地盤シミュレーションの高度化研究

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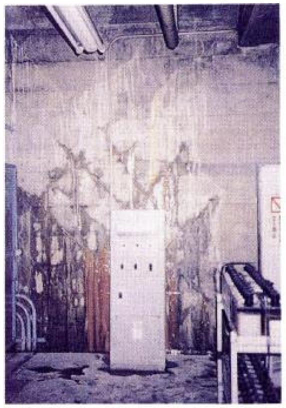

写真-3 電気室のひび割れ状況

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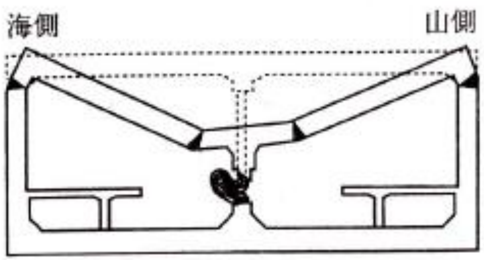


図-6 中柱(No.10)の破壊状況

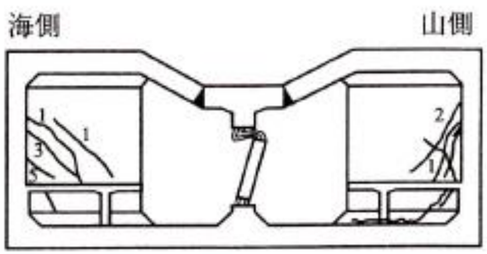


図-7 妻壁のひび割れ状況

Schematic diagram

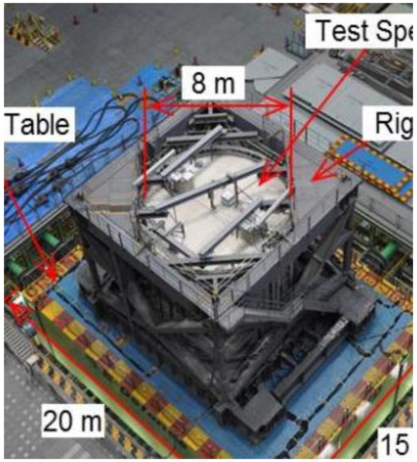
Damage to Daikai subway station during 1995 Great Hanshin Earthquake

1. Yamato *et al*, damage to Daikai subway station of Kobe rapid transit system and estimation of its reason during 1995Hyogoken-Nanbu earthquake ,土 木 学 会 論 文 集No. 537/1-35, 303-320, 1996

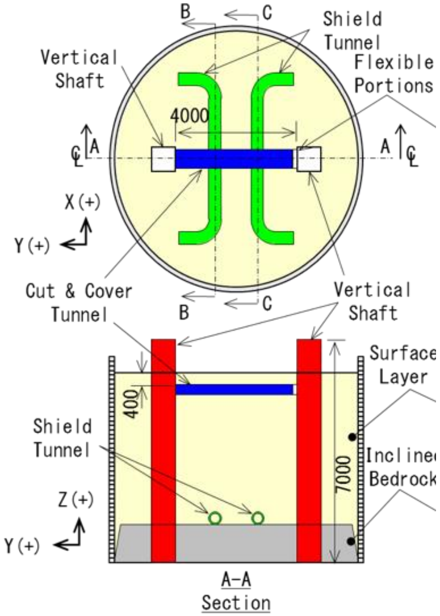
E-Defense shake table test on soil underground specimen

- About experiment:

  To comprehend a better understanding the soil-structure interaction a large-scale shake table test [2] was conducted at E-Defense in February 2012

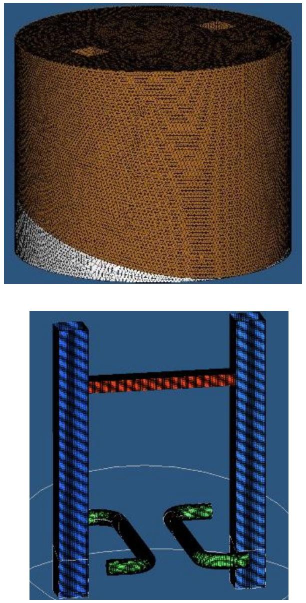


Experiment specimen



Drawing

CAD model



Analysis model

- Objectives
  - Reproduction of experimental results
  - Study of laminar soil container modeling

[2] Yohsuke K., Manabu N., Ikuo T. and Susumu Y.: Dynamic behaviour of underground structure in E-Defense shaking experiment, *Soil Dyn. And Earth. Engrg.*, 82, pp. 24-39, 2016.

これまでの成果

3.1 Generation of analysis model

3.2 Elasto-plastic analysis

3.3 Incorporation of soil container mass in analysis model

Material properties

Mechanical properties

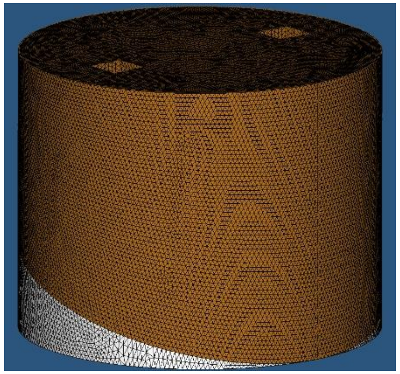
	Density (g/cm^3)	Young's modulus (MPa)	Poison's ratio
Aluminum	2.70	69.0×10^3	0.34
Acrylic Plastic	1.19	3200	0.35
Dry Sand 1	1.735	1	0.3
Dry Sand 2	1.614	12.85	
Cement mixed soil 1	2.245	1.0×10^4	0.3
Cement mixed soil 2	2.245	88.48	0.3

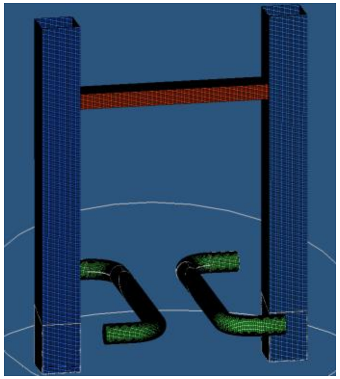
Cases considered for analysis

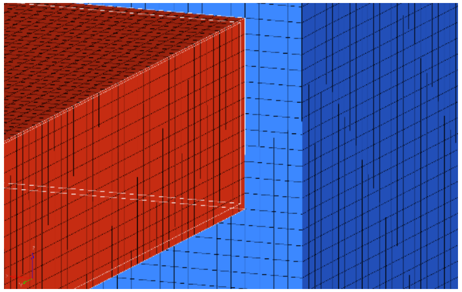
	Vertical shaft and cut-and-cover tunnel	Shield tunnel	Lower layer of soil strata	Upper layer of soil-strata	Remark
Case 1	Aluminum	Alumunium	Cement mixed soil 1	Dry Sand 1	Before experiment
Case 2	Aluminum	Acrylic Plastic	Cement mixed soil 2	Dry Sand 2	After experiment

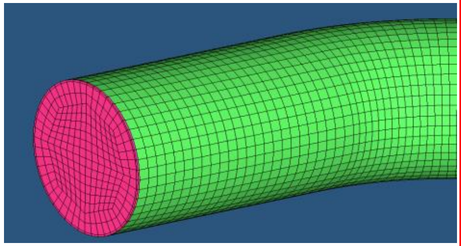
Analysis models

Non-Conformity mesh model



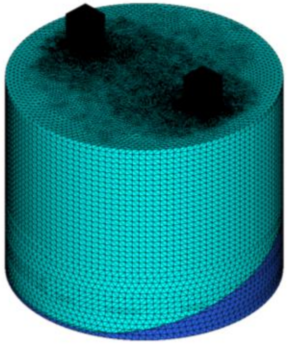


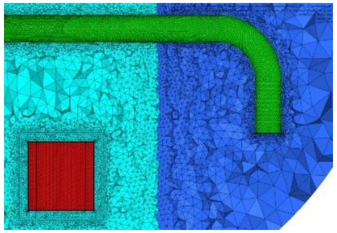


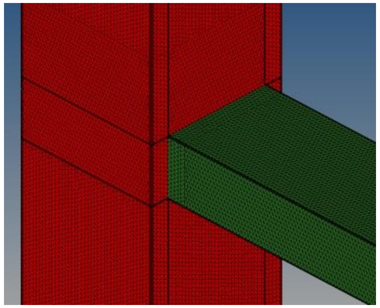


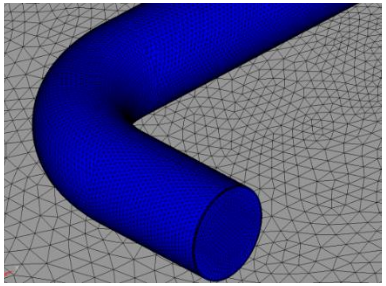
Structural component: Hexahedral element
Soil : Tetrahedral element
Interface: using Multi-Point Constraints (MPC)

Conformity mesh model









Structural component: Tetrahedral element
Soil : Tetrahedral element
Interface: adaptive mesh refinement

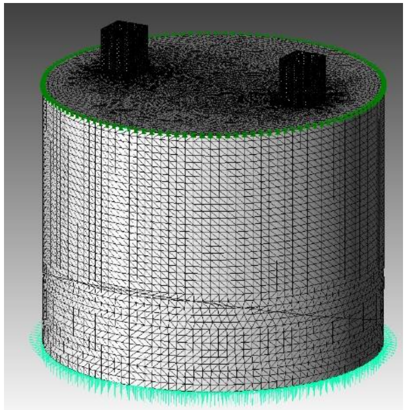
Analysis Model

Scale of analysis

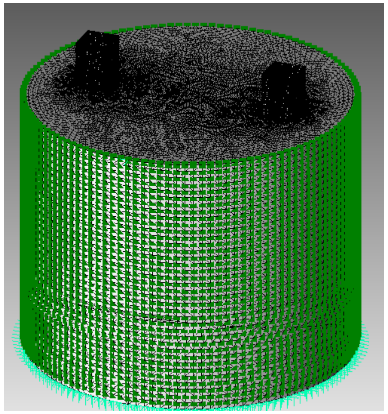
Mesh model	Elements	Nodes	Dofs
Non-conformity	1,539,094	520,959	1,562,877
Conformity	9,863,072	5,312,922	15,938,766

Computational demand*

Mesh model	Average Computation time for each time step (min.)	Average number of CG iterations per time step
Non-conformity	64.00	13255
Conformity	1.63	1314



MPC on top model



Full MPC model

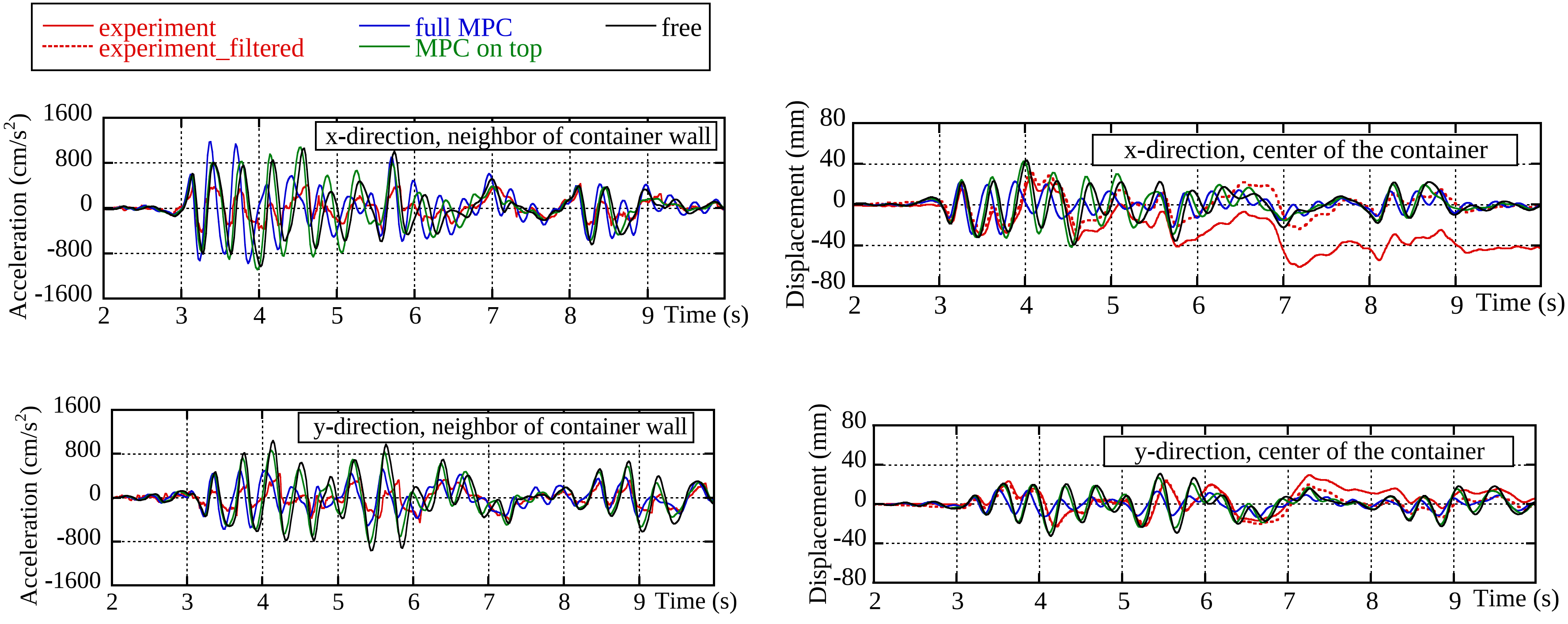
Modeling laminar soil container

Eigen value analysis

Model	1st Mode	2nd Mode	3rd Mode	4th Mode
Free	2.482	2.641	3.193	5.101
MPC on top	2.684	2.766	4.560	5.470
Full MPC	3.273	3.275	6.455	8.627
Experiment	5.27-5.56			

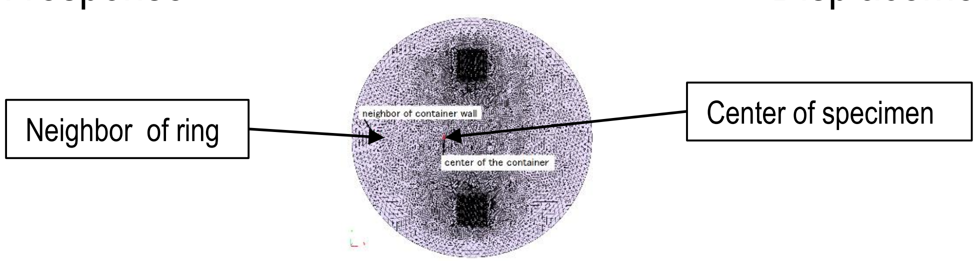
*The analysis is completed on Supercomputer of NIED by using flat MPI. Analysis is performed using 128 cores of SGI Altix4700 (CPU: dual core Intel Itanium processor 1.66 GHz).

Time history against 50% JR Takatori



Acceleration response

Displacement response



MPC on top has relatively better agreement with experimental results in compare with other two models namely, Free model and Full MPC model. Therefore, MPC on Top model has been chosen as appropriate analysis model.

Exponential Contractancy (EC) model

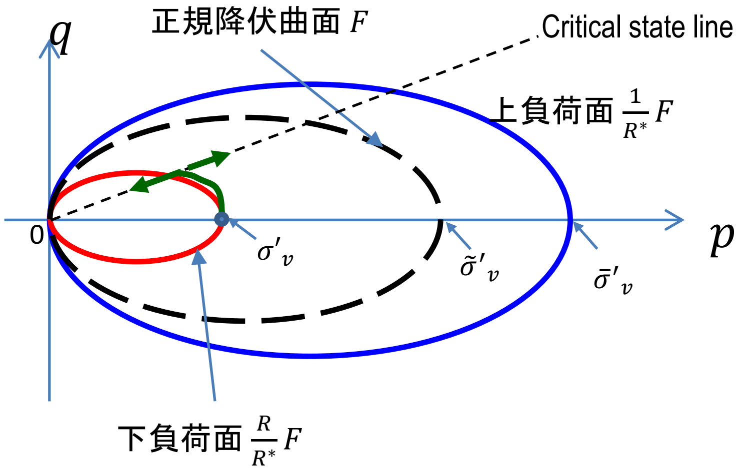
- **Normal yield surface**

$$F = MD \ln\left(\frac{p'}{p_0{}'}\right) + \frac{MD}{\eta_E}\left(\frac{\eta^*}{M}\right)^{\eta_E}$$

Where, M is critical state parameter, D is dilatancy factor, η_E is parameter controlling the shape of yield surface.

$$\eta^* = \sqrt{3/2}\,||(1/p)\boldsymbol{s} - (1/p_0)\boldsymbol{s_0}||$$

Where, p and $\boldsymbol{s}$ are the hydrostatic pressure and deviatoric stress tensor, respectively.



$$OCR = \frac{\bar{\sigma}'_v}{\sigma'_v}$$

$$R = \frac{\sigma'_v}{\bar{\sigma}'_v},\ R^* = \frac{\tilde{\sigma}'_v}{\bar{\sigma}'_v}$$

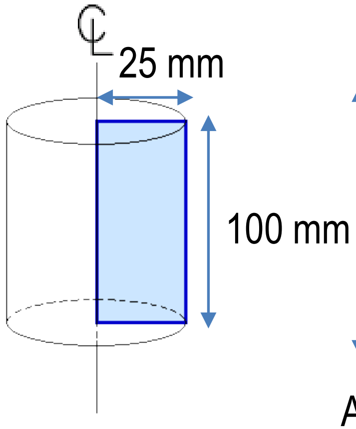
$$\frac{R^*}{R} = \frac{\frac{\tilde{\sigma}'_v}{\bar{\sigma}'_v}}{\frac{\sigma'_v}{\bar{\sigma}'_v}} = \frac{\tilde{\sigma}'_v}{\sigma'_v}$$

The sub-loading surface shall satisfy the following conditions

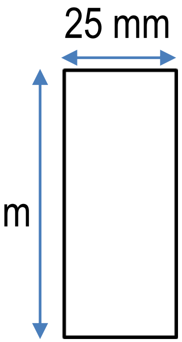
- Sub-loading surface is in similar shape as the normal yield surface.
- The current stress-point is always on sub-loading surface.
- Along with expansion of sub-loading surface, the normal yield surface also expands and thereby plastic deformation occurs.
- $R = 1$: the sub-loading surface coincides with normal yield surface

[3] Ohno, S., Iizuka, A. and Ohta H..: Two categories of constitutive model derived from non-linear description of soil contractancy, J of AM (JSCE), 9, pp. 407-414, 2006

Parameter identification



Experiment specimen

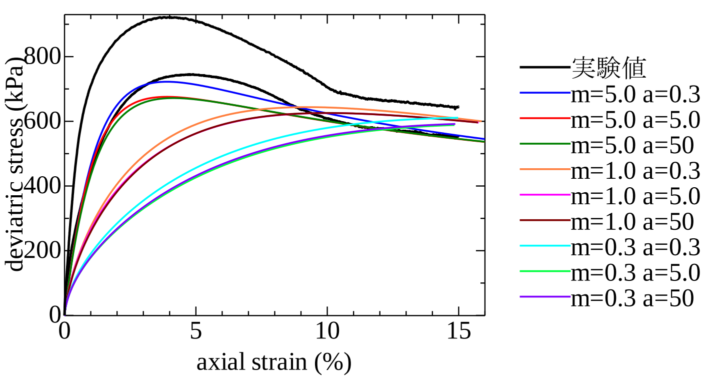


Analysis model

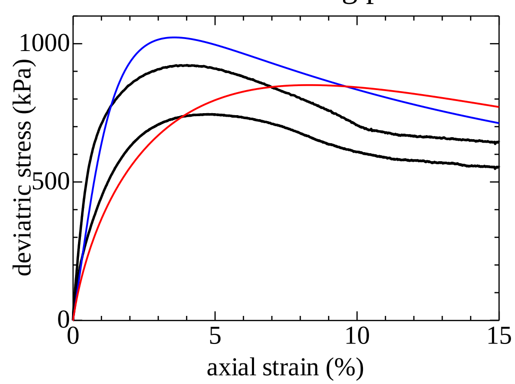
テストNo.	ρ(g/cm^3)	w(%)	e	S_r(%)	D_r(%)	B値
002	1.99	23.22	0.64	96.15	53.45	0.84
003	1.94	16.89	0.60	74.59	67.88	0.86
004	1.96	16.92	0.58	77.28	74.99	0.82
005	1.95	16.75	0.59	74.89	70.46	0.84
006	1.95	16.44	0.59	74.61	73.71	0.82

テストNo.	試験装置	排水条件	拘束圧
002	スマート三軸試験	排水	157kPa
003	スマート三軸試験	排水	200kPa
004	従来の三軸試験	排水	50kPa
005	従来の三軸試験	排水	100kPa
006	従来の三軸試験	排水	200kPa

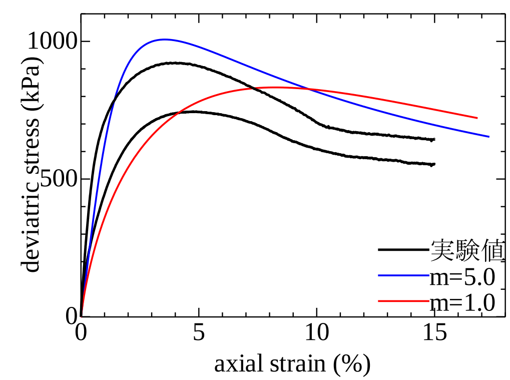
Yield stress is fixed



Yield stress is fitting parameter



OCR=10 is fitting parameter



OCR=10,拘束圧200kPa

スマート三軸試験装置（Nakayama,E., Kobayashi,I, Iizuka,A. and Ohta,H.: Chapter 22 Development of a Portable Triaxial Testing Apparatus-Smart Triaxial, Geotechnical Predictions and Practice in Dealing with Geohazards, Chu, Jian, Wardani, Sri P.R., Iizuka, Atsushi (Eds.), Geotechnical, Geological and Earthquake Engineering Series, ,Vol. 25, Springer, 2013

Material parameters

Elasto-plastic parameters		
S.No.	Parameter name	Value
1	Dilatancy (D)	0.065
2	Critical stress ratio (M)	1.41
3	Irreversible ratio Λ	0.973
4	Over-consolidation ratio (OCR)	10
5	Yield surface shape parameter η_E	1.5

Initial conditions		
S.No.	Parameter name	Value
1	Initial void ratio e_0	0.585
2	Swelling index κ_0	0.042
3	Coefficient of earth pressure K_i	1.0
4	Normal Yield stress $\tilde{\sigma}'_v$(kPa)	180
5	Initial vertical stress σ'_v(kPa)	20

Evolution parameter		
S.No.	Parameter name	Value
1	Sub-loading surface parameter (m_a)	5.0
2	Super-loading surface parameter $(a = m_a/D)$	76.92
3	Super-loading parameter (b, c)	1.0
4	Similarity ratio for sub-loading $(R_0 = 1/OCR)$	0.1
5	Similarity ratio for super-loading (R^*)	0.9

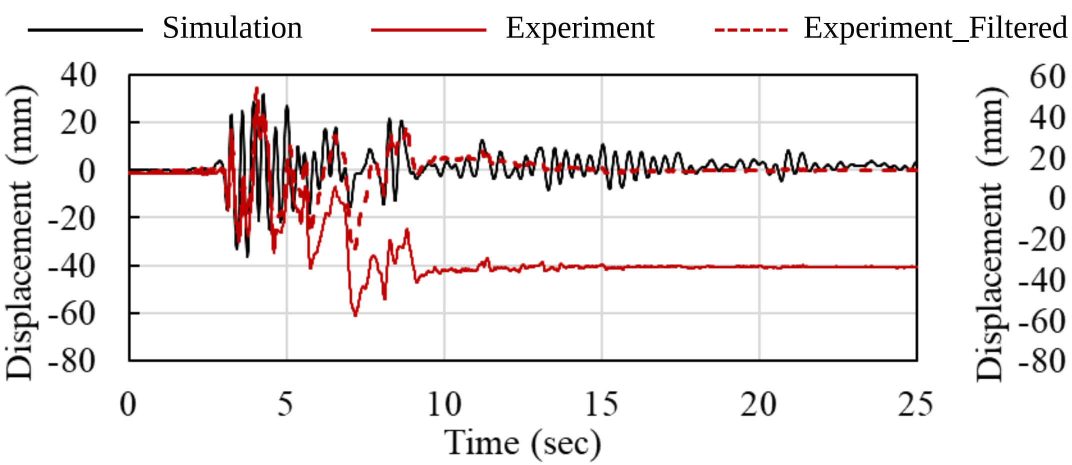
$$OCR = \frac{\bar{\sigma}'_v}{\sigma'_v}$$

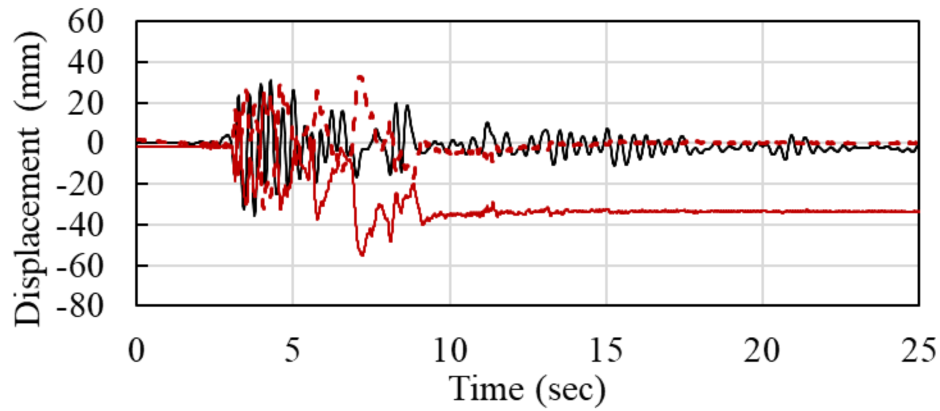
$$R = \frac{\sigma'_v}{\tilde{\sigma}'_v},\ R^* = \frac{\tilde{\sigma}'_v}{\bar{\sigma}'_v}$$

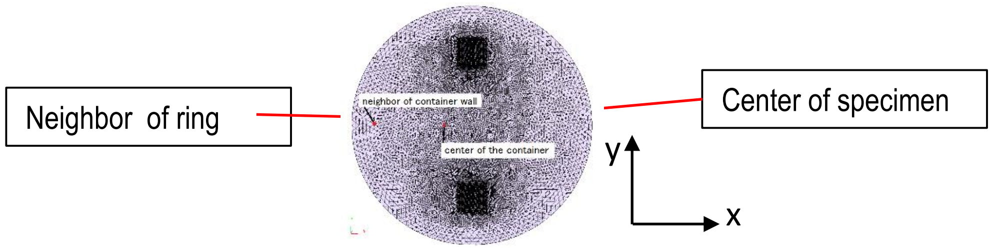
$$\frac{R^*}{R} = \frac{\frac{\tilde{\sigma}'_v}{\bar{\sigma}'_v}}{\frac{\sigma'_v}{\bar{\sigma}'_v}} = \frac{\tilde{\sigma}'_v}{\sigma'_v}$$

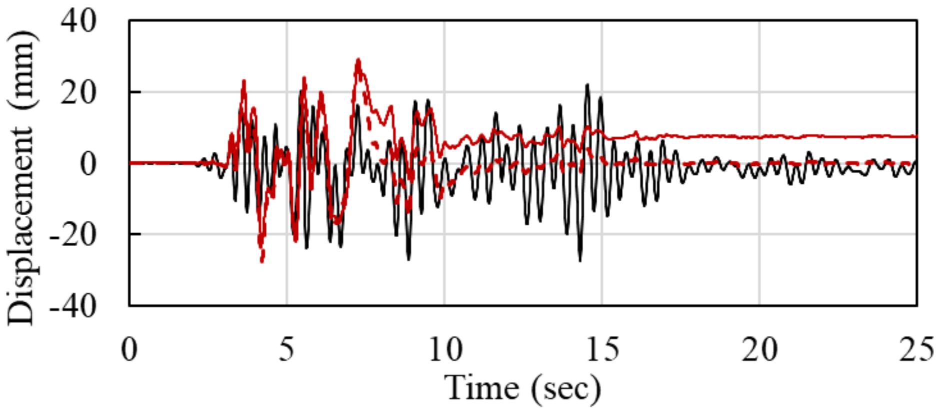
Here, σ'_v, $\tilde{\sigma}'_v$ and $\bar{\sigma}'_v$ are the stress on sub-loading, normal yield surface, and super-loading surface.

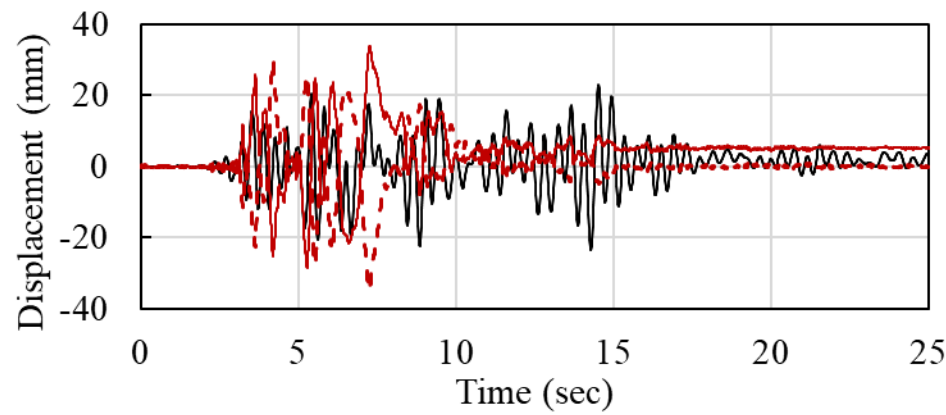
Displacement time history on top surface











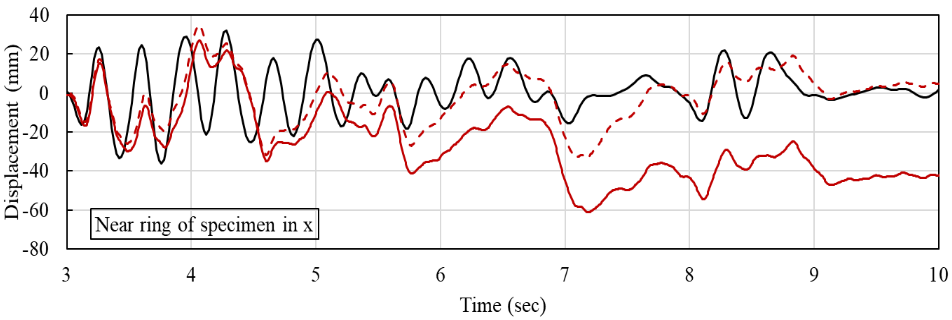
Neighbor of ring

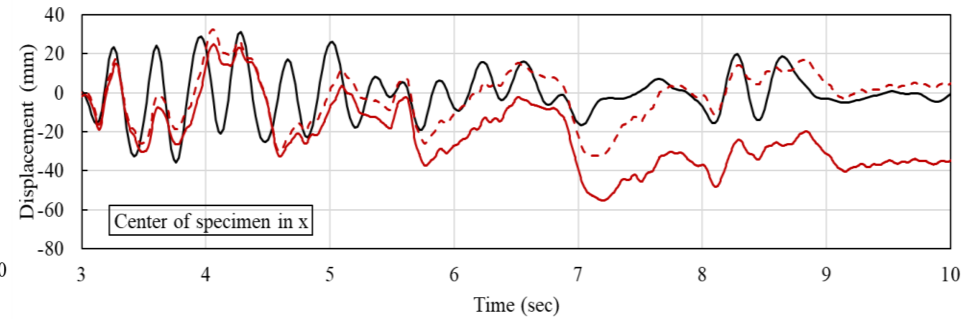
Center of specimen

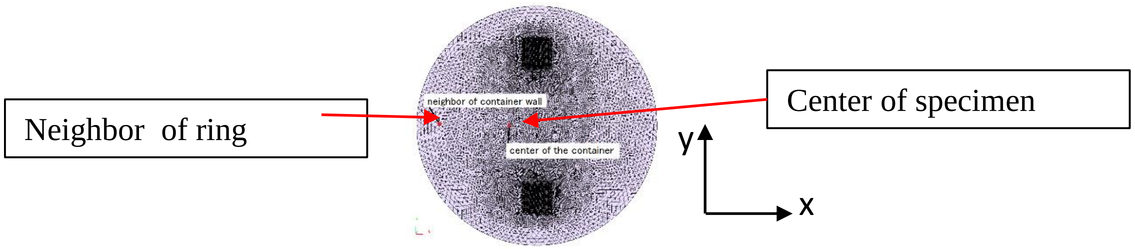
Displacement response

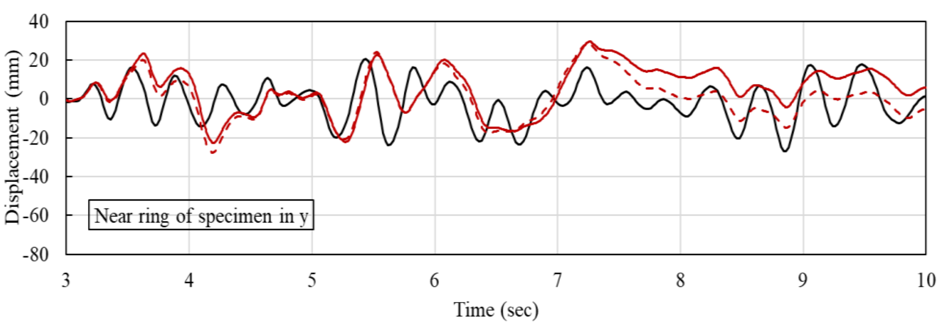
Displacement time history on top surface

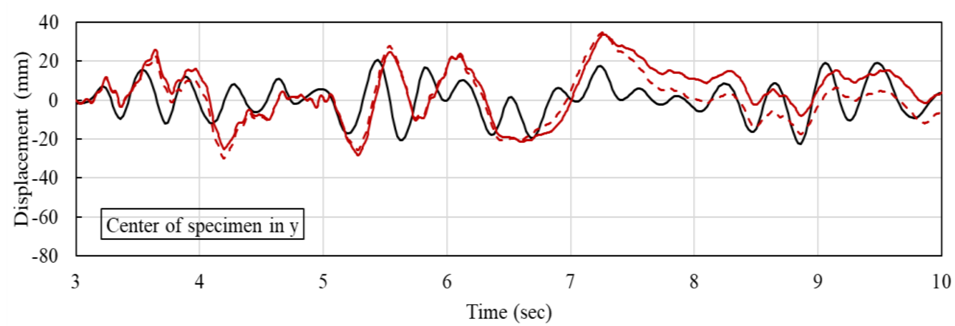
Simulation — Experiment - - - - - Experiment_Filtered









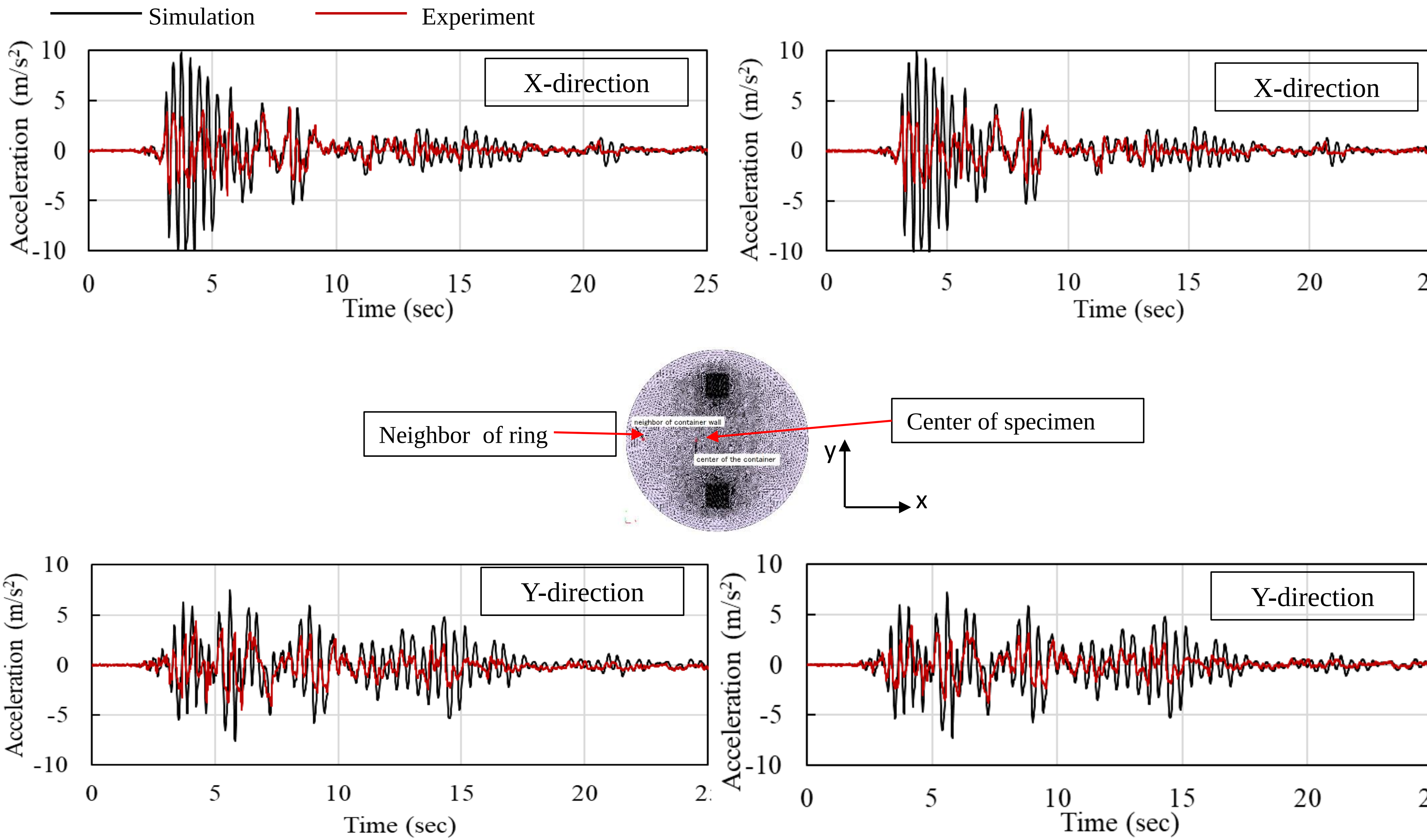


Neighbor of ring

Center of specimen

Displacement response

Acceleration time history on top surface

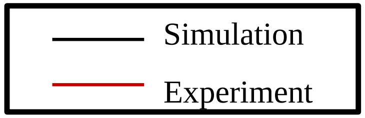


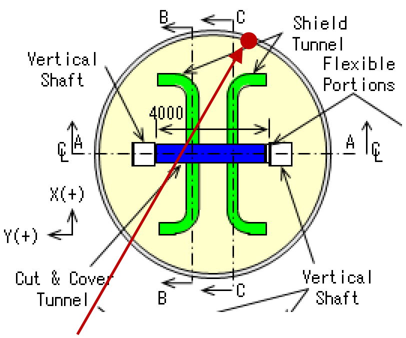
Neighbor of ring

Center of specimen

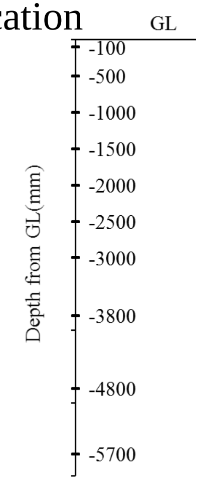
Acceleration response

Displacement time history

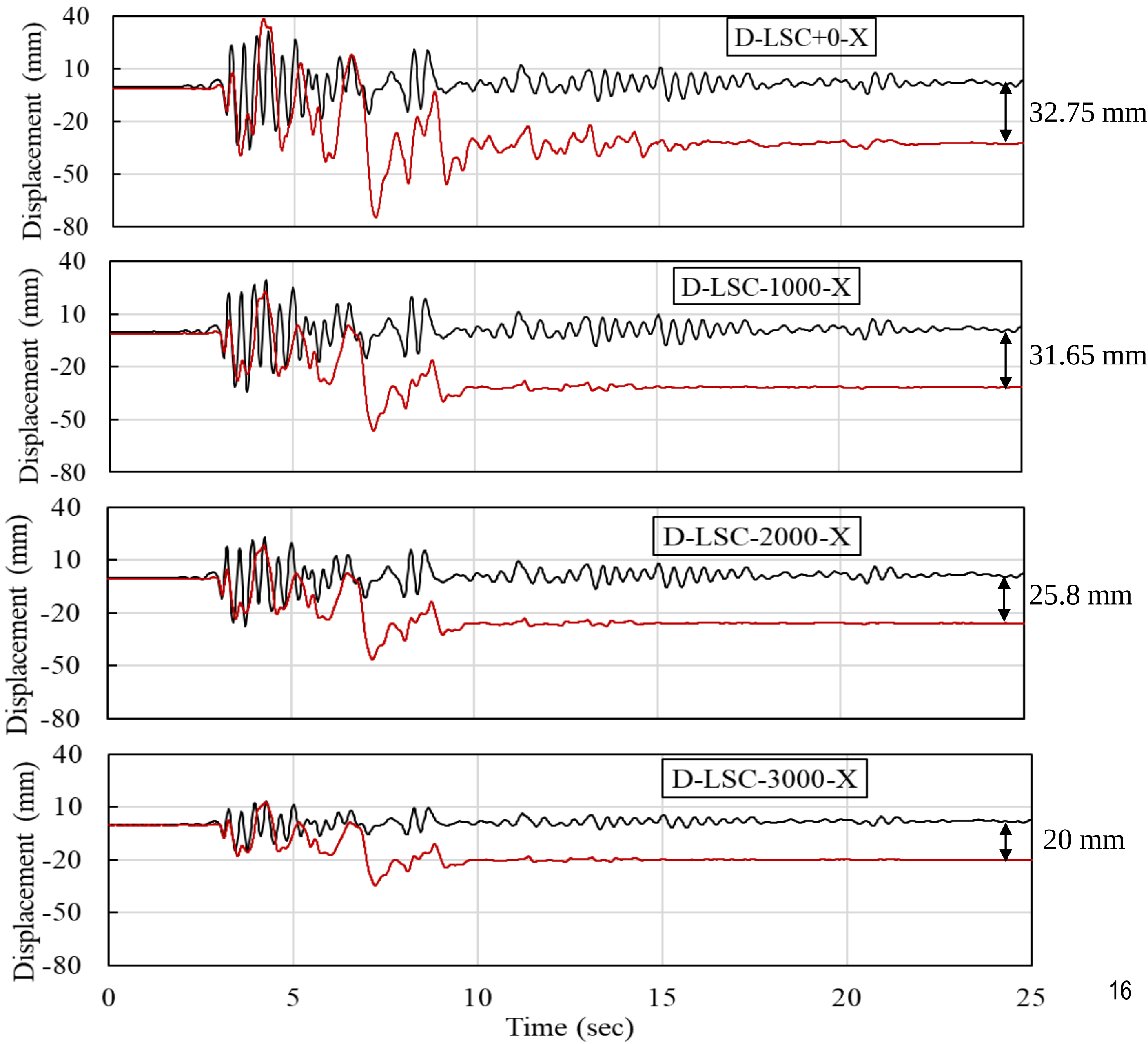




Location



Location of Disp. sensor



Laminar soil container modeling

<table>
<tr><th>S. No</th><th>Items</th><th colspan="2">Position</th><th>Weight (ton)</th><th colspan="2">No of rings</th><th colspan="2">Weight (ton)</th><th>Total</th></tr>
<tr><td rowspan="4">1</td><td rowspan="4">Laminar rings</td><td colspan="2">Top</td><td>3.1</td><td colspan="2">1</td><td colspan="2">3.1</td><td rowspan="3"></td></tr>
<tr><td rowspan="2">Middle</td><td>Upper</td><td>0.9</td><td>19</td><td rowspan="2">38</td><td>17.1</td><td rowspan="2">36.1</td></tr>
<tr><td>Lower</td><td>1.0</td><td>19</td><td>19</td></tr>
<tr><td colspan="2">Bottom</td><td>2.5</td><td colspan="2">1</td><td colspan="2">2.5</td><td>41.7</td></tr>
<tr><td rowspan="3">2</td><td rowspan="3">Slider</td><td colspan="2">SA</td><td rowspan="3"></td><td colspan="2" rowspan="3"></td><td colspan="2">0.159</td><td rowspan="2"></td></tr>
<tr><td colspan="2">SB</td><td colspan="2">0.058</td></tr>
<tr><td colspan="2">SC</td><td colspan="2">1.076</td><td>1.3</td></tr>
<tr><td rowspan="2">3</td><td rowspan="2">Rubber</td><td colspan="2">Water resistance</td><td rowspan="2"></td><td colspan="2" rowspan="2"></td><td colspan="2">0.50</td><td></td></tr>
<tr><td colspan="2">Slippage</td><td colspan="2">0.25</td><td>0.75</td></tr>
<tr><td colspan="9">Total weight (1+2+3):</td><td>43.7</td></tr>
</table>

S. No	Position	Weight/ring (ton)	No of rings	Weight (ton)	Total (ton)
1	Top	3.1+0.055	1	3.155	
2	Middle	1.03+0.055	35	37.975	
3	Bottom	2.5+0.055	1	2.555	43.69

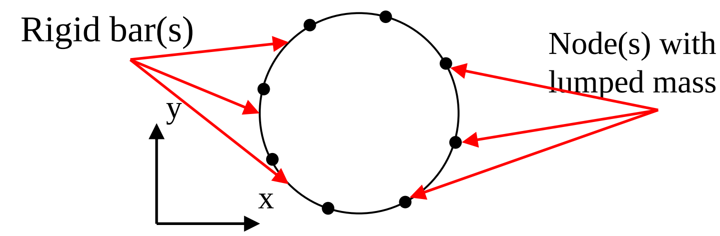
Note: Additional weight of rubbers and slider is equally distributed to all laminar rings. The value of contribution is equal to (2.05/37)=0.055

Constrained condition (拘束条件)

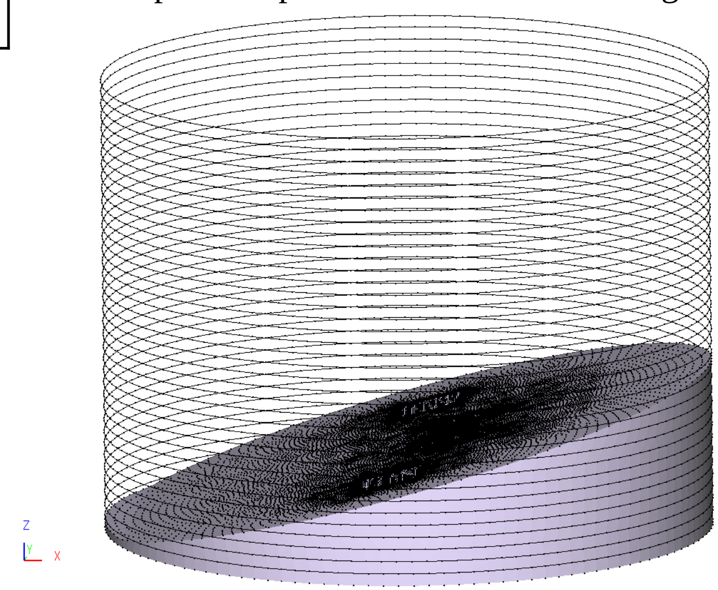
$$\boldsymbol{r}_1^t - \boldsymbol{r}_0^t - \boldsymbol{R}(\theta_0^t).(\boldsymbol{r}_1^0 - \boldsymbol{r}_0^0) = 0$$
$$\boldsymbol{\theta}_1^t - \boldsymbol{\theta}_0^t = 0$$

Here, $\boldsymbol{r}_i^t$, θ_i^t are position and rotation vector of i^{th} node at t^{th} time step, respectively.

$R(\theta)$ is rotation tensor corresponding to rotation vector θ

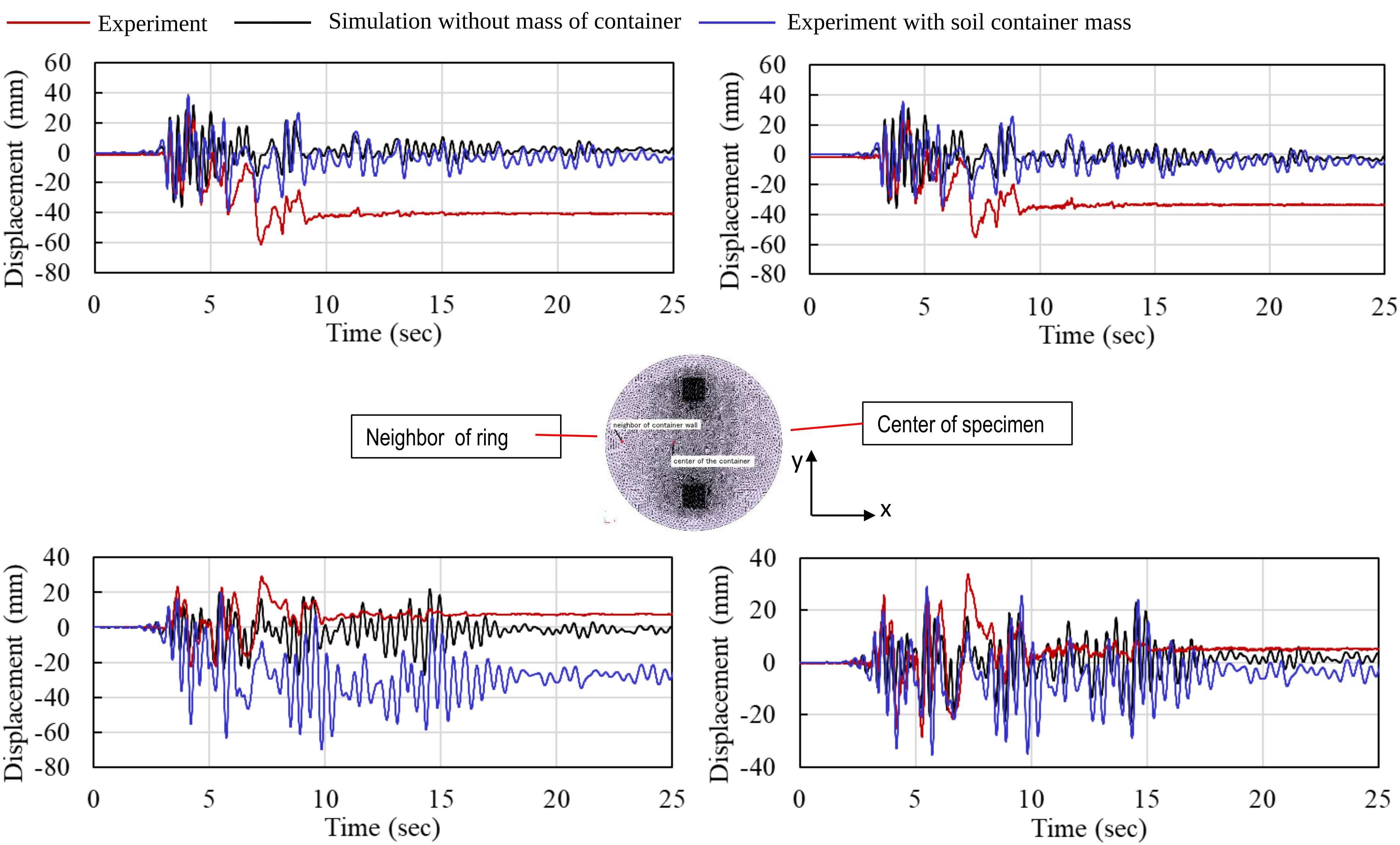


Graphical representation of laminar ring modeling



Laminar rings with lumped mass at nodes

Displacement time history on top surface

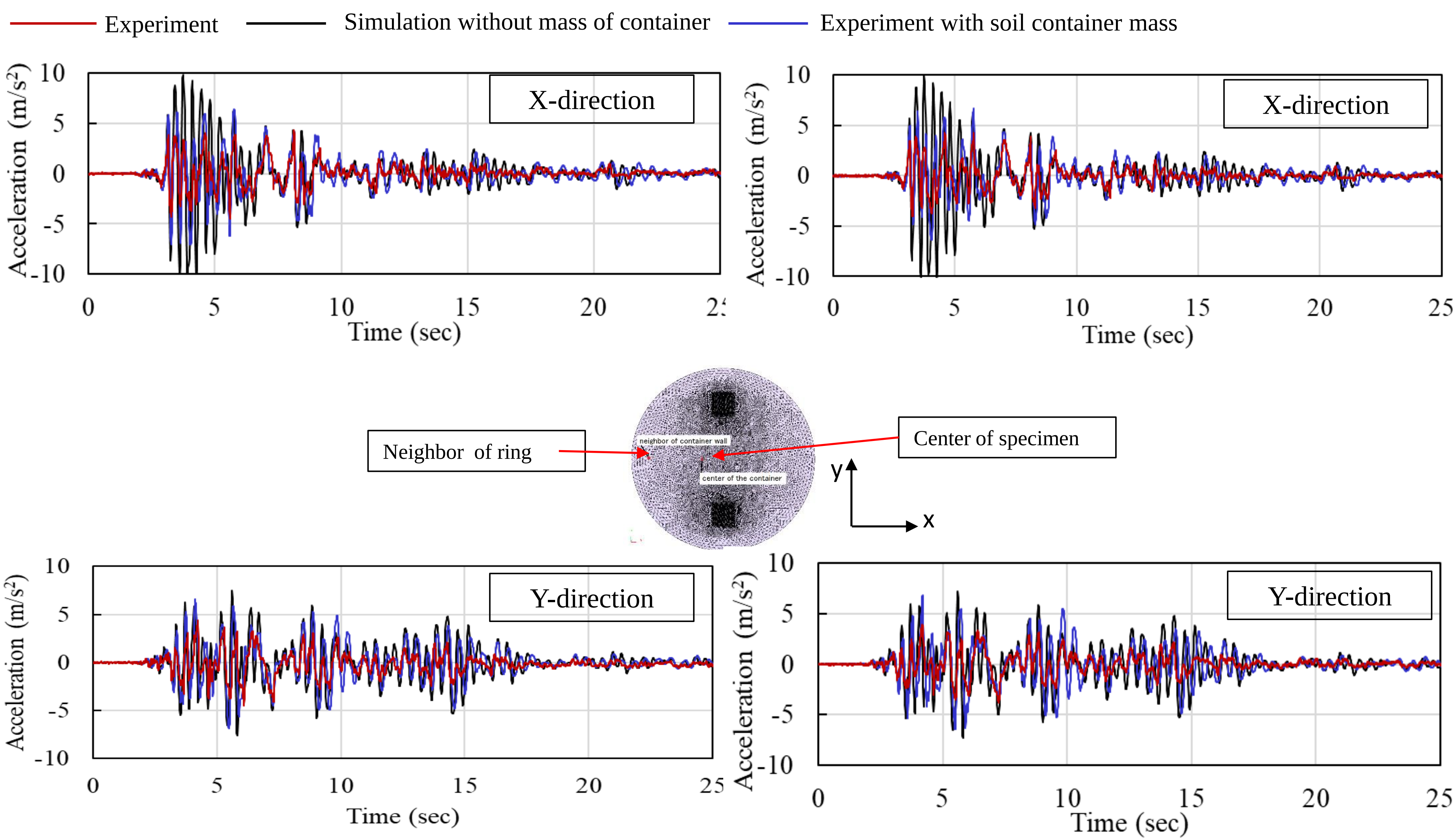


Neighbor of ring

Center of specimen

Displacement response

Acceleration time history on top surface

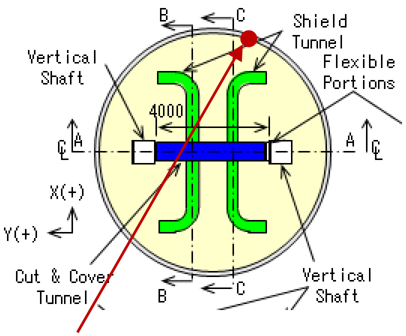


Neighbor of ring

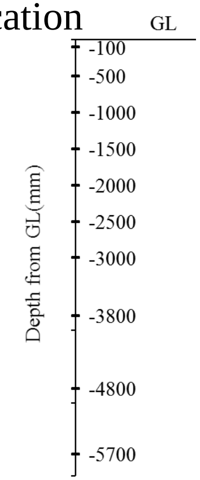
Center of specimen

Acceleration response

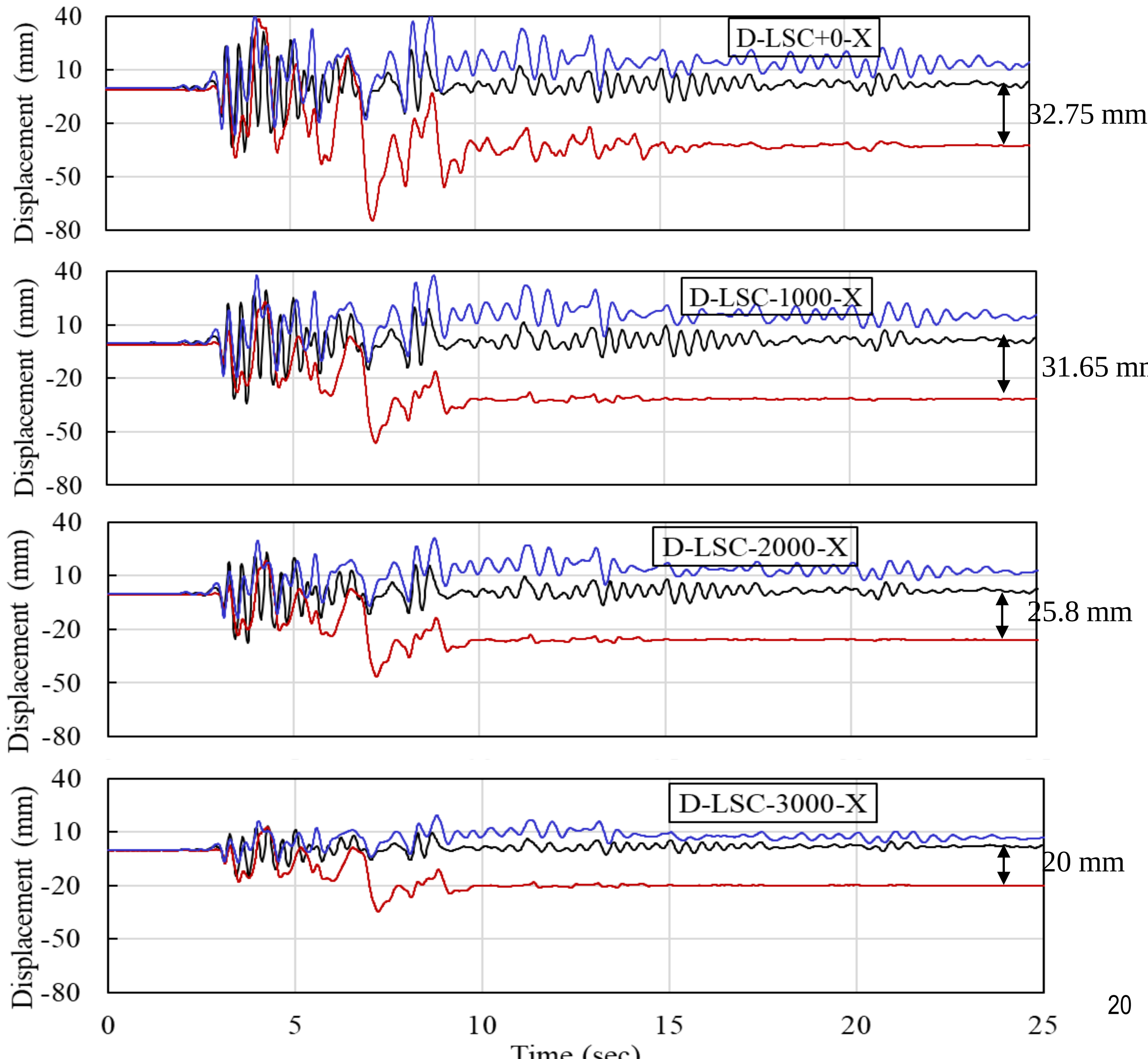
Displacement time history



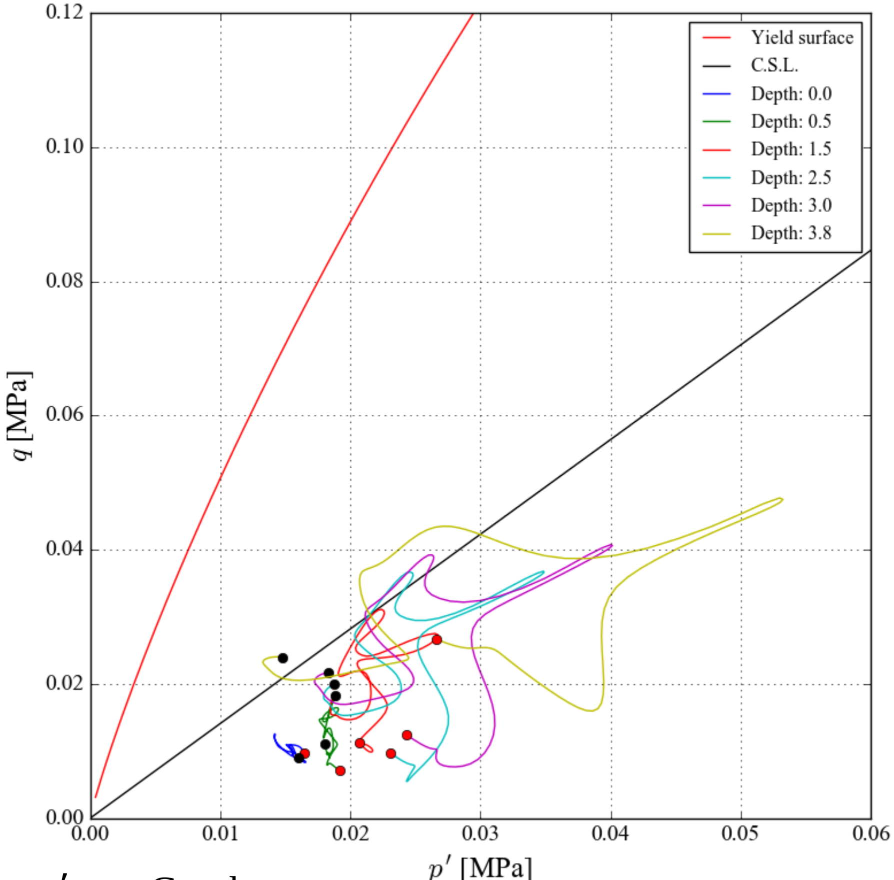
Location



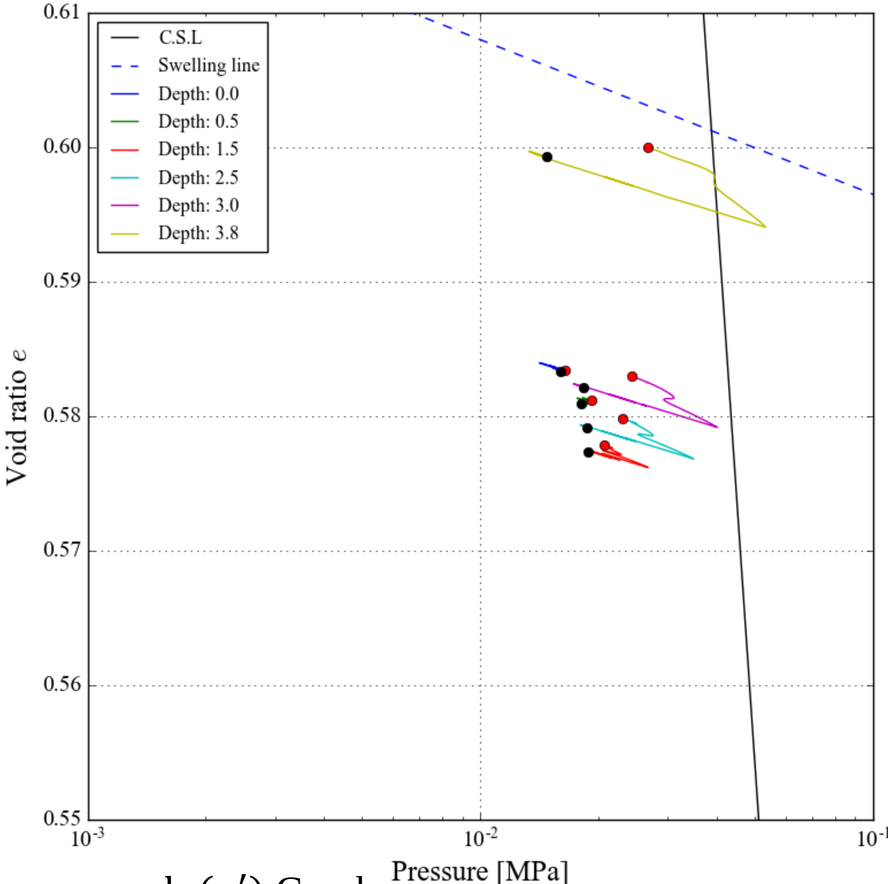
Location of Disp. sensor



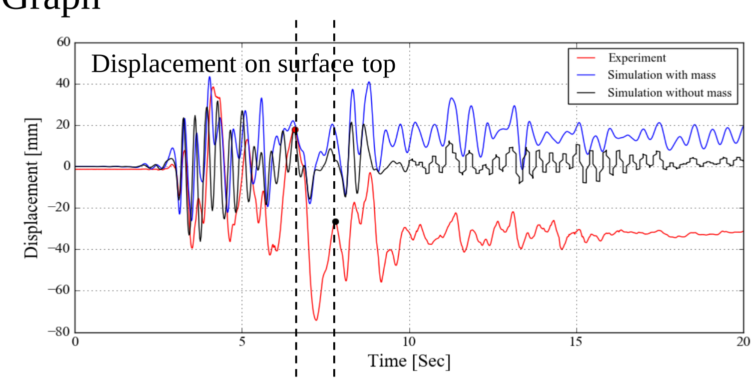
Effective Stress path

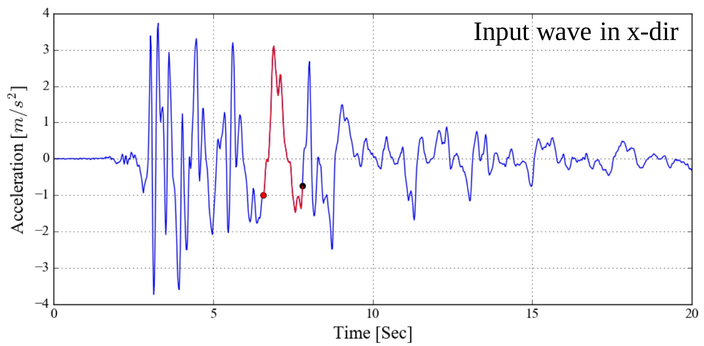


$p' - q$ Graph



$e - \ln(p')$ Graph





今後の構想

Summary and future work

- Acceleration time history results have good agreement with experimental results
- Except the residual deformation, displacement time history results also show reasonable agreement with experimental results.
- Incorporation of mass of laminar soil container may be essential to reproduce the residual deformation.
- Effective stress-path and e-ln(p) graph suggest that
  - Soil in the vicinity of soil-strata interface is failing
  - Plasticity is inadequately modeled
- Re-simulation by lowering the value of OCR is planned for next work in the to-do list with an aim to increase the plasticity

Thank you for listening