CHALLENGES & INNOVATIONS

FOR

BRIDGES' LONG-TERM RESILIENCE

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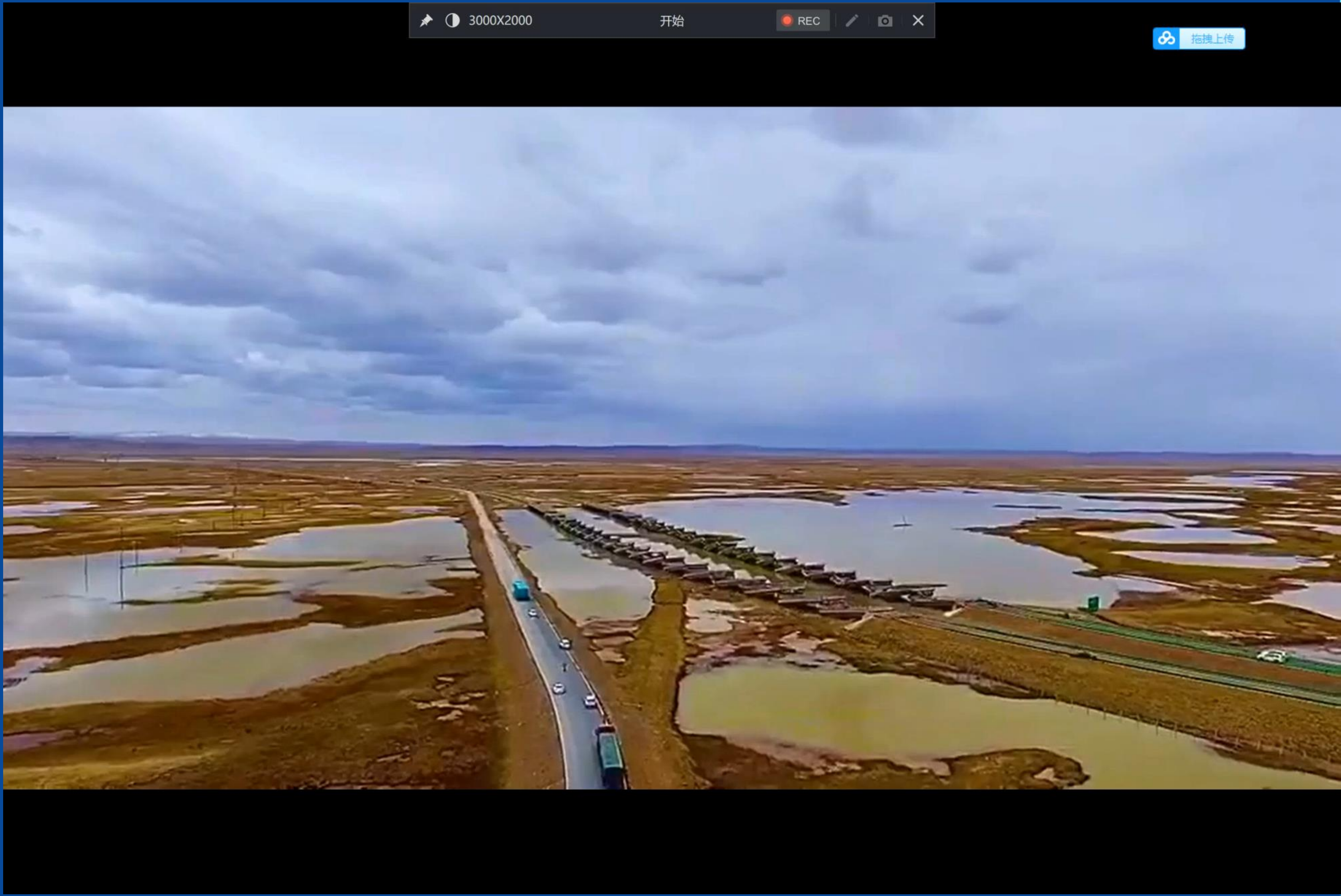
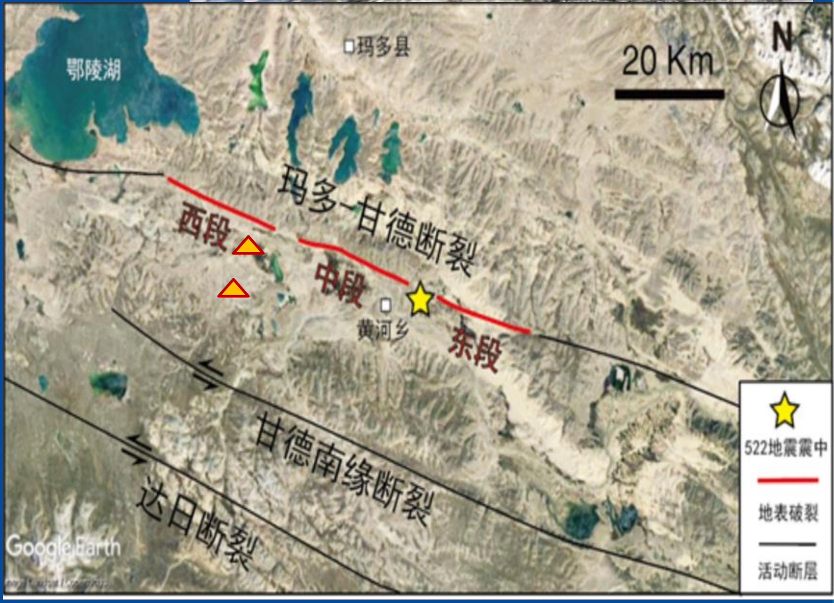
One Example: Qinghai Province, China -May, 21st, 2021



Maduo Earthquake, Qinghai Province, China

- **M7.3-7.4**
- **Two half mile-long highway bridges collapsed and many others severe damaged**
- **The bridges collapsed were equipped with RL Bearing**
- **The two bridges were about 20 miles away from epicenter**
- **More than 15 aftershocks with the magnitudes > M4**
- **The Highway with the bridges was built from 2014-2016, opened for publics at 2017**

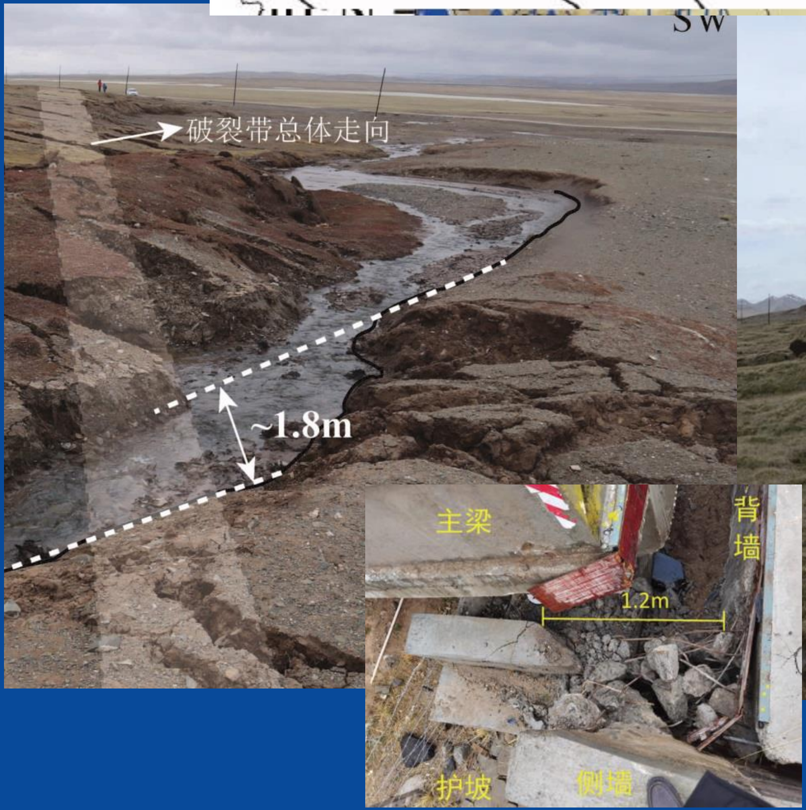


More Facts:

- Shallow hypocenter: 11 miles to surface
- Afterquake PGD
  horizontal: 1.4 - 1.8 meter
  vertical: 0.42 meter
- 1055 aftershocks within 7 days, among them 15 > M4.

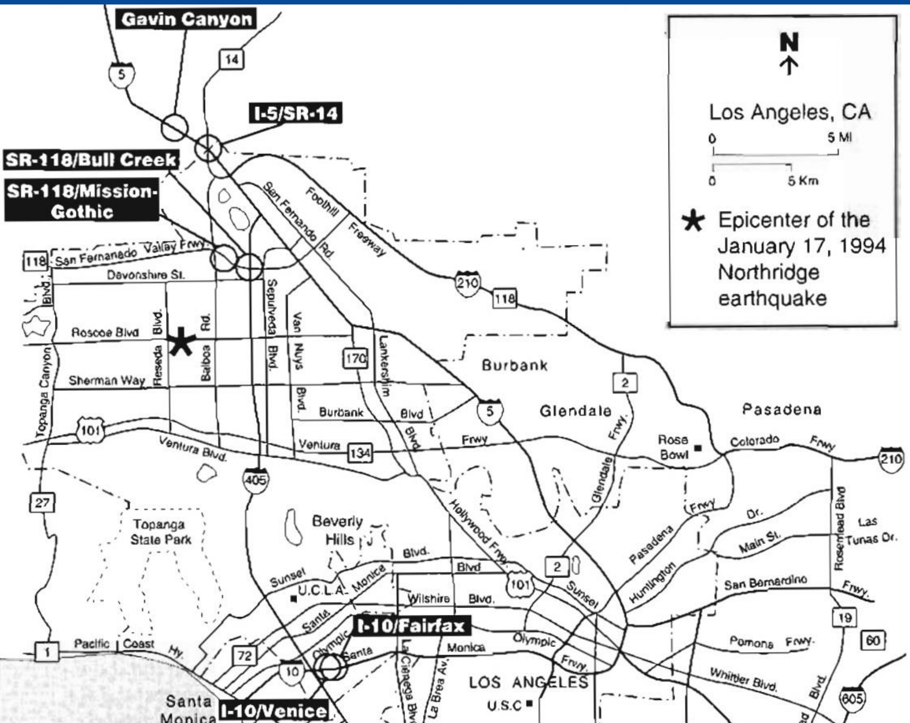
Lessons learned

- Vertical vibrations not ignorable
- Capacities to sustain aftershocks crucial
- Unification of rapid resilience and long-term performance

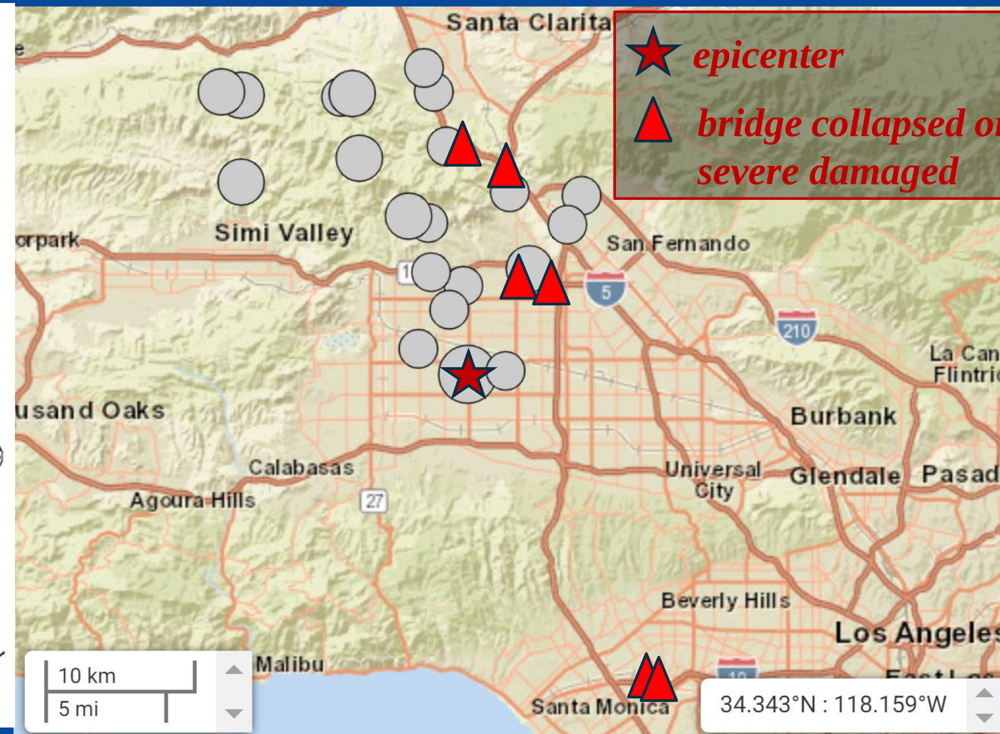


Refs
【1】地球物理学报，2021卷64第8期， 杨君妍等， 2671-2683页
【2】地球物理学报，2021卷64第8期，徐志国等， 2657-2670页
【3】地质学报，2021卷95第6期，潘家伟等， 1655-1669页
【4】2021讨论：戴君武，杨永强（地震局地震力学研究所）

M6.8 Northridge Earthquake, CA - 1994



Report of Caltrans on the Northridge Earthquake of 1994, “THE CONTINUING CHALLENGE”, Oct. 1994, page 2.

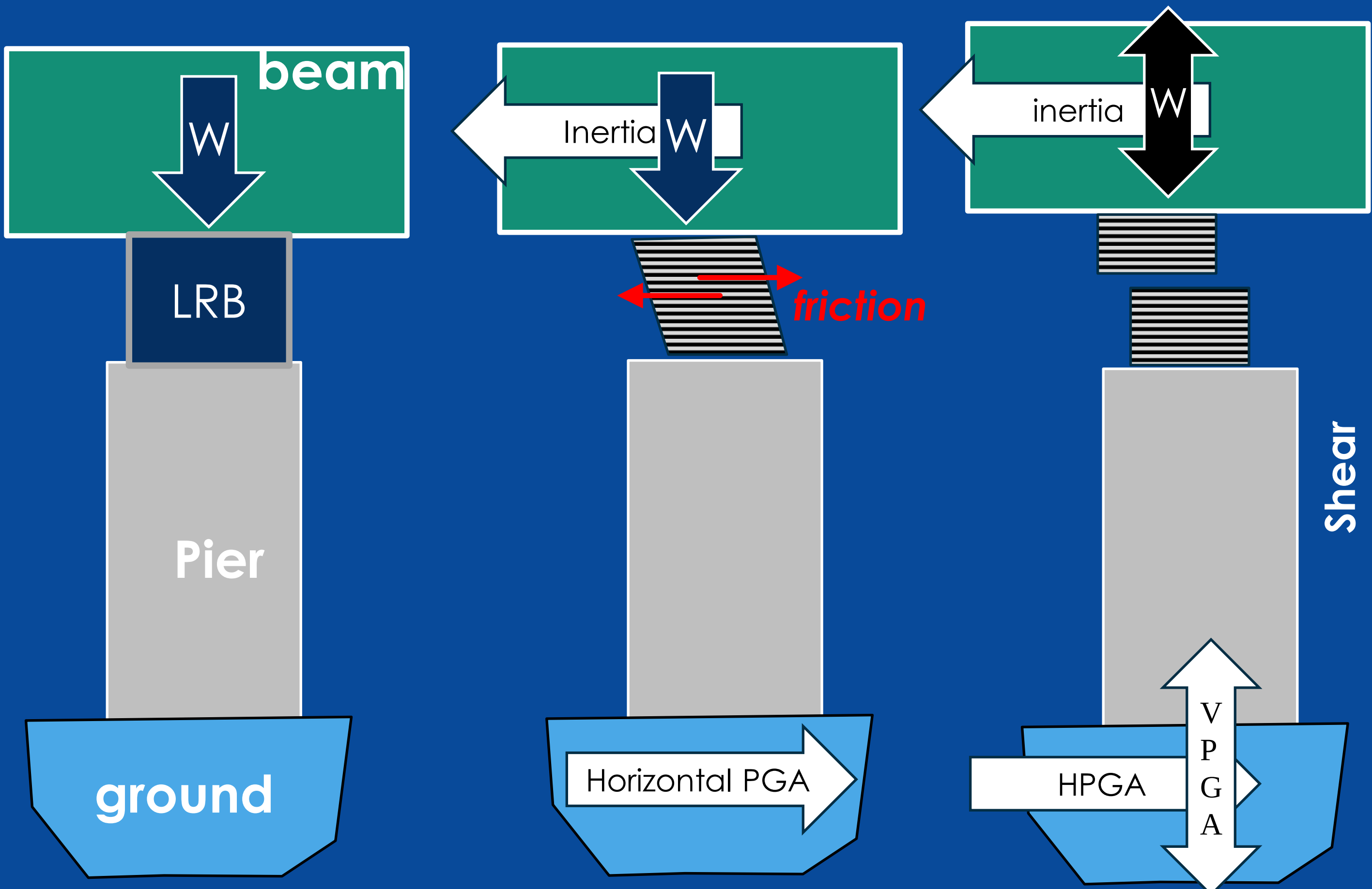


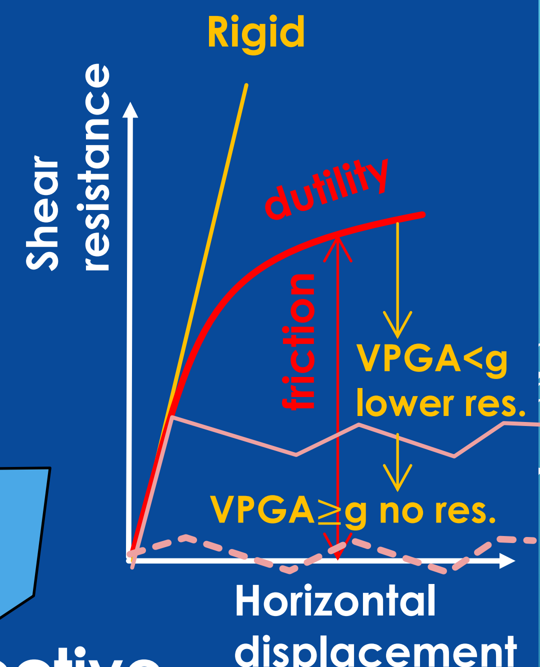
www.usgs.gov

Similarities

- 31 aftershocks > M4 within 72 hours after main shock
- Bridges collapsed and severe damaged away from epicenter
- 4 of the 6 collapsed bridges sat on the epicenters of aftershocks

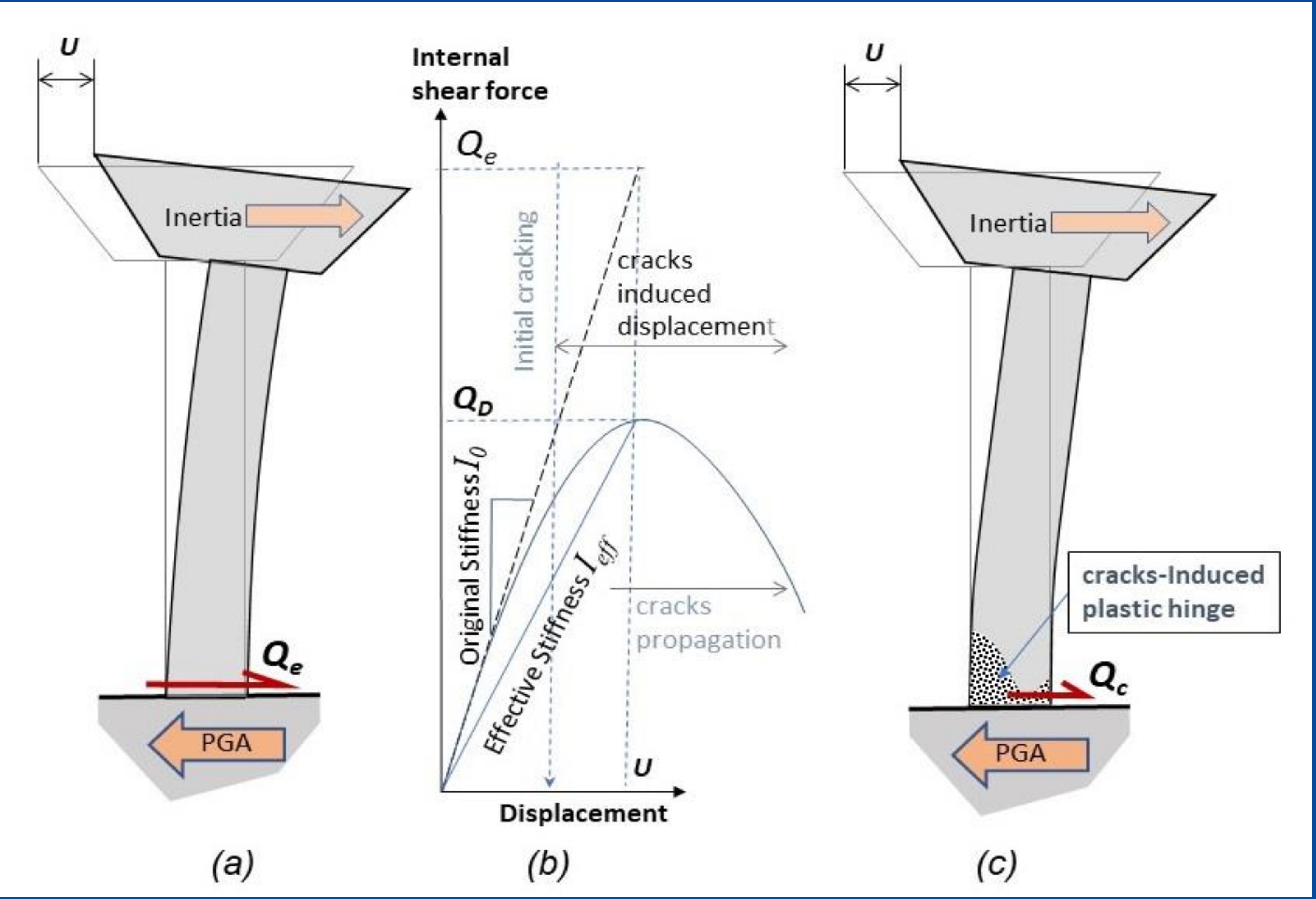
Exploration: Why LRB loses function?





For friction-based isolators, though very effective but vertical vibration may affect horizont resistance case by case; hence, integrated 3-D vibration and displacement control maybe is crucial for seismic safety of the cases

No friction-based isolation, e.g. Cast-in-Place



Preliminary

- Vertical seismic movement restriction and/or vibration isolation is crucial for structures' seismic behavior for some cases
- Consideration of the combined functions of vertical and horizontal ground motion is maybe necessary, so is the corresponding protection measurement
- Capacity to sustain aftershocks is vital important for bridges' safety
- Integration and rapid resilience and long-term performance maybe need more attention in next step

Thoughts & Proposals

Methodology "+"

(Methodology Plus)

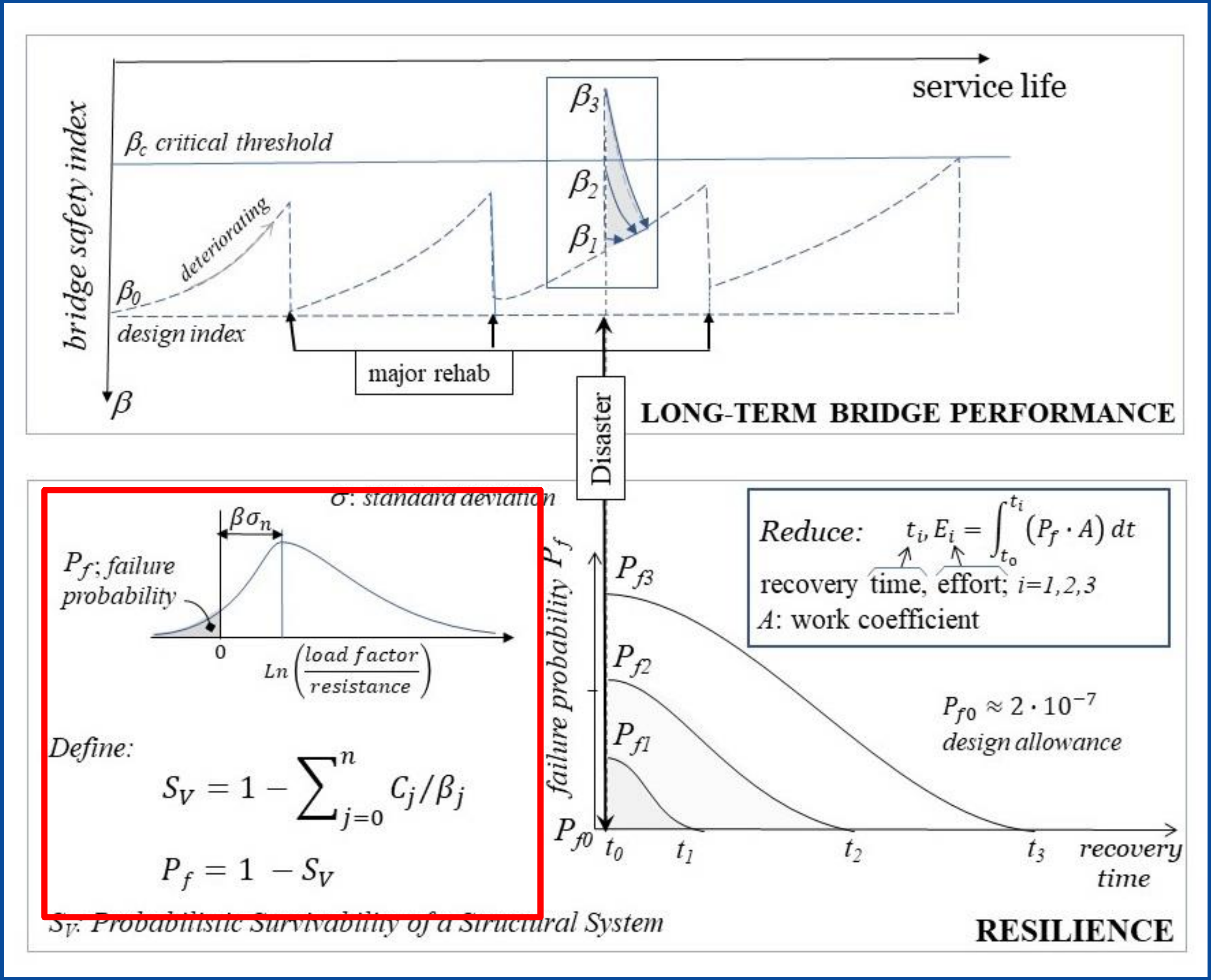
Rapid Resilience + long-term performance

Friction-based horizontal protection (e.g. RLB, FP)

+

Capability confining vertical vibration (V-connector)

Rapid Resilience + long-term performance



Rapid Resilience + long-term performance

According to statistic theory

$$S_{V1} = 1 - p_{f1},\ S_{V2} = 1 - p_{f2}, S_{V3} = 1 - p_{f3} \dots \dots\ S_{Vn} = 1 - p_{fn}, \qquad (6)$$

the failure probability of any part in series (5), i.e. p_{fk} for the k^{th} part, can be written as the following integral:

$$p_{fk} = \int_0^{\tau_k} f_k(\tau_k) d\tau_k, \qquad (7)$$

where $f_k(\tau_k)$ is the probability density function (PDF), which can be expressed as:

$$f_k(\tau_k) = -\frac{dS_{Vk}(\tau_k)}{d\tau_k}, \qquad (8)$$

the rate of change for failure probability:

$$\lambda_k(\tau_k) = \frac{f_k(\tau_k)}{S_{Vk}(\tau_k)}, \qquad (9)$$

Hence, the probabilistic survivability of the bridge system can by expressed as the form of the "competing mixture distribution risk model" as following:

$$S_V = S_{V1} \cdot S_{V2} \cdot S_{V3} \cdot \dots \dots \cdot S_{Vn}, \qquad (11)$$

$$S_V = exp\left[-\sum_{k=1}^{n} \int_0^{\tau_k} \lambda_k(\tau_k) d\tau_k\right] \qquad (12)$$

For a example of a concrete bridge,

$$S_V = 1 - p_f]_{strength\ limit\ state}, \qquad S_V = 1 - p_f]_{chloride\ corrosion}$$

the conducted probabilistic analysis indicates:

$$S_V = 1 - \left(p_f]_{strength\ limit\ state} + p_f]_{chloride\ corrosion}\right)$$

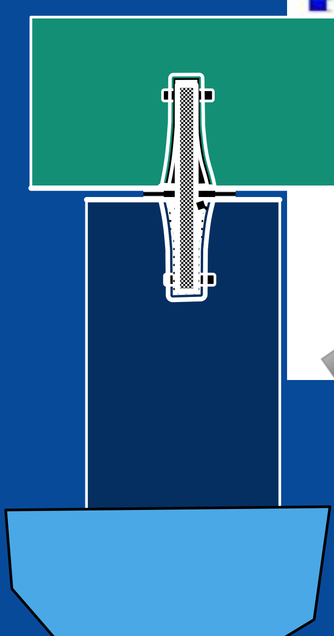
Horizontal protection

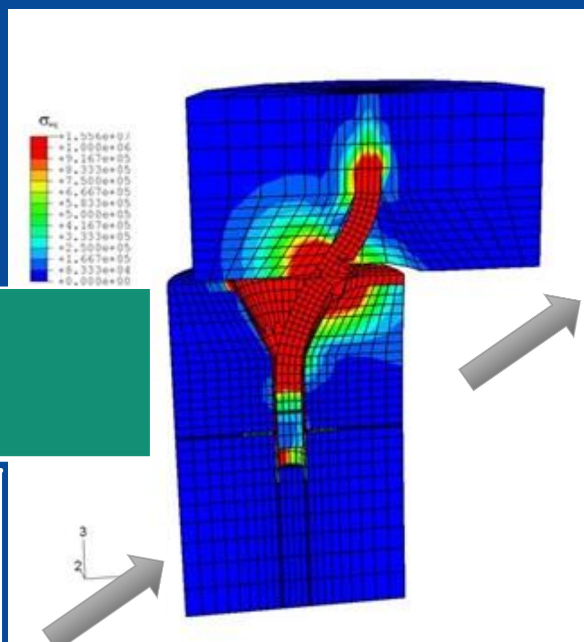
+

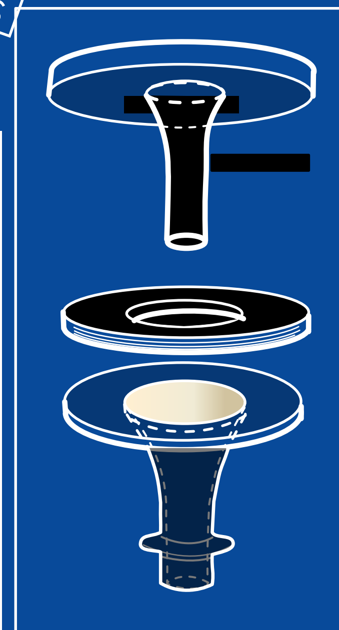
Confining vertical vibration

V-connector: Concepts of V

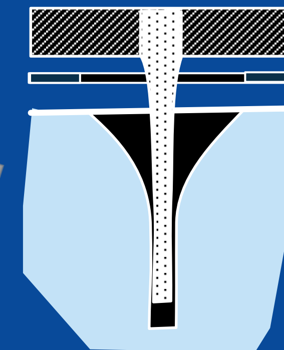
Further Developments for Engineering Design: Two Options



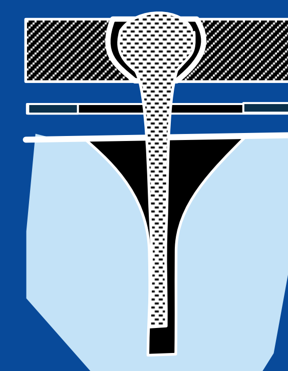




Single V-Tube



Fixed-End Pin (FP)

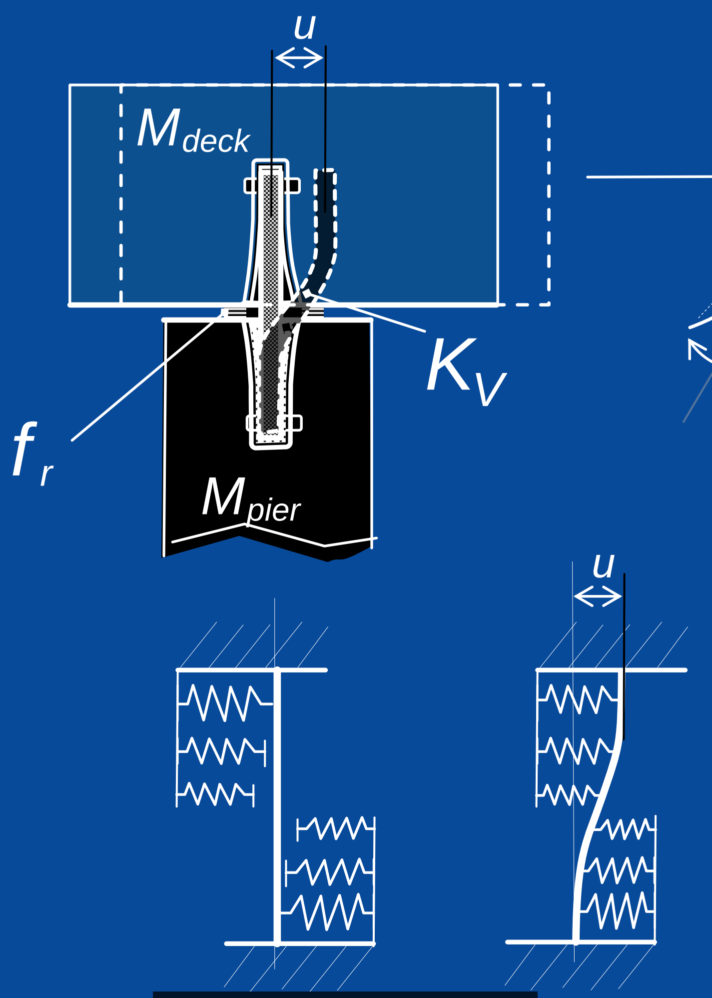


Hinge-End Pin (HP)

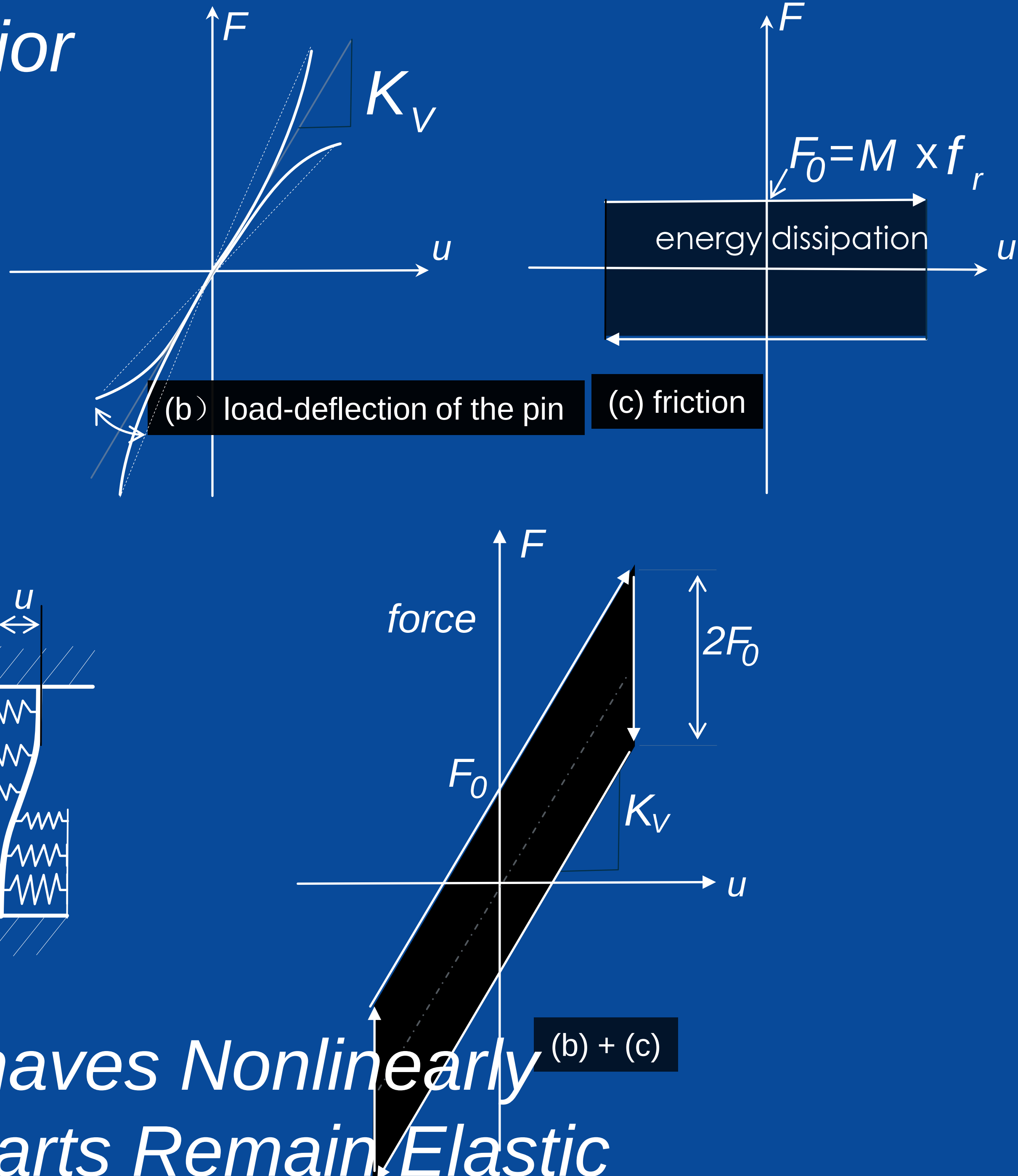
FP: easy for manufacture but deeper V-tube

HP: more expansive than FP for manufacture but better performance

Hysterical Behavior



(a) Model for the pin



(b) load-deflection of the pin

(c) friction

(b) + (c)

Key: System Behaves Nonlinearly

Structural Parts Remain Elastic

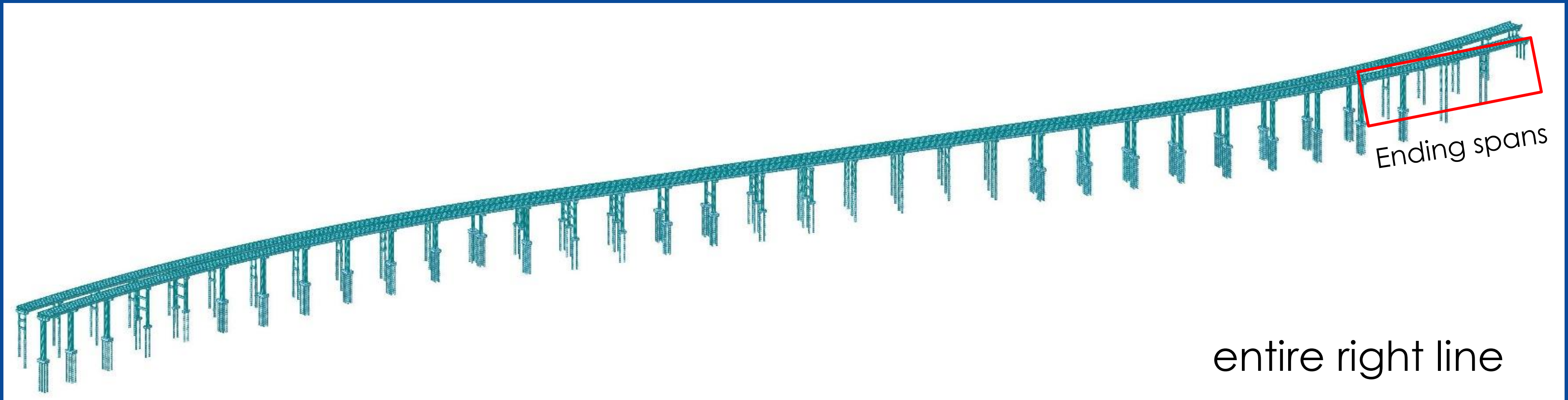
VIDEO: TEST AT UC-BERKELEY

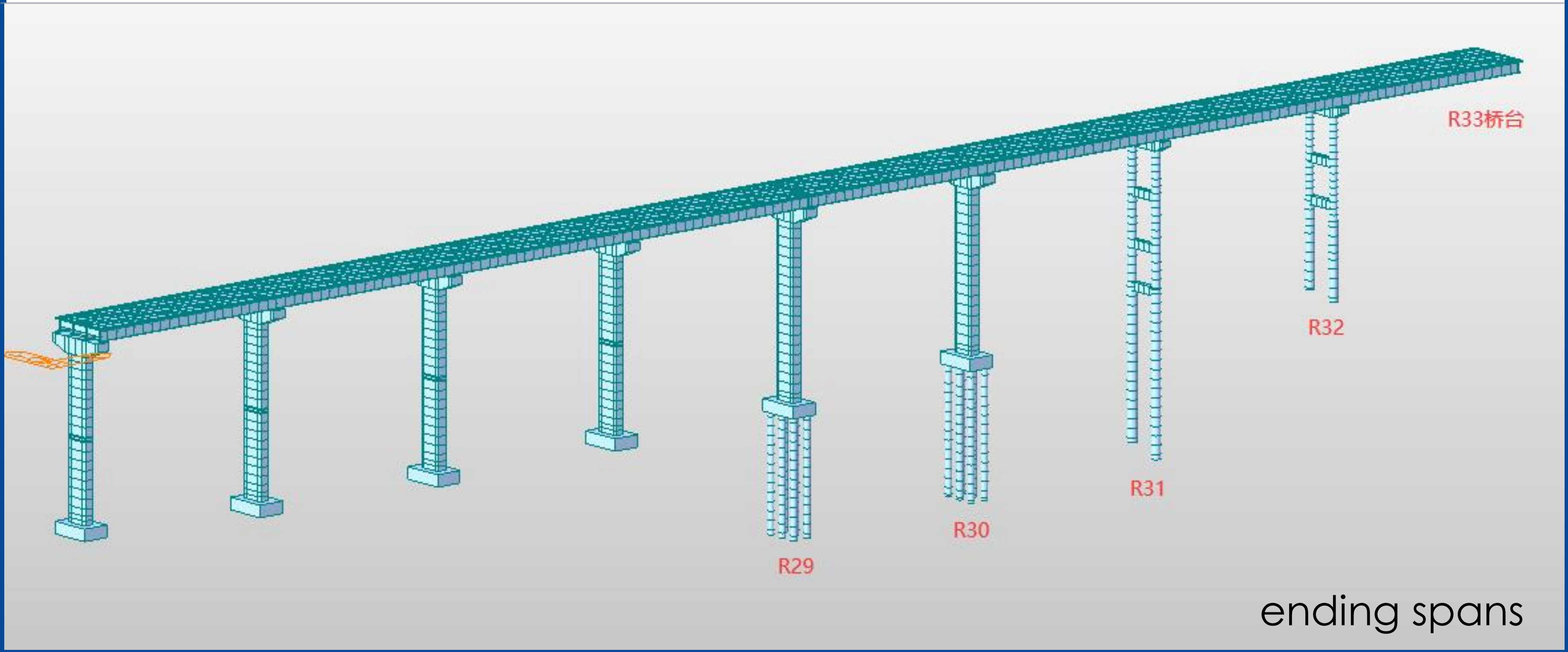
"V+" Application at Highway 109, Beijing, China

NEW HIGHWAY 109 AT THE WESTERN SUBURB OF BEIJING

BETWEEN SDC3 AND 4

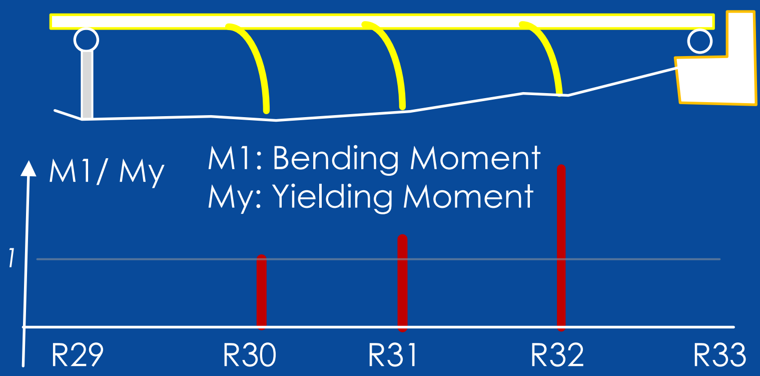
FEM MODEL OF THE BRIDGE



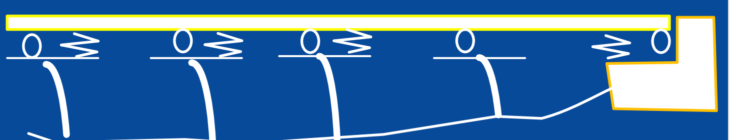


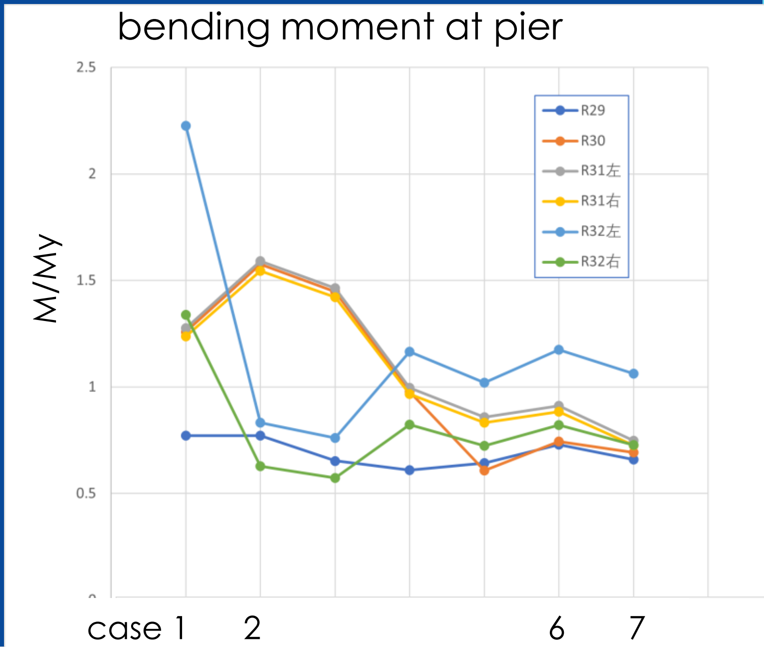
PROBLEM SOLVE - BALANCING BENDING MOMENT FOR PIERS

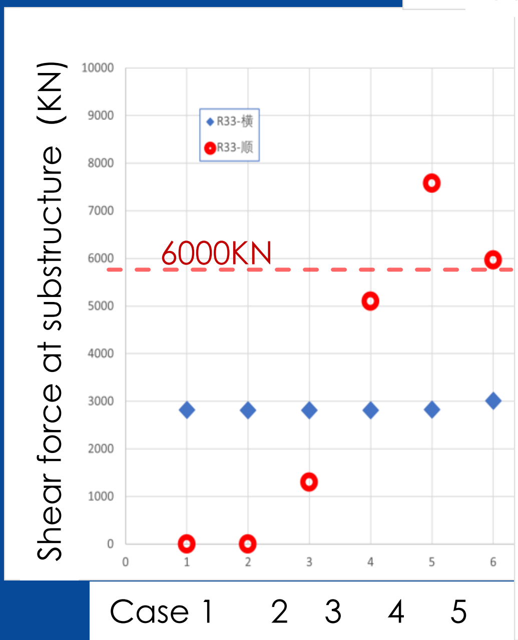
Case 1: No V-connector

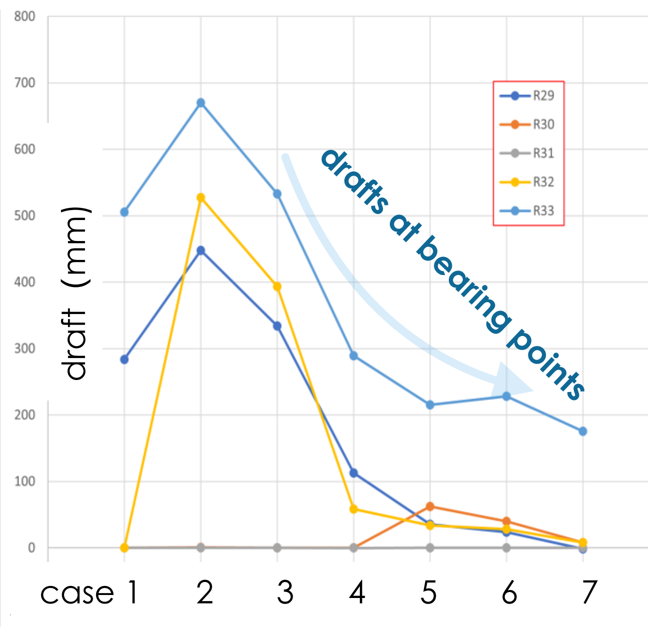


Case 4: Using V-connector to alternate constraint and stiffness









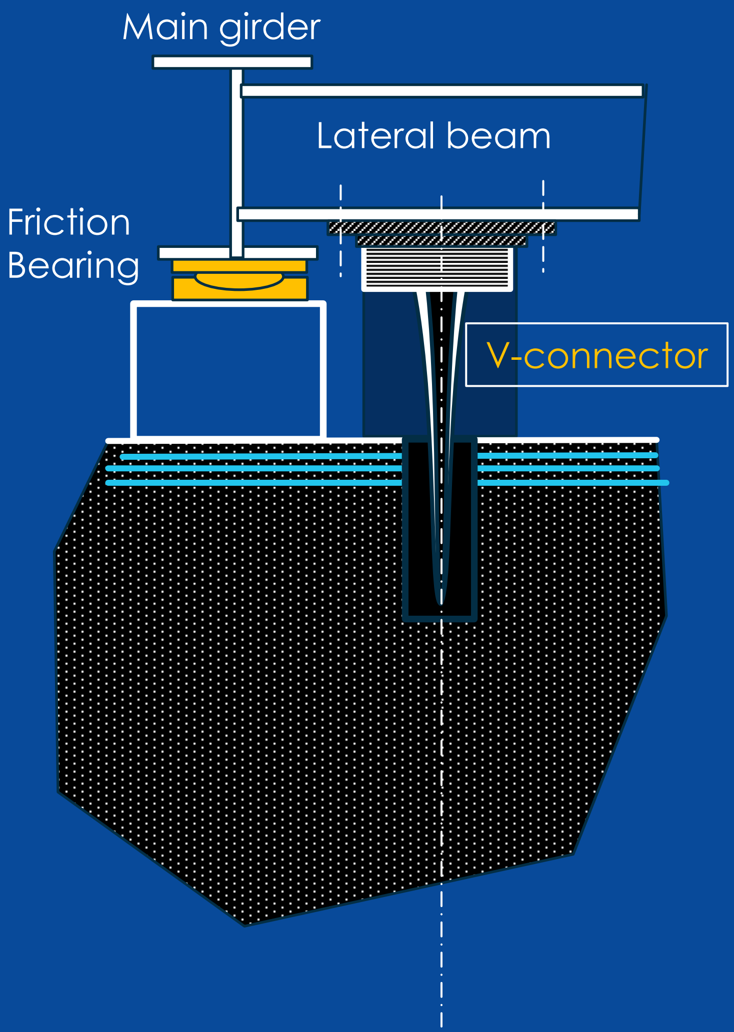
Results

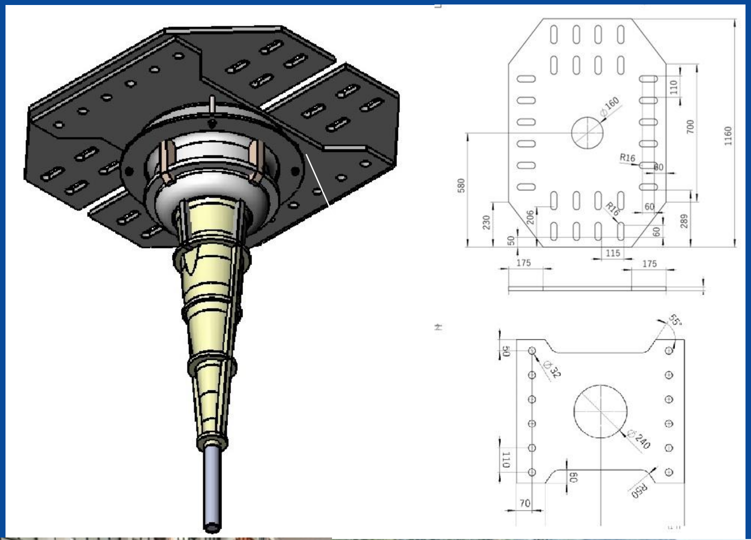
- Top bending moment reduced to half
- Span-ending draft reduces 30%

Further consideration

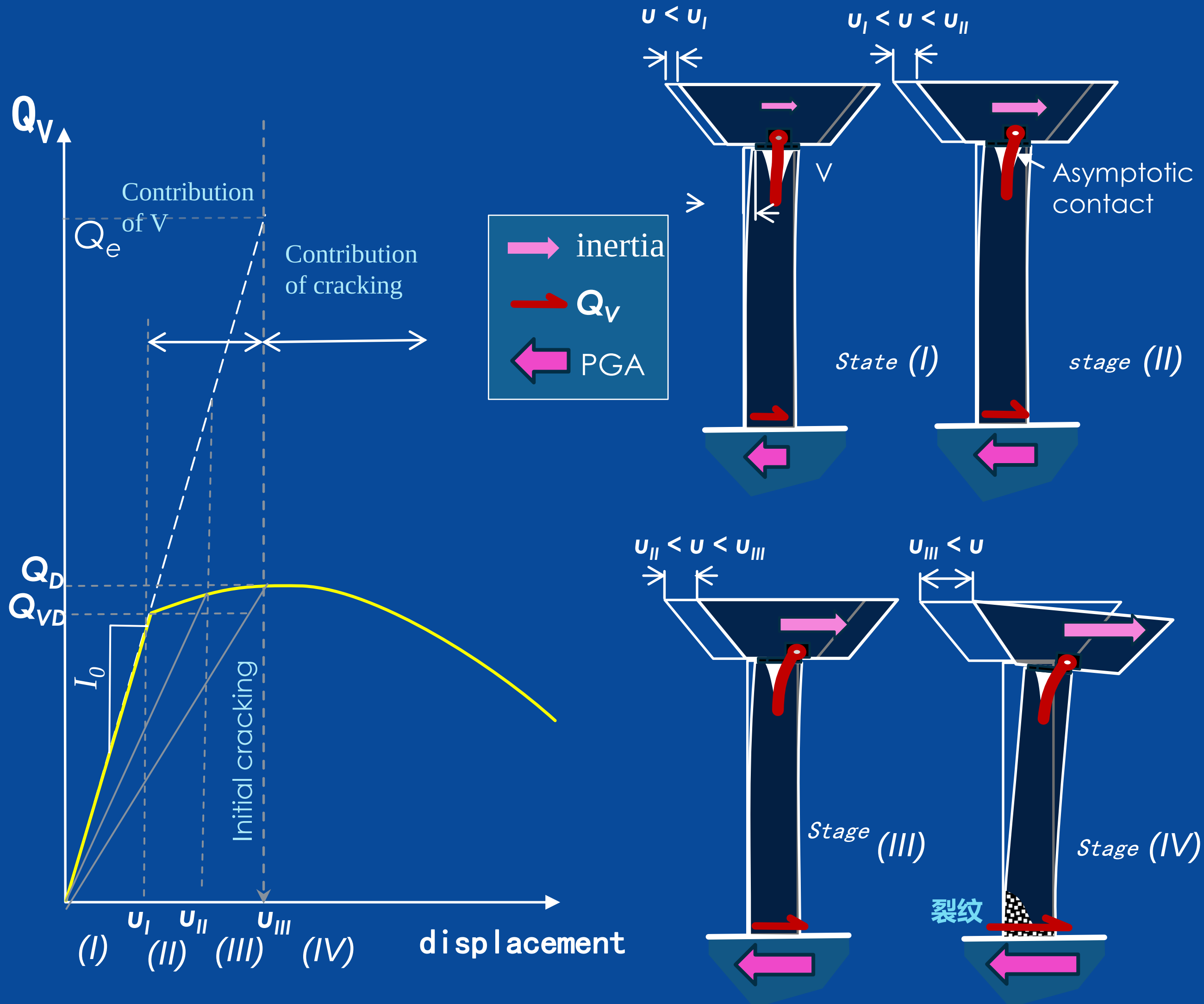
- Reduction of shear force on abutment
- Reduce span-ending draft

“V+” Application at Highway 109, Beijing, China





"V+" based three-level four-stage protection



‘V+” based three-level four-stage protection