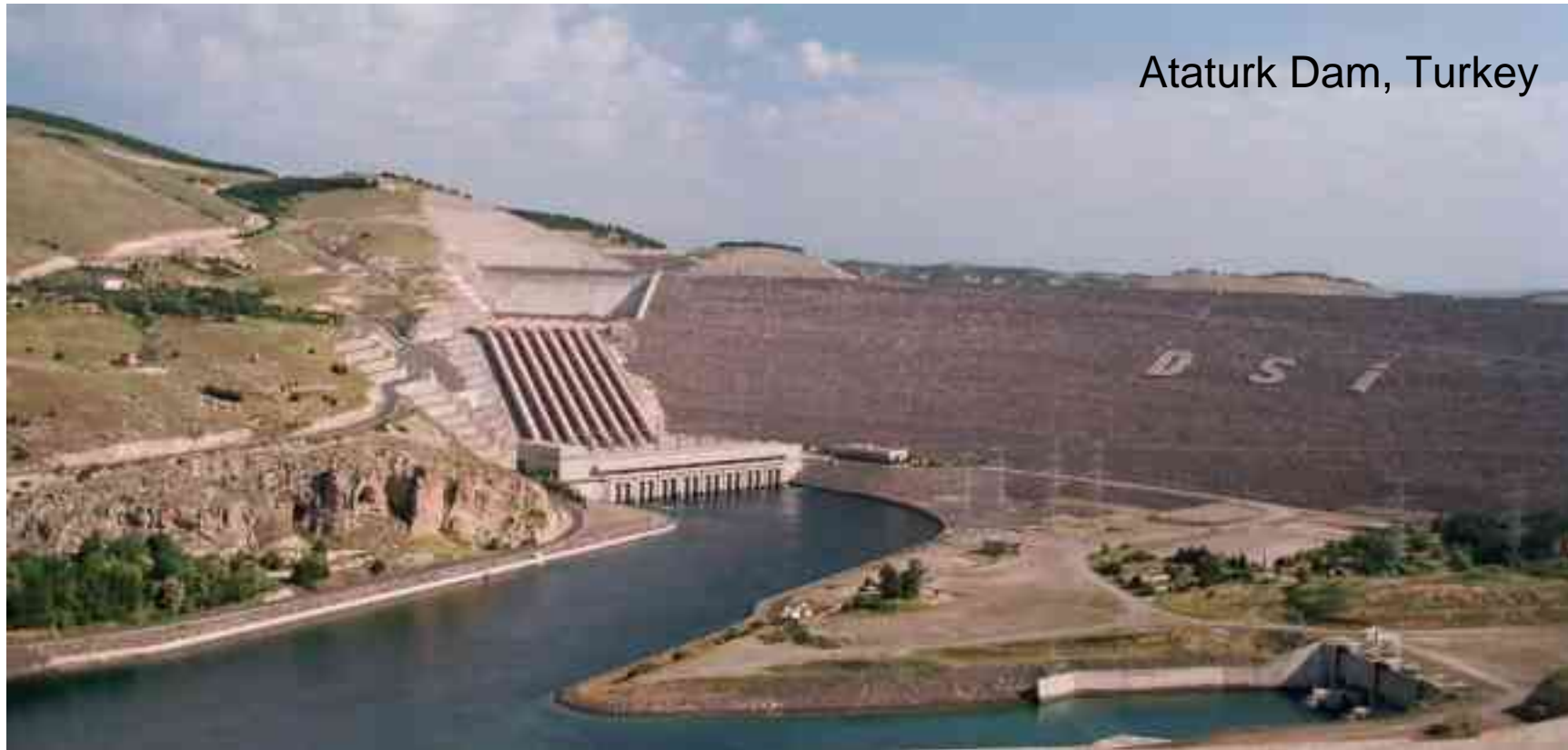


*A Study on Residual Displacements of Rockfill Dams for their Performance-Based Design by 1-G Model Tests and Hollow Cylindrical Torsional Shear Experiments*



Seda Şendir

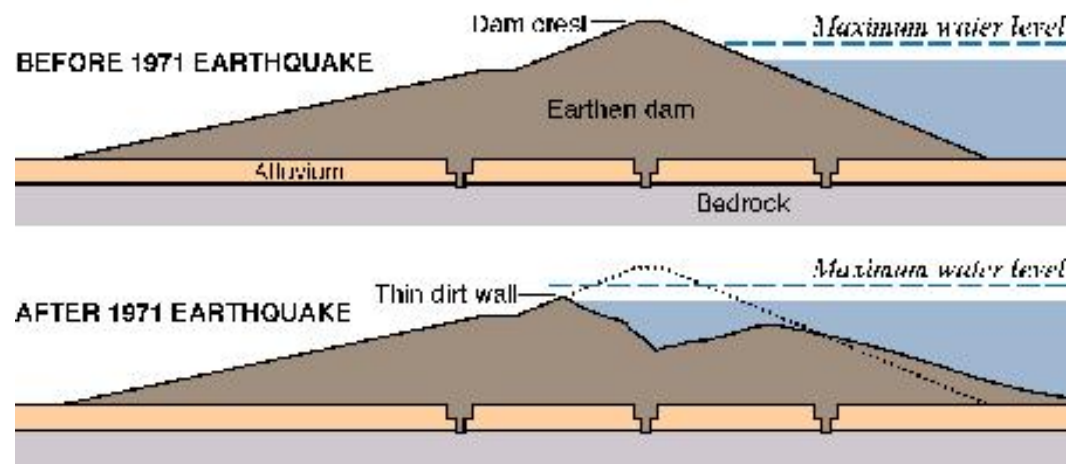
Advisor: Prof. Ikuo TOWHATA

# Aswan High Dam, Egypt



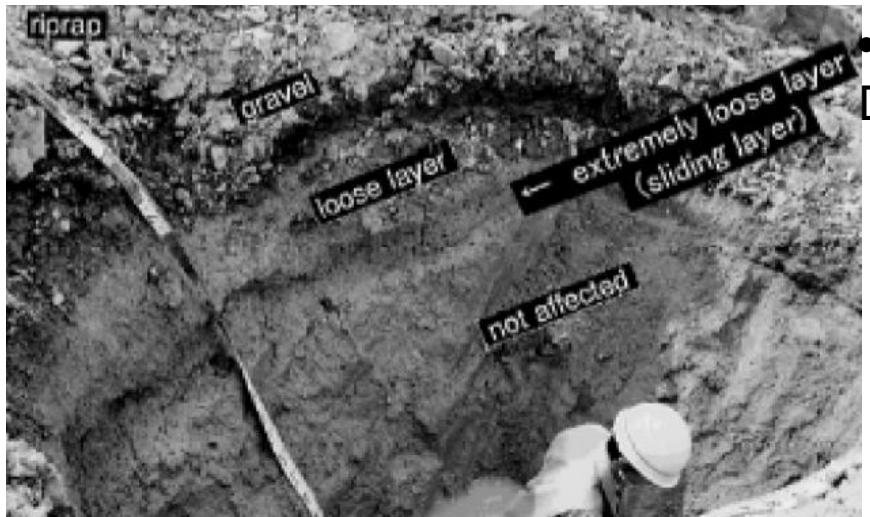
# San Fernando Earthquake (1971)

## Lower San Fernando Dam



<http://quake.usgs.gov/prepare/factsheets/LADamStory/>

# Kobe Earthquake, 1995



•Kitayama Dam



•Niteko Dam

# Tokachi-Oki Earthquake, 2003



•Takami Dam



•Makubetsu Dam

# Mid-Niigata Earthquake 2004



•Yamamoto Dam



•Asawagara Dam

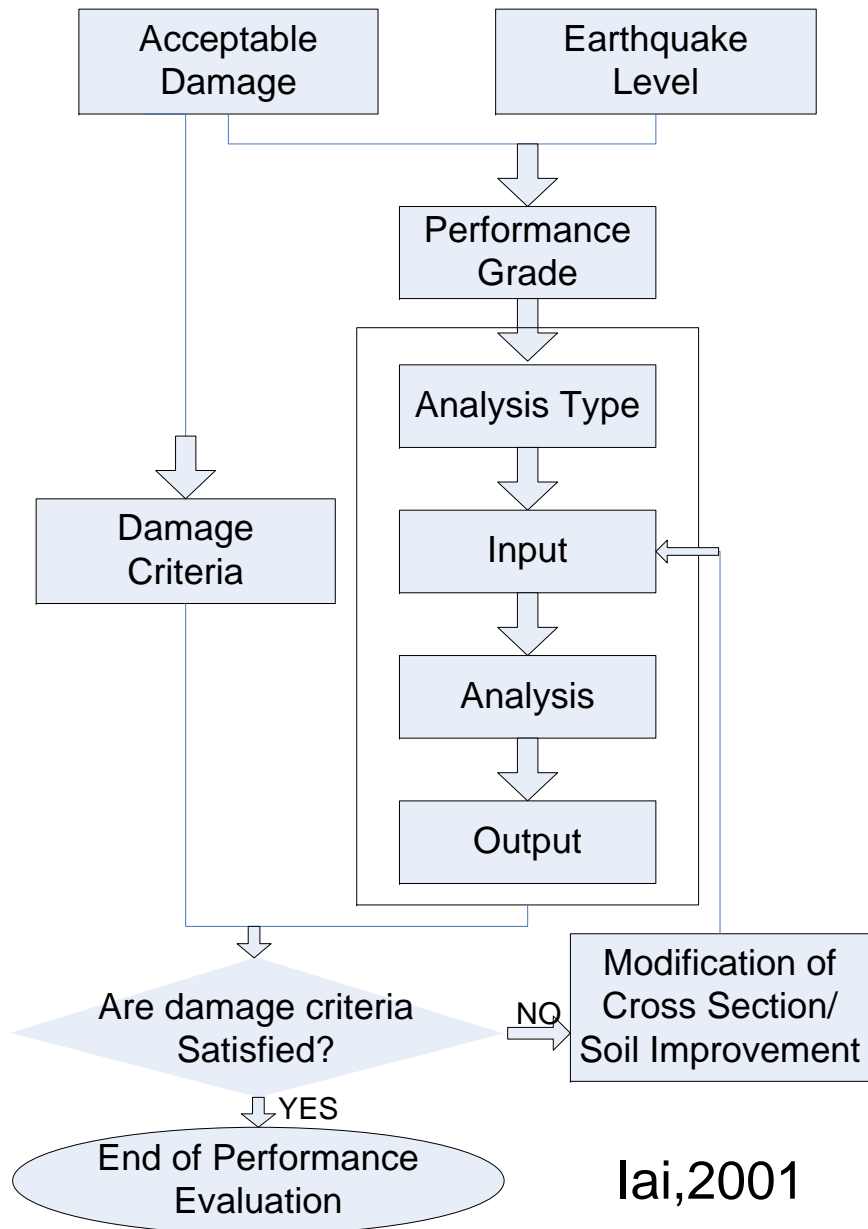


•Shin-Yamamoto Dam



•Tsuboyama Dam

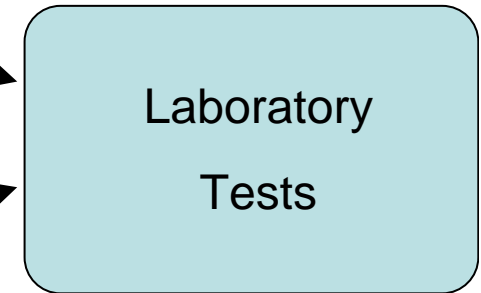
# Performance-based design



- Site investigation (SPT, sampling, CPT)

- Constitutive model

- Analytical tool



- Decision of allowable seismic performance

(residual displacement)

Iai,2001

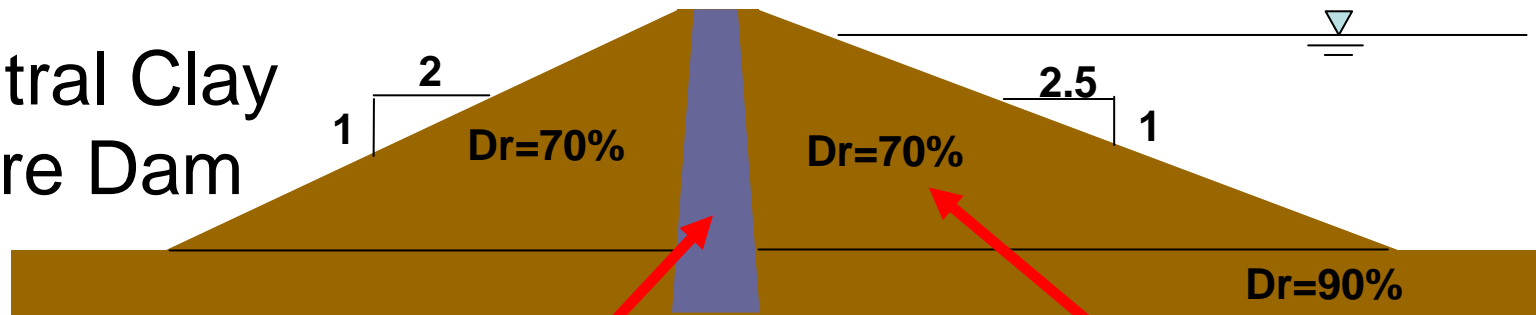
# Objective of This Study

- To investigate the performance and to understand nature of rockfill dams under seismic effects  
(by model tests)
- To reproduce the field conditions in the laboratory more realistically  
(torsion shear tests)
- To predict residual deformations more precisely by using the torsion shear test results



# Shaking Table Experiments

Central Clay  
Core Dam



Kibushi Clay  
( $w=55\%$ )



Toyoura  
Sand ( $w=5\%$ )

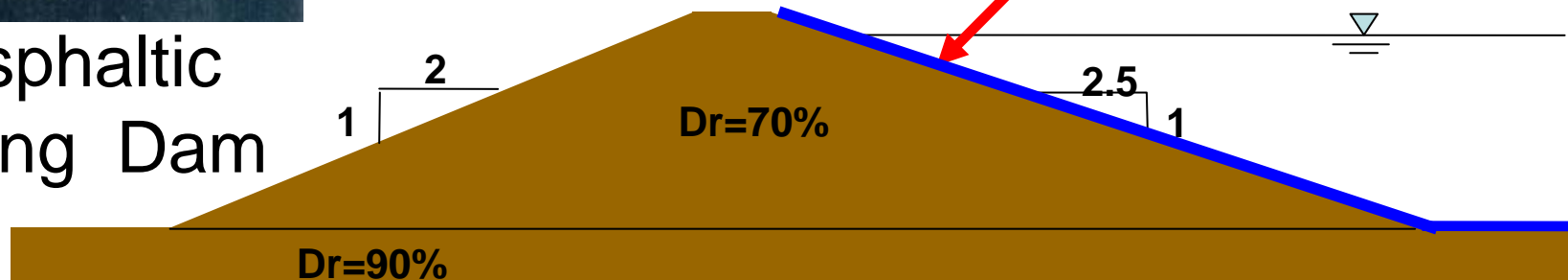


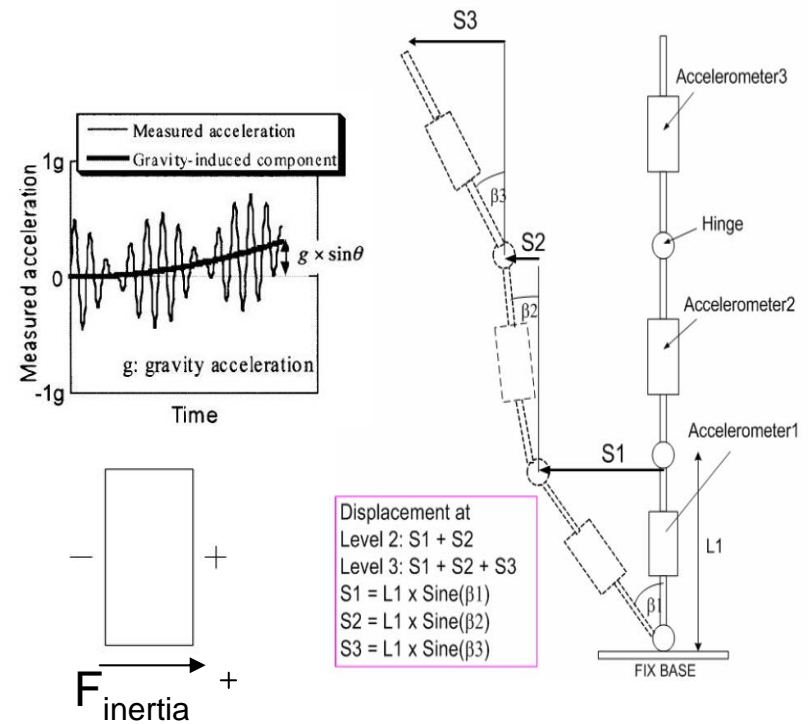
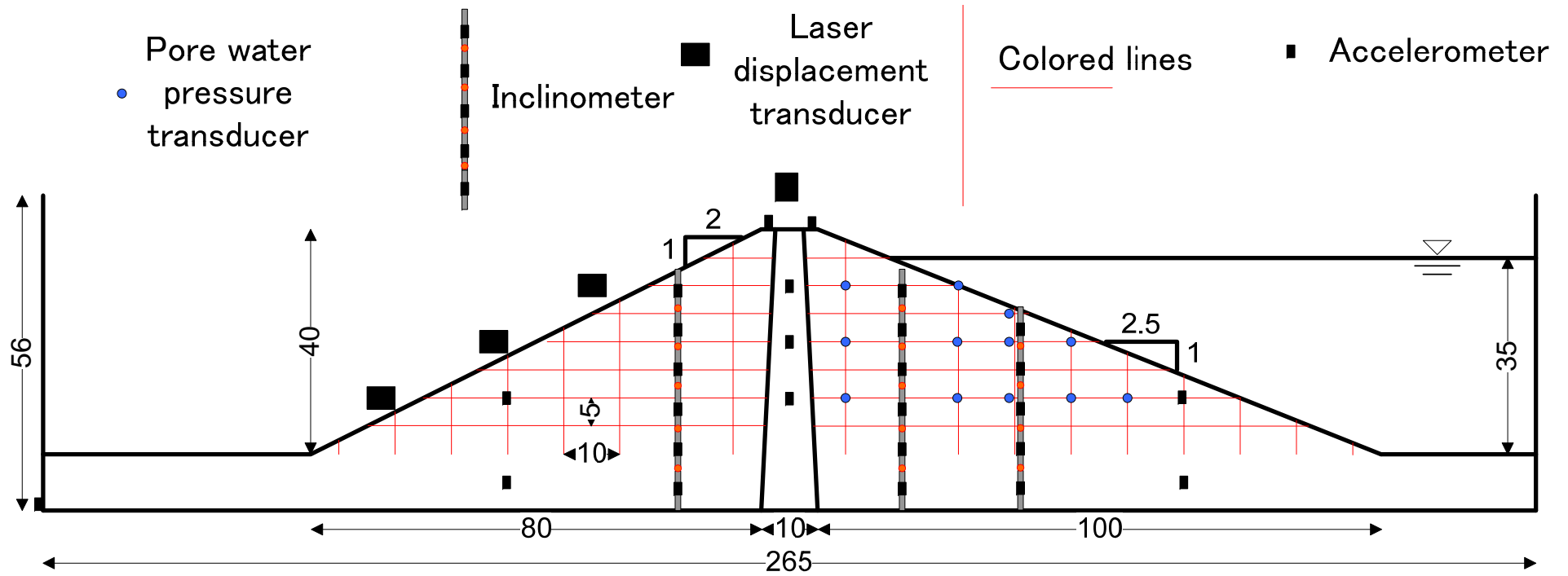
Reinforced concrete  
lining earth dam  
by Prof Towhata



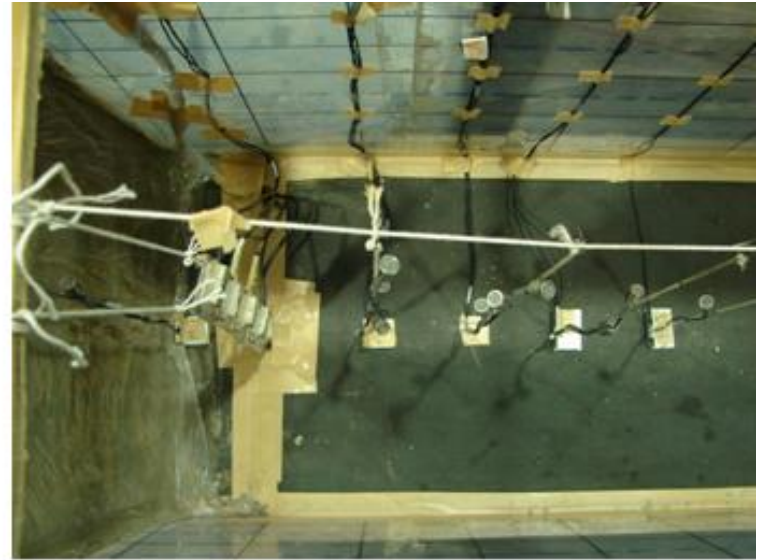
Membrane lining

Asphaltic  
Lining Dam

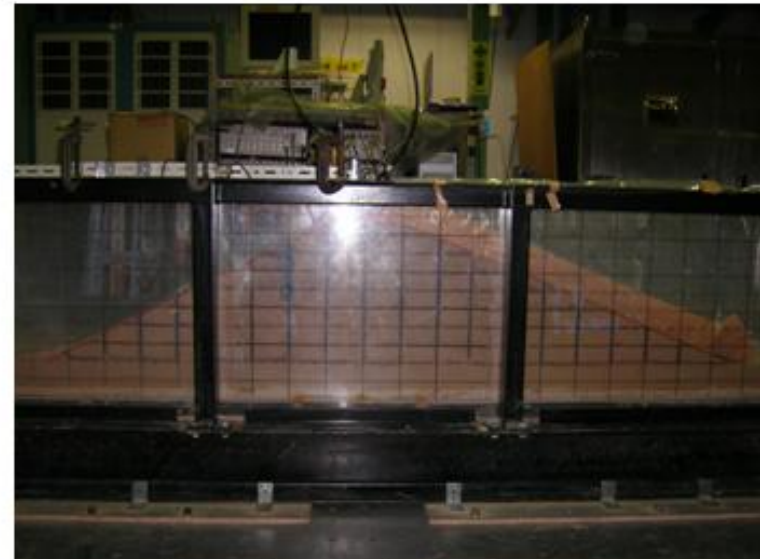
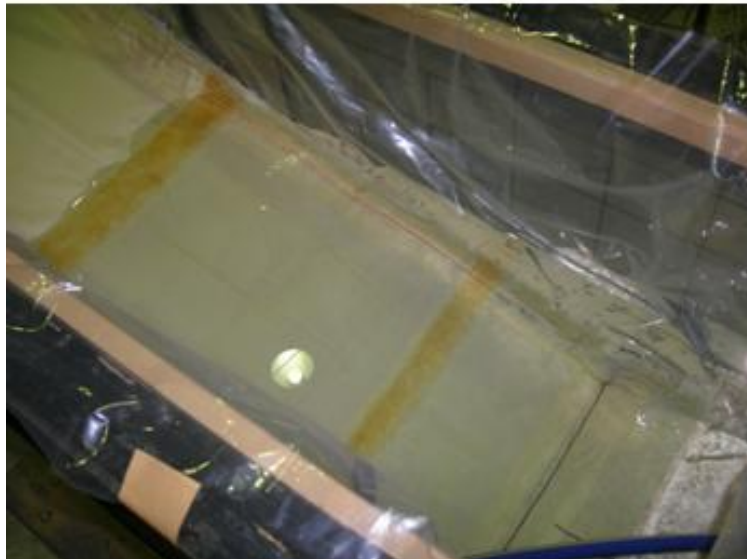




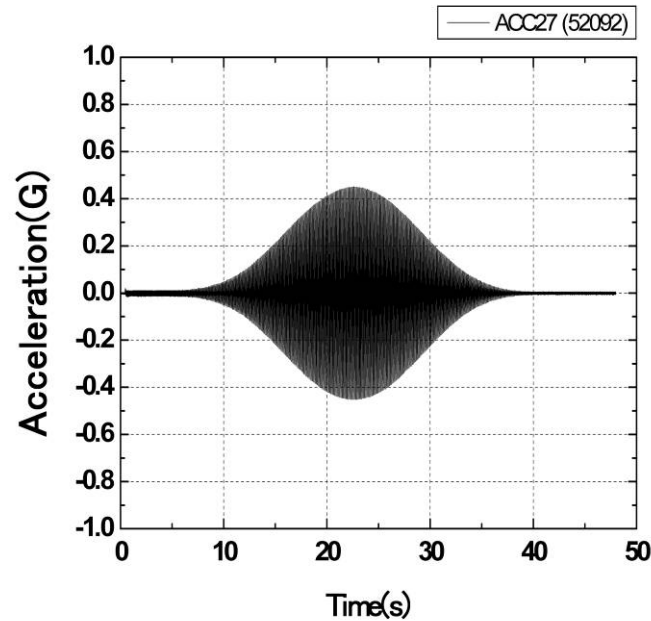
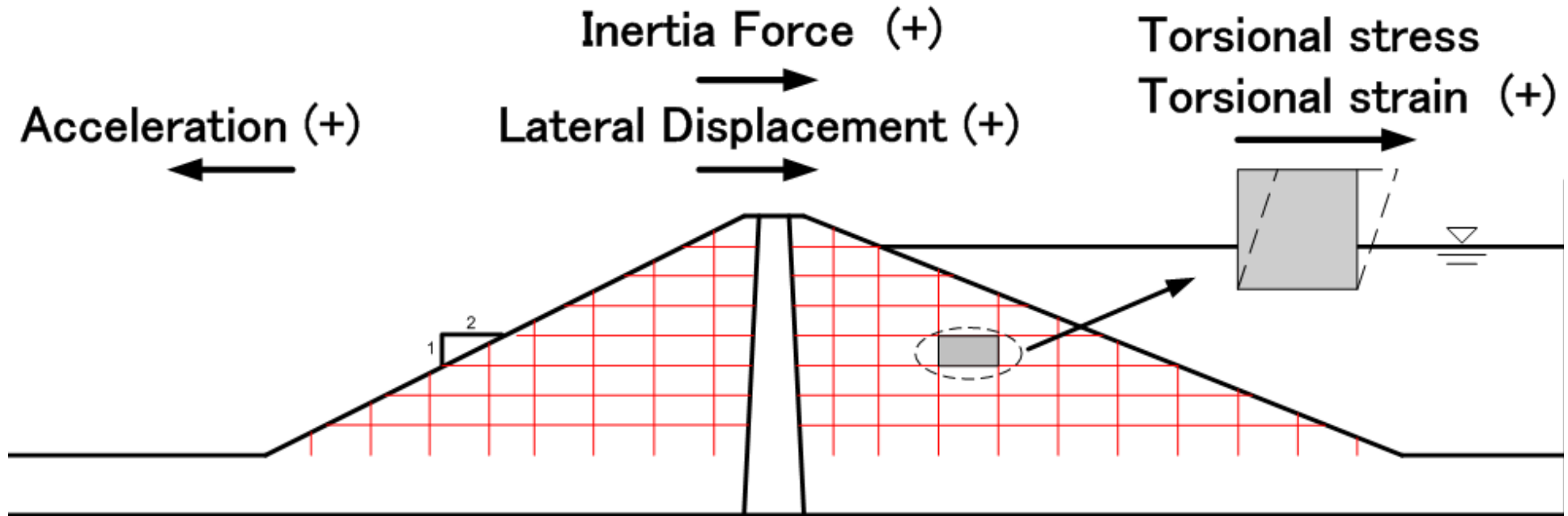
# Preparation of Central Core Dam



# Preparation of Membrane Lining Dam

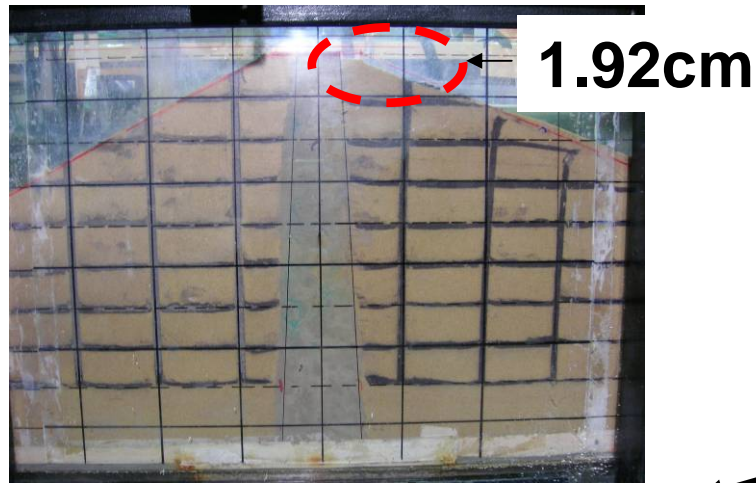


# Sign Conventions and Input Motion



# Visual Observations after experiments

**Dr=70%**

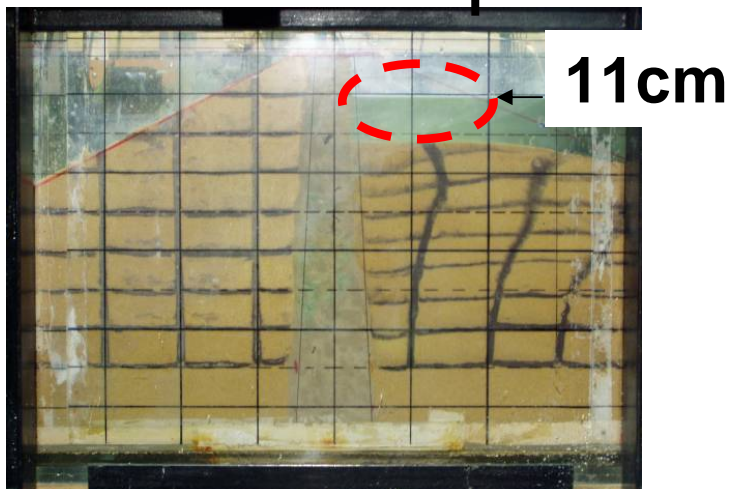


**Dr=50%**



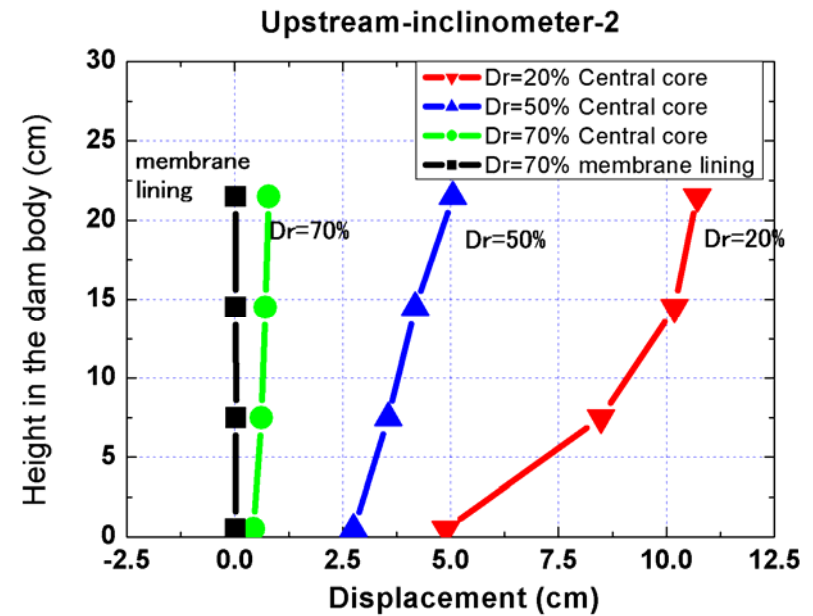
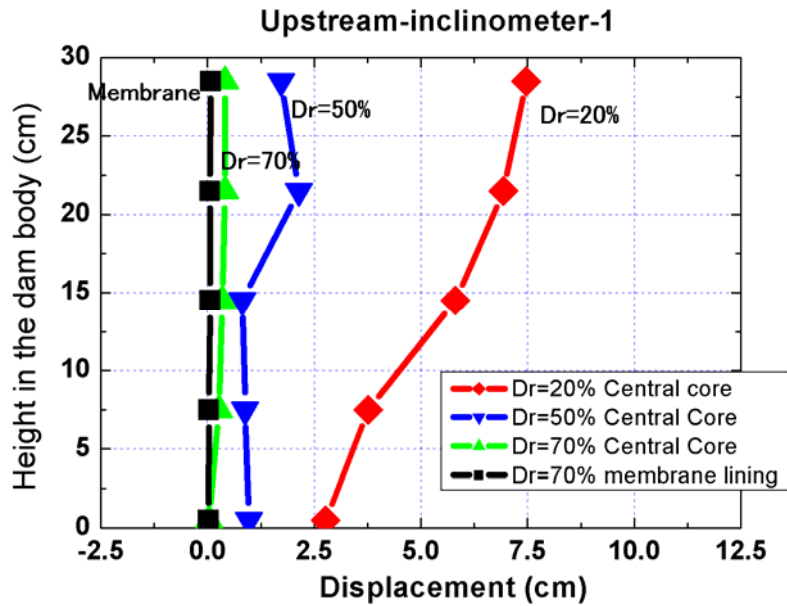
**Flow failure was observed. No slip line**

**Dr=20%**



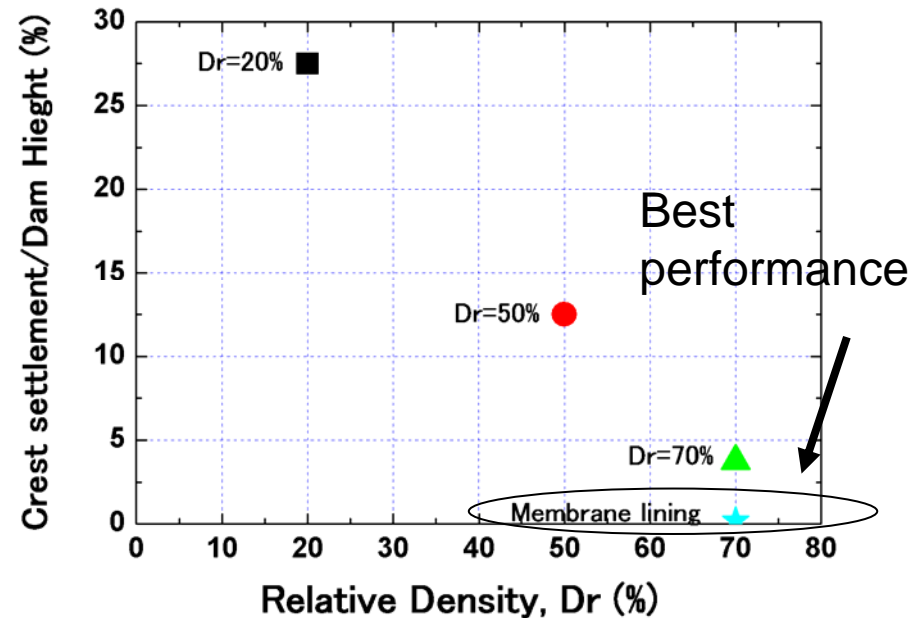
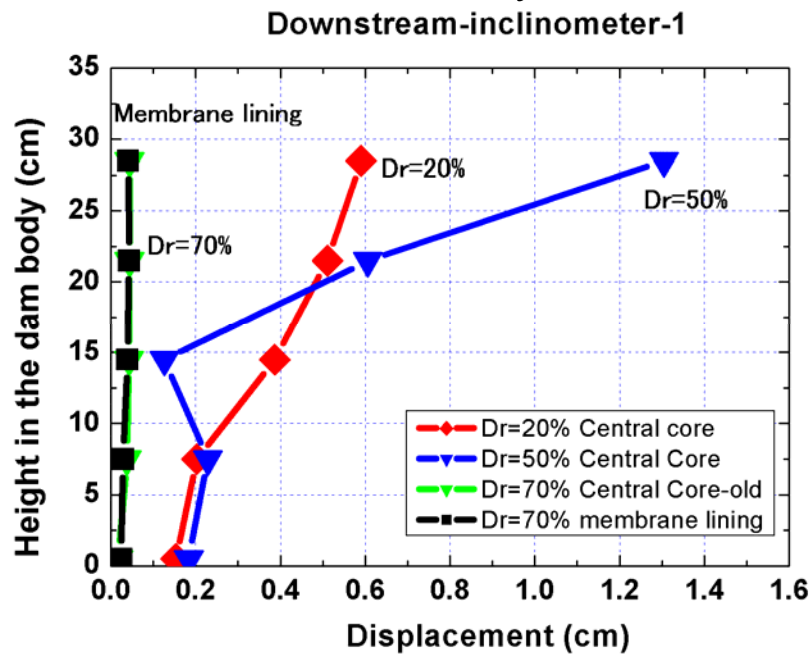
**Best performance**  
membrane lining dam model  
**Membrane lining**





➤ Greater lateral displacement close to the **slope face**

➤ Smaller relative density  $\longrightarrow$  Greater lateral deformation and settlement



# Evaluation of shear strain and stress histories

- Shear strains at level  $z_i$  and  $(z_{i+1}+z_i)/2$

$$\gamma_{i-1/2}(t) = \frac{u_i - u_{i-1}}{\Delta z_{i-1}}, i = 2, 3, \dots$$

- Equation of motion of 1D shear –wedge response

$$\frac{\partial(b\tau)}{\partial z} = \rho b \ddot{u}$$

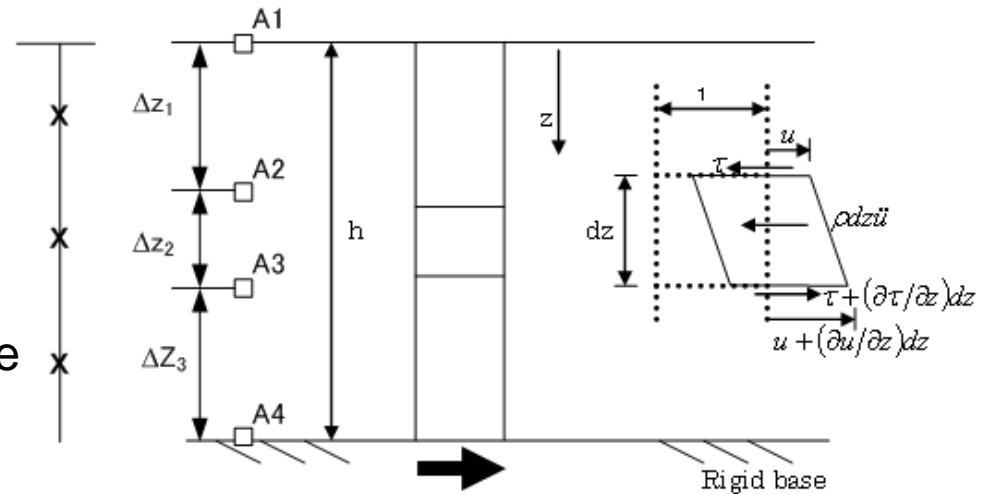
boundary cond.

$$u(h, t) = u_g(t)$$

$$\tau(0, t) = 0$$

□ Accelerometer

× Stress-strain sampling locations



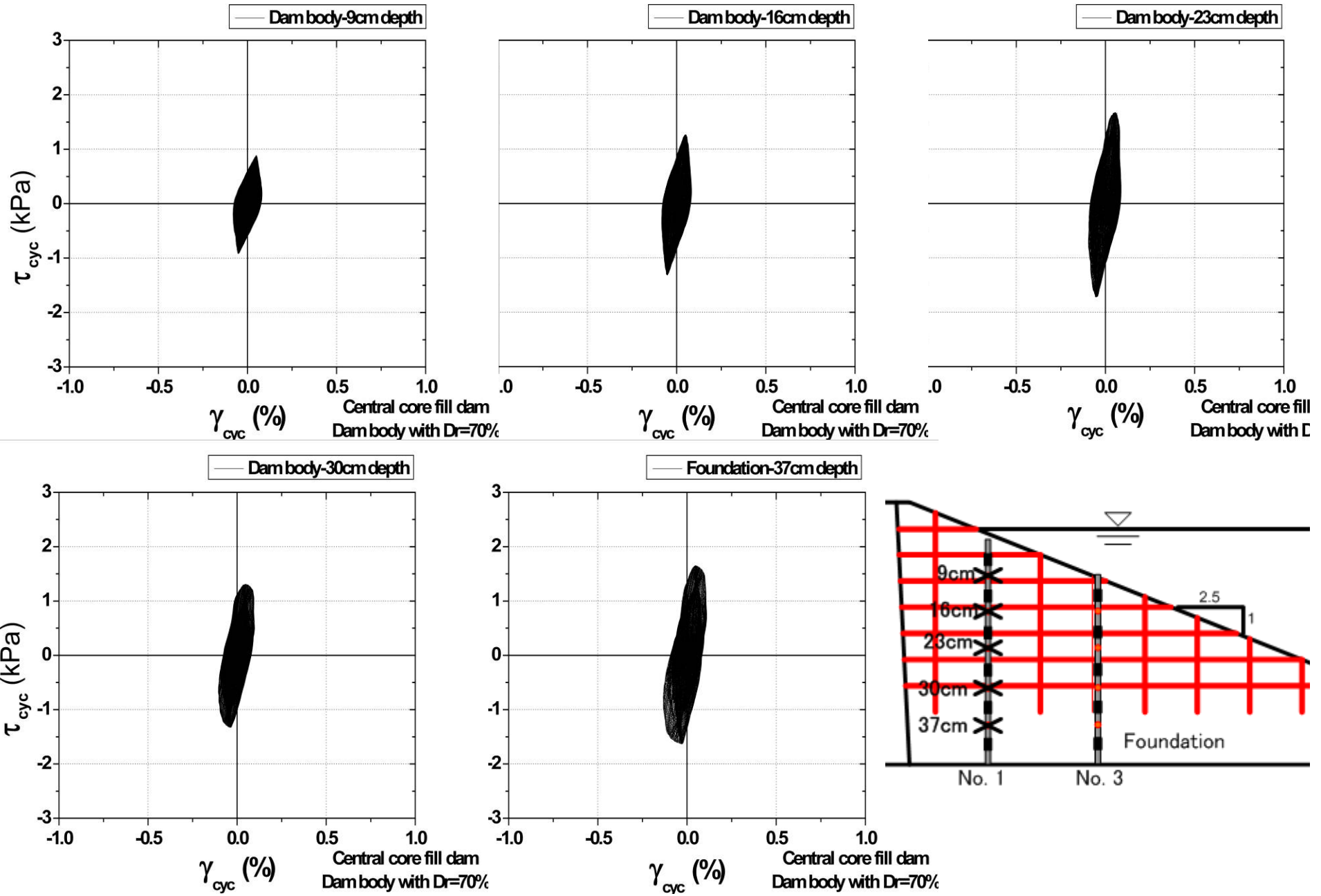
- Shear stress at level  $(z_{i+1}+z_i)/2$

$$\tau_{3/2}(t) = \left[ \frac{[\ddot{u}_1(b_1 + 2b_2) + \ddot{u}_2(2b_1 + b_2)]\Delta m_1}{12(b_1 + b_2)} \right]$$

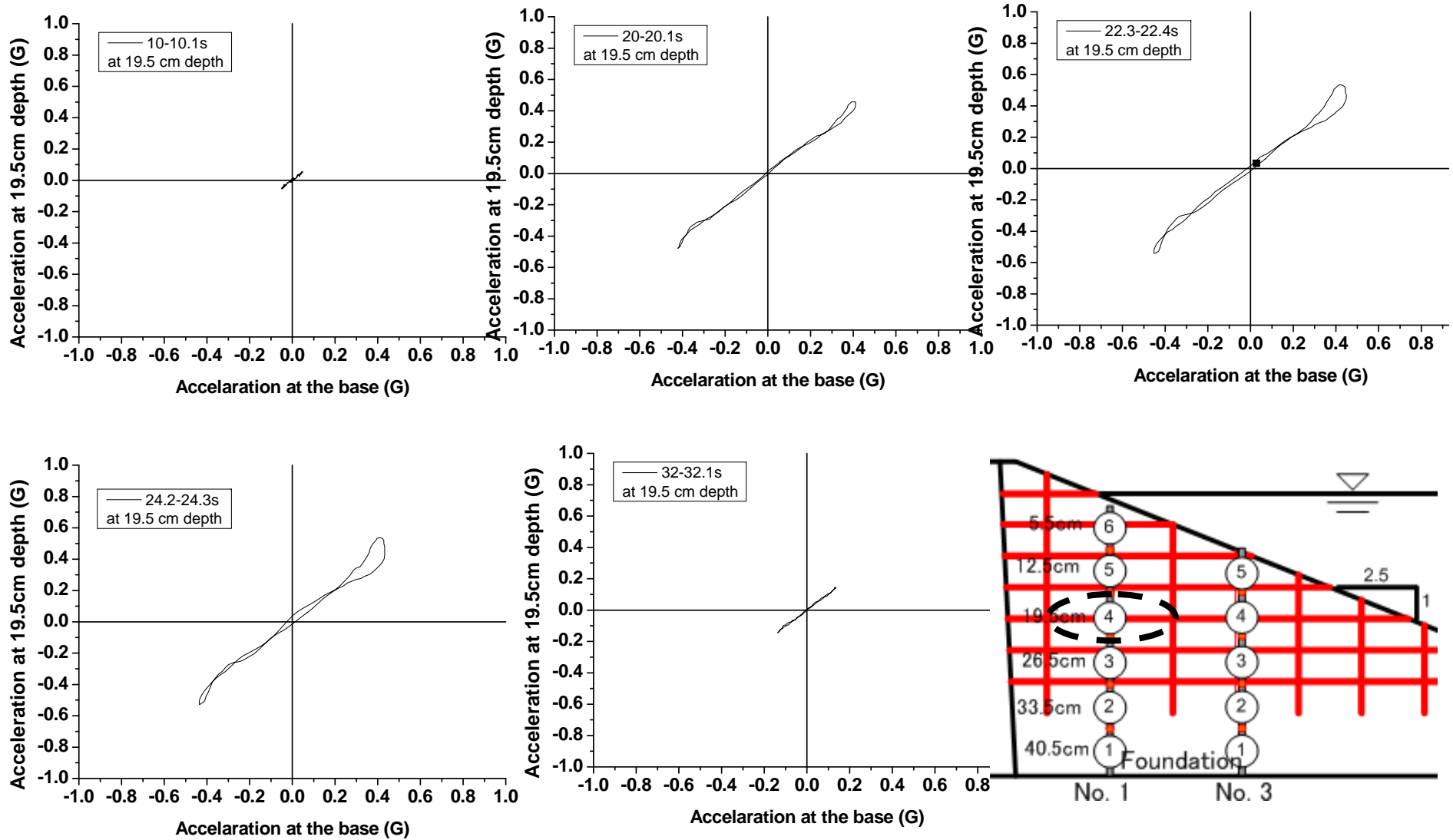
$$\tau_{i+1/2}(t) = \tau_{i-1/2} \frac{b_{i-1} + b_i}{b_i + b_{i+1}} + \frac{\ddot{u}_{i-1}(b_{i-1} + 2b_i)\Delta m_{i-1} + \ddot{u}_{i+1}(2b_i + b_{i+1})\Delta m_i + \ddot{u}_i [2b_{i-1}\Delta m_{i-1} + 7b_i(\Delta m_{i-1} + \Delta m_i) + 2b_{i+1}\Delta m_i]}{12(b_1 + b_2)}$$

$$\Delta m_i = \rho_i \Delta z_i$$

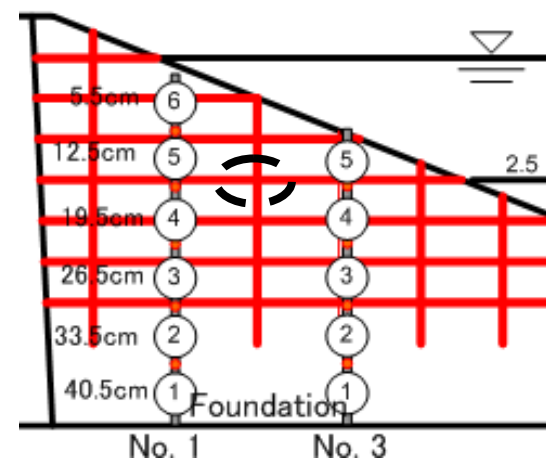
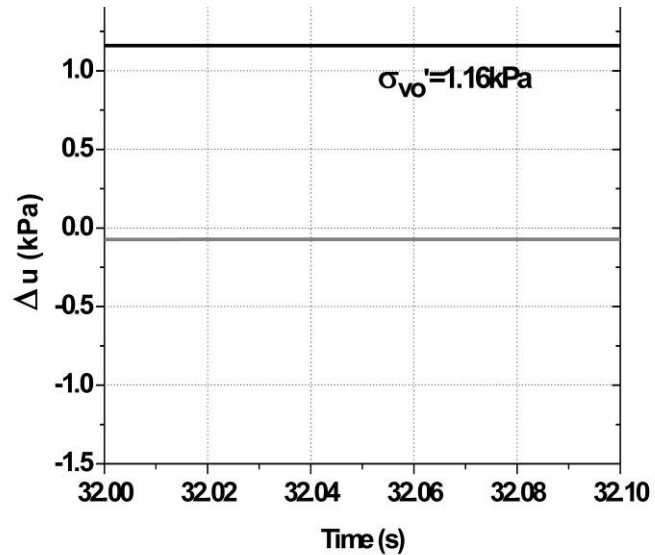
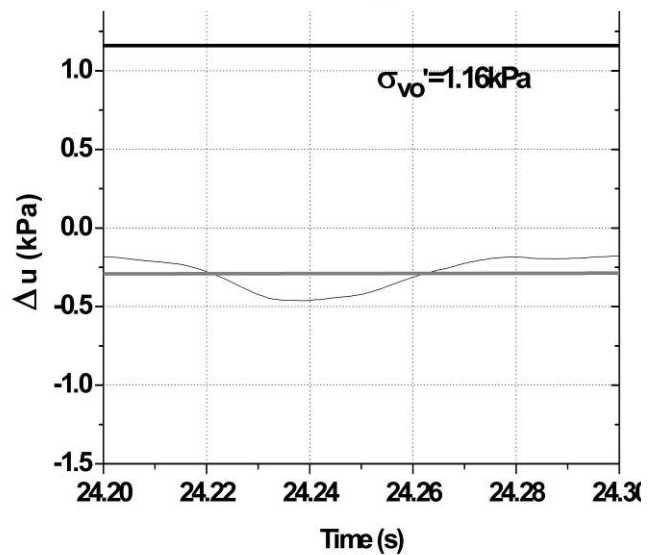
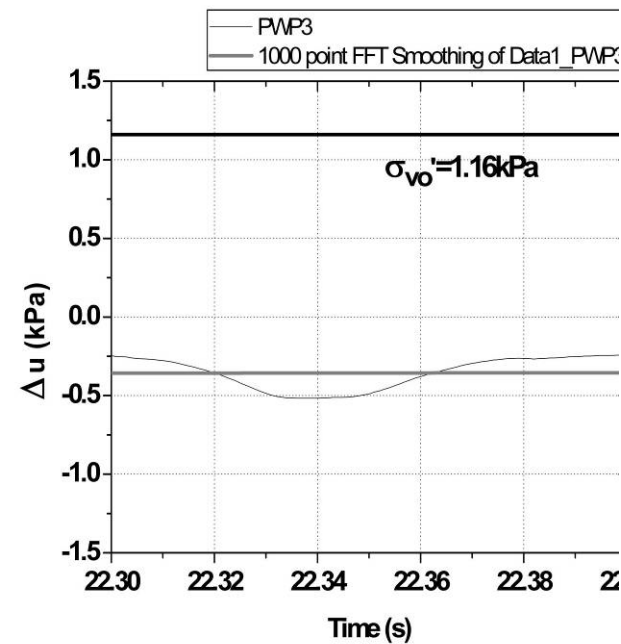
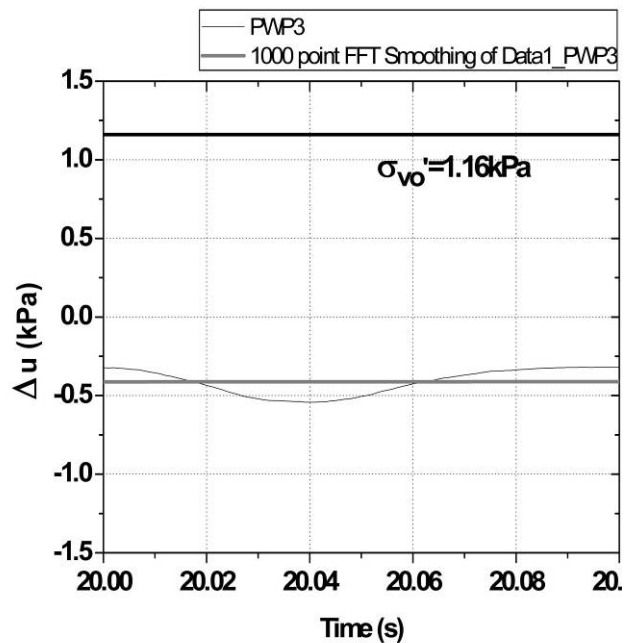
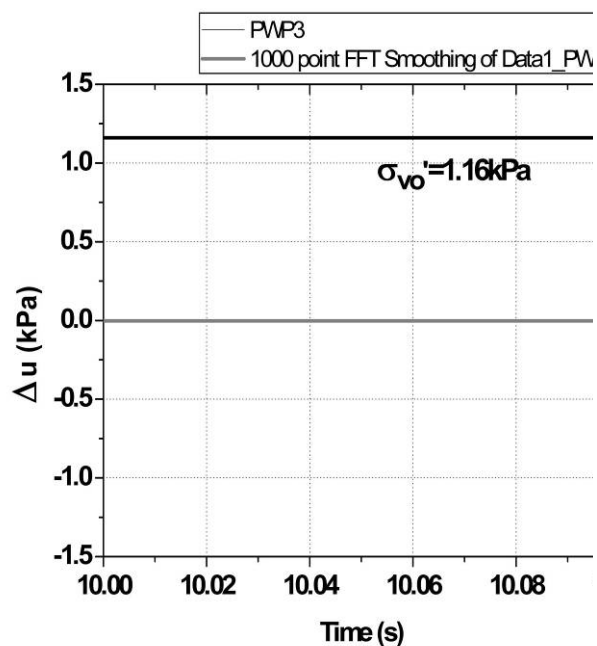
# Stress-strain response for Dr=70% (inclinometer1)



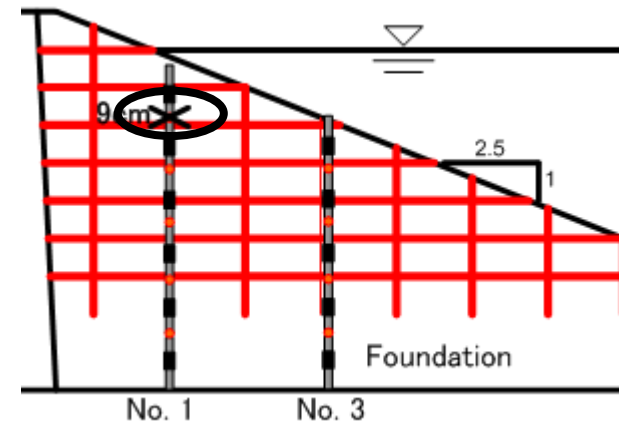
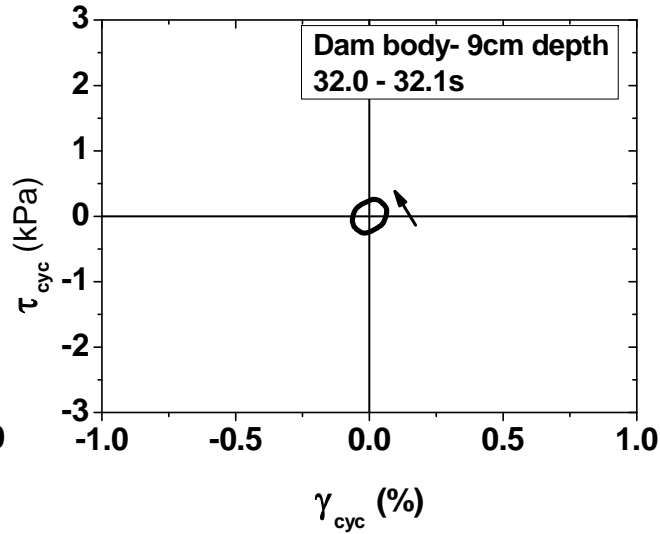
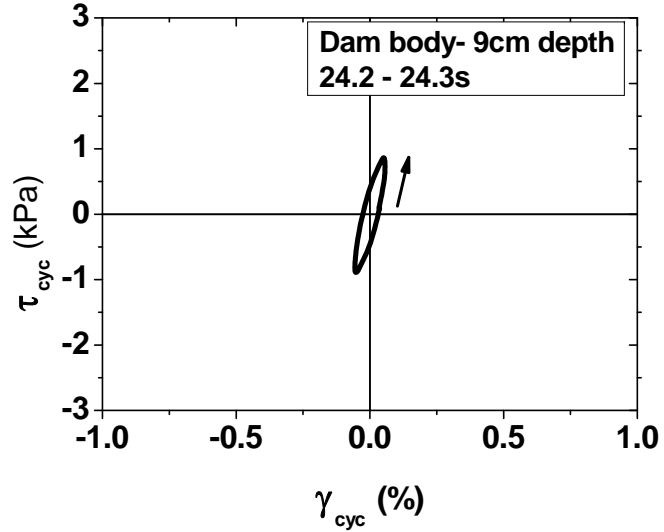
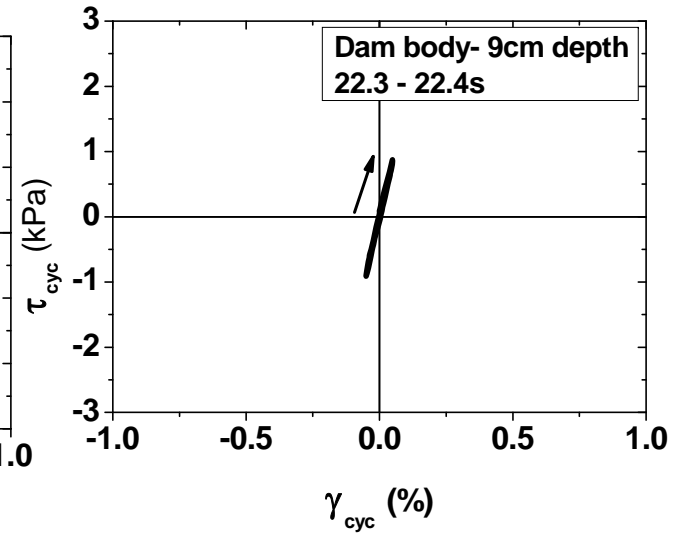
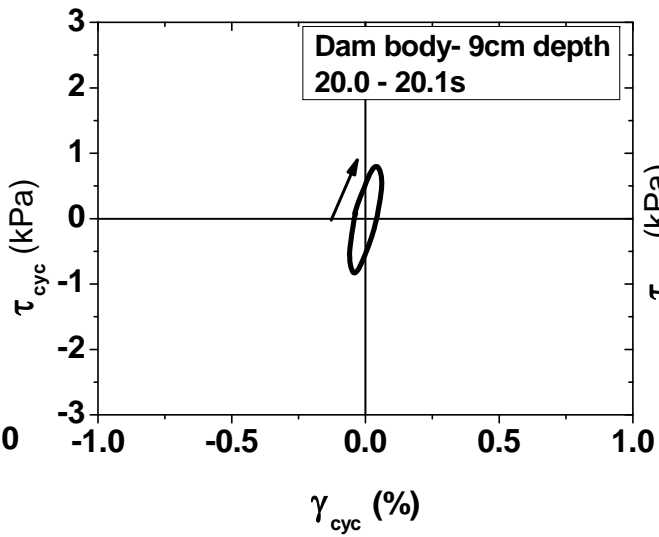
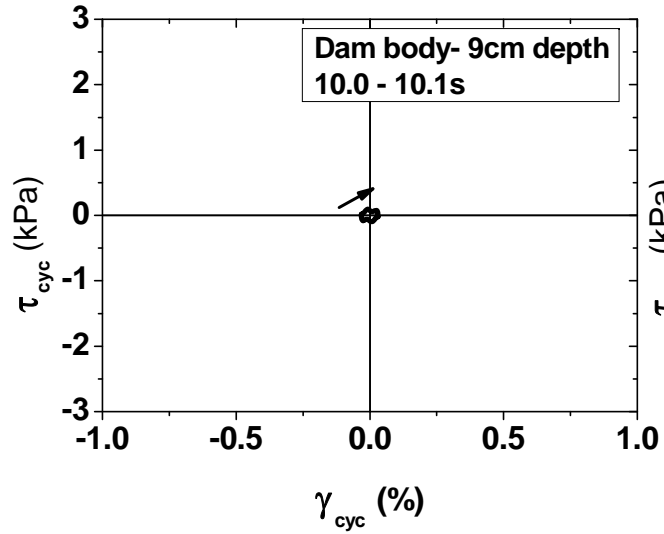
# Acceleration (at selected cycles)-Dr=70%



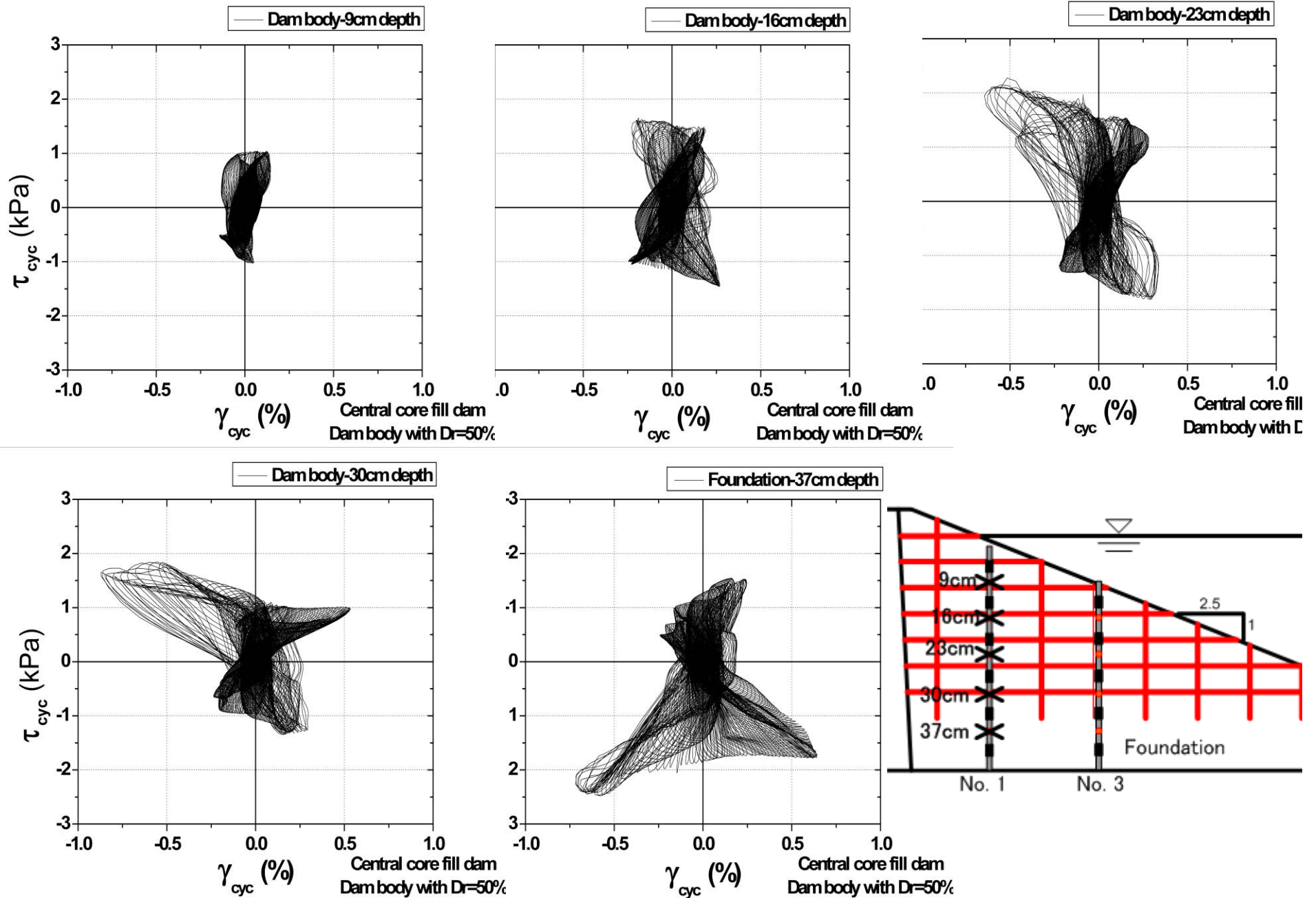
# Excess pore pressure (selected cycles-Dr=70%)



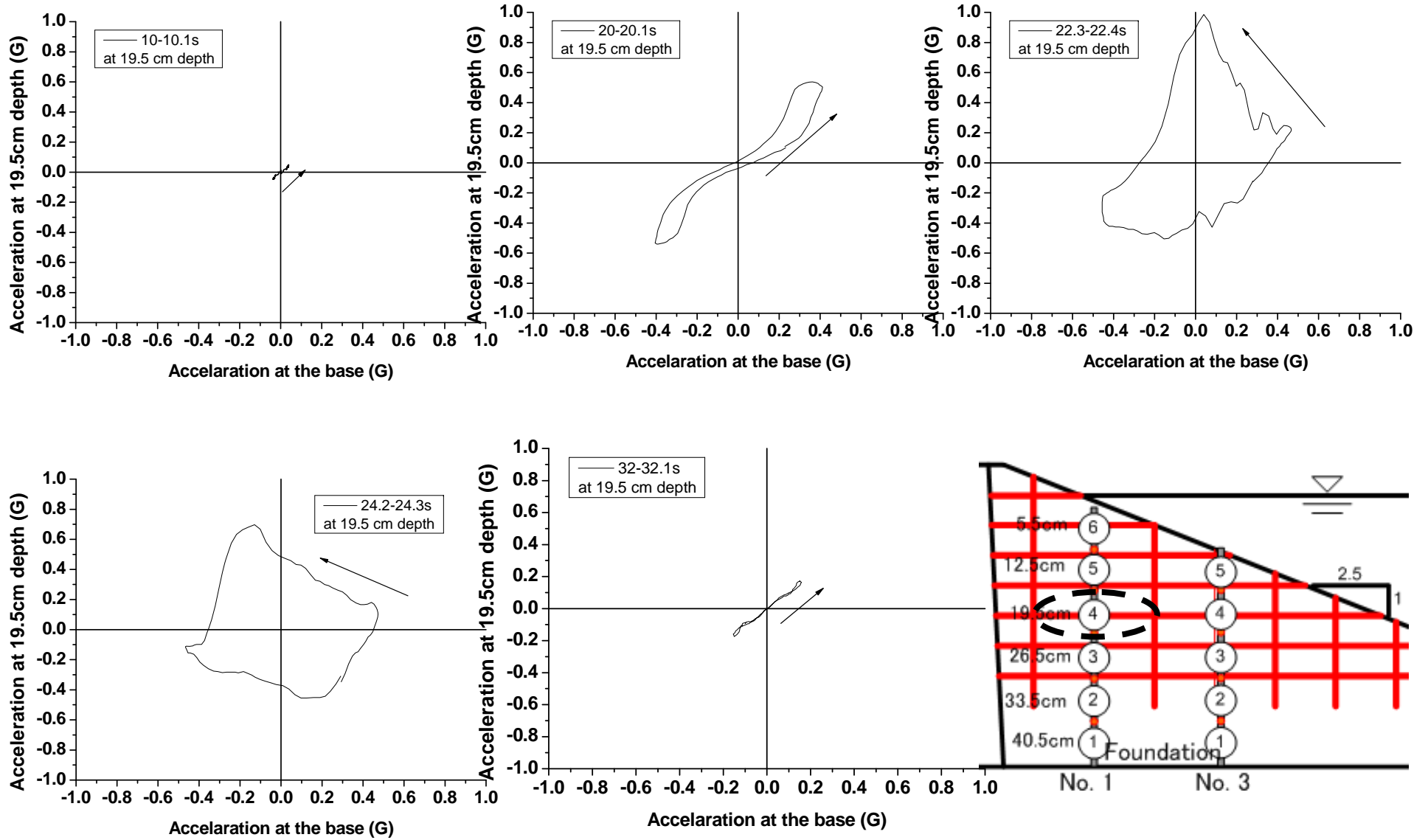
# Selected cycles of shear stress-strain response for $D_r=70\%$ (inclinometer1)



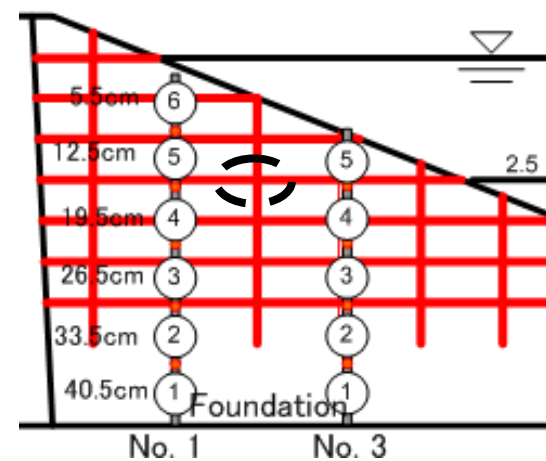
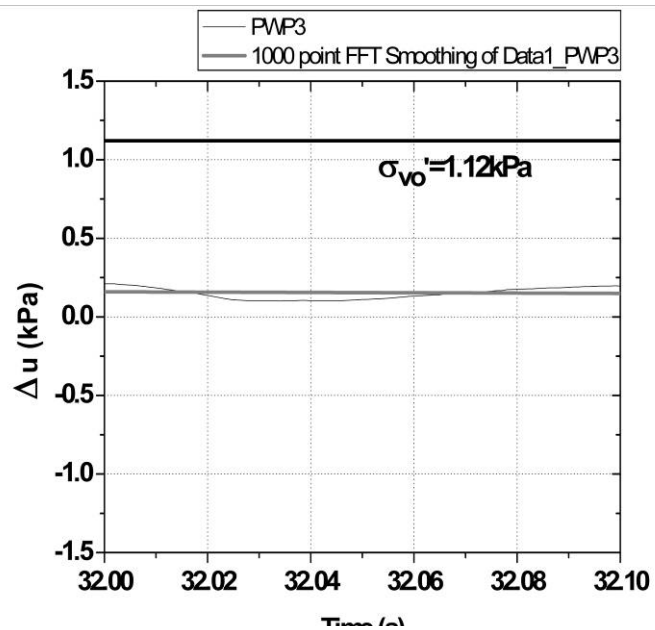
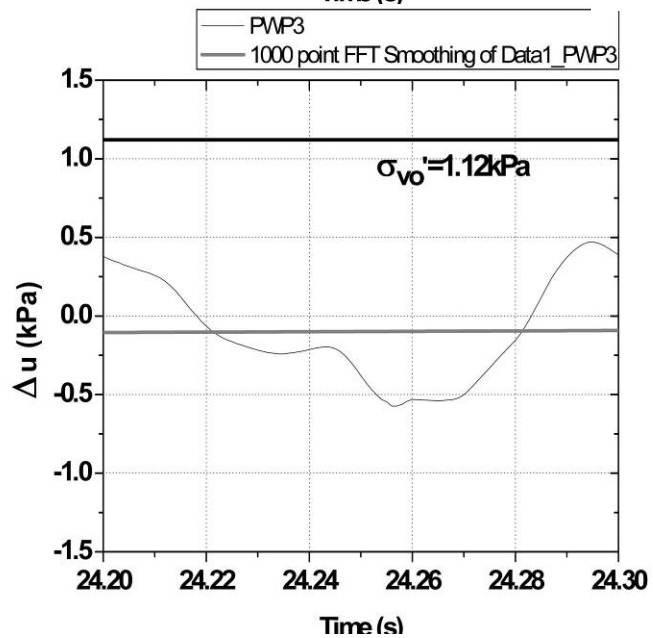
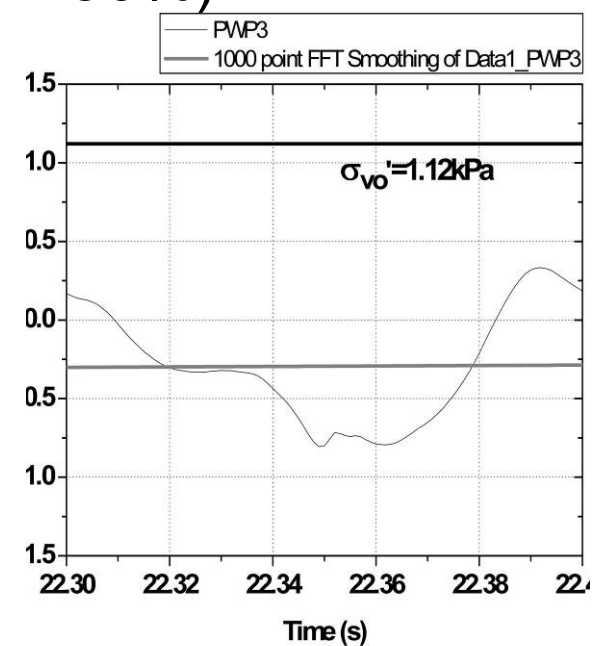
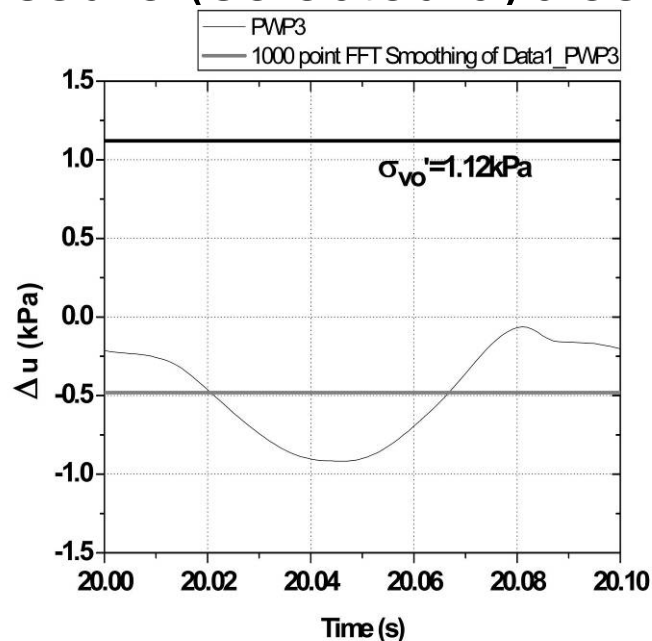
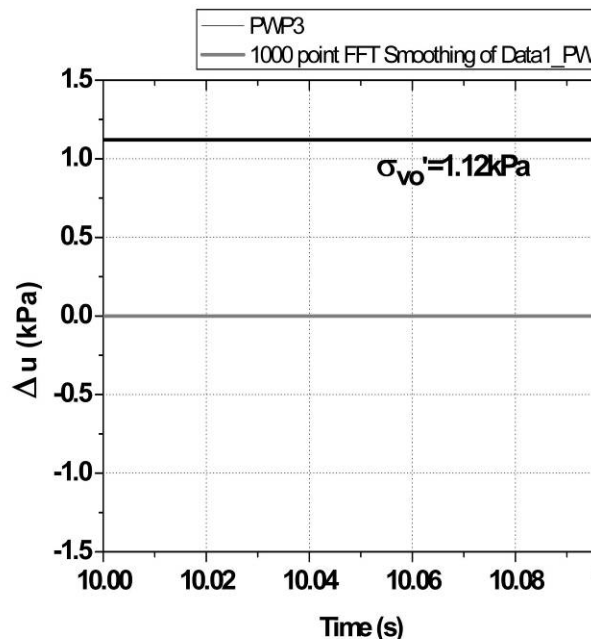
# Stress-strain response for Dr=50% (inclinometer1)



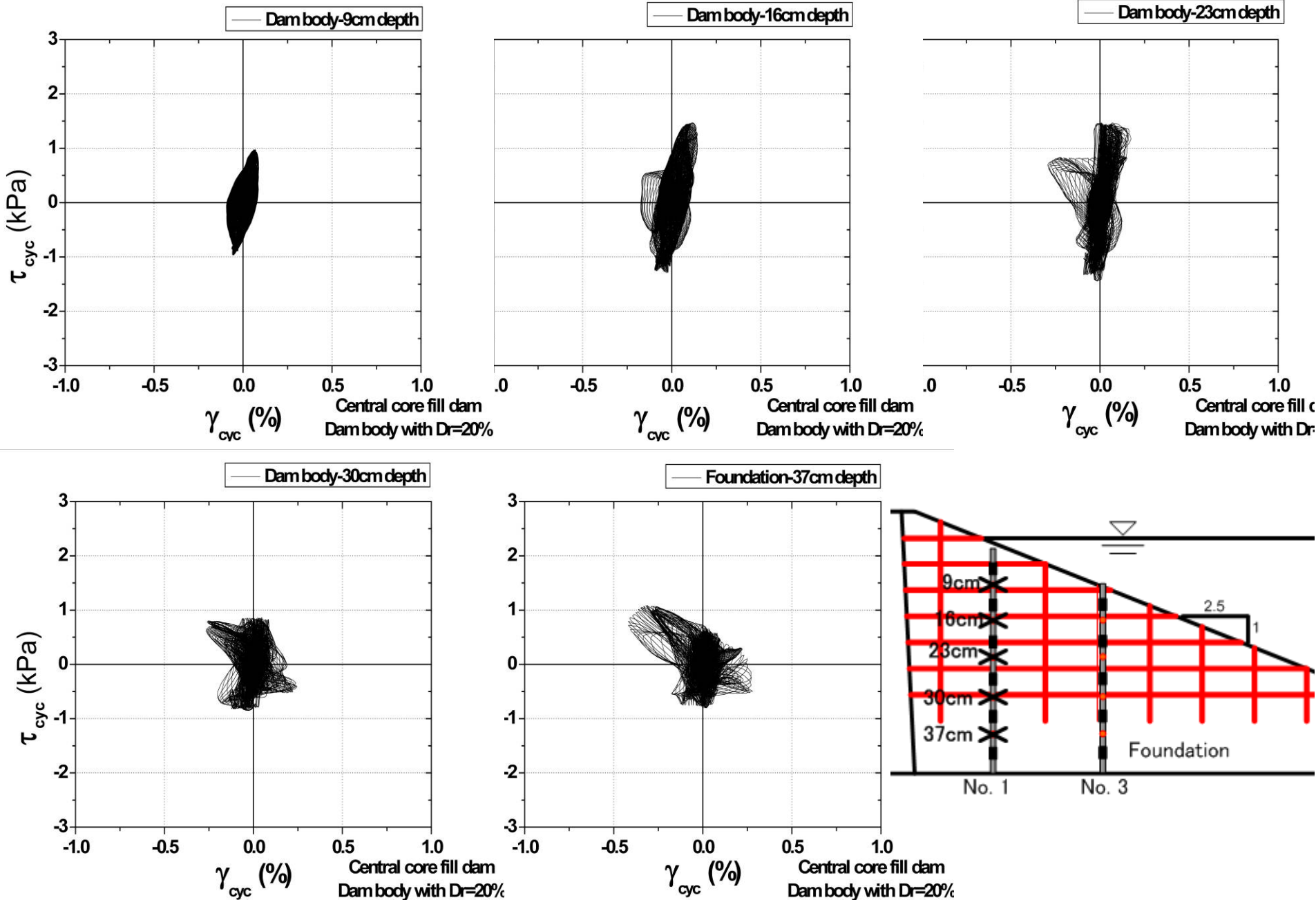
# Acceleration (at selected cycles)-Dr=50%



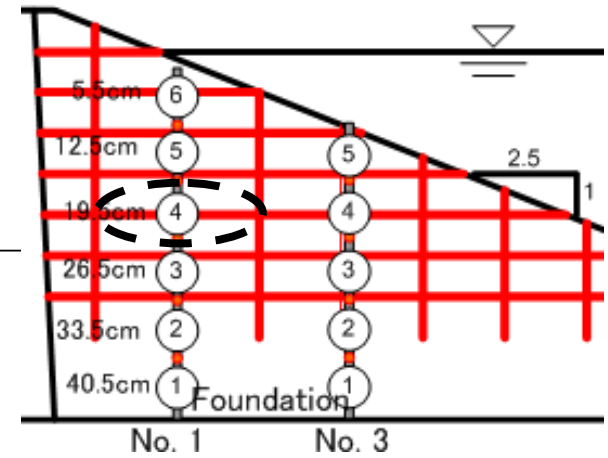
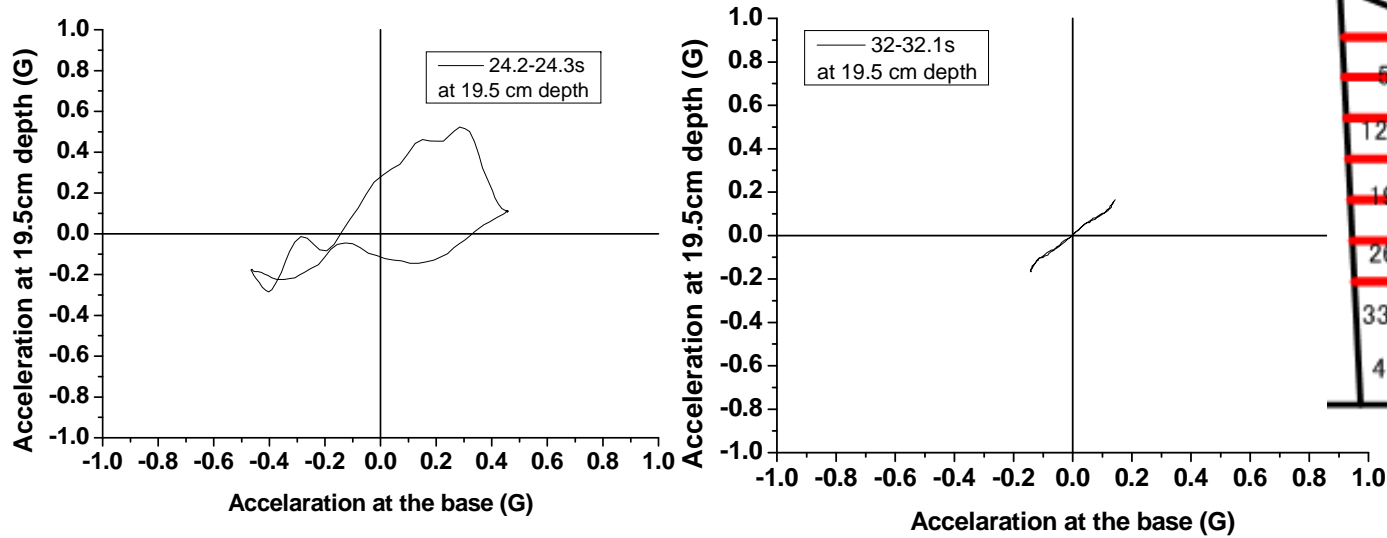
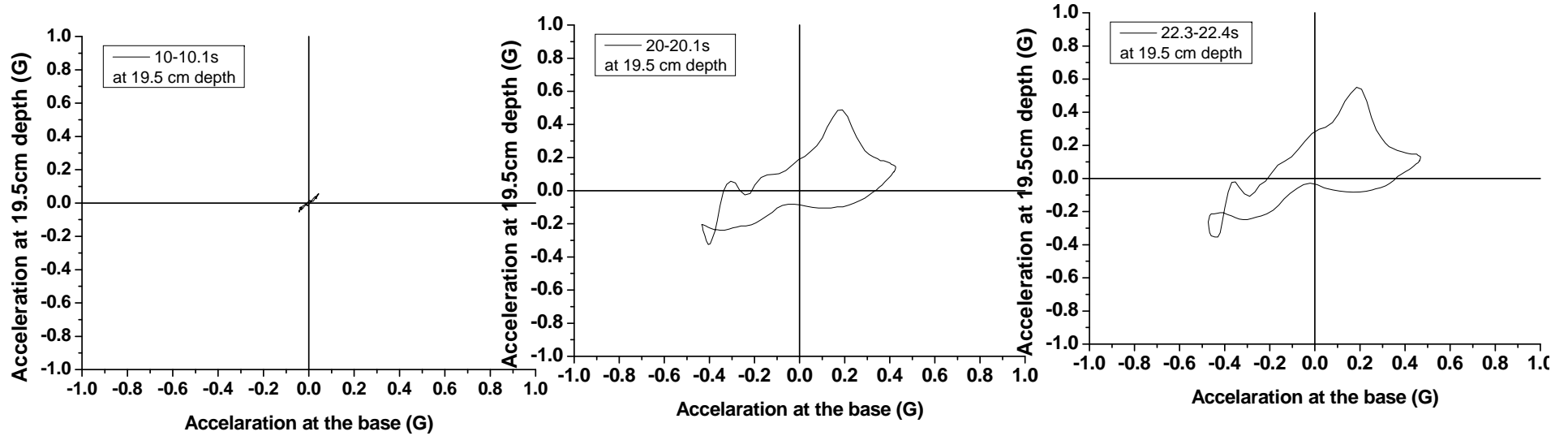
# Excess pore pressure (selected cycles-Dr=50%)



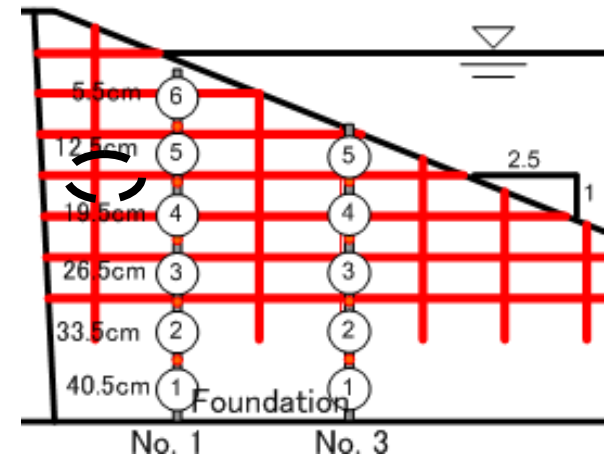
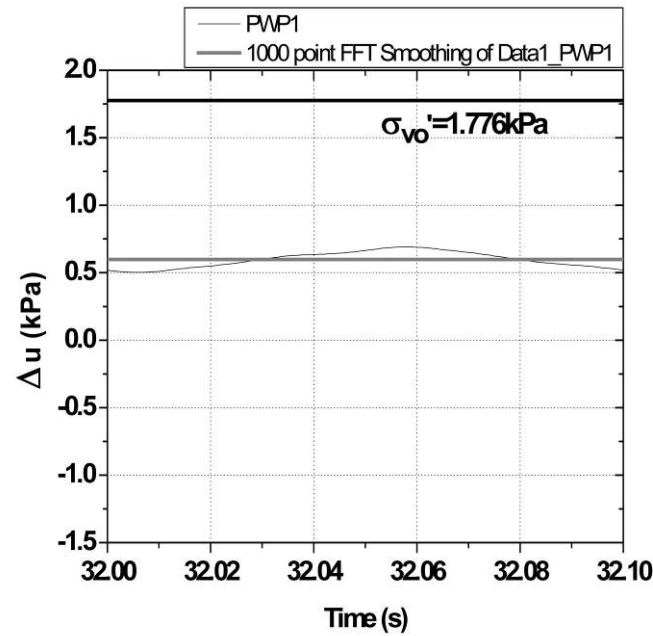
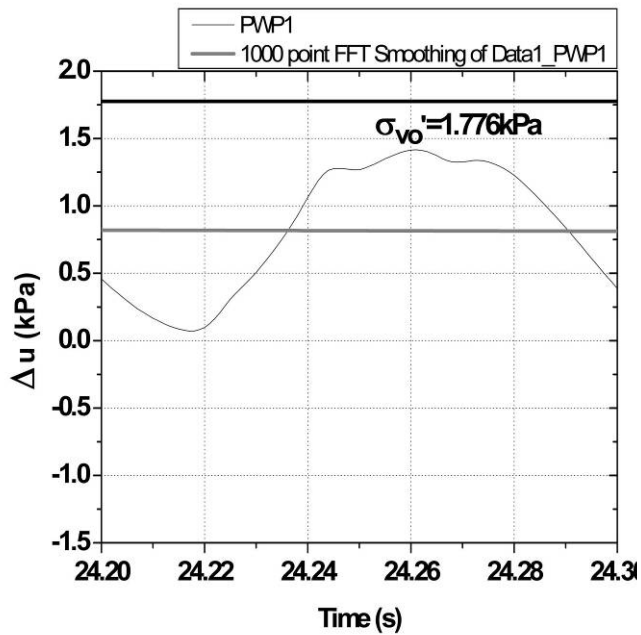
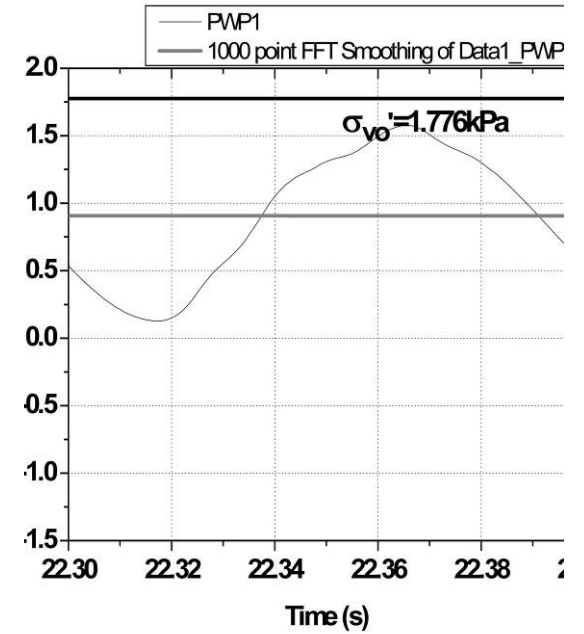
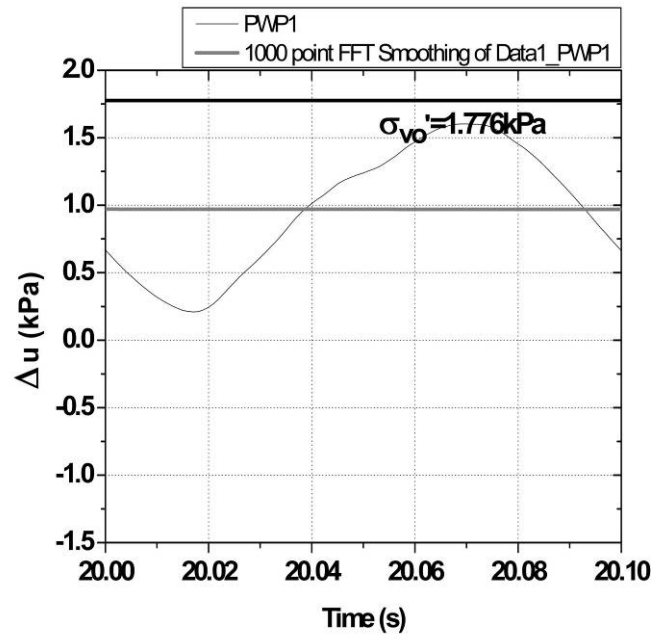
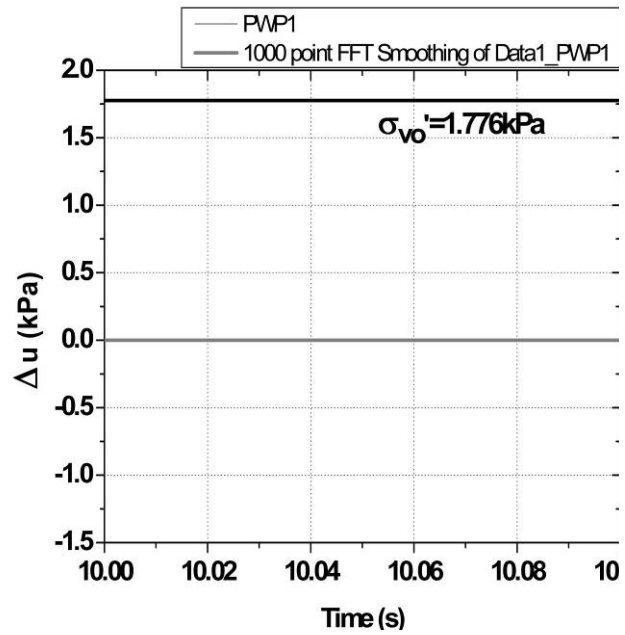
# Stress-strain response for Dr=20% (inclinometer1)



# Acceleration (at selected cycles)-Dr=20%

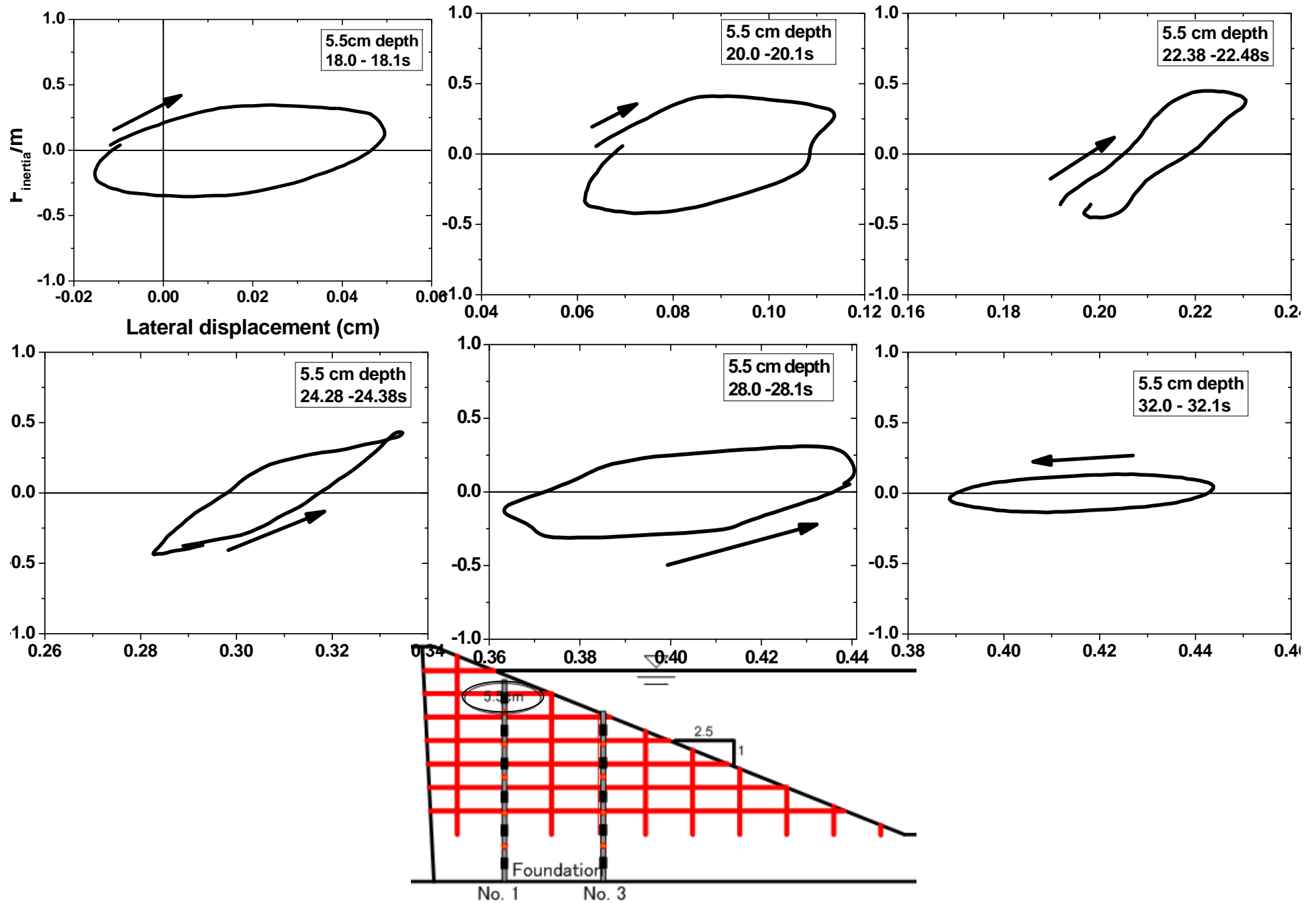


# Excess pore pressure (selected cycles-Dr=20%)





# Selected cycles of inertia force-lateral displacement for $D_r=70\%$ (inclinometer1)



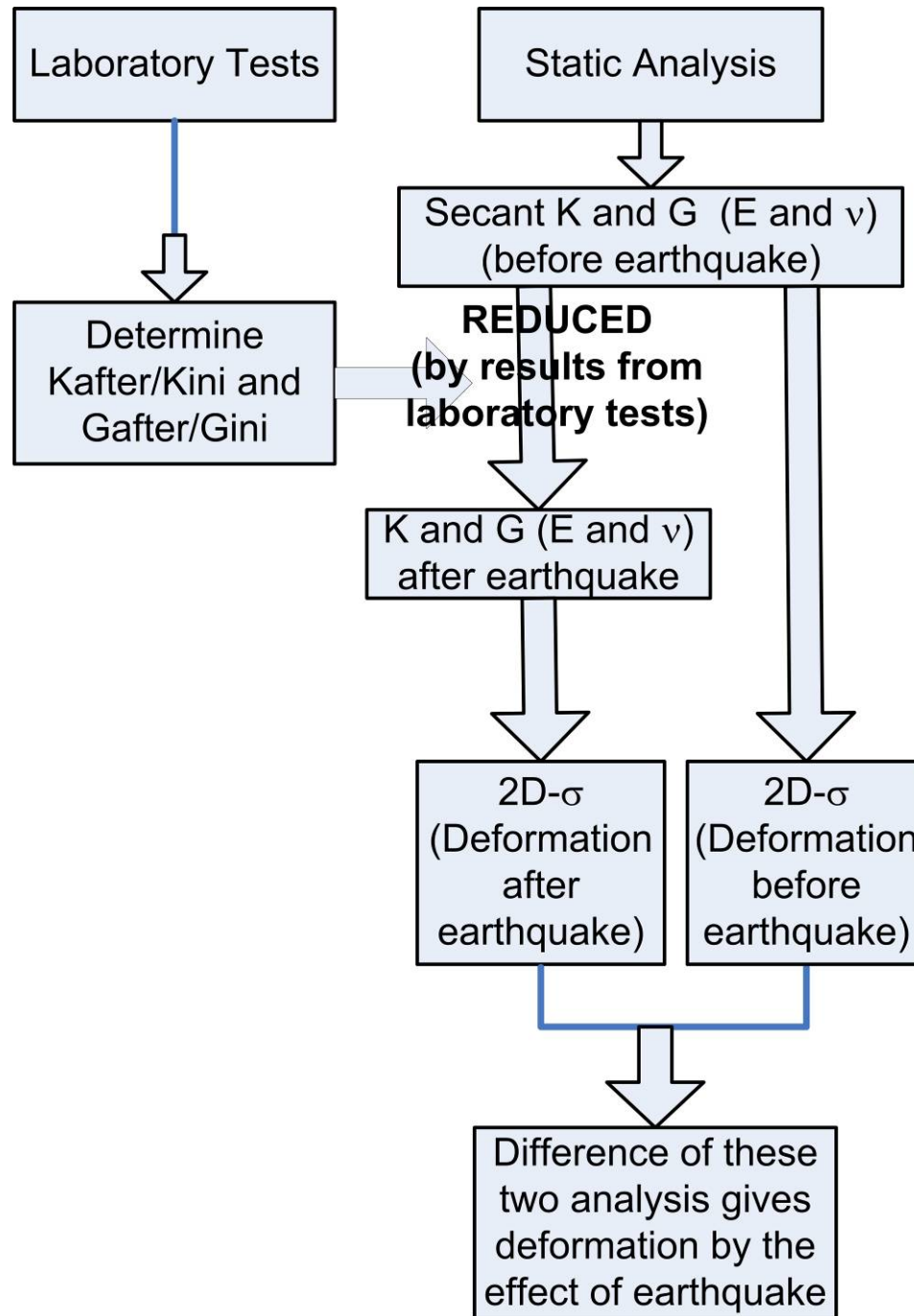
# Prediction

- Site investigations
- Constitutive model
- Analytical tool

LABORATORY  
EXPERIMENTS

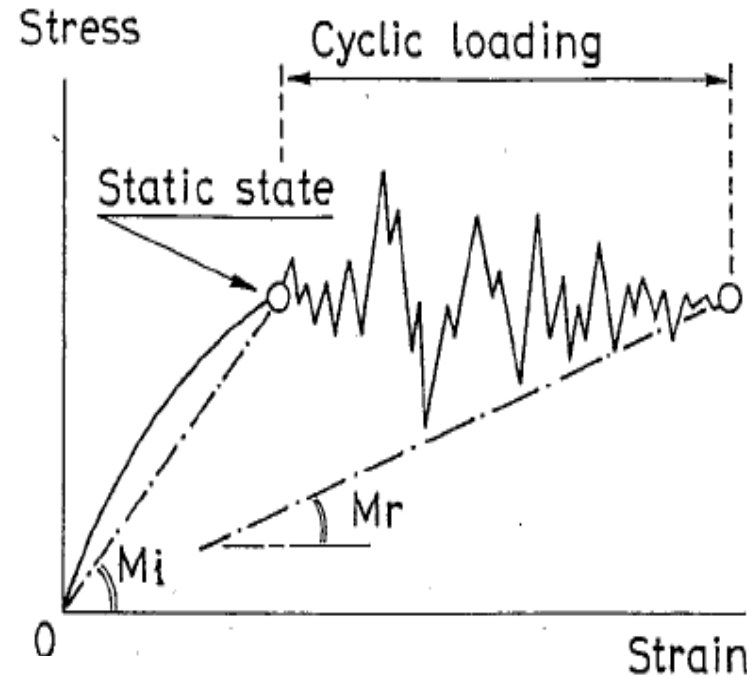
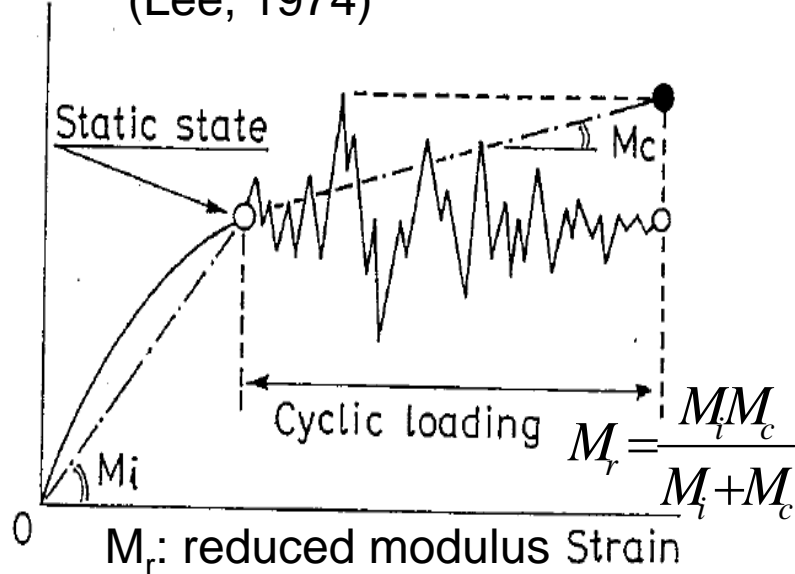
Reproduction of  
field conditions  
**more realistically**

*Prediction of  
residual  
displacements*



# Previous studies

Lee's concept of modulus modification  
(Lee, 1974)



$$M_b = \frac{\sigma_v - \sigma_h}{2(\varepsilon_v - \varepsilon_h)} \quad \text{Bulk modulus}$$

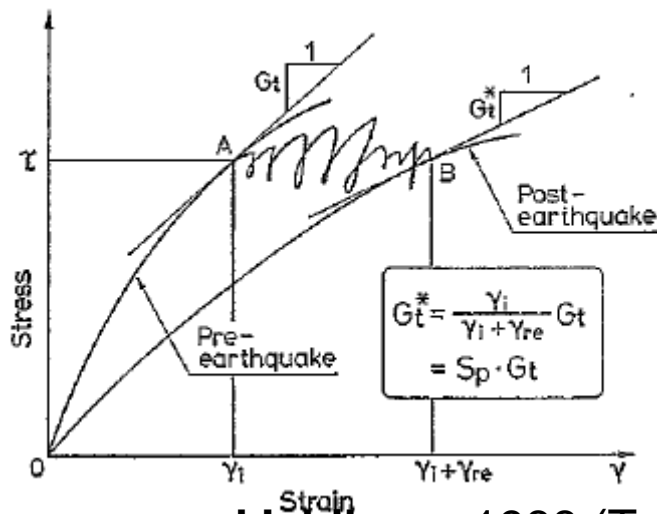
$$M_d = \frac{(\sigma_v - \sigma_h)(\varepsilon_v - \varepsilon_h) + \tau_{vh}\gamma_{vh}}{2(\varepsilon_v - \varepsilon_h)^2 + \gamma_{vh}^2} \quad \text{Shear modulus}$$

$$\Delta\varepsilon_v = (\Delta\varepsilon_a + \Delta\varepsilon_r)/2, \quad \Delta\varepsilon_v = 0, \quad \Delta\gamma_{vh}/2 = (\Delta\varepsilon_a - \Delta\varepsilon_r)/2$$

$$\Delta\varepsilon_r = (\Delta v - \Delta\varepsilon_a)/2 \quad \text{Strain potential:}$$

**Shi, Towhata and Wieland, 1989**

(Triaxial test, rotation of principal stress axis is not possible)

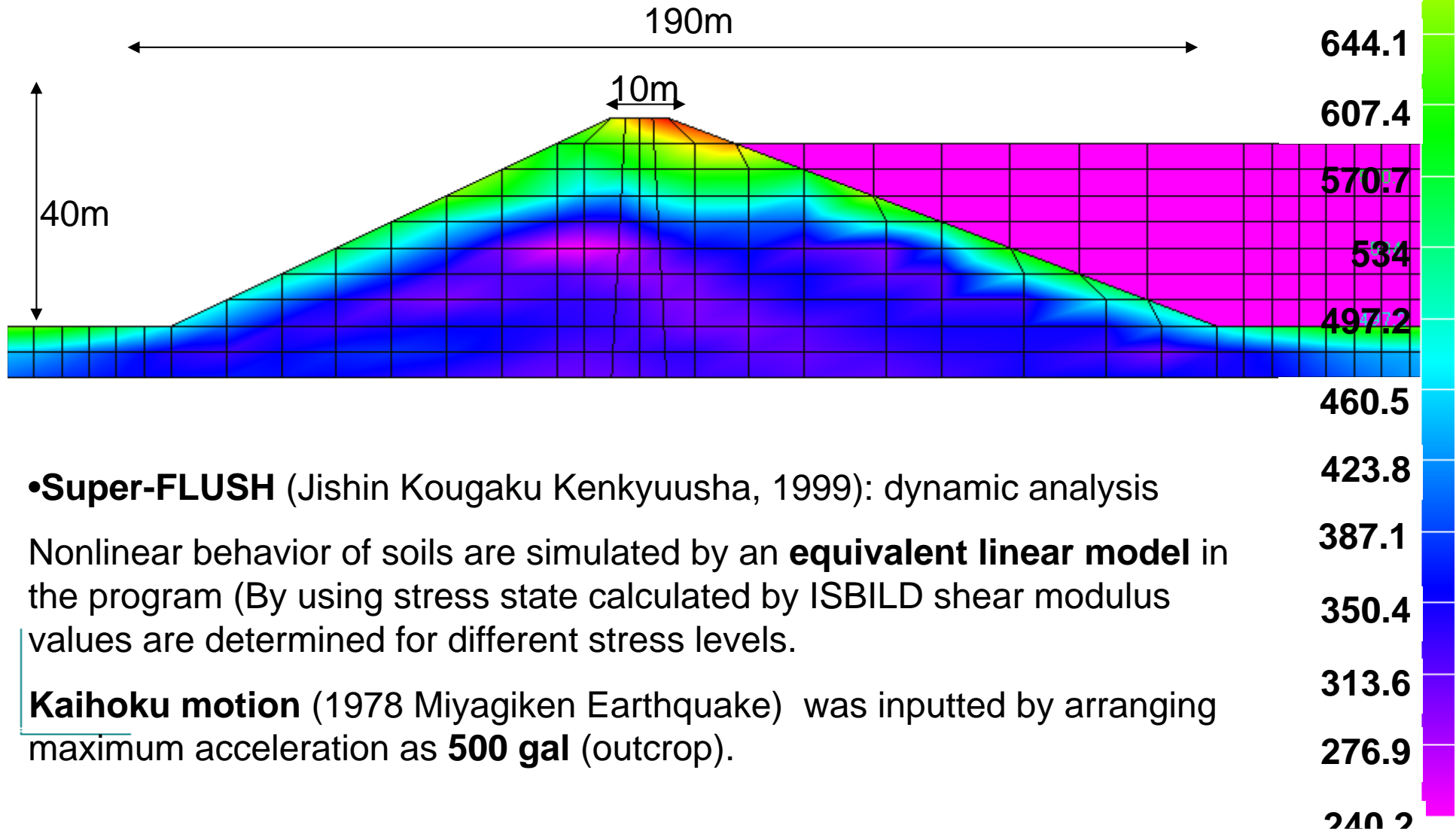


**Kuwano and Ishihara, 1988** (Torsional shear tests, stresses on a plane which the normal stress vanishes)

# Imaginary Dam

- **ISBILD** (Ozawa, et al. 1973): static analysis

**Nonlinear behavior** of soils are taken into account by changing soil parameters with the change in current stress state (**stepwise construction**)

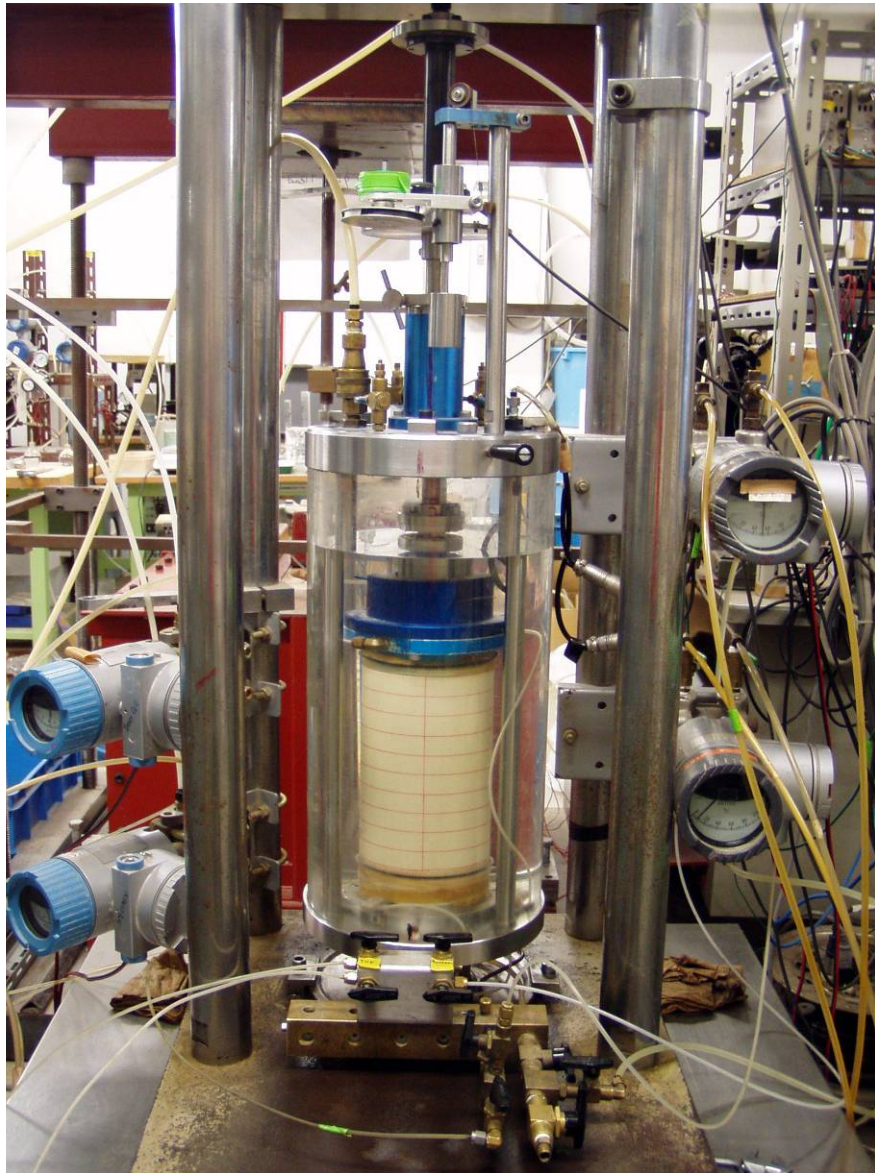


- **Super-FLUSH** (Jishin Kougaku Kenkyuusha, 1999): dynamic analysis

Nonlinear behavior of soils are simulated by an **equivalent linear model** in the program (By using stress state calculated by ISBILD shear modulus values are determined for different stress levels).

**Kaihoku motion** (1978 Miyagiken Earthquake) was inputted by arranging maximum acceleration as **500 gal** (outcrop).

# Material & Testing Procedure



## Hollow Cylindrical Torsional Shear Test

**ADVANTAGE:** can control torque, vertical force and inner and outer cell pressures independently

**Material:** Toyoura Sand;

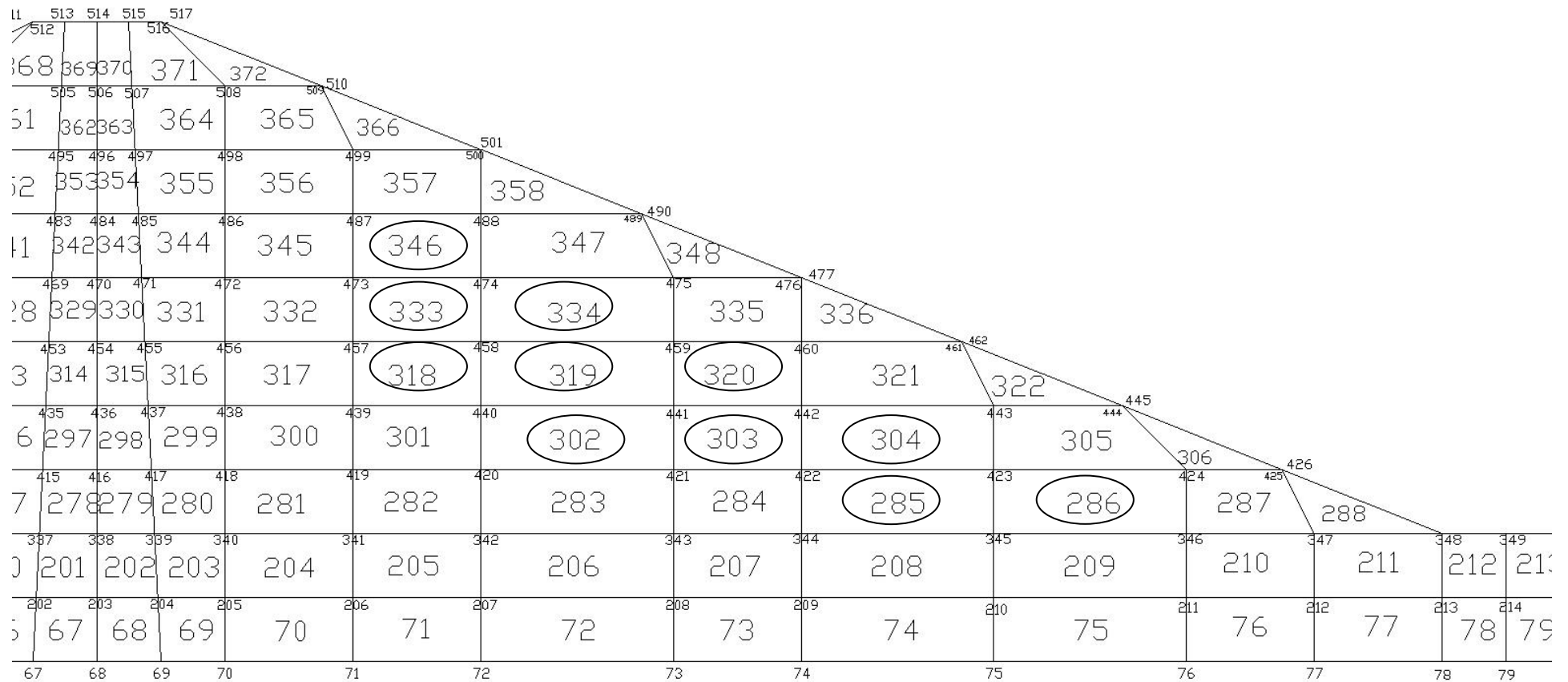
$$D_{50} = 0.2, U_c = 1.46$$

$$e_{\max} = 0.97, e_{\min} = 0.60$$

## Procedure

- Sample prepared by **Air Pluviation**
- Relative Density = 81-83%
- **Anisotropically** consolidated with **initial shear stress** (stress condition by ISBILD Analysis)
- Loaded under **undrained** condition, drainage was allowed at the end of loading (irregular cyclic load by Super-FLUSH Analysis) (***Torque and vertical force* controlled SIMULTANEOUSLY**)

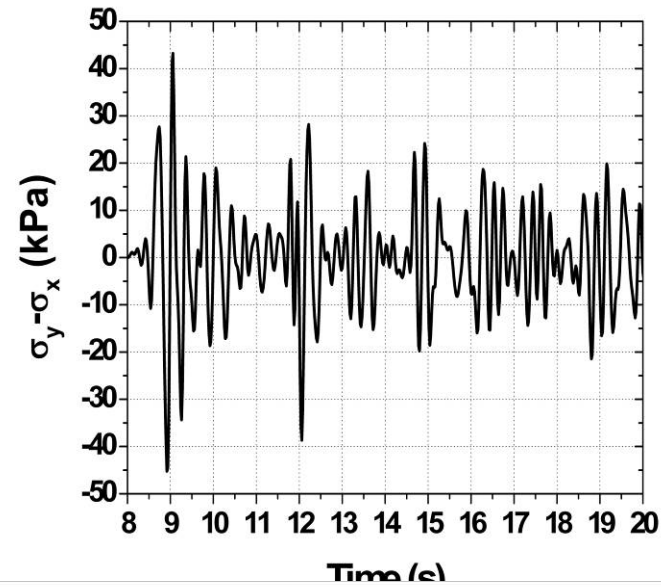
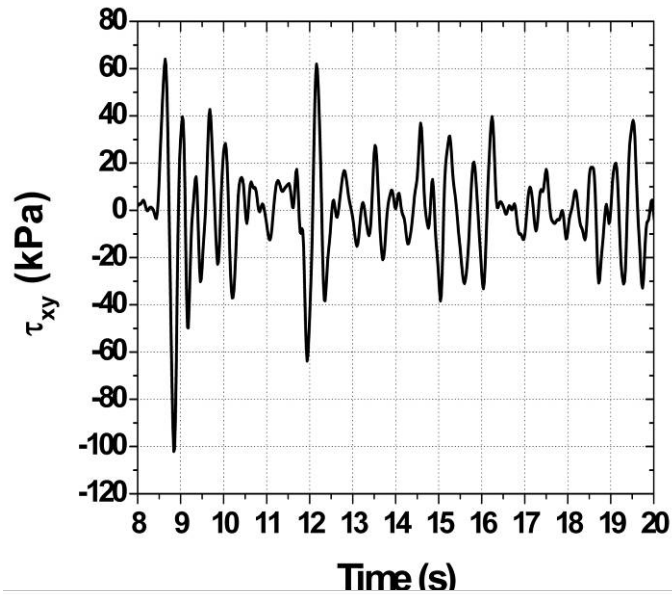
# Elements that hollow cylindrical torsion shear tests were performed



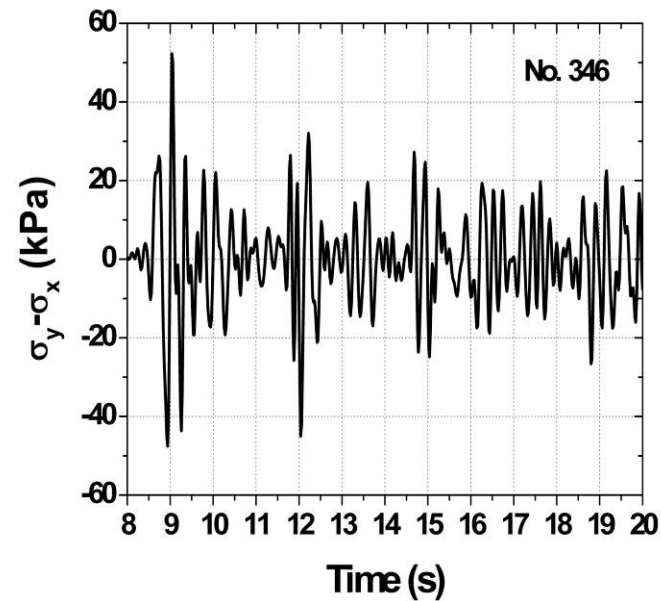
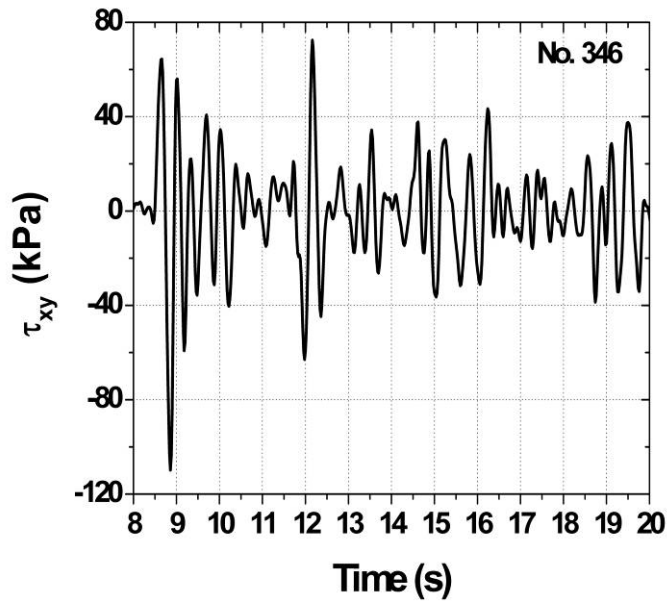
# Stress histories from Super-FLUSH analysis

## Irregular cyclic loading

333



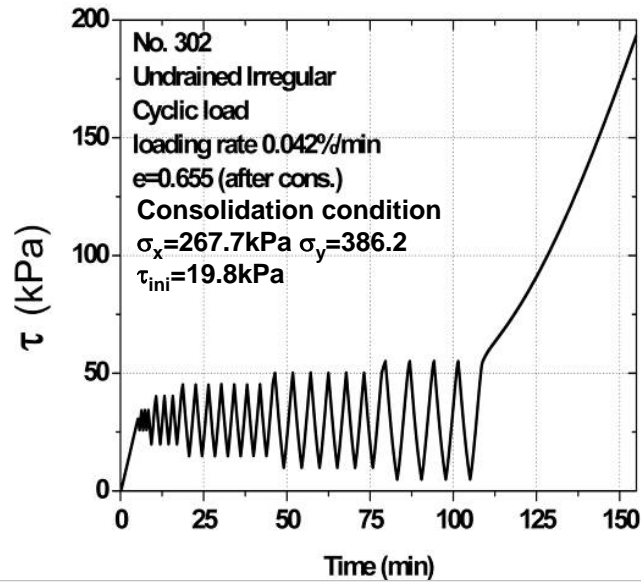
346



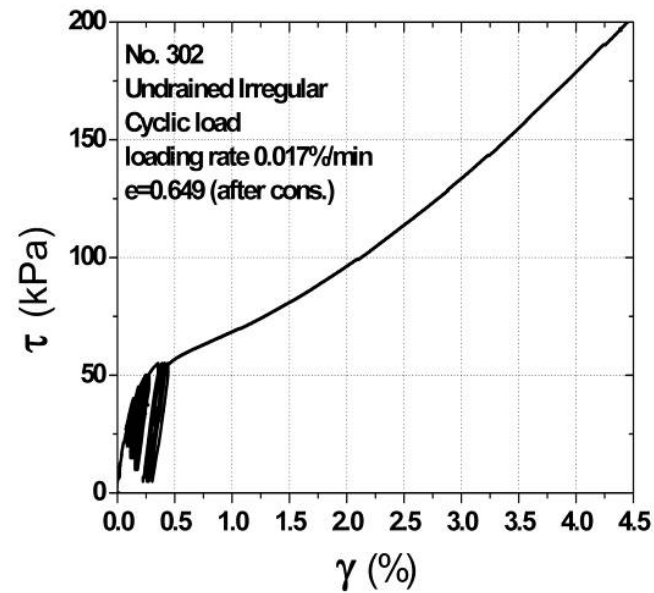
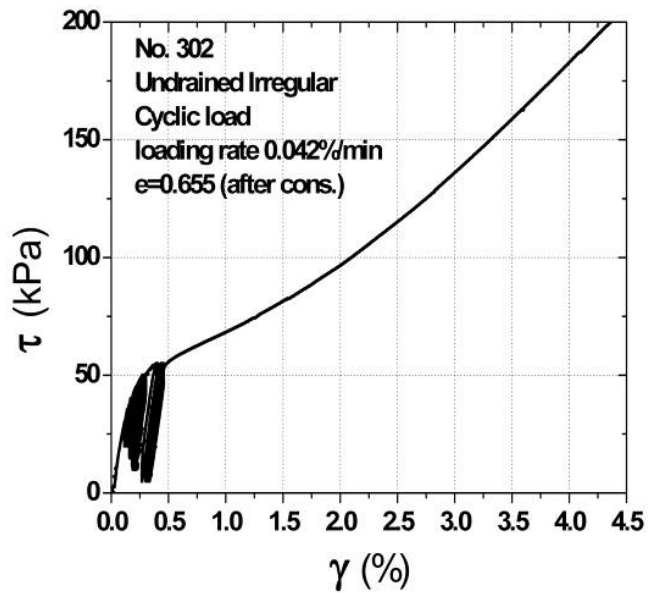
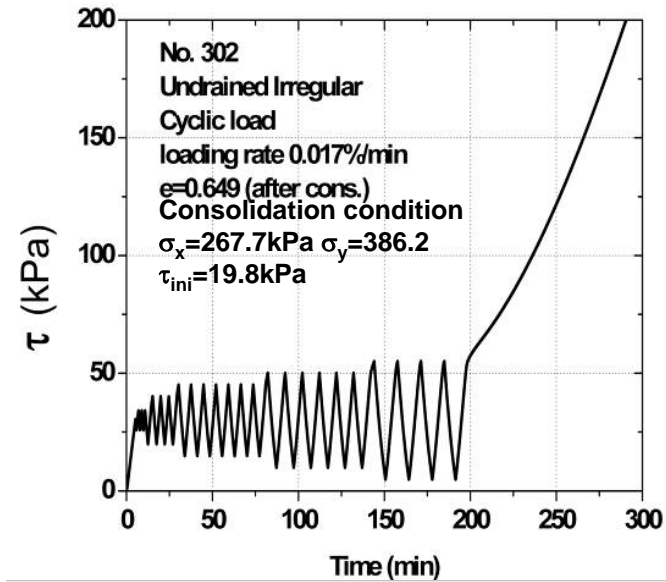
# Preliminary torsion shear tests-1

## *Effect of strain rate*

0.042%/min

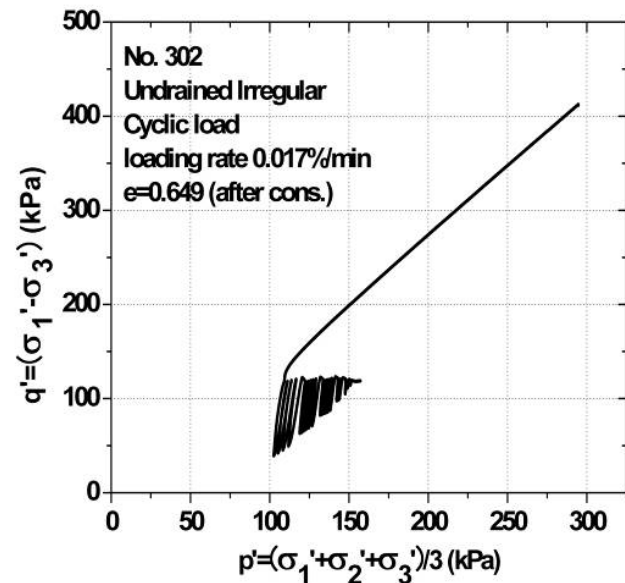
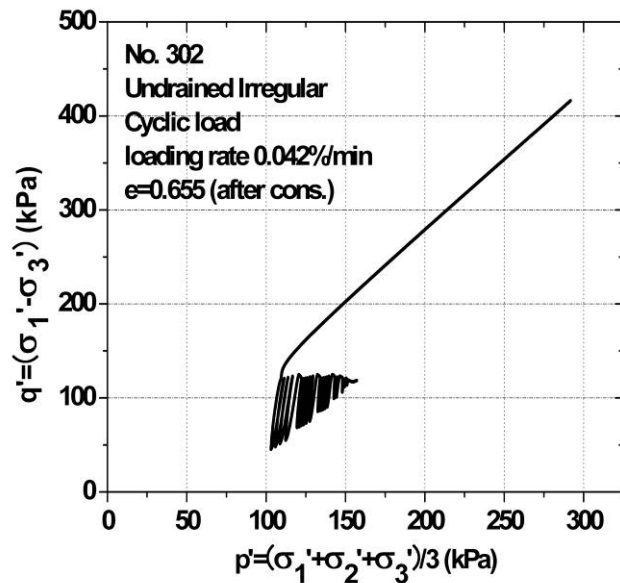
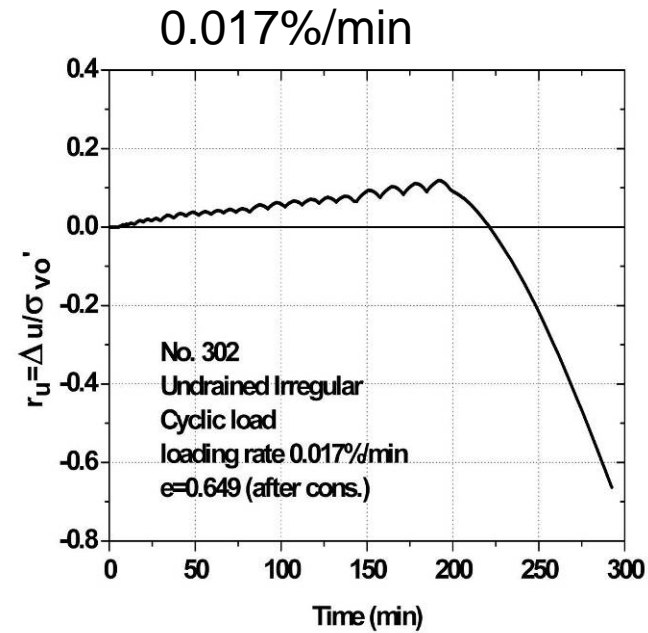
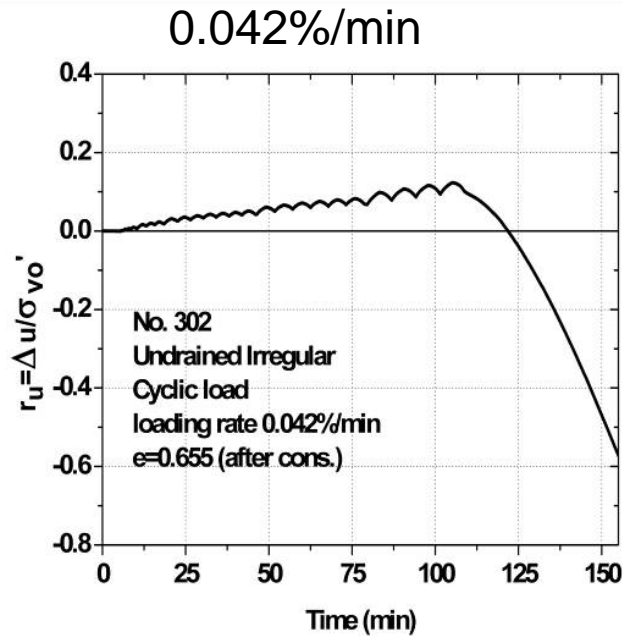


0.017%/min

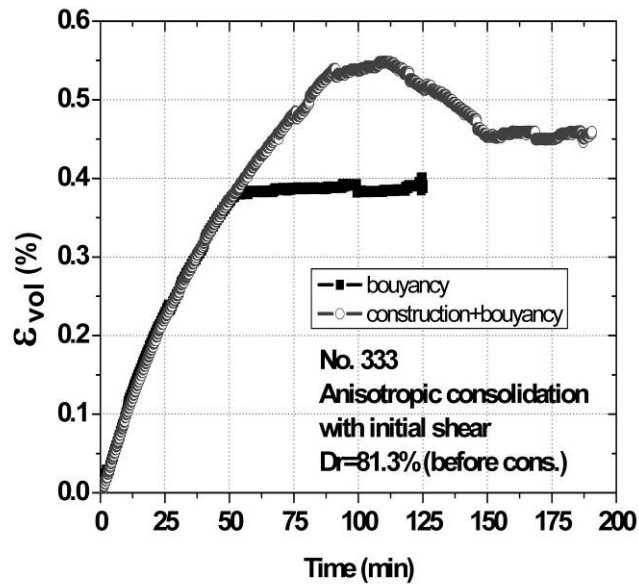
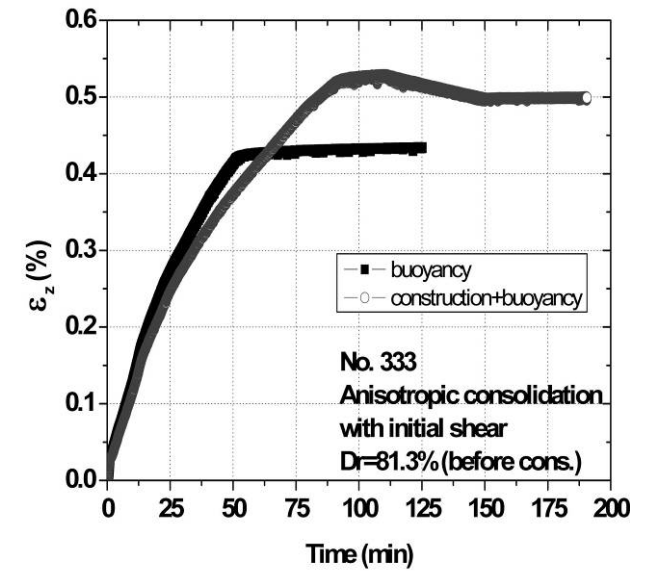
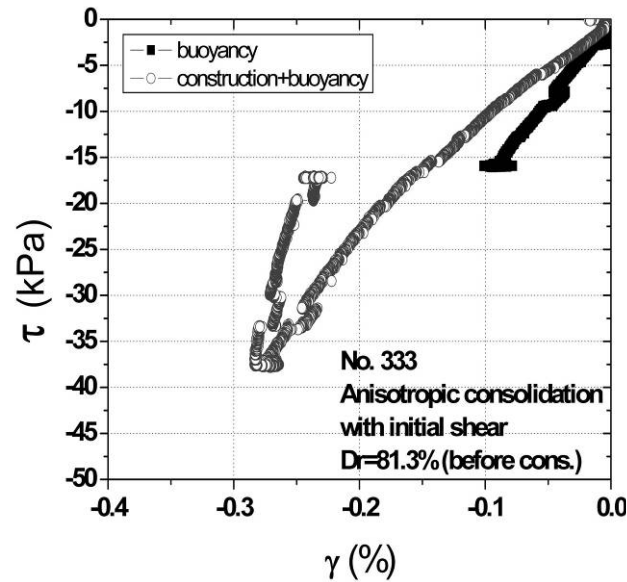
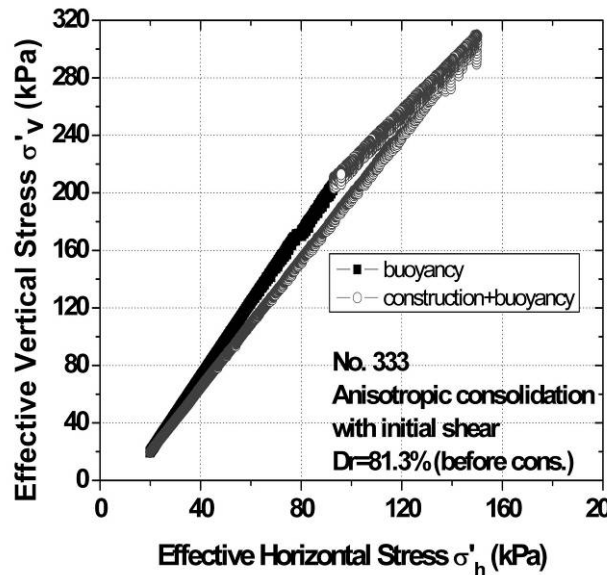


# Preliminary torsion shear tests-2

## Effect of strain rate

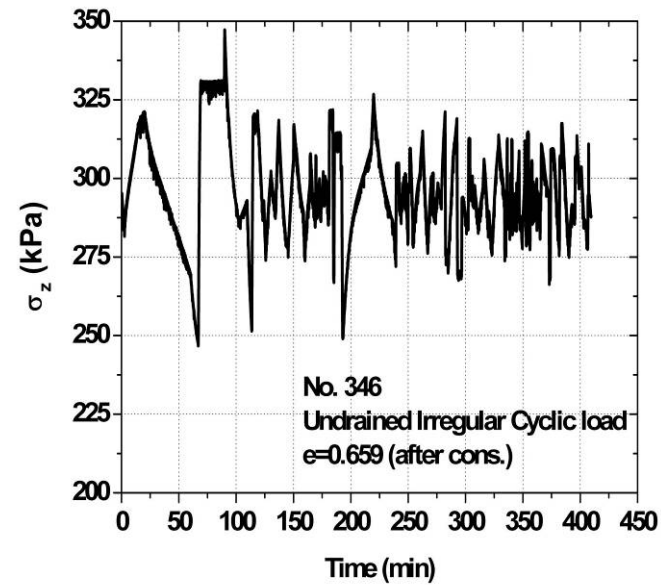
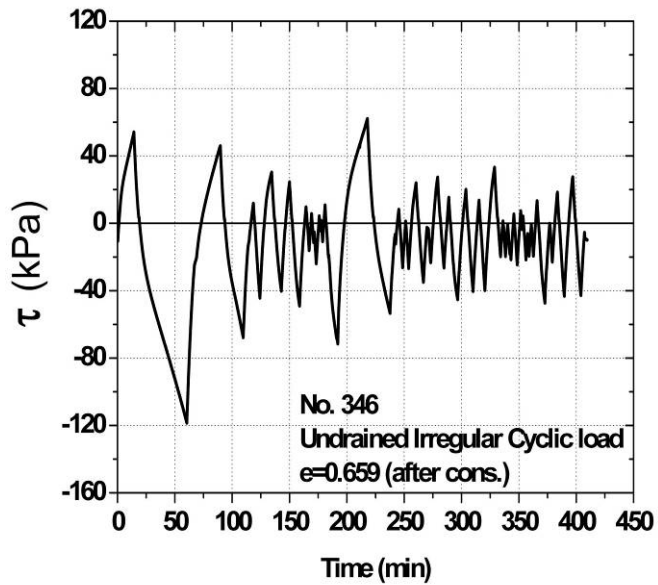
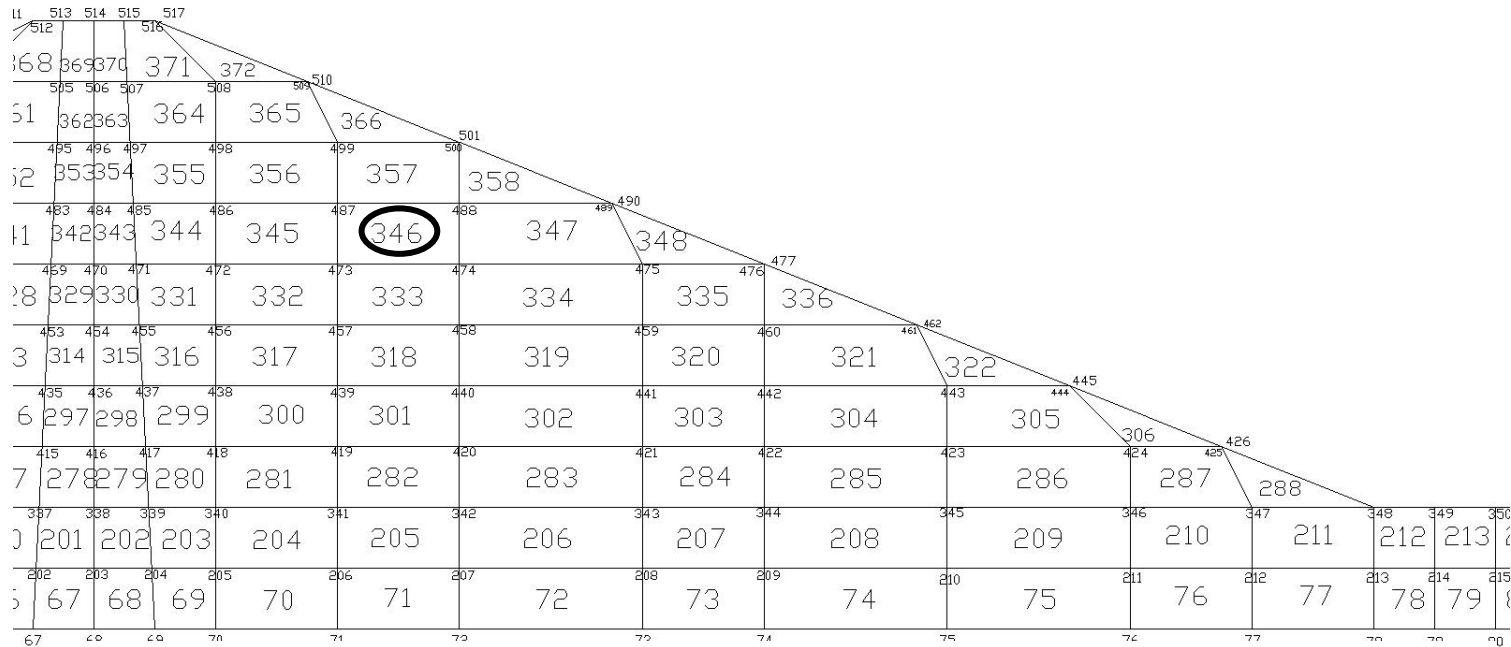


# Anisotropic consolidation state

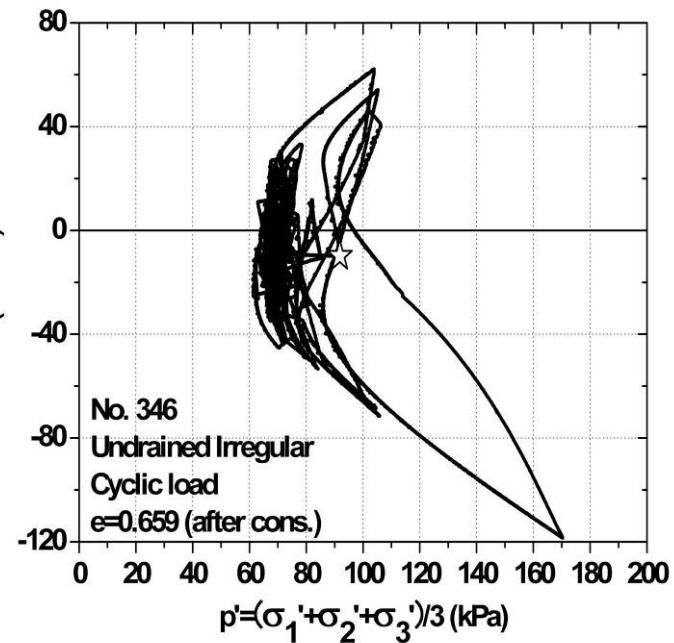
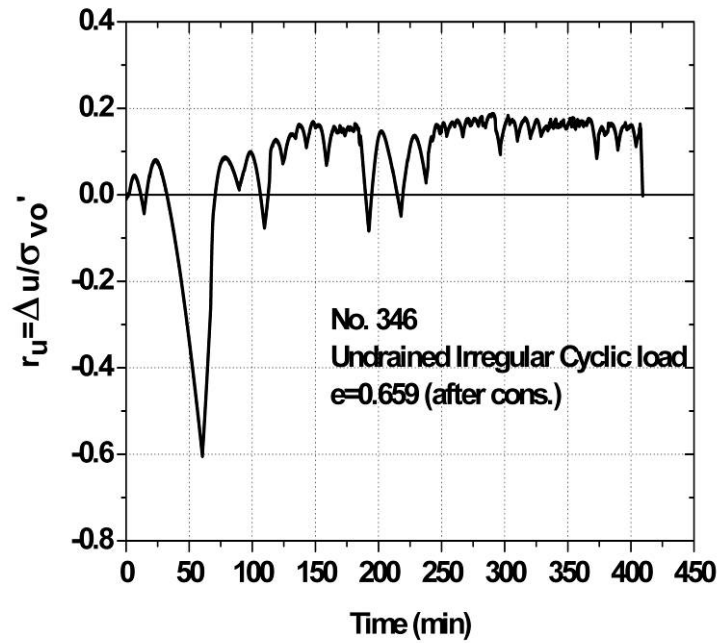
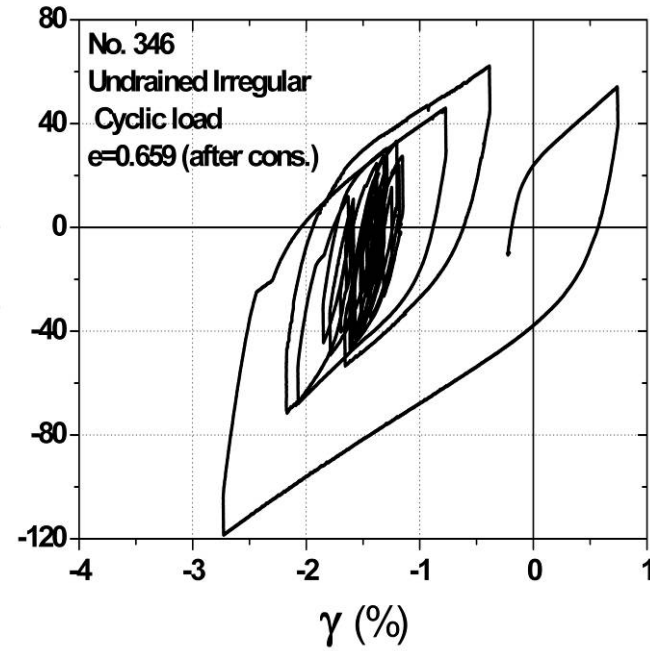
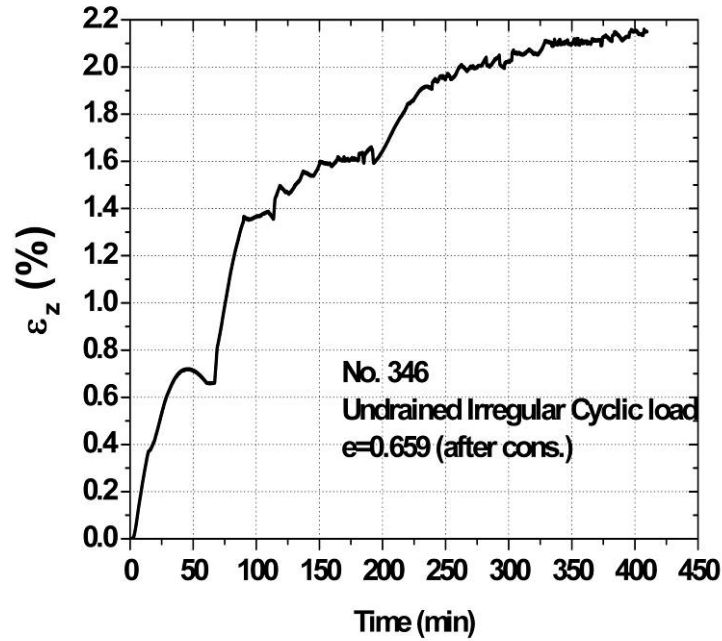


| Element No | $\epsilon_{vol}$ (%)   |   |
|------------|--|---|
|            | Stress condition<br>At the end of construction<br>+<br>At the end of reservoir<br>was filled | Stress condition<br>At the end of reservoir<br>was filled |
| 302        | 0.492  | 0.455   |
| 333        | 0.451  | 0.388   |
| 346        | 0.353  | 0.299   |

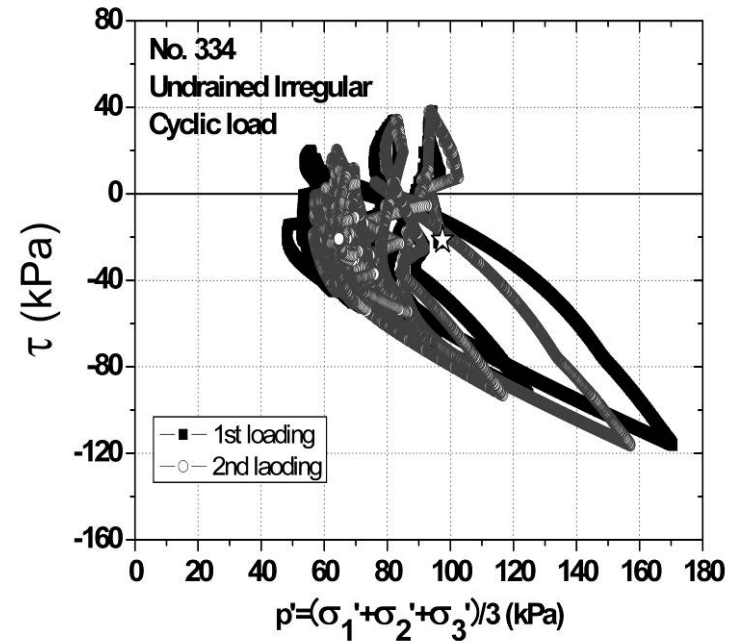
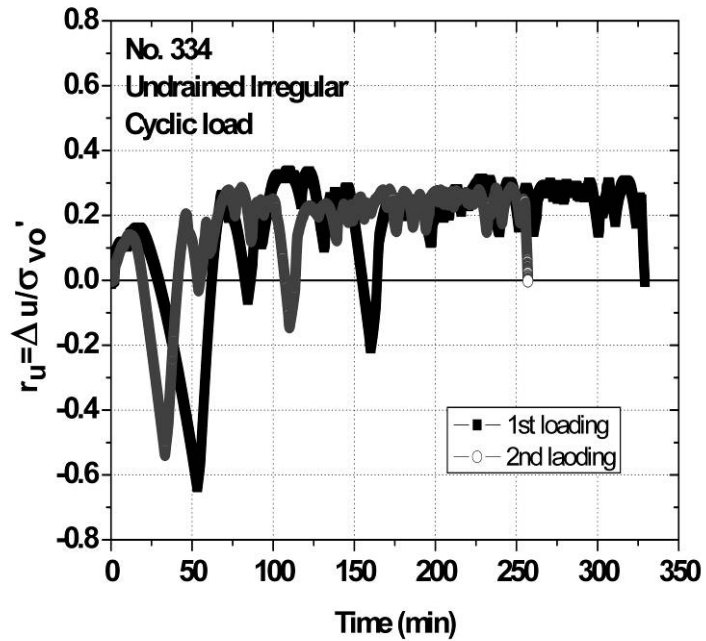
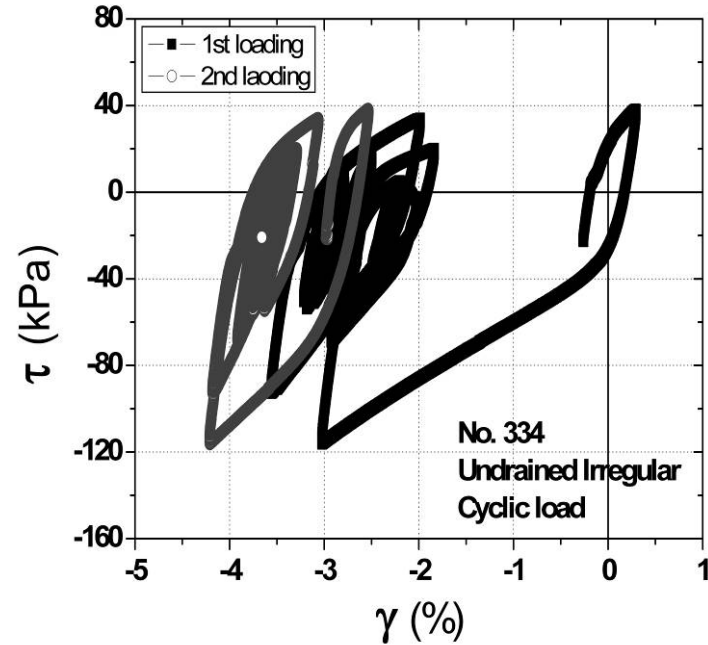
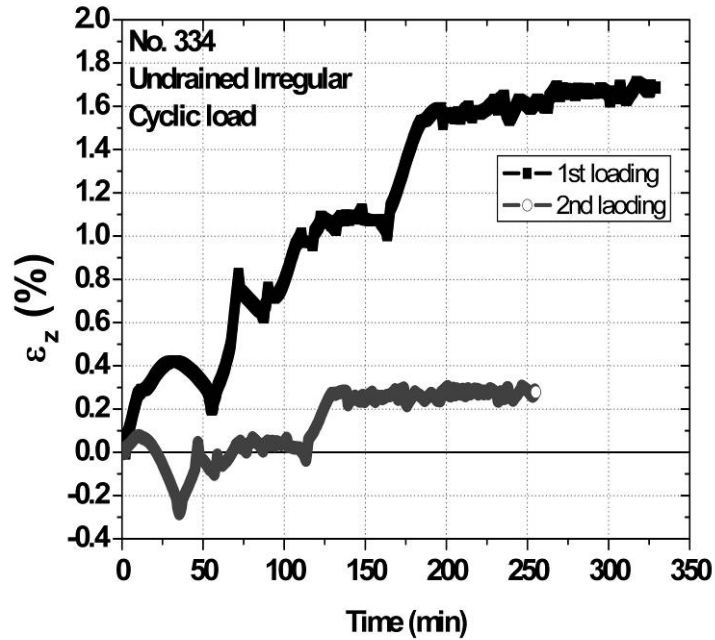
# Torsion shear test (Element No. 346)-1



# Torsion shear test (Element No. 346)-2



# Repeated loading (Element No. 334)



## Analysis to determine residual displacements

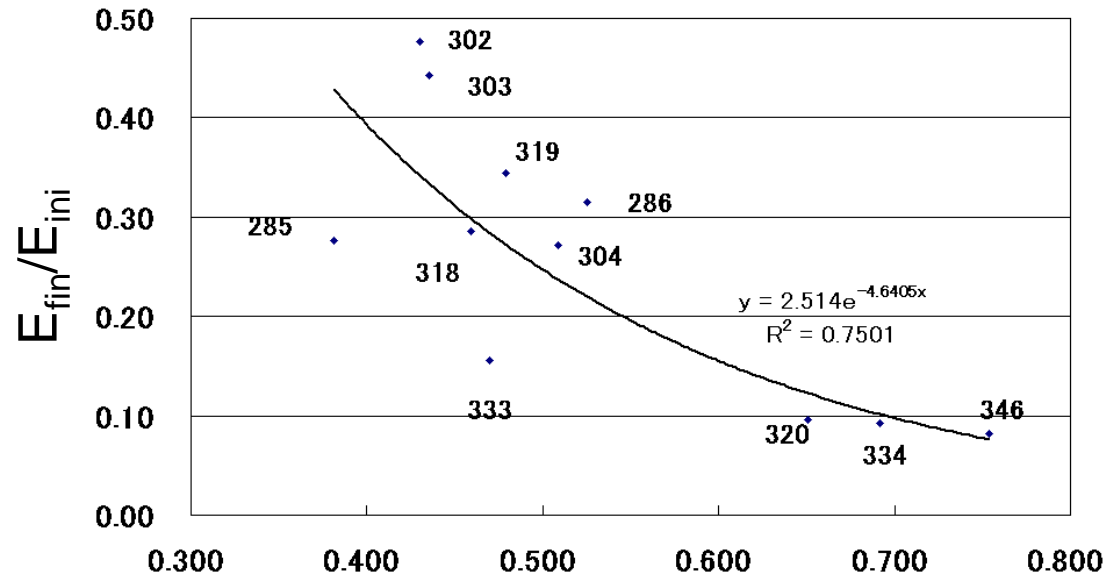
1. Analysis by using material properties that were determined by ISBILD to find out the deformed shape **before earthquake**,
2. Analysis by using modified values of E and n to determine the residual displacements **after the end of an earthquake** and
3. Analysis by using modified values of E and n to determine the residual displacements **after the dissipation of excess pore pressure**.

$$K = \frac{(\sigma_x + \sigma_y + \sigma_z) - (\sigma_x + \sigma_y + \sigma_z)_o}{3(\varepsilon_{vol} - (\varepsilon_{vol})_o)} \quad G = \frac{(\sigma'_1 - \sigma'_3) - (\sigma'_1 - \sigma'_3)_o}{2((\varepsilon_1 - \varepsilon_3) - (\varepsilon_1 - \varepsilon_3)_o)}$$

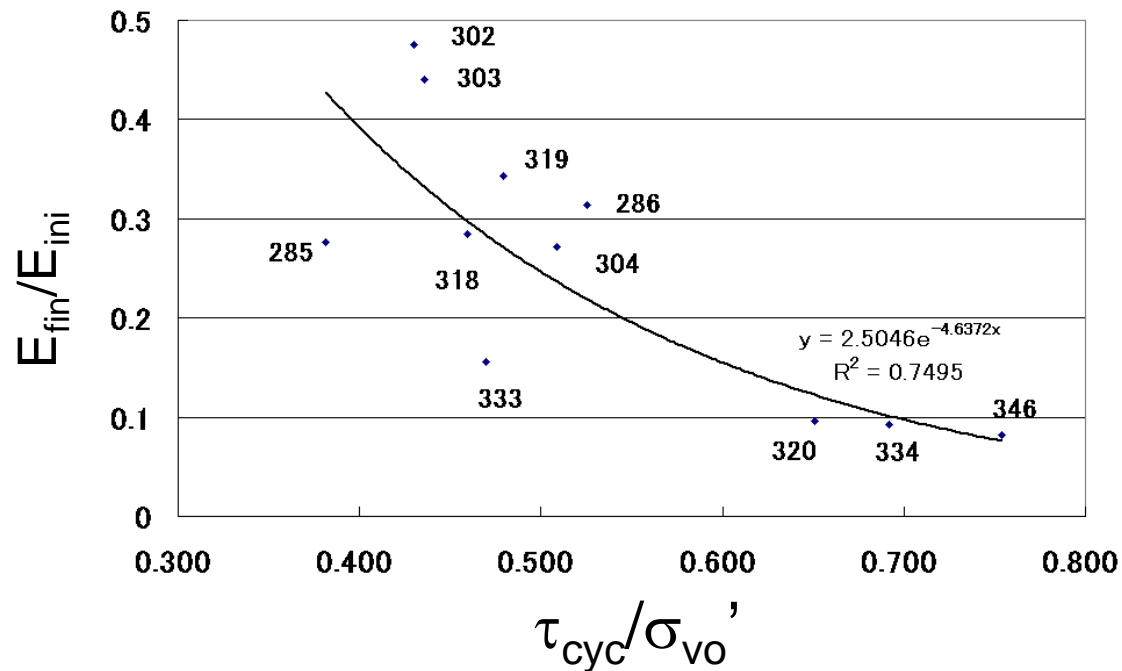
$$K = \frac{E}{3(1-2\nu)} \quad G = \frac{E}{2(1+\nu)} \quad \longrightarrow \quad E = \frac{9KG}{G+3K} \quad \nu = \frac{3K-2G}{2G+6K}$$

# Ratio of final and initial Elastic modulus from torsion shear tests

**AFTER  
CYCLIC  
LOADING**

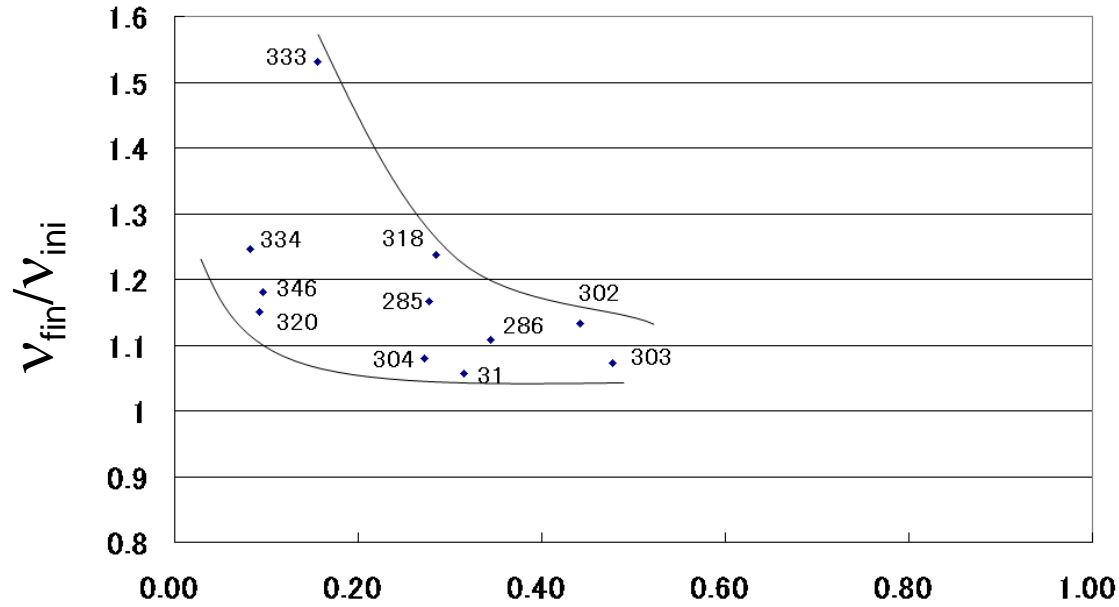


**AFTER  
DRAINAGE**

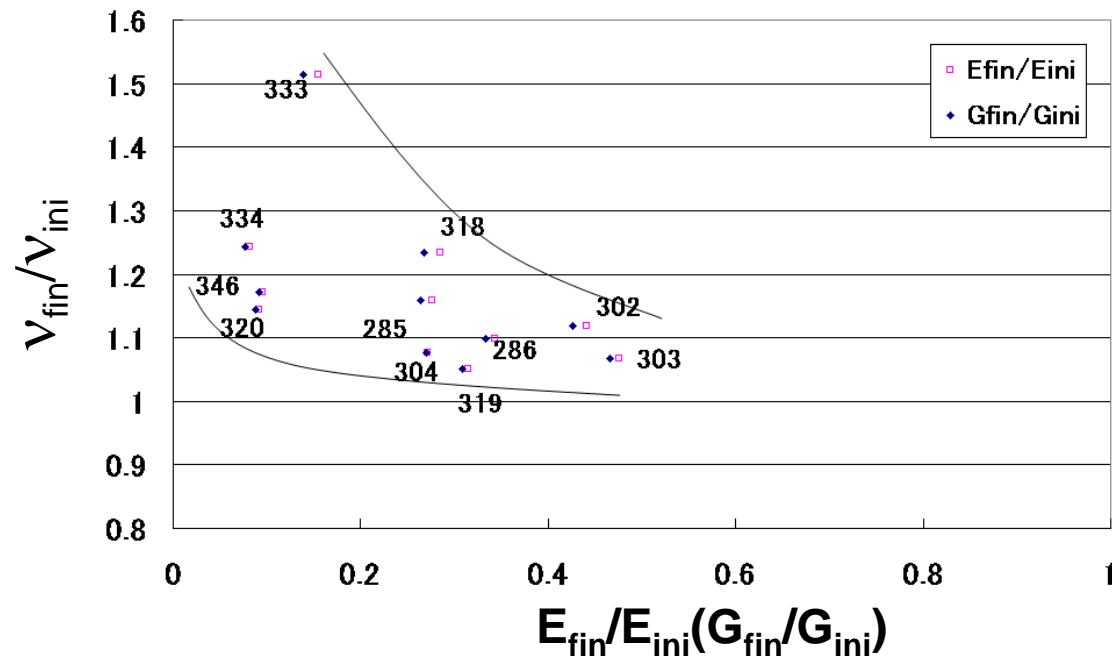


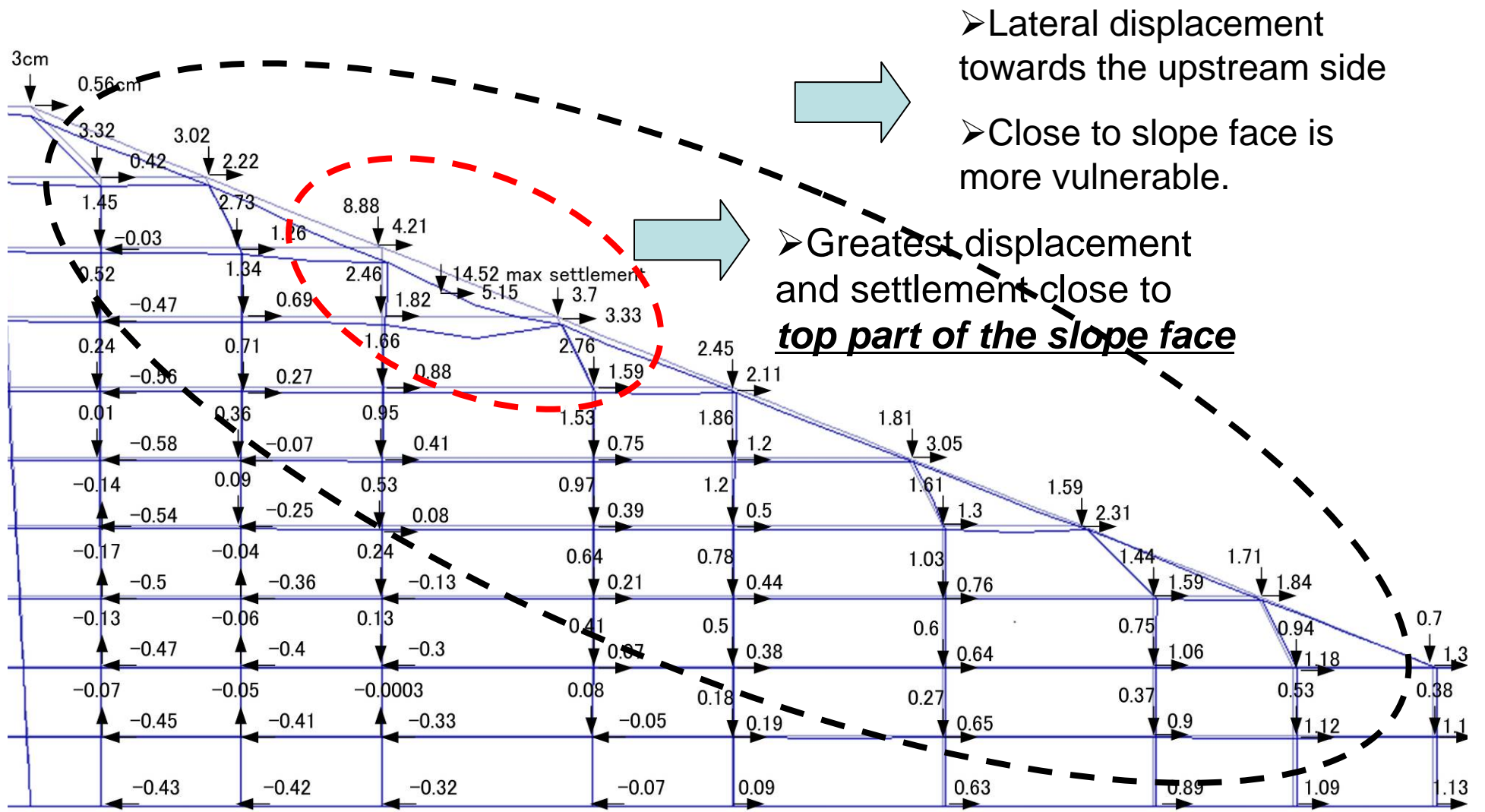
# Ratio of final and initial Poisson's ratio from torsion shear tests

**AFTER  
CYCLIC  
LOADING**

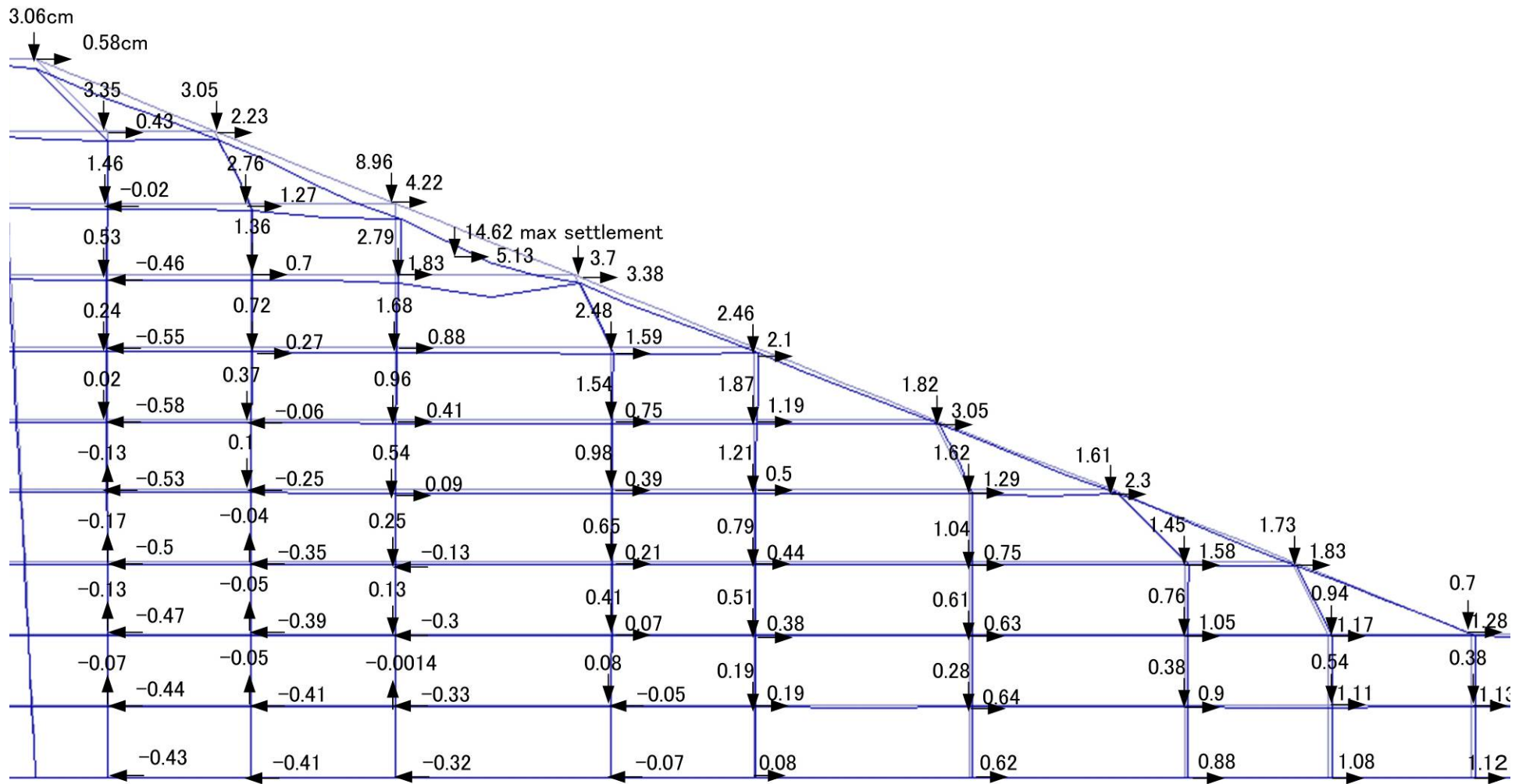


**AFTER  
DRAINAGE**



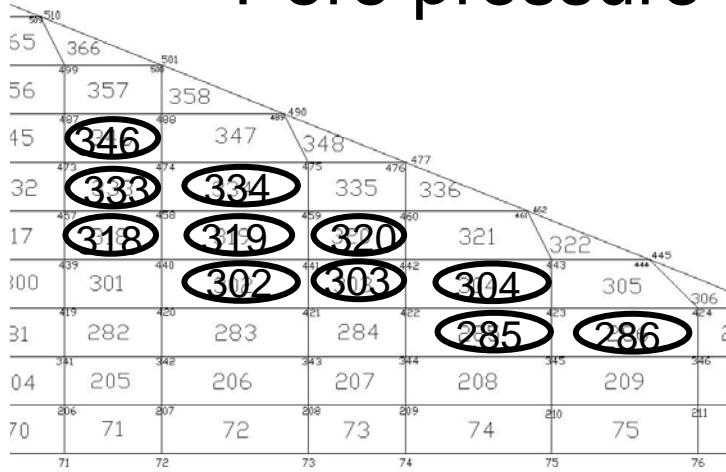


**Permanent deformations immediately after earthquake**



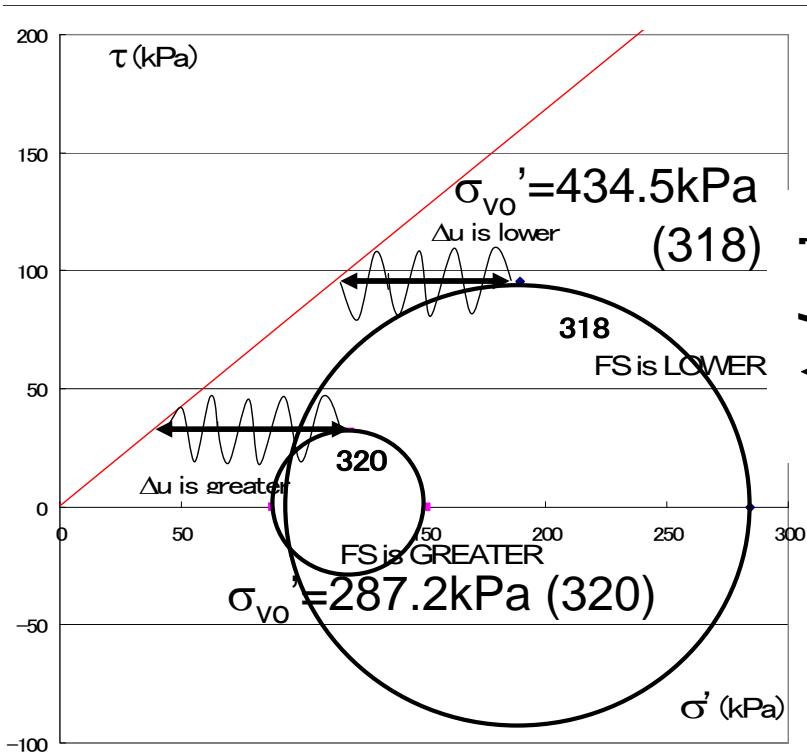
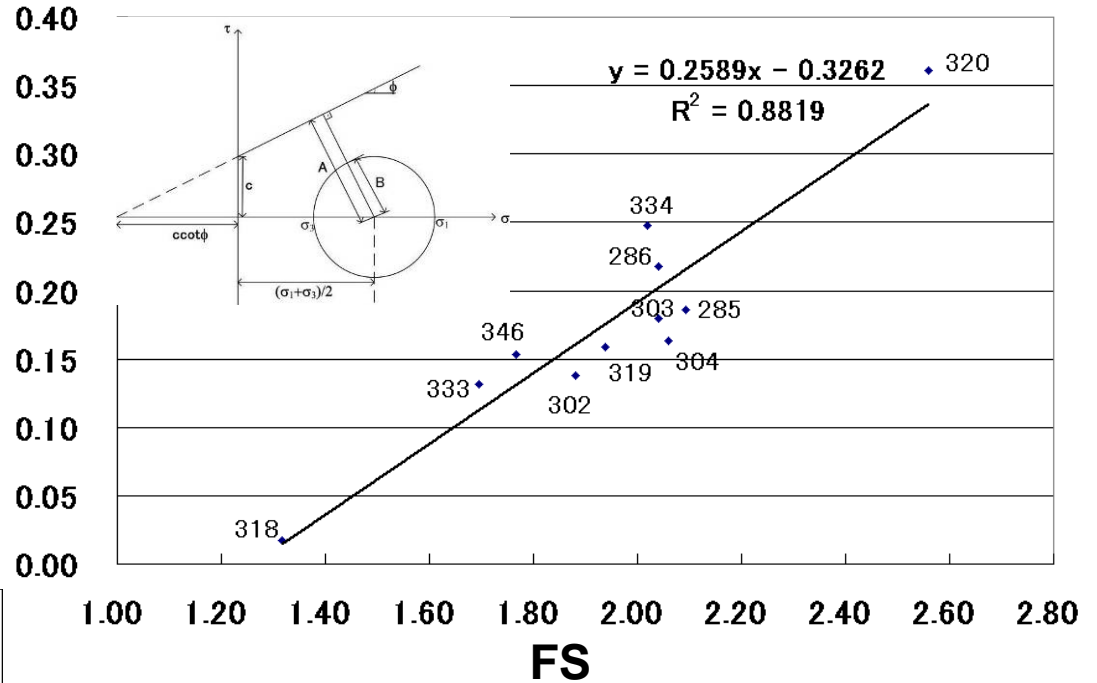
**Permanent deformations after dissipation of excess pore pressure**

# Pore pressure ratios from torsion shear tests

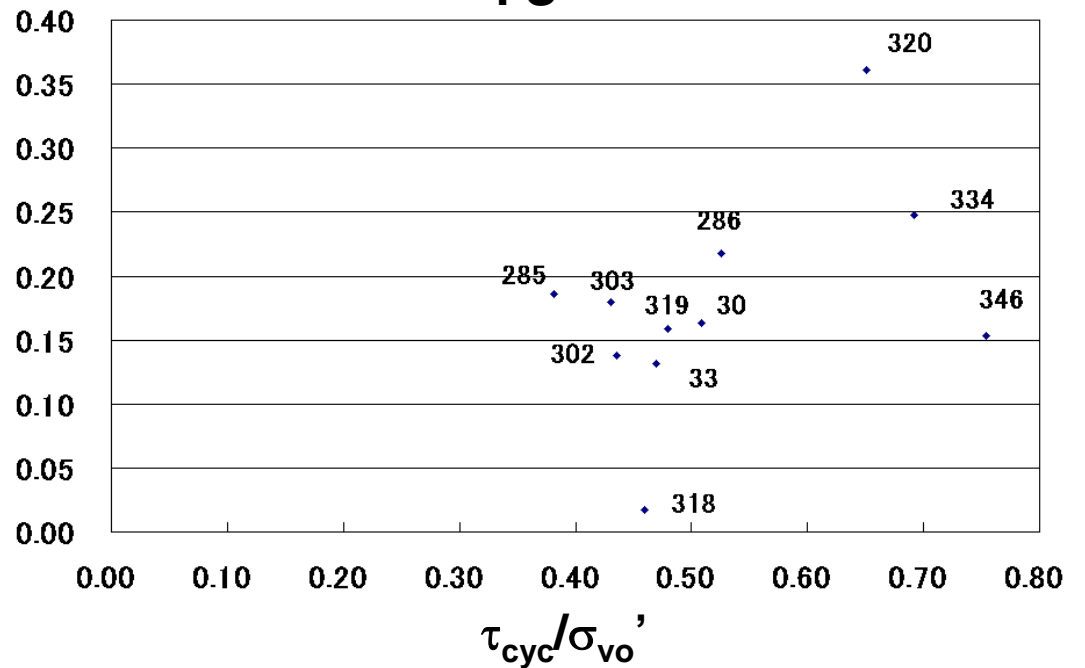


$$FS = \frac{(c \cot \phi + (\sigma_1 + \sigma_3)/2) \sin \phi}{(\sigma_1 - \sigma_3)/2}$$

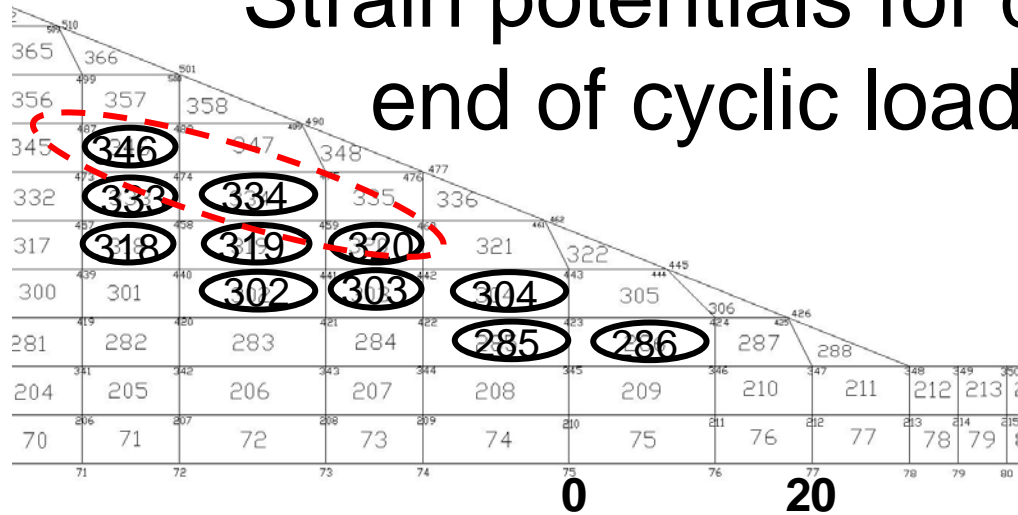
$$r_u = \Delta u / \sigma'_{vo}$$



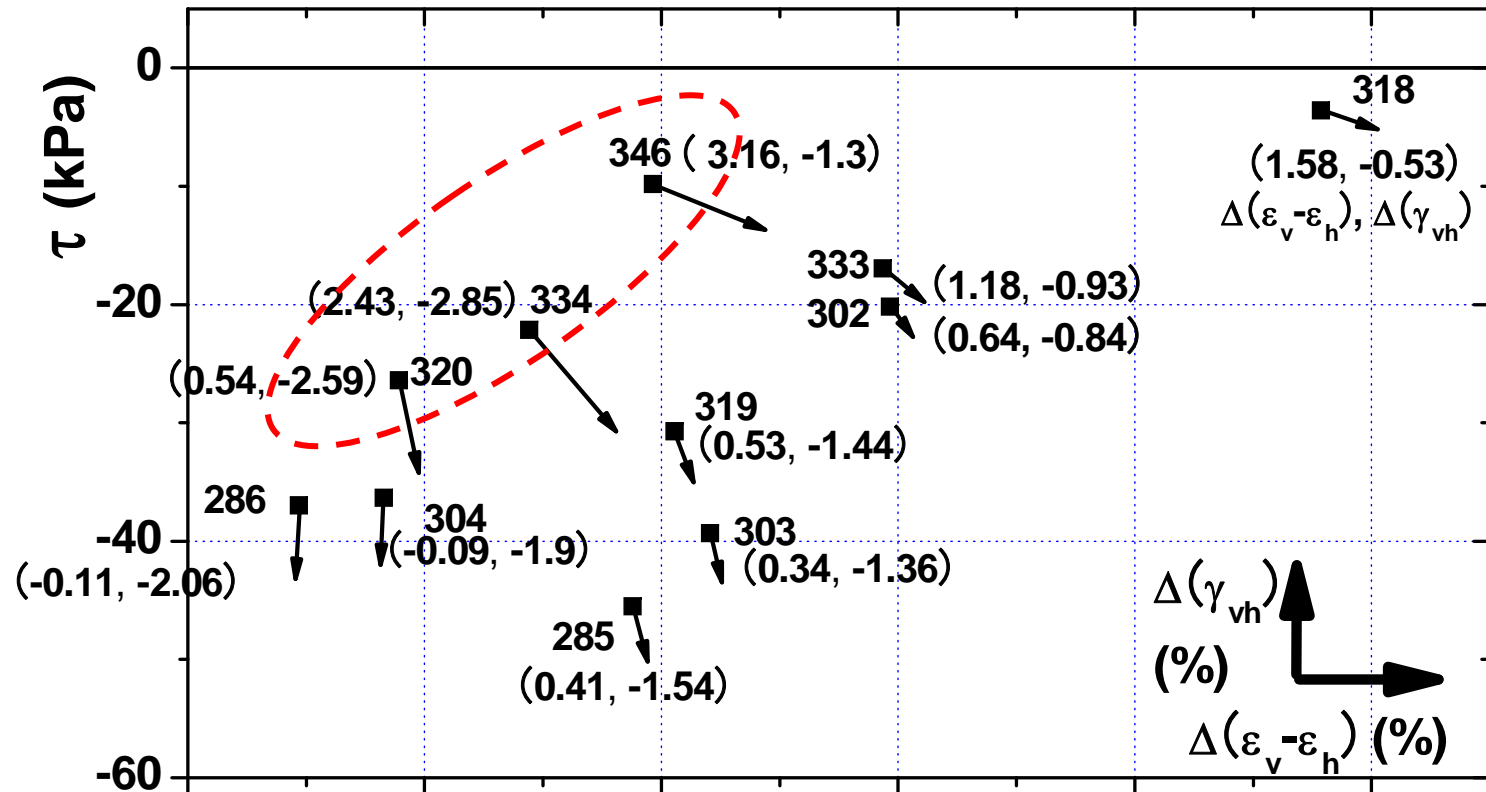
$$r_u = \Delta u / \sigma'_{vo}$$



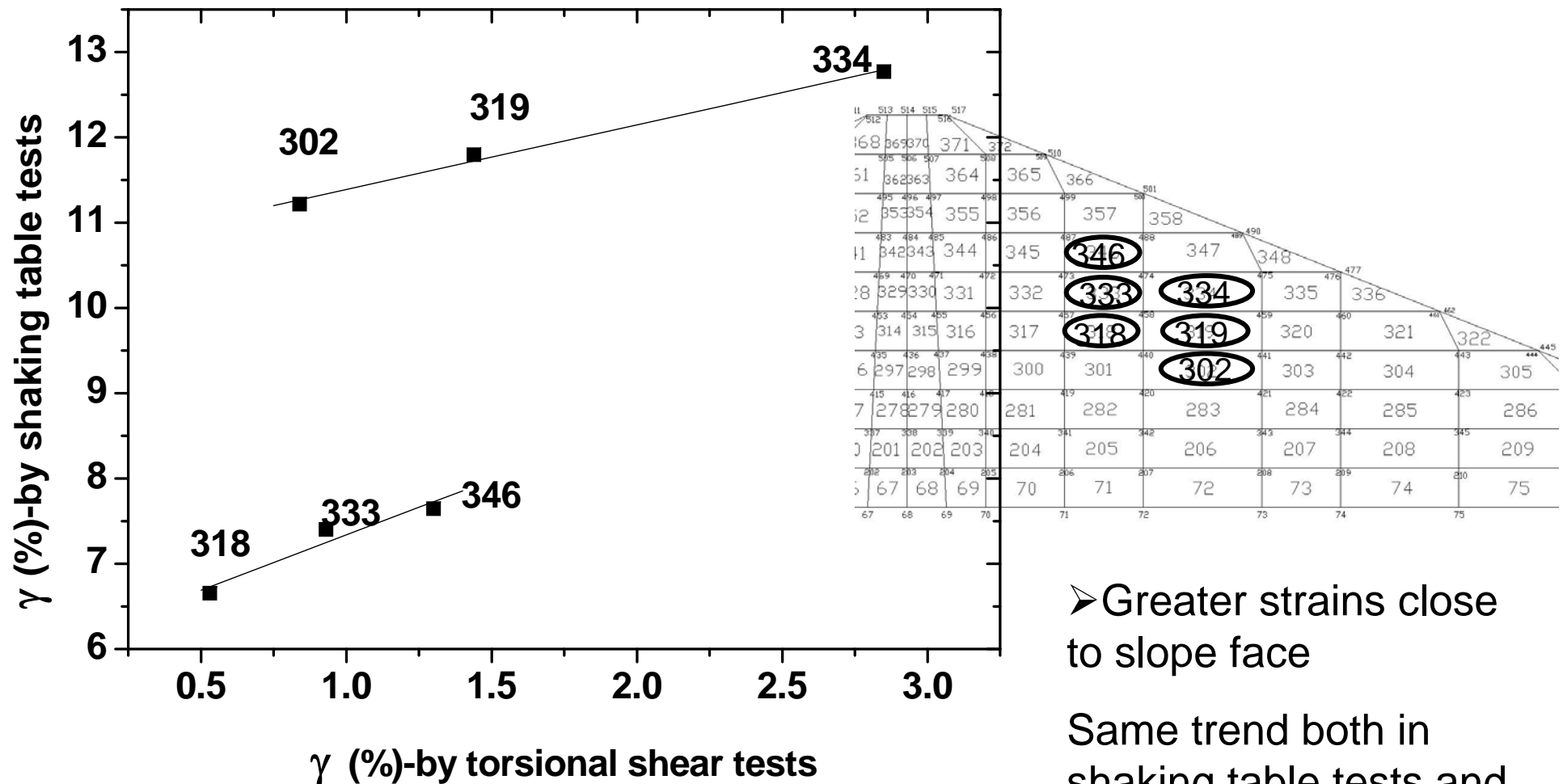
# Strain potentials for different elements at the end of cyclic loading (torsion shear tests)



$$(\sigma_v - \sigma_h) / 2 \text{ (kPa)}$$



# Comparison of shear strains from shaking table and torsion shear tests



➤ Greater strains close to slope face

Same trend both in shaking table tests and torsion shear tests

# Conclusions

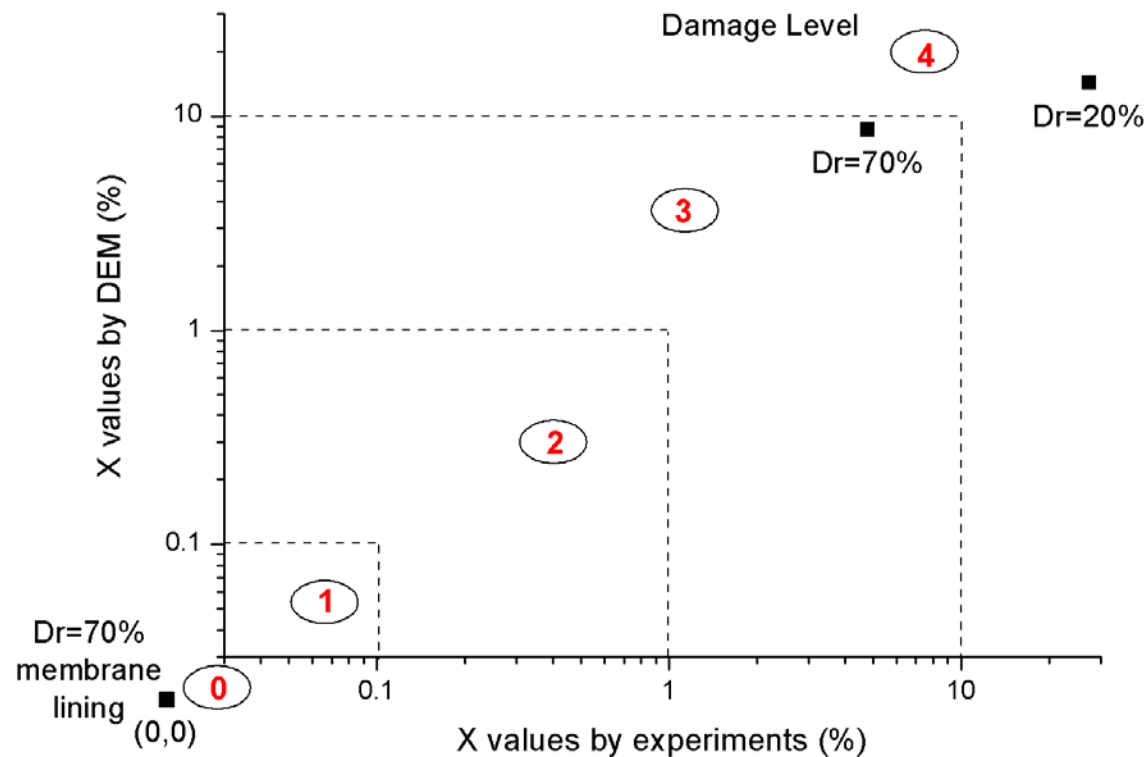
- **Asphaltic lining dam** model showed a **better performance** against earthquake loading than impervious core dam (model tests).
- **Residual displacements** at the **upstream side** were **greater** than the ones at the downstream side (model tests).
- **Flow failure** occurred in the dam body. **Slip lines were not observed** (model tests).
- **Strain potentials** were greater **close to the slope face** (torsion shear tests). **Static condition** is more effective on **strain potentials** for a fill dam.
- **Pore pressure ratios** were greater for greater **factor of safety**.
- **Deformations** in the elements that are **close to the slope face** were **greater** (both in model test , torsion shear tests test and prediction)

# Previous Damages caused by Earthquakes on Earth Dams (by Sato, J., 2007)

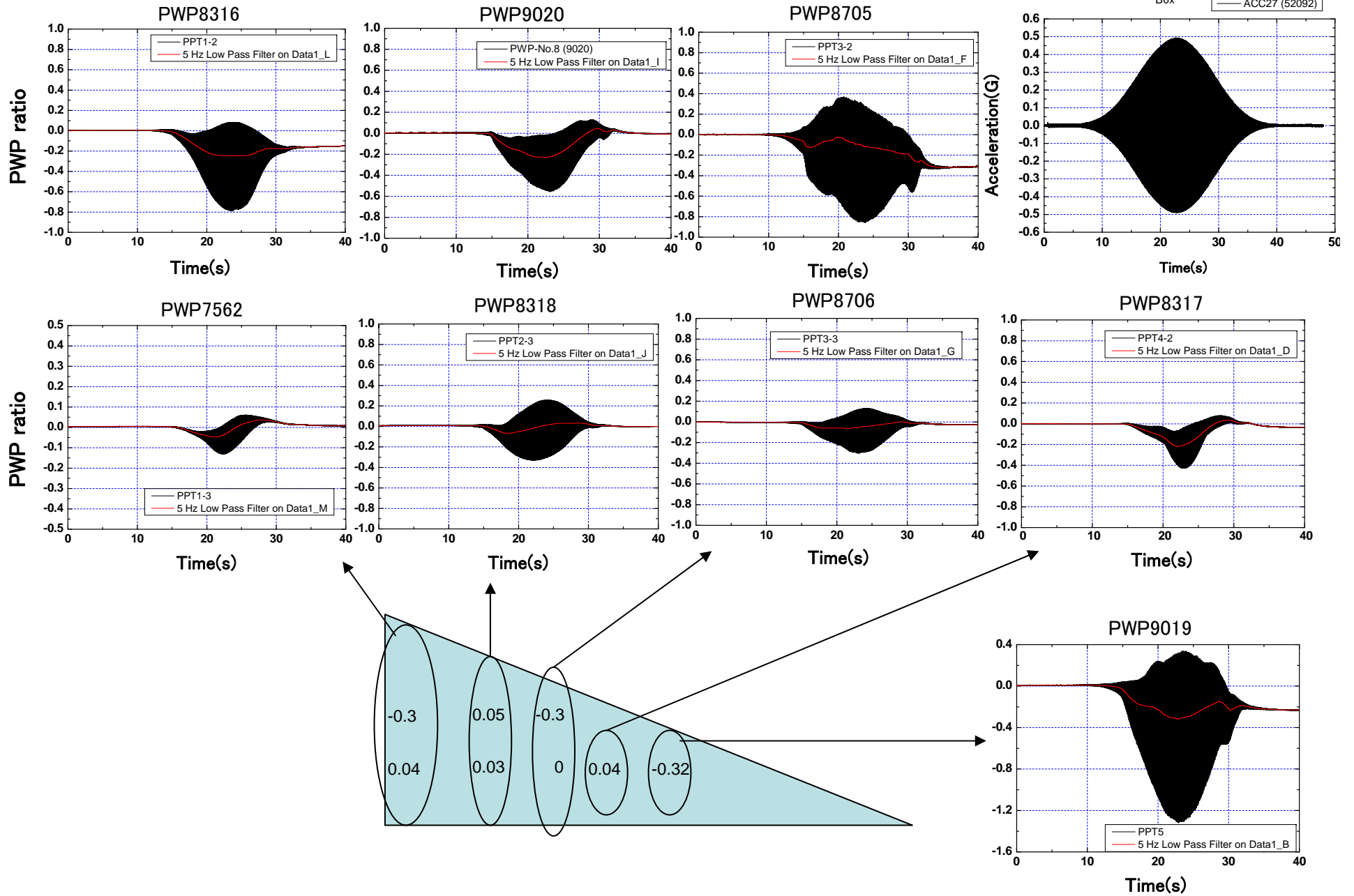
| Dam             | Earthquake                               | Dam Height (m) | Settlement (cm) | Situation after earthquake   | X value(Crest settlement /dam height) | Damage level |
|-----------------|--|----------------|-----------------|--|---------------------------------------|--------------|
| Yugawara        | Niigata Earthquake, 2004                 | 35             | 70              | Restoration was conducted after water drained out of reservoir in 1 day    | 1.9 %                                 | 3            |
| Shin Yamamoto   | Niigata Earthquake, 2004                 | 27.22          | > 50            |  | 1.8 %                                 | 3            |
| Yamamoto        | Niigata Earthquake, 2004                 | 44.5           | 50              |  | 1.1 %                                 | 3            |
| Unoki           | Nihonkai Chubu Earthquake, 1983          | 4.9            | 340             | Overflow of reservoir  | 69.4 %                                | 4            |
| Koromogawa No.1 | Off-Miyagi Earthquake,1978               | 35.5           | A little        | There was a small damage. After the investigation restoration was started. | 0-0.1 %                               | 1            |
| Koromogawa No.5 | Off-Miyagi Earthquake,1978               | 19.1           | A little        |  | 0-0.1 %                               | 1            |
| Kanyuu          | Off-Miyagi Earthquake,1978               | 27.6           | A little        |  | 0-0.1 %                               | 1            |
| Shukunosawa     | Off-Miyagi Earthquake,1978               | 26             | A little        |  | 0-0.1 %                               | 1            |
| Makio           | Nagano-ken Seibu (West) Earthquake, 1984 | 105            | 40              | The crest settled. Quick restoration was performed by filling              | 0.38 %                                | 2            |

# Categorization of Damage Levels (by Sato, J., 2007)

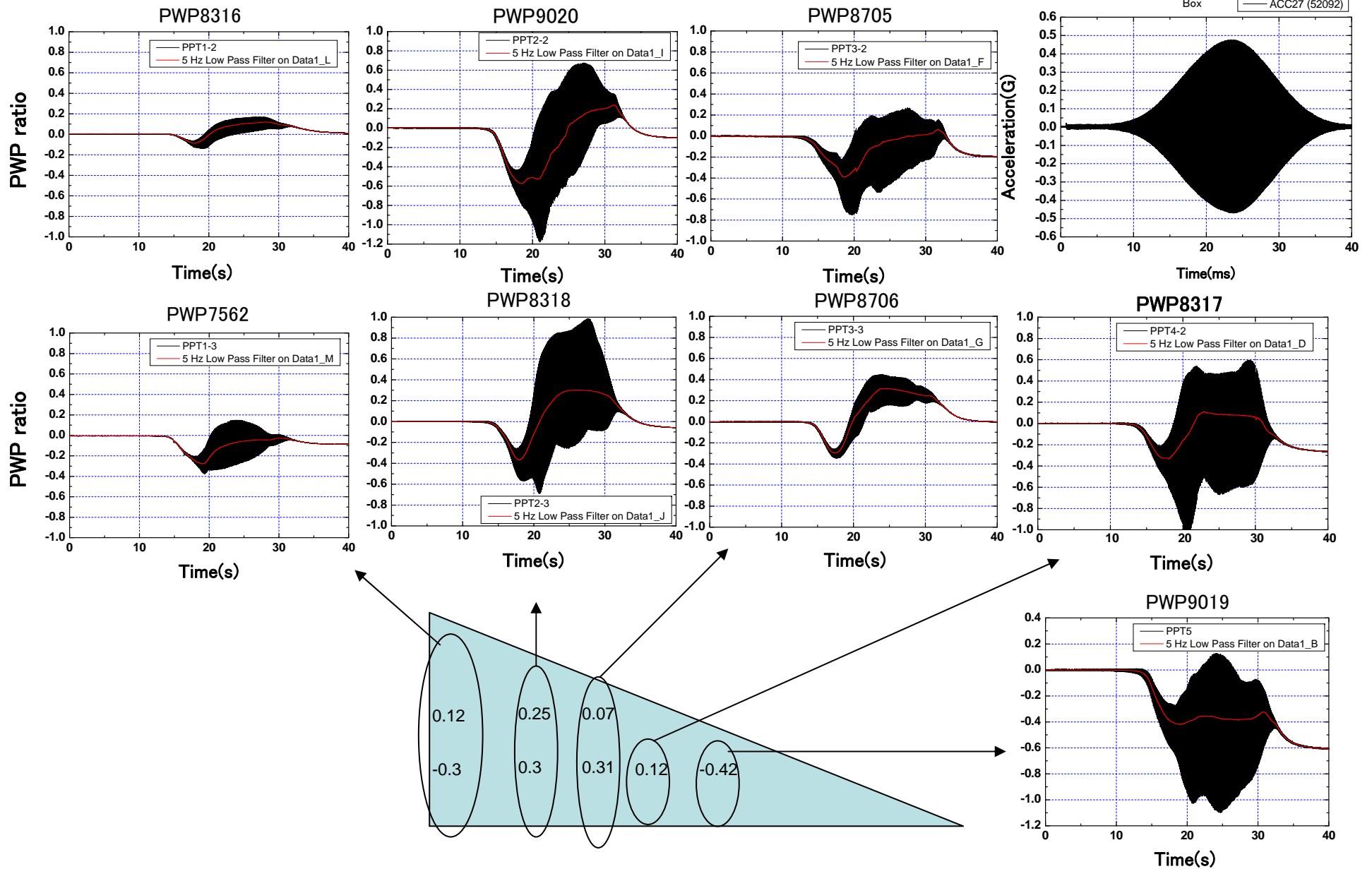
| Damage level | X value(Crest settlement /dam height) | Description  |
|--------------|---------------------------------------|--|
| 4            | $10\% < X$                            | Collapse, High damage                                    |
| 3            | $1\% < X \leq 10\%$                   | Unable to serve, need to be repaired as soon as possible |
| 2            | $0.1\% < X \leq 1\%$                  | Can serve with minimum performance, need to be repaired  |
| 1            | $0\% < X \leq 0.1\%$                  | Minor damage, need to be repaired                        |
| 0            | 0%                                    | No damage  |



# Dr=70% with central core



# Dr=50% with central core



# Dr=20% with central core

