5th International Bridge Seismic Workshop

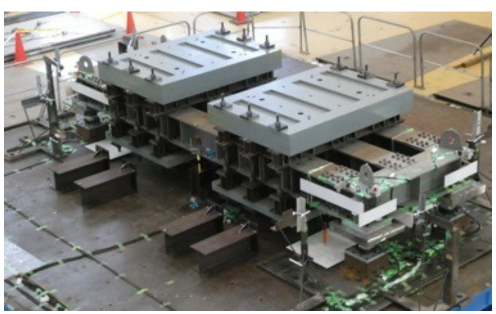
华南理工大学
South China University of Technology

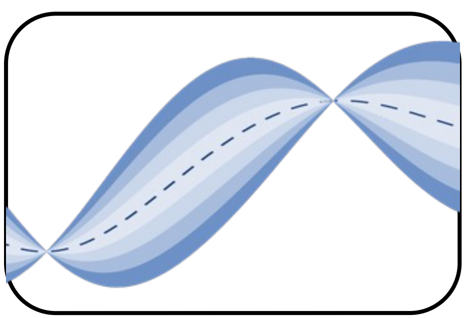
Finite element model updating of a unidirectional isolation bridge under earthquakes

Xinhao HE (presenter), Shigeki UNJOH

Professor, South China University of Technology, China

Professor, Tohoku University, Japan



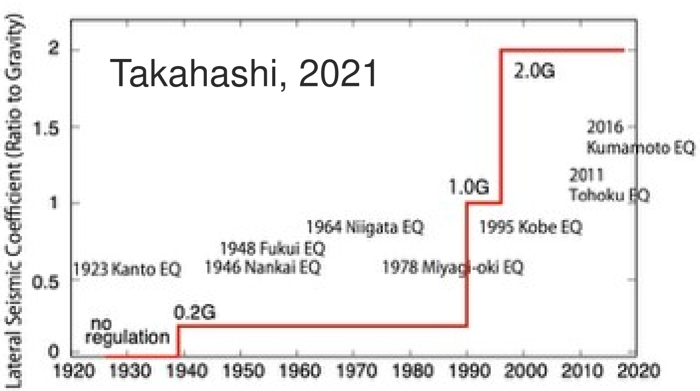


Outline

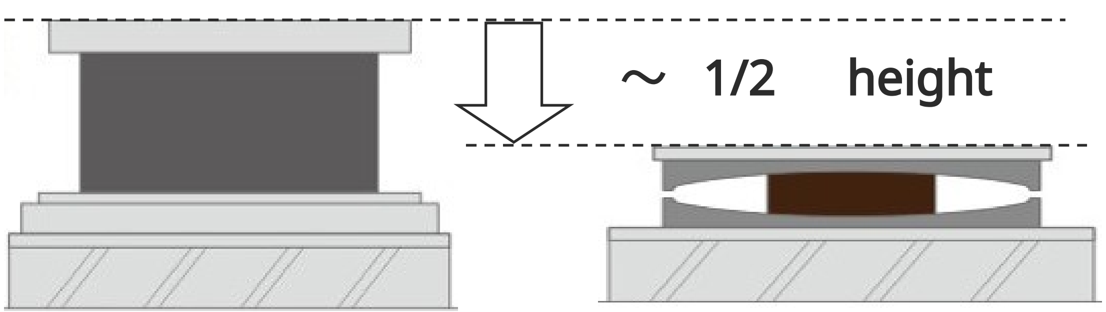
- Isolation bridges
- Unidirectional isolation of bridges
- Earthquake records of a bridge with SSB
- Verification-Updating-Prediction

Background: isolation bridges in Japan

- ✓ Since the 1995 Hyogo-ken Nanbu Earthquake, seismic isolation techniques have been widely adopted in Japan's bridges (**new projects and retrofitting**).
- ✓ However, current **design seismic force is 10 times stronger** than those in the 1970s, but many bridges are still designed to the old standards.
- ✓ As a result, the number of existing non-compliant bridges is increasing, leading to the need for **seismic reinforcement**.
  - ➢ Of ~1000 isolation bridges to date, **the majority use rubber bearings**.
- ✓ ***Challenges***: Securing **installation space** and extensive retrofitting of bearings make construction a major undertaking.
  - ➢ Structural height: **Steel bearings (existing) < Rubber bearings (new)**
  - ➢ ***Spherical sliding bearings (SSB) stand out for their lower height***



Design seismic forces (JRA)



Rubber-type bearings

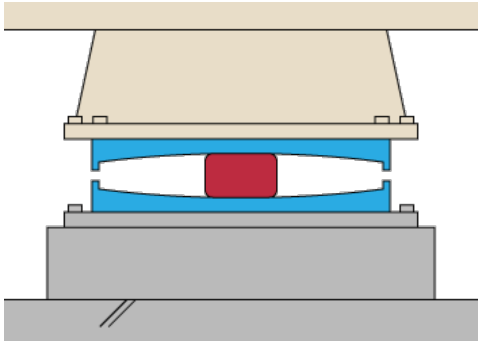
Spherical Sliding bearings

出典： NS-SSB® × 振り子免震技術 | ProStruct® [プロストラクト]

Spherical Sliding Bearing in Bridges

Two important parameters in seismic design:

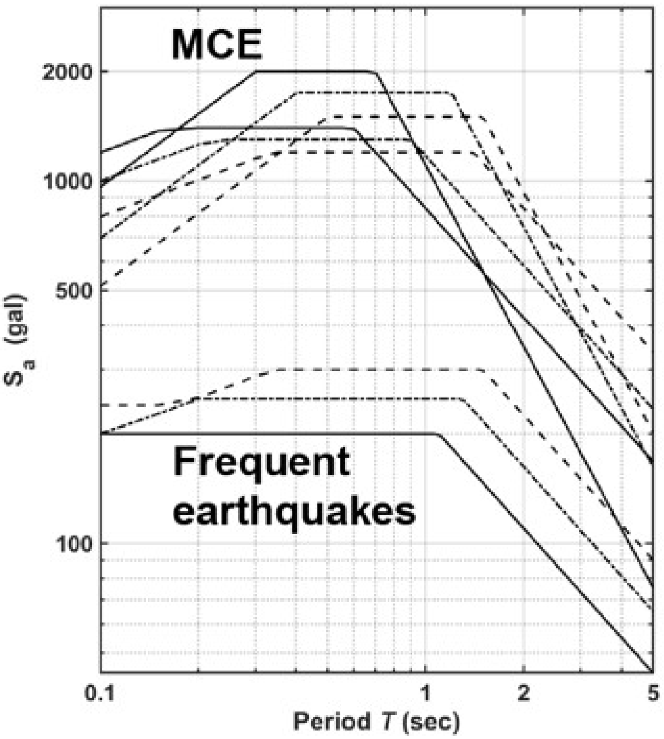
1) Natural period: Depends on the geometric size of the spherical surface
   - ➢ Relatively stable
2) Energy dissipation: Friction coefficient
   - ➢ Depend on various factors such as the material used, surface pressure, temperature, heating, and sliding speed



出典：球面すべり支承とは：金属を用いた合理的な免震システム - バッコ博士の構造塾

Although SSBs are widely used in buildings, prior to 2021 they had not been employed in bridges in JP.

- ➢ **Severe soil conditions and seismic demand (0.5~1.6 s, 1500~2000 gal)**
- ➢ **Relatively low energy dissipation (hard to control seismic displacement)**
- ➢ **Bridge expansion joints' limit (e.g., ~200mm)**
- ➢ **…**



Tsopelas and Constantinou et al., EESD, 1996
Unjoh S., Menshin (seismic isolation) Bridges in Japan, 2014
JRA, Design Specification for Highway Bridges, Part V, 2017

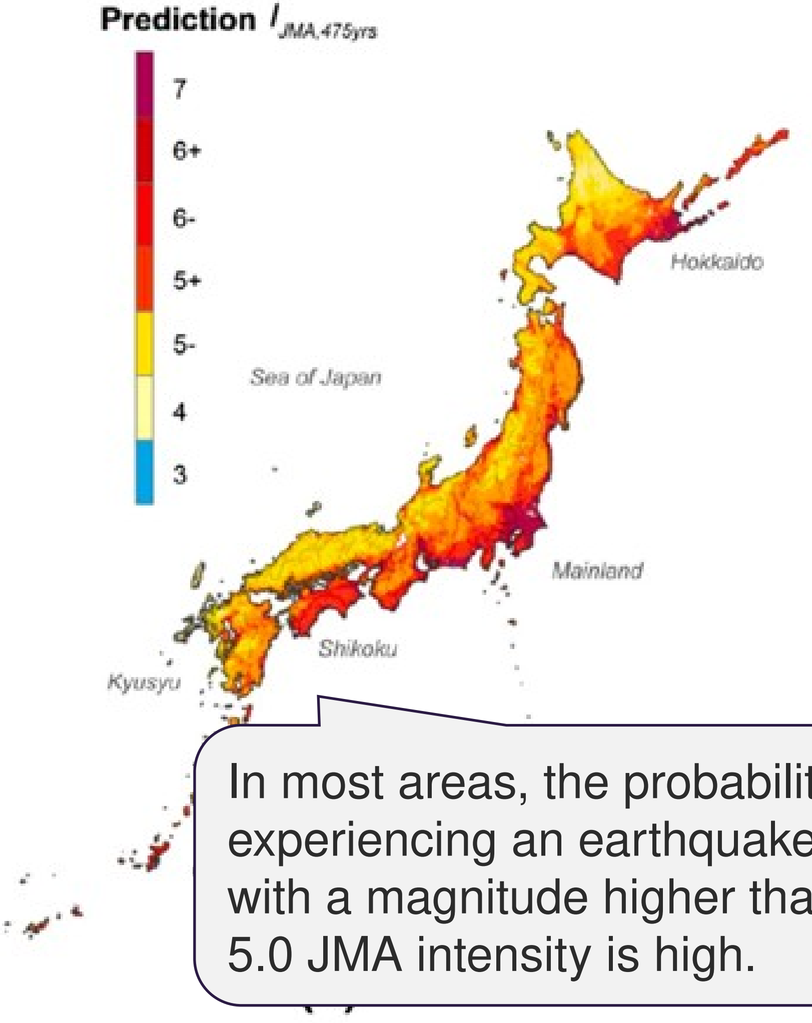
Shimizu Viaduct and Earthquake Monitoring

The first FPS/SSB isolation bridge in Japan

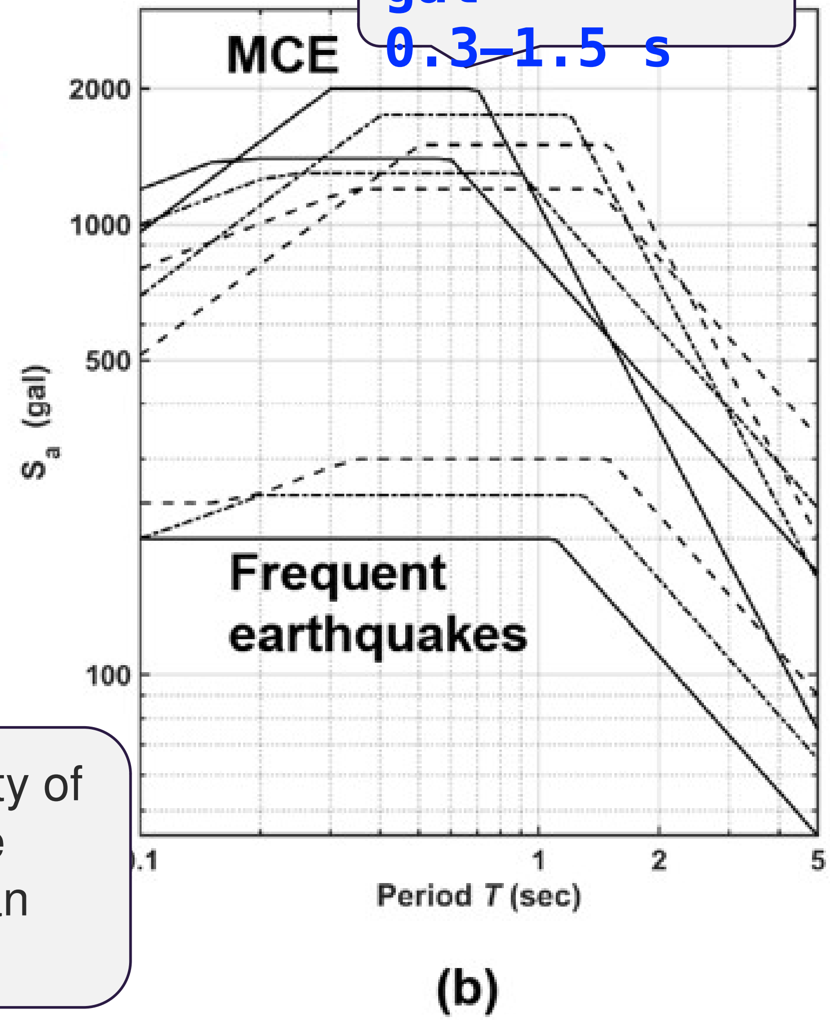
1. **Uni-isolation design**
→Natural period: **2sec**
→Friction: **0.05**
2. Structural details
→50m length, 12m width
→Side blocks (restrainers)
→Deck is extended to abut.
→Simply supported
3. Accelerometers (3-axis)
→3 on main girders' end amd middle
→2 on the top of A1
→1 in the ground
4. Displ. transducers
→Lg. and Tr. of two bearings at A1

- Local saving and 4D cellular modules allow *remote and instant access*.

Seismic demand in design is very high



In most areas, the probability of experiencing an earthquake with a magnitude higher than 5.0 JMA intensity is high.

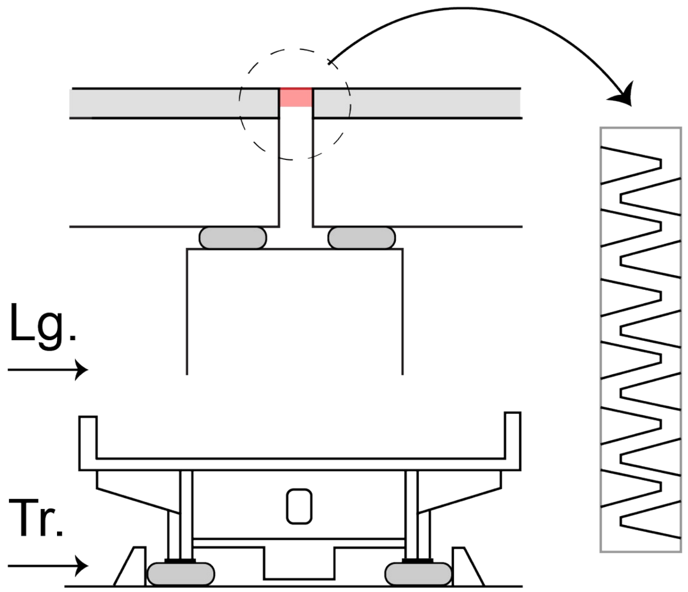


1600–2000 gal
0.3–1.5 s

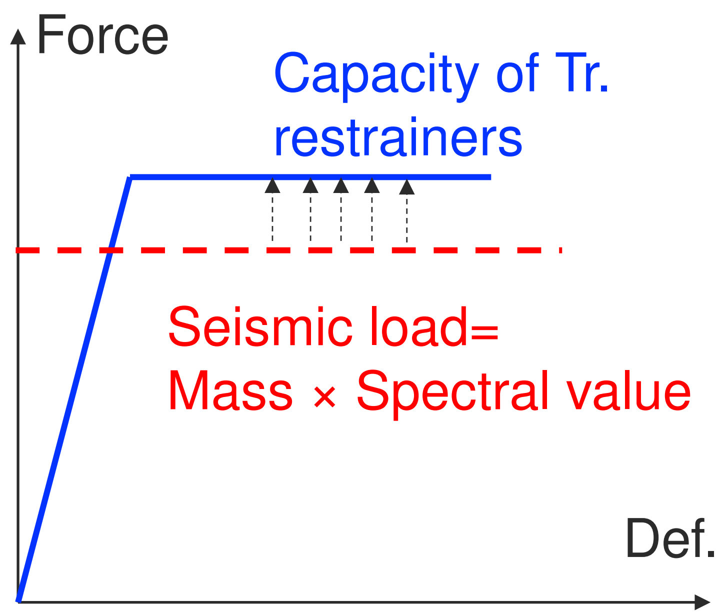
Unjoh S., Menshin (seismic isolation) Bridges in Japan, 2014
JRA, Design Specification for Highway Bridges, Part V, 2017

Bridge isolation direction

- *Expansion joints are regarded as crucial elements for maintaining the functionality of bridges and facilitating rapid recovery.*



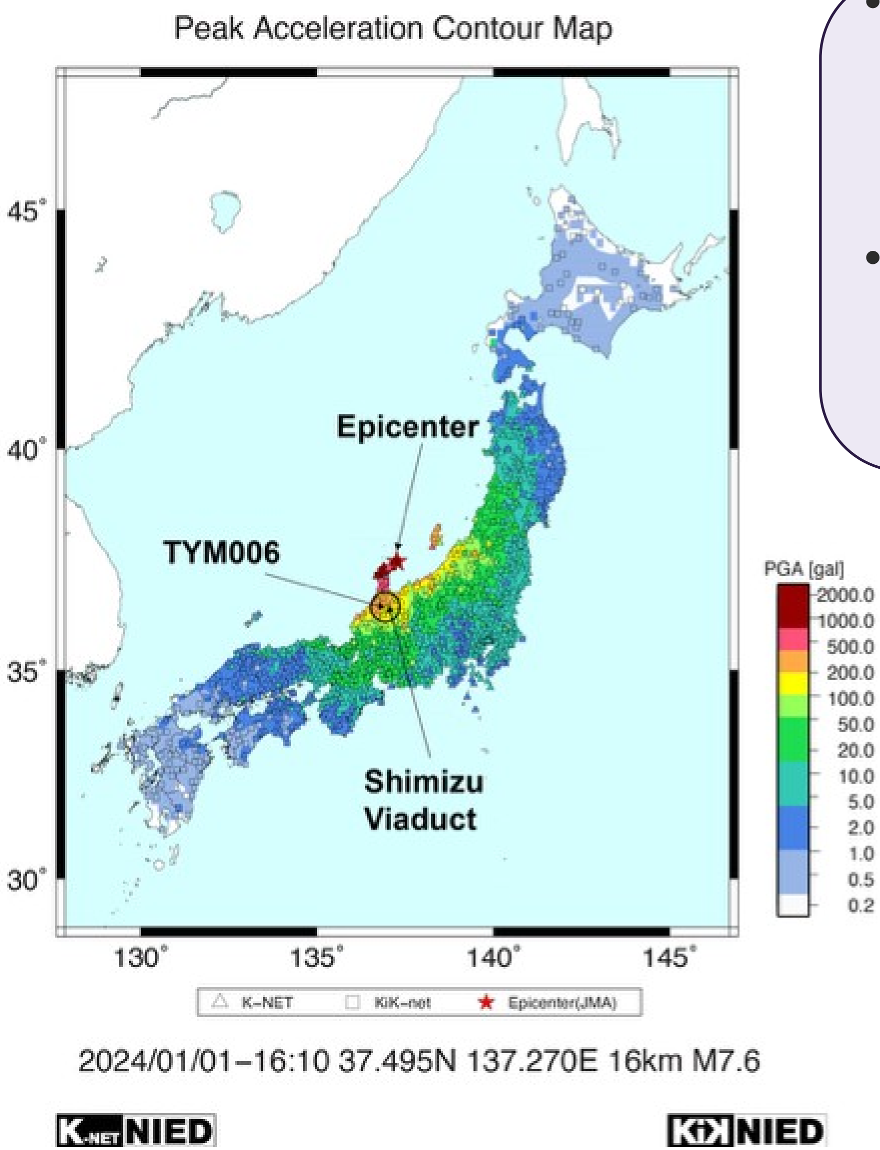
Completely uni- isolation (L1/L2)



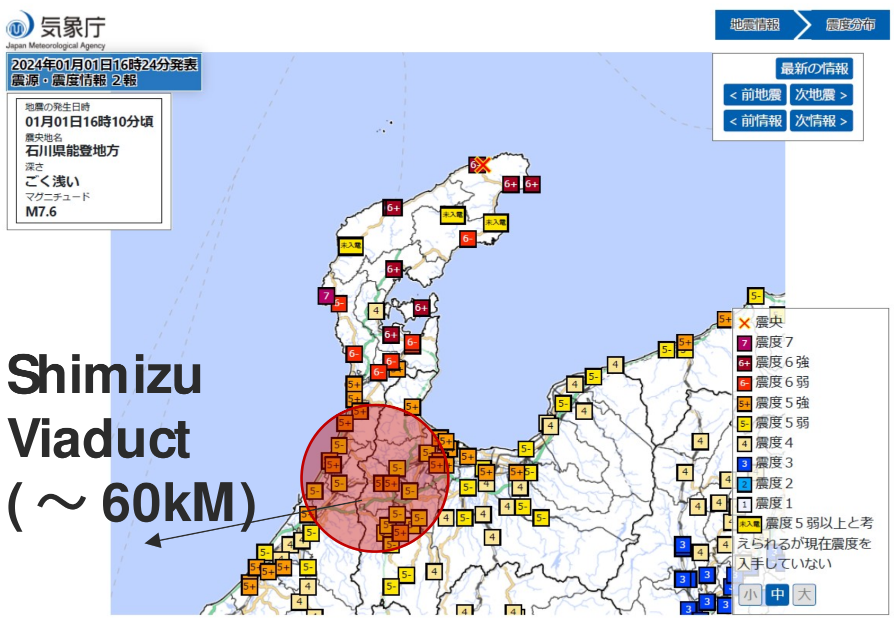
- **Remain function** even under MCE;
- Avoid damage to expansion joints.

Verification of the unidirectional isolation design assumptions

2024/01/01 Noto Peninsula Earthquake



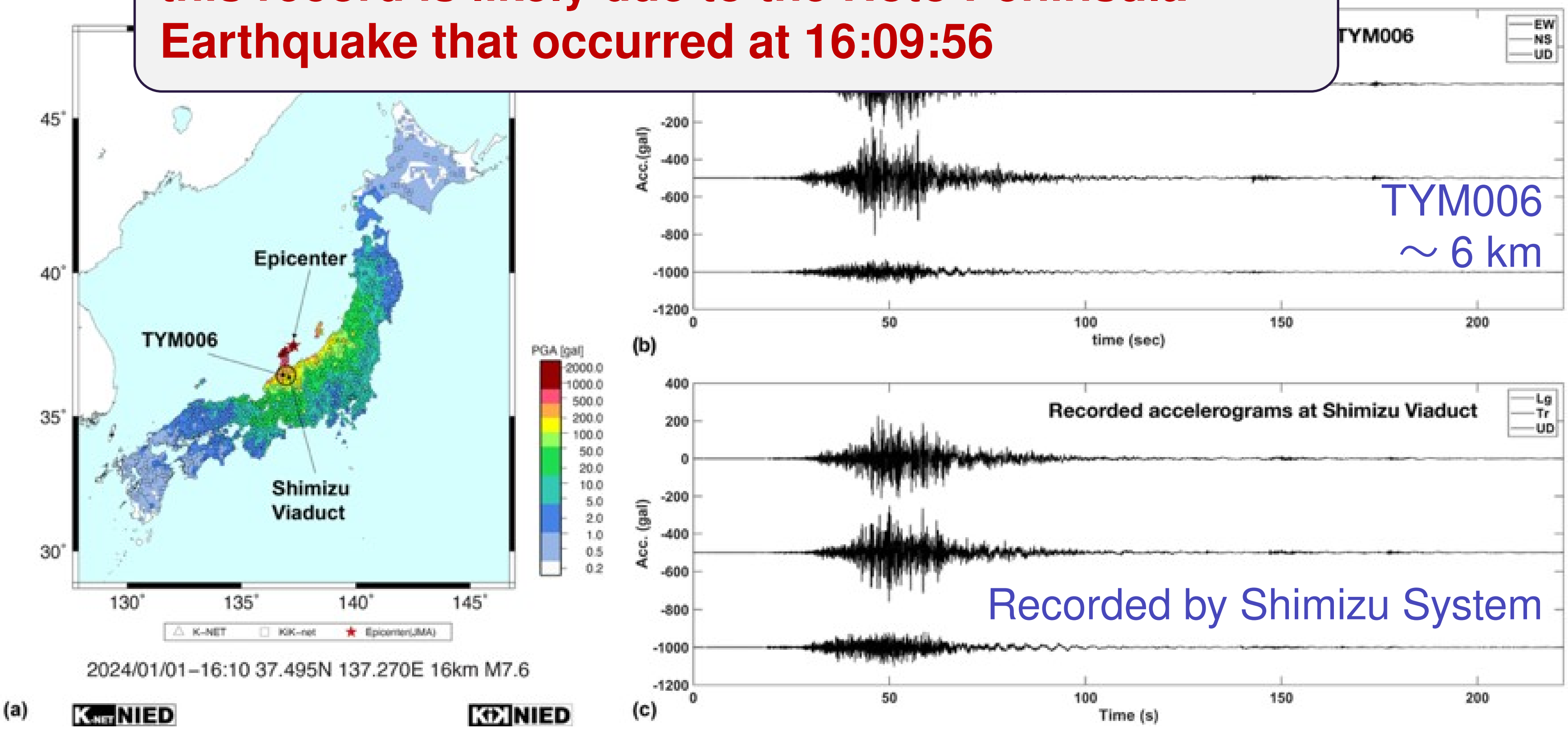
- According to the NIED, a magnitude **7.6 earthquake** occurred on the Noto Peninsula at **4:09:56 PM**.
- The **seismic intensity distribution** is shown below, and the **maximum acceleration distribution** is shown on the left.



Seismic observations in Shimizu Viaduct

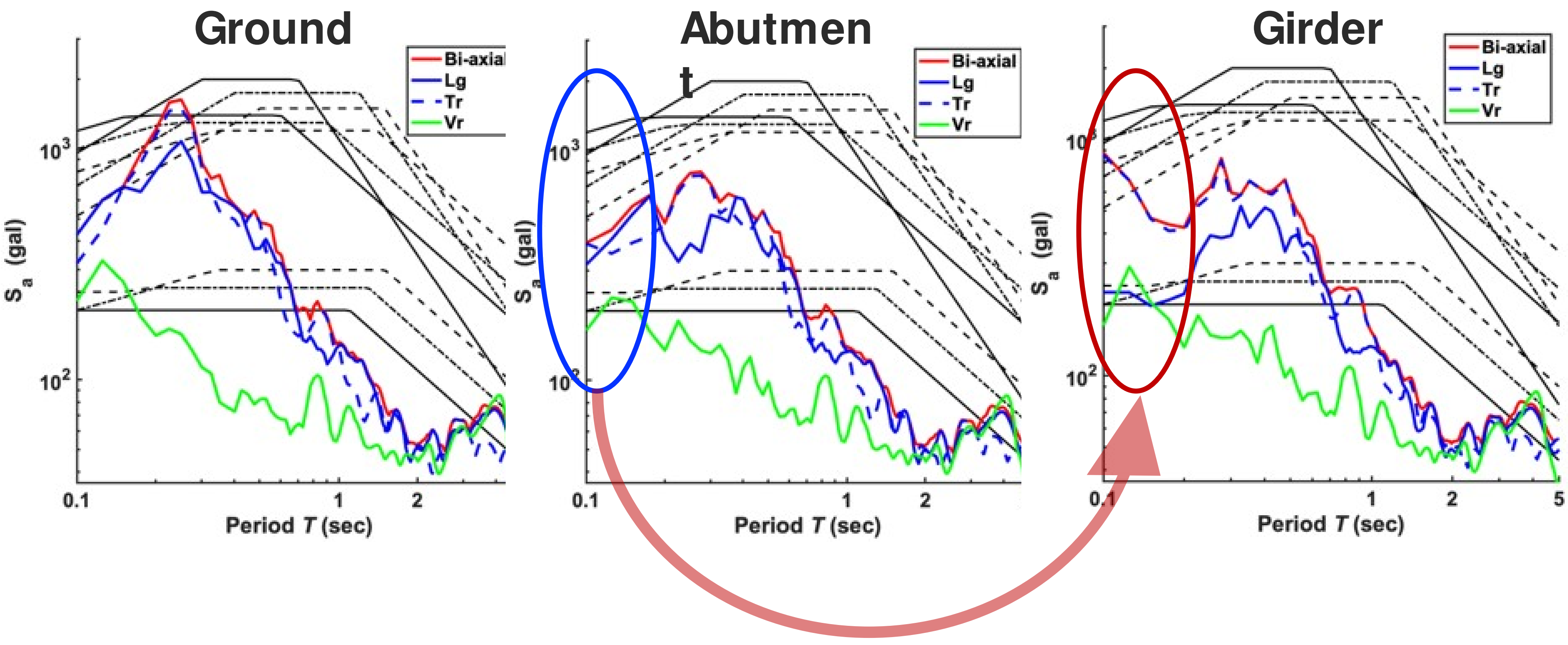
- The system recorded a 410-second period beginning **at 16:10:30 (~34s after the NIED record)**.
- Records were also confirmed at the **K-Net TYM006** Oyabe observation point, **approximately 6 km** from the Shimizu Viaduct.
- Considering the similarity of waveforms and the propagation time of the seismic motion:

this record is likely due to the Noto Peninsula Earthquake that occurred at 16:09:56



Response spectra (5%): acceleration

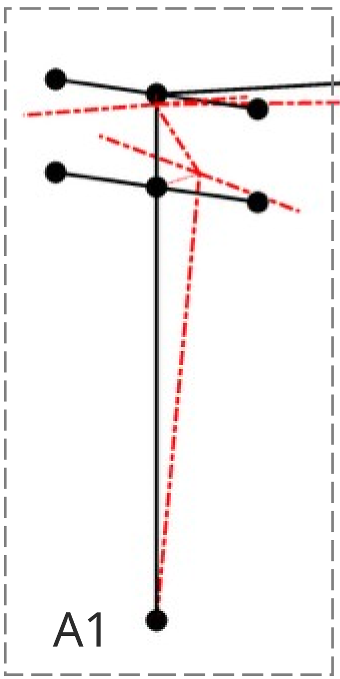
- In the short-period range (0.1–0.2 s), the **Lg. component exhibits a decrease** (from 300 gal to 200 gal), suggesting the **intended isolation effect**
- The **Tr. component shows a sharp increase** (from **400 gal to 900 gal**) due to the contact phenomena at the clearances range



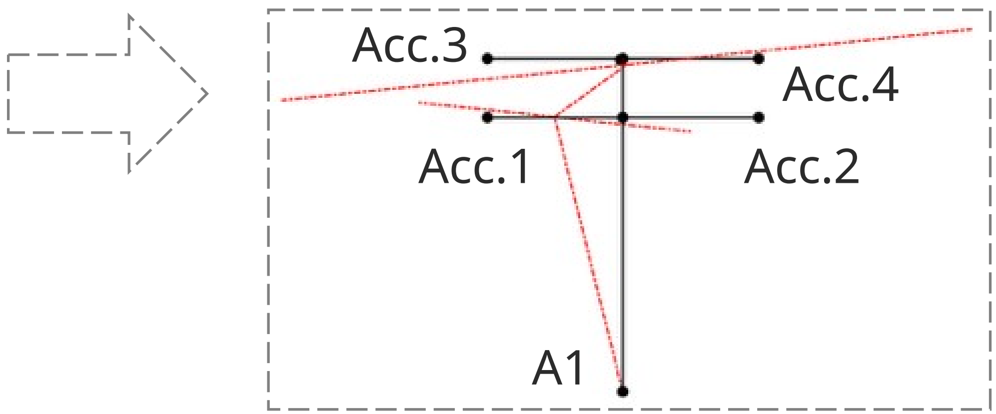
Peak accelerations w.r.t the ground

Observation 1:
The acceleration response at the center of the girder is most pronounced

3D close-up



Observation 2:
- In **Tr.**, girder response **exceeds** substructure
- In **Lg.**, girder response is **lower than** the substructure



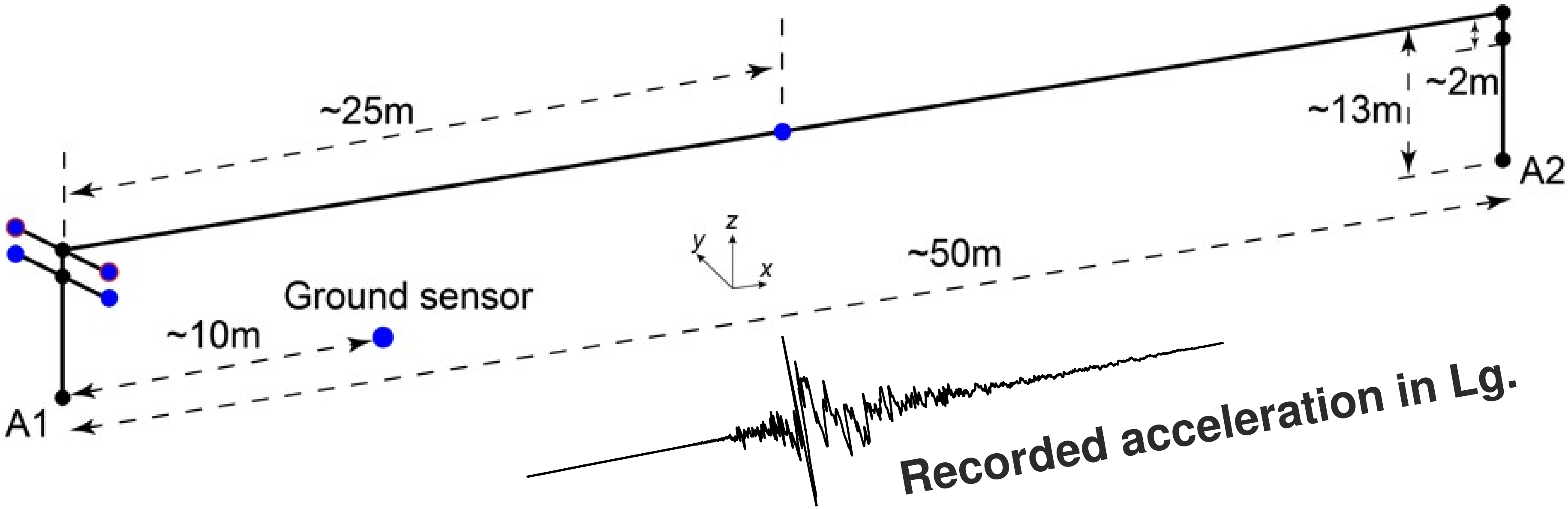
2D close-up

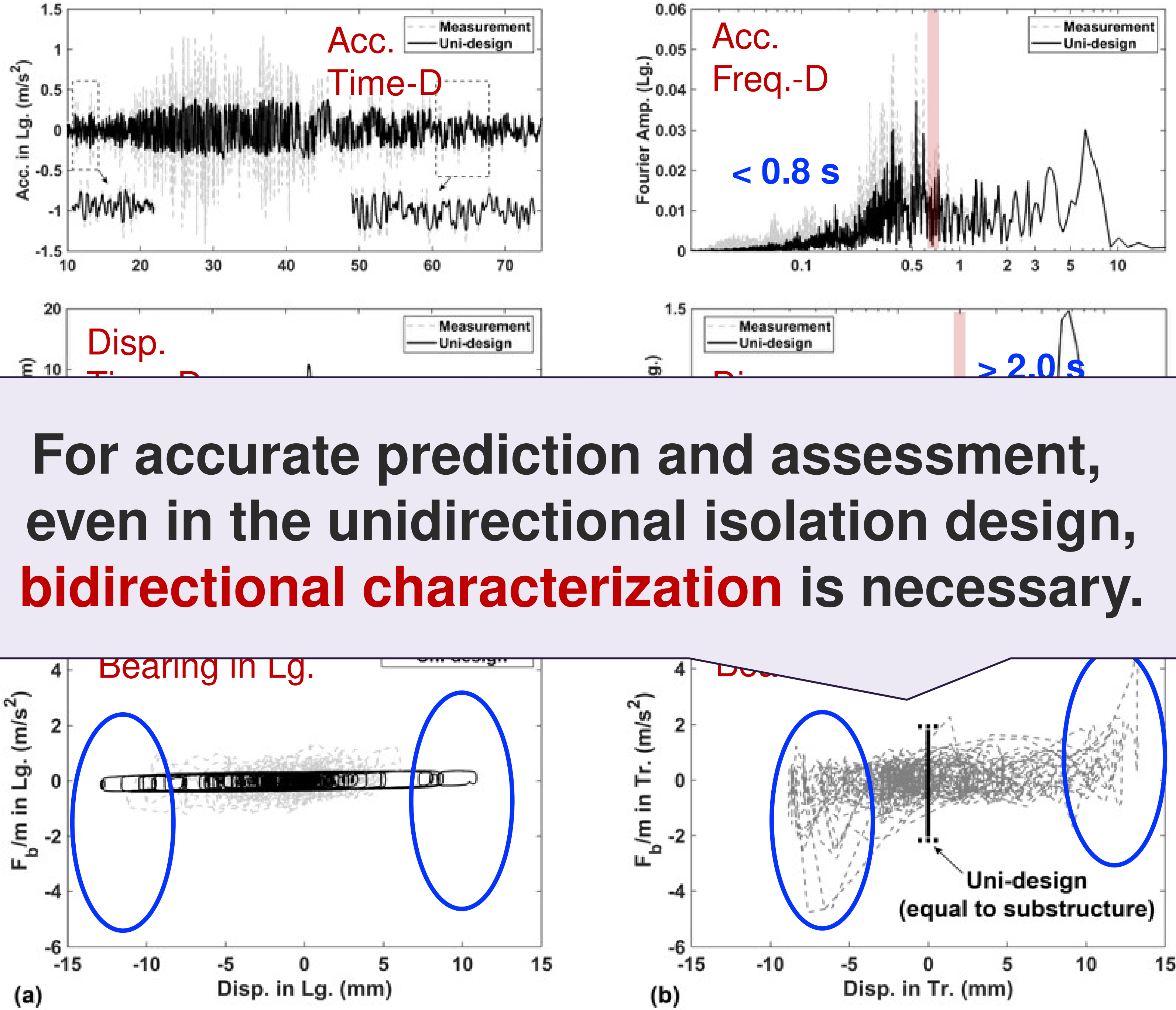
Validation according to seismic design practice

It is important to assess whether the **current unidirectional isolation design method** can accurately predict its seismic responses.

In the seismic design practices:

1) The dynamic behavior of the bridge is analyzed independently in the Lg. and Tr. directions, with the latter assumed to be a fixed condition.
2) Unidirectional design ground motions are applied along either the Lg. or Tr. direction of the established bridge.





For accurate prediction and assessment, even in the unidirectional isolation design, bidirectional characterization is necessary.

Summary of this study

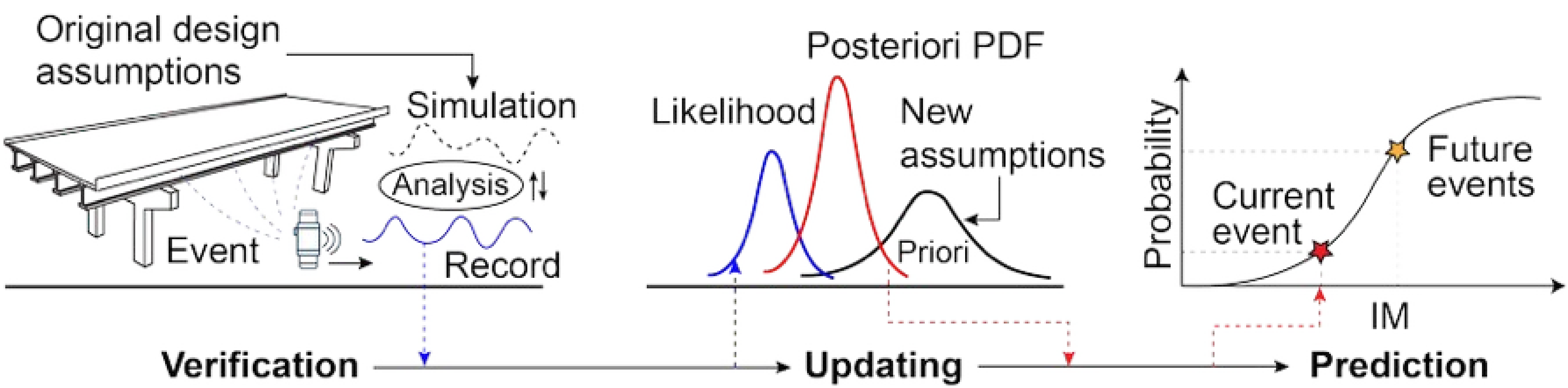
Data: Approximately **1,000 earthquake records** have been collected over 3.5 years of operation since 2022.

Demands: Accurate mechanical characterization of the unidirectional isolation bridge after construction

Challenges:

1) The **unique complexities of each civil engineering structure**, including geometric configurations, imperfect design modeling assumptions, soil conditions, and pervasive uncertainties in actual operational environments;
2) Simulations in **seismic design are conducted unidirectionally**.

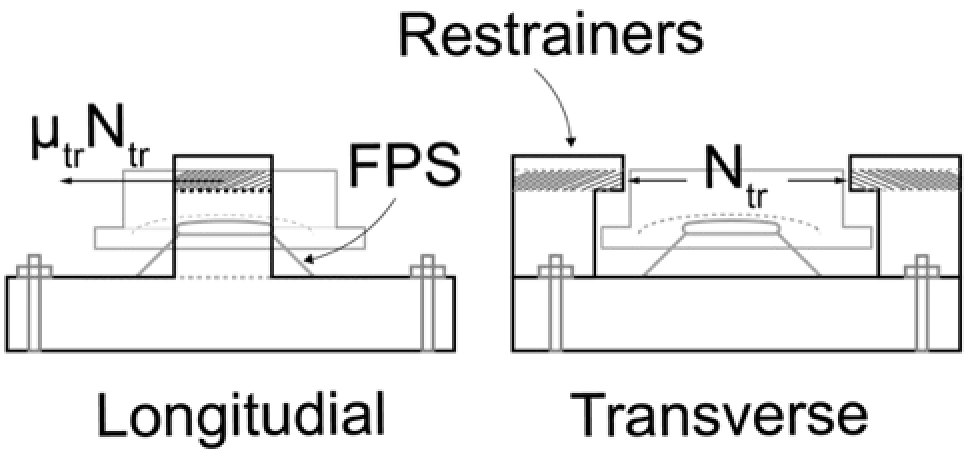
Solutions: A 3-step SHM analysis framework.



Stochastic model updating

Potential influence of side blocks (restrainers)

- Tr.: Assume gap, primary stiffness, and secondary stiffness.
- Lg.: Assume friction due to contact and relative motion.



Design information:

Design strength of side blocks :
2156 kN × 4 = 8624 kN
*Does not yield under level 2 earthquake motion (refer to design documents)

Weight of superstructure during earthquake :
1352 × (40/27) × 4 = 8011 kN
Each bearing

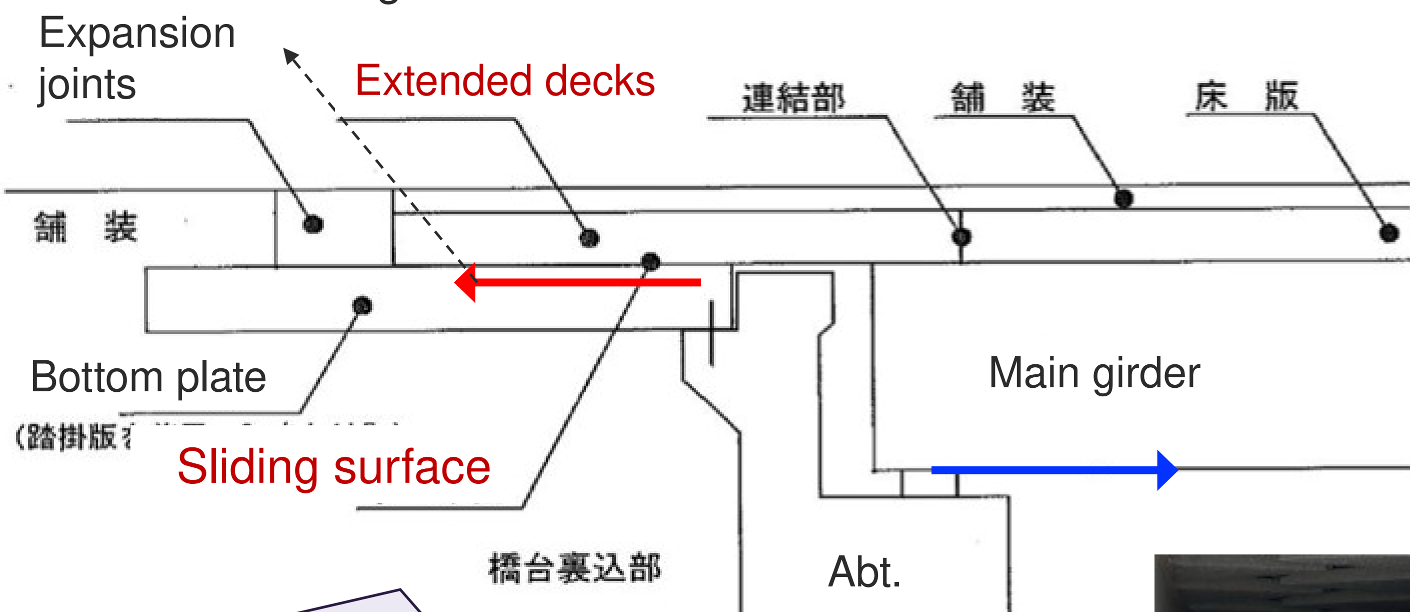
Yielding acc. : 8624 kN / (8011 kN / 9.8) ＝ 10.55 m/s²

Influence of extended decks

Friction force of extended deck (design data):

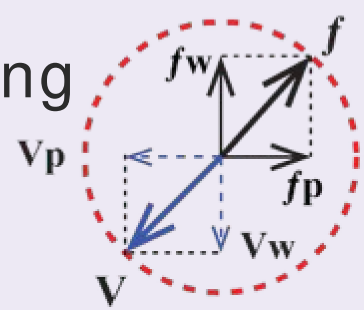
※ Design value：57.8 kN × 1.2 × 2 =138.72 kN

Weight of one side Friction coefficient

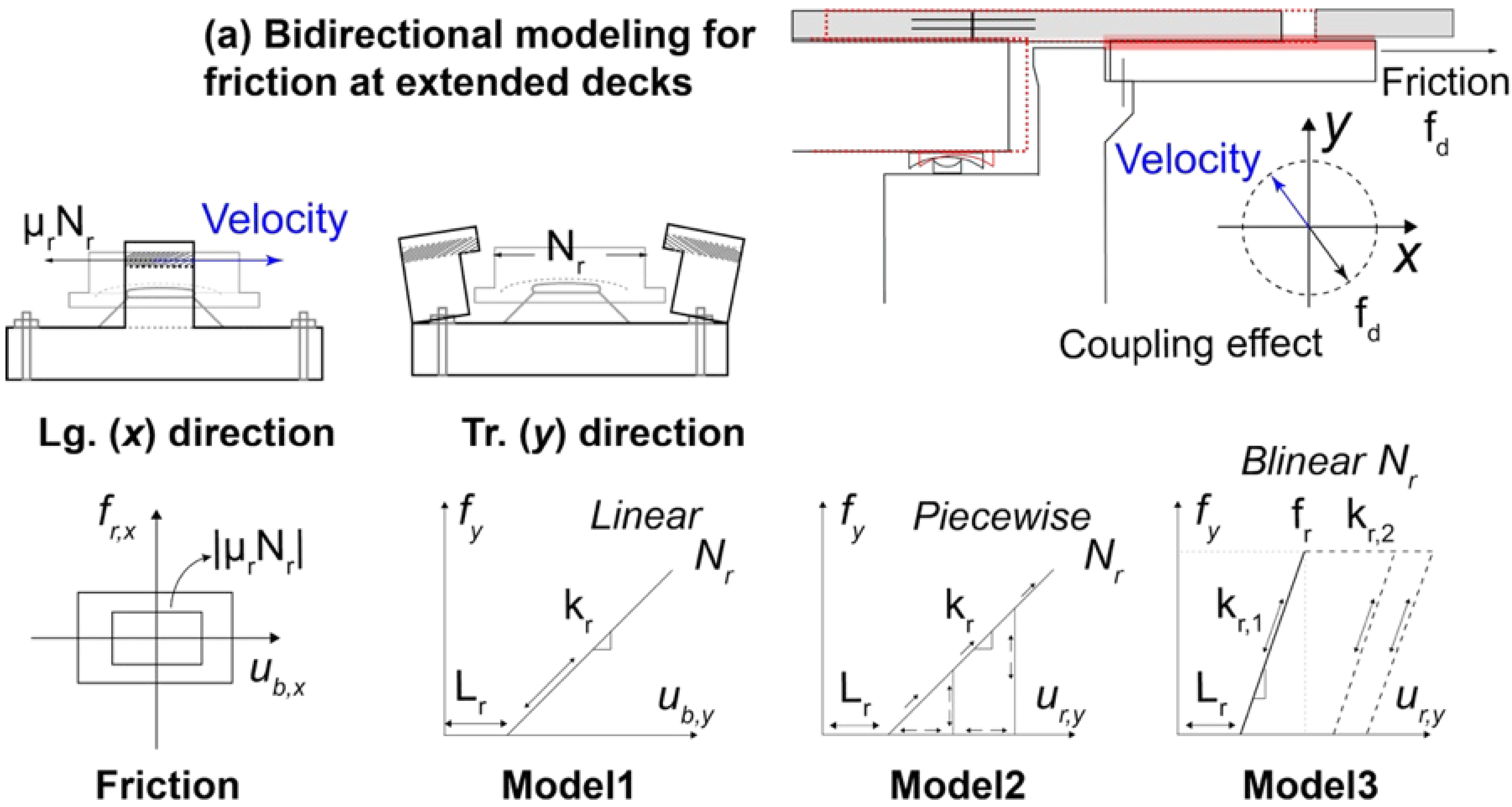


Friction force modeling

- Coulomb model
- Coupling effects



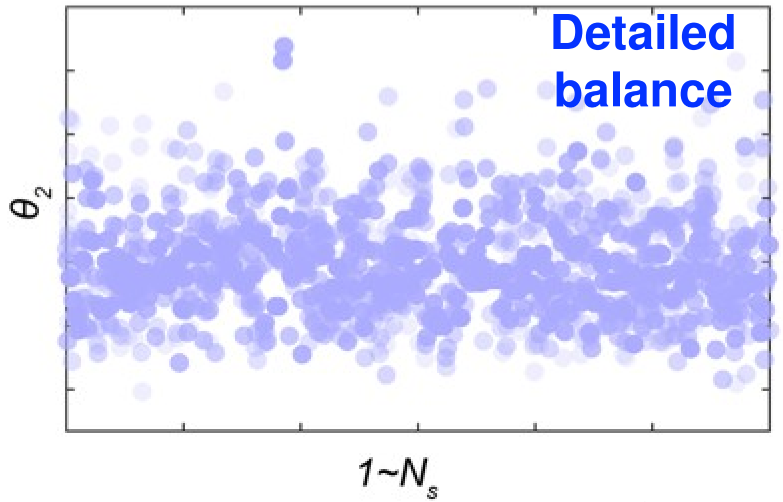
Epistemic and aleatoric uncertainties in modeling



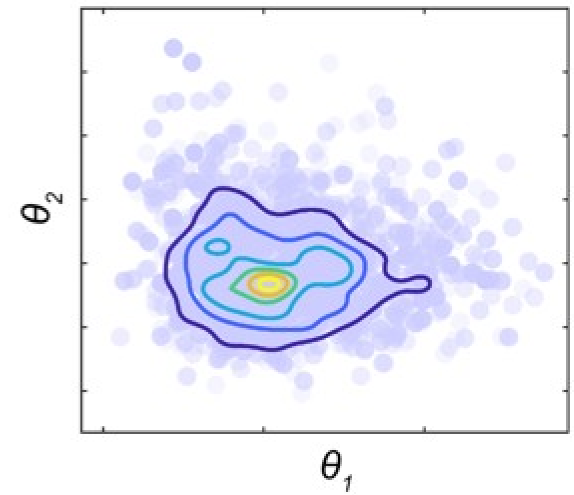
(b) Bidirectional modeling of restrainers

Question: Which one is the best? How likely is it?

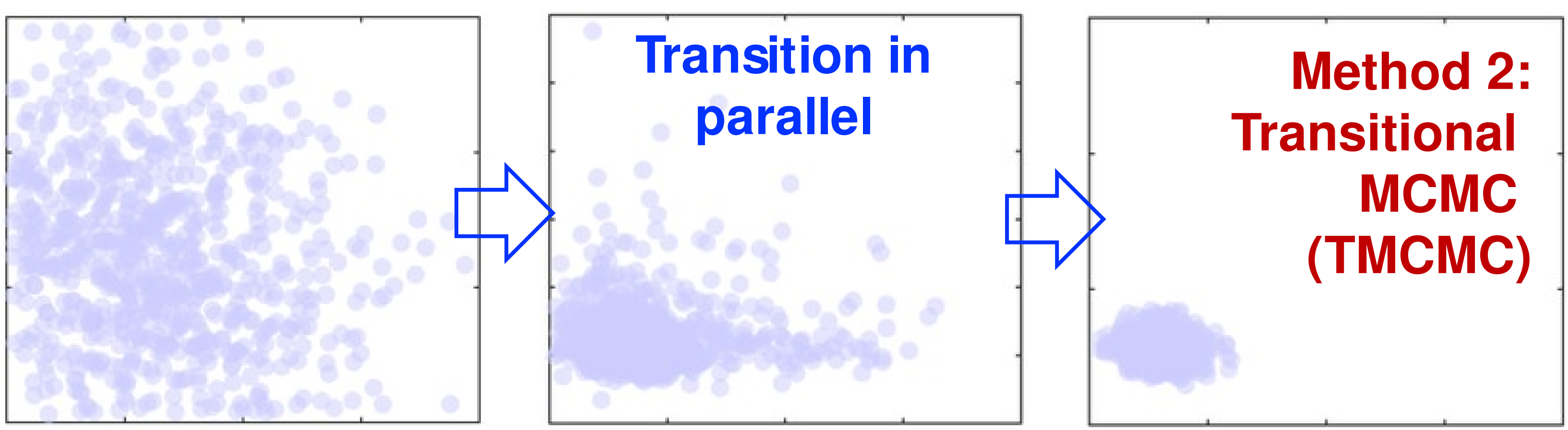
Method 1: Monte Carlo Markov Chain (MCMC)



Sequentially generates a chain of samples



Posterior PDF



Initial

Intermediate

Final (Posterior PDF)

Model selection based on Bayesian evidence

$$p(\theta|\mathcal{M})\frac{p(\mathcal{M}|\theta)p(\theta)}{\underbrace{p(\mathcal{M})}_{\text{Bayesian evidence of a model class } \mathcal{M}} = \int p(\mathcal{M}|\theta)p(\theta)d\theta}$$

- Analytcal solutions usually do not exist, however, it can be approximated during the TMCMC process:

$$p(\theta|u_{1:N}, y_{1:N})_0 \rightarrow$$
$$p(\theta|u_{1:N}, y_{1:N})_{\beta_j} \rightarrow \cdots \rightarrow \quad (\beta_j = 0, ..., 1)$$
$$p(\theta|u_{1:N}, y_{1:N})_1$$

- Weights of each particle:

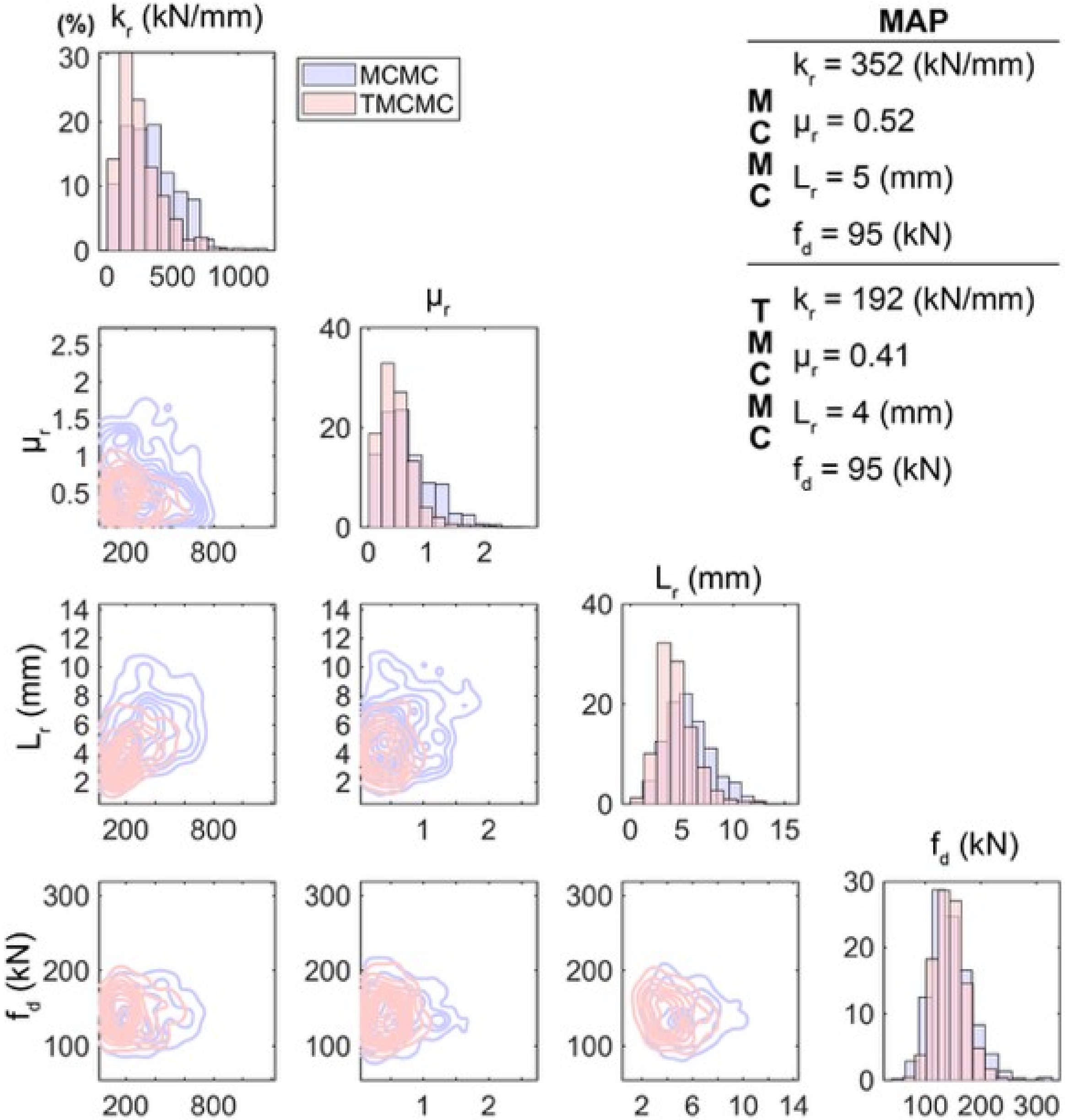
$$w_{j,i} = p(\mathcal{M}|\theta_{j,i})^{\beta_{j+1}-\beta_j}, i = 1, ..., N_p$$

- Bayesian evidence is the sum:

$$S_j = \sum_1^{N_p} w_{j,i}/N_p \qquad p(\mathcal{M}) \approx \prod_{j=0}^{m-1} S_j$$

Ching Jianye and Chen Yi-Chu, JEM, 2007

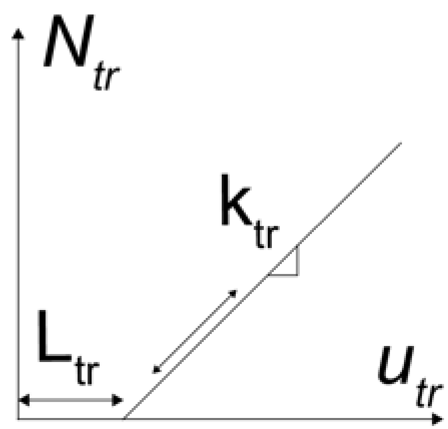
Model 1 – Bayesian estimation results



MAP

MCMC	k_r = 352 (kN/mm)
	μ_r = 0.52
	L_r = 5 (mm)
	f_d = 95 (kN)
TMCMC	k_r = 192 (kN/mm)
	μ_r = 0.41
	L_r = 4 (mm)
	f_d = 95 (kN)

- Consistent results
- The most plausible Model 1 suggests that the restrainers remained within the linear-elastic range during the earthquake.
- This conclusion is consistent with the design documents and on-site inspections.

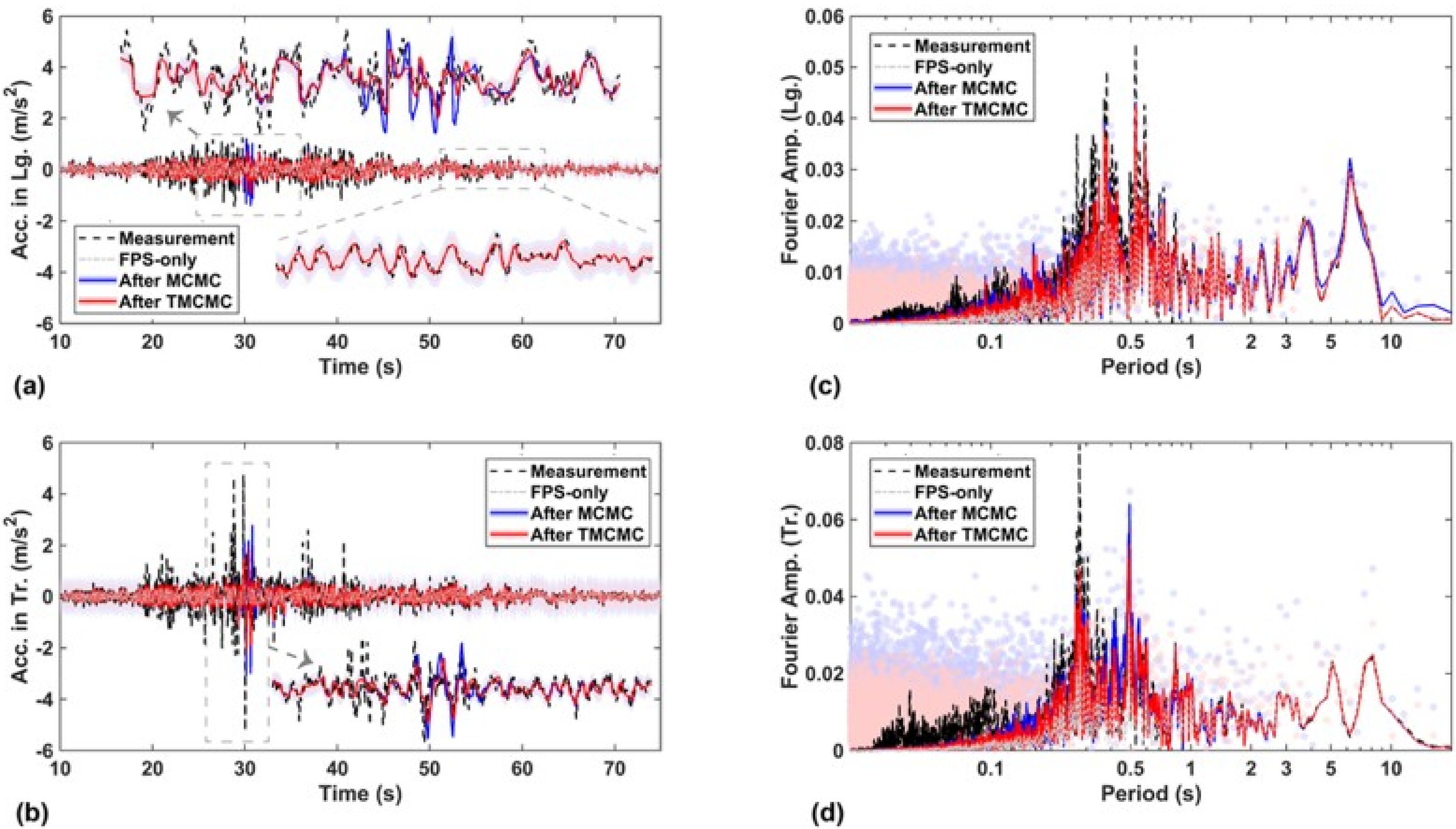


Acceleration response reproduction

- <u>In the frequency domain</u>, still struggle **in the short-period range (< 0.4 s)**.
- In the long-period range (above 3.0 s), **TMCMC shows closer agreement**, particularly in the Lg. direction.
- TMCMC provides **a better balance** between deterministic predictions and quantified uncertainties across both low- and high-period ranges.

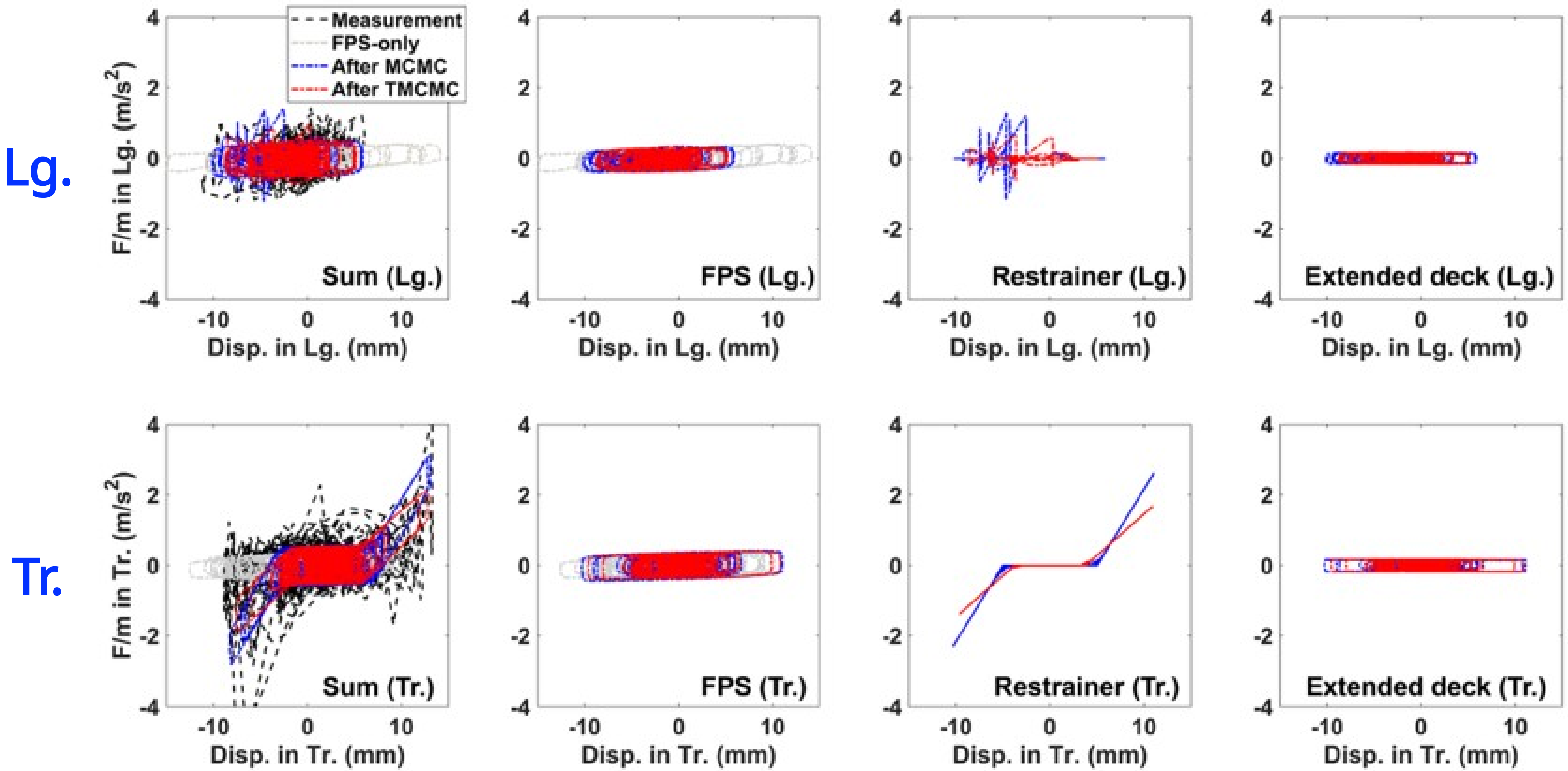
Lg.

Tr.



Structural behavior reproduction

- Still fall short of capturing finer details observed in the measured forces.
- This discrepancy likely arises from the **simplified modeling** of the steel restrainer and extended deck, as they involve complex dynamic phenomena such as **pounding and sliding over uneven surfaces**.



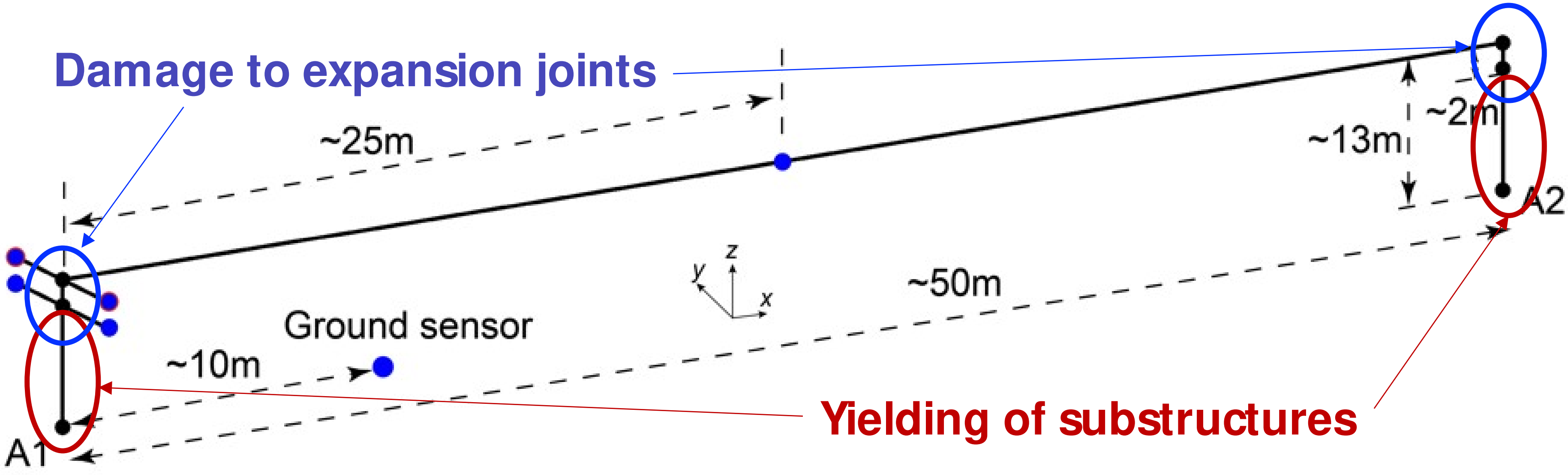
Structural performance prediction

- Based on posterior estimation results

Various assumptions in prediction analysis

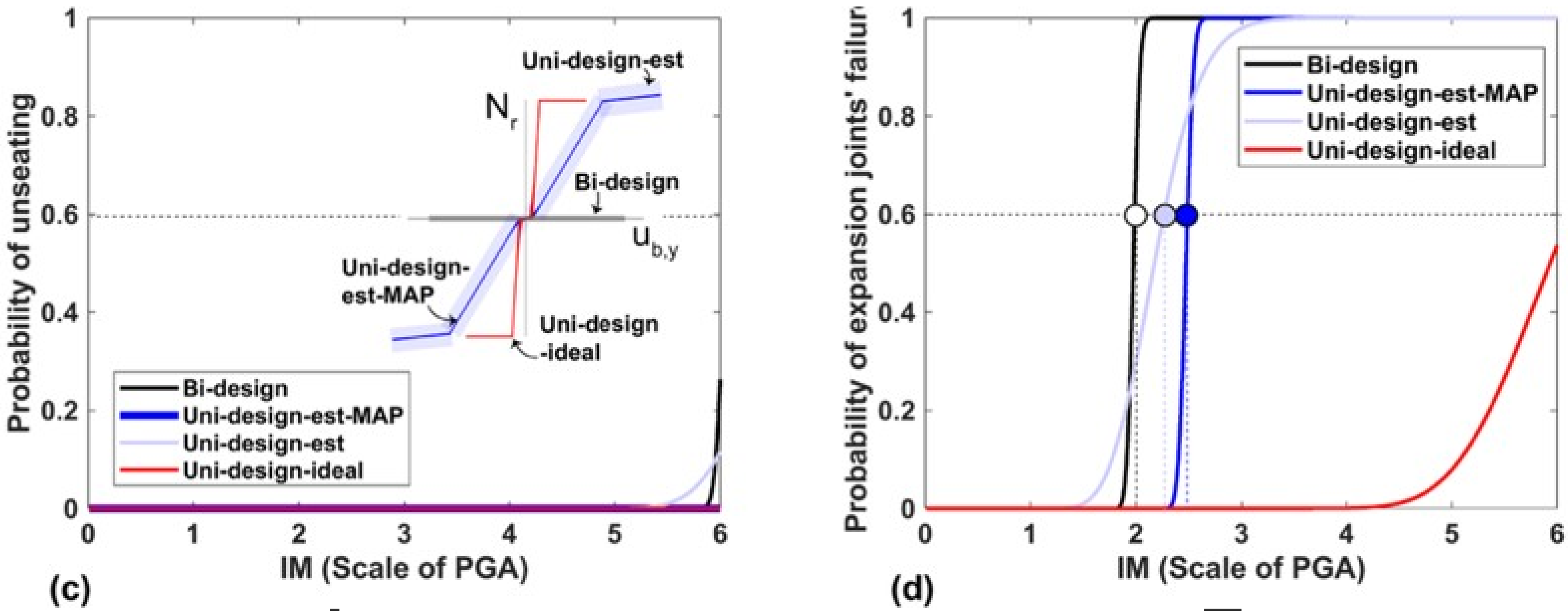
	FPS's model	Extended deck's model	Restrainer's model
Bi-design			-
Uni-design-ideal			
Uni-design-est			
Uni-design-est-MAP			

⊝: Design value (deterministic);
⊙: Estimated MAP value (deterministic);
⊗: Estimated values (probabilistic)



The probability of significant displacements (60%)

- **In Lg.**: sufficient safety margins for different modeling assumptions
- **In Tr.**: **~2.0 times intensity** is required to lead to damage, except for uni-design-ideal scenario with >6.0 safety margin



Lg. **Tr.**

The required intensities in the three unidirectional cases are **higher than that in the bi-design case**, indicating that **the inclusion of restrainers can provide a certain safety margin for expansion joint damage**.

Safety margins under different design conditions

Design conditions	Model assumptions	Yielding (Lg.)	Yielding (Tr.)	Unseating (Lg.)	Damage (Tr.)
Bi-isolation	Ideal	> 6.0	> 6.0	> 6.0	2.0
Uni-isolation (Model1)	Uni-design-ideal	3.5	3.0	> 6.0	> 6.0
	Uni-design-est	> 6.0	4.5	> 6.0	2.1
	Uni-design-est-MAP	3.7	3.3	> 6.0	1.8
Uni-isolation (Model3)	Uni-design-ideal	> 6.0	> 6.0	> 6.0	> 6.0
	Uni-design-est	> 6.0	> 6.0	> 6.0	2.3
	Uni-design-est-MAP	> 6.0	> 6.0	> 6.0	2.5

- Current unidirectional isolation design for the bridge provides sufficient safety margin to maintain functionality in future events.

- **Uni-isolation is comparable to the bi-isolation in the 4 indicators.**

Conclusions

- The **intended isolation effect was achieved in the longitudinal direction**.
- **Spike-like force** (acceleration) peaks were observed in the transverse direction due to the **contact between girders and restrainers**.
- **Bidirectional characterization** of its mechanical components is important, despite the adoption of a unidirectional isolation design.
- The unidirectional isolation cases offer **sufficient safety margins** across all four performance indicators.

Future:

- The behavior of restraints has not yet been fully captured, resulting in gaps in understanding of its nonlinear behavior.
- Solution: Continuous monitoring in the future is expected to improve the bridge model, enhancing its predictive accuracy and reliability.

Thank you for your kind attension !

華南理工大學

South China University of Technology