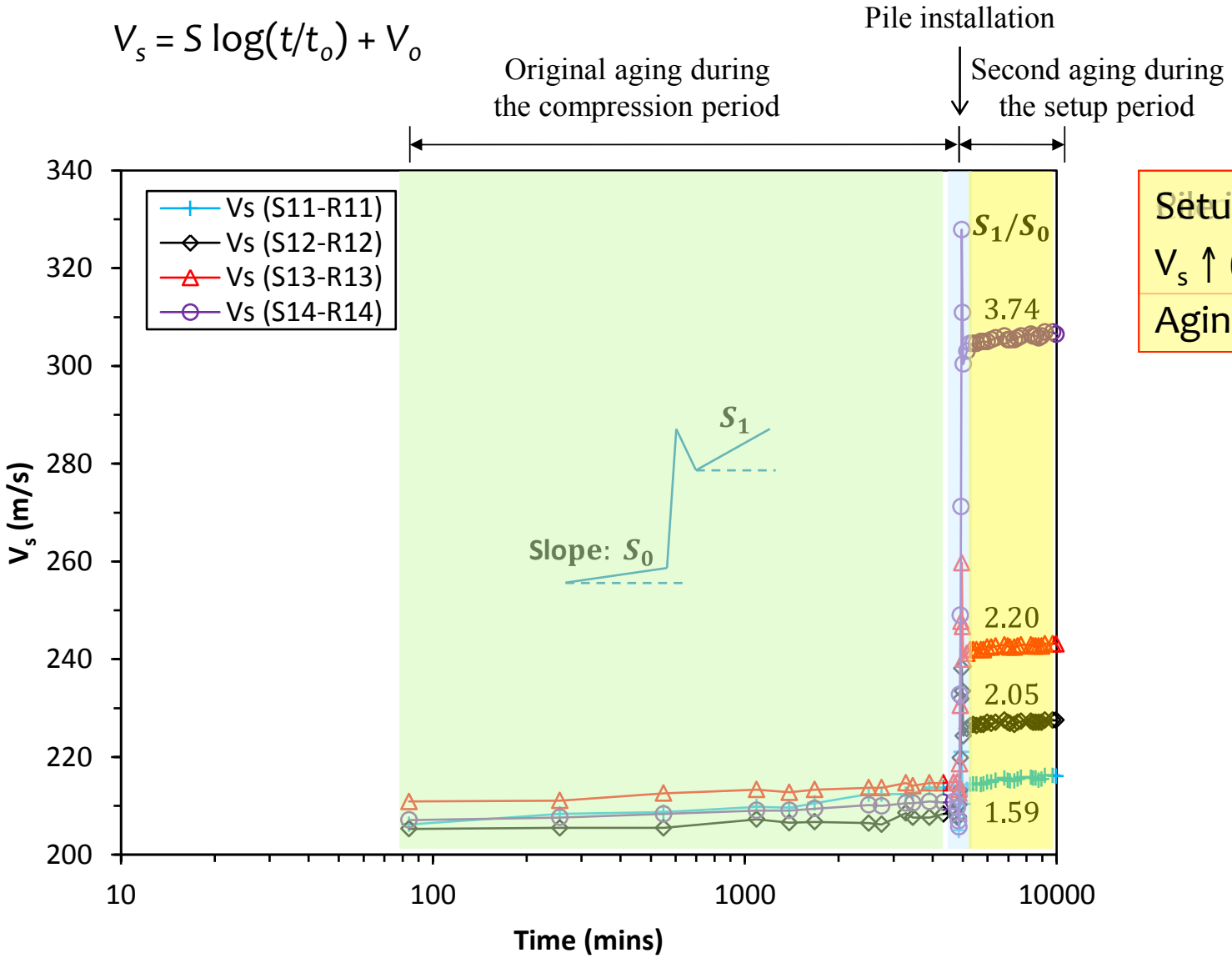
Change in the shaft resistance



Pile setup effect can be observed

Experimental results - Changes in V_s (or G)

$V_s = S \log(t/t_o) + V_o$

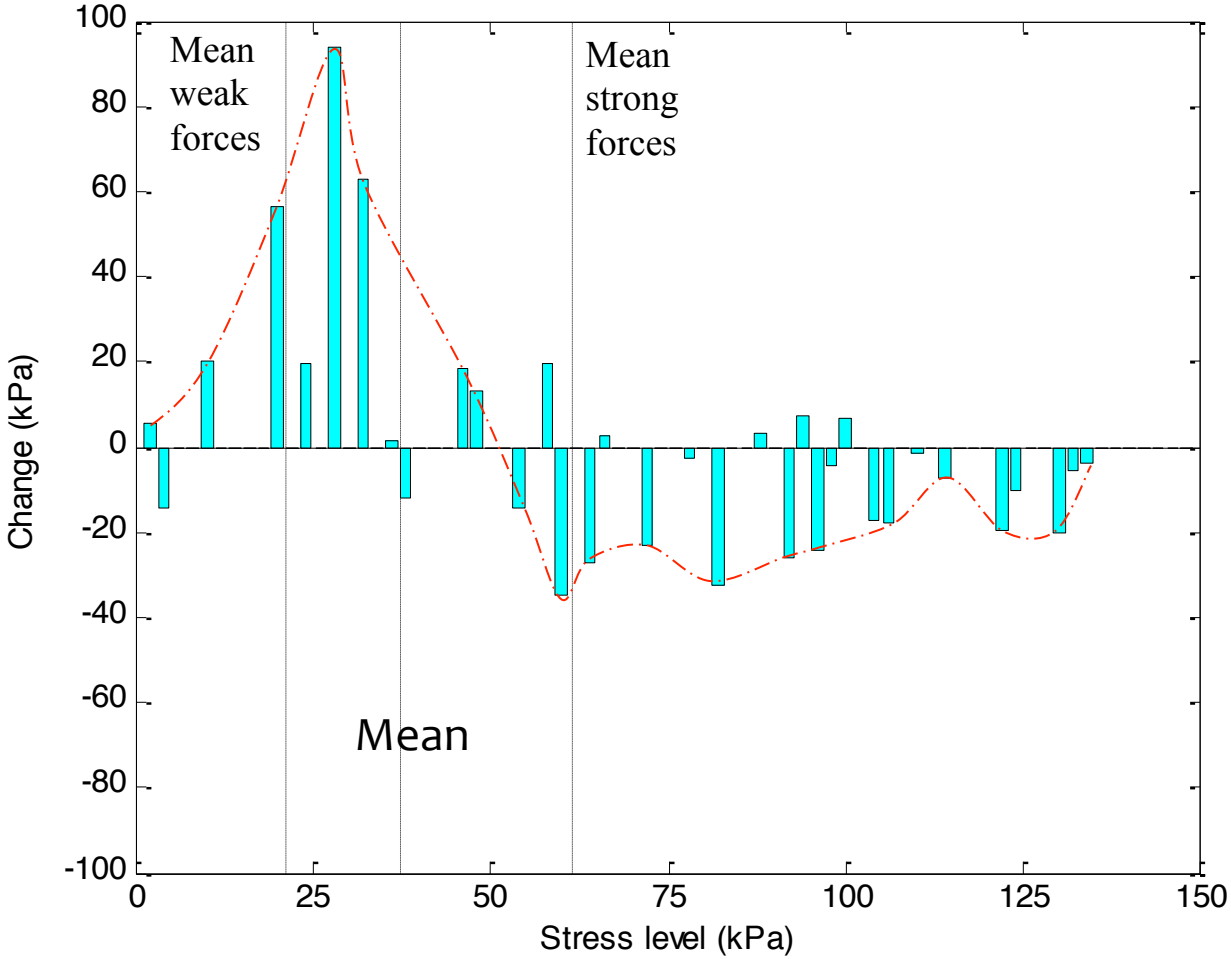


Setup period

V_s ↑ (2nd aging effect)

Aging rate S_1

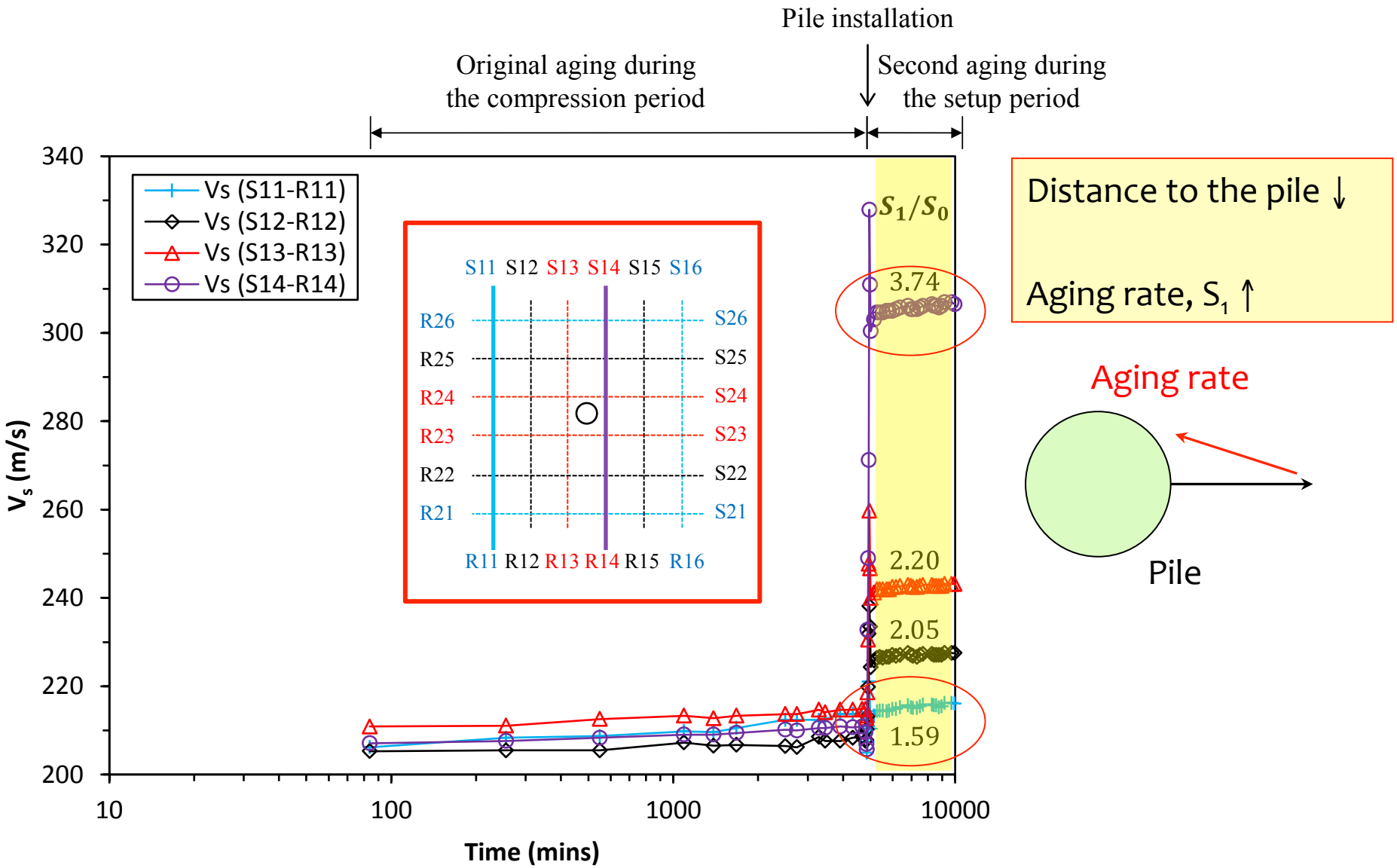
Experimental results – Interparticle contact forces



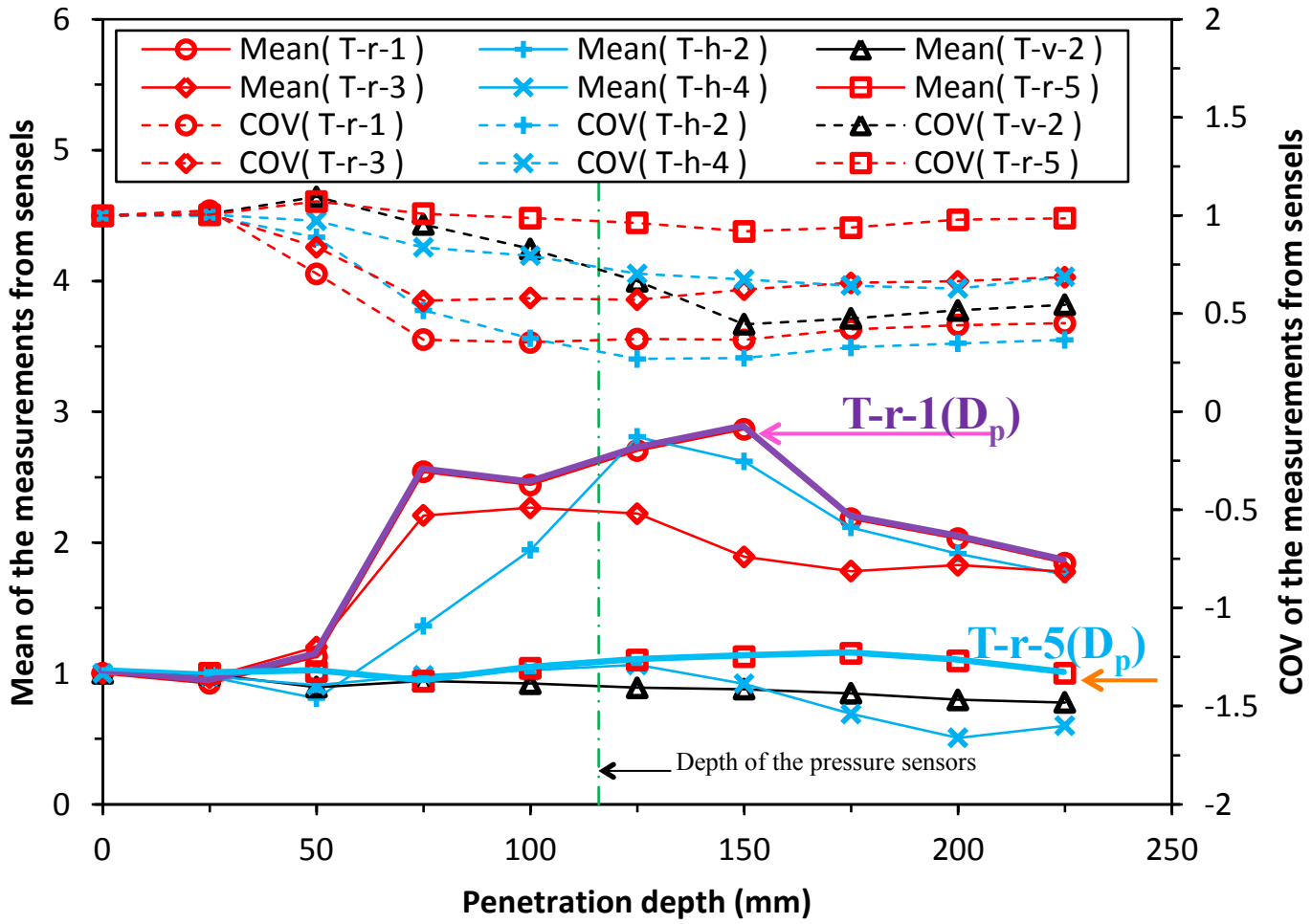
V_s (or G) increase is due to contact force homogenization

T-r-1 sensor and others

Experimental results - Changes in V_s (or G)



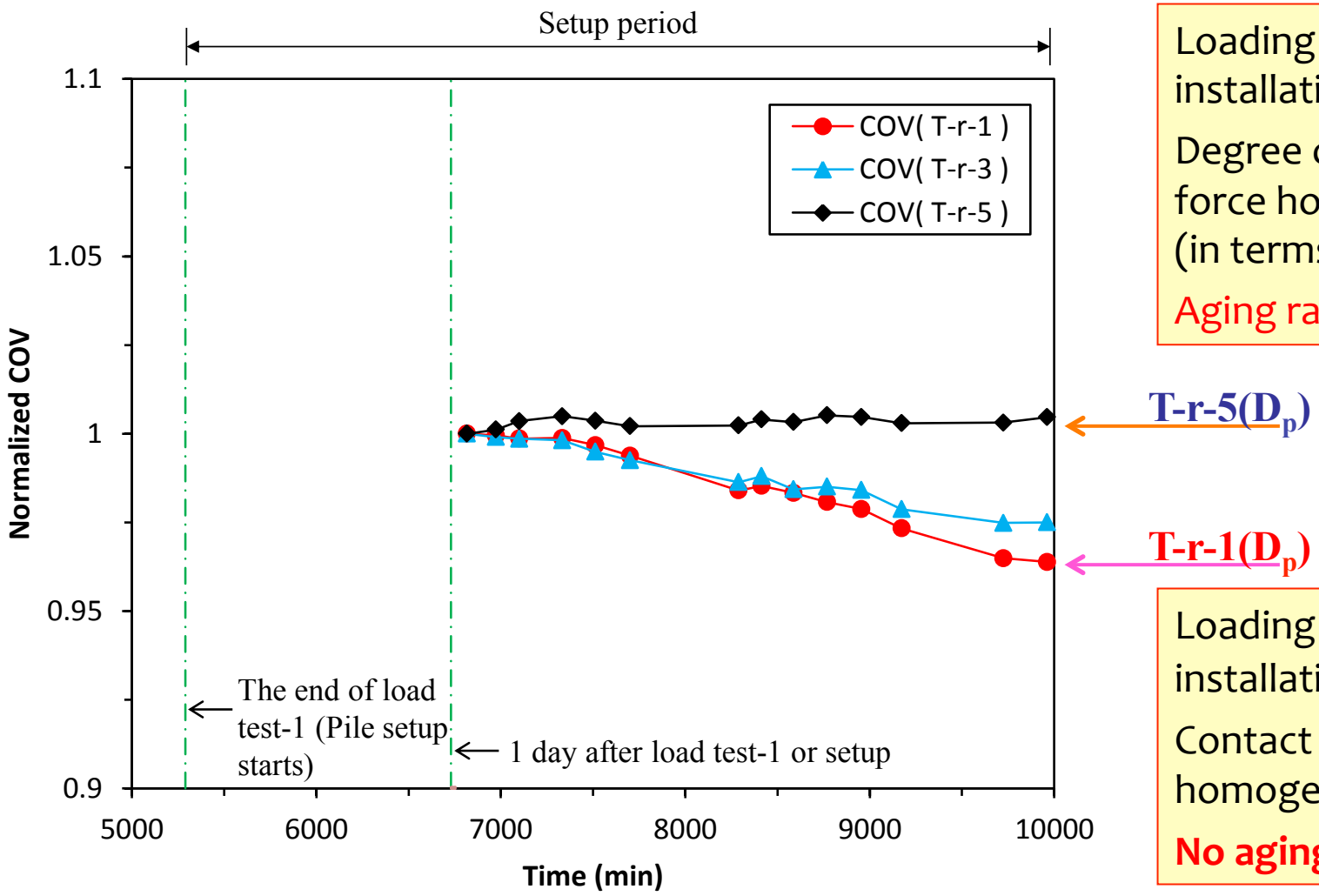
Experimental results – Changes in stress



Distance to the pile ↓

Loading due to pile installation ↑

Experimental results – COV of contact forces



Loading due to pile installation ↑

Degree of contact force homogenization (in terms of COV) ↑

Aging rate ↑

Loading due to pile installation ×

Contact force homogenization ×

No aging effects

Summary

$$\tau_f = (\sigma'_{rp} + \Delta\sigma'_{rp})\tan\delta'_f$$

- Pile installation pushes the surrounding soil to the side, thereby imposing additional loading on the soil inside the influence zone. This loading action initiates an associated (2nd) aging (or creep) process during the setup period. Therefore, the soil stiffness G continues to rise and ultimately an increase in $\Delta\sigma'_{rp}$ and the pile shaft resistance can be measured (the constrained dilation can also be a cause).

- **The absence of pile setup in bored piles** — Without the loading action induced by pile installation, the 2nd aging process during pile setup period cannot be triggered .

- In a similar logic, the setup rate is higher in large-displacement piles than in small-displacement piles.

Final thought

How can we make the best use of aging-induced soil properties enhancement in our engineering design?

Dr. GAO Yan

TSUI King Yuen

MOK Chit Man

ZHANG Zitao

TONG Liwei

XU Dapeng

LAU Yun Man

Thank You

香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

RGC
Research Grant Council,
Hong Kong

References

- Gao, Y., Wang, Y.H., and Su, J.C.P. (2013). "Mechanisms of aging-induced modulus changes in sand under isotropic and anisotropic loading," *Journal of Geotechnical and Geoenvironmental Engineering, ASCE,* Vol. 139, No. 3, pp. 470-482.
- Wang, Y.H. and Gao, Y. (2013). "Mechanisms of aging-induced modulus changes in sand with inherent fabric anisotropy," *Journal of Geotechnical and Geoenvironmental Engineering, ASCE,* Vol. 139, No. 9, pp. 1590-1603.
- Gao, Y. and Wang, Y.H. (2013). "Calibration of tactile pressure sensors for measuring stress in soils," *ASTM Geotechnical Testing Journal*. Vol. 36, No. 4, doi:10.1520/GTJ20120143.
- Wang, Y. H. and Gao Y. (2014). "Examining the behavior and mechanisms of structuration in sand under the K_0 condition," *Granular Matter*. Vol. 16, No. 1, pp. 55-68. (DOI) 10.1007/s10035-013-0457-1.
- Gao, Y. and Wang, Y. H. (2014). "Experimental and DEM examinations of K_0 in sand under different loading conditions," *Journal of Geotechnical and Geoenvironmental Engineering, ASCE,* Vol. 140, No. 5, DOI: 10.1061/(ASCE)GT.1943-5606.0001095.
- Tong, L. and Wang, Y.H. (2014). "DEM simulations of shear modulus and damping ratio of sand with emphasis on the effects of particle number, particle shape, and aging," *Acta Geotechnica,* DOI: *10.1007/s11440-014-0331-2.*
- Zhang, Z. and Wang, Y.H. (2014). "Setup mechanisms of driven piles in sand," submitted to *Journal of Geotechnical and Geoenvironmental Engineering, ASCE.*
- Wang, Y.H. and Tsui, K.Y. (2009). "Experimental characterization of dynamic property changes in aged sands," *Journal of Geotechnical and Geoenvironmental Engineering, ASCE*, Vol. 135, No. 2, pp. 259-270.