Multi-fault rupture focal mechanism simulation using spectral element method and its application to seismic analysis of a multi-span continuous highway bridge

Reporter: Wang Wenzhe

School of Civil Engineering , Southeast University

Outline

I. Research Background

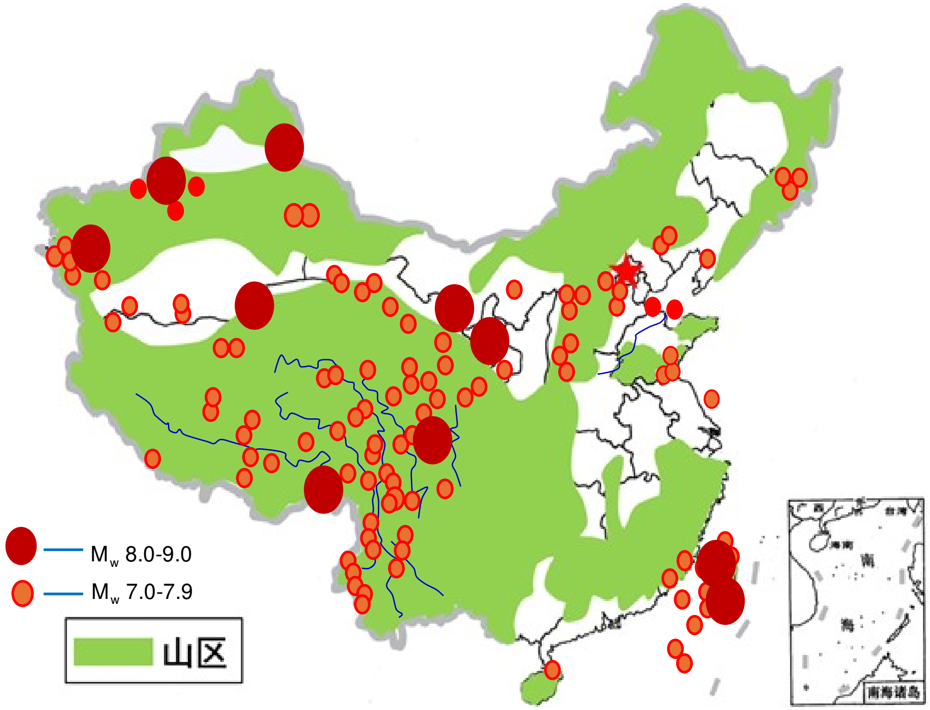
II. Ground-Motion Simulation

III. Bridge Response Analysis

IV. Conclusions

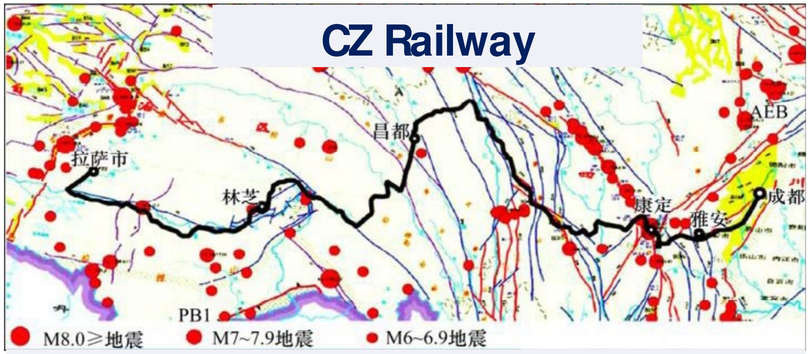
Research Background

- China's transport network is rapidly expanding into mountainous regions like Sichuan and Tibet.



Distribution of Significant Earthquakes in China Since 1900

In the past two decades, **the Sichuan-Tibet region** has experienced **9** strong earthquakes ($M > 7$)



Highly Dense Deep Faults

National Strategic Need

Sichuan-Tibet Railway	Qinghai-Tibet Railway
Xinjiang-Tibet Railway	Yunnan-Tibet Railway
Beijing-Tibet Highway	Sichuan-Tibet Highway

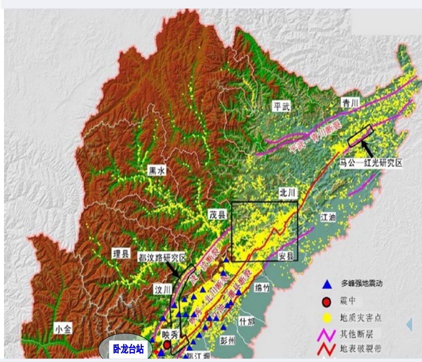
14th Five-Year Plan for a Modern Integrated Transport System

Research Background

- Strong earthquakes occur frequently in active fault-dense regions, where multi-fault rupture is prominent.

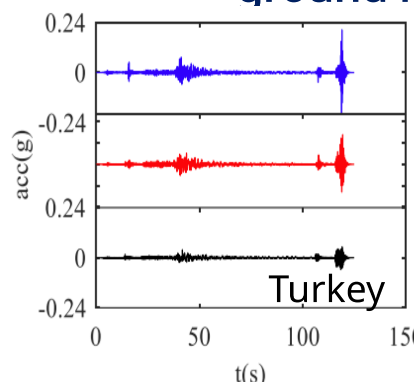
Multi-fault rupture-type strong earthquakes

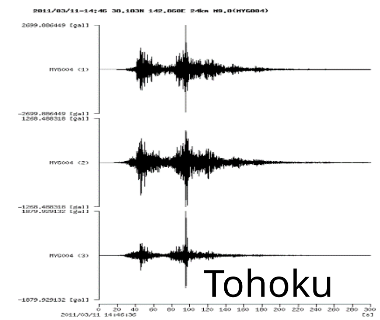
M_w7.8 Turkey earthquake

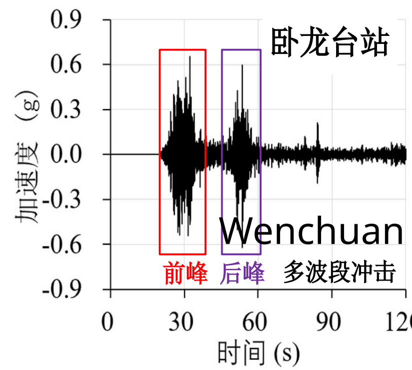


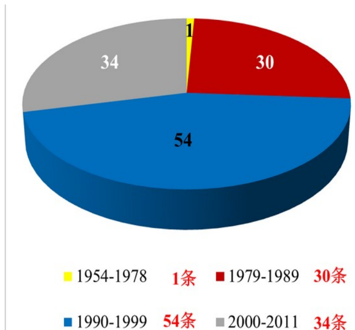
M_w8.0 Wenchuan M_w9.0 Tohoku

Multiple sequential ground motions





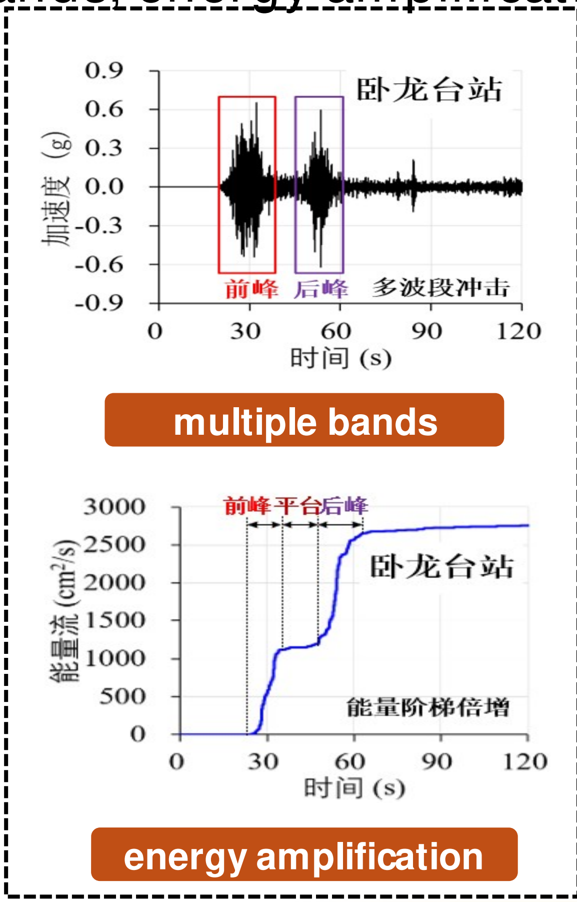


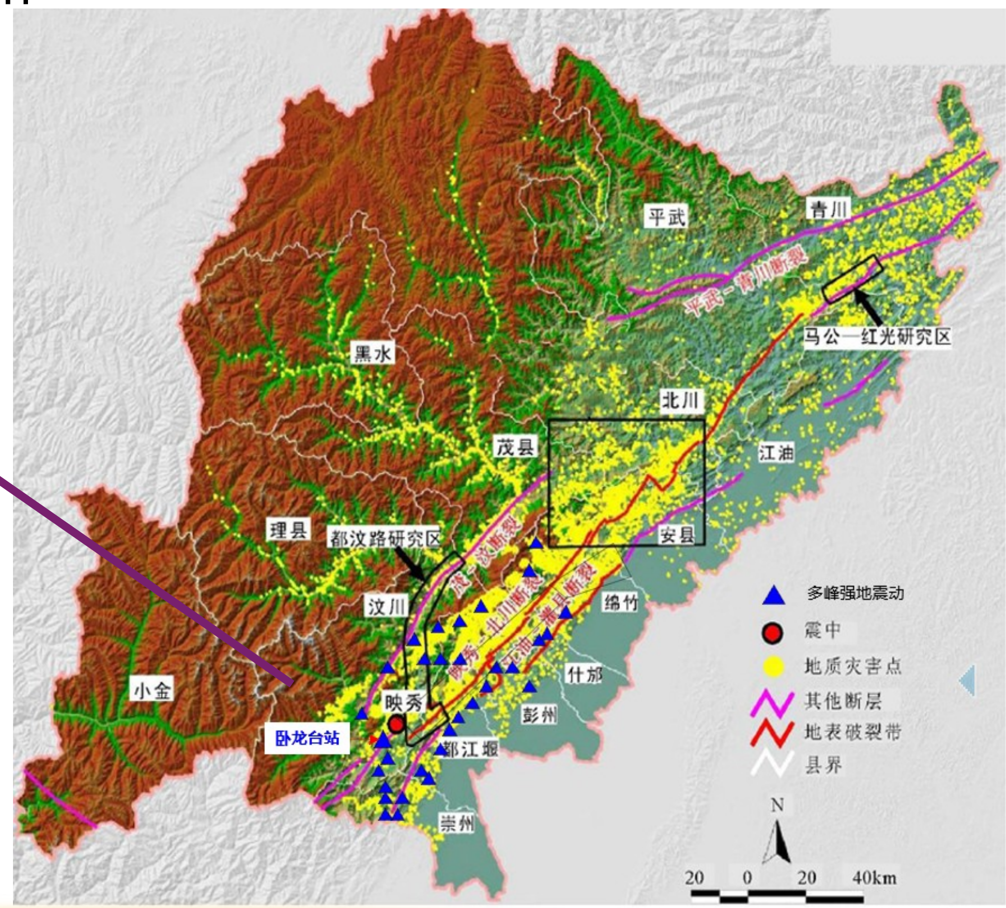


- Available records of multiple sequential strong ground motions remain highly limited

Research Background

- Multiple sequential ground motions are characterized by multiple bands, energy amplification





Earthquake research urgently needs to expand from single-fault rupture to multi-fault rupture.

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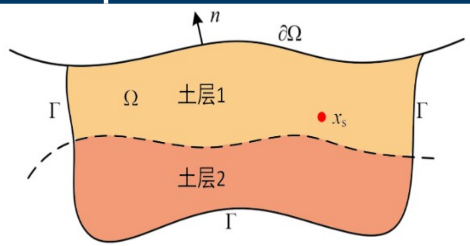
2 Multi-fault ground-motion simulation

- Spectral Element Method was used for ground motion simulation

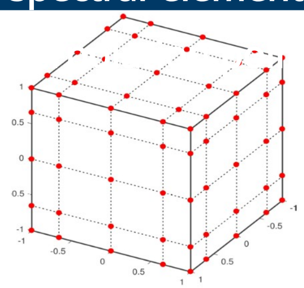
spectral element



Solving linear elastic wave equation:

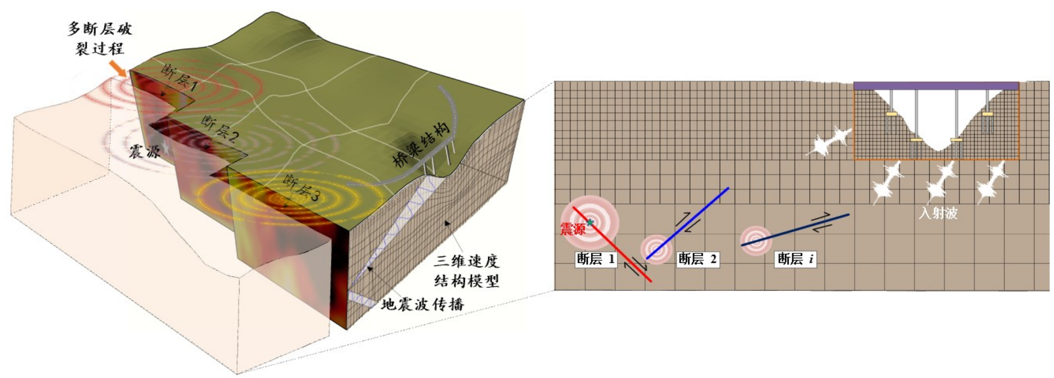
$$\rho \frac{\partial^2 s}{\partial t^2} = \nabla \cdot T + f$$

spectral-element



integration points GLL by solving equations:

[illegible]



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RESEARCH ARTICLE

Multi-Fault Rupture Focal Mechanism Simulation Using Spectral Element Method and Its Application to Seismic Analysis of a Multi-Span Continuous Highway Bridge

Shuai Li, Wenzhe Wang, Mingdong Wang, Fan Zhang, Jingquan Wang, M. Shahria Alam, Junwu Dai

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2 Multi-fault ground-motion simulation

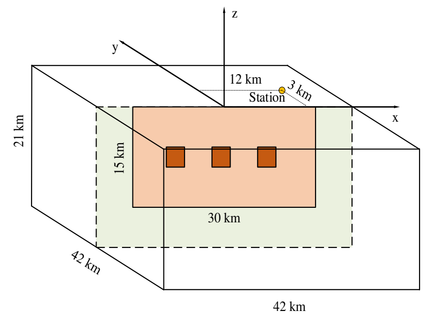
➢ A basic benchmark model was built and the results matched well with the Discontinuous Galerkin method.

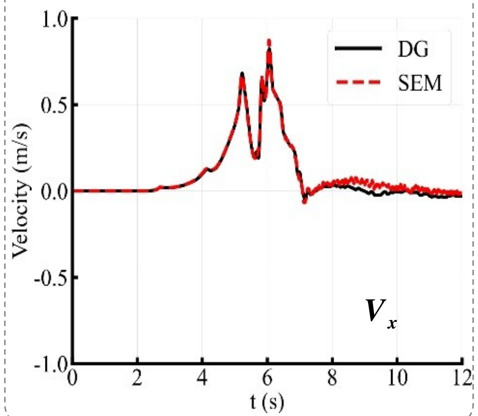
single-/dual-fault rupture

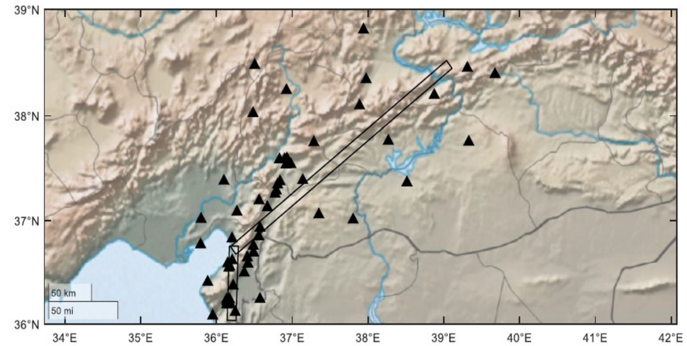
Single-fault velocity-field snapshot

Multi-fault velocity-field snapshot

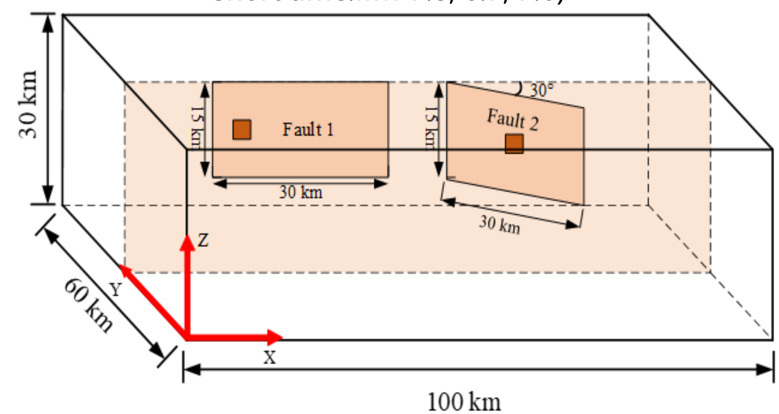
model validation







2023 Turkey earthquake strong event
(two strike-slip faults; three strong events occurred within a short time:Mw 7.8, 6.7, 7.6)

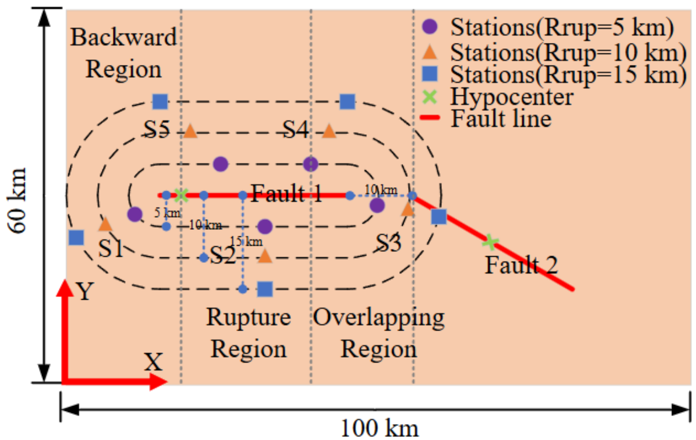


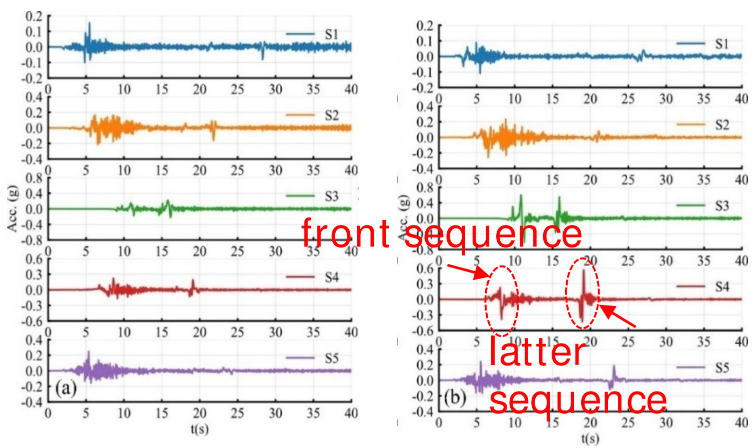
Based on the Turkey earthquake event, a regional-scale model with two strike-slip faults was built

2 Multi-fault ground-motion simulation

➢ Spatiotemporal distribution characteristics of multi-fault ground

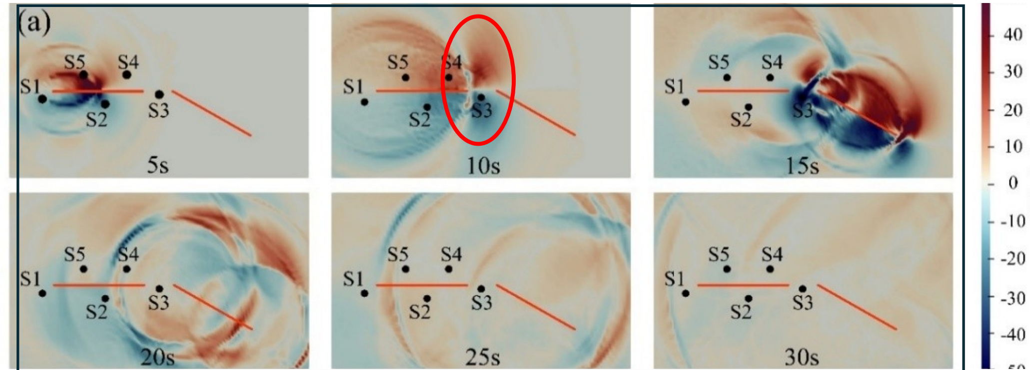
Station Layout



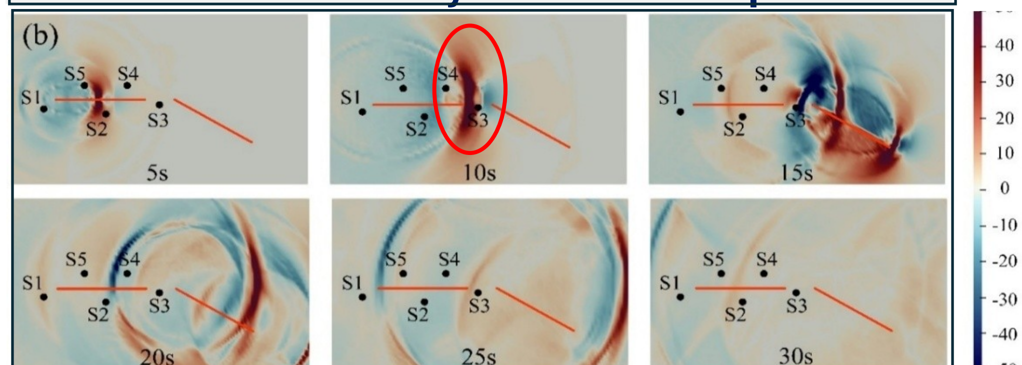


x direction

y direction



x direction velocity wavefield snapshot

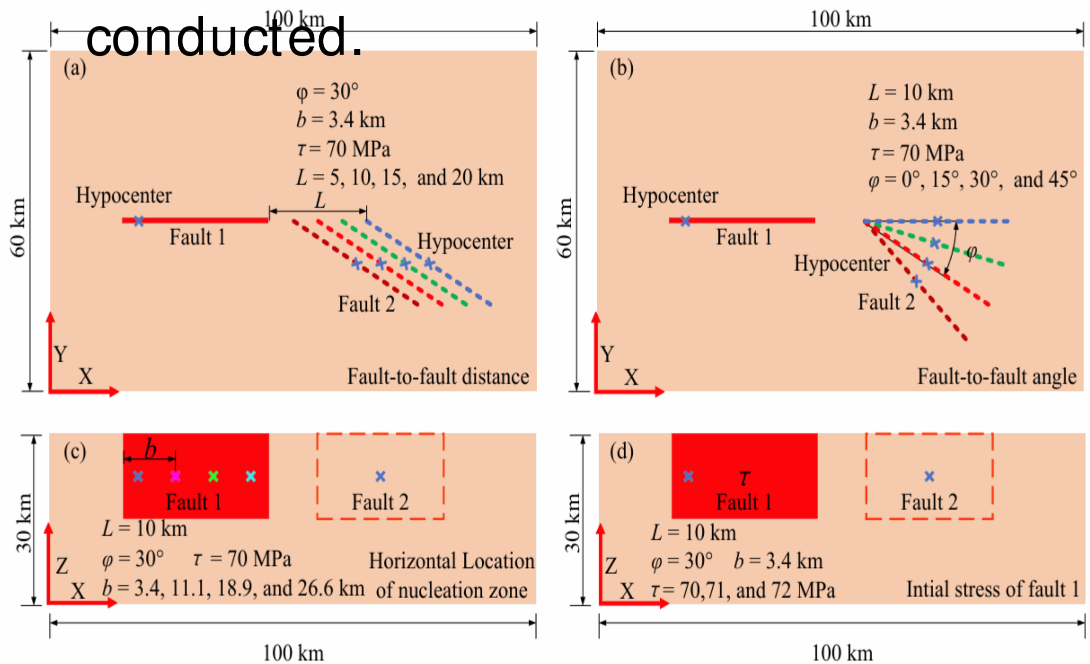


y direction velocity wavefield snapshot

- The y-direction ground motions at the S3 and S4 stations exhibit distinct multi-peak and pulse-like characteristics, and the ground-motion amplitude is significantly larger than those at other stations

2 Multi-fault ground-motion simulation

➢ To study the effects of fault distribution and source parameters on ground motion characteristics, parametric sensitivity analysis was conducted.

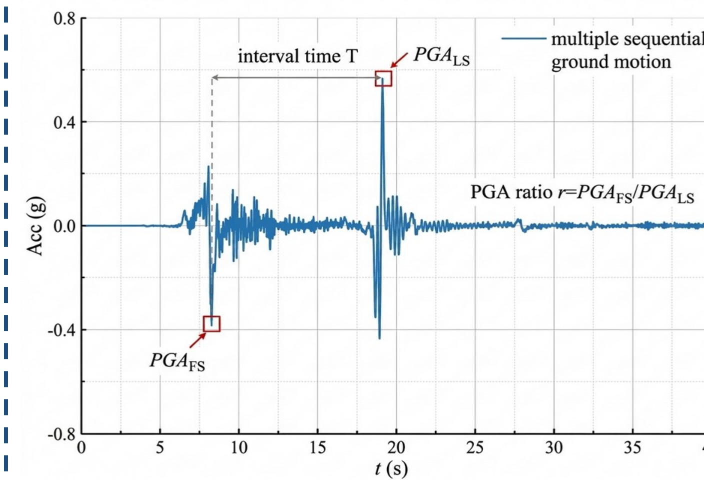


➢ **Fault-to-fault distance *L* :**5, 10, 15 and 20 km

➢ **Fault-to-fault angle *φ* :**0, 15, 30 and 45°

➢ **nucleation-zone position *b*:** 3.4, 11.1, 18.9 and 26.6 km

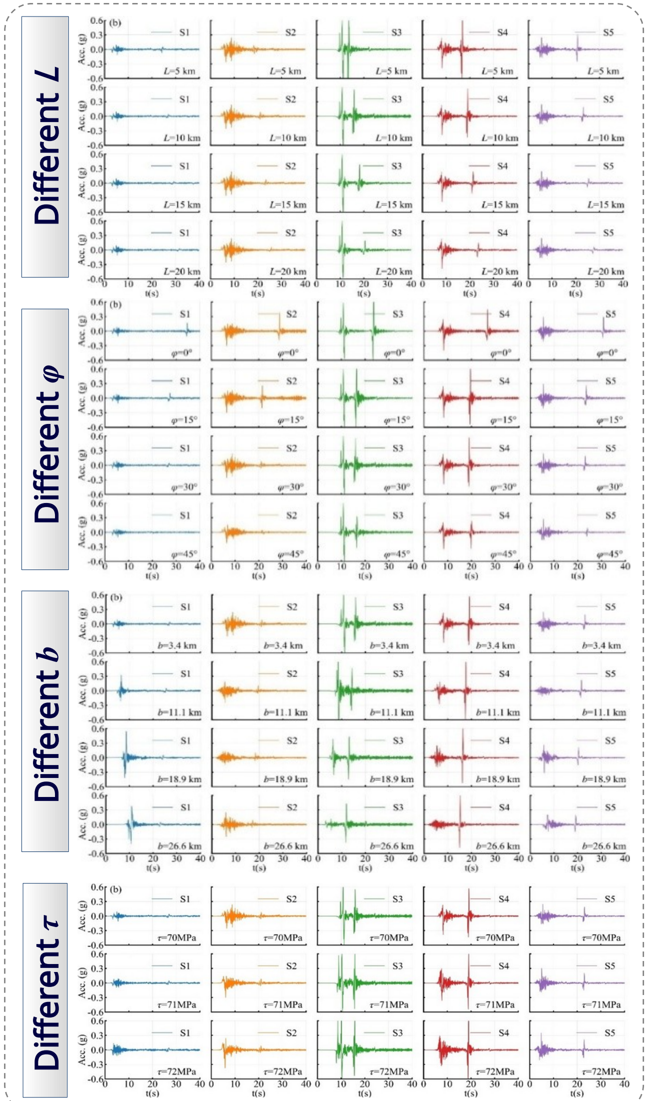
➢ **initial shear stress *τ*:**70, 71 and 72 MPa



□ To quantitatively describe the variations in the characteristics of ground motion under the influence of these parameters, the peak ground acceleration ratio r (PGA_{FS}/ PGA_{LS}) and the time interval T between the front and latter sequence are

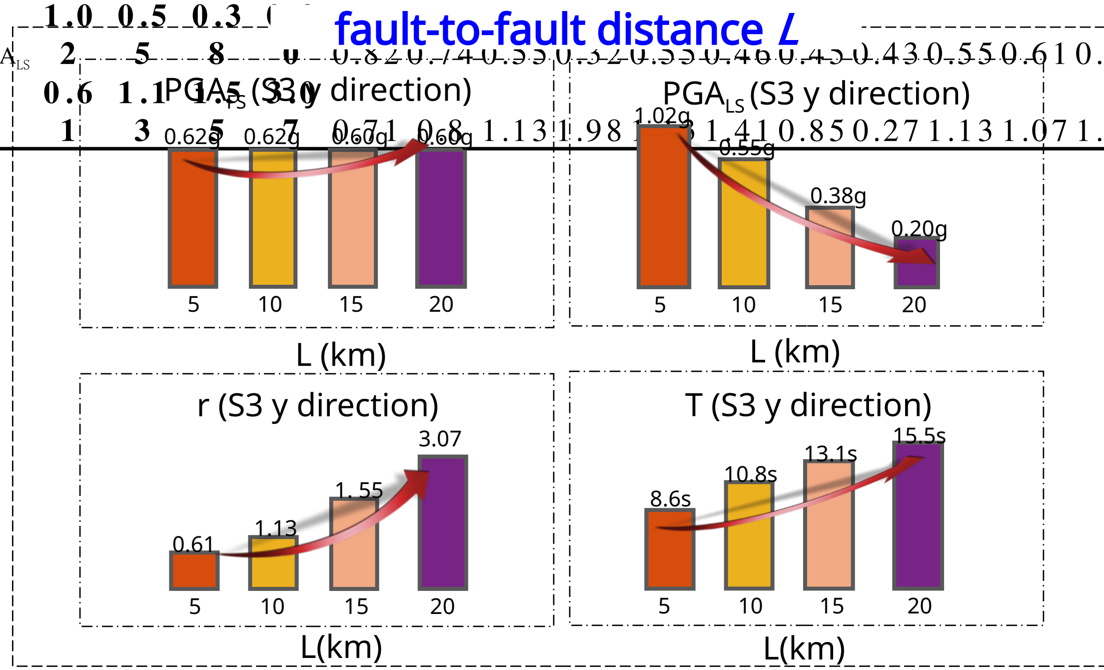
2 Multi-fault ground-motion simulation

- Each parameter significantly affects ground-motion characteristics.



S3 stations

Parameter	Fault-to-fault distance L (km)				Fault-to-fault angle φ (°)				nucleation-zone position b (km)				initial shear stress τ (MPa)		
Values	5	10	15	20	0	15	30	45	3.4	11.1	18.9	26.6	70	71	72
PGA_{FS}	**0.62**	**0.62**	**0.60**	**0.60**	0.58	0.59	0.62	0.64	0.62	0.65	0.38	0.12	0.62	0.66	0.75
PGA_{LS}	**1.02**	**0.55**	**0.38**	[illegible]	0.82	0.74	0.55	0.52	0.55	0.46	0.45	0.43	0.55	0.61	0.62
r	**0.61**	**1.13**	**1.55**	**3.07**	0.71	0.8	1.13	1.98	[illegible]	1.41	0.85	0.27	1.13	1.07	1.22



- Fault-to-fault distance and angle mainly affect the latter sequence, while nucleation position and initial shear stress affect both sequences.

Outline

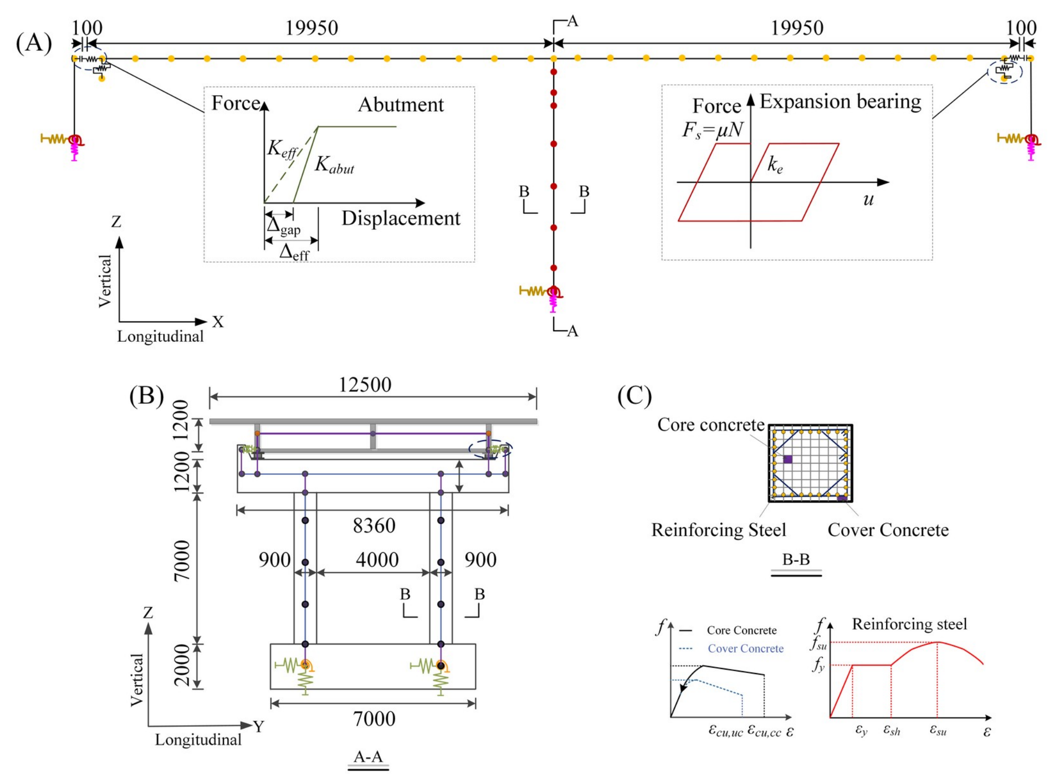
3 Seismic performance analysis of bridges

➢ bridge numerical analysis model

- **concrete—Concrete02**
- **reinforcement—ReinforcingSteel**

material property parameters

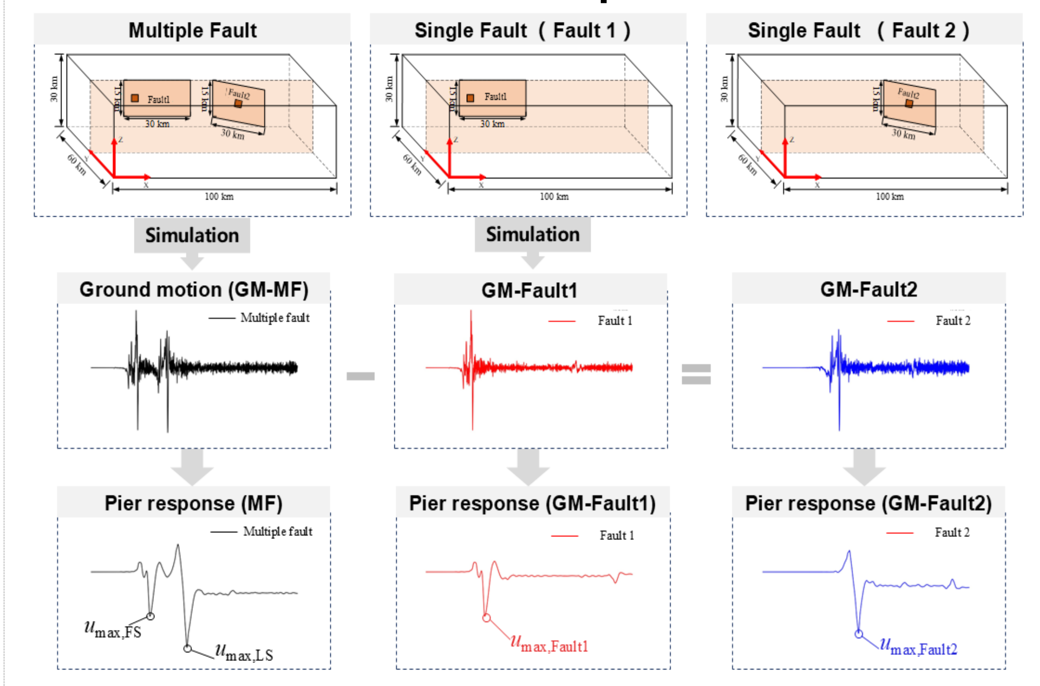
Material	property	Value	Unit
Confined/ unconfined concrete	compressive strength f_c'	30/36.78	MPa
	tensile strength f_t	2.51	MPa
	peak strain ε_0	0.26	%
	ultimate strength $0.2f_c'$	6/7.36	MPa
	ultimate compressive strain ε_{cu0}	1.4	%
	ultimate tensile strain	0.3	%
	elastic modulus, E_s	200	GPa
	yield	330	MPa



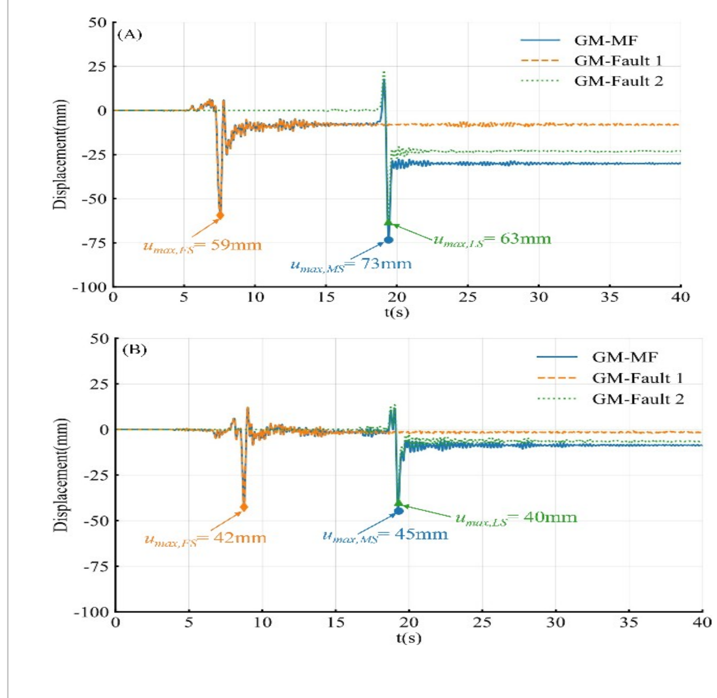
3 Seismic performance analysis of bridges

- To clearly illustrate the influence of multi-fault rupture, ground motion simulations were conducted for both multi-fault rupture and single-fault rupture.

Single- and multi-fault ground motion input



Pier top displacement

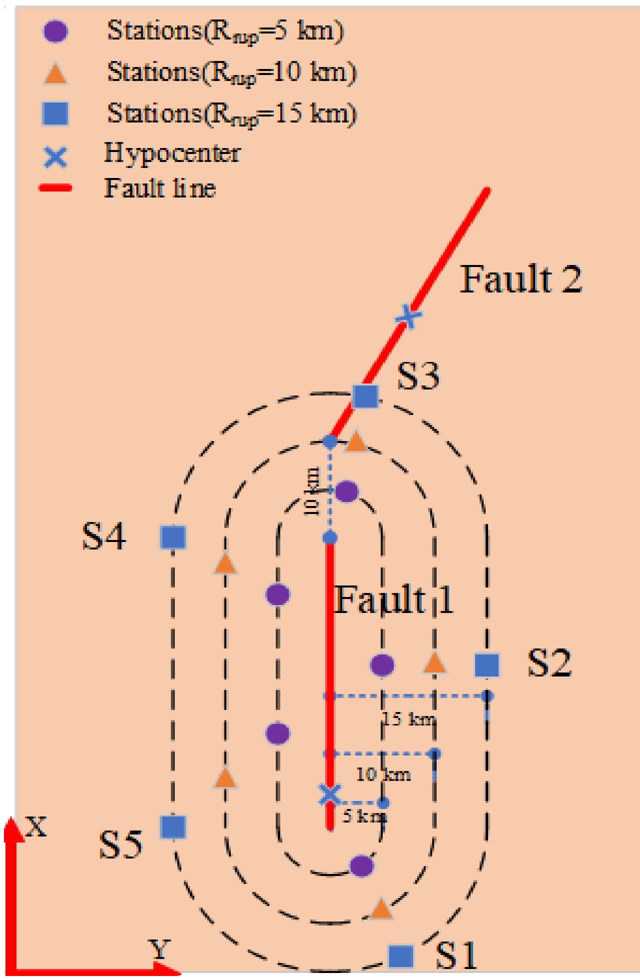


- Multi-fault rupture causes the seismic response of bridge piers to increase, with the maximum displacement at the top of the pier increasing by 10%

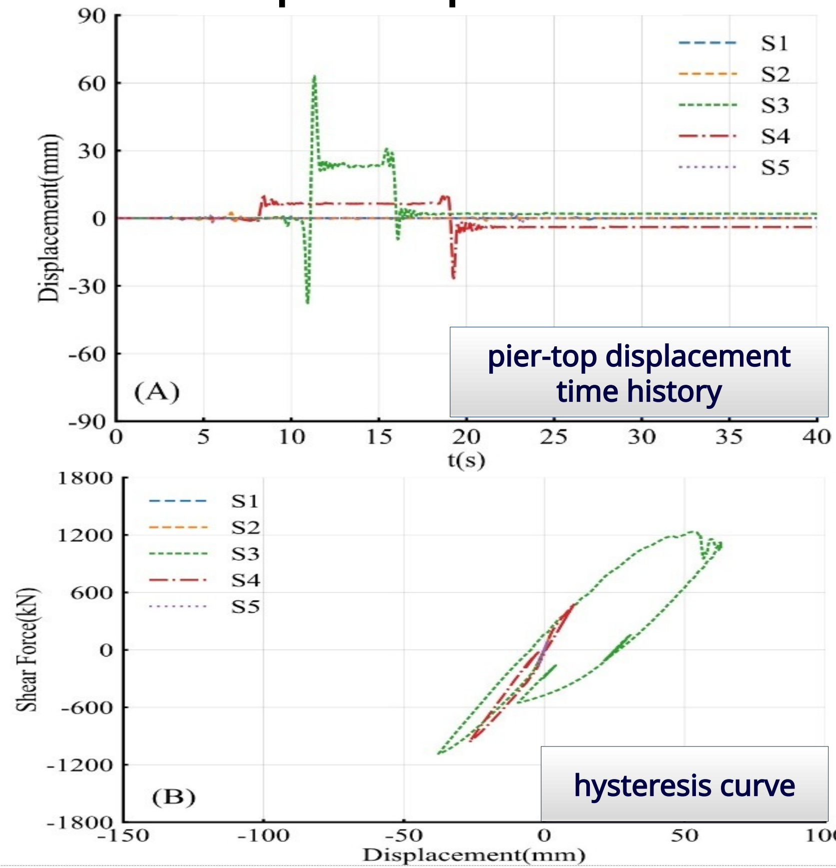
3 Seismic performance analysis of bridges

- The spatiotemporal distribution of bridge seismic response in different multi-fault regions was studied.

station layout



pier response

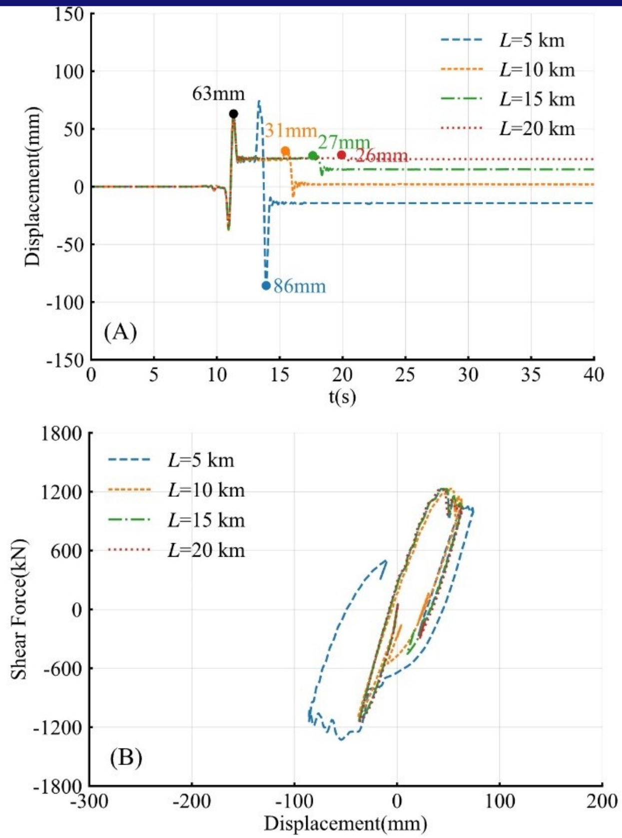


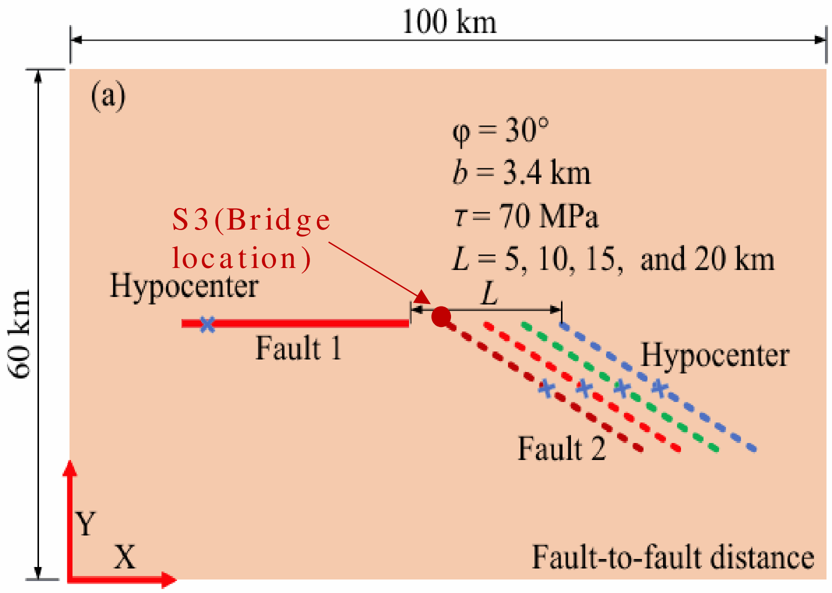
- The seismic response of the bridge at S3 and S4 are significantly larger than that at other stations.

3 Seismic performance analysis of bridges

➢ As L increases from 5 to 20 km, the maximum pier-top displacement under the latter sequence gradually decreases from 86 to 26 mm.

Pier response	Simulation parameter *L*



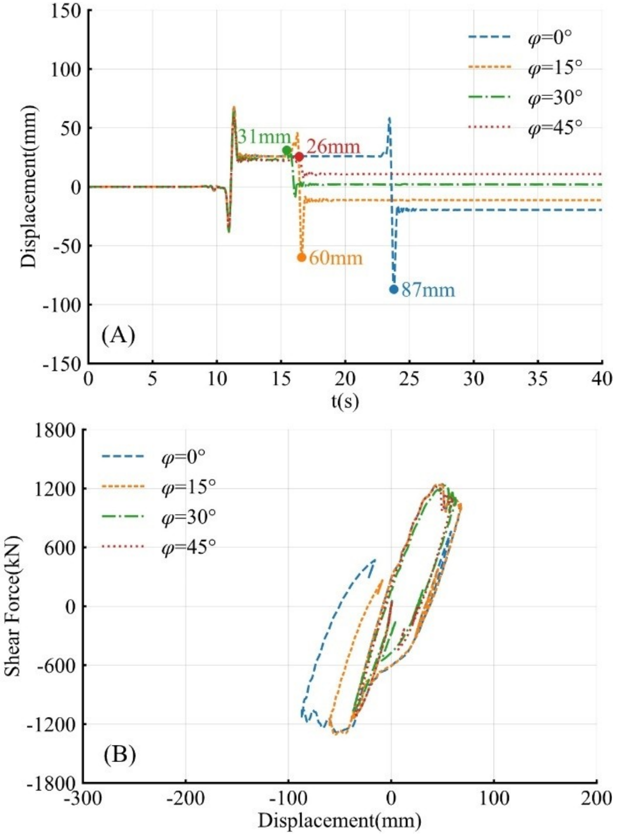


- A smaller fault-to-fault distance leads a greater seismic response in the overlap region

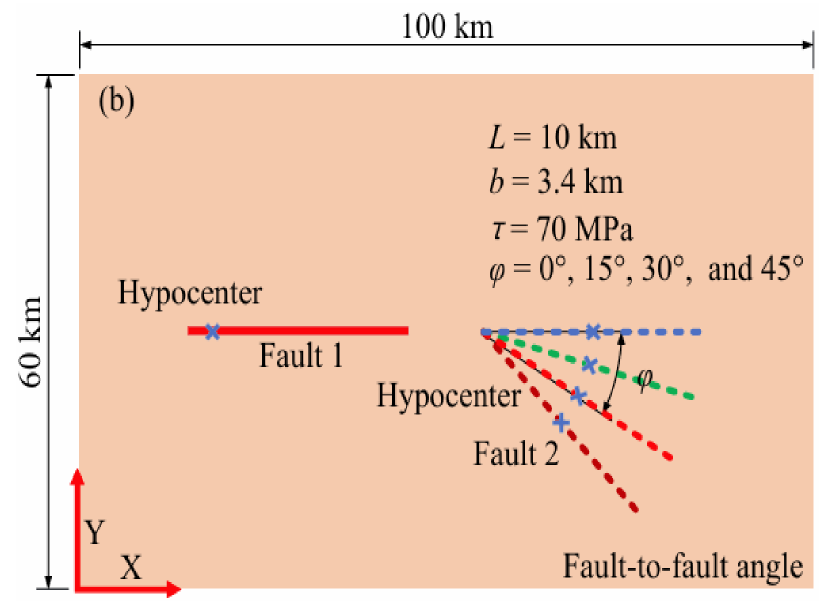
3.2 Seismic performance analysis of bridges

➢ As the angle increases from 0 to 45°, the maximum pier-top displacement under the latter sequence decreases from 87 to 26 mm

Pier response



Simulation parameter φ

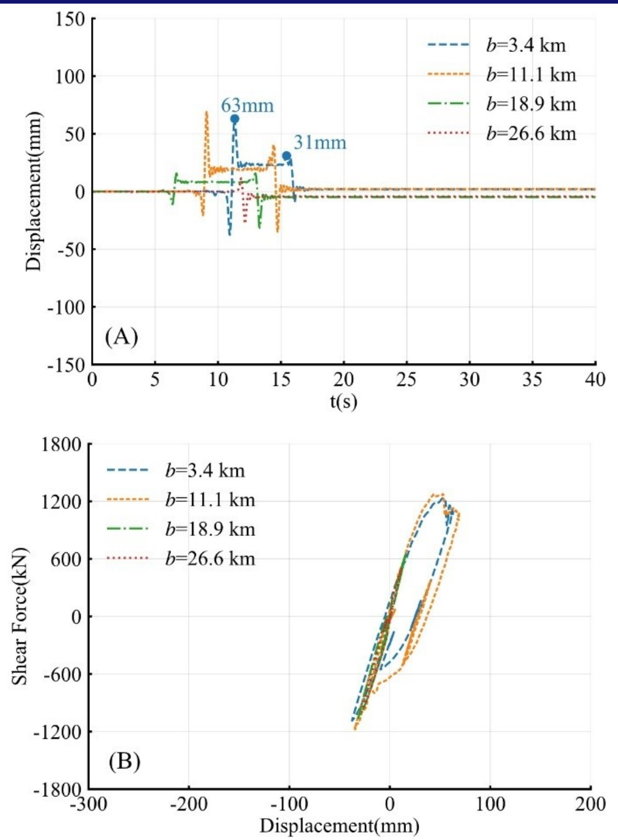


- Smaller fault-to-fault angles have the greatest effect on bridge seismic response in the fault-overlap region

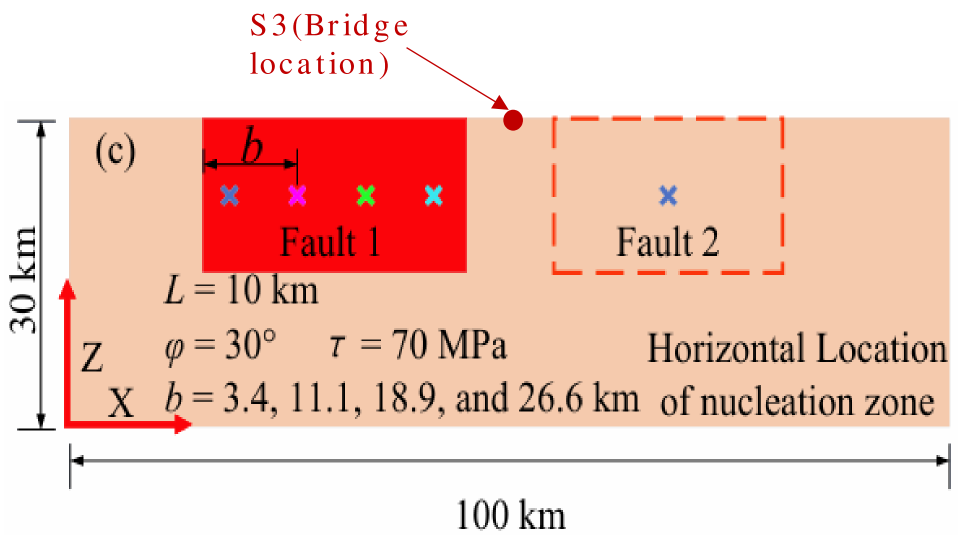
3 Seismic performance analysis of bridges

➢ As b increases, the seismic response of the bridge piers exhibits a decreasing trend.

Pier response



Simulation parameter *b*

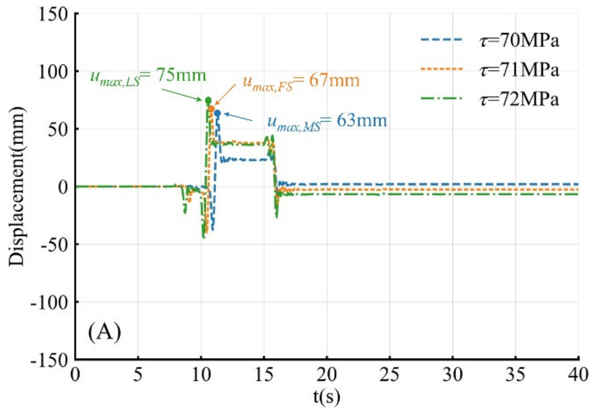


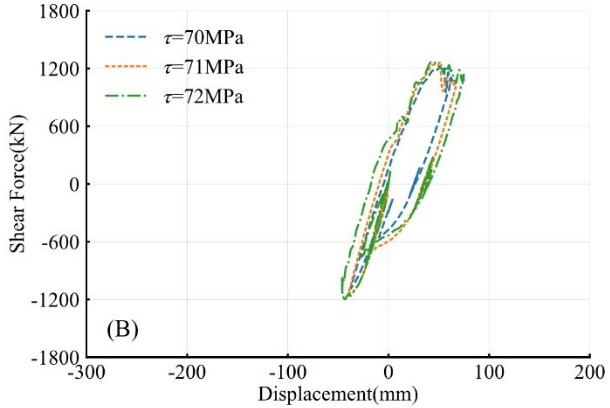
- The variation in hypocenter location alters the fault rupture direction, which consequently weakens forward directivity effect on the bridge.

3 Seismic performance analysis of bridges

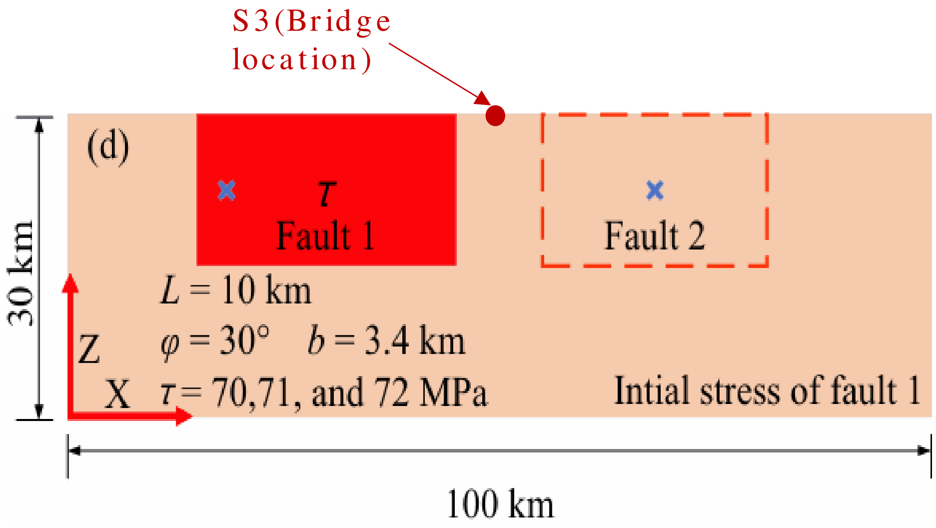
- As the stress increases, both the maximum pier top displacement and cumulative hysteretic energy gradually increase

Pier response





Simulation parameter τ



- A higher initial shear stress leads to a larger stress drop and releases more rupture energy, which consequently amplifies the overall seismic response of the bridge pier.

Outline

4 Conclusions

- Multi-fault rupture results in ground motions that exhibit multi-peak characteristics, which are particularly pronounced in the fault rupture overlap zones (S3 and S4)

- Smaller fault-to-fault distances and angles lead to greater bridge seismic responses in the fault-rupture overlap region, causing more severe seismic damage

- Multi-fault rupture ground motion significantly amplifies bridge seismic response. Compared with single-fault rupture ground motion, the maximum pier-top displacement increases by more than 10%

東南大學
SOUTHEAST UNIVERSITY

Thank you for your attention

Near-Fault Ground-Motion Simulation and High-Resilience

Bridge Team:

Wang Jngquan Li Shuai Zhang Fan Wang Mingdong Wang Wenzhe Hou Fenghuan Xu Zuohong Liu Can