International Symposium
Qualification of dynamic analyses of dams and their equipments
and of probabilistic assessment seismic hazard in Europe
31th August – 2nd September 2016 – Saint-Malo

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Japan Dam Engineering Center

Session : 4

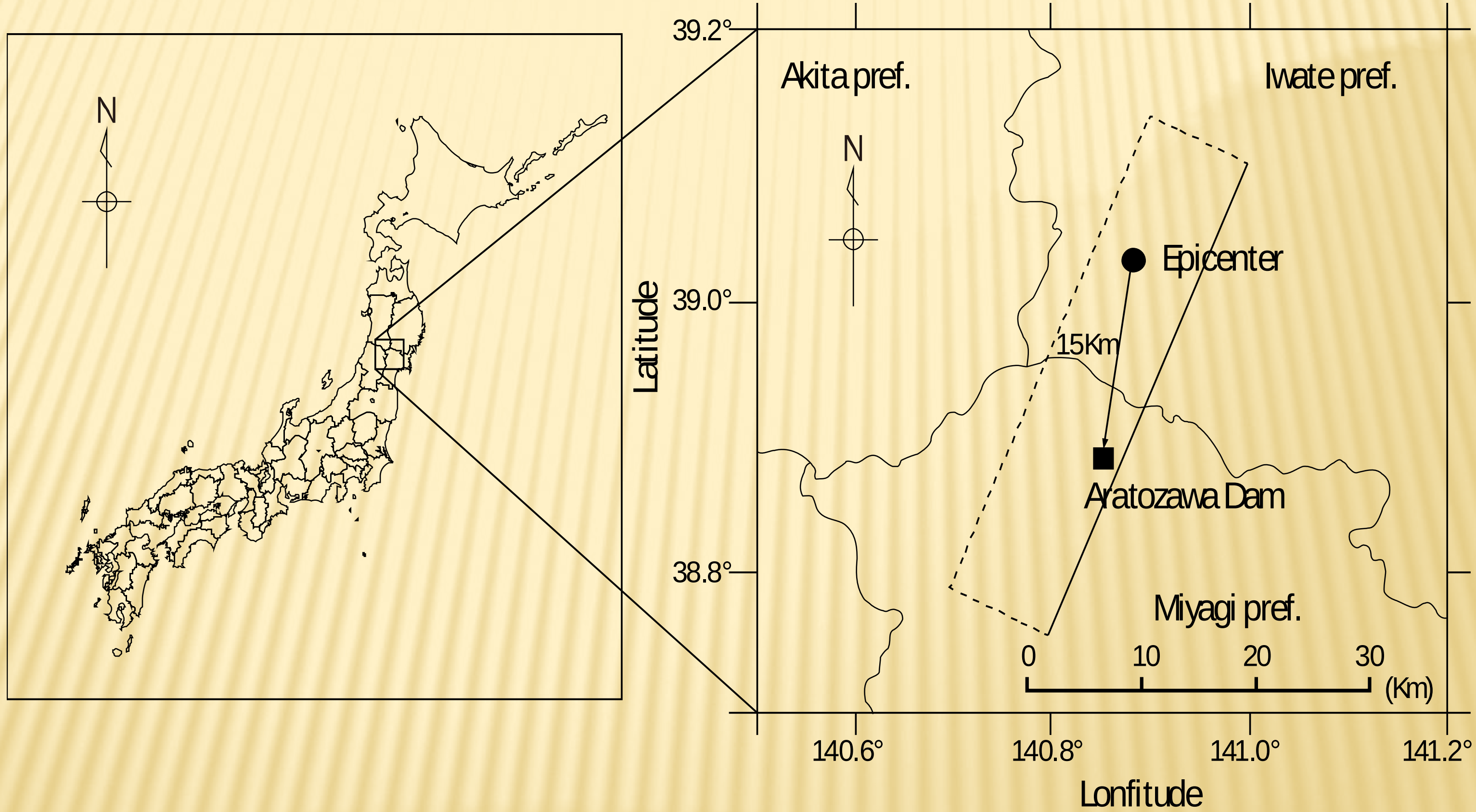
THE REPRODUCTION ANALYSIS OF ARATOZAWA DAM DURING 2008 EARTHQUAKE

1. Main Features of Aratozawa dam

Homepage of Miyagi Prefectural Government

Dam type	Rockfill dam with central clay core (1998)
Dam height	74.4 m
Crest length	413.7 m
Crest width	10.0 m
Slope gradients	Upstream: 1:2.7 , Downstream: 1:2.1
Design seismic coefficient	0.15 (dam body), 0.18 (intake tower, bridge) 0.16 (spillway)

2. Location of Aratozawa dam



3. Gigantic landslide by the Earthquake

after Takashi IGUCHI

20cm of settlement at dam crest

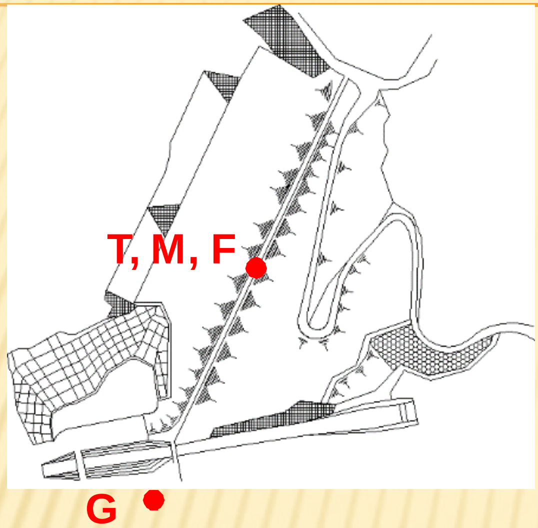
after Kyodo Press

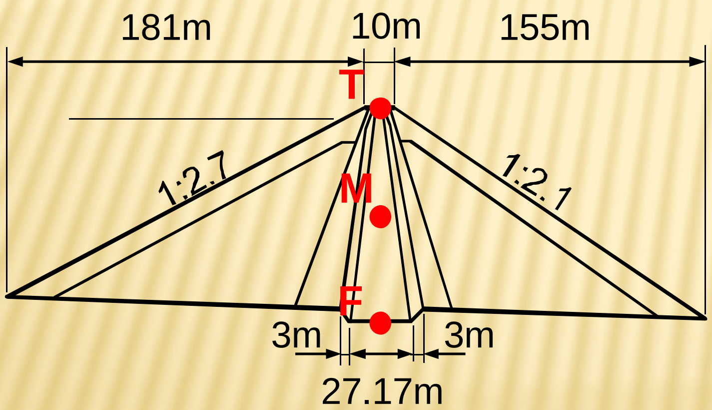
4. Repair work of landslide

2009/Oct/16

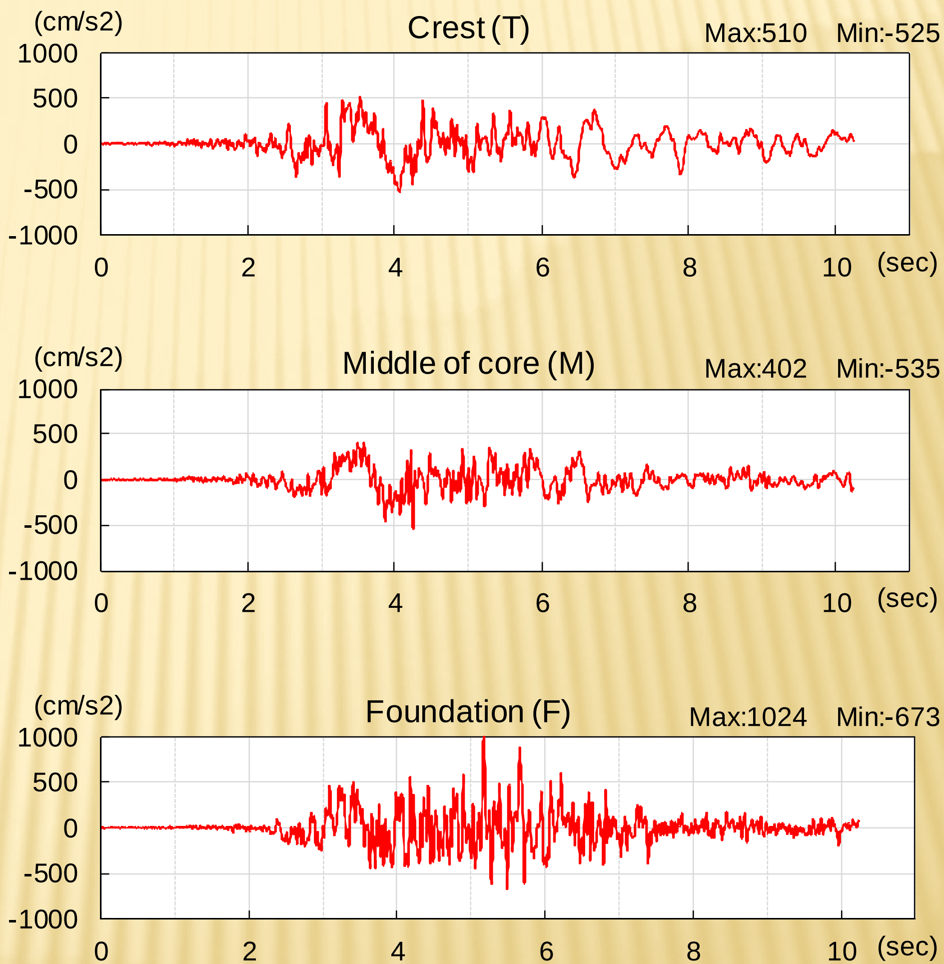
2011/Apr./6

5. Earthquake monitoring (1/2)





Locations of Seismographs

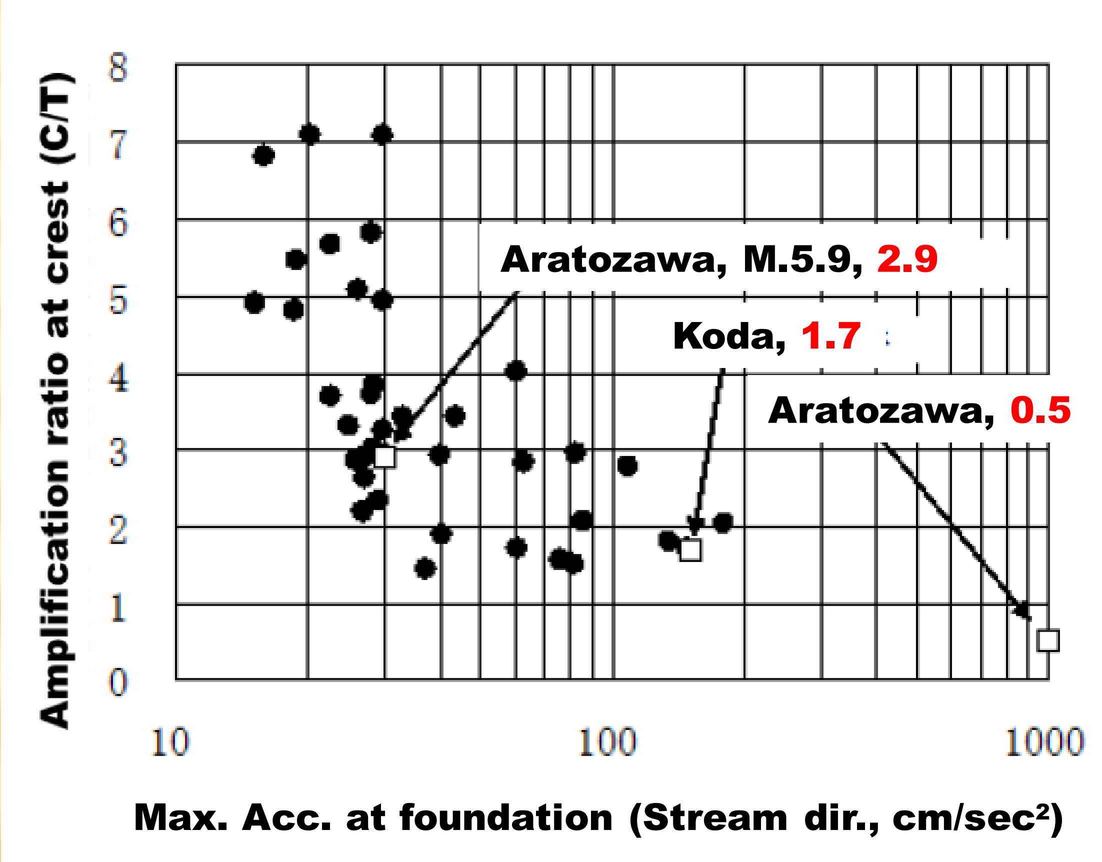


Earthquake Records in Stream Dir.

Iwate-Miyagi Nairiku Earthquake, 2008

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

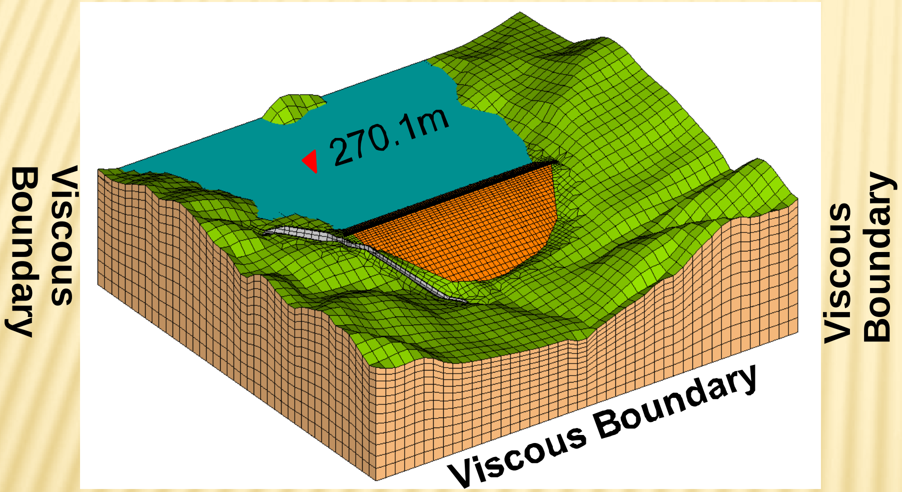
5. Earthquake monitoring (2/2)



Acceleration amplification ratio of dam body (Crest/Foundation)

6. Investigation with numerical analysis

(1) Why such peculiar phenomenon occurred ?
(2) What caused the permanent deformation ?



Analytical Model

Method for Earthquake Behavior Simulation
- 3-D FEM model
- Equivalent Linear Analysis

Method for Permanent Deformation Reproduction
- a) Stability analysis based on circular slip surface
- b) Deformation calculation based on the theory of cumulative damage

6-1 Procedure of numerical analysis

(1) G_0 Identification

↓

(2) Reproduction of earthquake motion at the bottom of model

↓

(3) Identification of reference strain and damping ratio

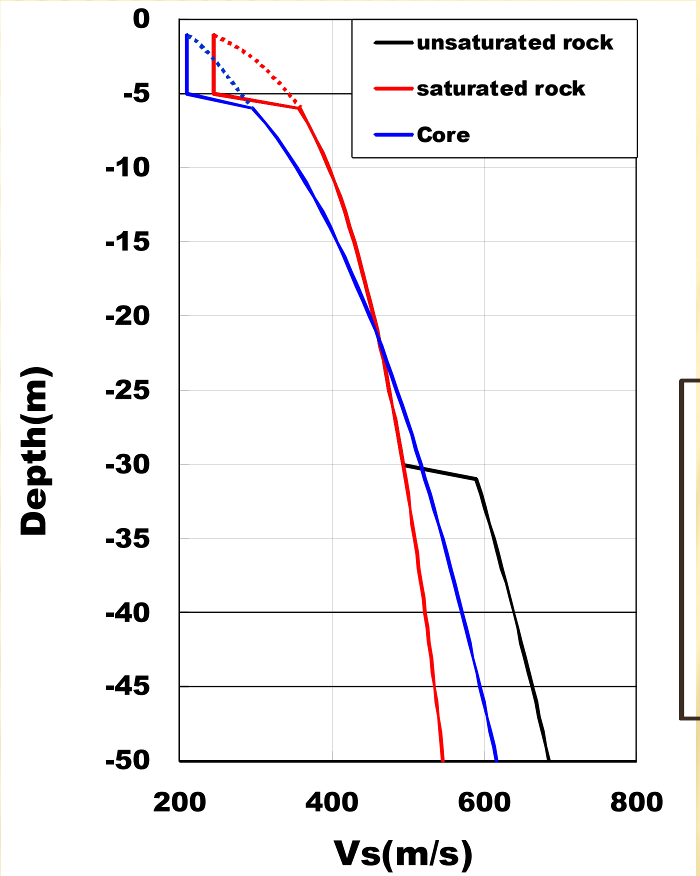
↓

(4) Simulation of the dynamic behavior in Iwate-Miyagi Nairiku earthquake

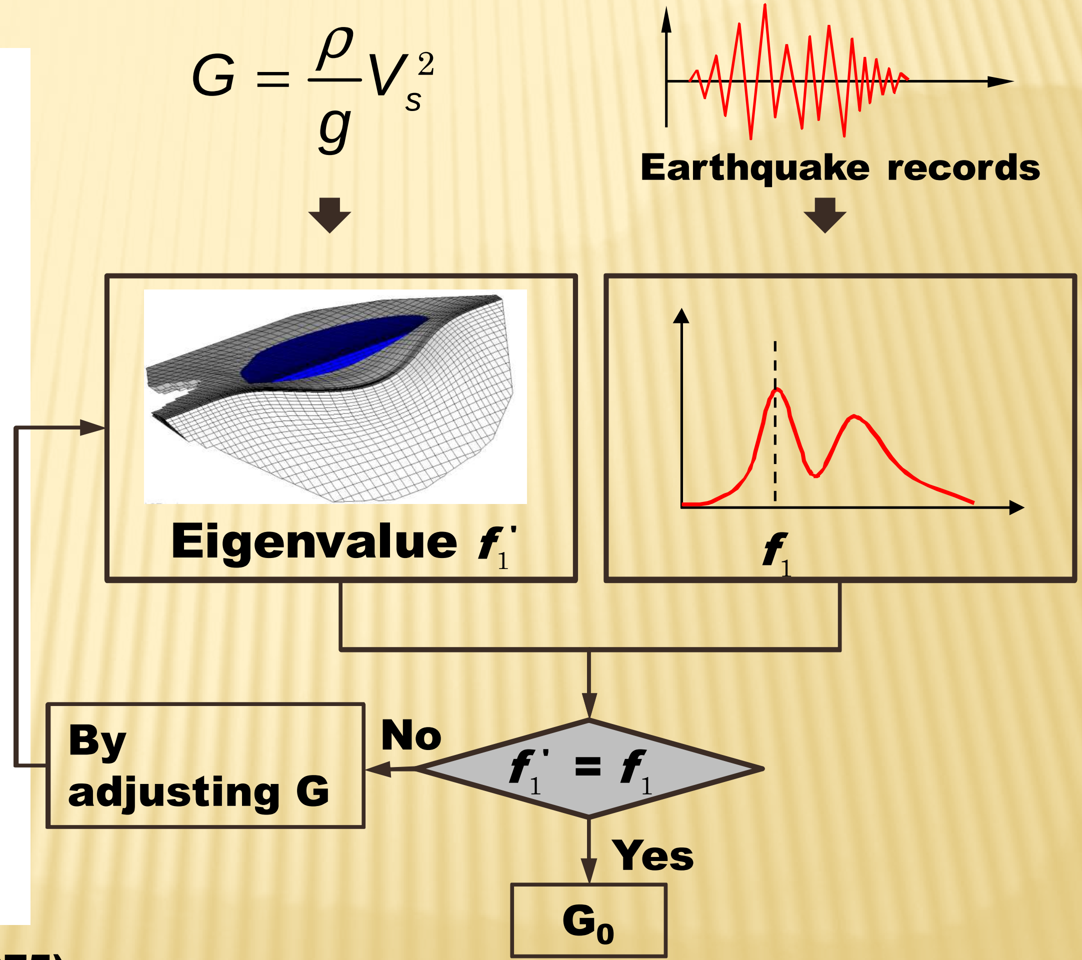
↓

(5) Calculation of permanent deformation

6-2 Identification of initial shear moduli G_0



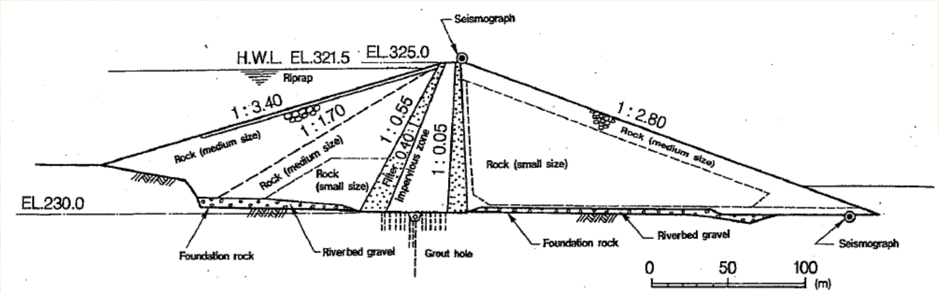
after Sawada and Takahashi (1975)

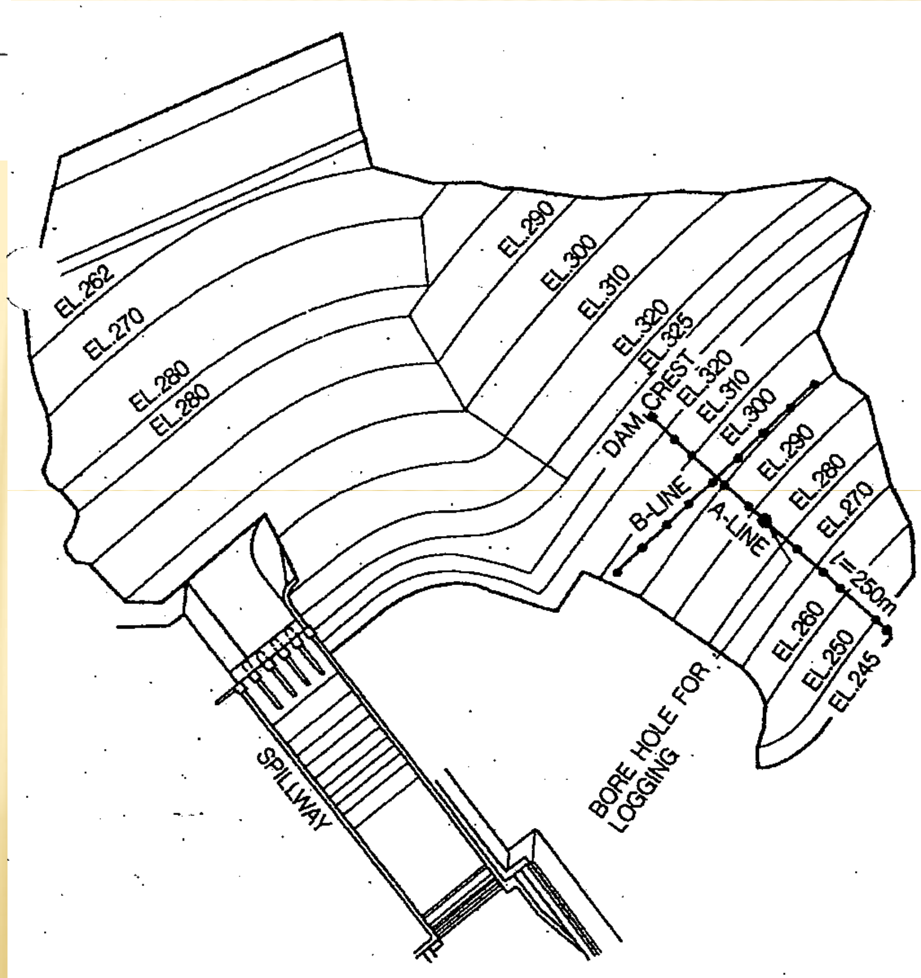


The reproduction analysis of Aratozawa dam during the 2008 Earthquake

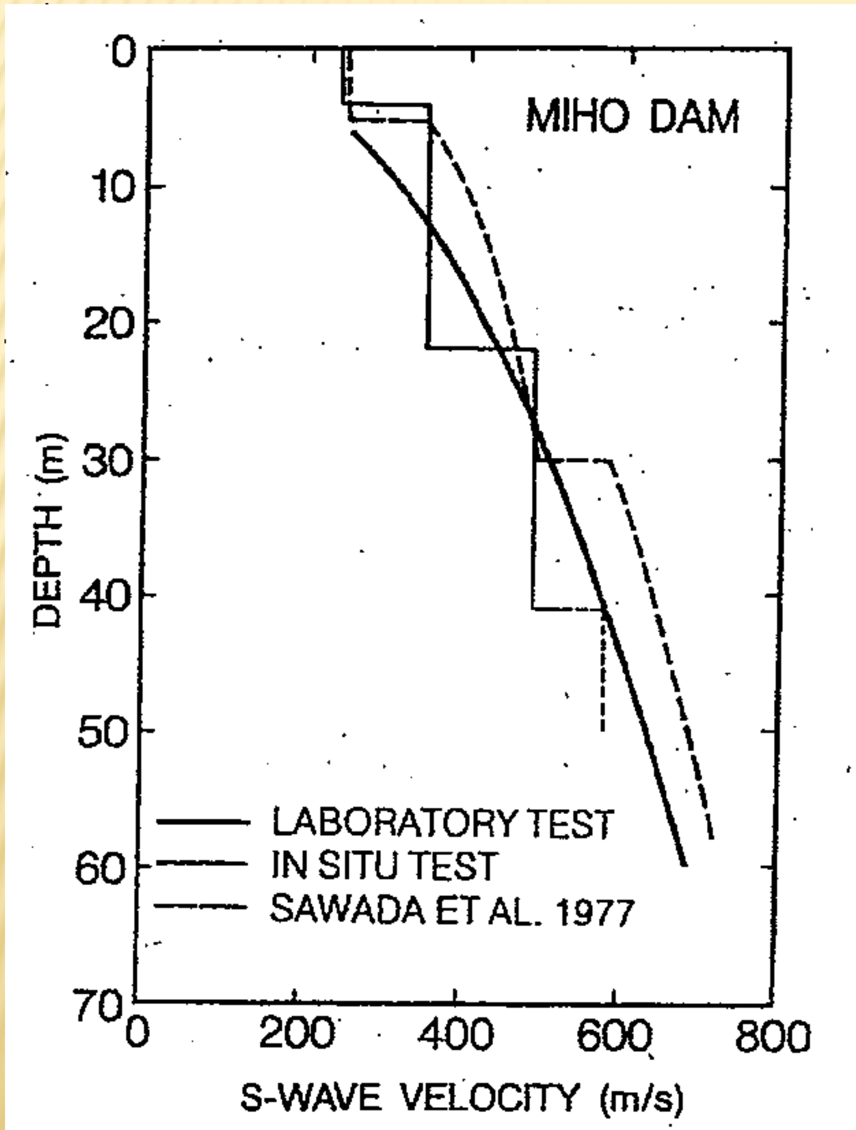
Measurement of shear wave velocity

Case of Miho dam

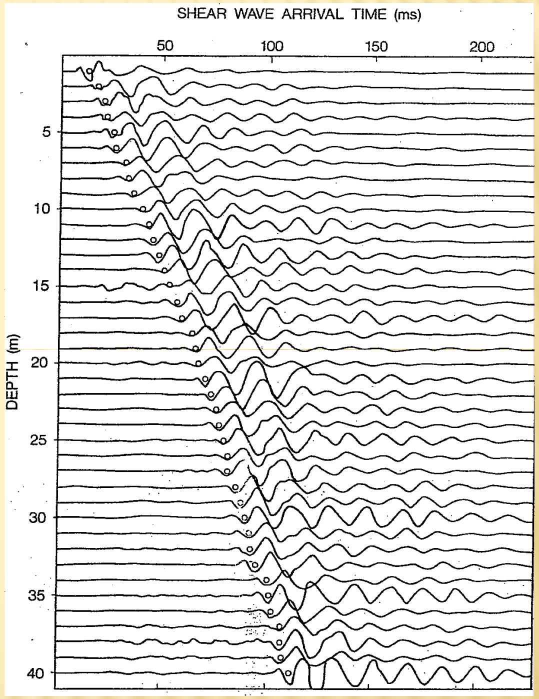




Measurement of shear wave velocity



Case of Miho dam



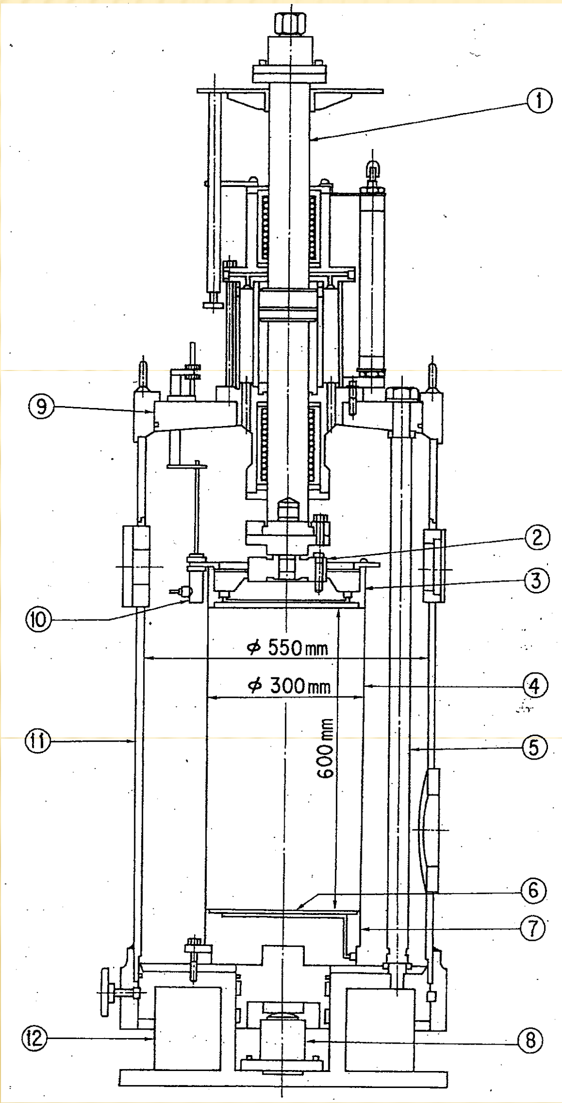
$$G_{max} = 558\ P_a \frac{(2.17-e)^2}{1+e}\left(\frac{\sigma'_m}{P_a}\right)^{0.88} \quad \text{(Miho Dam)}$$

$$\sigma'_m = \frac{1}{3}(1+K)\rho_t g D$$

$$V_s = \left(\frac{G_{max}}{\rho_t}\right)^{0.5}$$

Measurement of shear wave velocity

Case of Miho dam



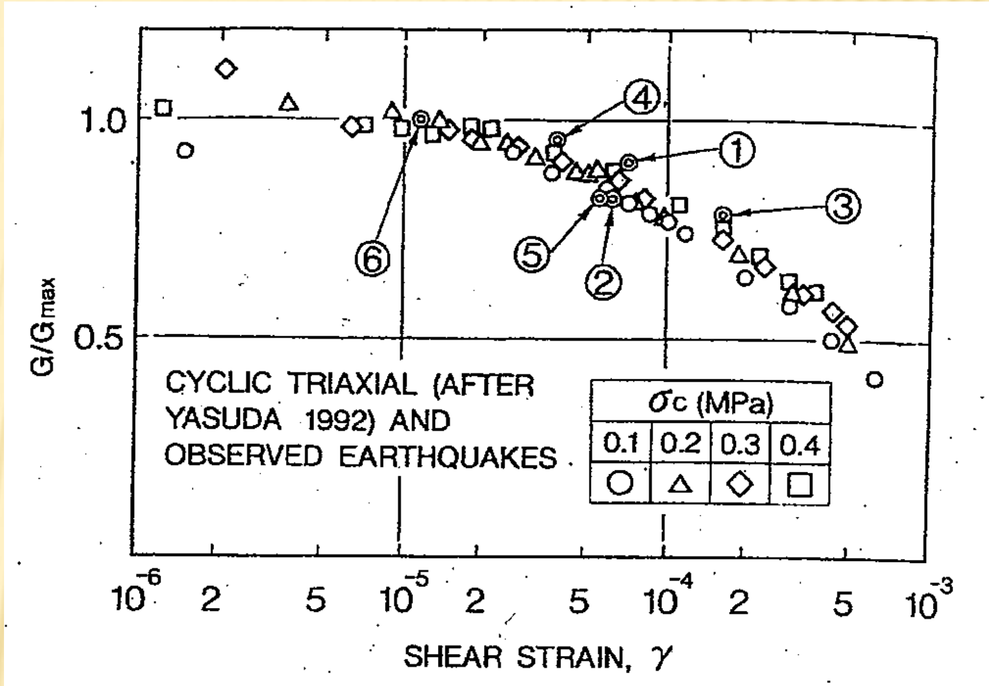
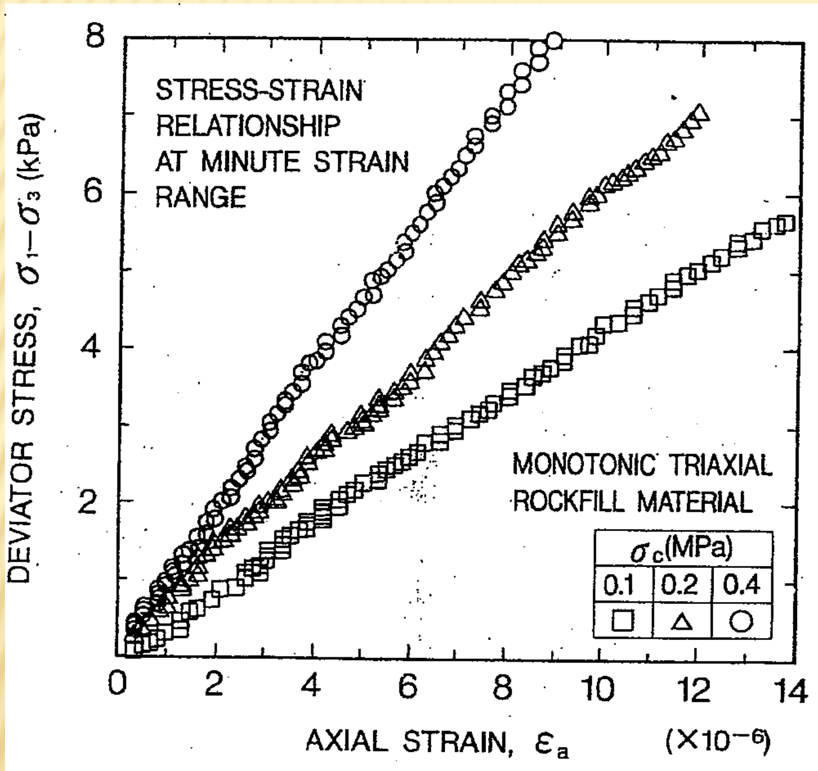


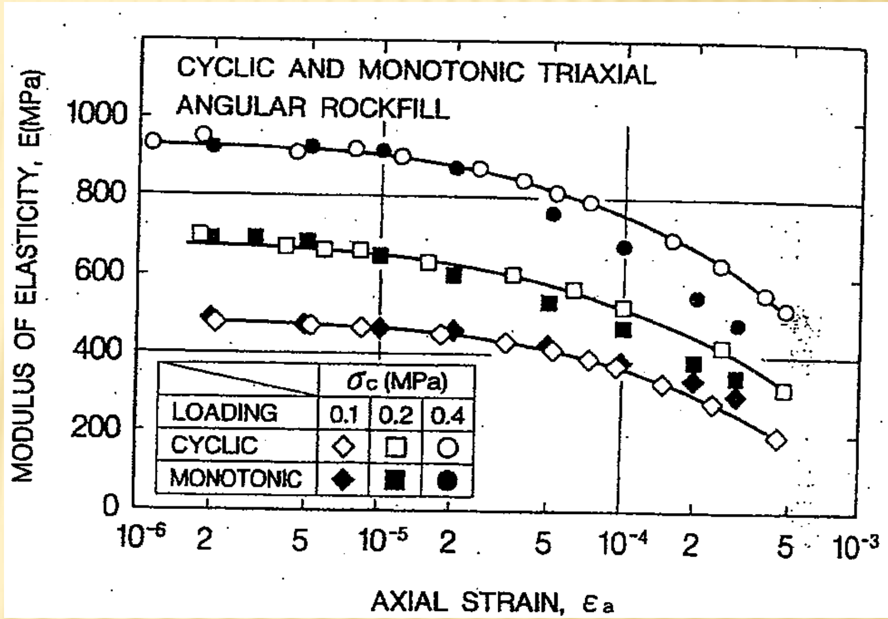
TABLE 4. Data from six earthquakes at Miho Dam for comparison with those from laboratory

	Name of earthquake	Date	Magnitude	1st natural frequency	Shear strain	Reduction of shear modulus
1	Izu Peninsula Off	29 June 1980	6.7	1.95	6.37×10^{-5}	0.91
2	East Yamanashi	14 April 1981	4.5	1.86	5.40×10^{-5}	0.82
3	West Kanagawa	8 Aug. 1983	6.0	1.81	1.63×10^{-4}	0.78
4	Chiba West Off	17 Dec. 1987	6.7	2.00	4.00×10^{-5}	0.95
5	Hakone	5 Aug. 1990	5.1	1.86	5.35×10^{-5}	0.82
6	Tokyo Bay	2 Feb. 1992	5.7	2.05	2.22×10^{-5}	1.00

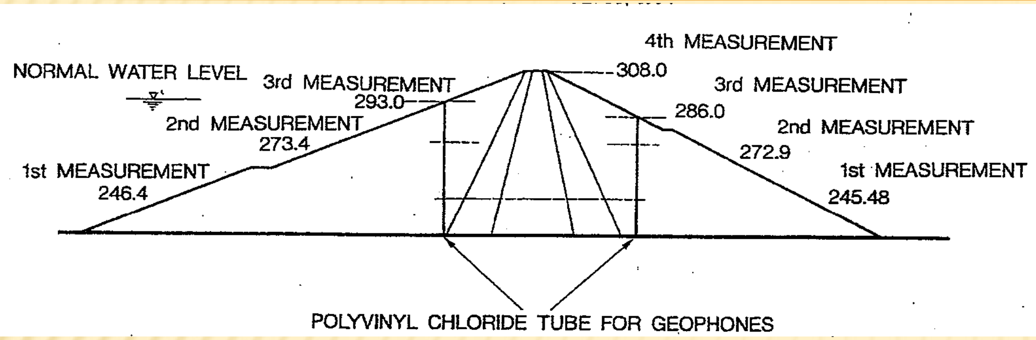
Measurement of shear wave velocity

Case of Miho dam

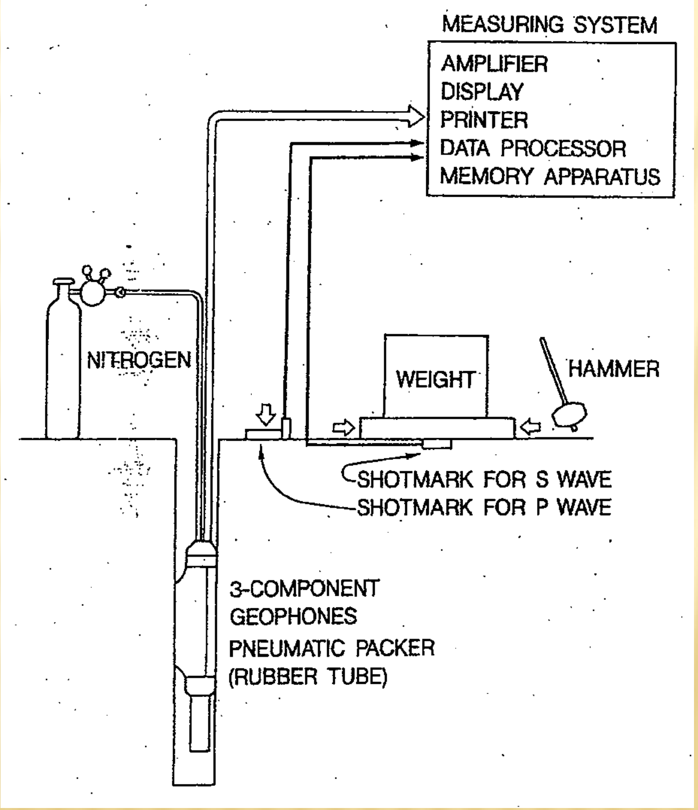




Measurement of shear wave velocity

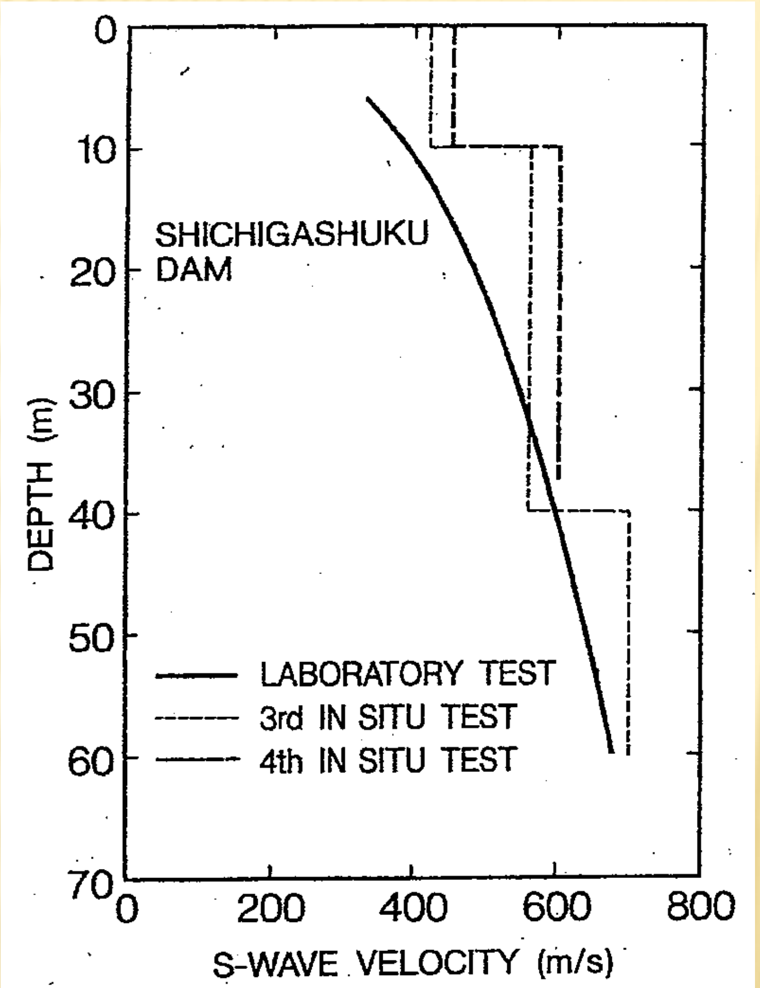


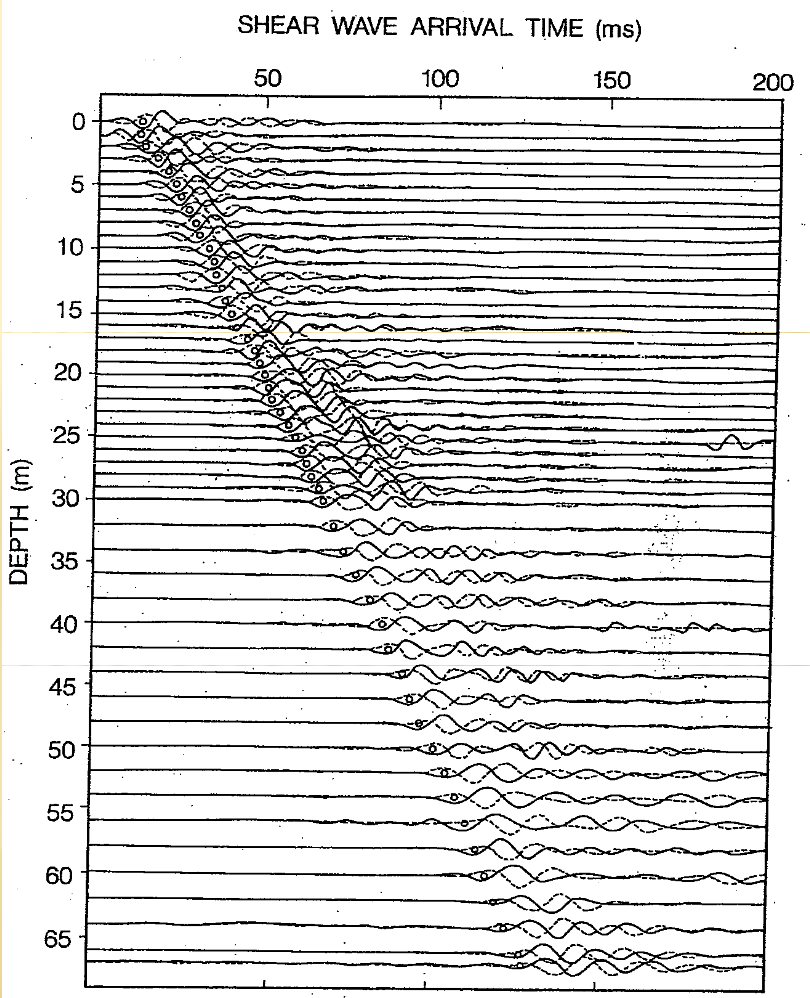
Case of Shichigasyuku dam



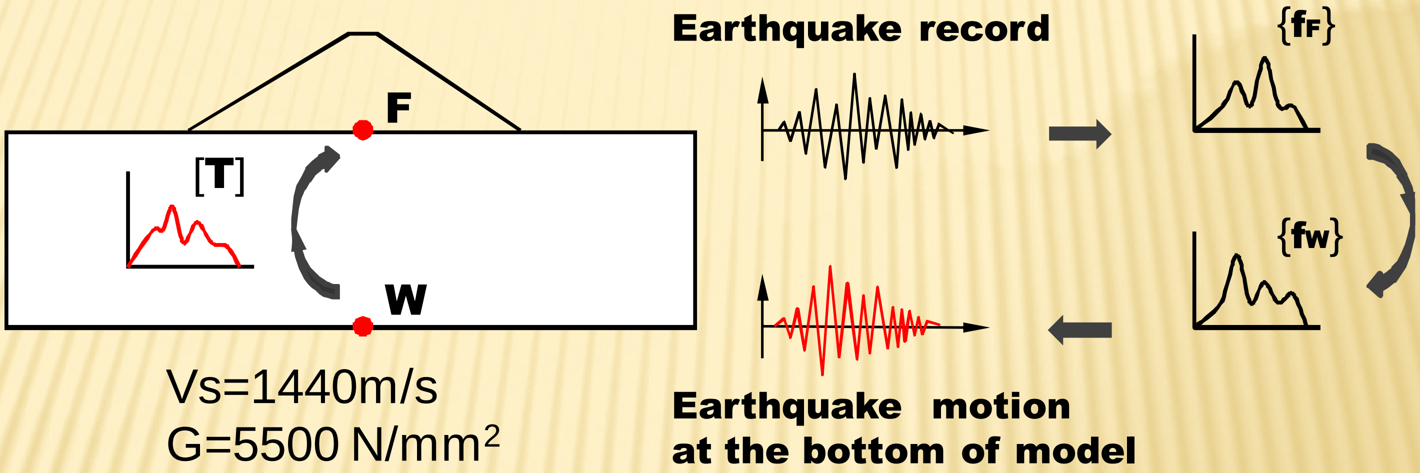
Measurement of shear wave velocity

Case of Shichigasyuku dam





6-3 Reproduction of Earthquake Motion at the Bottom of the Analytical Model



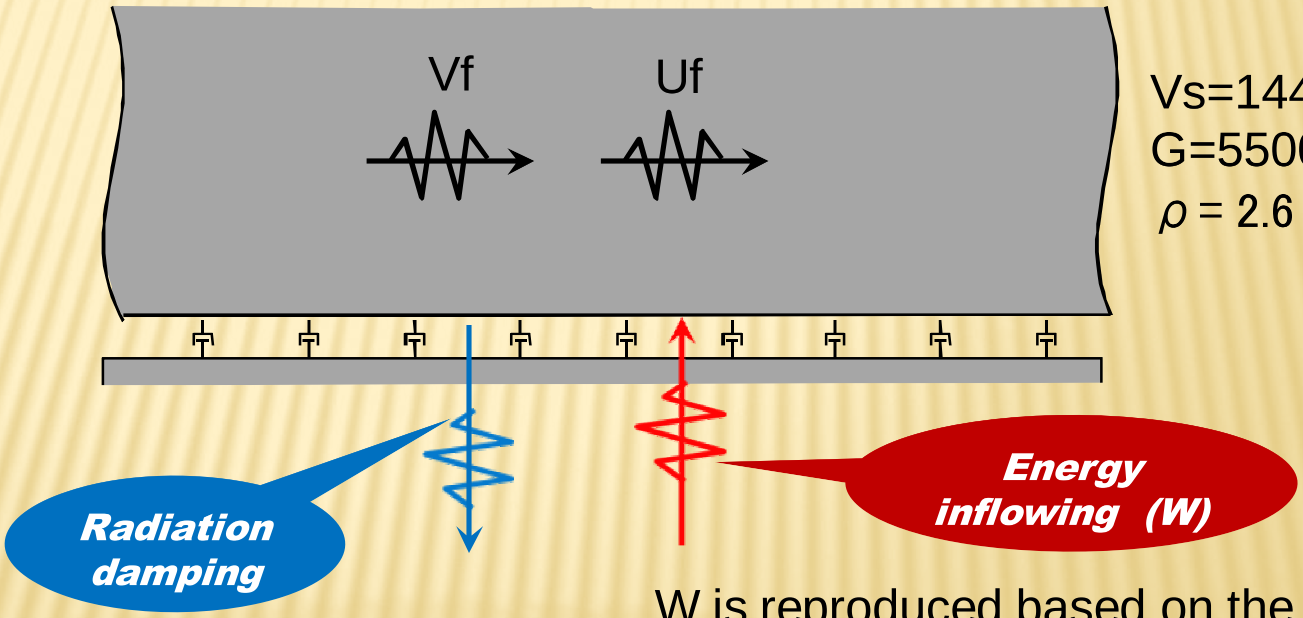
Vs=1440m/s
G=5500 N/mm^2
ρ = 2.6 t/m^3

$$\begin{Bmatrix} F_{AX} \\ F_{AY} \\ F_{AZ} \end{Bmatrix} = \begin{bmatrix} T_{XX} & T_{YX} & T_{ZX} \\ T_{XY} & T_{YY} & T_{ZY} \\ T_{XZ} & T_{YZ} & T_{ZZ} \end{bmatrix} \begin{Bmatrix} F_{BX} \\ F_{BY} \\ F_{BZ} \end{Bmatrix}$$

6-4 Boundary condition (1/2)

First, input the earthquake wave (W) to the bottom of free field, to get the velocity response (Vf) and the displacement response (Uf) of the free field.

Free field

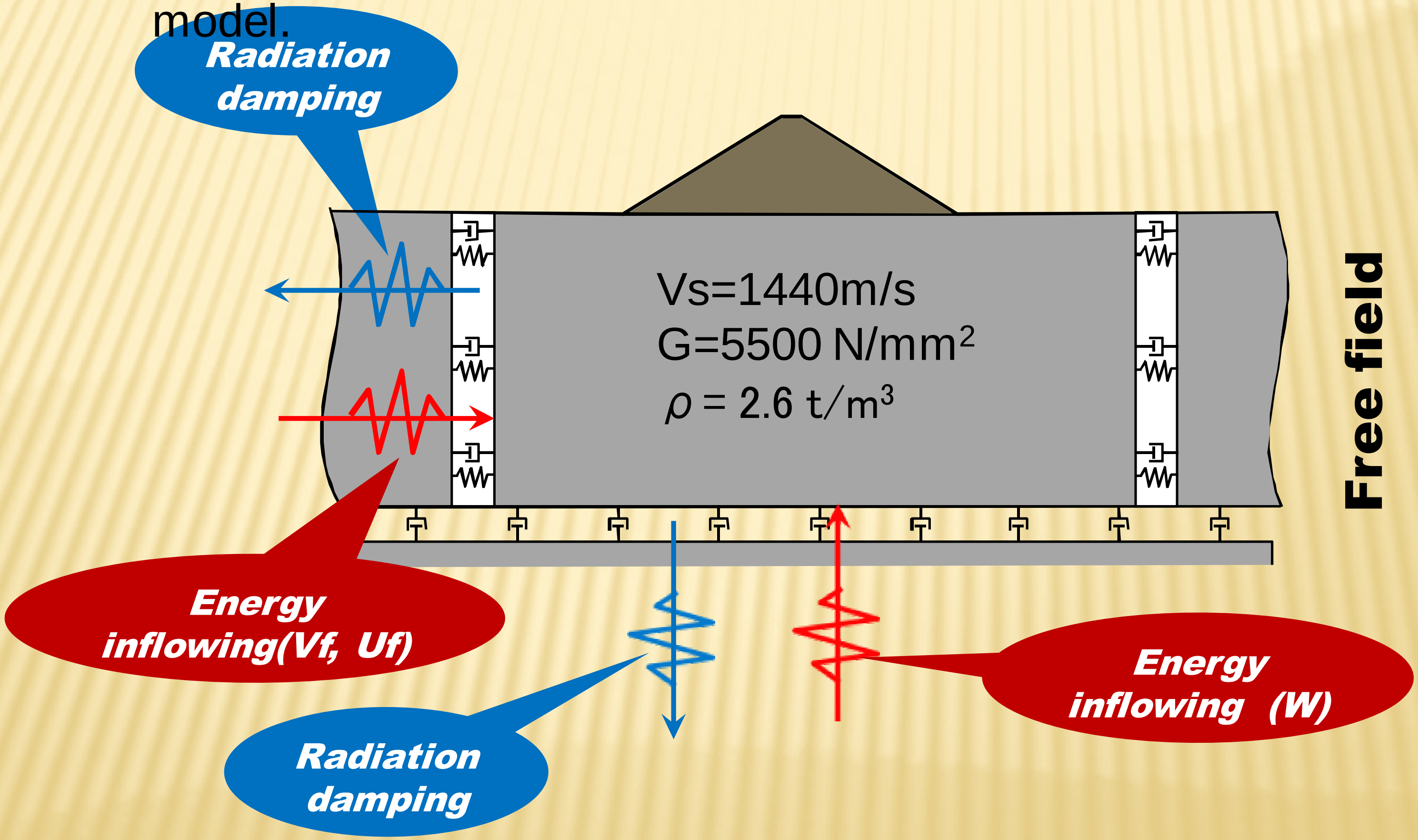


Vs=1440m/s
G=5500 N/mm^2
ρ = 2.6 t/m^3

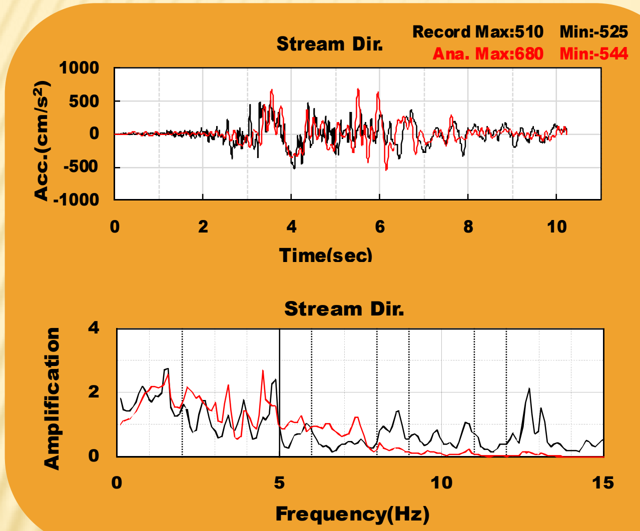
W is reproduced based on the earthquake record of the foundation (F)

6-4 Boundary condition (2/2)

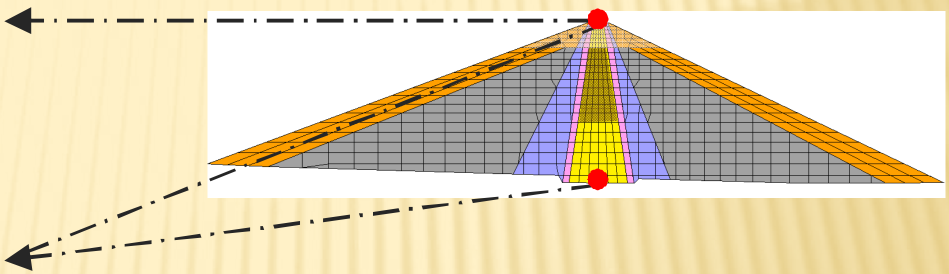
Then, input the earthquake wave (W) to the bottom of foundation, and at the same time, input the responses of the free field (Vf, Uf) to the lateral boundary of the foundation, to get the responses of the whole model.



6-5 Identification of reference strain and damping ratio (1/2)



Earthquake Response Analysis

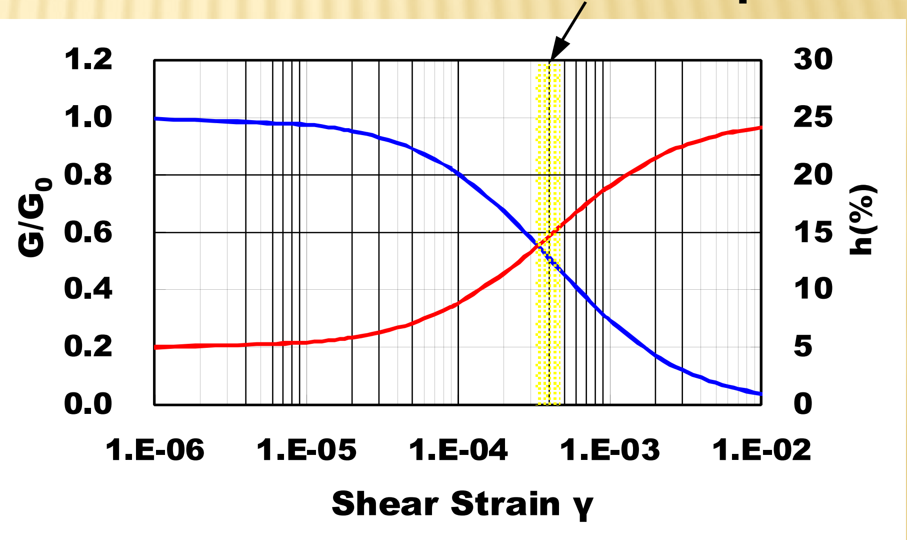


By adjusting γ_r & h_{max}

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

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

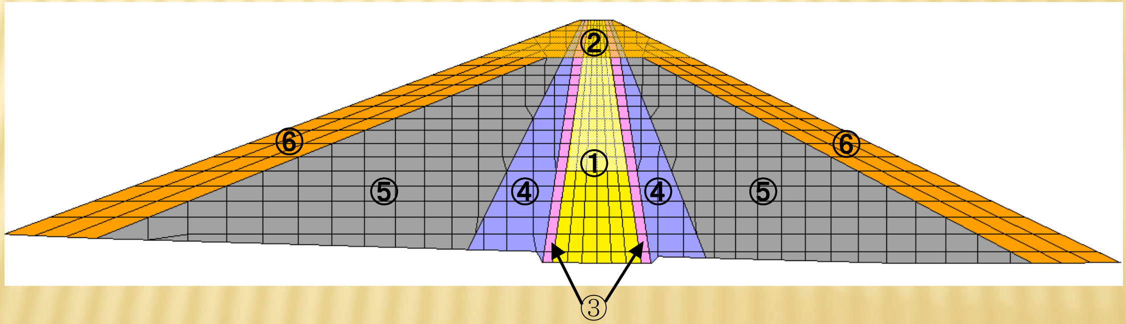
Reference strain γ_r



The reproduction analysis of Aratozawa dam during the 2008 Earthquake

6-5 Identification of reference strain and damping ratio (2/2)

Category	Max. damping	Reference shear strain
① Core (lower parts)	20%	3.0×10^{-4}
② Core (upper part)	30%	
③ Filter ④ Transition	30%	4.0×10^{-4}
⑤ Rock (inner) ⑥ Rock (outer)	23%	



Identification of material properties

6-6 Damping and it's nonlinearity

Rayleigh type

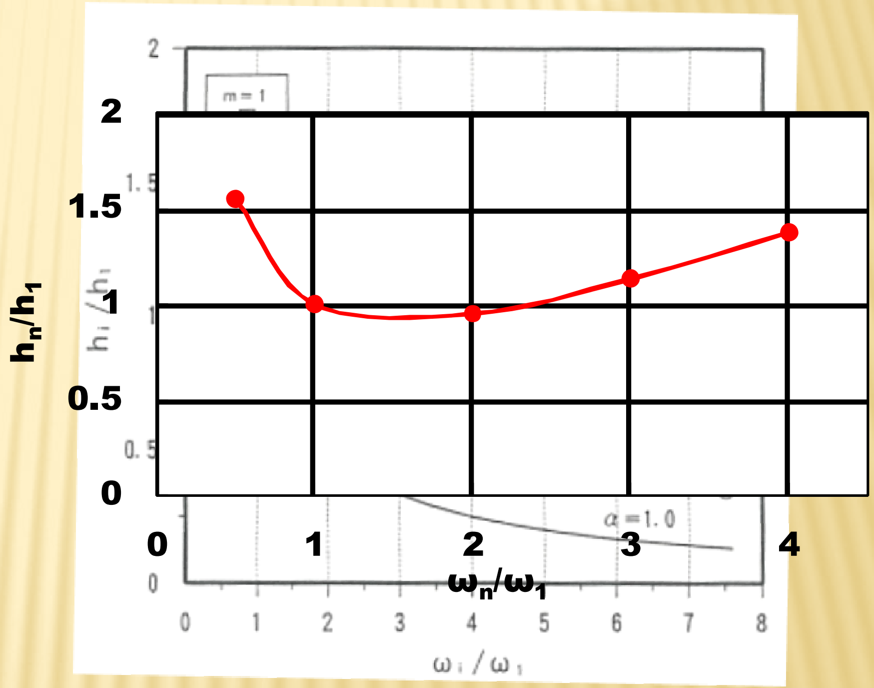
$$[C]^e = \alpha[M]^e + \beta[K]^e$$

Here:

$$\alpha = f(h,\omega_1)$$

$$\beta = g(h,\omega_1)$$

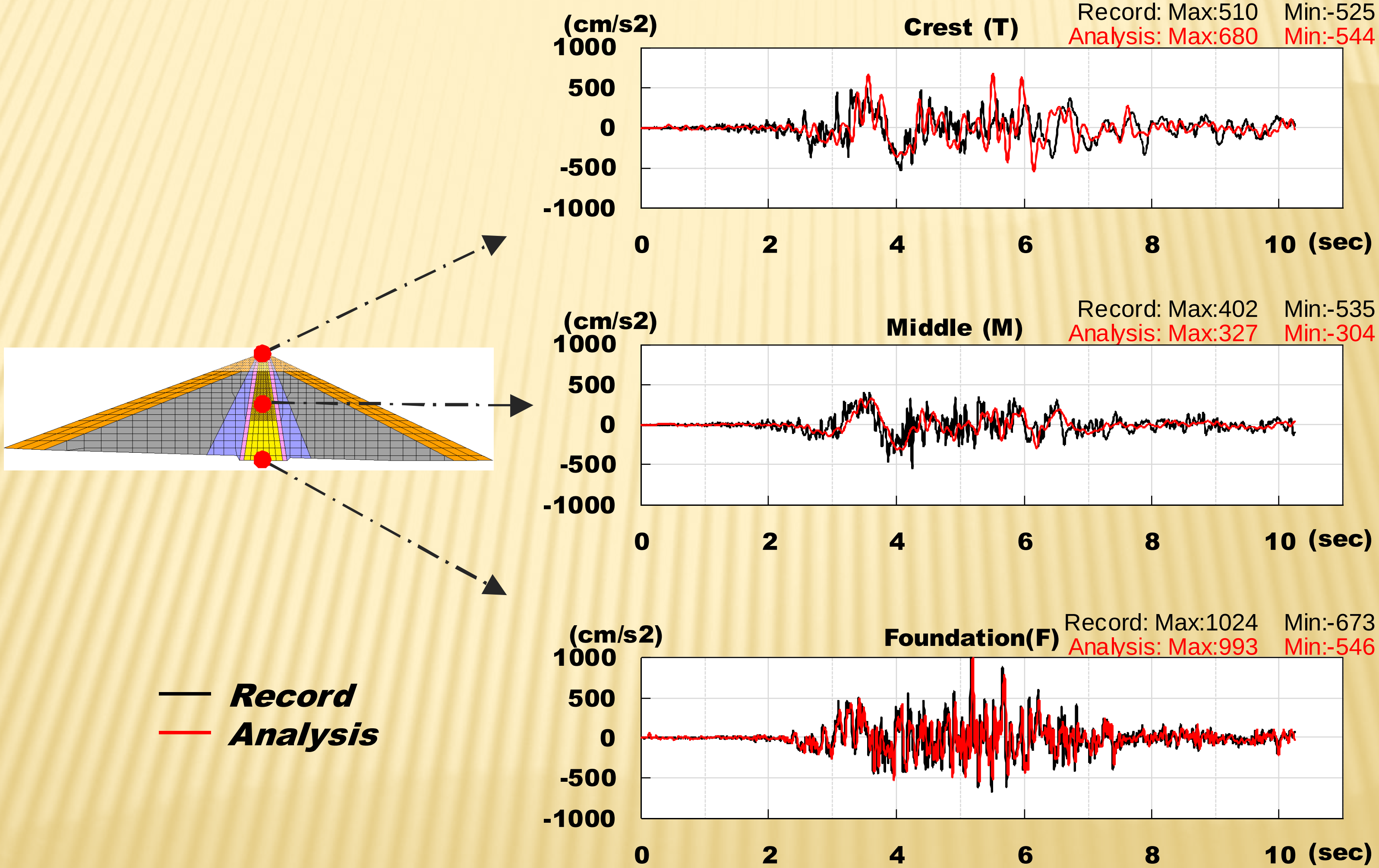
$$h = h_{max}\frac{\gamma}{\gamma + \gamma_r} + h_0$$



Based on the frequency independency of internal damping of soil materials

7-1 Acceleration response (1/3)

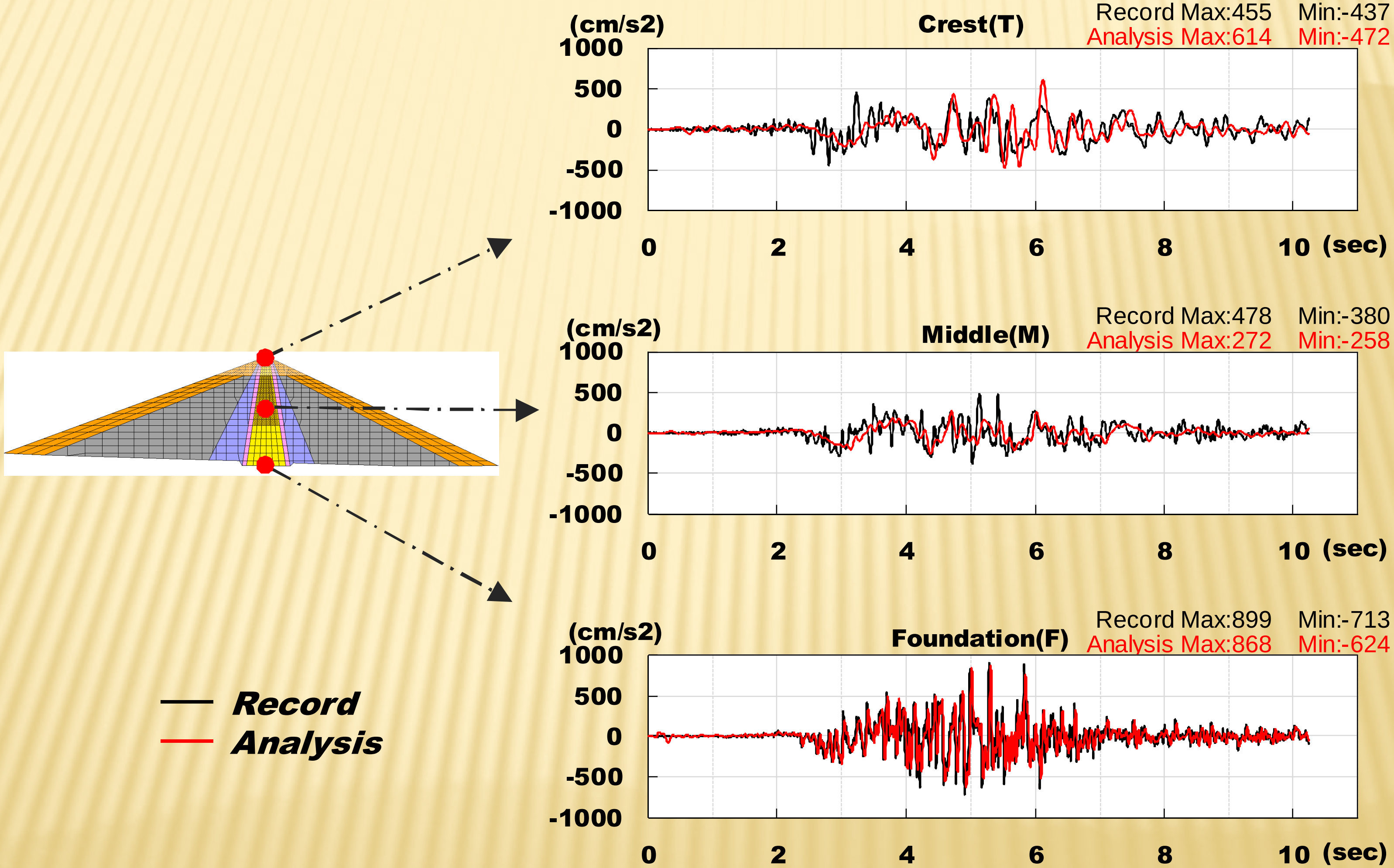
Stream Direction



The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-1 Acceleration response (2/3)

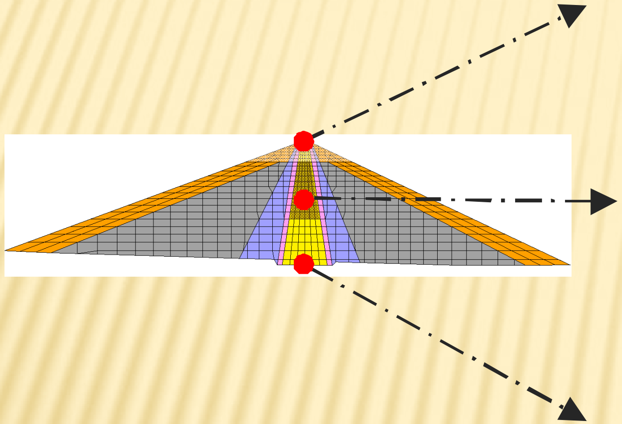
Cross Stream Direction

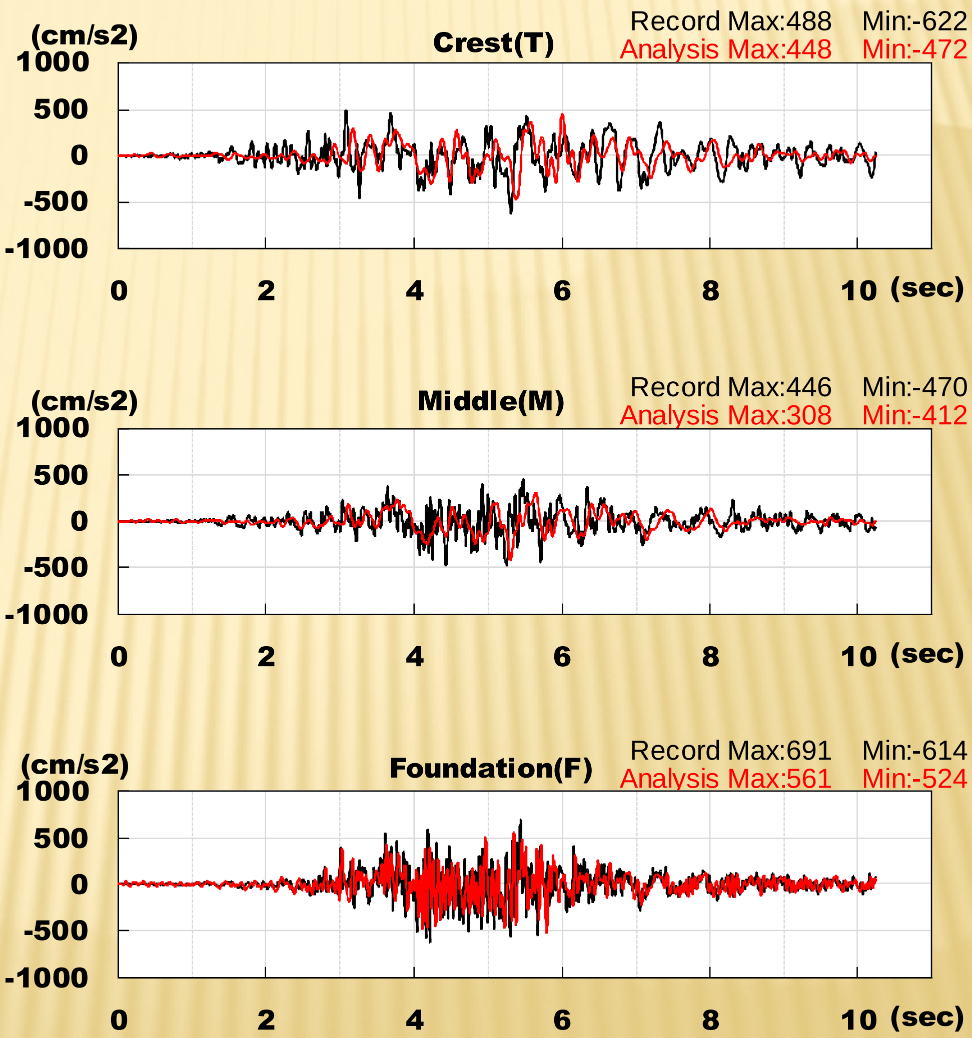


The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-1 Acceleration response (3/3)

Vertical Direction

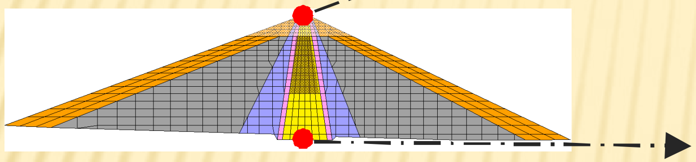


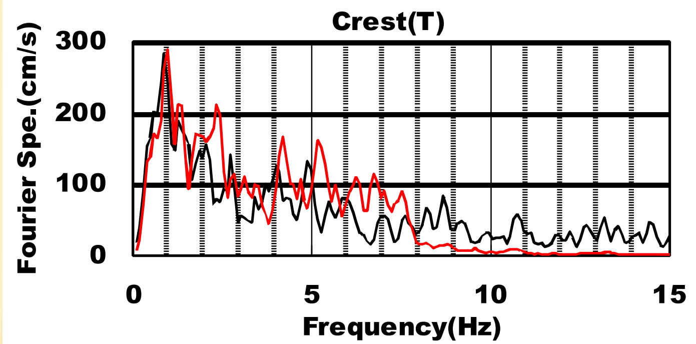


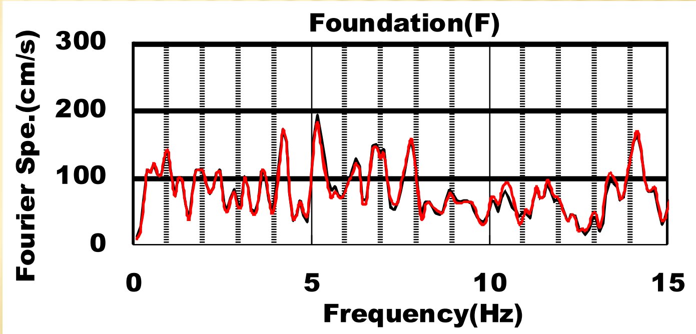
The reproduction analysis of Aratozawa dam during the 2008 Earthquake

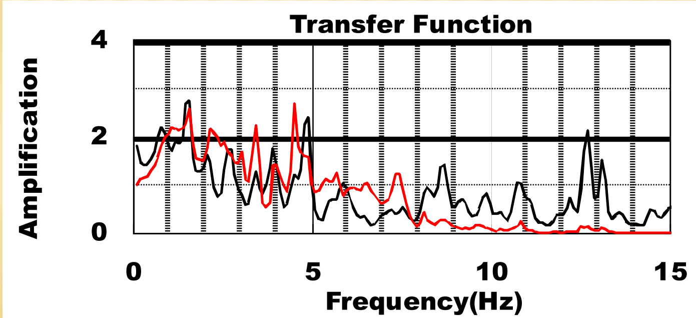
7-2 Spectra & transfer functions (1/6)

Stream Direction







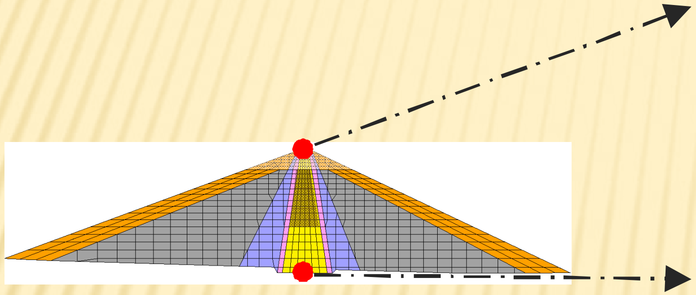


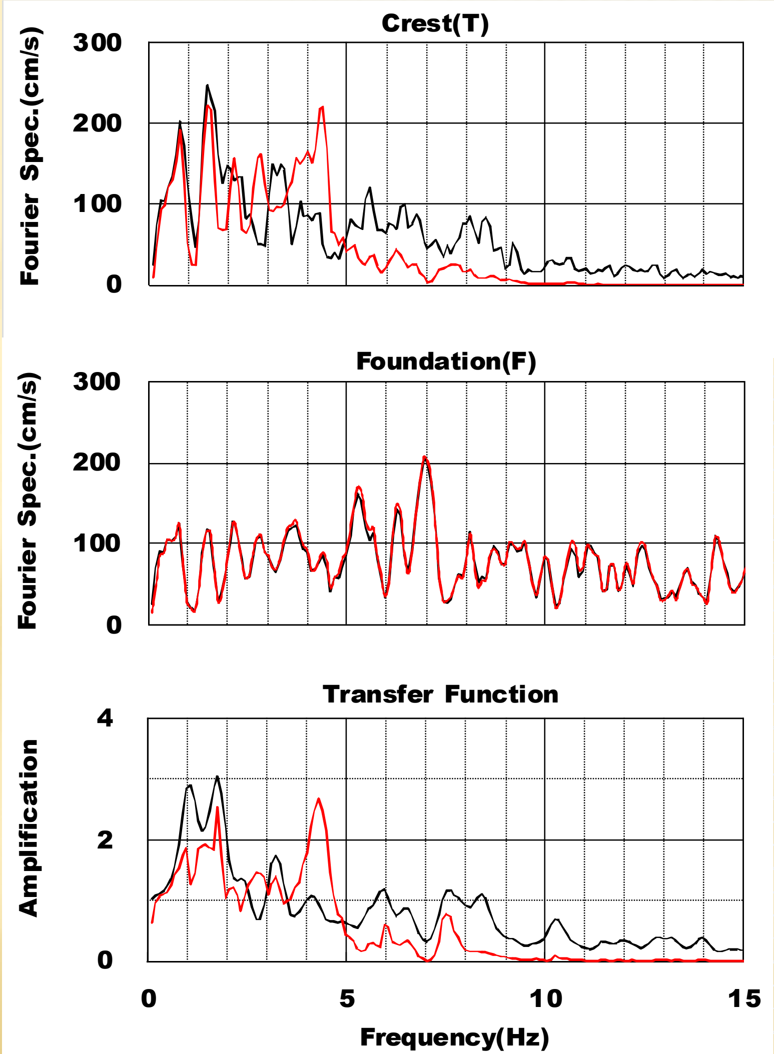
Record
Analysis

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-2 Spectra & transfer functions (2/6)

Cross Stream Direction



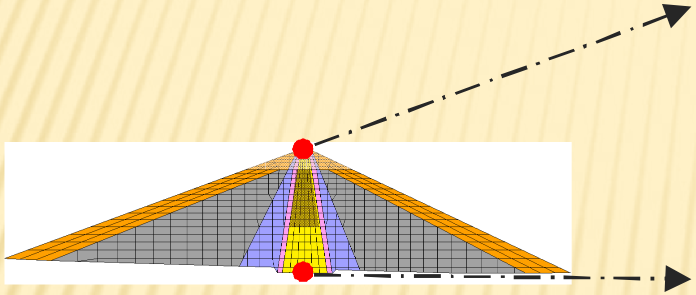


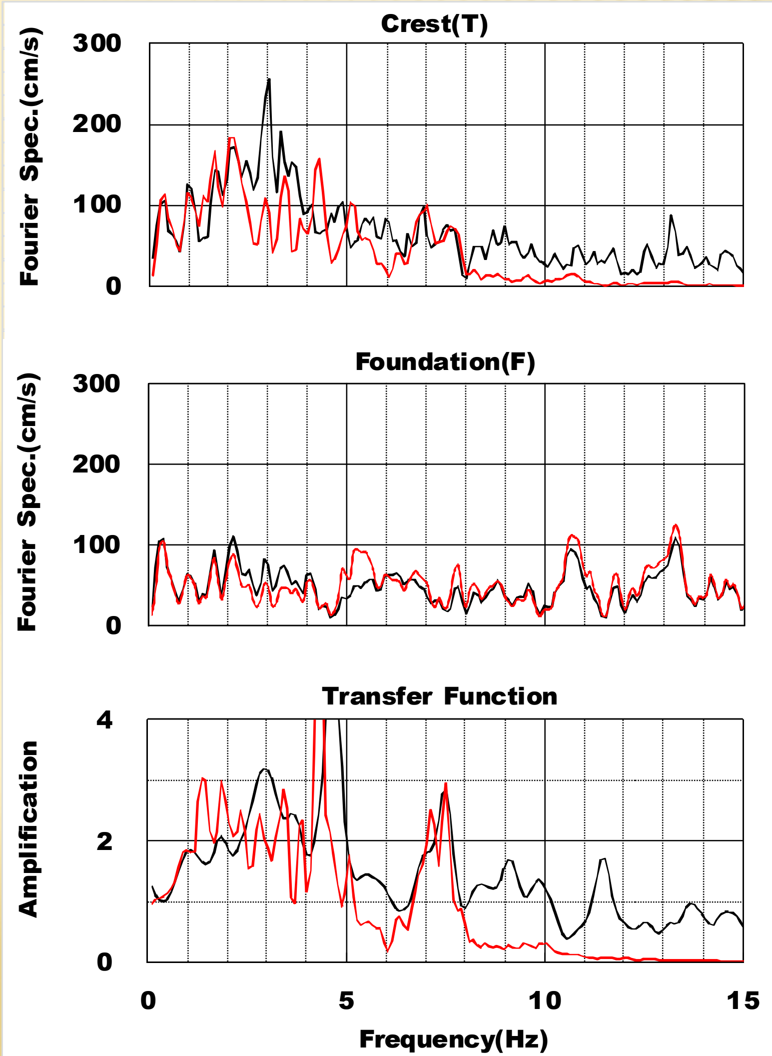
Record
Analysis

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-2 Spectra & transfer functions (3/6)

Vertical Direction



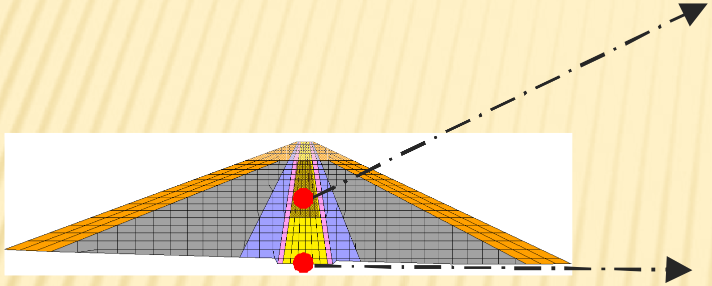


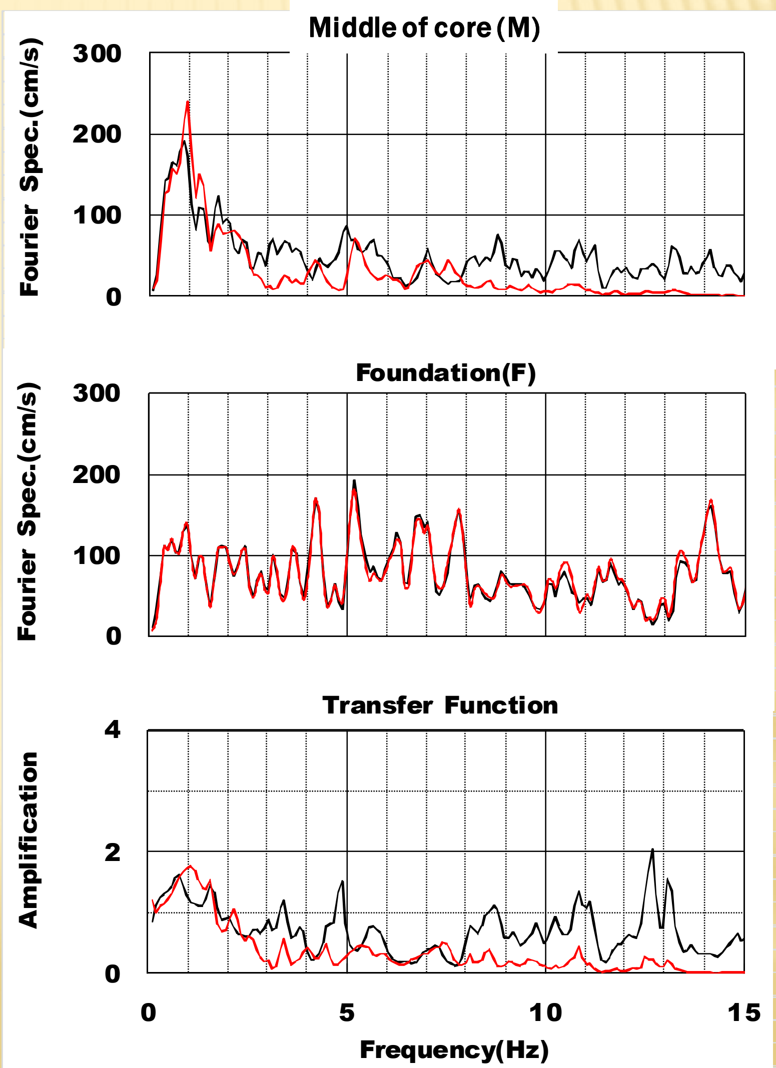
Record
Analysis

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-3 Spectra & transfer functions (4/6)

Stream Direction



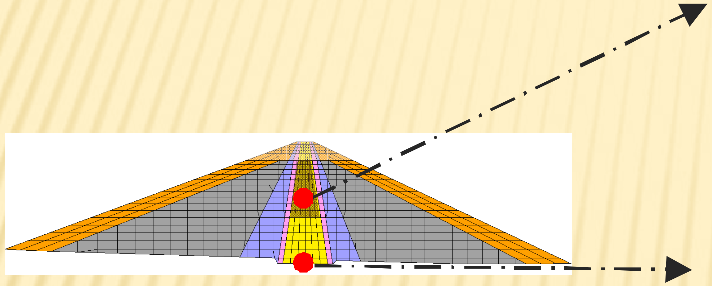


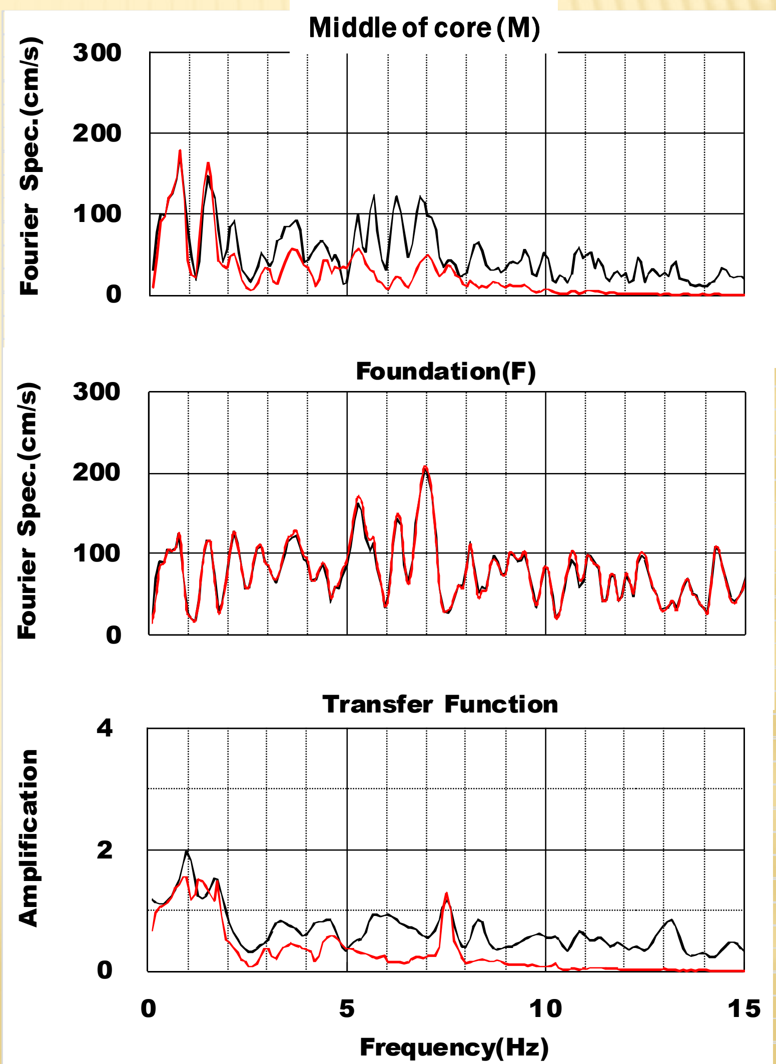
Record
Analysis

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-3 Spectra & transfer functions (5/6)

Cross Stream Direction



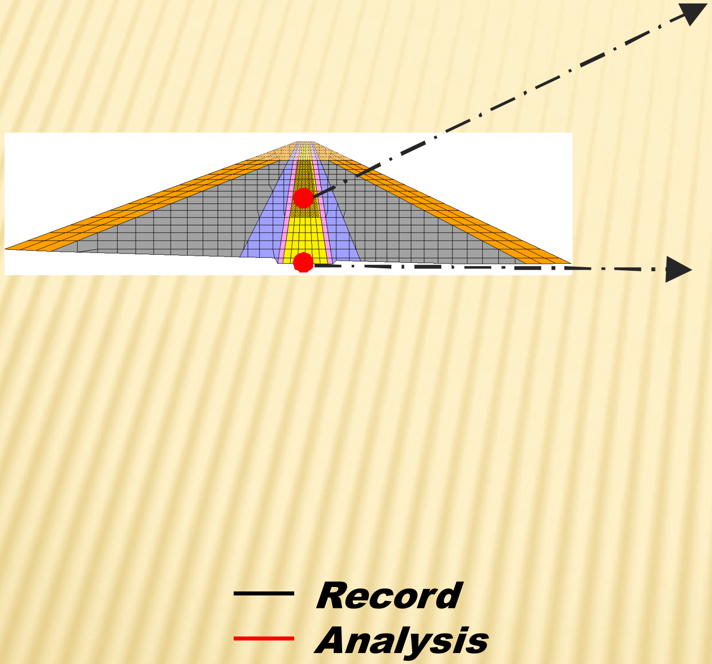


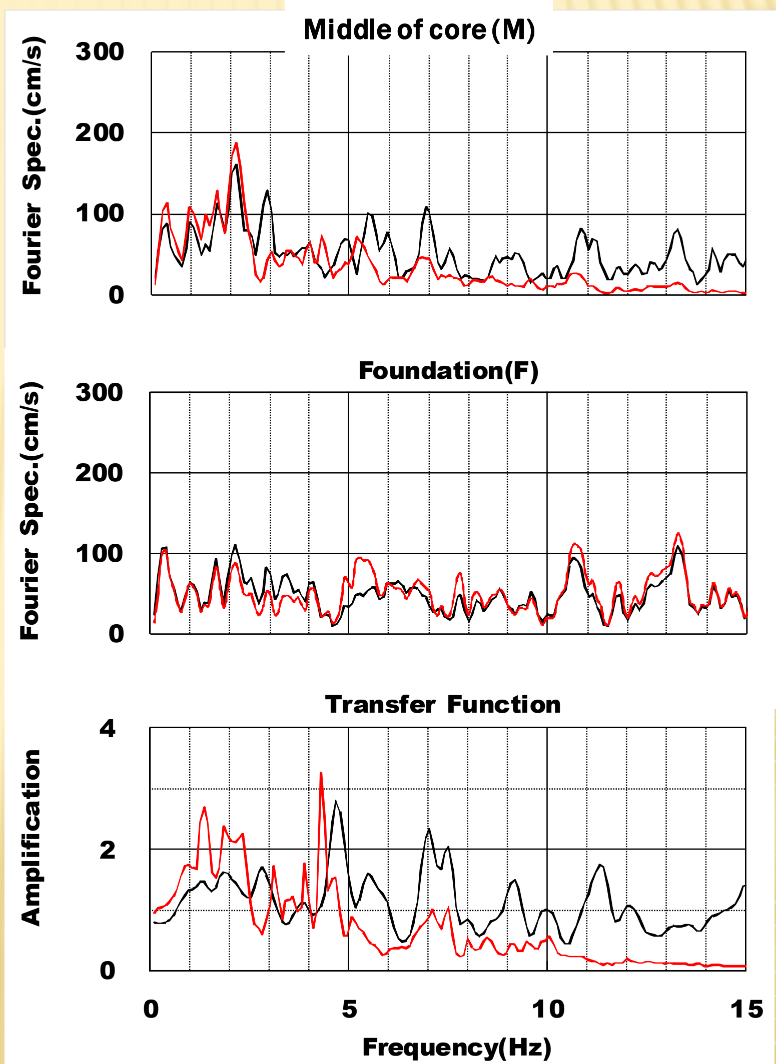
Record
Analysis

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-3 Spectra & transfer functions (6/6)

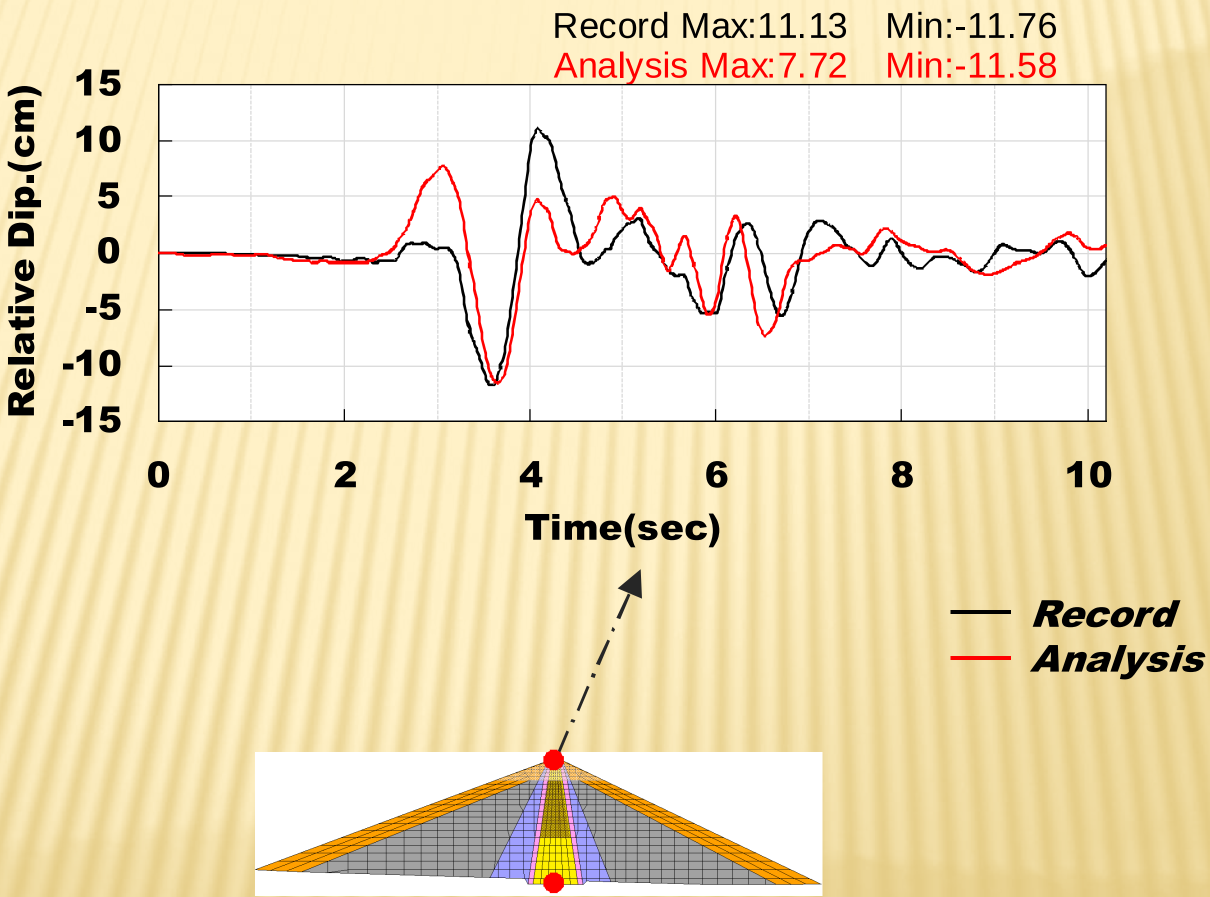
Vertical Direction





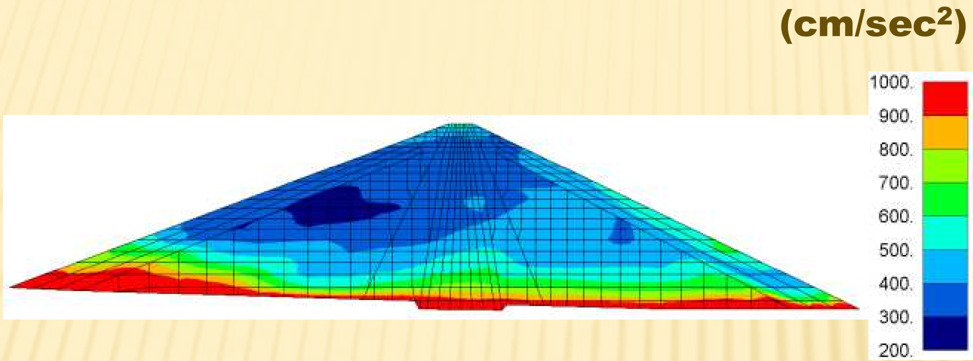
The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-4 Comparison of relative displacement in stream direction

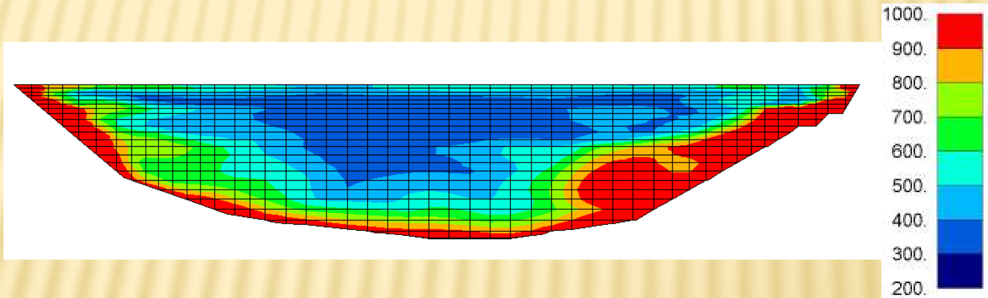


The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-5 Distribution of the max. acceleration



(a) Cross Section

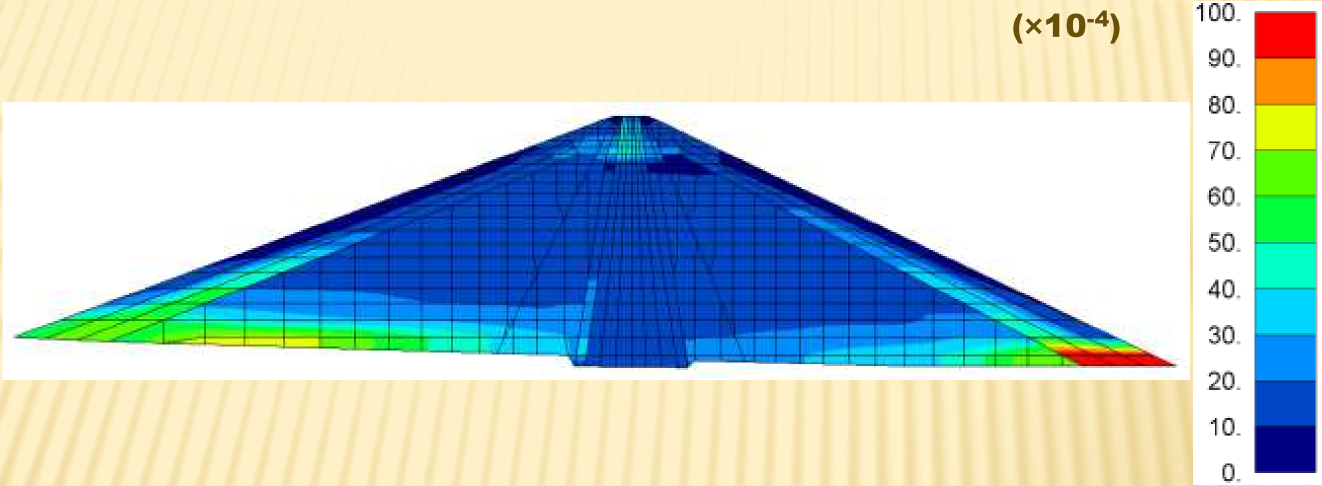


(b) Axial Section

The max. acceleration response of each nodal point in stream dir. occurred at different time.

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

7-6 Distribution of the max. shear strain



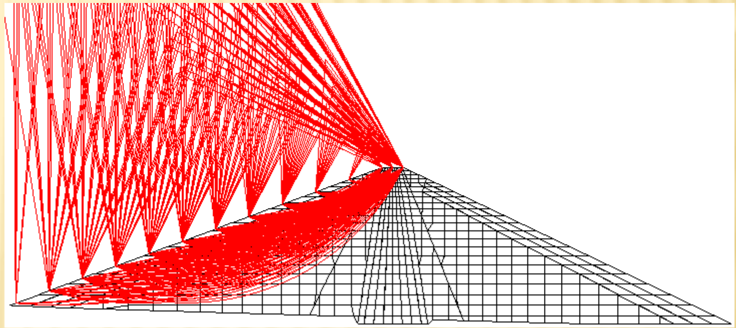
Shear strain	～10^{-4}	10^{-4}～10^{-2}	10^{-2}～
Phenomenon	Wave motion, vibration	Crack, settlement	Sliding, compaction, liquefaction
Mechanical characteristics	Elastic	Plastic	Fracture

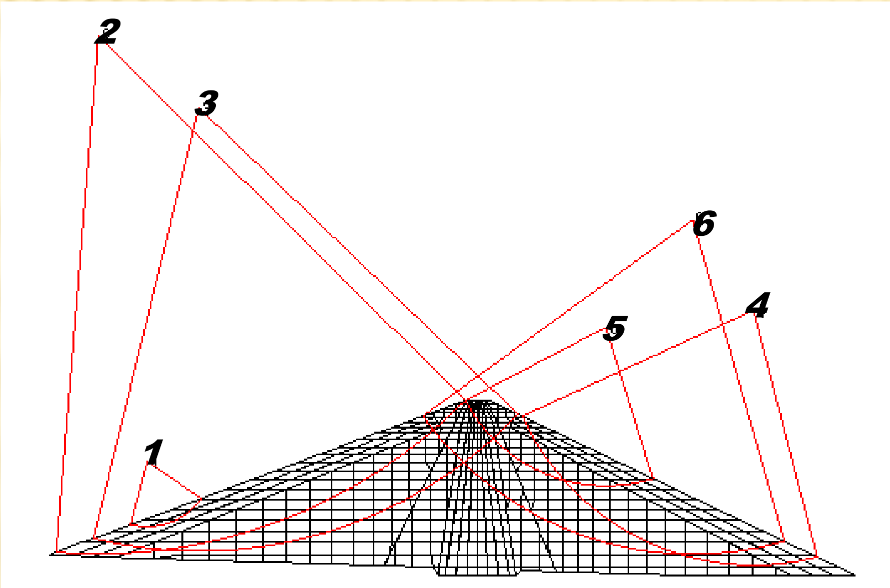
The max. shear strain of each element occurred at different time.

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

8. Mechanism of permanent deformation

8-1 Stability analysis based on circular slip surface

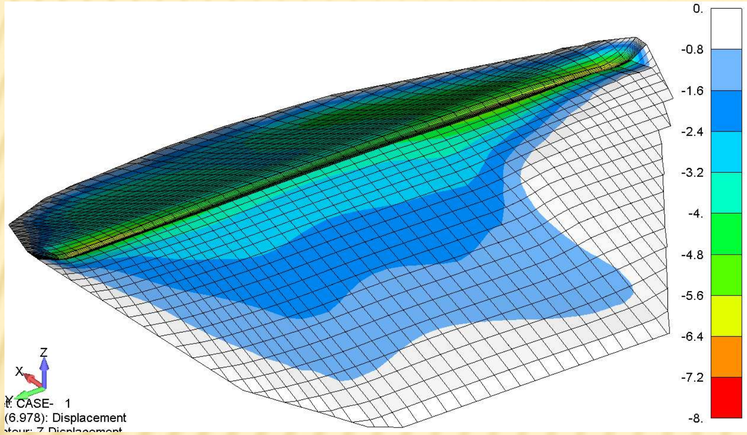




Sliding dir.	Arc No.	Safety Factor	Sliding Disp.(cm)
Upstream side	1	0.839	0.0006
	2	2.027	—
	3	2.395	—
Downstream side	4	2.581	—
	5	2.090	—
	6	2.135	—

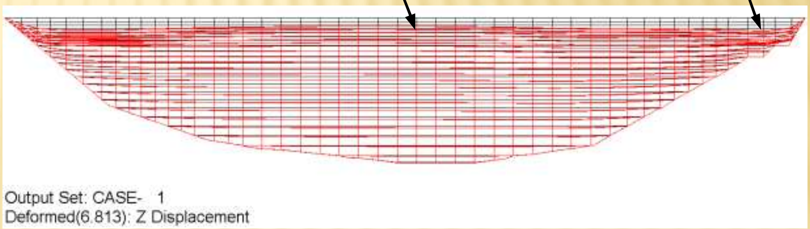
The reproduction analysis of Aratozawa dam during the 2008 Earthquake

8-2 Deformation calculation based on the theory of cumulative damage



4.26 cm

6.81 cm

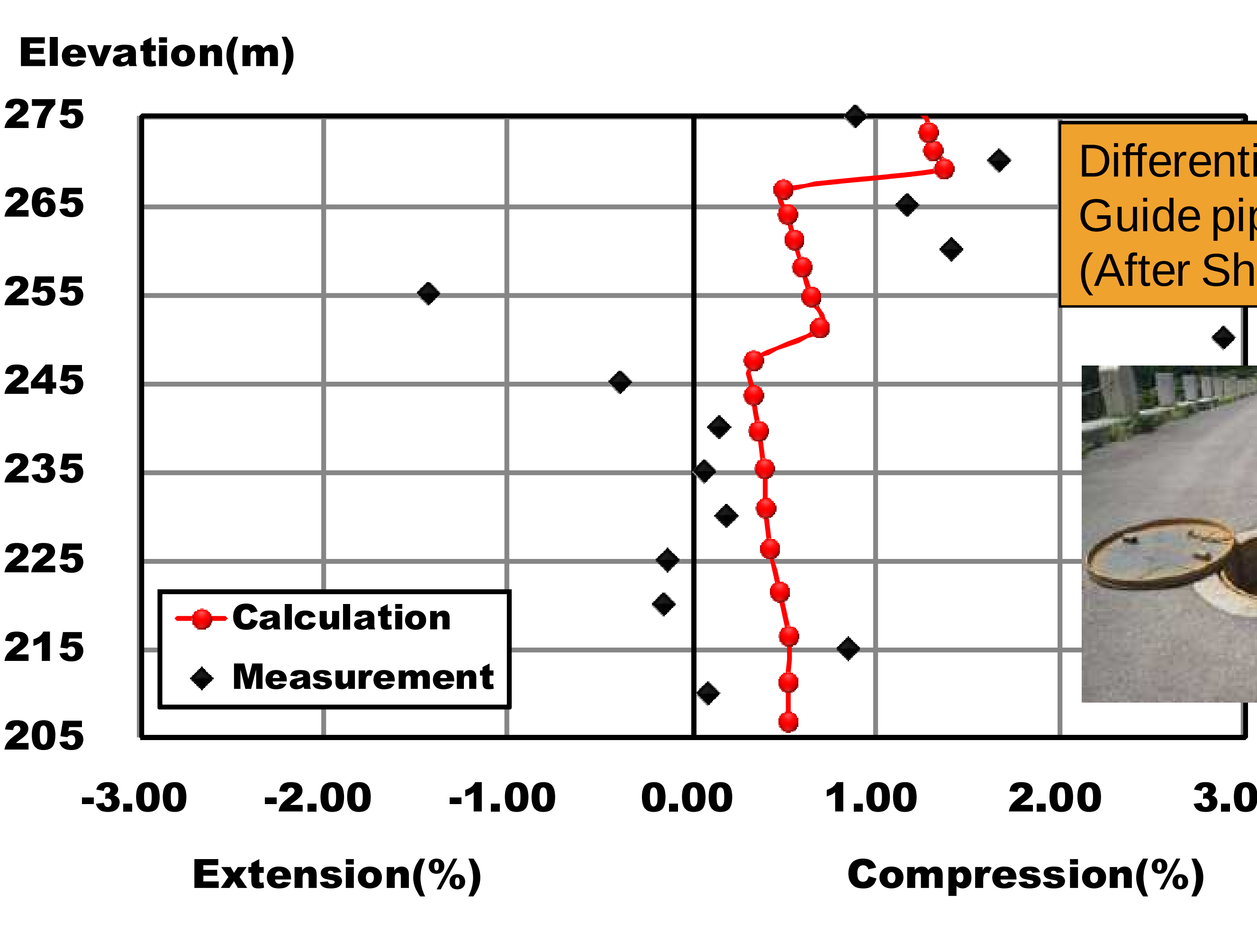


Deformation after the earthquake

$$U_r = U_a - U_b$$

The reproduction analysis of Aratozawa dam during the 2008 Earthquake

8-3 Distribution of the max. shear strain



Differential settlement gage
Guide pipe popped out 40cm.
(After Shimamoto, *et al.* 2008)

Comparison of measured and calculated subsidence strain

(Measurement period: Dec. 4, 2007 to June 17, 2008)

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9. CONCLUSIONS

Mechanism of the peculiar seismic behavior

Large shear strain occurred near the rock contact surface, which reduced the stiffness and increased the damping of the embankment.

The material near the crest and the slope surface became loosely during the earthquake, hence, the high frequency components lost.

Mechanism of permanent deformation

Permanent deformation was mainly due to the shaking subsidence of the soil materials. Sliding phenomenon did not occur during the earthquake.


THANK YOU FOR YOUR ATTENTION