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and of probabilistic assessment seismic hazard in Europe
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JDEC

Session : 4 Qualification of seismic analysis of embankment dams

# Application of non-linear constitutive models to three-dimensional simulation analysis of Aratozawa Dam

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# SUMMARY

1. **Non-linear constitutive models**
2. **Laboratory simulation test**
3. **Analysis Model & Input Earthquake Motions**
4. **Simulation analysis of Aratozawa Dam**
5. **Conclusions**

# Analysis Code

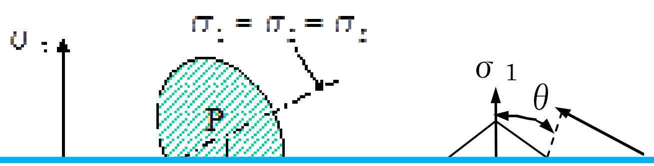
- MuDIAN

  **Mu**ltiphase **D**ynamic **I**nteraction **A**nalysis

- MuDIAN is based on the effective stress analysis code DIANA-J (Zienkiewicz, 1990).
  - Variety of non-linear constitutive models
  - Parallel computation algorithm
  - Conducted seismic analysis of fill dams using both effective stress analysis and a total stress analysis

# Three Non-linear Constitutive Models

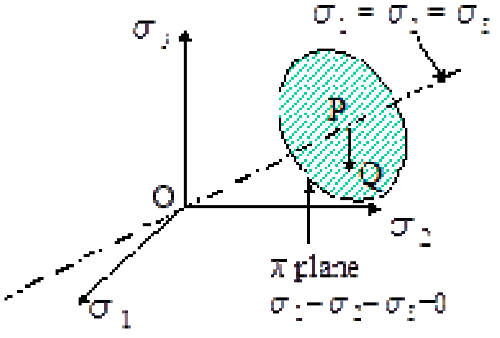
$$\sigma_m = \frac{1}{3}\sigma_{ii} \qquad \bar{\sigma} = \left\{\frac{1}{2} S_{ij}\, S_{ij}\right\}^{1/2}$$

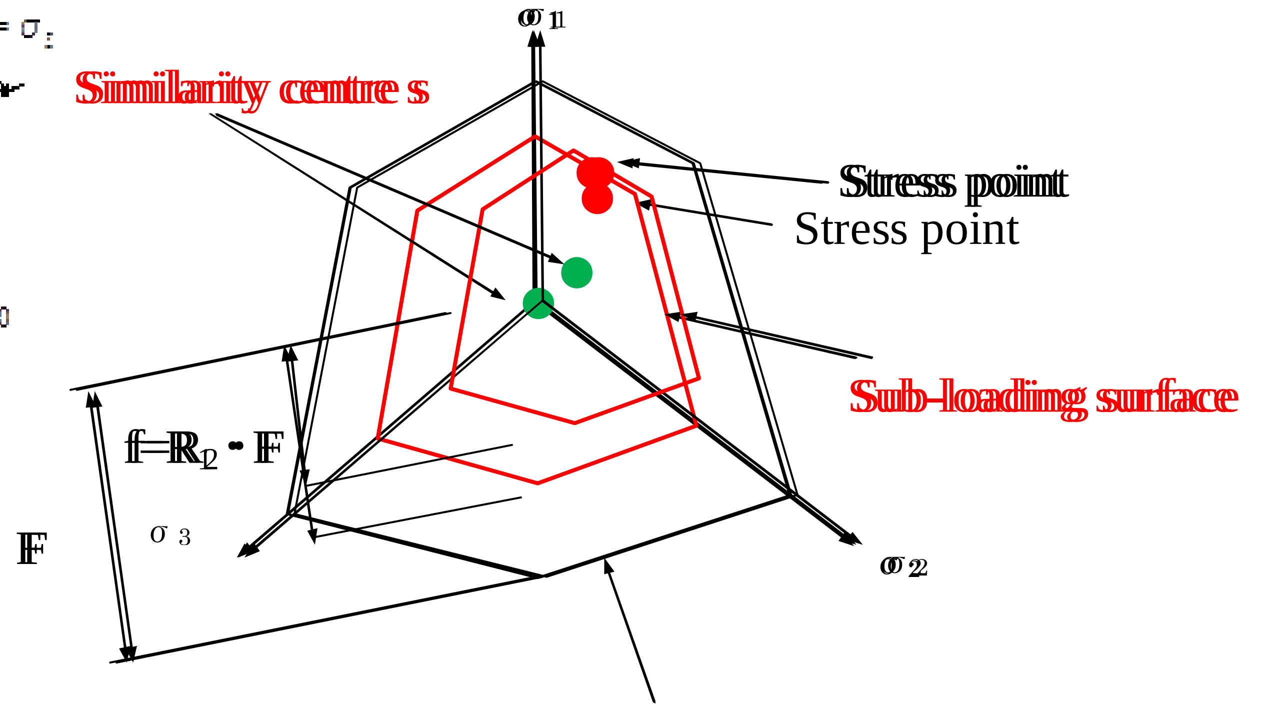


- **PL model shows elastic behavior within the yield surface.**
- **PL model shows plastic behavior when the stress point reaches the Mohr Coulomb yield surface.**

| | PL model | SL model | MH model |
|---|---|---|---|
| Yield surface | Mohr- Coulomb | Mohr- Coulomb | Mohr- Coulomb |
| Within yield surface | Elastic shear strain | Plastic shear strain<br>Sub-loading Surface | Plastic shear strain<br>Skeleton curve |
| Parameters | Cohesion C<br>Friction angle φ | C, φ<br>u, c | C, φ<br>Dynamic properties |

# SL Model (Sub-Loading surface model)





$$f = R \cdot F$$

$$\dot{R} = U(R) \cdot \left\| d\varepsilon_s^p \right\|$$

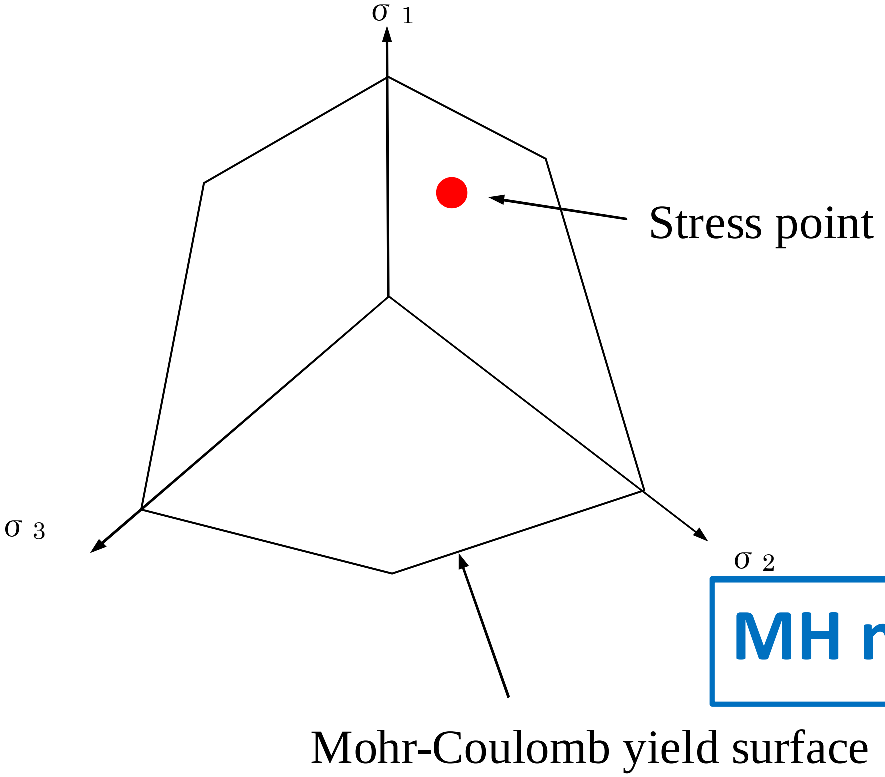
$$U = -u \cdot \ln R$$

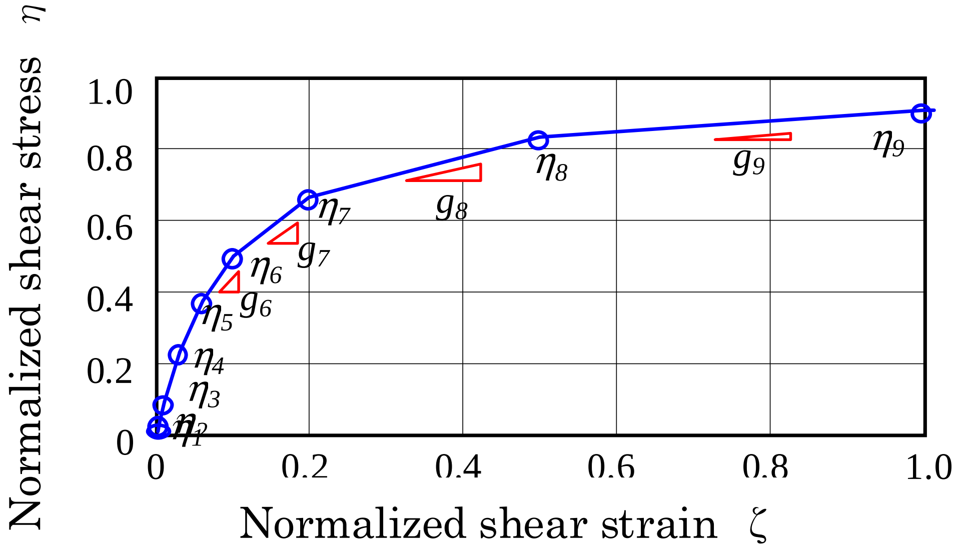
Similarity center : moving

$$ds = c \left\| d\varepsilon_s^p \right\|$$

**In accordance with the movement of the similarity center, the SL model can calculate the plastic shear strain under un-loading.**

# MH Model (Multi Hardening model)





**MH model adopts a skeleton curve.**

**The amount of damping determined by Masing’s rule corresponds to the relationship between damping h and shear strain $\gamma$, which is obtained through dynamic property testing.**

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# Hollow Torsional Test (Sagurigawa Dam)

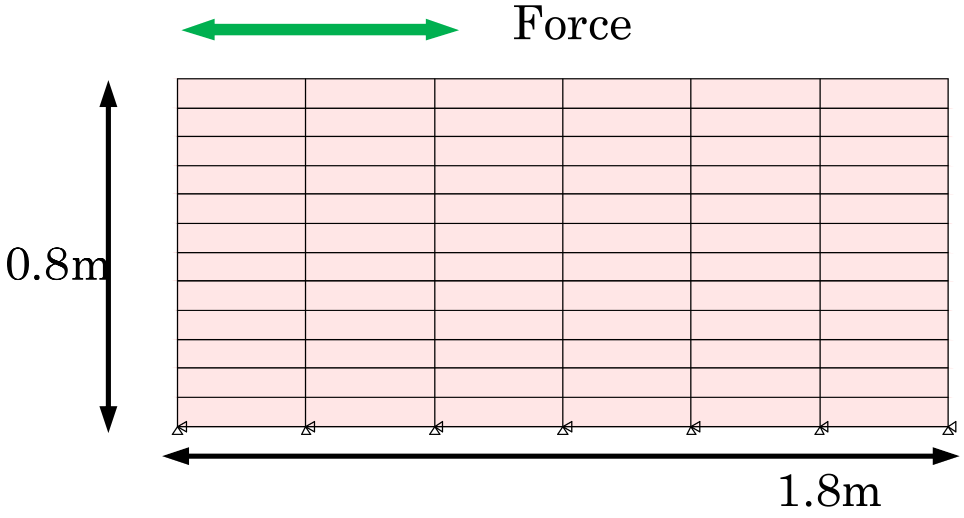
**Specimens were composed of rock fill material from Sagurigawa Dam.**

**Specimens were prepared with a relative density of $D_r$ = 85%.**

## Simulation condition

| | |
|---|---|
| Internal friction angle (Degree) | 50.9 |
| Cohesion (kPa) | 68.6 |
| Initial shear modulus (Mpa) | 475 |
| Poisson's ratio | 0.25 |

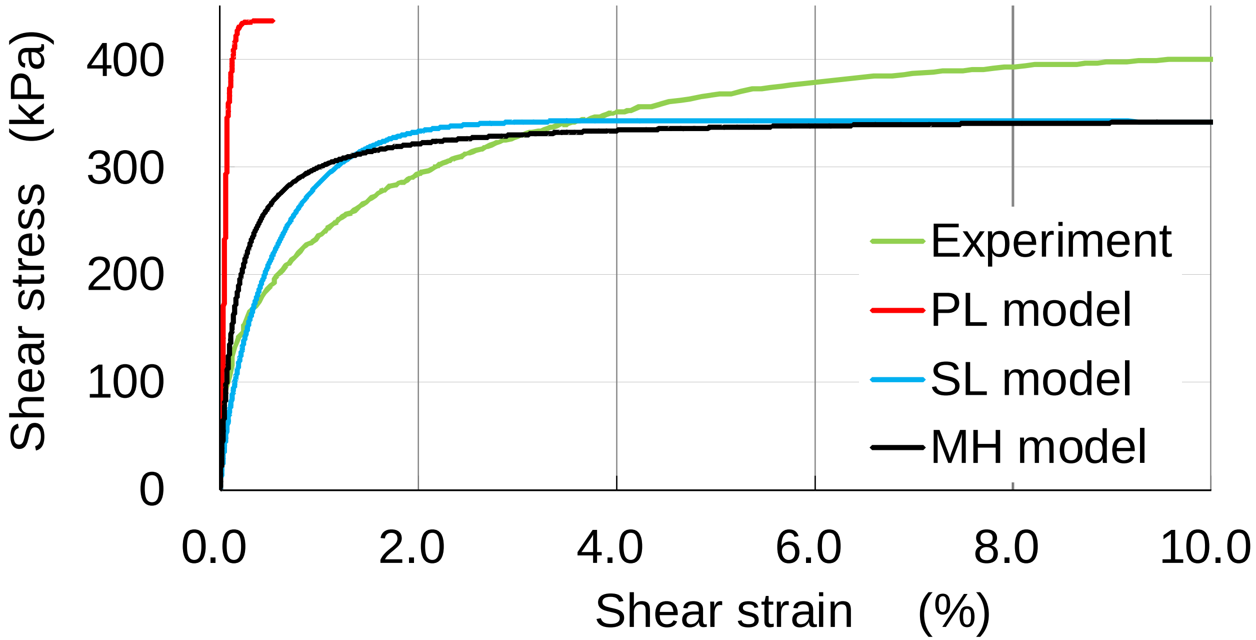
Drain condition Plane strain



Bottom boundary: Fixed

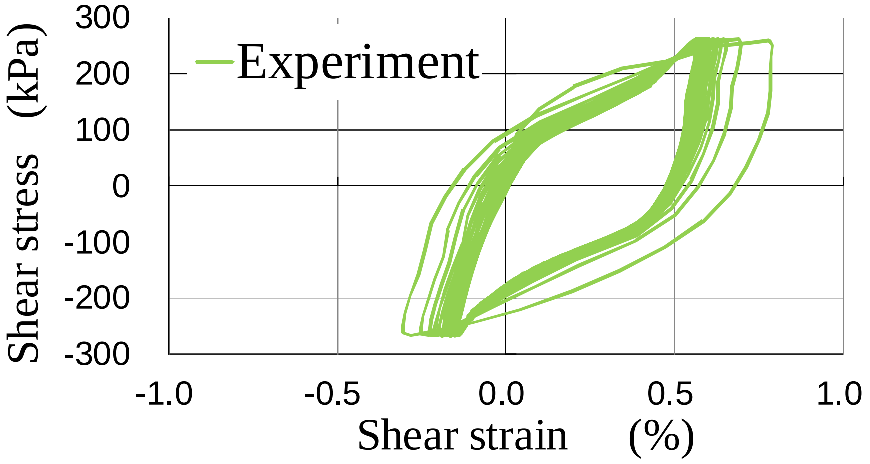
Side boundary: Periodical boundary

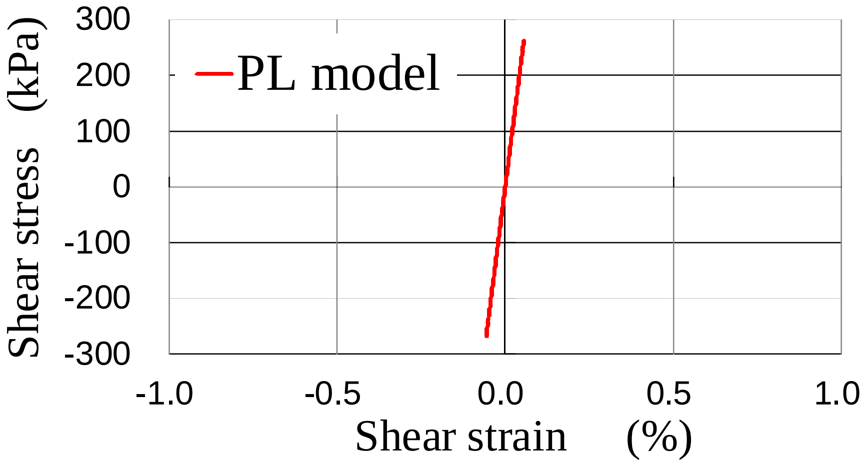
# Simulation of Monotonic Loading Test



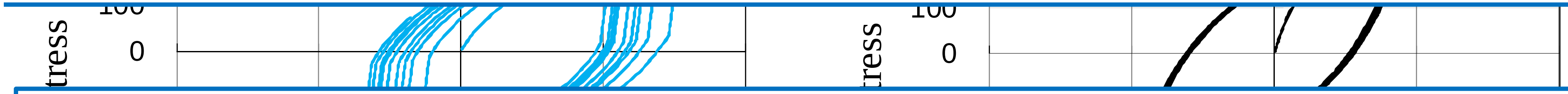
**The shear strain obtained from simulation underestimated the experimental results because the PL model could not estimate the occurrence of the plastic shear strain within the Mohr Coulomb yield surface.**

# Simulation of Cyclic Loading Test



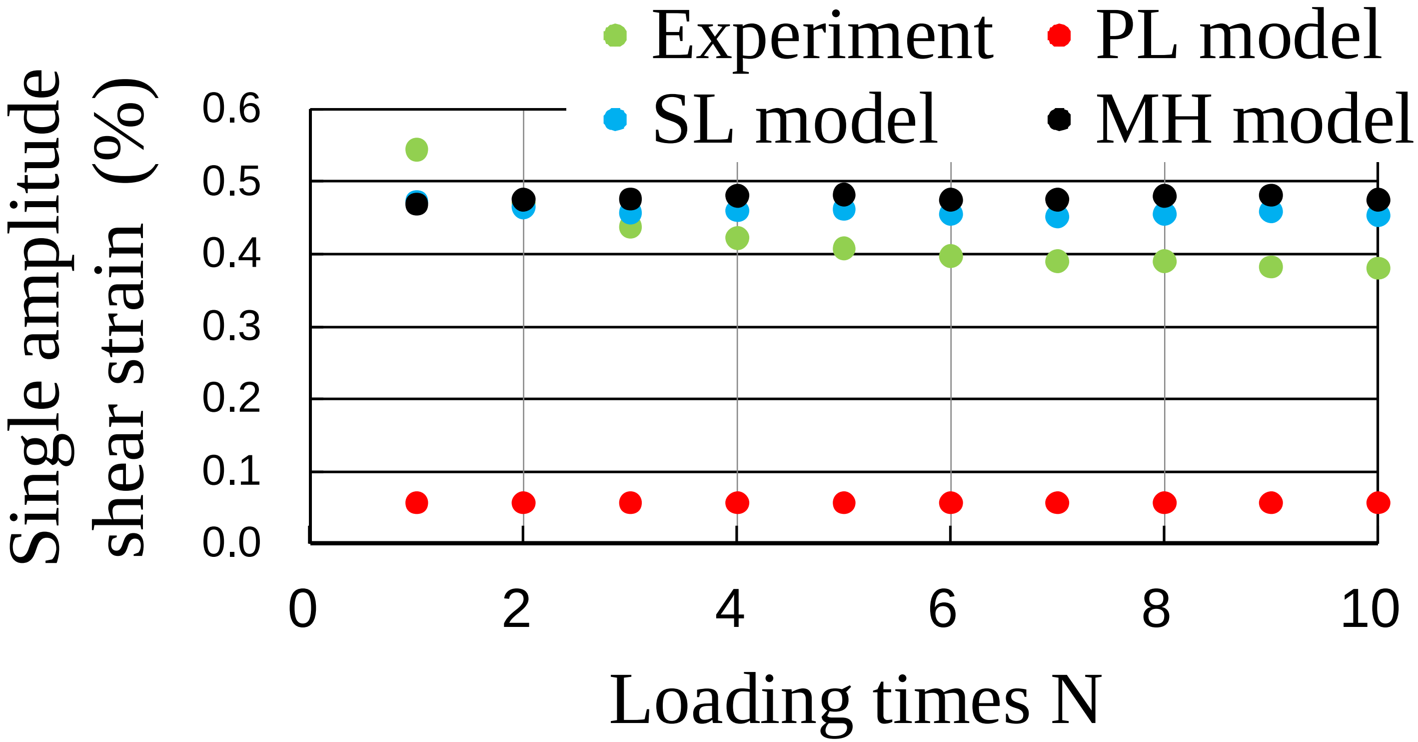


**The results obtained from the PL model show elastic behavior.**



**The relationships between the shear strain and the shear stress obtained from both the SL and MH models were in close agreement with the corresponding experimental results.**

# Simulation of Cyclic Loading Test



**The single amplitude shear strain of the PL model underestimated the experimental results.**

**The single amplitude shear strains obtained from both the SL and MH models were in close agreement with the experimental results.**

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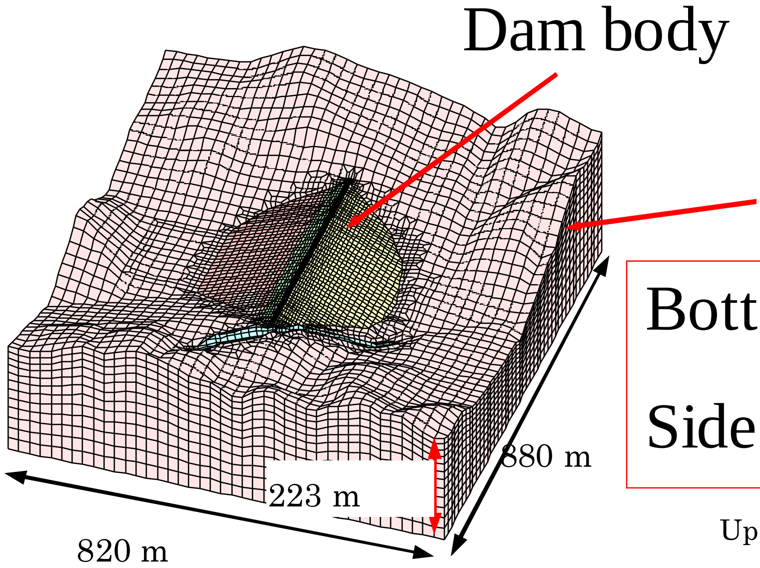
# Three-Dimensional Analysis Model

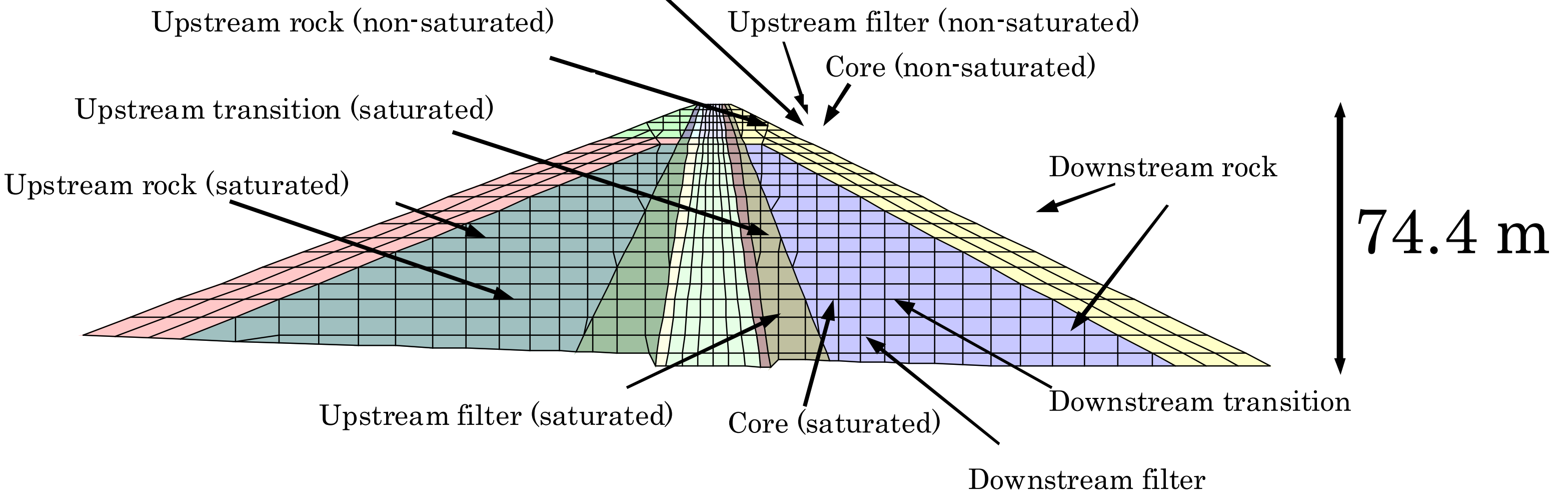


Elements : 79,043, Nodes : 82,219

Bedrock (CM, $V_s$ = 1440 m/s)

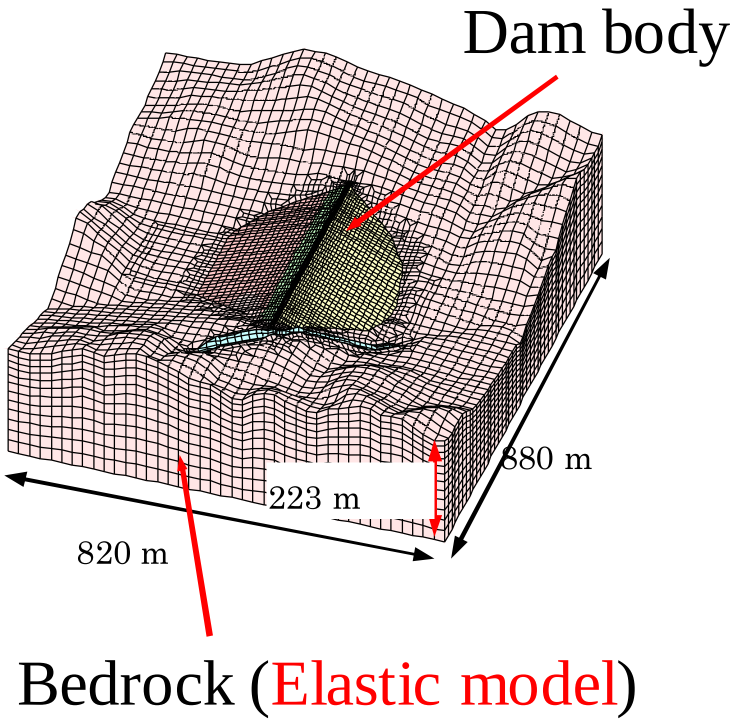
Bottom: Viscous boundary

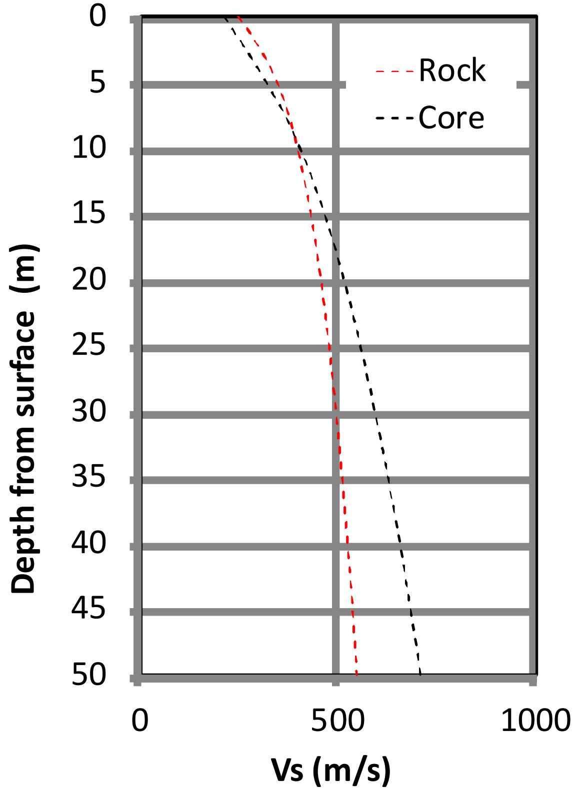
Side: Same displacement as free field

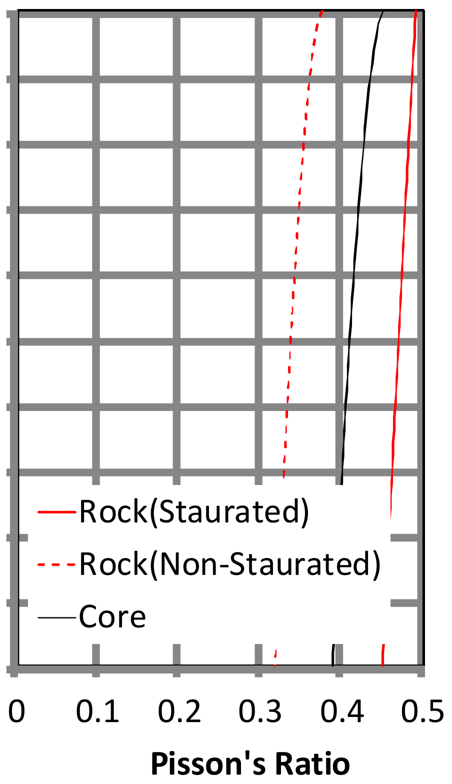


Cross-section of dam body

# $V_s$ and Poisson's Ratio of Dam Body







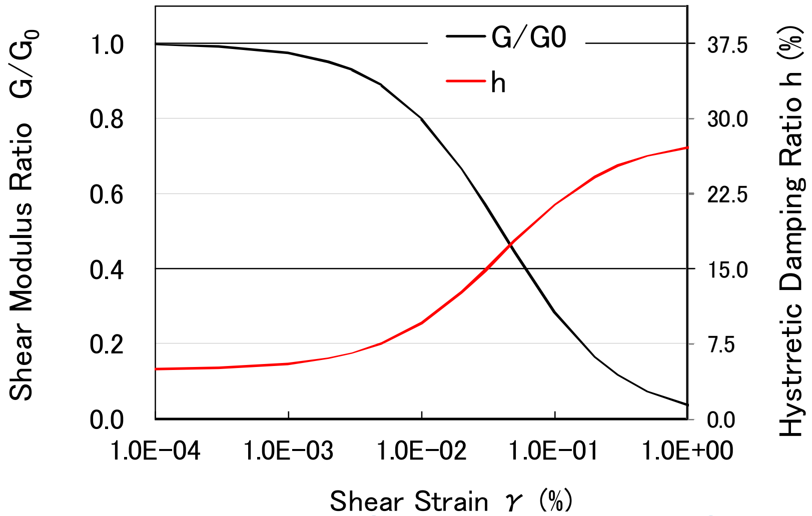
**The initial shear modulus of the dam body was determined using the shear velocity $V_s$, which was calculated from Sawada's formula (Sawada, 1975). The Poisson's ratio of the dam body was also calculated from Sawada's formula.**

# *Parameters Used in Equivalent Linear Analysis*

| Material | Unit Weight ($t/m^3$) | Dynamic Property | |
|---|---|---|---|
| | | $\gamma_r$ (%) | hmax |
| Core (low, middle) | 2.1 | 0.03 | 20% |
| Core (Surface) | 2.05 | 0.03 | 30% |
| Filter, Transition | 2.24～2.43 | 0.04 | 30% |
| Rock (inner, outer) | 2.13～2.32 | 0.04 | 23% |

$$\frac{G}{G_0} = \frac{1}{1+\gamma/\gamma_r}$$

$$h = h_{max}\frac{\gamma}{\gamma+\gamma_r} + h_0$$

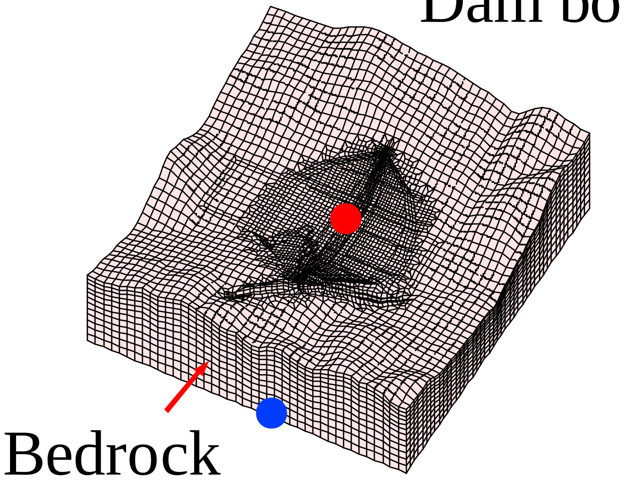


**The MH model also used these dynamic properties.**

**were determined based on the**
**led at the dam during the 2008**
**earthquake (Sato, 2012).**

# *Formulation of Input Earthquake Motions*

## First stage



Bedrock

| Input |
|---|
| Bottom of bedrock |
| Earthquake motion of unit amplitude |

Transfer function

(● Bottom ⇒ ● Top)

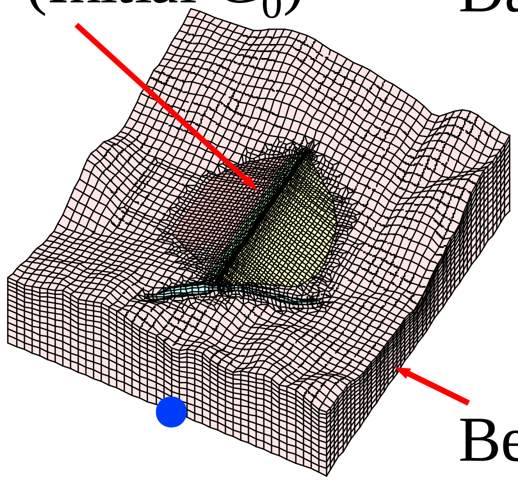
\+

Observed earthquake motions

Input motion to bedrock

## Second stage

Dam body (Initial $G_0$)



Bedrock

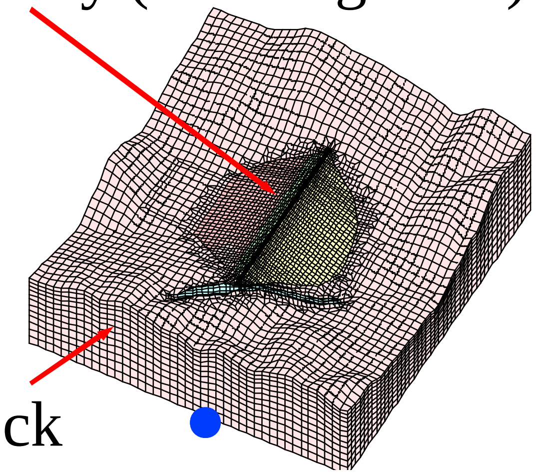
| Input |
|---|
| Bottom of bedrock |
| Input motion calculated in first stage |

Equivalent linear analysis

Converged shear modulus of dam body

## Third stage

Dam body (Converged G)



| Input |
|---|
| Bottom of bedrock |
| Earthquake motion of unit amplitude |

Transfer function

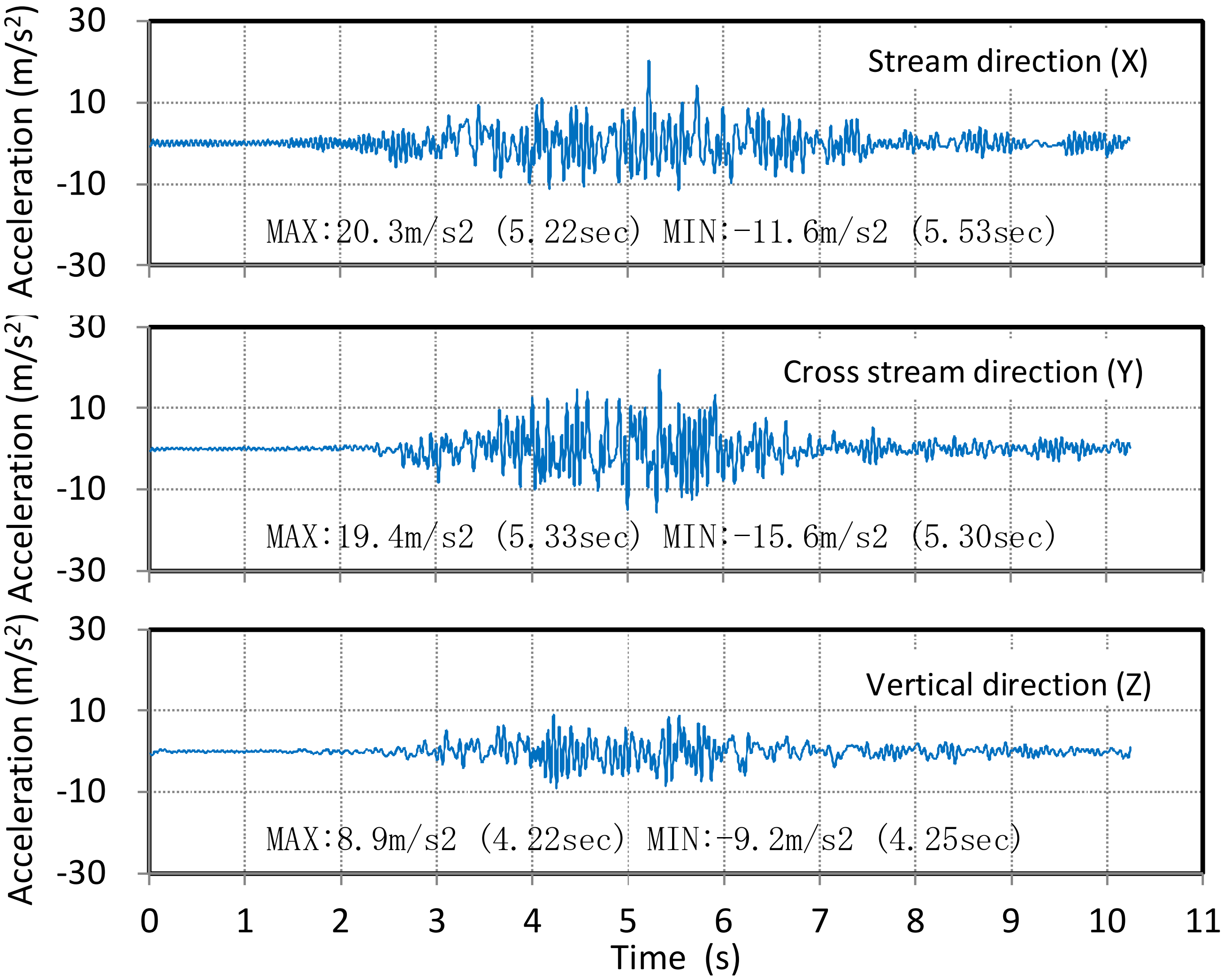
(from bottom to top of bedrock)

\+

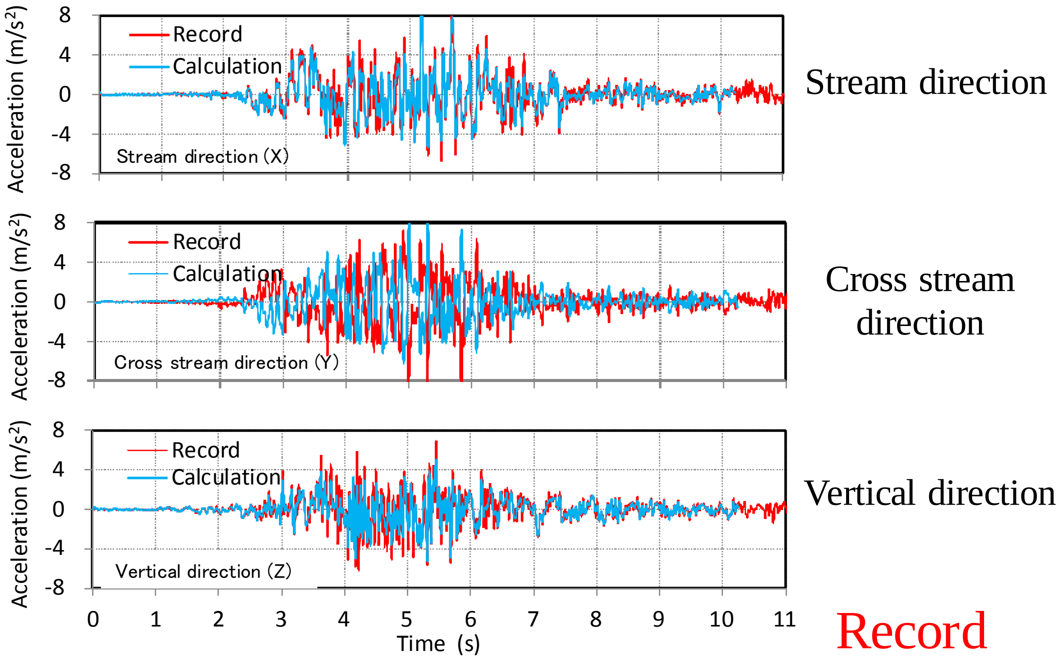
Observed earthquake motions

Input motion to bedrock

# Formulated Input Earthquake Motions

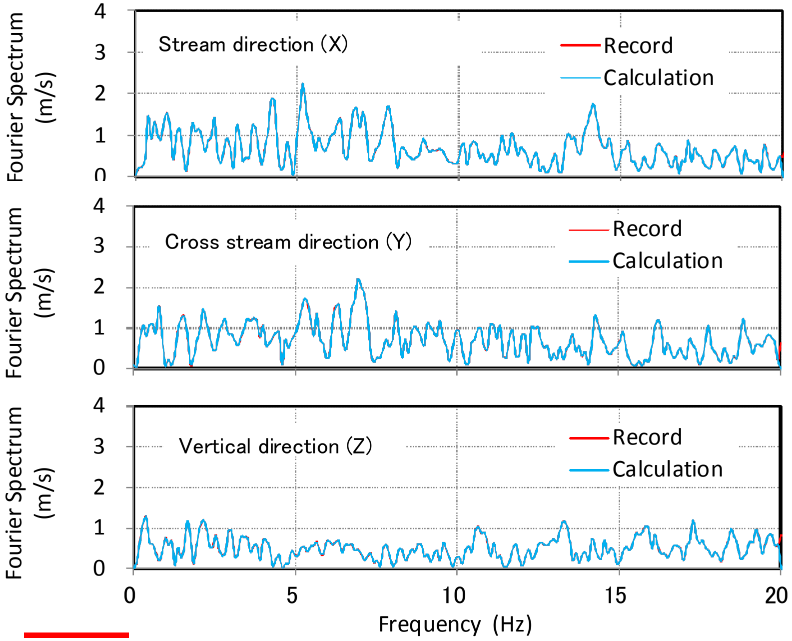


# *Accuracy of Formulated Input Motions*



Time history of acceleration
(at inspection gallery)

Record ━━
Calculation ━━



Fourier spectrum
(at inspection gallery)

**The earthquake motions obtained from the calculation and the recorded values are very close agreement at the inspection gallery.**

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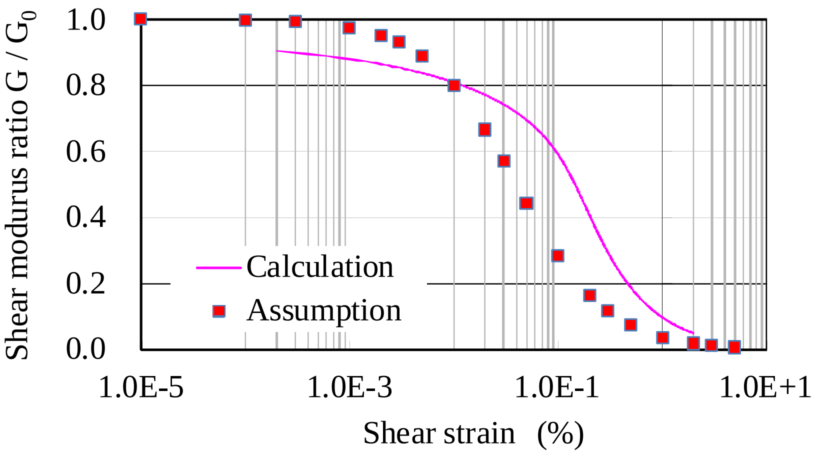
# *Parameters Used in Non-Linear Analysis*

| | Material | Unit weight ($t/m^3$) | Internal friction angle (degree) | Cohetion (kPa) |
|---|---|---|---|---|
| 1 | Bedrock | 2.6 | - | - |
| 2 | Core (saturated) | 2.1 | 33.2 | 49 |
| 3 | Core (non-saturated) | 2.05 | 33.2 | 49 |
| 4 | Filter of upstream (saturated) | 2.43 | 42.2 | 78 |
| 5 | Filter of upstream(non-saturated) | 2.34 | 42.2 | 78 |
| 6 | Filter of downstream | 2.34 | 42.2 | 78 |
| 7 | Transition of upstream (saturated) | 2.33 | 39.9 | 39 |
| 8 | Transition of upstream (non-saturated) | 2.24 | 39.9 | 39 |
| 9 | Transition of downstream | 2.24 | 39.9 | 39 |
| 10 | Inner rock of upstream (saturated) | 2.29 | 42.7 | 49 |
| 11 | Outer rock of upstream (saturated) | 2.32 | 43.4 | 49 |
| 12 | Outer rock of upstream (non-saturated) | 2.15 | 43.4 | 49 |
| 13 | Inner rock of downstream | 2.18 | 40.2 | 49 |
| 14 | Outer rock of upstream | 2.13 | 42.7 | 49 |
| 15 | Spillway | 2.4 | - | - |

- **A total stress analysis was conducted.**
- **The same internal friction angles and cohesion values were used for all 3 models (PL, SL, and MH).**

# *Parameters Used in Non-Linear Analysis*



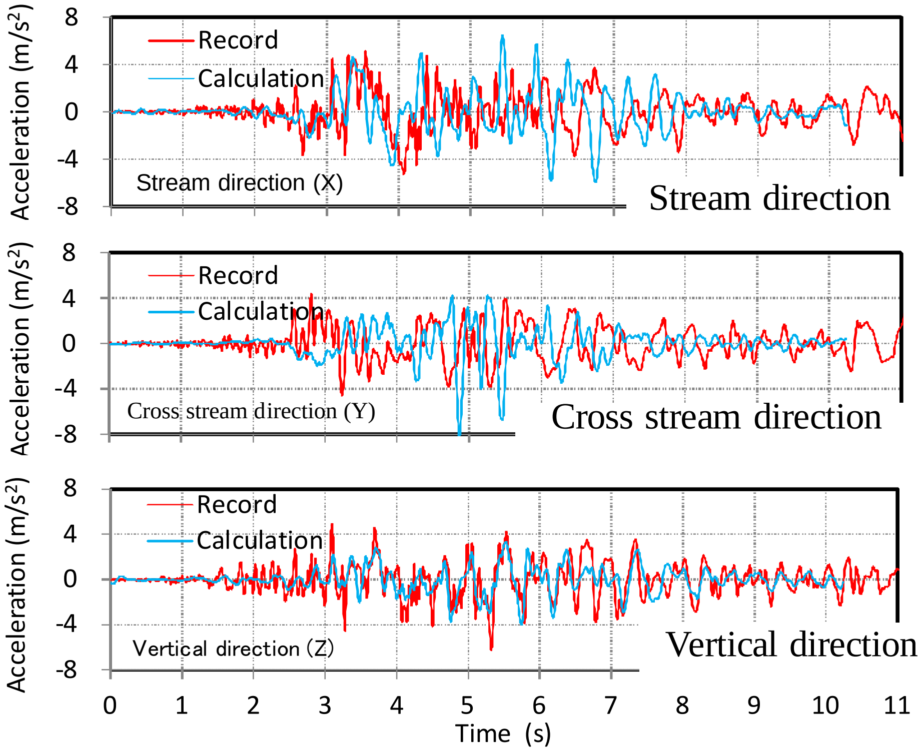
Dynamic properties obtained using SL model for rock material.

**Because the SL model controls the dynamic properties using only two parameters, *u* and *c*, it is difficult to estimate these dynamic properties over a wide range of strain levels.**

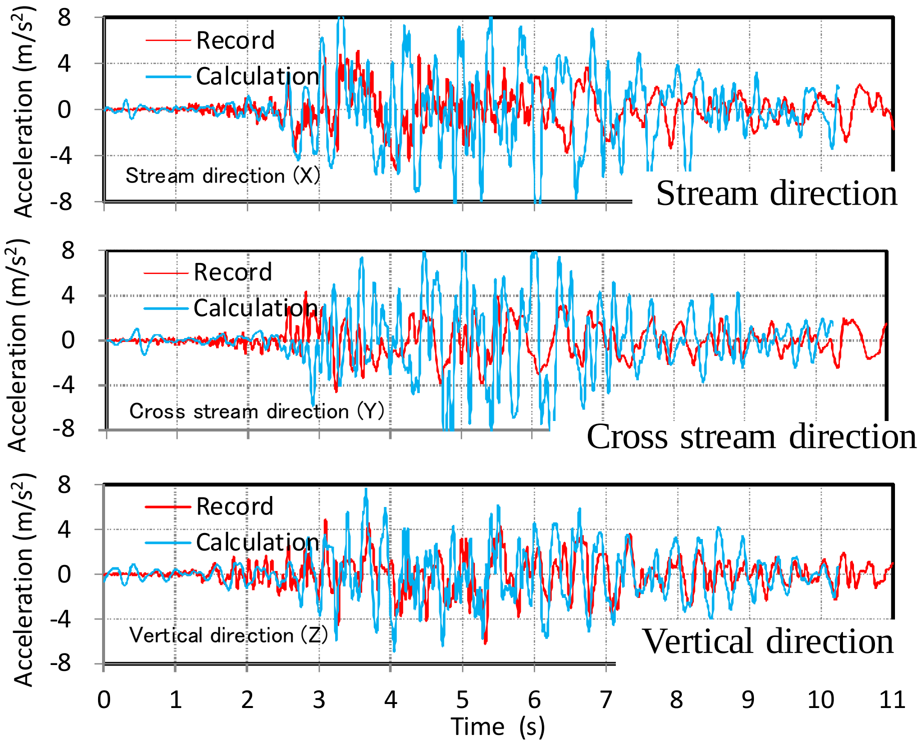
**The dynamic properties used in the equivalent linear analysis were used as input parameters for the MH model.**

**The Rayleigh damping ratio as determined using the natural frequencies of the first (2.33 Hz) and second (5.43 Hz) modes, was 5.0% for both the bedrock and the dam body.**

# *Time History of Acceleration at the Crest (equivalent linear analysis and PL model)*



Equivalent linear analysis

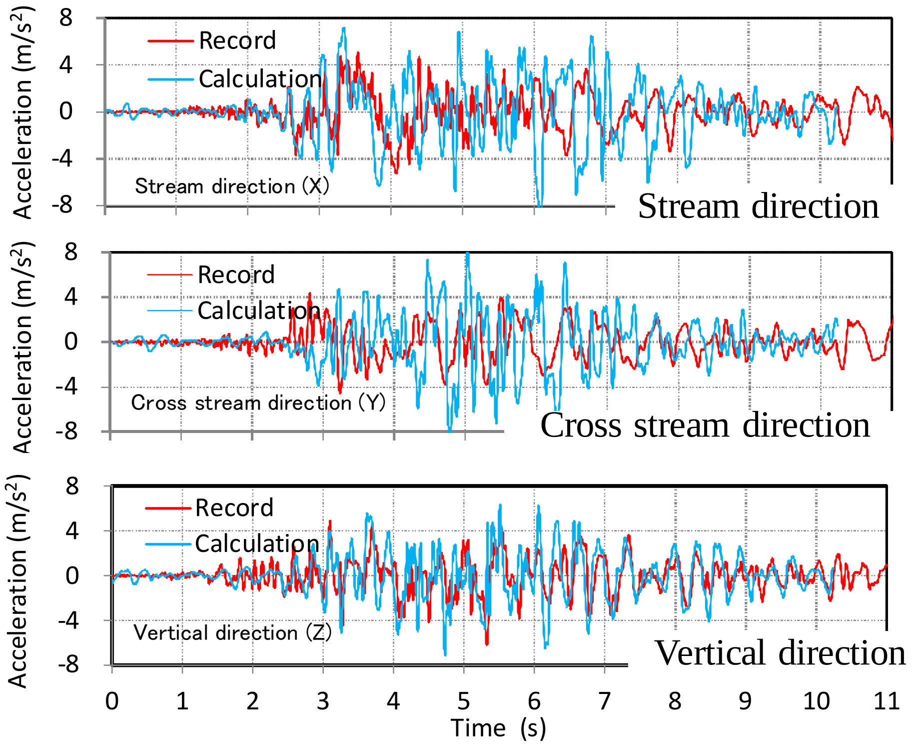


PL model

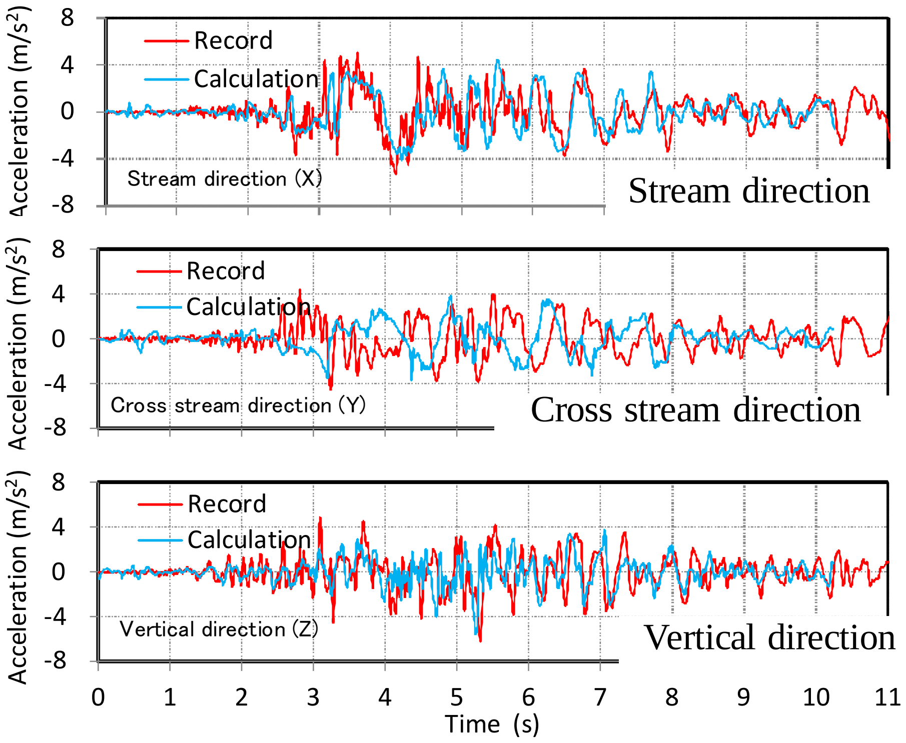
Record 🟥

Calculation 🟦

**Both the time history and phase of acceleration were in close agreement with the recorded values. This is because the MH model adopted the dynamic properties used in the equivalent linear analysis.**



SL model

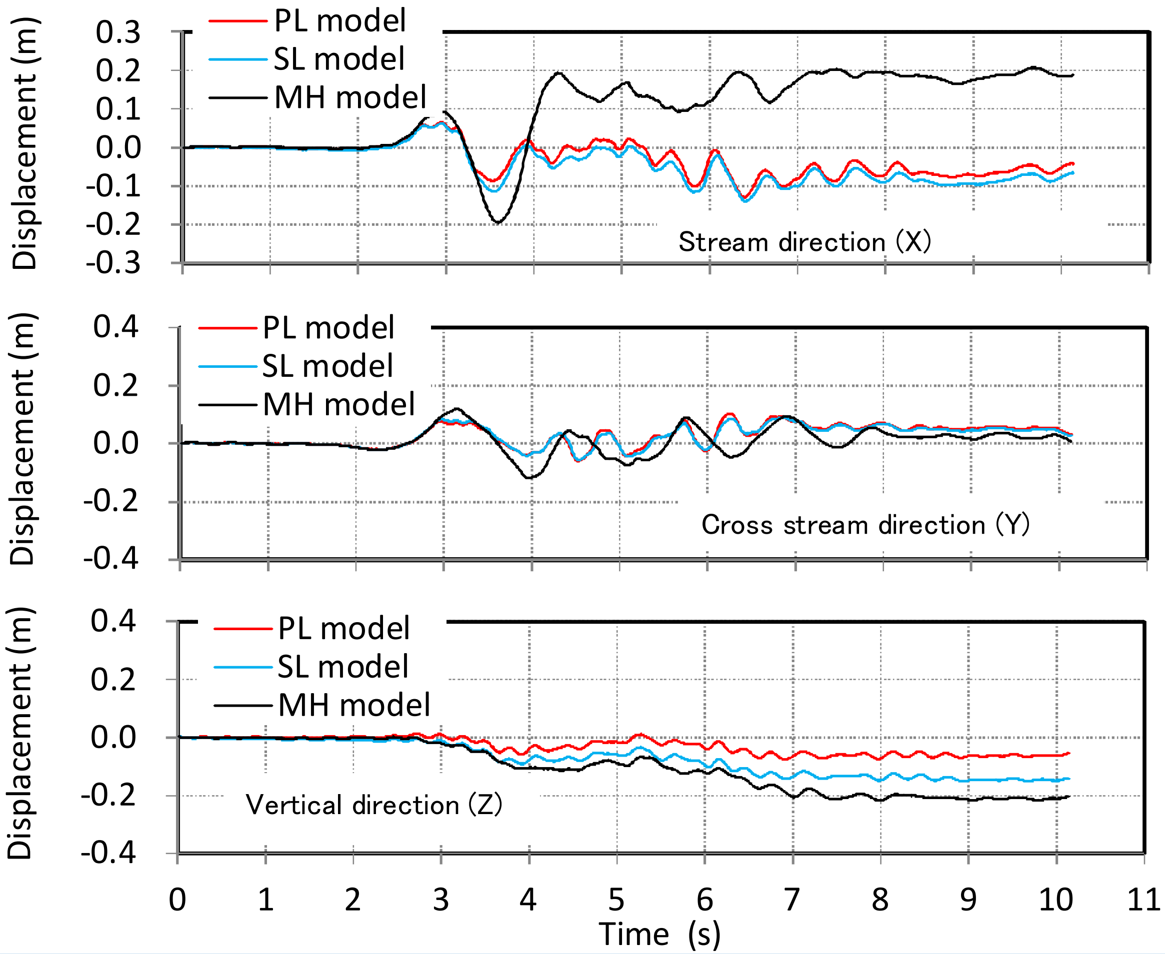


MH model

Record —

Calculation —

# Time History of Displacement at the Crest



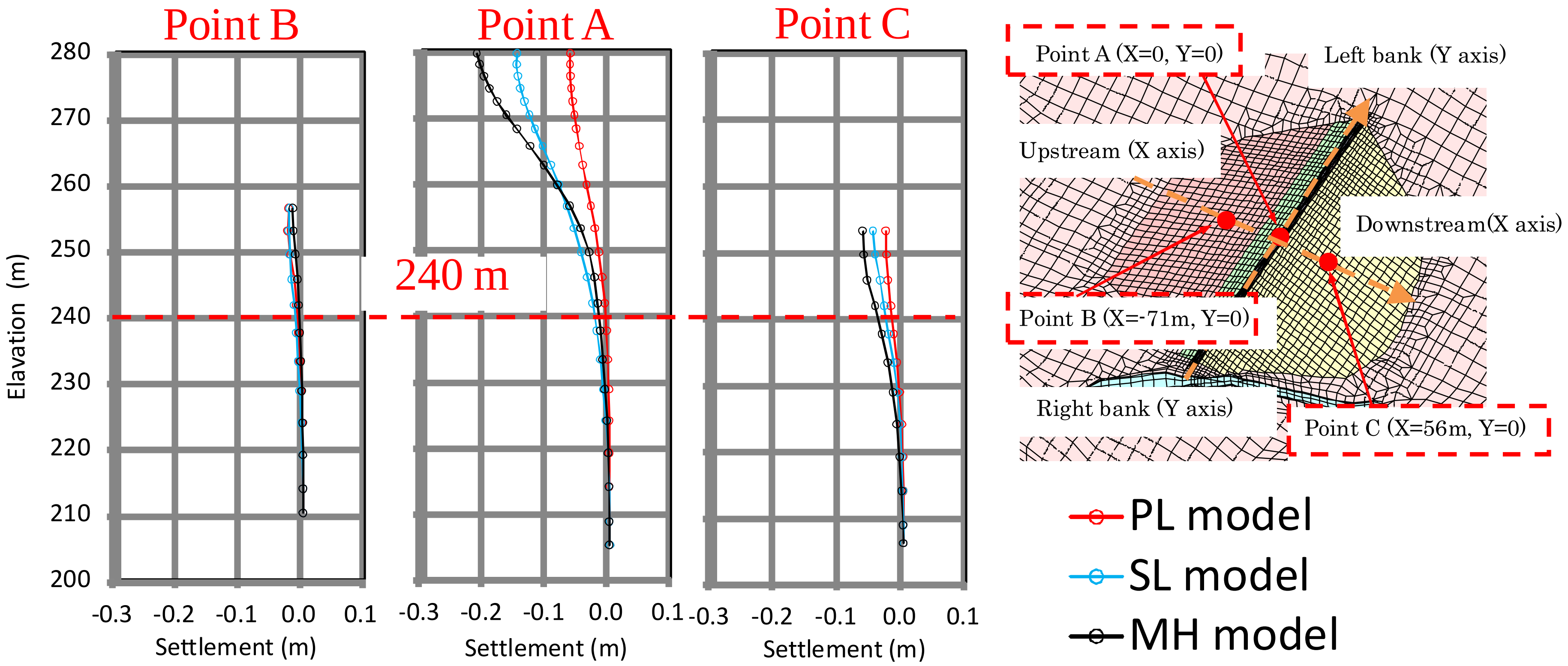
Stream direction

Cross stream direction

Vertical direction

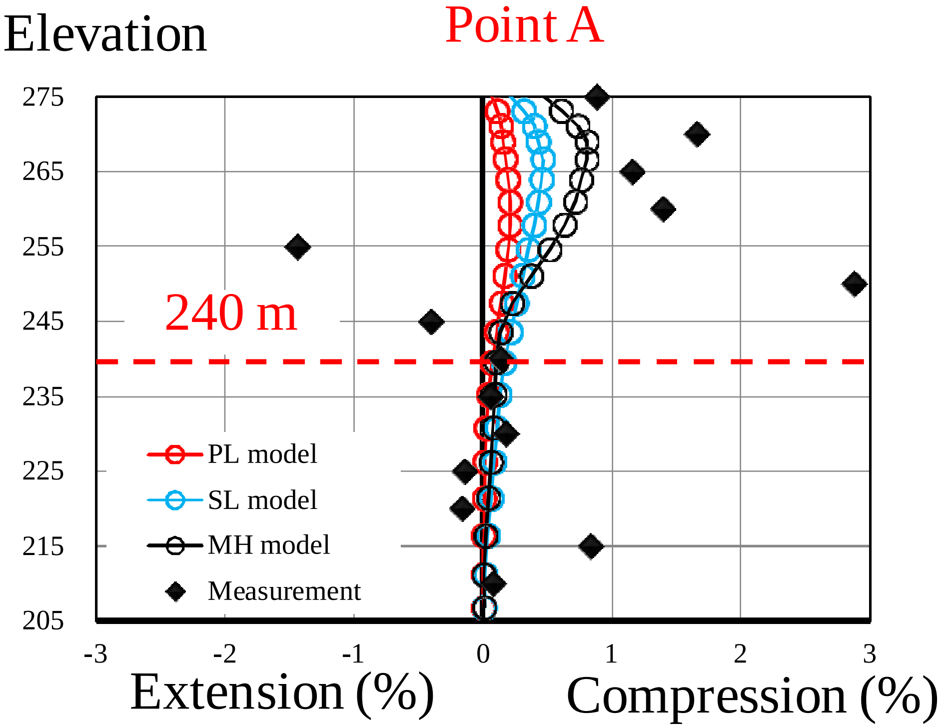
**Residual settlement values of 75 mm, 150 mm, and 226 mm were obtained from the PL, SL, and MH models.**

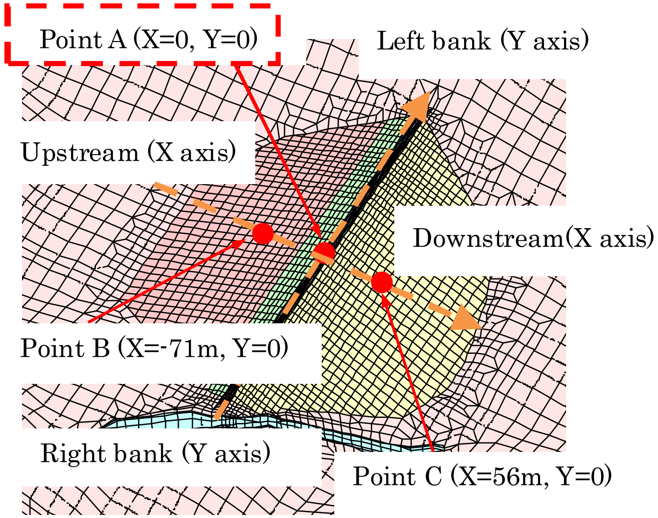
# *Settlement Distribution in direction of Elevation*



- **Residual settlement did not appear in any of the model results below 240 m.**
- **The residual settlement value occurring above 240 m differed by model.**

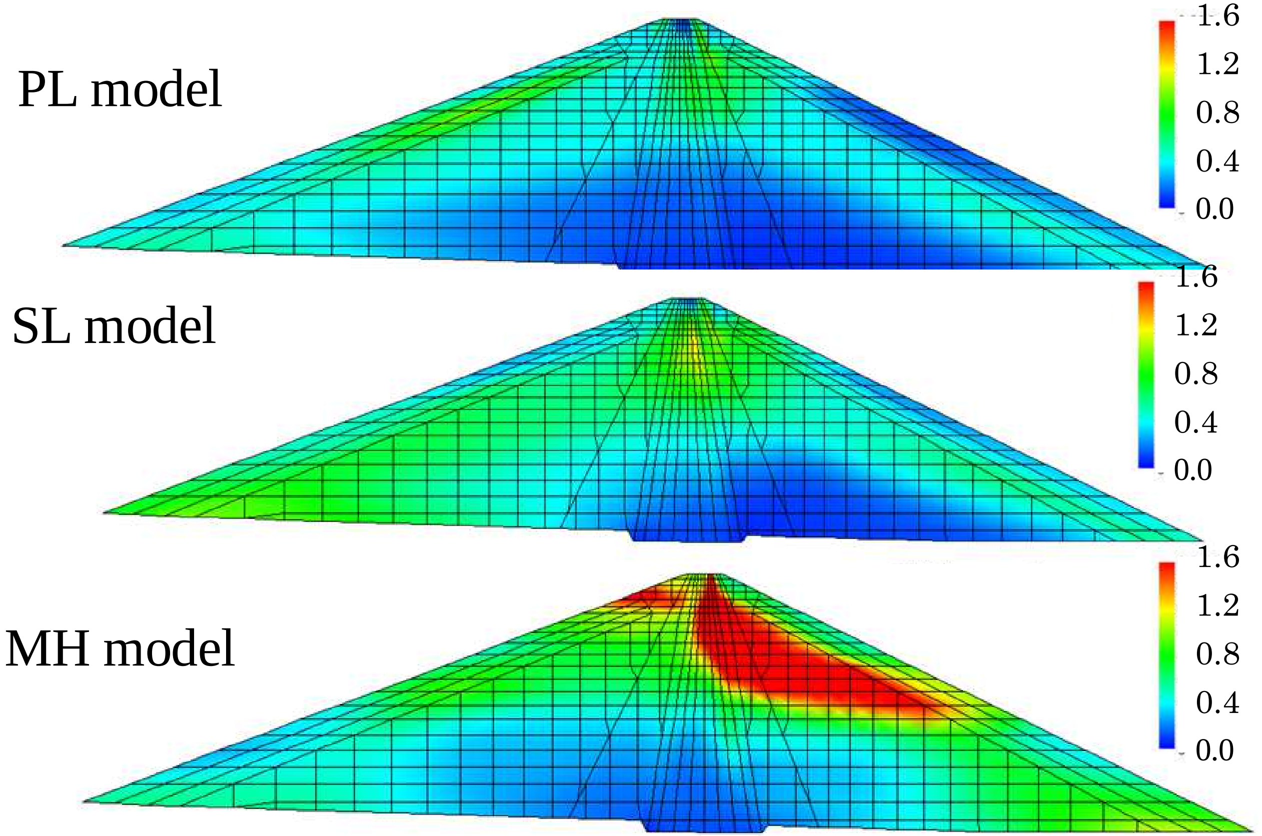
# *Comparison of measured and calculated subsidence strain*





- **From the measurement, it was clear that the vertical strain occurred above 240 m.**
- **The vertical strain distribution from the MH model was closest to that obtained from the measurement.**

# *Maximum Value of Maximum Shear Strain (%)*



**Because the strength of the core material is lower than that of the rock material, the large shear strain occurred at the boundary. The successive peak shear strain appeared in the downstream slope side as a slip slope.**

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# *Simulation Analysis of Torsional Shear Test*

1. **The PL model underestimates the shear strain obtained by laboratory testing because, in the model, elastic behavior appears within the Mohr Coulomb yield surface;**

2. **The SL and MH models are able to estimate the shear strain obtained by laboratory testing accurately because both models estimate the plastic shear strain within the Mohr Coulomb yield surface.**

# *Simulation Analysis of Aratozawa Dam*

1. **The acceleration obtained from the PL model was in poor agreement with the recorded values.**
   **The PL model underestimates the settlement of the dam body;**

2. **The acceleration from the SL model was in close agreement with records.**
   **However, the acceleration obtained from the MH model was in even better agreement with the recorded values;**

3. **The settlement values on the downstream side that were obtained from the PL and SL models were larger than the settlements on the upstream side because the slope of the downstream side was steeper than that of the upstream side;**

4. **The distributions of the vertical strain in the direction of elevation closely corresponded to the measured distribution.**
   **In particular, the distribution that was calculated using the MH model was closest to that obtained from the measurement.**

# THANK YOU FOR YOUR ATTENTION

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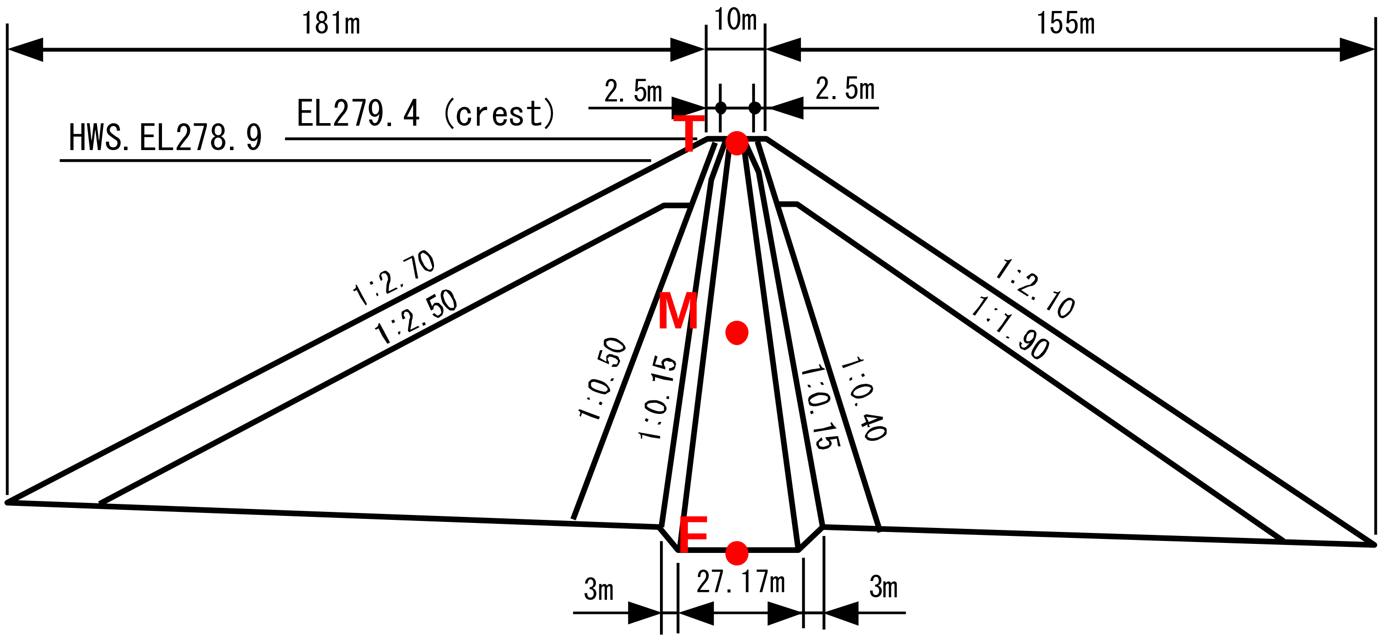
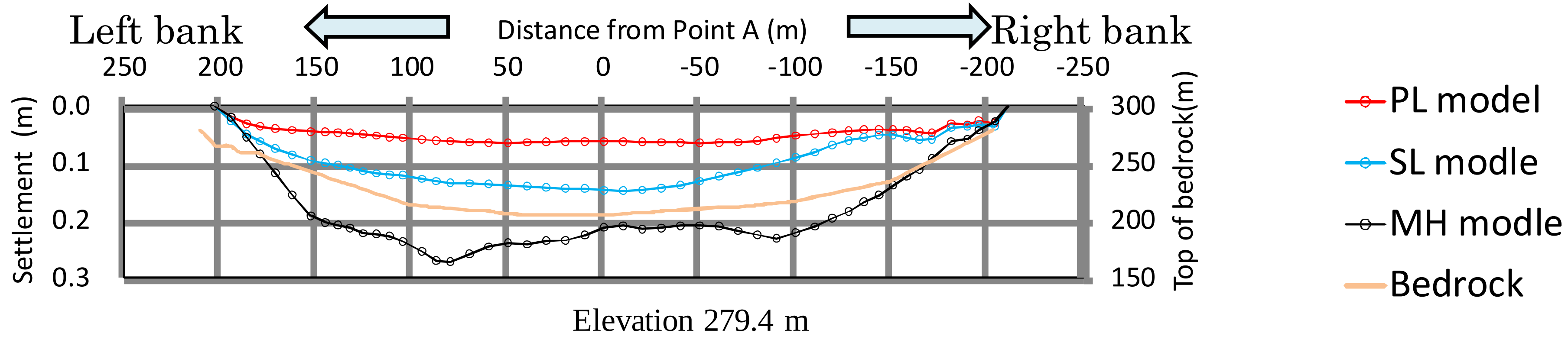
# Earthquake Motions & Settlements (2008)

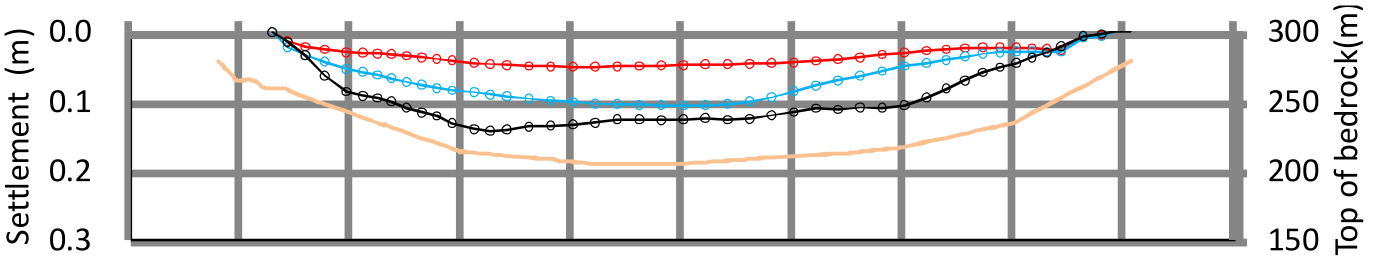


- **Earthquake motions were recorded at the crest, the middle, and the inspection gallery during the Iwate-Miyagi Nairiku Earthquake in 2008.**
- **The settlements distributions in direction of elevation were also recorded at the dam center.**

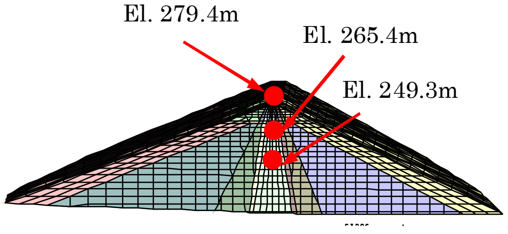
# *Settlement Distribution on the Horizontal of Cross Stream*

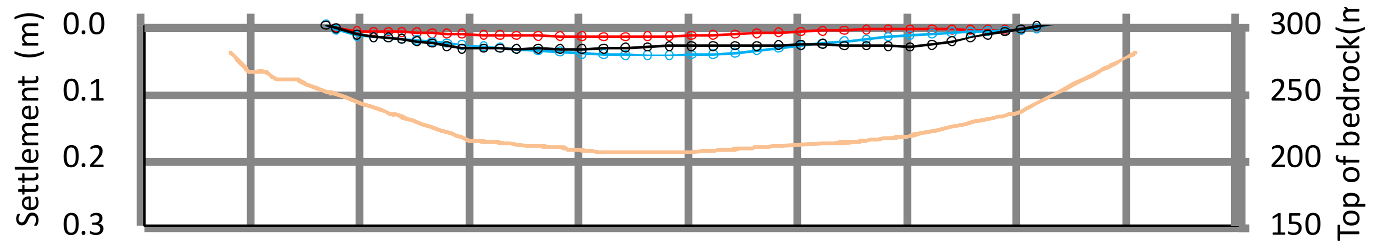


Elevation 279.4 m



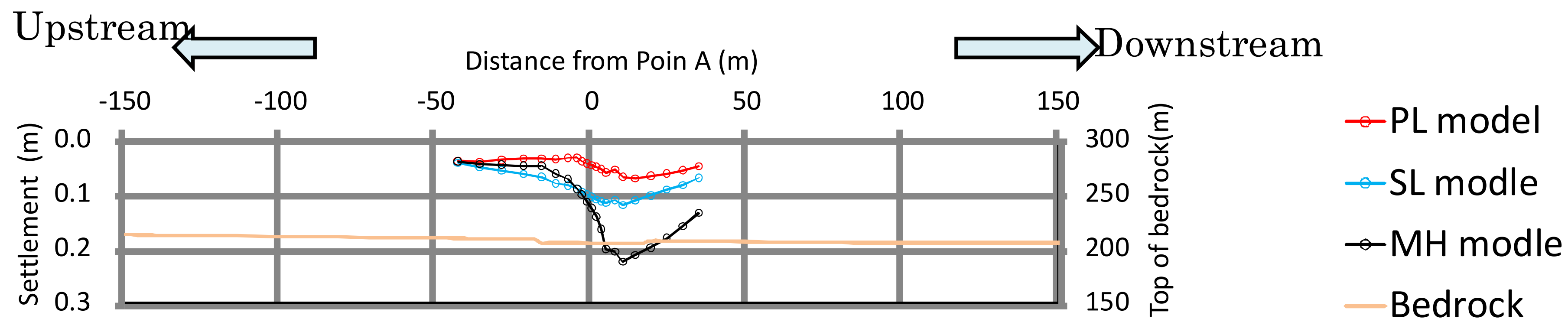
Elevation 265.4 m



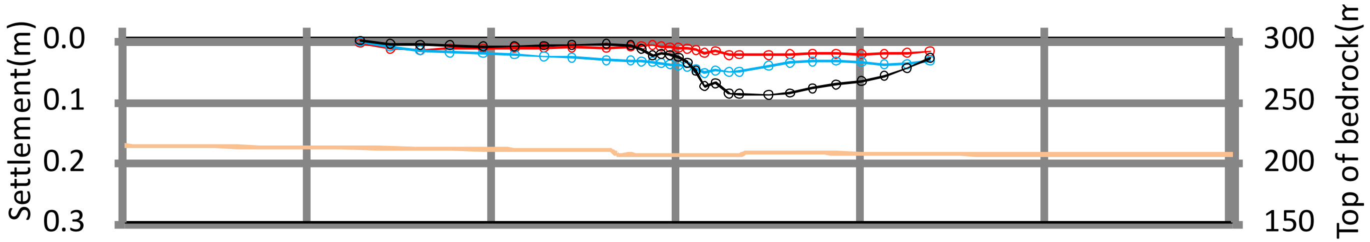


Elevation 249.3 m

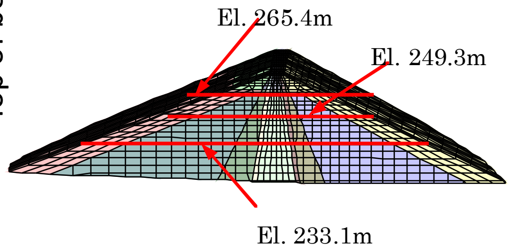
# *Settlement Distribution on the Horizontal of Stream Direction*

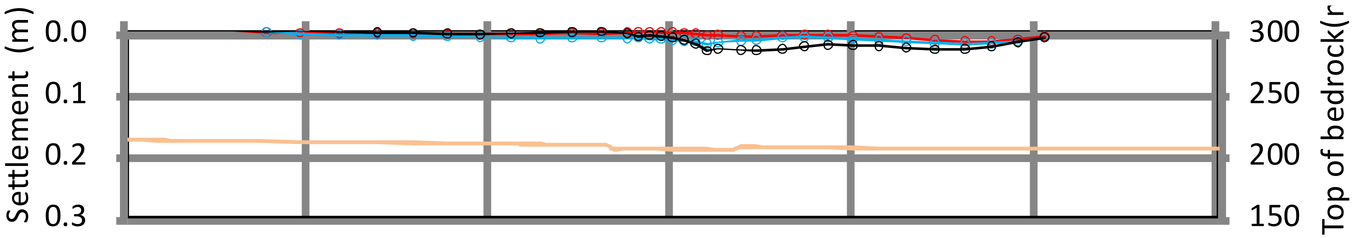


Elevation 279.4 m



Elevation 265.4 m

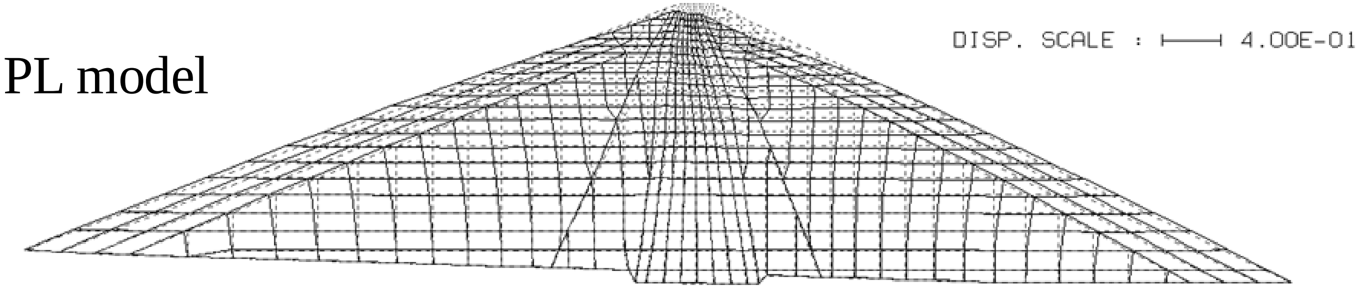




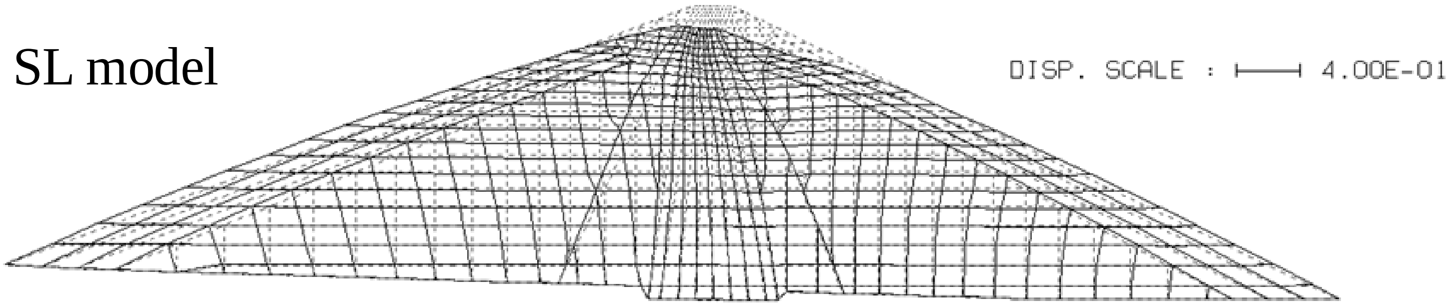
Elevation 249.3 m

# *Residual Deformation at Center Cross-Section*

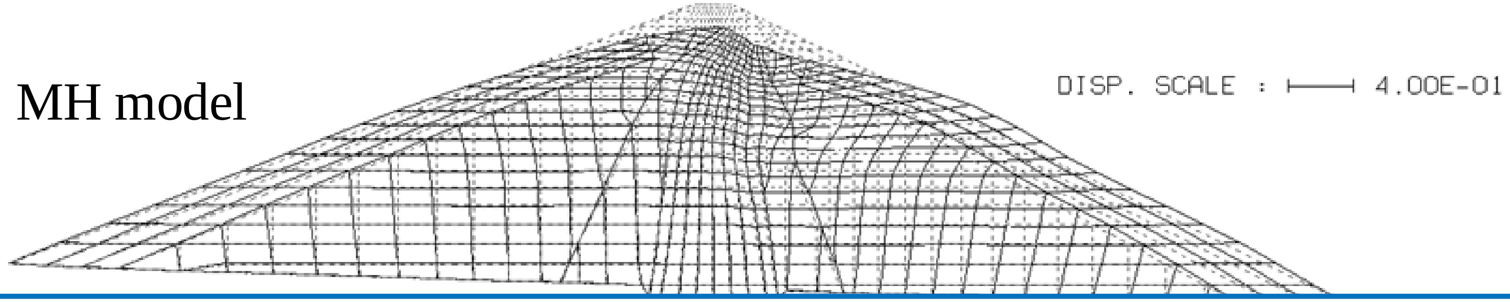
PL model



SL model



MH model



**The deformation obtained by the MH model shows settlement of the crest occurring toward the downstream side.**