SDM8/9 - THEORY, MEASUREMENT AND MODELLING OF DAMPING FOR SEISMIC RESPONSE ANALYSIS OF LARGE-SCALE STRUCTURES

MONITOR 24

IDENTIFICATION OF DYNAMIC CHARACTERISTICS FOR STEEL ARCH BRIDGE BY SEISMIC OBSERVATION RECORDS

ISHII Yosuke[1], NAKAO Yoshihiro[2] and SHOJI Gaku[3]

[1]Earthquake Disaster Management Division, NILIM, MLIT, Japan, Ph. D. (Eng.)

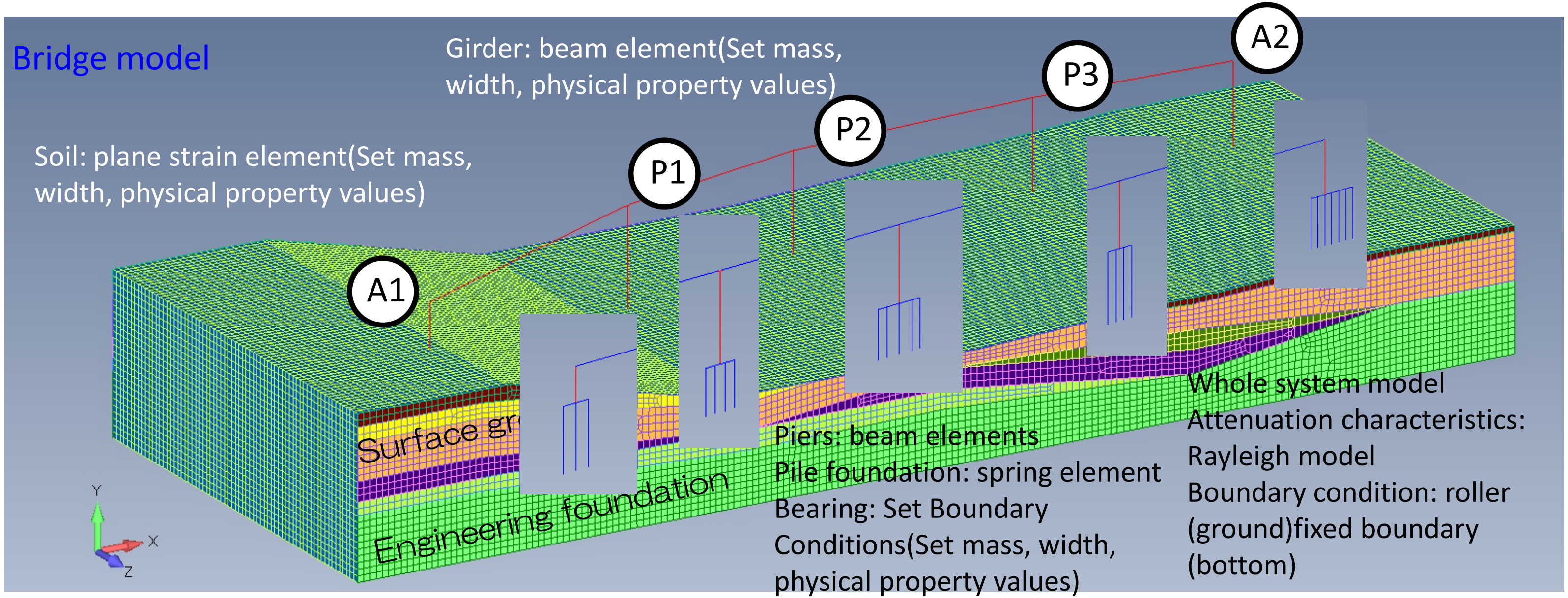
[2]Head of Earthquake Disaster Management Division, NILIM, MLIT, Japan（At the time of the research）

[3]Professor, Faculty of Engineering, Information and Systems, University of Tsukuba, Japan, Dr. Eng

Introduction; Structural characteristics of bridges

- A bridge is a composite structural system consisting of members such as girders, piers, foundations, and the ground.
- Road bridge models are complex due to the inclusion of various elements.

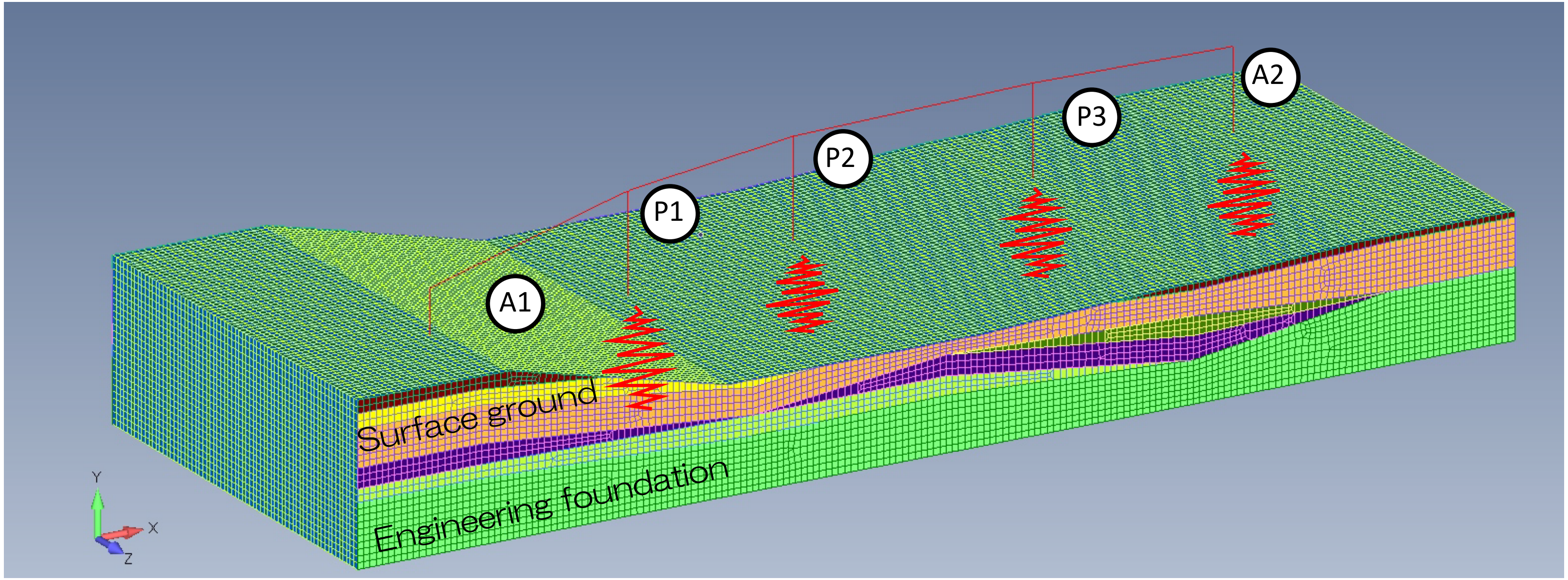
✓ Bridge structure-ground system includes various natural frequencies, damping characteristics, and boundary conditions.



Introduction; Importance of understanding the vibration characteristics of bridges

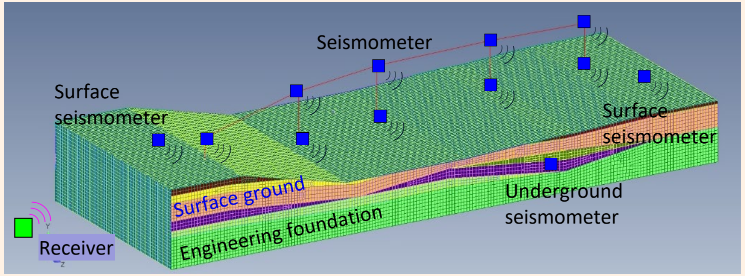
- Road bridges are affected by stationary external forces such as traffic vibrations and unsteady external forces such as seismic ground motion.
- The vibration phenomenon (input-output relationship) of road bridges is difficult to quantitatively understand.
- Vibration of road bridges is excited by the characteristics of external forces.

✓ Need to understand vibration characteristics of bridges by vibration observation.



Introduction; Research framework

Development of the strong motion monitoring system "SMMS"



→*Y. Ishii, Y. Nakao, G. Shoji: EVACES 2023, LNCE, volume 433, pp. 479–489, 2023.*

Observation of bridge structure-ground system vibration records

Comparison

Comparison

Waveform processing

- Identification of dominant frequency

System identification

- Evaluation of natural frequencies, damping characteristics, and vibration modes of bridge structure-ground systems

Modeling

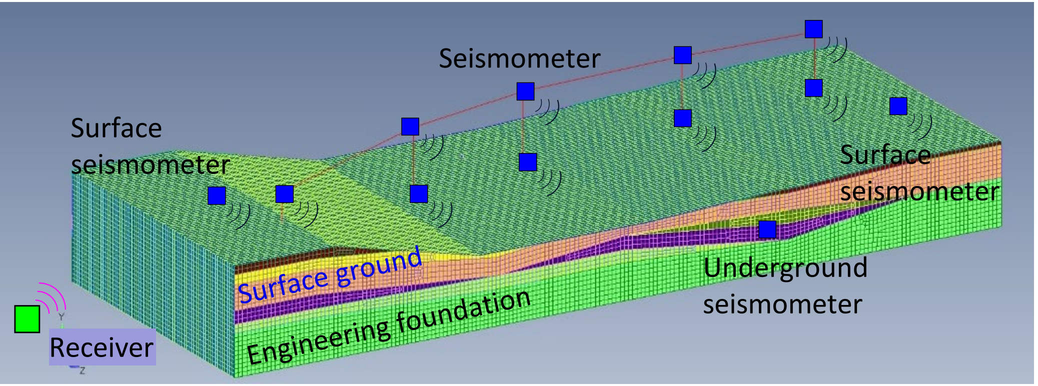
- Estimation of natural vibration mode of analytical model
- Verification of damping characteristics

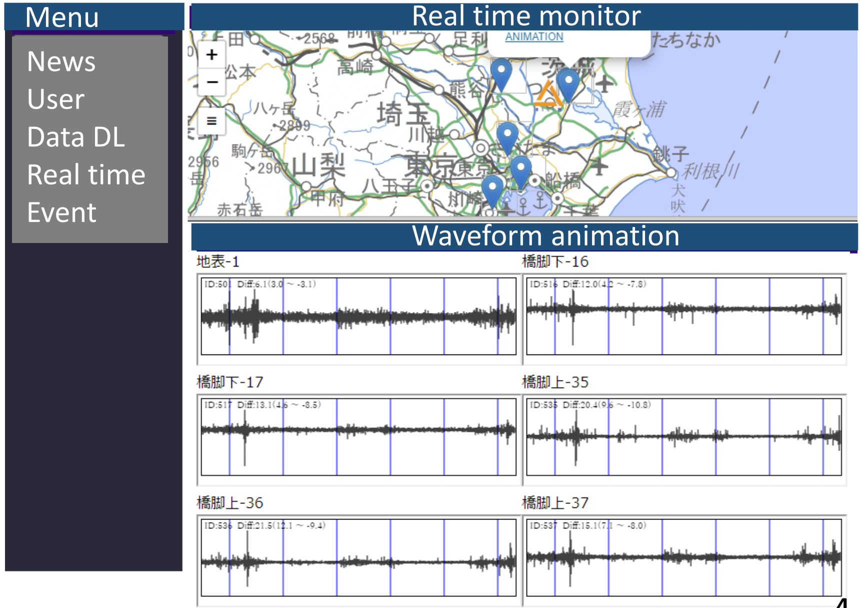
Identification of vibration mode of target bridge by combining multiple methods

Strong Motion Monitoring System

→*Y. Ishii, Y. Nakao, G. Shoji: Estimation of vibration characteristics for a bridge-underground system by subspace model identification method using multi-point monitoring seismic records, EVACES 2023, LNCE, volume 433, pp. 479–489, 2023.*

- Transmission of observation data by wireless communication.
- The seismometer is always working. →SMMS enables continuous vibration observation.





Strong Motion Monitoring System

→Y. Ishii, Y. Nakao, G. Shoji: EVACES 2023, LNCE, volume 433, pp. 479–489, 2023.

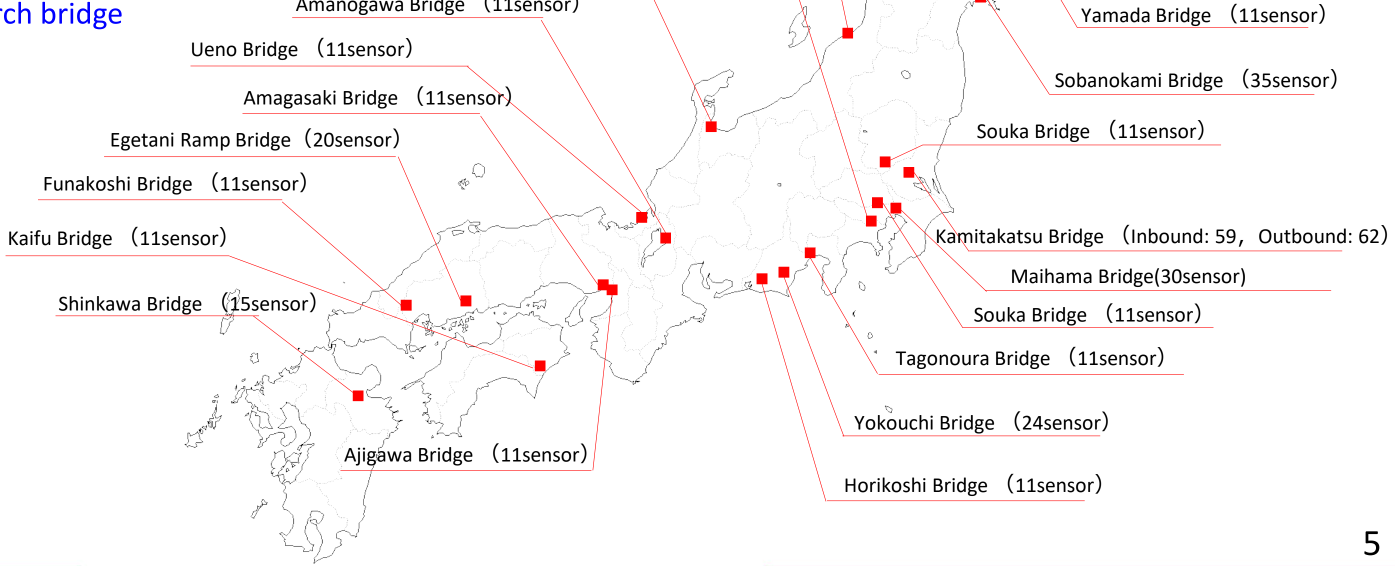
- Installed on road bridges of various structure types designed according to Japanese seismic design standards.

e.g. Girder bridge

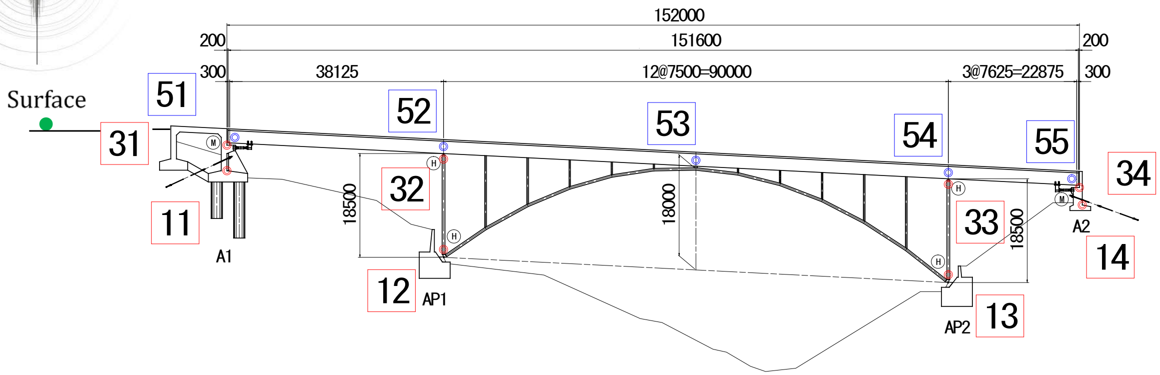
e.g. Arch bridge

e.g. Damping device

Sensor installation status



Case study of SMMS for applying a bridge



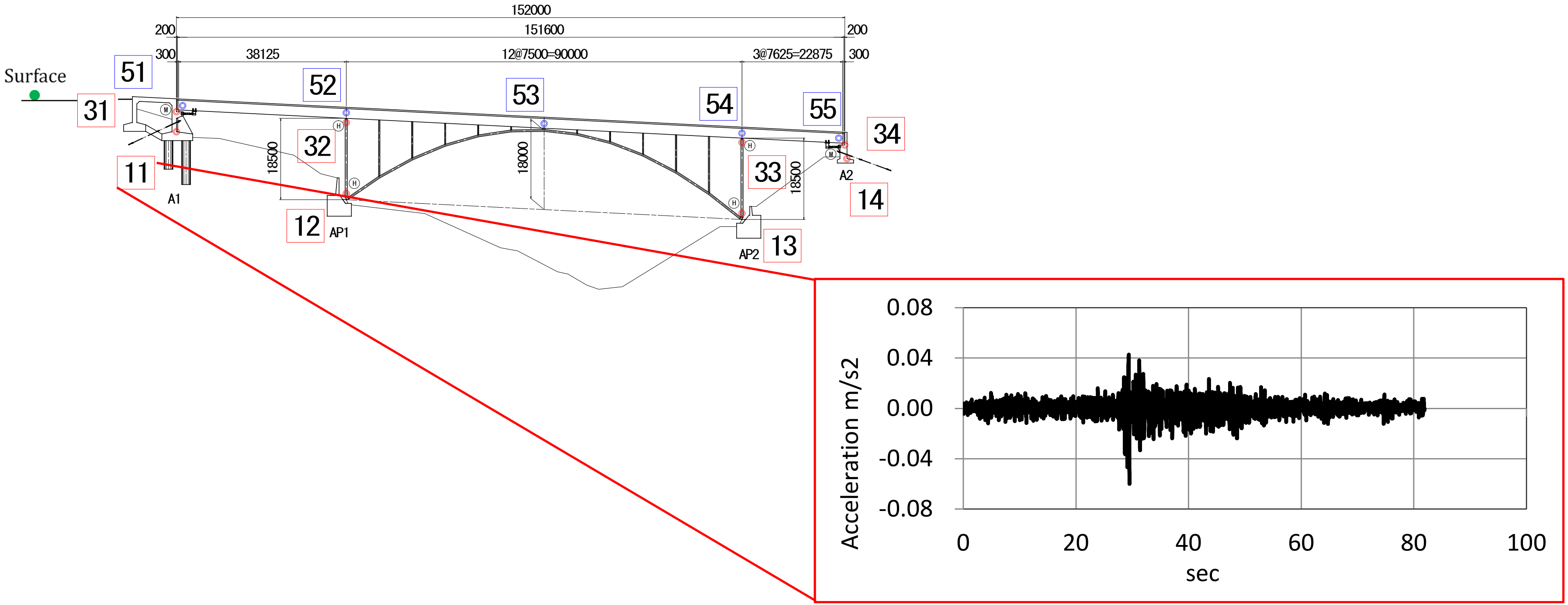
Target bridge and SMMS installation location

Specifications of the target bridge

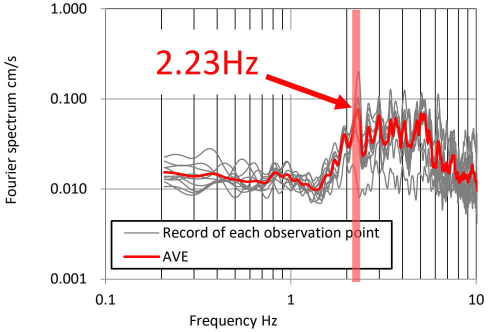
Bridge length	152.0m
Span length	38.125m + 90.000m + 22.875m
Superstructure	3-span continuous steel arch girder (steel reverse langer)
Substructure	Inverted T-shaped abutment
Foundation	Deep foundation pile, direct foundation
Ground type	Type I ground

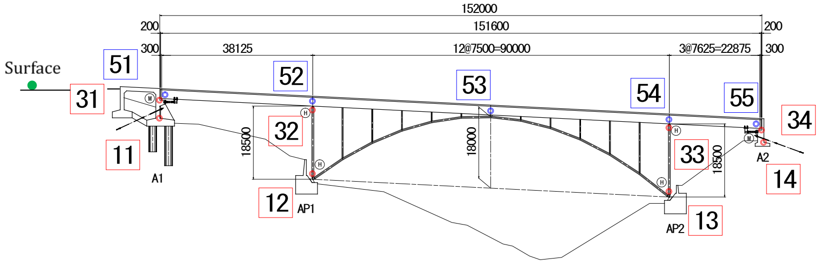
Case study of SMMS for applying a bridge

- Observation of earthquake off the coast of Fukushima Prefecture on March 16, 2022
  → Seismic intensity of about 2 on the target bridge
- The waveform was cut out 30 seconds from the start of the earthquake and 50 seconds from the end of the earthquake.

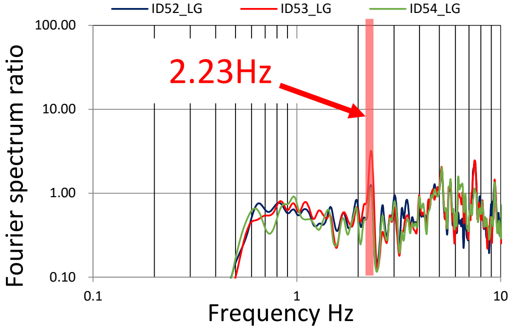


Fourier Spectral Ratio for the LG direction

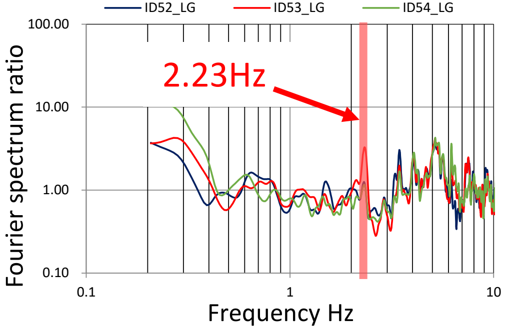




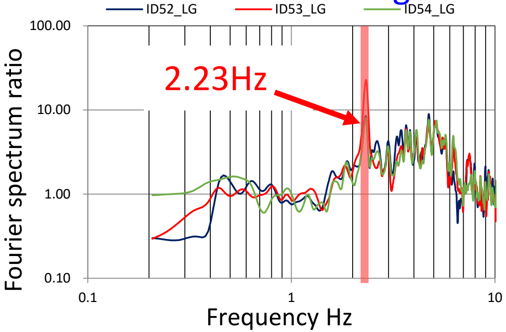
Ground surface - girder

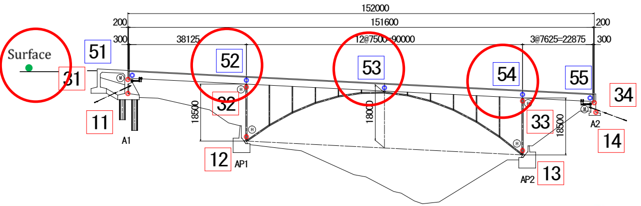


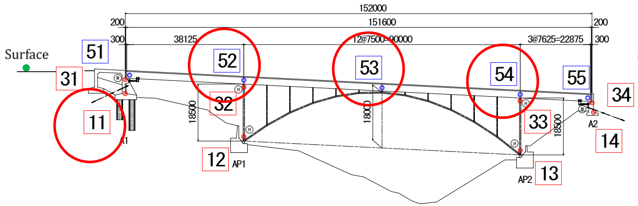
A1 abutment base - girder

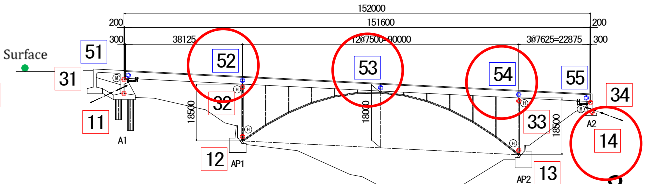


A2 abutment base - girder

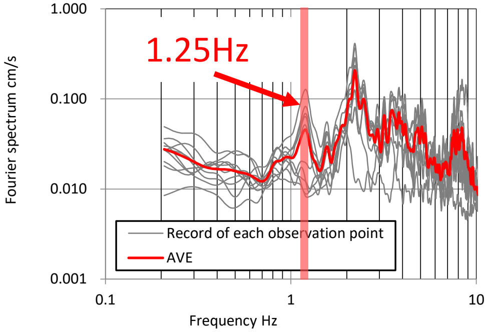


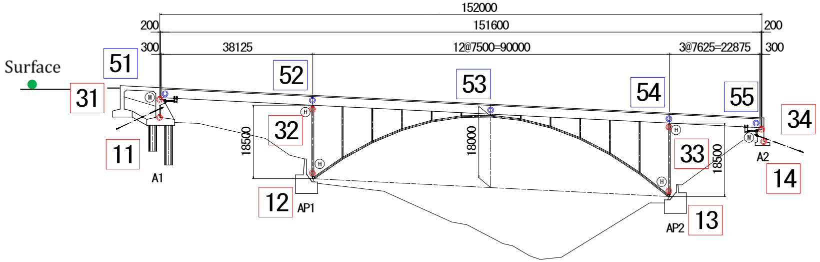




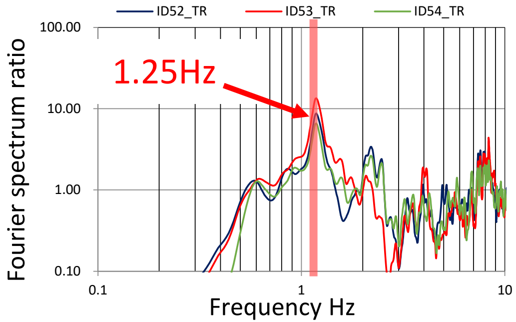


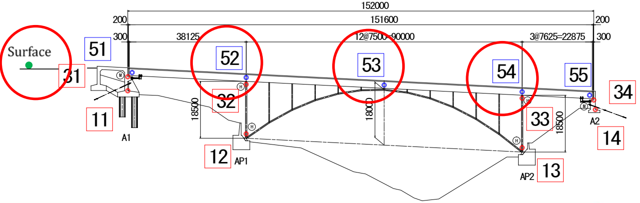
Fourier Spectral Ratio for the TR direction



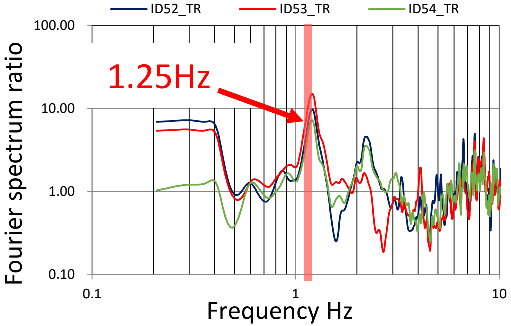


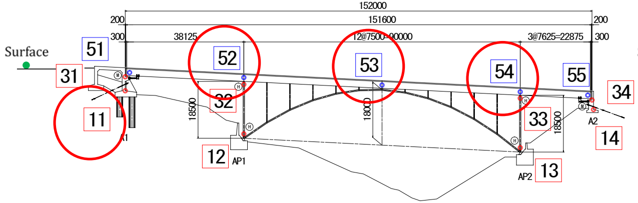
Ground surface - girder



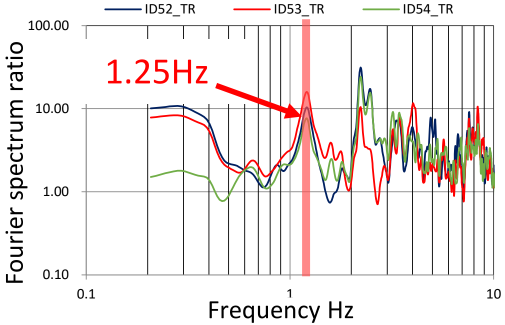


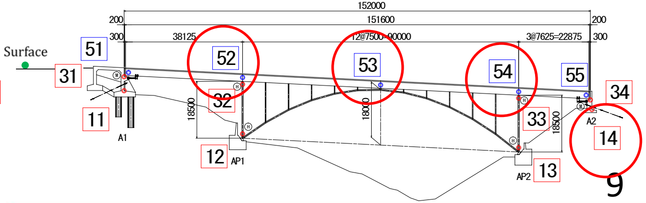
A1 abutment base - girder



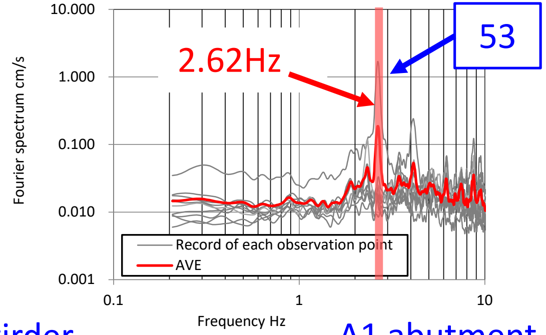


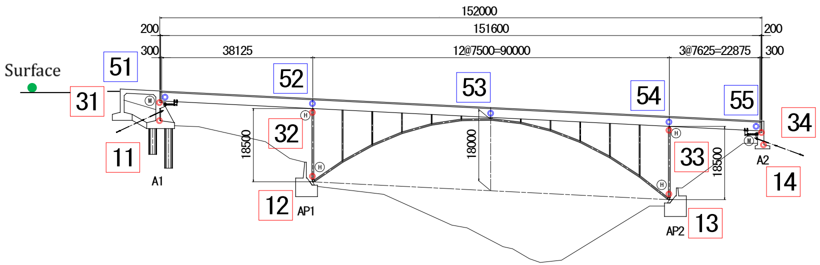
A2 abutment base - girder



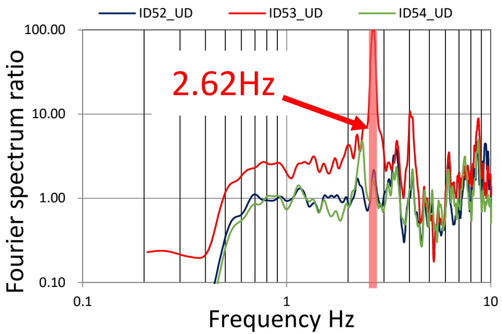


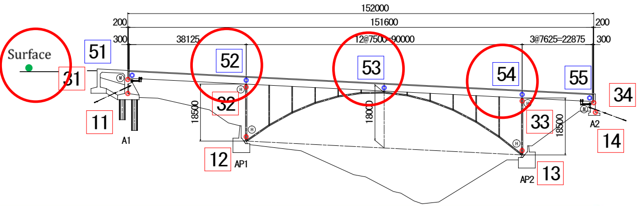
Fourier Spectral Ratio for the Vertical direction



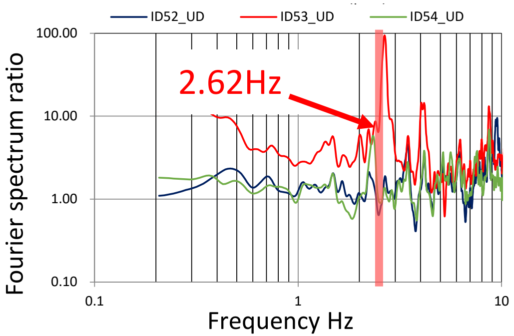


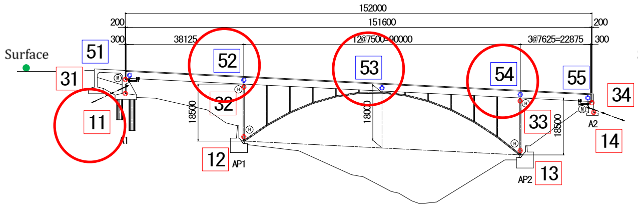
Ground surface - girder



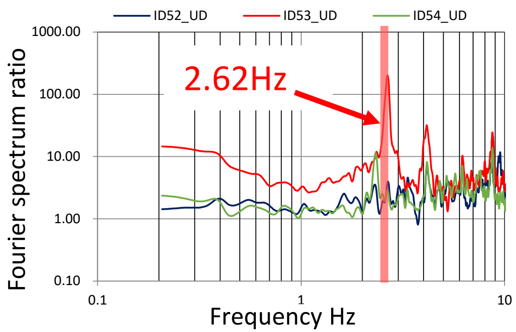


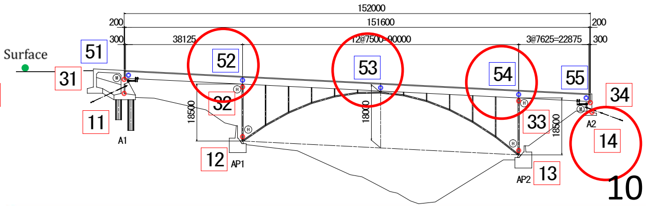
A1 abutment base - girder





A2 abutment base - girder

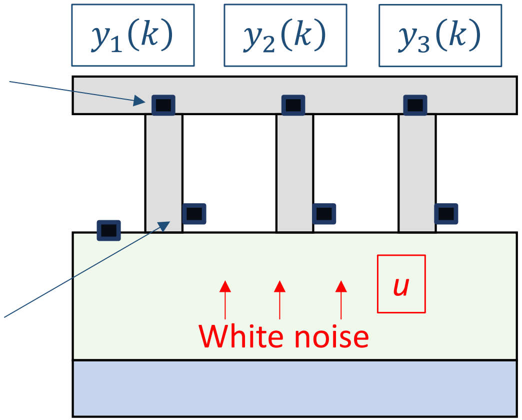


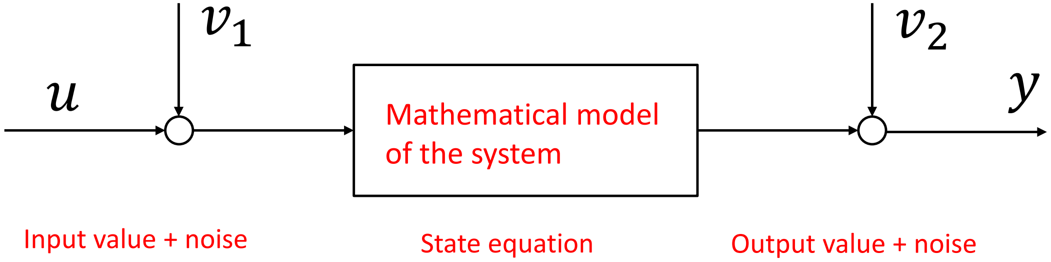


System identification based on the subspace method

- The Ordinary MOESP method; Ordinary Multi variable Output-Error State sPace method using input and output was proposed by Verhaegen *et al*. (1992).
- The SSI-COV method; COVariance-driven Stochastic Subspace Identification method, which performs identification calculations using only output, was developed by Peeters (2000).

System identification (e.g.; Peeters)





Equation of motion

$$[M]\{\ddot{\boldsymbol{z}}_{\boldsymbol{k}}\} + [\xi]\{\dot{\boldsymbol{z}}_{\boldsymbol{k}}\} + [K]\{\boldsymbol{z}_{\boldsymbol{k}}\} = -[M]\{1\}\{\ddot{\boldsymbol{u}}_{\boldsymbol{o},\boldsymbol{k}}\}$$

State equation

$$\{\boldsymbol{x}_{\boldsymbol{k}}\} \equiv \{\{\boldsymbol{z}_{\boldsymbol{k}}\}^T \quad \{\dot{\boldsymbol{z}}_{\boldsymbol{k}}\}^T\}^T$$

$$\{\boldsymbol{x}_{\boldsymbol{k+1}}\} = [A]\{\boldsymbol{x}_{\boldsymbol{k}}\} + [B]\{\ddot{\boldsymbol{u}}_{\boldsymbol{o},\boldsymbol{k}}\}$$

Equation of output

$$\{\boldsymbol{y}_{\boldsymbol{k}}\} = [C]\{\boldsymbol{x}_{\boldsymbol{k}}\} + [D]\{\ddot{\boldsymbol{u}}_{\boldsymbol{o},\boldsymbol{k}}\}$$

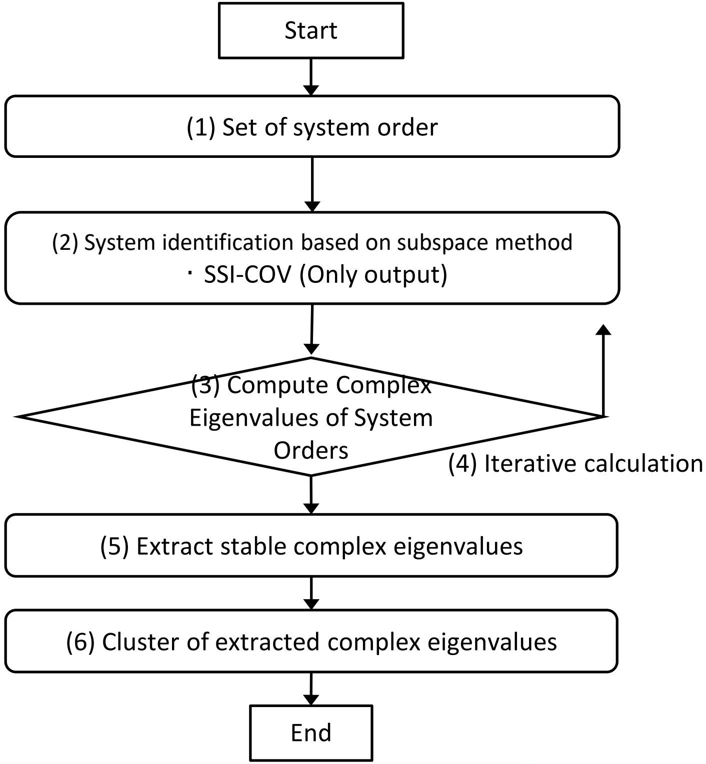
$[\xi]$: Damping matrix
$[M]$: Mass matrix
$[K]$: Stiffness matrix

$\boldsymbol{z}_{\boldsymbol{k}}$: Relative displacement
$\ddot{\boldsymbol{u}}_{\boldsymbol{o},\boldsymbol{k}}$: Disturbance
$\boldsymbol{k}$: Number of steps

Case study of SMMS for applying a bridge

- We estimated the natural frequency and damping characteristics of the bridge using both Ordinary MOESP and SSI-COV.

System identification flow



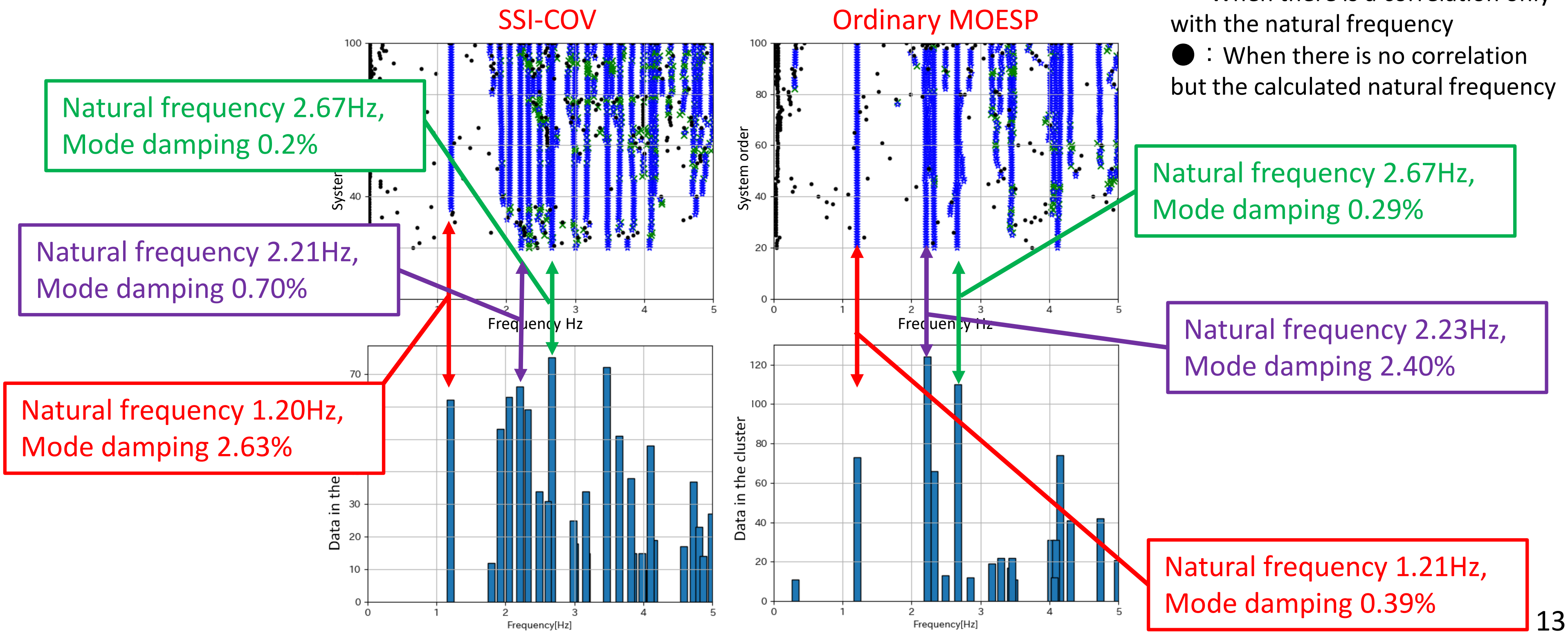
Classification	Item description	CASE1 (No input)	CASE2 (Abutment base input)
System identification (1)～(4)	Technique	SSI-COV	Ordinary MOESP
	Time interval Δt	0.025 s	0.025 s
	Number of inputs	-	2 points under the pier
	Number of outputs	2 points under the pier 3 points on pier top 5 points girder parts 1 point surface	3 points on pier top 5 points girder parts
	Number of samples N	4800 (120s)	4800 (120s)
	Number of block lines M	100 (5.0s)	100 (5.0s)
Complex eigenvalue extraction (5)	System order maximum n	100	100
	System order Minimum n	20	20
	Natural frequency Stability judgment threshold ε_f	0.01	0.01
	Mode shape Stable judgment threshold ε_ψ	0.02	0.02
	Upper limit of attenuation h_{max}	0.4	0.4
Clustering (6)	Technique	Hierarchical clustering (group average method)	

System Identification Results for Arch Bridge

- Natural frequencies evaluated were around 1.20/1.21Hz, 2.21/2.23Hz, and 2.67Hz.

☆ : When there is a correlation between the natural frequency and the eigenvector
× : When there is a correlation only with the natural frequency
● : When there is no correlation but the calculated natural frequency

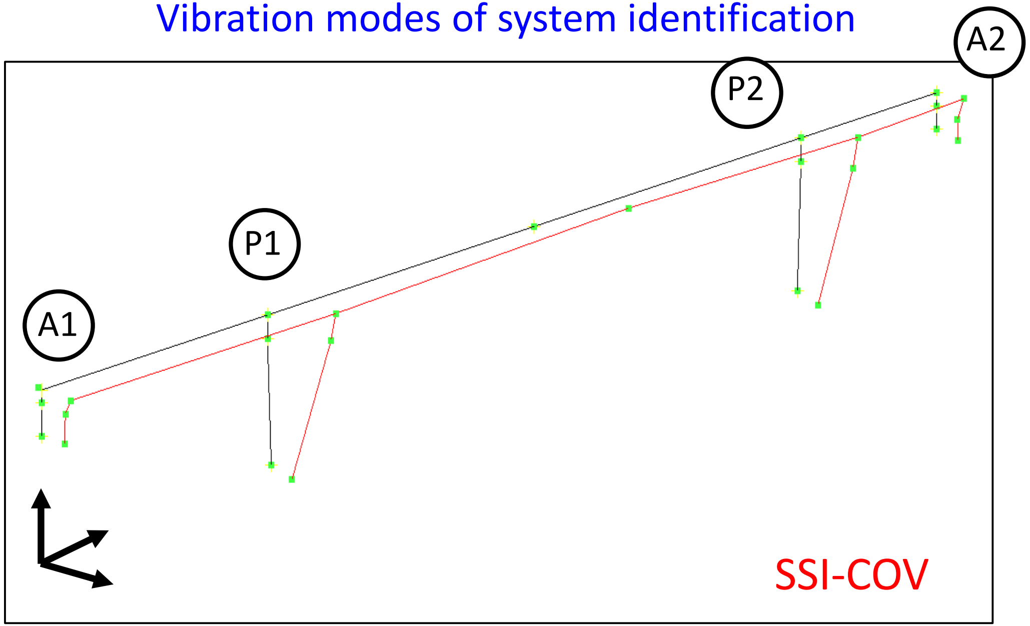
Stabilization diagram (top) and number of data (bottom)



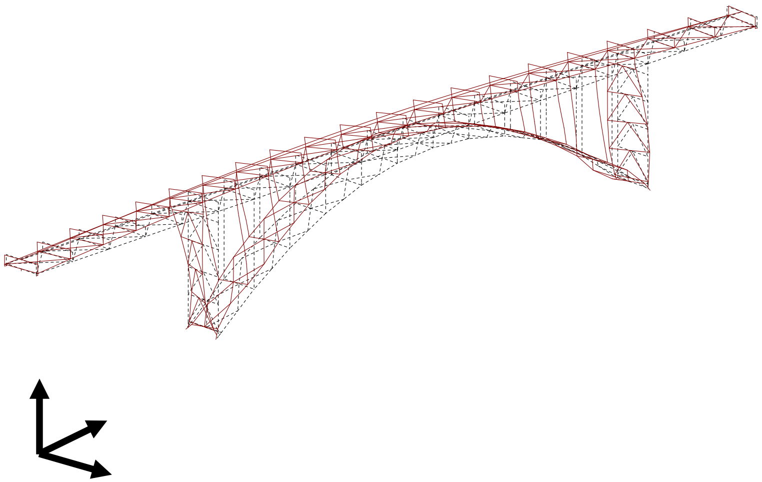
Vibration mode of SSI-COV system identification for the TR direction

- The 1.21Hz vibration mode estimated by system identification is exerted in the bridge TR direction.
  → Matches the dominant frequency in the bridge TR direction.
- Also matches the vibration mode obtained from the eigenvalue analysis of the target bridge.

Vibration modes of system identification



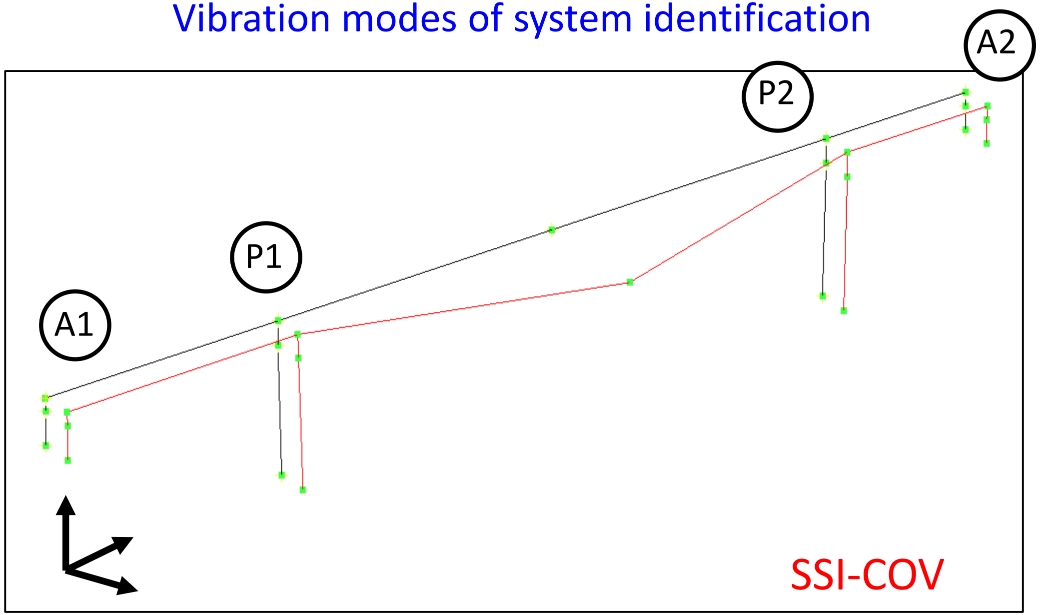
Vibration modes of eigenvalue analysis



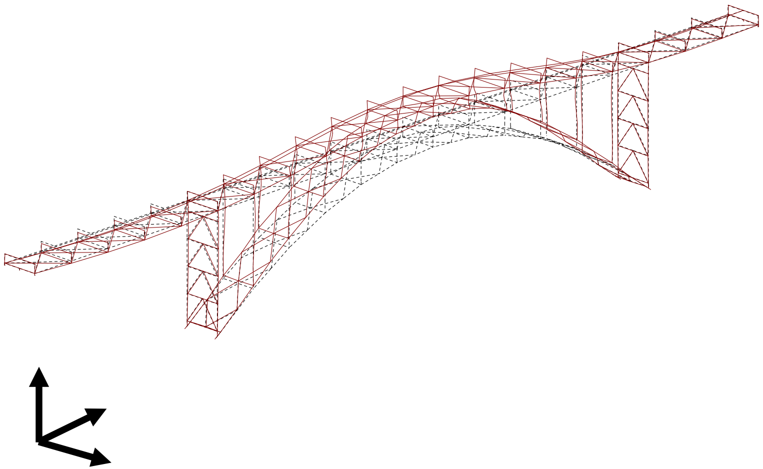
Vibration mode of SSI-COV system identification for the vertical direction

- The 2.67Hz vibration mode estimated by system identification is exerted in the vertical direction.
  → Matches the dominant frequency in the vertical direction.
- The center of the girder has a larger response than the other observation points
  → It is believed that this reflects the difference in response in the observation records.

Vibration modes of system identification



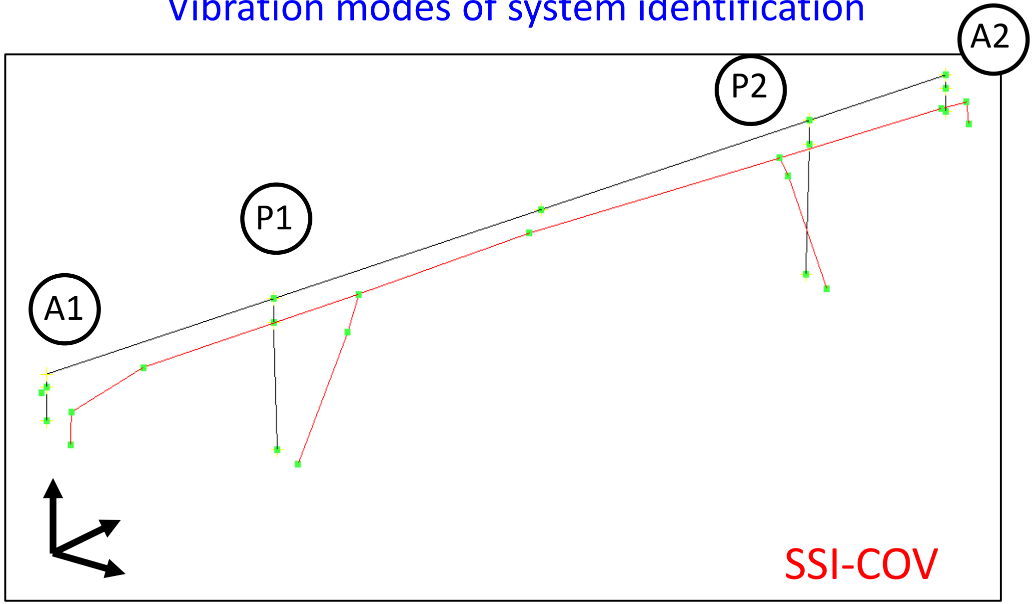
Vibration modes of eigenvalue analysis



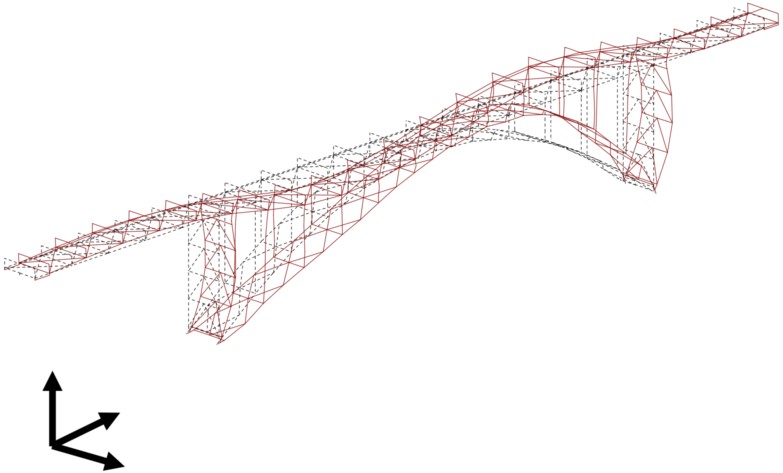
Vibration mode of SSI-COV system identification for the LG direction

- The vibration mode of 2.23Hz estimated by system identification is a mode in which the left and right pillars are in opposite phase toward the center, and is expressed in the bridge LG direction.
- The fact that a vibration mode appeared in the bridge LG direction is consistent with the dominant frequency.

Vibration modes of system identification



Vibration modes of eigenvalue analysis



Summary

Development of the strong motion monitoring system "SMMS"

Observation of vibration records of the arch bridge

Waveform processing

- Estimated dominant frequency

→2.23Hz in the bridge LG direction
→1.21Hz in the bridge TR direction
→2.67Hz vertical direction

System identification

- SSI-COV, Ordinary MOESP

→Evaluation of natural frequencies
→Evaluation of damping characteristics
→Evaluation of vibration modes

Modeling

- Natural vibration modes based on analytical models

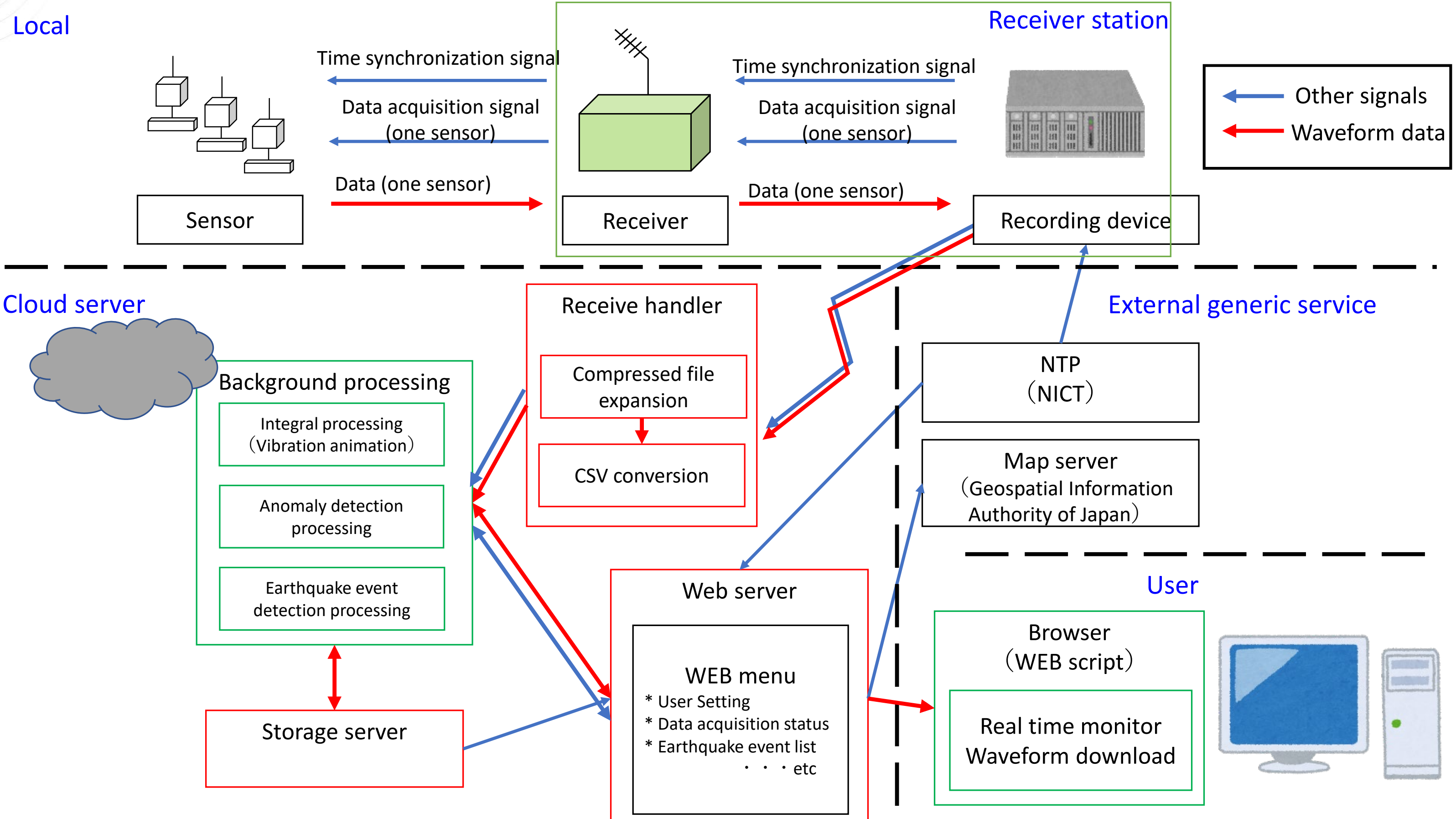
→Evaluation of natural frequencies

○Findings gained from the study

- ✓ The vertical observation records in the center of the arch structure showed particularly large accelerations and prominent peak amplitudes compared to other observation records.
- ✓ The vibration mode was evaluated by system identification in the TR direction and the vertical direction.
- ✓ The vibration mode in the LG direction evaluated by system identification was a vibration mode that could not be expressed by the vibration mode obtained by eigenvalue analysis of the analysis model.
- ✓ The damping characteristics estimated by system identification need to be verified by model analysis.

References

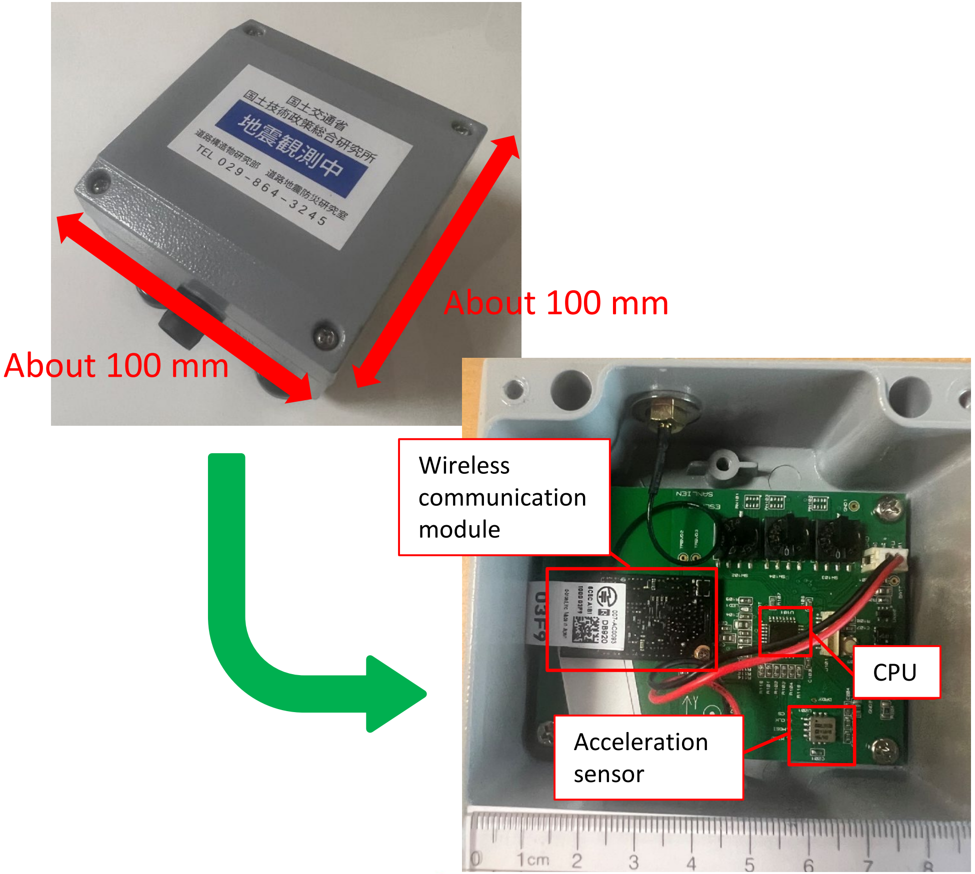
Strong Motion Monitoring System



Strong Motion Monitoring System

Seismometer performance

Sensor type	Accelerometer
Measurement range	±10m/s^2
Resolution	1 mm/s^2
Measuring axis	3 axes (2 horizontal directions, 1 vertical direction)
Observation method	24-hour continuous observation
Data transmission method	920MHz band wireless communication
Sampling frequency	100Hz
Waterproof performance	IP65
Weight	600g
Power supply	Battery



System Identification Results for Arch Bridge

- Natural frequency and mode damping

SSI-COV: no input

Mode order	Natural frequency		Mode damping		Data
	f_{mean} (Hz)	f_{σ} (Hz)	h_{mean} (%)	h_{σ} (%)	n_c (-)
1	1.20	0.00	2.63	0.04	62
2	1.79	0.02	6.32	0.26	12
3	1.92	0.01	0.56	0.14	53
4	2.05	0.00	1.06	0.22	63
5	2.21	0.00	0.70	0.12	66
6	2.32	0.00	0.52	0.07	59
7	2.49	0.00	1.93	0.26	34
8	2.62	0.01	1.53	0.13	31
9	2.67	0.00	0.20	0.04	75
10	2.99	0.01	1.58	0.05	25
11	3.00	0.01	1.26	0.05	18
12	3.17	0.01	0.32	0.12	34
13	3.18	0.00	0.27	0.09	15
14	3.46	0.01	0.76	0.25	72
15	3.65	0.01	1.17	0.19	51

Ordinary MOESP: input of abutment base

Mode order	Natural frequency		Mode damping		Data
	f_{mean} (Hz)	f_{σ} (Hz)	h_{mean} (%)	h_{σ} (%)	n_c (-)
1	0.31	0.01	6.68	1.45	11
2	1.21	0.00	0.39	0.03	73
3	2.23	0.03	2.40	0.59	124
4	2.33	0.00	0.63	0.03	66
5	2.49	0.00	1.28	0.46	13
6	2.67	0.02	0.29	0.14	110
7	2.85	0.01	1.31	0.14	12
8	3.17	0.01	0.59	0.14	19
9	3.29	0.01	4.46	0.63	22
10	3.44	0.01	0.93	0.05	17
11	3.45	0.00	0.63	0.10	22
12	3.48	0.00	1.16	0.09	11
13	4.02	0.01	0.94	0.66	31
14	4.07	0.00	0.27	0.03	12
15	4.09	0.01	0.66	0.03	31