# on the safety of high-speed trains running on bridges during earthquakes

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# outline

**motivation**

**proposed model**

**results – frequent earthquakes**

**results – rare earthquakes**

**conclusions**

# outline

**motivation**

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results – frequent earthquakes

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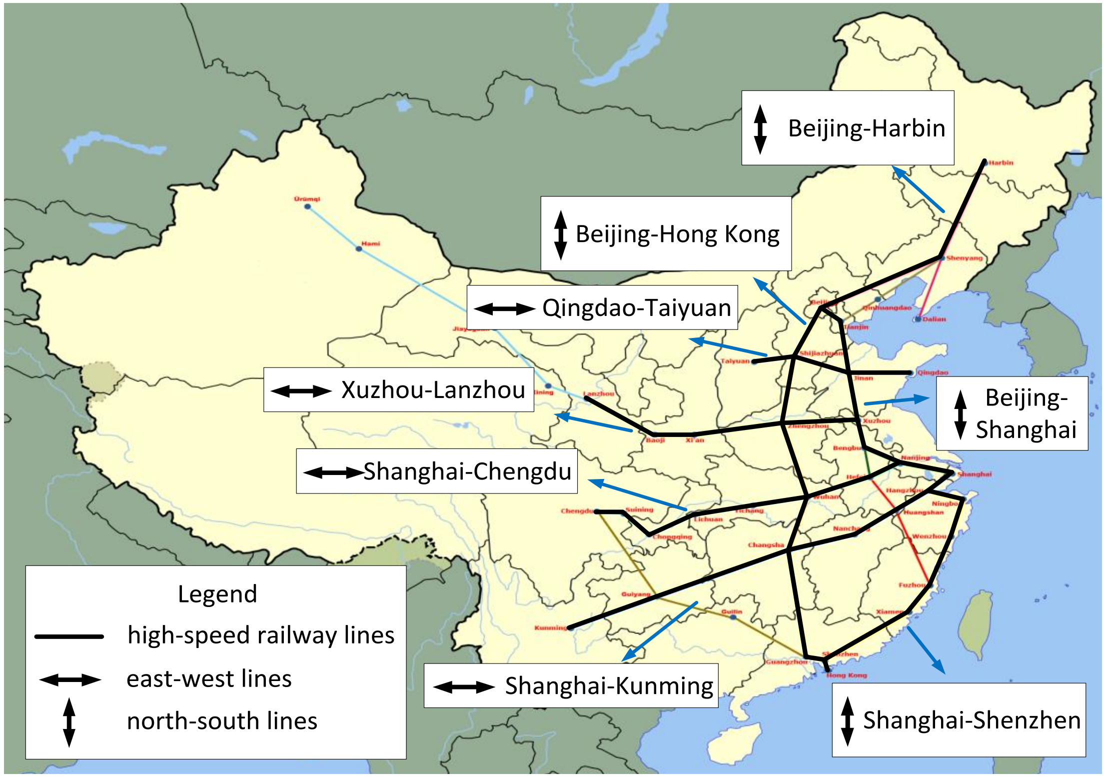
conclusions

# motivation

## contemporary high-speed railways (HSR's)




China's HSR

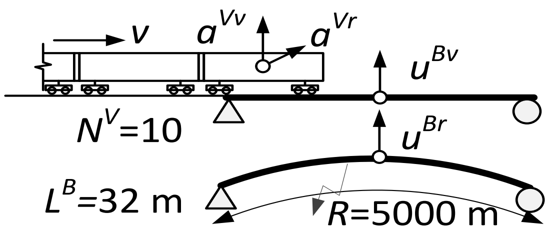
- operational speed: **300-350** km/h
- total HSR length: **16, 000** km (to 28/12/2014)
- longest bridge : **164** km (over 4000 bridges)
- bridge/line ratio :

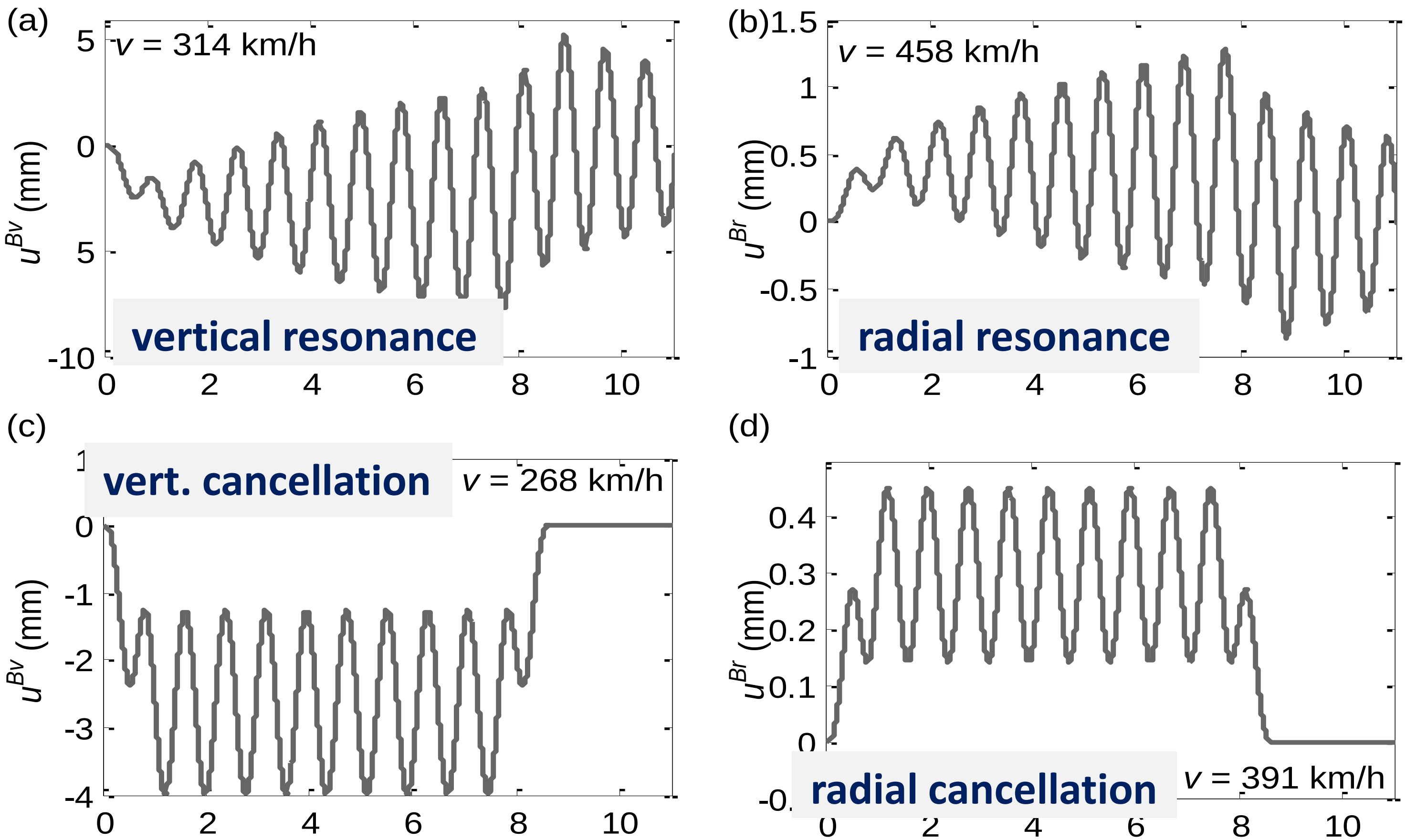
| | |
|---|---|
| Beijing-Shanghai, China | 80.5% |
| Taipei-Kaohsiung, Taiwan | 73% |
| Beijing-Tianjin, China | 86.6% |

# motivation

## VBI: bridge resonance and cancellation

- ten identical 3D vehicles
- single span curved simple bridge
- *u*: displacement; *a*: acceleration
- *V*: vehicle, B: bridge
- *v*: vertical, *r*: radial



# motivation

**accidents:** derailment of trains during earthquakes

Chūetsu Earthquake, Japan
($M_w$ = 6.8   23 Oct 2004)

- Shinkansen railway, 200 km/h
- broke the 48-year safety record

Jiashian earthquake, southern Taiwan
($M_w$ = 6.4   04 Mar 2010)

- 300 km/h high-speed train

**from VBI to SVBI: Seismic Vehicle-Bridge Interaction**

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**proposed model**

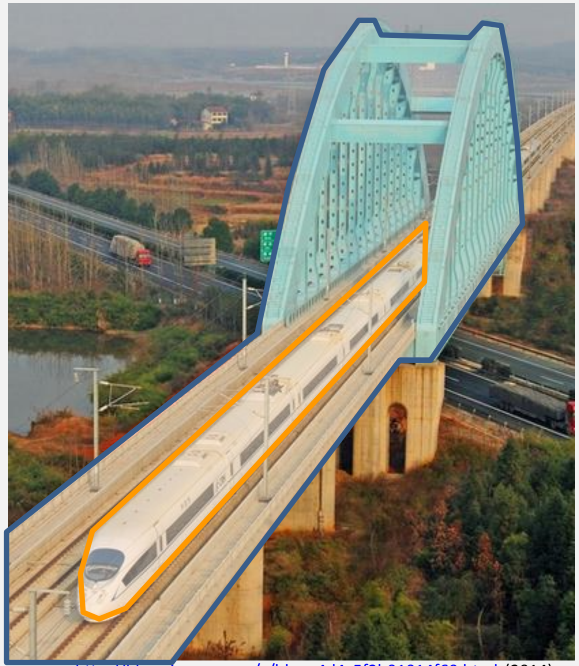
results – frequent earthquakes

results – rare earthquakes

conclusions

# proposed SVBI model

## railway bridges



http://blog.sina.com.cn/s/blog_4d4c5f2b01014f60.html (2014)

**modelling**

- vehicle
- bridge
- interaction

**approach**

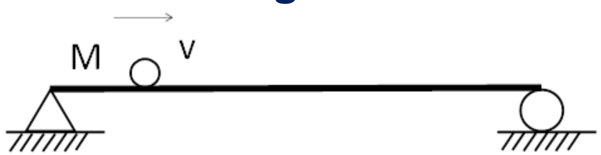
- multibody dynamics
- finite element method
- nonsmooth dynamics

# vehicle modelling

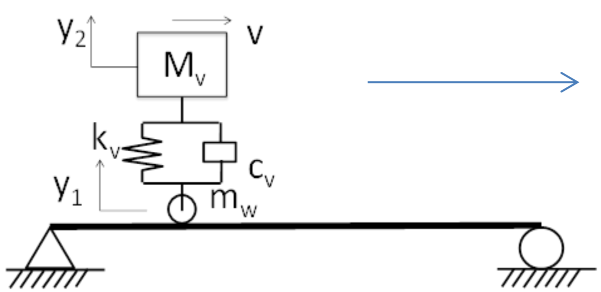
## brief history

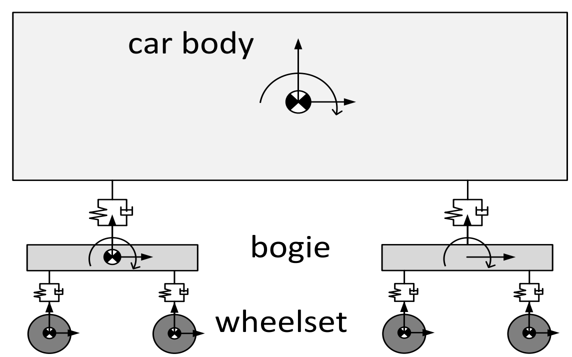
**moving loads**


**moving masses**




**moving sprung masses**



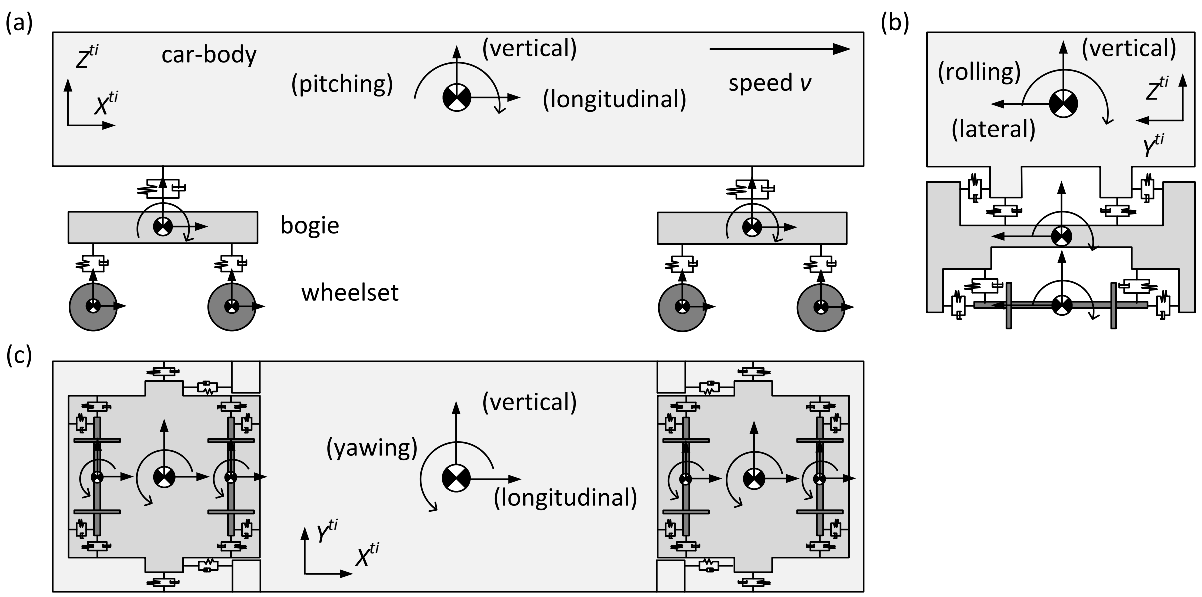

**current trend**

- beyond moving load analsis
- vehicle-bridge interaction analysis YB Yang (1995)

- **interdisciplinary**
  civil + mechanical engineering

# vehicle modelling

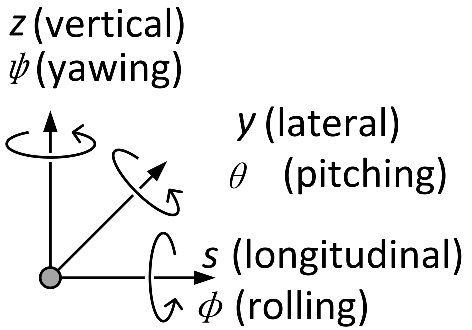
## railway train vehicle




### multibody assembly

- wheelsets, bogies, car-body → **rigid bodies**
- suspension → springs + dashpots
- e.g. 38 total DOF's

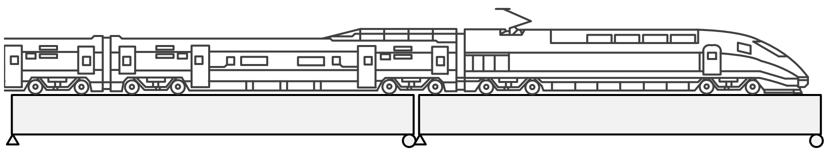
### terminology

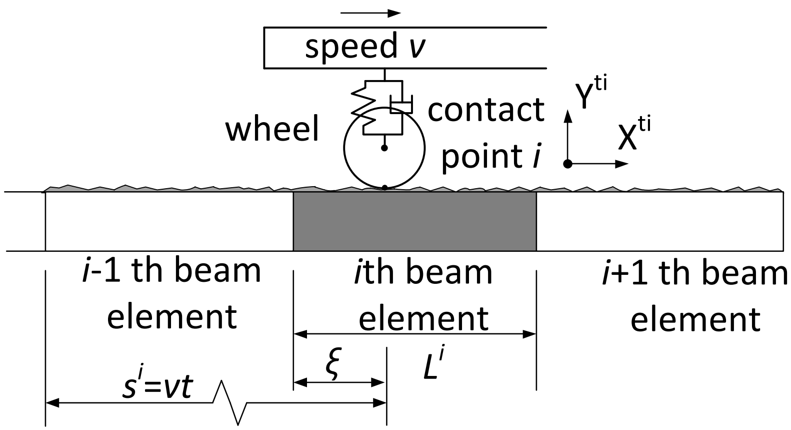


# bridge subsystem

## equation of motion

$$\mathbf{M}^B\ddot{\mathbf{u}}^B + \mathbf{C}^B\dot{\mathbf{u}}^B + \mathbf{K}^B\mathbf{u}^B + \mathbf{W}_N^B\boldsymbol{\lambda}_N + \mathbf{W}_H^B\boldsymbol{\lambda}_T = \mathbf{F}^B$$






- expressed in the inertia global system
- direction matrices $\mathbf{W}^B{}_N$ and $\mathbf{W}^B{}_T$

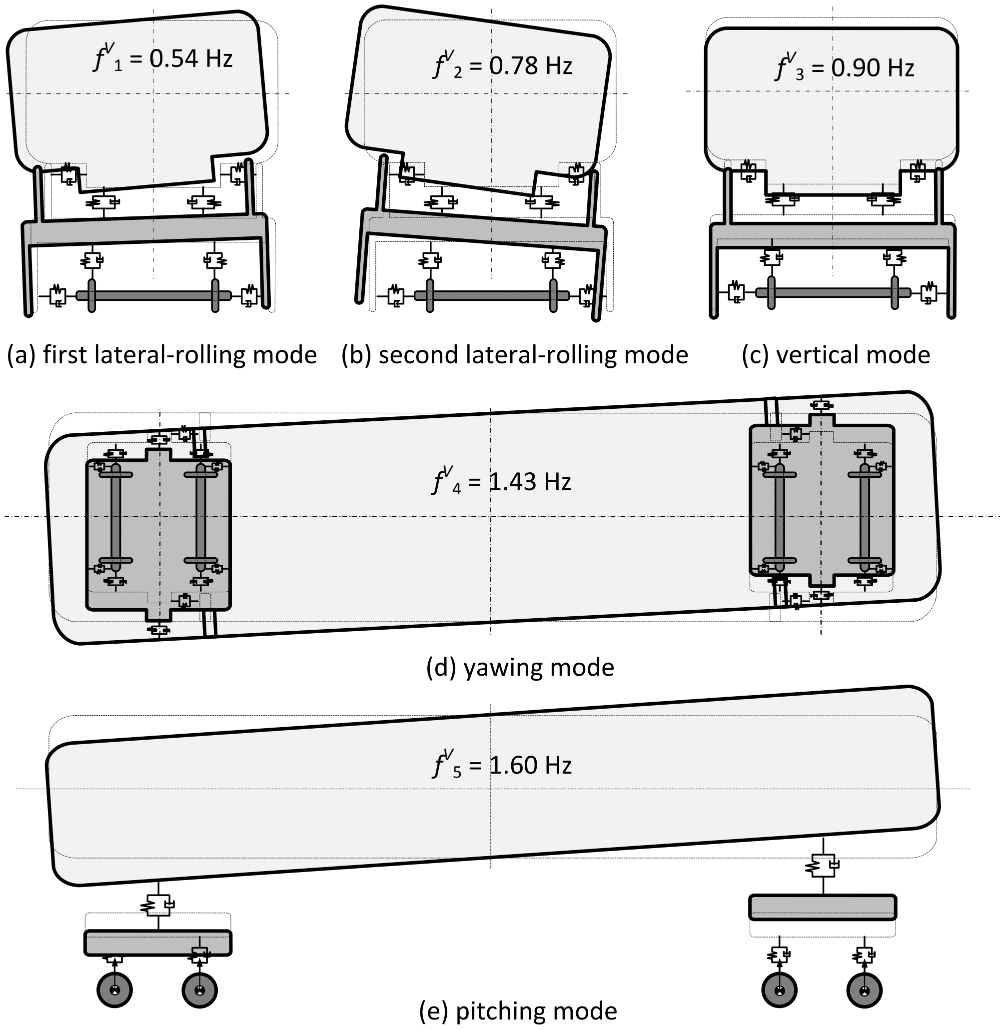
e.g. for a beam element

- **linear shape functions** for the axial (longitudinal) and torsional DOF's
- **cubic (Hermitian) shape functions** for the flexural DOF's
- the only **non-zero** entries in $\mathbf{W}^B{}_N$ and $\mathbf{W}^B{}_T$ →elements in **contact** with the wheel

- as vehicle wheel moves, different bridge element contact with wheel
- $\mathbf{W}^B{}_N$ and $\mathbf{W}^B{}_T$ : **time-dependent**

# vehicle modelling

## railway train vehicle

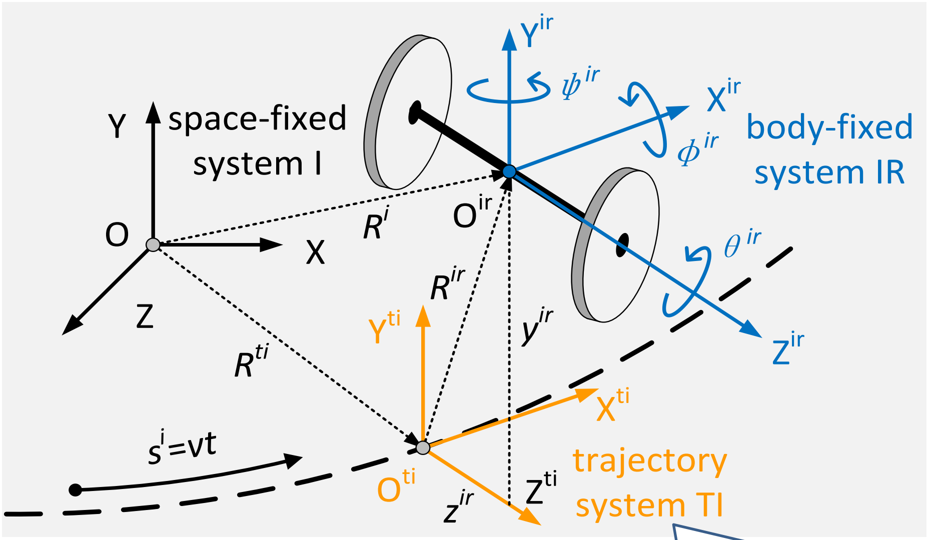



### multibody assembly

- wheelsets, bogies, car-body → **rigid bodies**
- suspension → springs + dashpots

# vehicle modelling

## vehicle-dynamics




**3 systems of reference**
(*Shabana* 2010)

- inertial (space-fixed) system I
- body-fixed system IR
- **moving trajectory system TI**

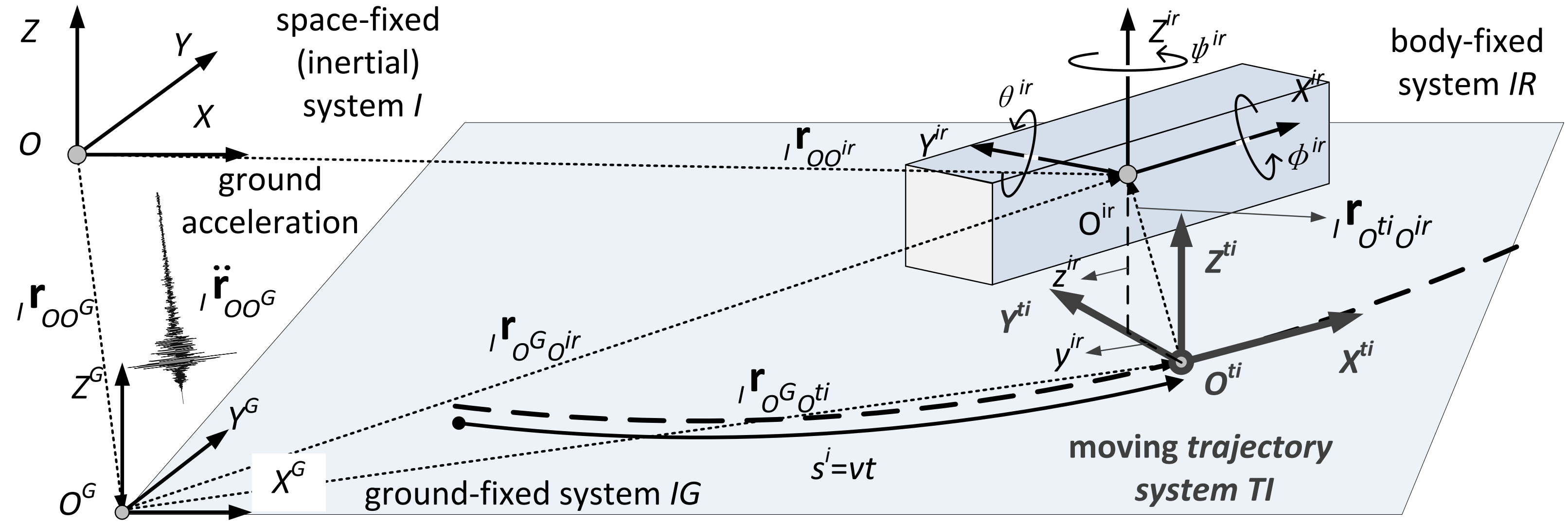
**moving trajectory system TI** (for curved paths)

- moves along the curve
- longitudinal direction $O^{ti}X^{ti}$ : tangent to the curve
- origin and orientation : defined by the arc length, $s^i$

# vehicle subsystem

## equation of motion on a curved path

$$_I\ddot{\mathbf{r}}^i_{OO^{ir}} = {}_I\ddot{\mathbf{r}}_{OO^G} + {}_I\mathbf{L}^i{}_{TI}\ddot{\mathbf{u}}^i + {}_I\boldsymbol{\gamma}^i_R$$




$$\mathbf{M}^i(t) = {}_I\mathbf{L}^i(t)^{\mathrm{T}} m^i{}_I\mathbf{L}^i(t) + {}_{IR}\mathbf{H}^i(t)^{\mathrm{T}}{}_{IR}\mathbf{I}^i_{\theta\theta IR}\mathbf{H}^i(t)$$

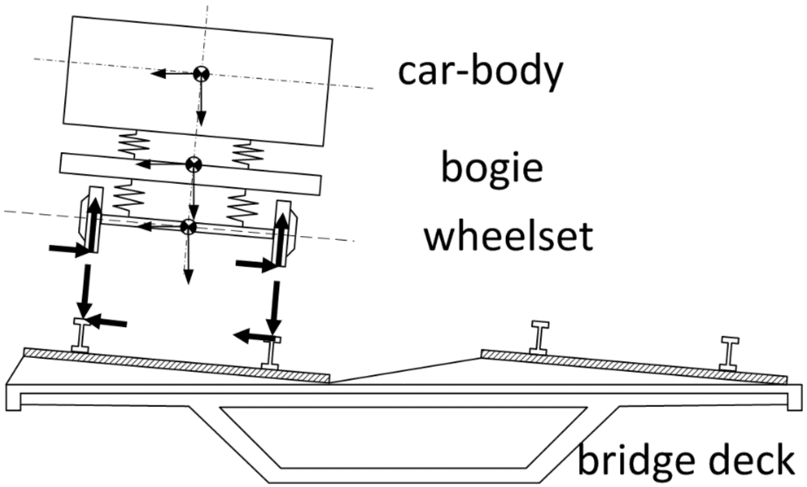
$$\mathbf{F}^i_v = -m^i{}_I\mathbf{L}^i(t)^{\mathrm{T}}{}_I\boldsymbol{\gamma}^i_R - {}_{IR}\mathbf{H}^i(t)^{\mathrm{T}}\left({}_{IR}\mathbf{I}^i_{\theta\theta IR}\boldsymbol{\gamma}^i_\alpha + {}_{IR}\boldsymbol{\omega}^i \times \left({}_{IR}\mathbf{I}^i_{\theta\theta IR}\boldsymbol{\omega}^i\right)\right)$$

$$\mathbf{F}^i_G = -m^i{}_I\mathbf{L}^i(t)^{\mathrm{T}}{}_I\ddot{\mathbf{r}}_{OO^G}$$

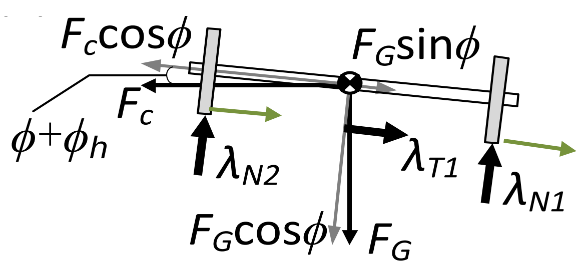
# vehicle subsystem

## equation of motion

$$\mathbf{M}^V(t)\ddot{\mathbf{u}}^V + \mathbf{C}^V\dot{\mathbf{u}}^V + \mathbf{K}^V\mathbf{u}^V - \mathbf{W}_N^V\boldsymbol{\lambda}_N - \mathbf{W}_T^V\boldsymbol{\lambda}_T = \mathbf{F}^V$$




- expressed in the moving **trajectory system**
- $\mathbf{M}^V(t)$ → time varying for curved path
- $\boldsymbol{\lambda}_N$ and $\boldsymbol{\lambda}_T$ = **normal** and **tangential** contact force vector
- $\mathbf{W}^V{}_N$ and $\mathbf{W}^V{}_T$ = **direction matrices** of $\boldsymbol{\lambda}_N$ and $\boldsymbol{\lambda}_T$




- $\mathbf{F}^V$ = gravity,
  **inertia (centrifugal** and **coriolis forces)** due to the **curved path**
  **seismic** loads if considered

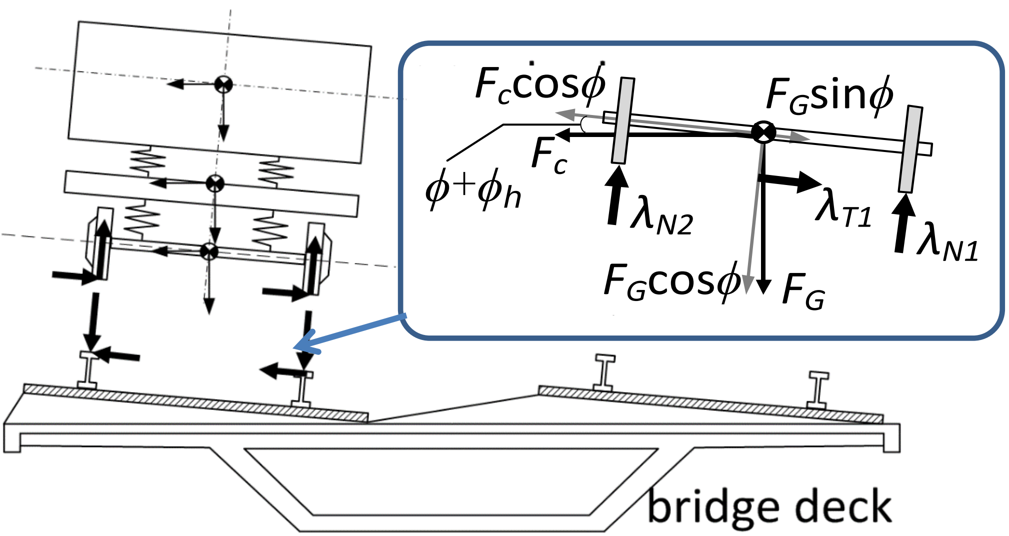
# coupled vehicle-bridge system

## equation of motion

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} - \mathbf{W}\boldsymbol{\lambda} = \mathbf{F}$$

contact forces (coupling)

- global matrices
- **contact forces $\boldsymbol{\lambda}$**



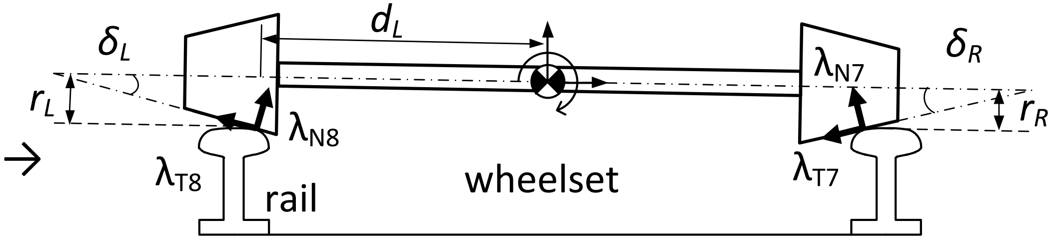

$$\begin{cases} \mathbf{M} = \begin{bmatrix} \mathbf{M}^V(t) & \mathbf{0} \\ \mathbf{0} & \mathbf{M}^B \end{bmatrix}, \mathbf{C} = \begin{bmatrix} \mathbf{C}^V & \mathbf{0} \\ \mathbf{0} & \mathbf{C}^B \end{bmatrix}, \\ \mathbf{K} = \begin{bmatrix} \mathbf{K}^V & \mathbf{0} \\ \mathbf{0} & \mathbf{K}^B \end{bmatrix}, \mathbf{u} = \begin{Bmatrix} \mathbf{u}^V \\ \mathbf{u}^B \end{Bmatrix}, \mathbf{F} = \begin{Bmatrix} \mathbf{F}^V \\ \mathbf{F}^B \end{Bmatrix}, \\ \mathbf{W} = [\mathbf{W}_N \ \ \mathbf{W}_H], \boldsymbol{\lambda} = \begin{Bmatrix} \boldsymbol{\lambda}_N \\ \boldsymbol{\lambda}_T \end{Bmatrix}, \\ \mathbf{W}_T = \begin{Bmatrix} \mathbf{W}_T^V \\ -\mathbf{W}_T^B(t) \end{Bmatrix}, \mathbf{W}_N = \begin{Bmatrix} \mathbf{W}_N^V \\ -\mathbf{W}_N^B(t) \end{Bmatrix} \end{cases}$$

**W** contains the coupling
is **time-dependent**

# coupled vehicle-bridge system

## wheel-rail contact interaction

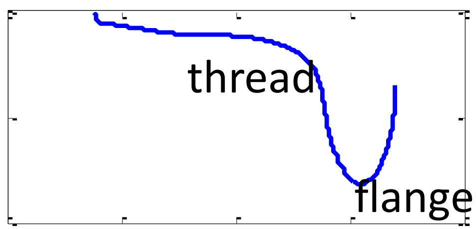
$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} - \mathbf{W}\boldsymbol{\lambda} = \mathbf{F}$$

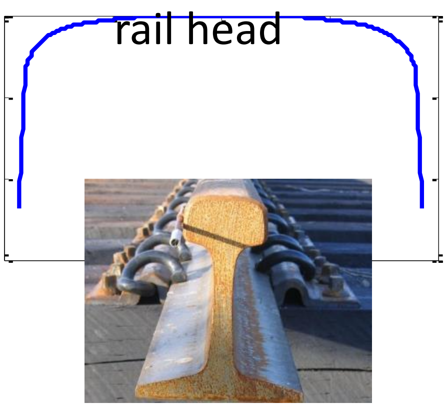


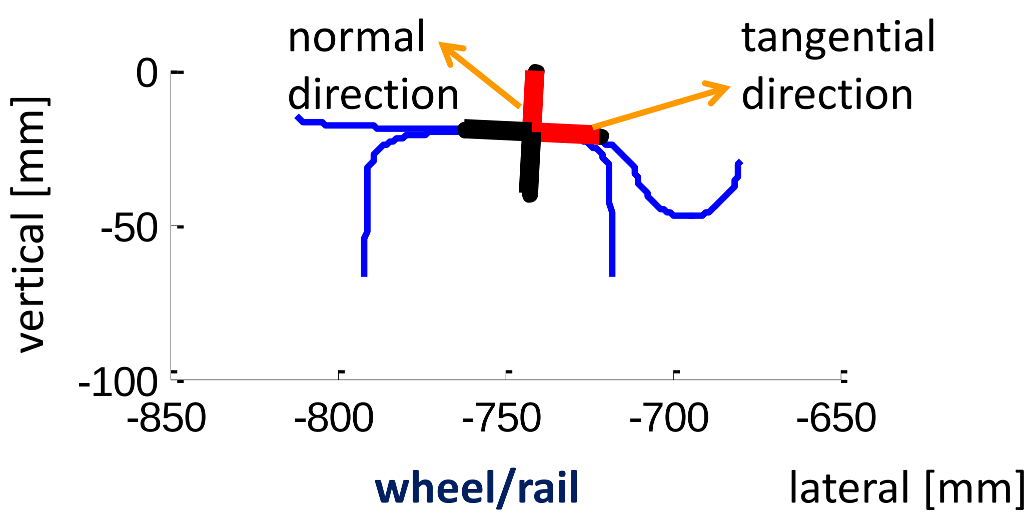

## point and direction of contact

- **continuous contact**

  the wheel is in contact with the rail → nonlinear wheel, rail profile




**wheel/rail**

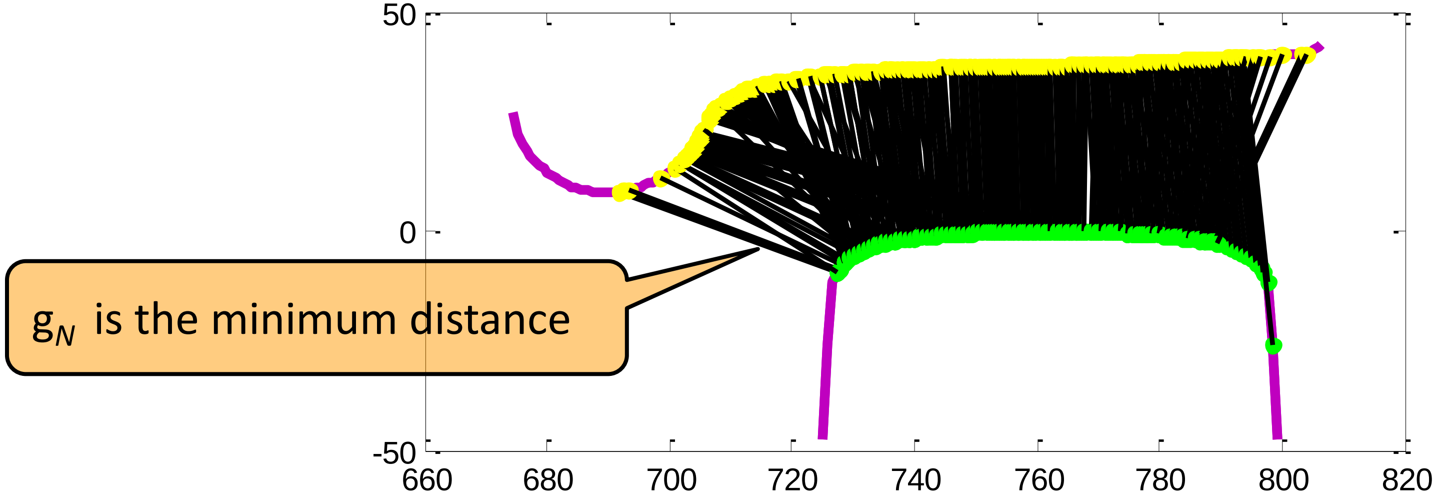
# coupled vehicle-bridge system

## wheel-rail contact interaction

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} - \mathbf{W}\boldsymbol{\lambda} = \mathbf{F}$$

## point and direction of contact

- **wheel-rail separation/ detachment** (uplifting)




- **single/double separation**

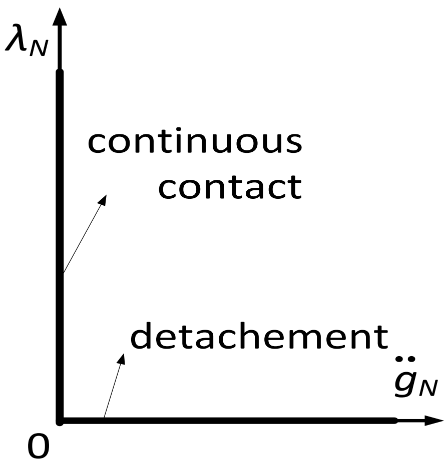
# coupled vehicle-bridge system

## wheel-rail contact interaction

$$\mathbf{M}\ddot{\mathbf{u}}+\mathbf{C}\dot{\mathbf{u}}+\mathbf{K}\mathbf{u}-\mathbf{W}\boldsymbol{\lambda}=\mathbf{F}$$

## normal direction

- **continuous contact** vs **detachment** (separation)




contact-detachment transition is formulated as a **Linear Complimentary Problem** (**LCP**)
→ **nonsmooth approach**

- contact: zero contact acceleration
- detachment: zero normal contact force

$$\begin{cases} \ddot{g}_N = 0 \wedge \lambda_N \geq 0 \text{ continuous contact} \\ \ddot{g}_N \geq 0 \wedge \lambda_N = 0 \text{ detachment} \end{cases}$$

- **impact and recontact**

- Newton's law
- normal contact displacement $g_N = 0$ and $(\dot{g}_N < 0)$
- velocity jump on the velocity level

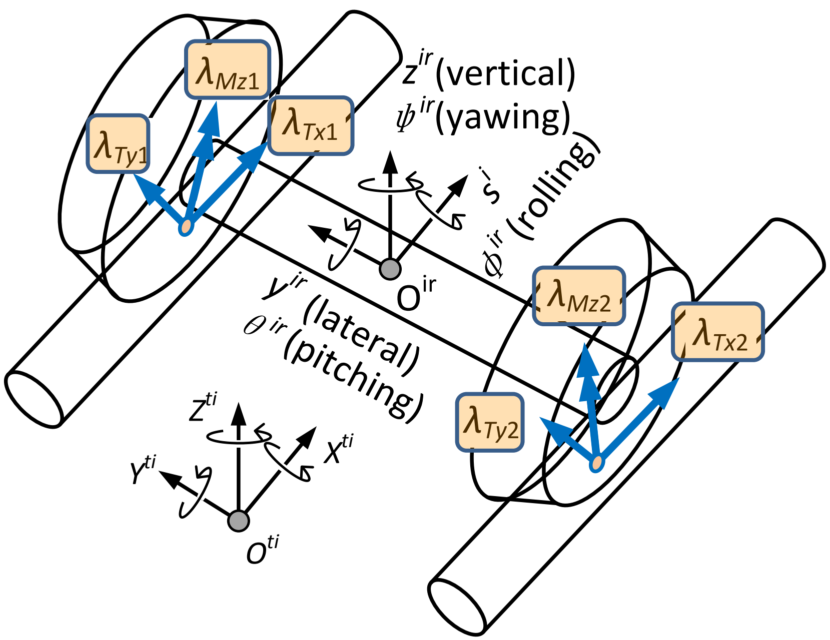
# coupled vehicle-bridge system

## wheel-rail contact interaction

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} - \mathbf{W}\boldsymbol{\lambda} = \mathbf{F}$$

## tangential direction $\boldsymbol{\lambda}_T = \left[ \boldsymbol{\lambda}_{Tx} \; \boldsymbol{\lambda}_{Ty} \; \boldsymbol{\lambda}_{Mz} \right]^{\mathrm{T}}$

- creep lateral / longitudinal forces
- creep spin moment
- rolling contact



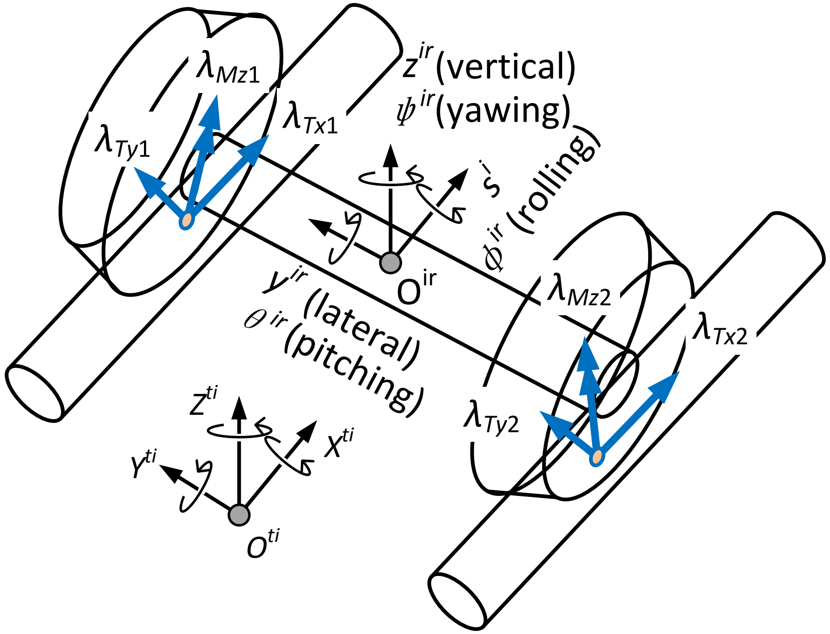
# coupled vehicle-bridge system

## wheel-rail contact interaction

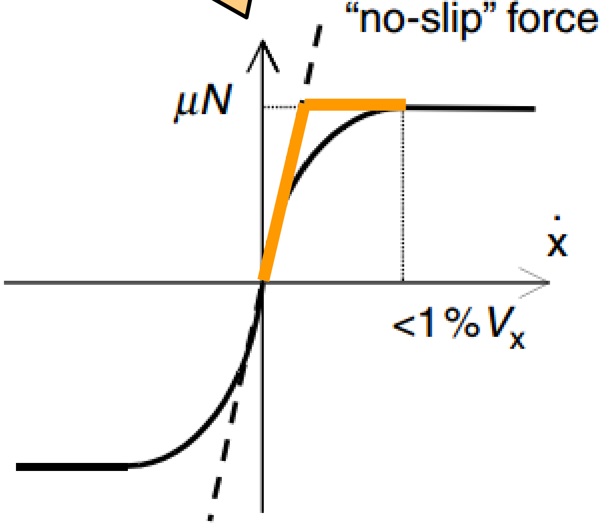
$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} - \mathbf{W}\boldsymbol{\lambda} = \mathbf{F}$$

### tangential direction $\boldsymbol{\lambda}_T = [\, \boldsymbol{\lambda}_{Tx} \;\; \boldsymbol{\lambda}_{Ty} \;\; \boldsymbol{\lambda}_{Mz} \,]^{\mathrm{T}}$

- creep lateral / longitudinal forces
- creep spin moment




nonlinear relationship between creep forces and creepage




wheel-rail friction model

# coupled vehicle-bridge system

## final equations of motion

$$\mathbf{M}^*(t)\ddot{\mathbf{u}}(t)+\mathbf{C}^*(t)\dot{\mathbf{u}}(t)+\mathbf{K}^*(t)\mathbf{u}(t)=\mathbf{F}^*(t)$$

$$\begin{cases}
\mathbf{C}^* = \left[\mathbf{E}-\mathbf{W}_N\mathbf{G}_{NN}{}^{-1}\mathbf{W}_N{}^{\mathrm{T}}\mathbf{M}^{-1}\right]\left(\mathbf{C}+\mathbf{C}_\xi\right)+2v\mathbf{W}_N\mathbf{G}_{NN}{}^{-1}\mathbf{W}_N''^{\mathrm{T}} \\
\mathbf{K}^* = \left[\mathbf{E}-\mathbf{W}_N\mathbf{G}_{NN}{}^{-1}\mathbf{W}_N{}^{\mathrm{T}}\mathbf{M}^{-1}\right]\mathbf{K}+v^2\mathbf{W}_N\mathbf{G}_{NN}{}^{-1}\mathbf{W}_N'^{\mathrm{T}} \\
\mathbf{F}^* = \left[\mathbf{E}-\mathbf{W}_N\mathbf{G}_{NN}{}^{-1}\mathbf{W}_N{}^{\mathrm{T}}\mathbf{M}^{-1}\right]\left(\mathbf{F}-\mathbf{F}_\xi\right)-v^2\mathbf{W}\mathbf{G}_{NN}{}^{-1}\mathbf{r}''_{cN}
\end{cases}$$

effect of: **normal** contact forces **creep** forces **rail irregularities**

- $\mathbf{M}^*$ → **time-dependent** (for curved path)
- $\mathbf{K}^*$ and $\mathbf{C}^*$ → **time-dependent** and **coupled**
- $\mathbf{F}^*$ → **time-dependent**

- $\mathbf{E}$ → identity matrix;
- $\mathbf{G}(t)^{-1} = (\mathbf{W}^{\mathrm{T}}\mathbf{M}^{-1}\mathbf{W})^{-1}$ → the **effective mass** during contact
- $()'$ and $()''$ → the derivatives with respect to the arc length

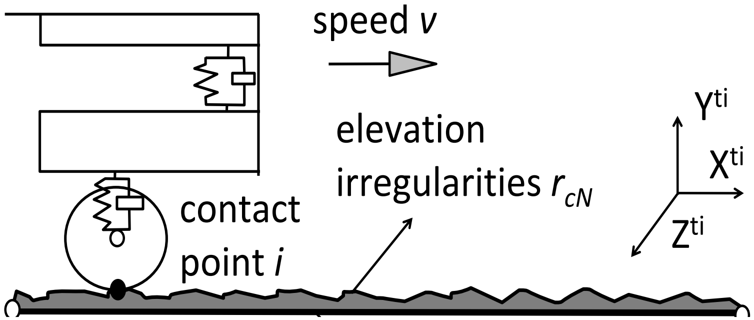
# coupled vehicle-bridge system

## final equations of motion

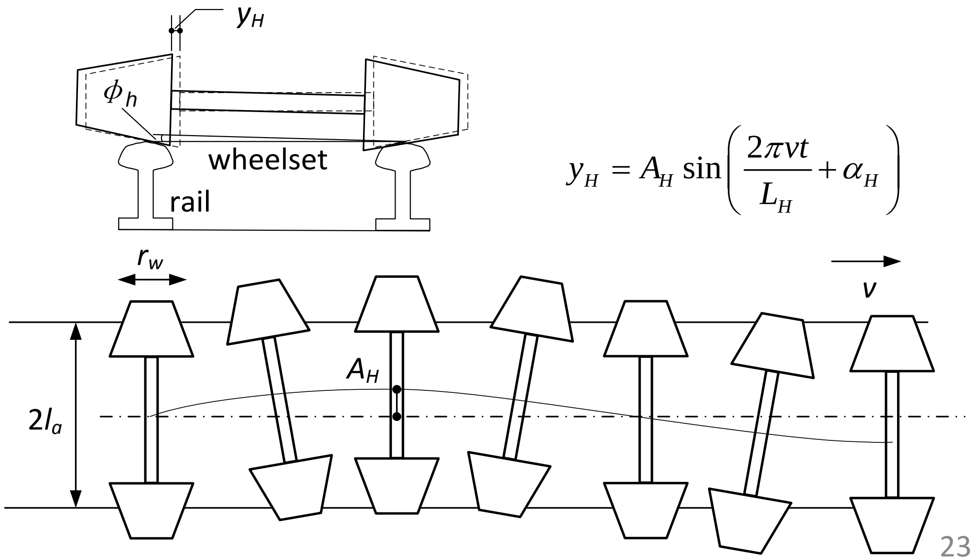
$$\mathbf{M}^*(t)\ddot{\mathbf{u}}(t)+\mathbf{C}^*(t)\dot{\mathbf{u}}(t)+\mathbf{K}^*(t)\mathbf{u}(t)=\mathbf{F}^*(t)$$

### sources of excitation

- **external excitation**: earthquake ground motion, wind loading etc.
- **Coriolis and centrifugal forces**: curved bridges and/or curved rails
- **self-excitation** : wheel-hunting, creep forces, rail irregularities




$$r_c=\sqrt{2}\sum_{n=1}^{N_c}A_n\cos(\omega_n s^i+\alpha_n)$$




$$y_H=A_H\sin\left(\frac{2\pi vt}{L_H}+\alpha_H\right)$$

# proposed analysis platform

**finite element software**

**multibody software**

**in-house algorithm**

ANSYS

MATLAB

**pre-processing**

**ANSYS** → bridge FEM model ($\mathbf{M}^B$, $\mathbf{C}^B$ and $\mathbf{K}^B$)

**Workbench** → vehicle multibody model ($\mathbf{M}^V(t)$, $\mathbf{C}^V$ and $\mathbf{K}^V$)

→

**processing**

system **global matrices** (mass/stiffness/damping)

$\mathbf{M}^*$, $\mathbf{C}^*$ and $\mathbf{K}^*$

↓

perform VBI **analysis** in MATLAB → time-history solutions

← **time-history** solutions

**post-processing**

deformed shapes,

member forces diagrams

**ANSYS** → **bridge**

**Workbench** → **vehicle**

# outline

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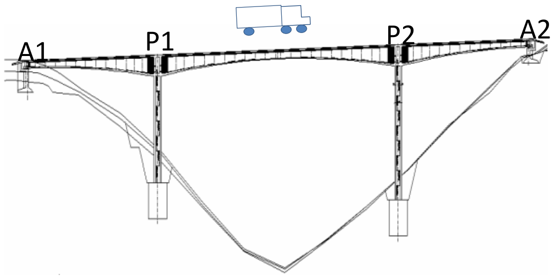
**results – frequent earthquakes**

results – rare earthquakes

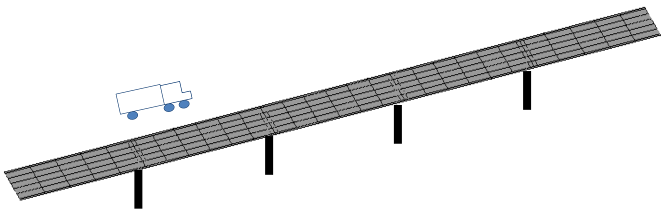
conclusions

# case studies

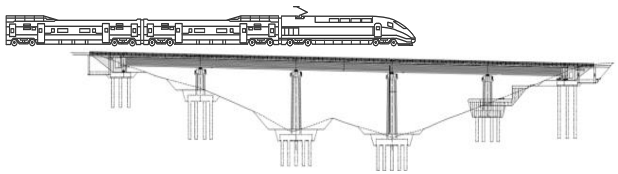
straight continuous highway bridge
interacting with trucks during earthq. (2D)



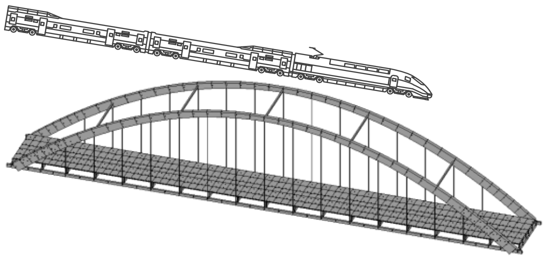

straight continuous slab highway bridge
interacting with trucks no earthq. (3D)



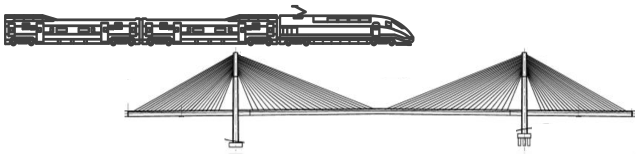
curved continuous railway bridge
interacting with train during earthq. (3D)



straight steel arch truss railway bridge
interacting with train no earthq. (3D)

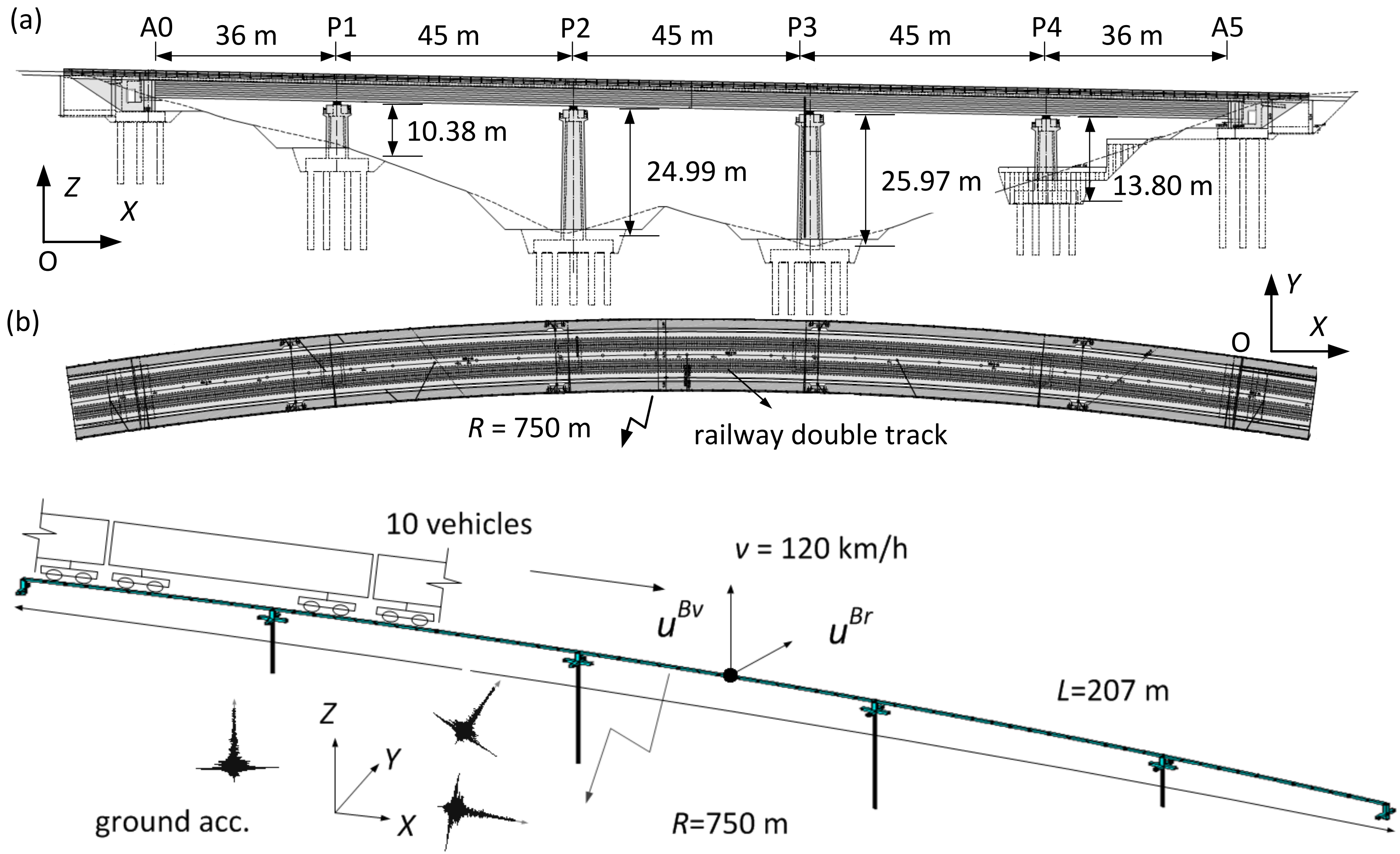


straight cable-stayed bridge
interacting with train no earthq. (3D)



# SVBI frequent earthquakes

## horizontally curved continuous bridge



# SVBI frequent earthquakes

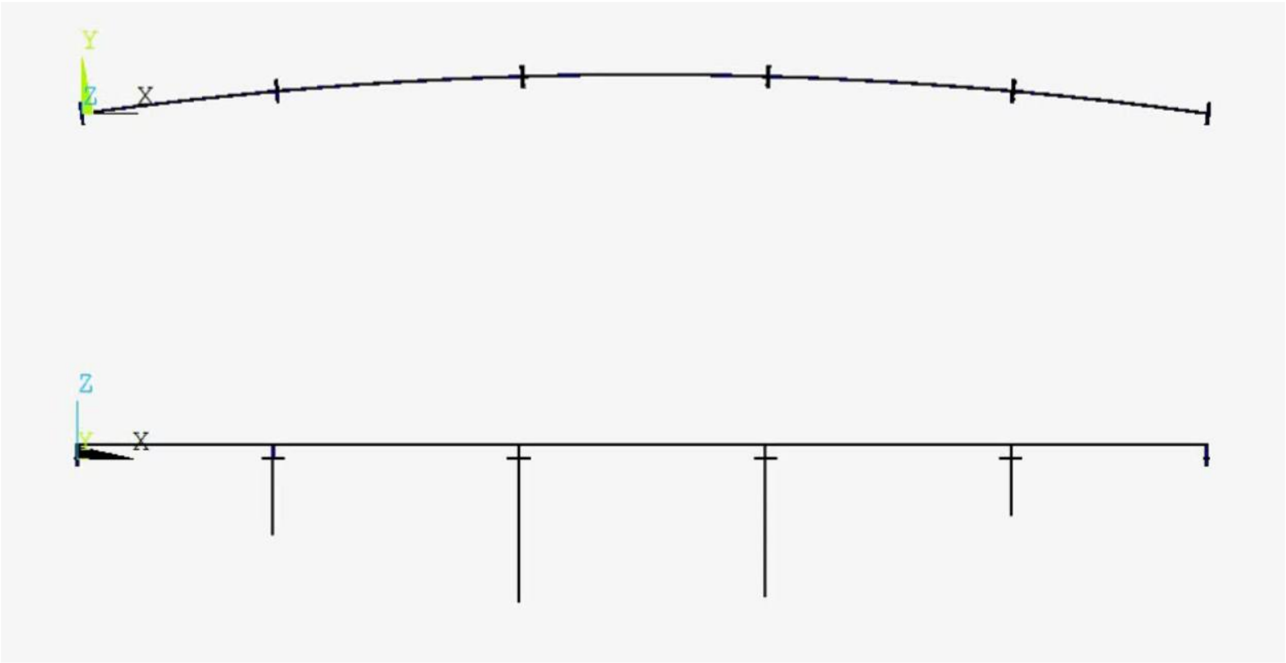
## horizontally curved continuous bridge

deformation animation of the whole bridge

- 10 passing vehicles, **without** earthquake

top view

elevation view



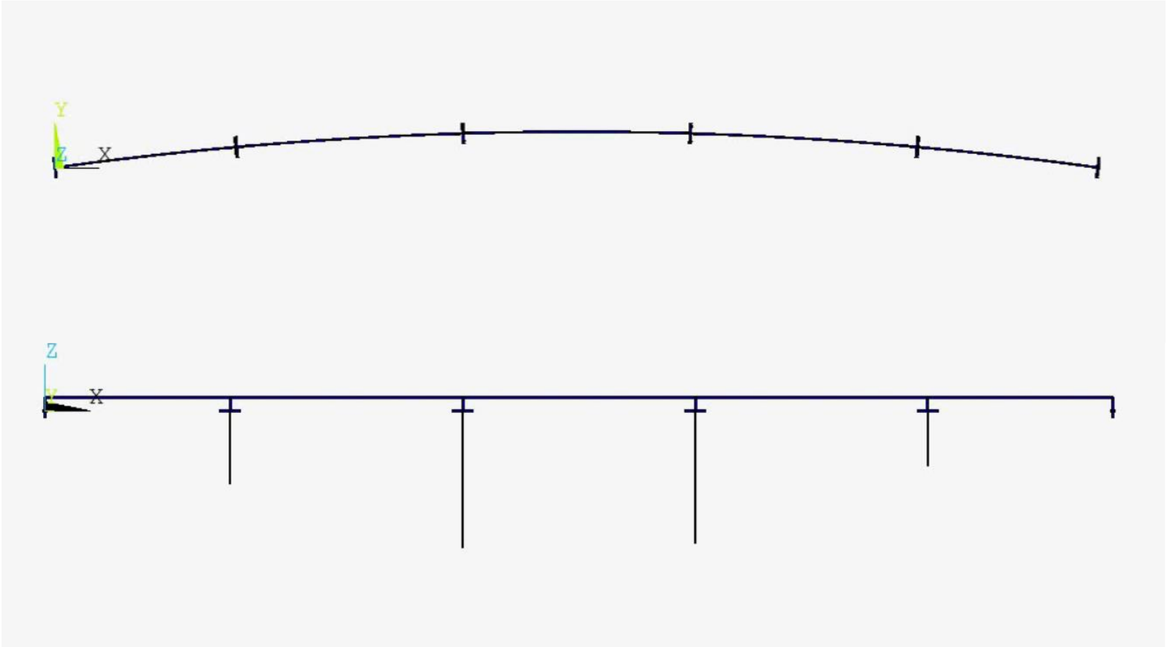
# SVBI frequent earthquakes

## horizontally curved continuous bridge

deformation animation of the whole bridge

- 10 passing vehicles, **with** earthquake

top view



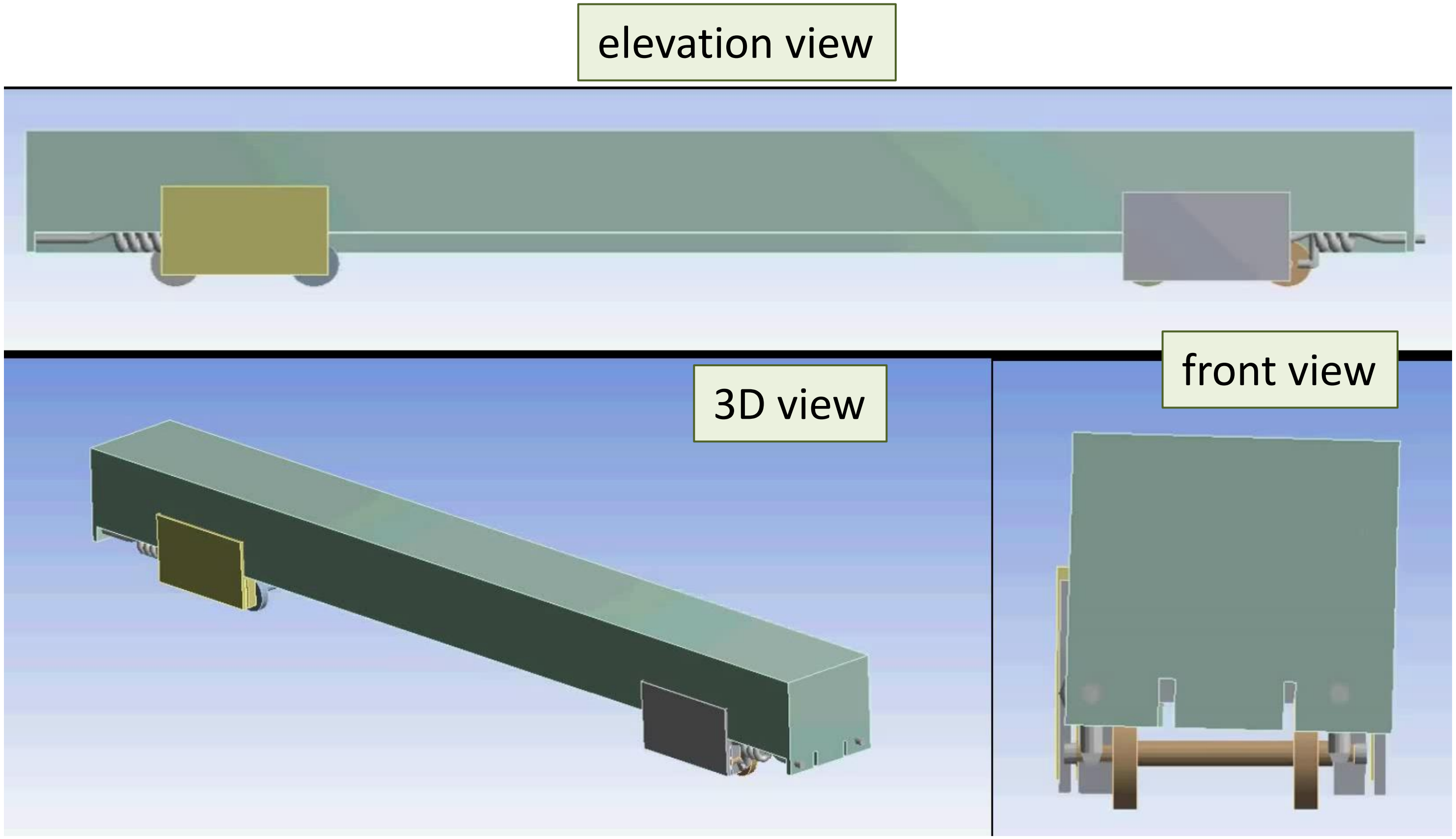

elevation view

# SVBI frequent earthquakes

## horizontally curved continuous bridge

deformation animation of the vehicle

- 10 passing vehicles, **with** earthquake

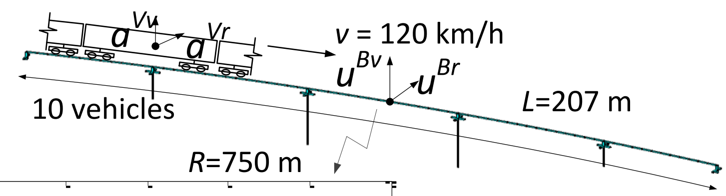


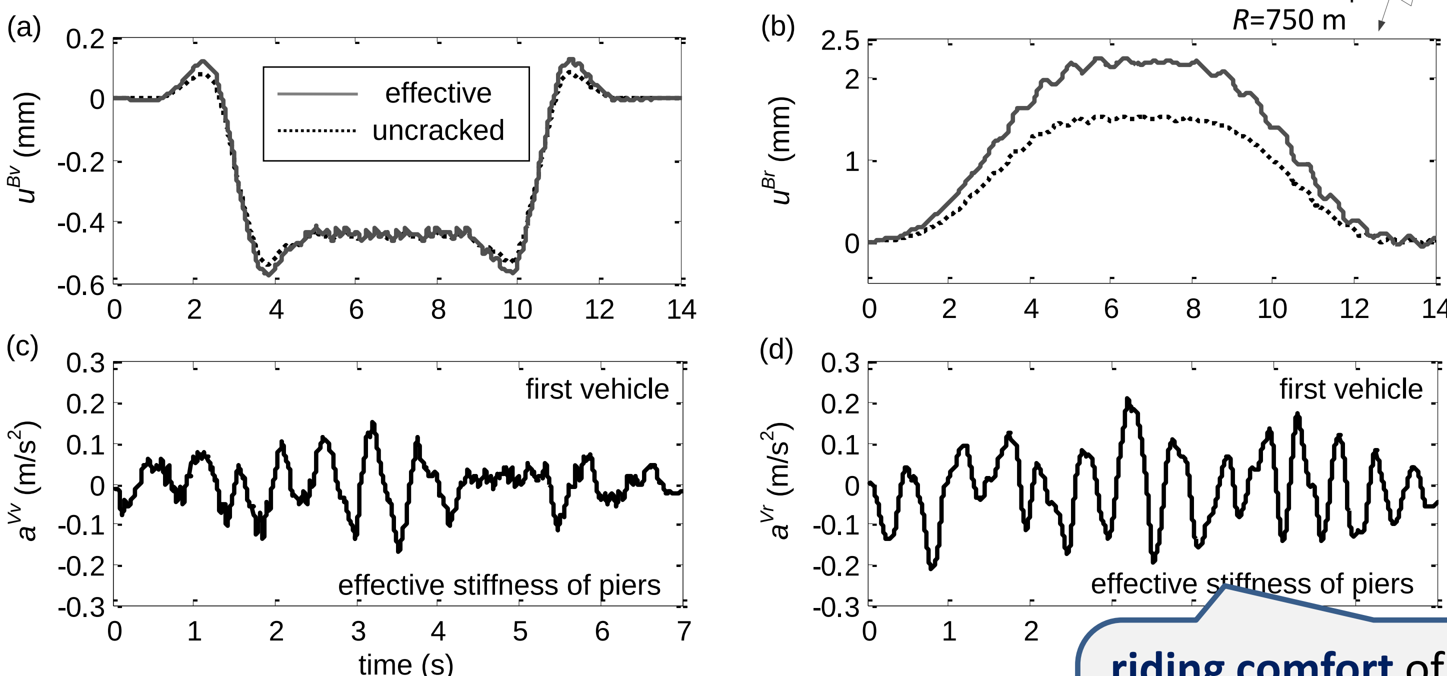
# SVBI frequent earthquakes

## horizontally curved continuous bridge

- VBI model
- no earthquake excitation
- *u*: displacement
- *a*: acceleration

- vertical and radial disp. of bridge midpoint
- vertical and radial accel. of vehicle car-body




**riding comfort** of the passengers

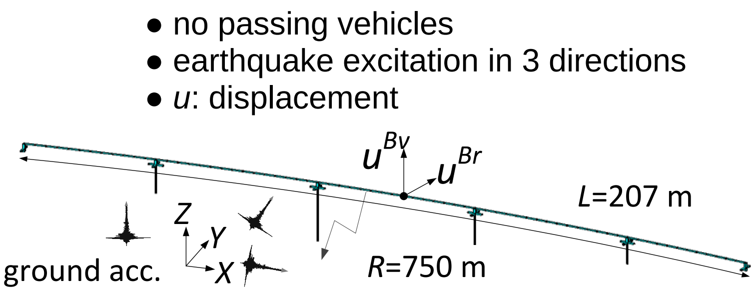
→ acceleration of the car-body

- vertical ≤ 2.0 m/s$^2$
- radial (lateral) ≤ 1.5 m/s$^2$.

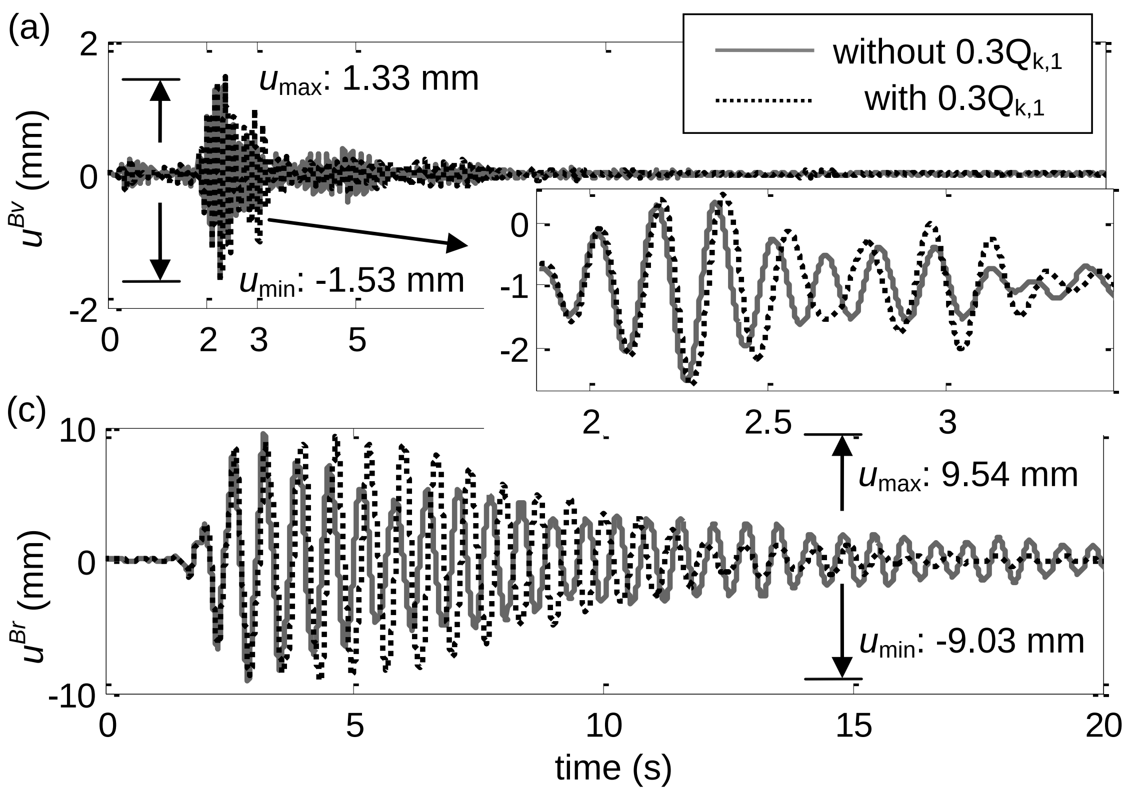
# SVBI frequent earthquakes

## horizontally curved continuous bridge

- vertical and radial disp. of bridge midpoint




- $0.3Q_{k,1}$: the additional mass due to traffic

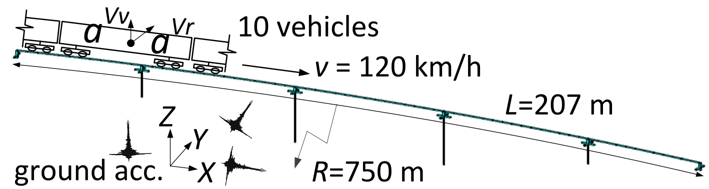


# SVBI frequent earthquakes

## horizontally curved continuous bridge

- vertical and radial accel. of car-body
- accel. of the vehicle on bridge
  > accel. of the vehicle on ground

- VBI model
- earthquake excitation in 3 directions
- *a*: acceleration
- *V*-1 and *V*-10: the first and tenth vehicle

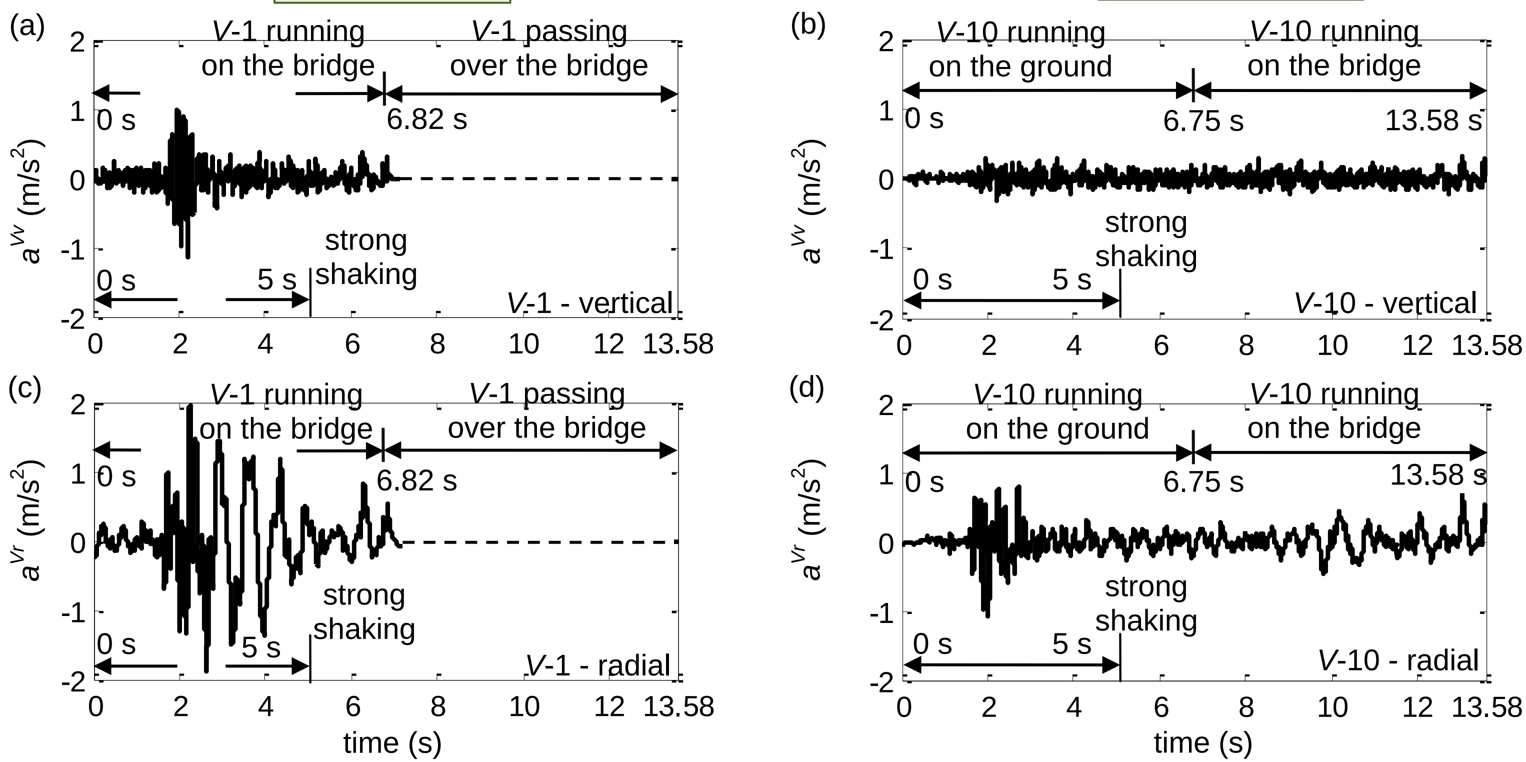



1st vehicle

10th vehicle

vertical

radial



# SVBI frequent earthquakes

## horizontally curved continuous bridge

Table I. Properties of the examined earthquakes.

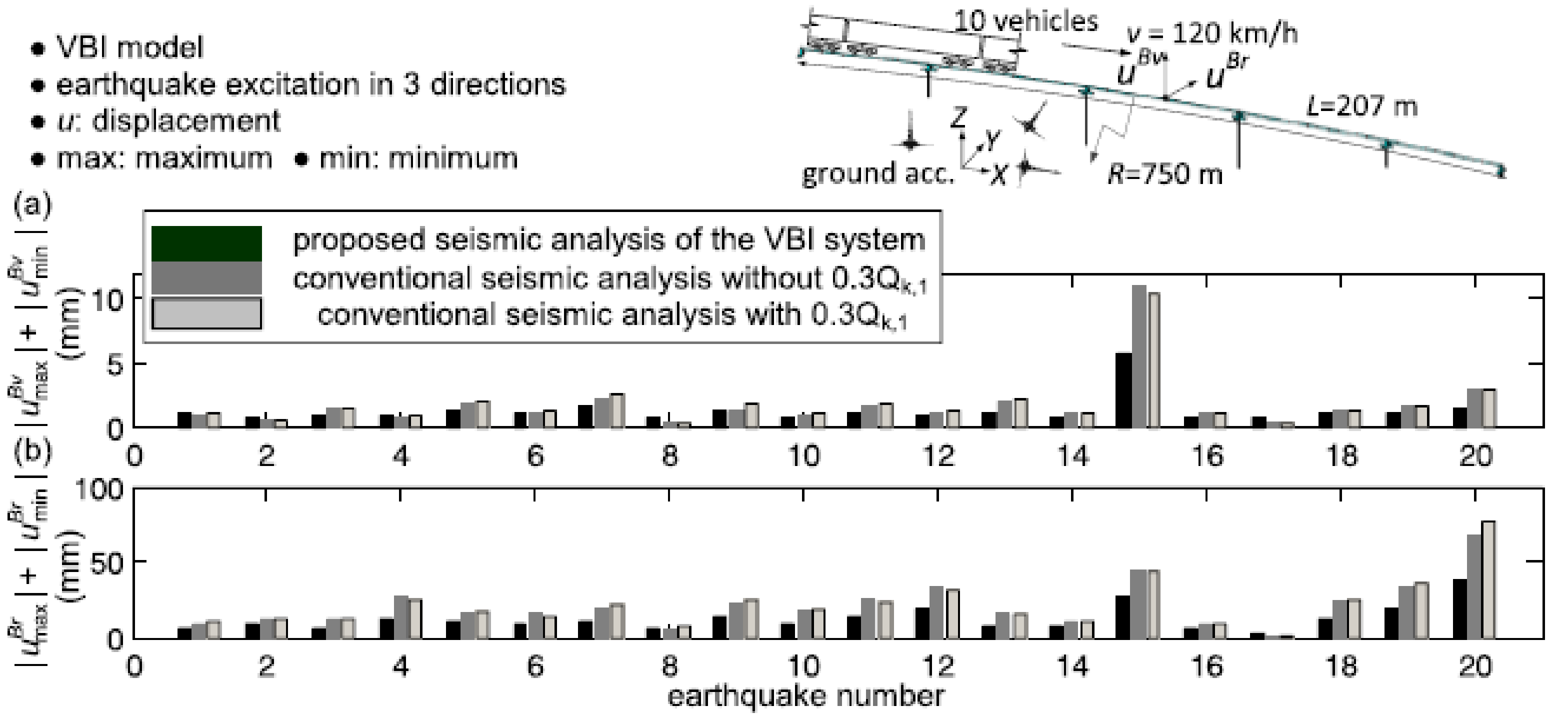
| number | name | Station | Mag. | Epic. Dist. (km) | Dur. (s) | X PGA (g) | Y PGA (g) | Z PGA (g) |
|---|---|---|---|---|---|---|---|---|
| 1 | Coyote Lake | CDMG Station 1492 | 5.74 | 26.85 | 26.83 | 0.07 | 0.11 | 0.04 |
| 2 | Livermore | CDMG Station 67070 | 5.42 | 31.54 | 30.00 | 0.11 | 0.05 | 0.01 |
| 3 | San Francisco | CDMG Station 1117 | 5.28 | 27.03 | 25.50 | 0.10 | 0.11 | 0.05 |
| 4 | Trinidad | CDMG Station 1498 | 5.7 | 71.24 | 21.45 | 0.17 | 0.13 | 0.03 |
| 5 | Jiashi | Xiker, Northwest China | 5.8 | 39.73 | 40.00 | 0.14 | 0.08 | 0.05 |
| 6 | Chalfant Valley | CDMG 54100 | 5.77 | 27.03 | 39.97 | 0.06 | 0.05 | 0.03 |
| 7 | Matata, New Zealand | Edgecumbe substation | 5.7 | 45.76 | 29.50 | 0.04 | 0.04 | 0.04 |
| 8 | Yorba Linda | La Harba & Monte Vista | 4.27 | 16.63 | 43.00 | 0.03 | 0.04 | 0.01 |
| 9 | Northwest Calif-01 | Ferndale City Hall | 5.5 | 43.28 | 40.00 | 0.15 | 0.09 | 0.03 |
| 10 | Lytle Creek | Cedar Springs Pumphouse | 5.33 | 22.94 | 10.22 | 0.06 | 0.07 | 0.04 |
| 11 | Almiros-01, Greece | Almiros | 5.2 | 14.76 | 22.59 | 0.07 | 0.07 | 0.07 |
| 12 | Hollister-04 | CDMG 47189 | 5.45 | 11.35 | 80.00 | 0.04 | 0.09 | 0.05 |
| 13 | Nakagawa | HKD025 | 4.2 | 7.00 | 70.00 | 0.11 | 0.10 | 0.03 |
| 14 | San Francisco | Golden Gate Park | 5.28 | 11.02 | 39.72 | 0.09 | 0.10 | 0.03 |
| 15 | Managua Nicaragua-02 | Managua ESSO | 5.2 | 4.33 | 48.00 | 0.26 | 0.22 | 0.18 |
| 16 | Oroville-04 | Medical Center | 4.37 | 10.50 | 12.52 | 0.08 | 0.05 | 0.03 |
| 17 | Oroville-03 | DWR Garage | 4.7 | 6.03 | 13.60 | 0.11 | 0.22 | 0.09 |
| 18 | Imperial Valley-07 | Calexico Fire Station | 5.01 | 13.32 | 19.42 | 0.10 | 0.07 | 0.03 |
| 19 | Almiros-02, Greece | Almiros | 5.2 | 13.25 | 22.60 | 0.07 | 0.07 | 0.09 |
| 20 | Mammoth Lakes-10 | Convict Creek | 5.34 | 6.50 | 40.00 | 0.16 | 0.15 | 0.10 |

# SVBI frequent earthquakes

## horizontally curved continuous bridge

vertical

radial




- vertical and radial disp. of bridge midpoint
- the conventional seismic analysis overestimates the response of the bridge
- the multibody vehicle acts as a additional damping to the bridge and reduce its response

# SVBI frequent earthquakes

## horizontally curved continuous bridge

- 20 different earthquakes
- comfort: vertical and radial accel. of car-body
- safety: derailment and offload factor

comfort:

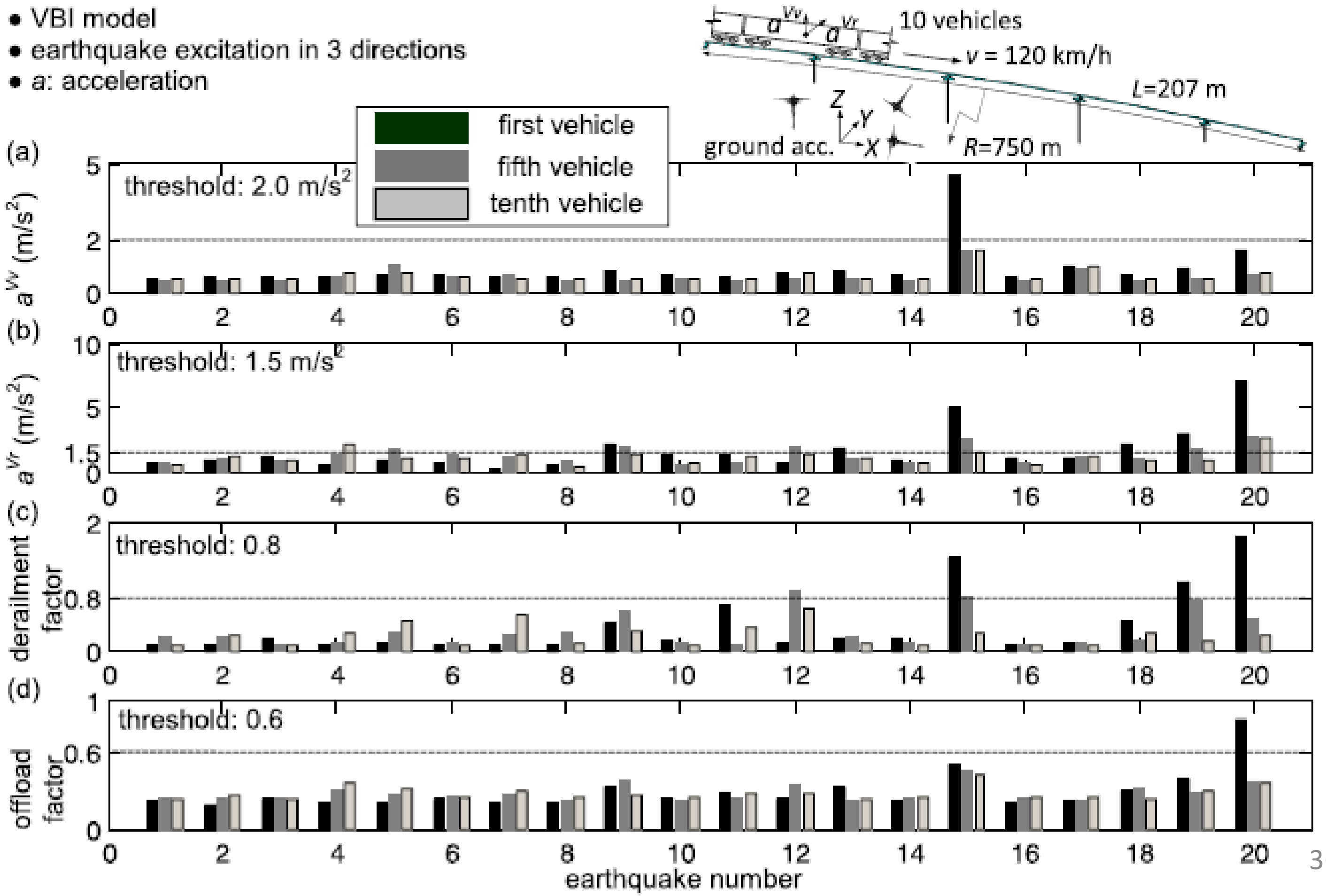
safety

Derail factor

$$= \frac{\lambda_{Ti}}{\lambda_{Ni}}$$

Offloading factor

$$= \frac{|\lambda_{Nli} - \lambda_{Nri}|}{\lambda_{Nli} + \lambda_{Nri}}$$



# outline

motivation

proposed model

results – frequent earthquakes

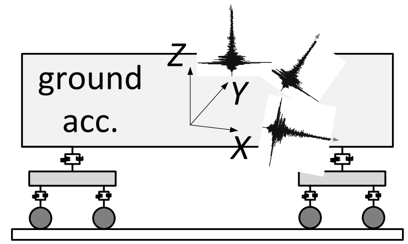
**results – rare earthquakes**

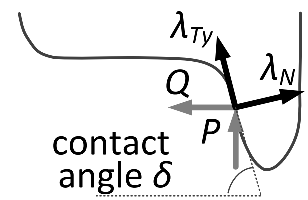
conclusions

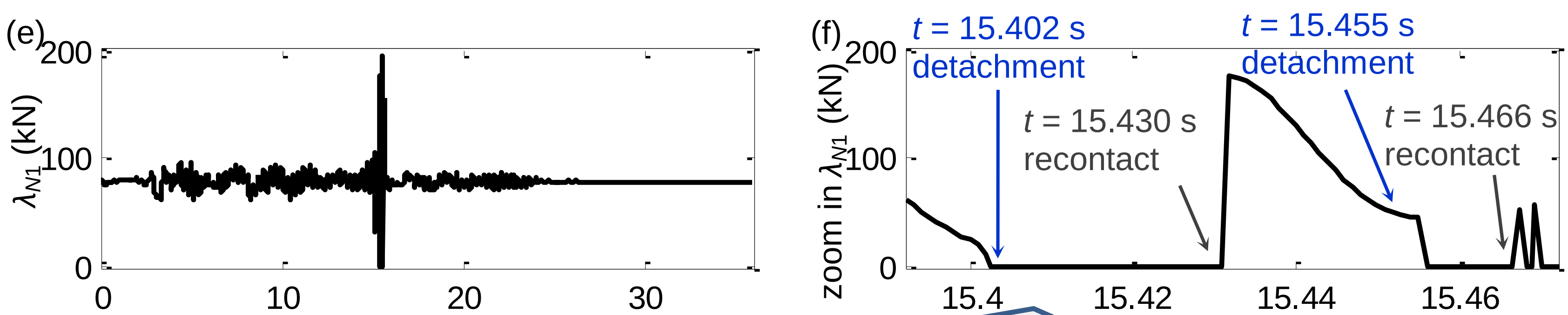
# SVBI rare earthquakes

## horizontally curved continuous bridge

- $a^{Vr}$ and $a^{Vv}$: radial and vertical accel. of car body
- $u^{Vr}$ and $u^{V\Phi}$: vertical and rolling disp. of car body
- $\lambda_{N1}$: normal contact force of wheel 1
- $P$ and $Q$: dynamic vertical and horizontal force



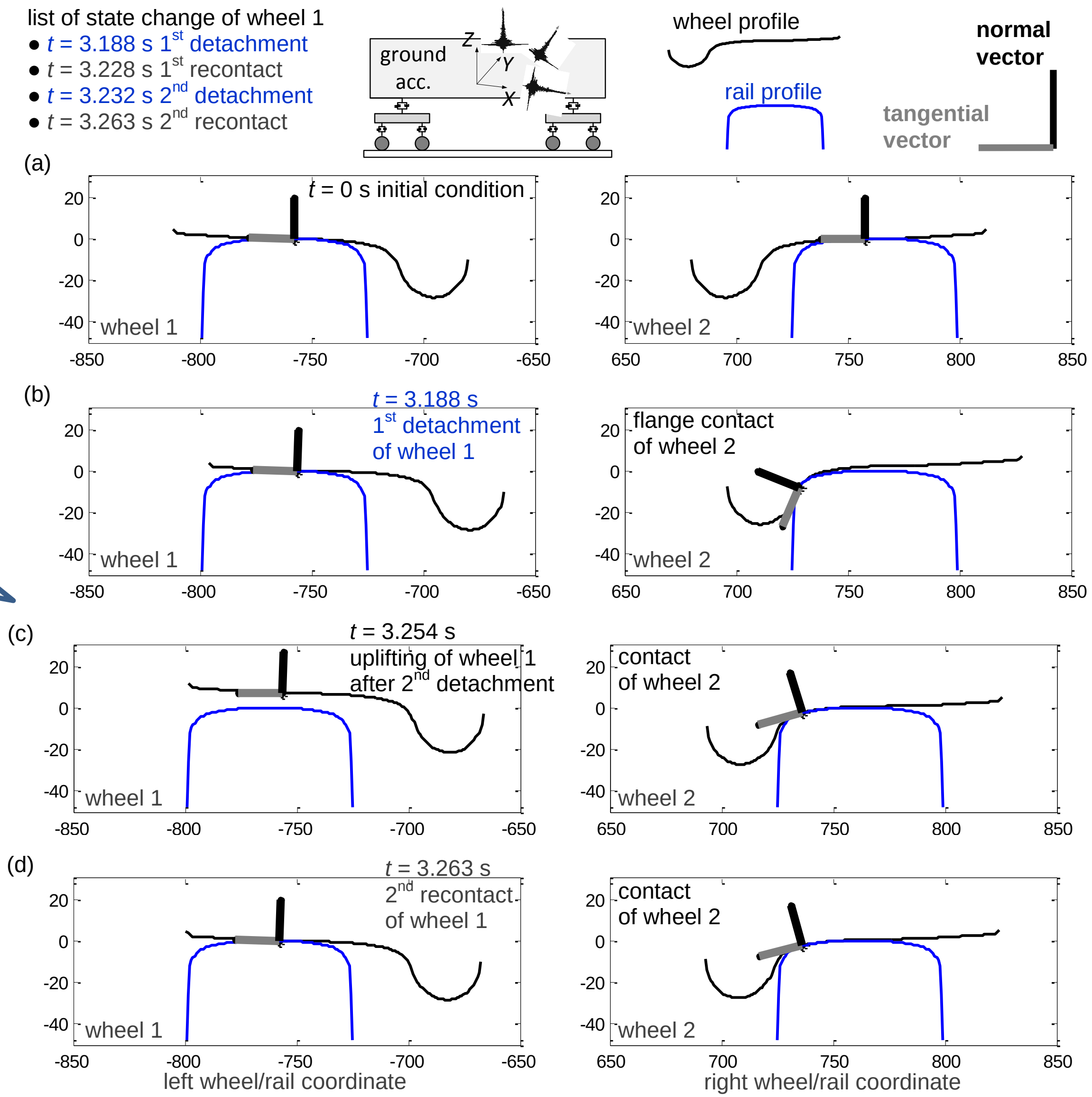

- contact: nonzero normal contact force
- detachment: zero normal contact force

- three components of the ground motion recorded on April 25, 1992 in Cape Mendocino USA, at Petrolia station (0.59g, 0.66g, 0.19g)

# SVBI rare earthquakes

## separation sequence

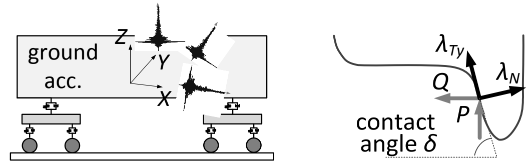
separation
- no need for high lateral accelerations

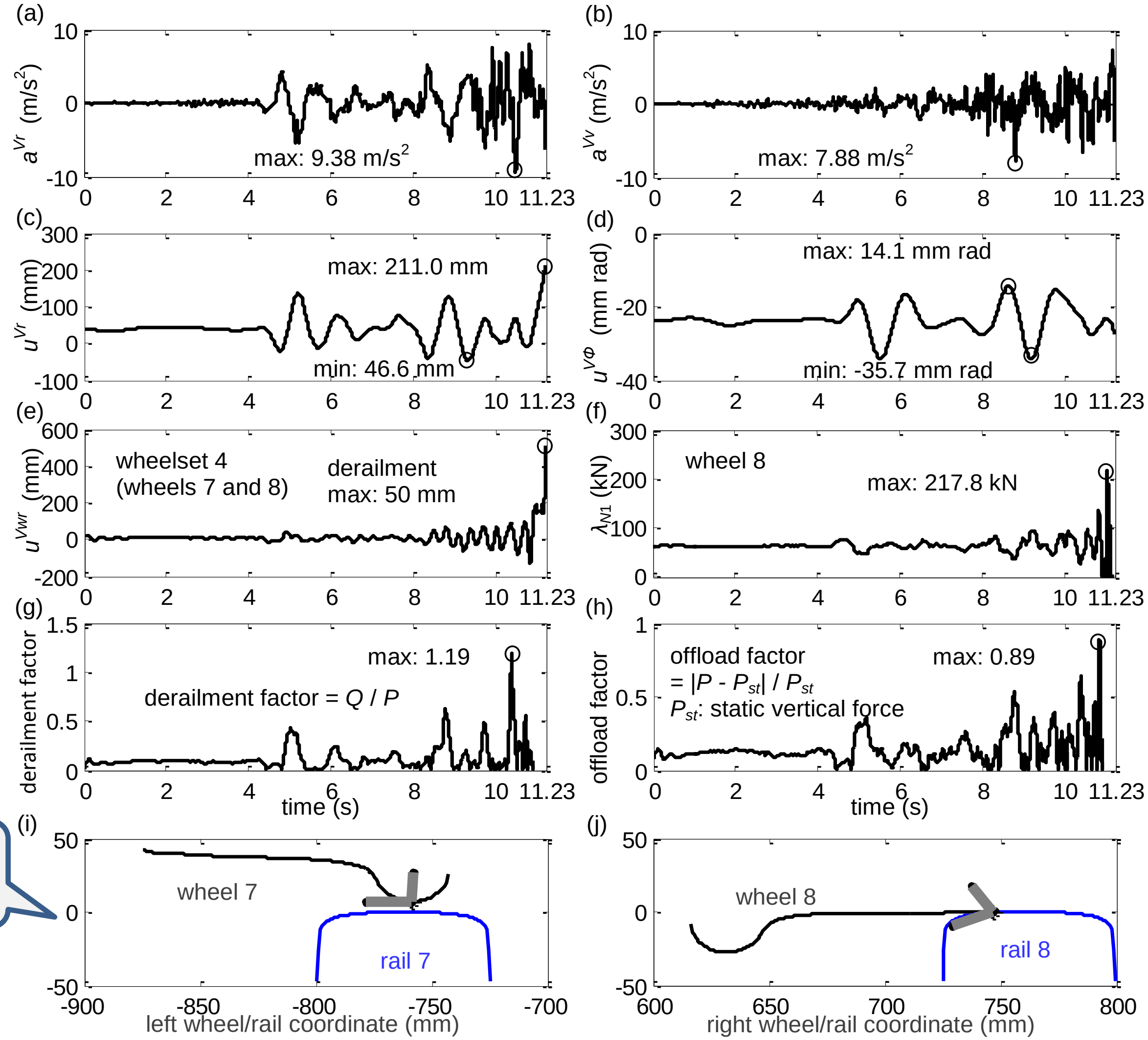


# SVBI rare earthquakes

## separation sequence

- $a^{Vr}$ and $a^{Vv}$: radial and vertical accel. of car body
- $u^{Vr}$ and $u^{V\Phi}$: vertical and rolling disp. of car body
- $u^{Vwr}$: radial disp. of the wheelset
- $\lambda_{N1}$: normal contact force of wheel 1
- $P$ and $Q$: dynamic vertical and horizontal force




derailment

# outline

motivation

proposed model

results – frequent earthquakes

results – rare earthquakes

**conclusions**

# conclusions

- scheme for seismic response of interacting vehicle and horizontally **curved** bridges
- the mass / stiffness / damping matrix of the coupled vehicle-bridge system become **time-dependent**
- the scheme accommodates easily different number of vehicles, and with various DOFs
- the seismic response of the bridge affects (adversely) the safety of the vehicle
- Vehicles-bridge-earthquake **timing** problem
- lack of **performance** (comfort and safety) **criteria** for vehicles → probabilistic
- complicated dynamics, multi-parametric problem

# references

## list of relevant journal publications


1. Zeng Q., **Dimitrakopoulos** E.G. (2016) “Seismic Response Analysis of an Interacting Curved Bridge-Train System Under Frequent Earthquakes” *Earthquake Engineering and Structural Dynamics*, published online, 13 Jan 2016 DOI 10.1002/eqe.2699

2. Zeng Q., Yang Y.B., **Dimitrakopoulos** E.G. (2016) “Dynamic response of high speed vehicles and sustaining curved bridges under conditions of resonance” *Engineering Structures*, published 1 May 2016, vol. 114 pp 61-74, DOI: 10.1016/j.engstruct.2016.02.006

3. **Dimitrakopoulos** E.G. & Zeng Q. (2015) "A Three-dimensional Dynamic Analysis Scheme for the Interaction between Trains and Curved Railway Bridges" *Computers & Structures*, vol. 149 43-60.

4. Paraskeva T.S., **Dimitrakopoulos** E.G., Zeng Q., (2016) “Dynamic Vehicle-Bridge Interaction Under Simultaneous Vertical Earthquake Excitation” *Bulletin of Earthquake Engineering*, accepted 28/5/2016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# thank you for your kind attention!

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# low-cost high impact bamboo bridges

# case studies and results

## steel arch truss bridge

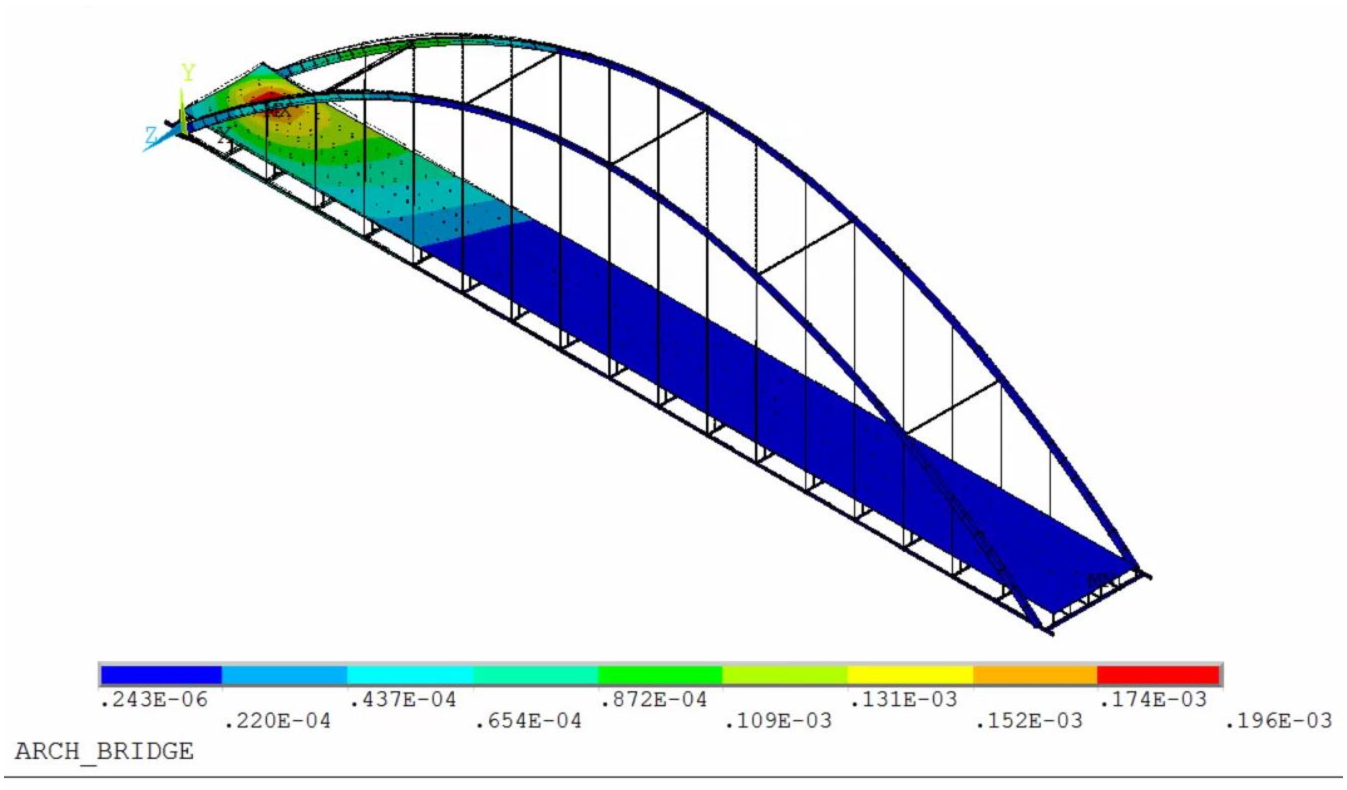
Ting Sihe Bridge of High-speed railway line in China

http://campus.liepin.com/tsy/enterprisefeatures (2015)

# case studies and results

## steel arch truss bridge

- deformed shape of the whole bridge
- 1 vehicle: speed of train = 300 km/h

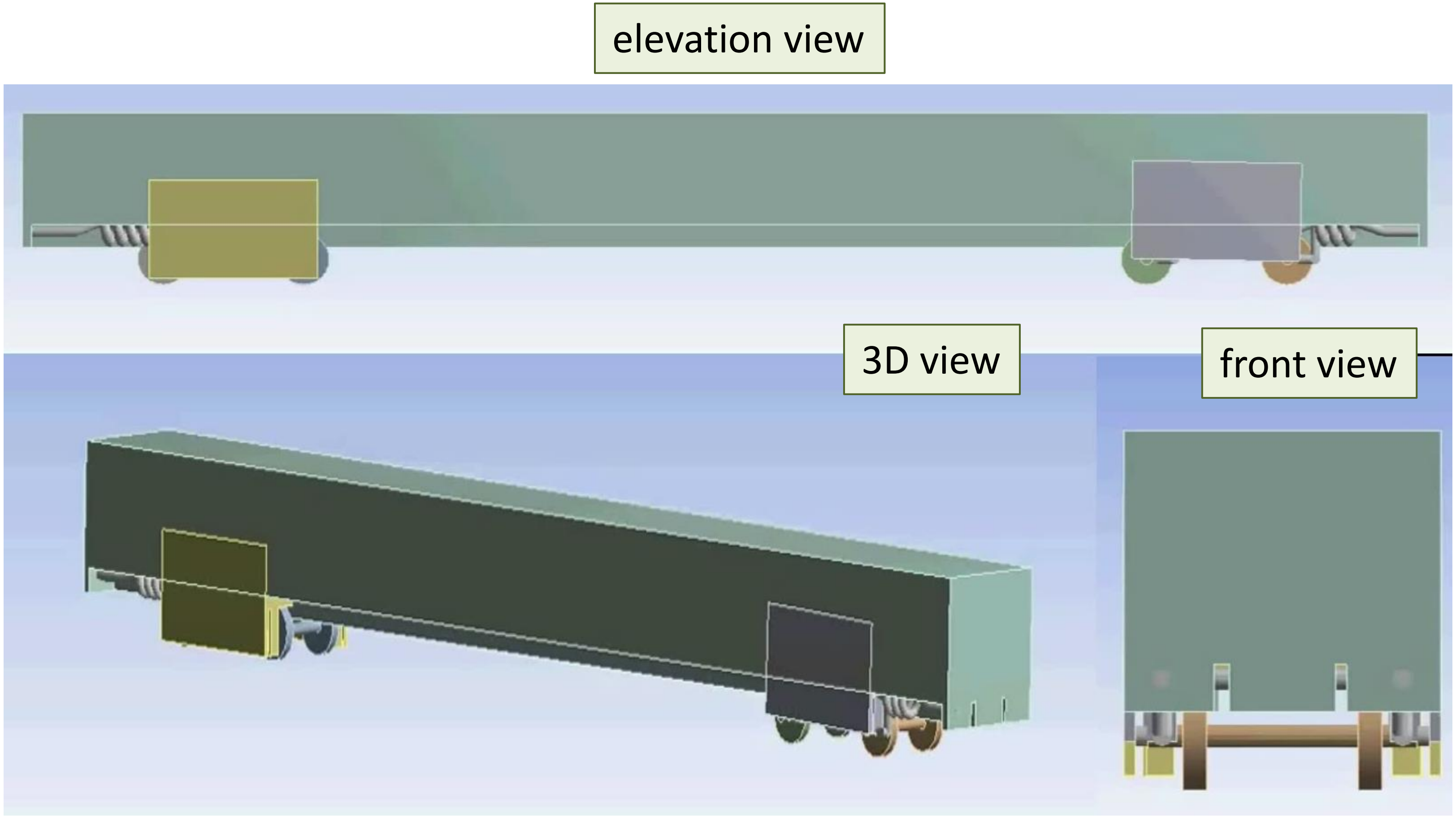


# case studies and results

## steel arch truss bridge

deformation animation of the vehicle

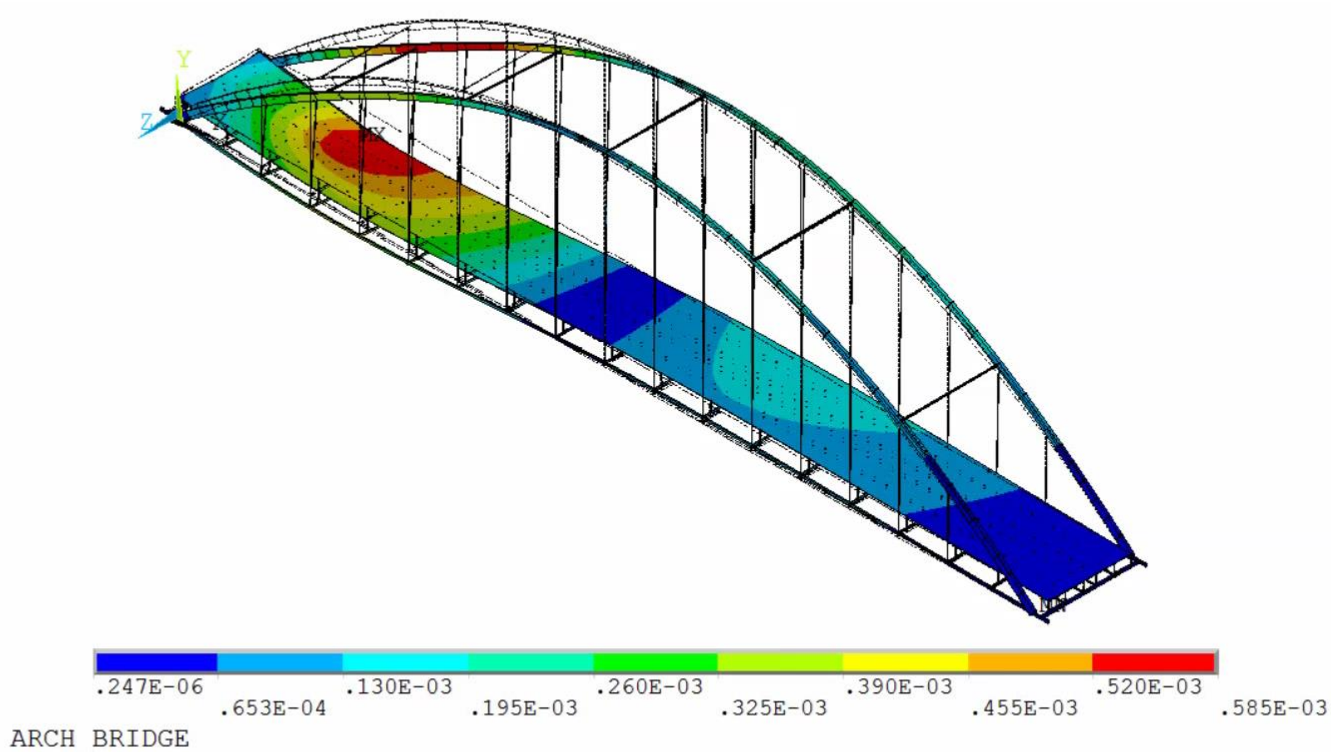
- 1 vehicle: speed of train = 300 km/h
- vibration due to the **track irregularities**



# case studies and results

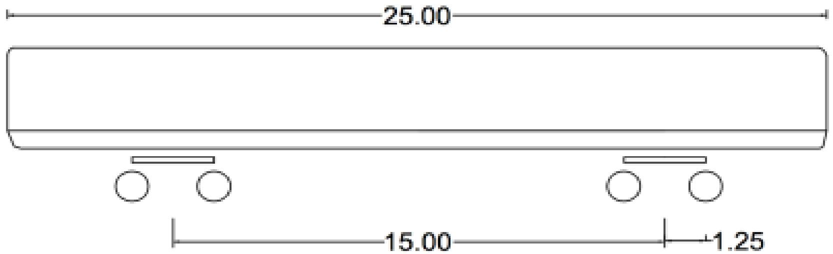
## steel arch truss bridge

- deformed shape of the whole bridge
- 10 vehicle: speed of train = 300 km/h



# case studies and results

## cable-stayed bridge with the passage of MTR




Kap Shui Mun Bridge (KSMB) in **Hong Kong**

http://en.wikipedia.org/wiki/Kap_Shui_Mun_Bridge

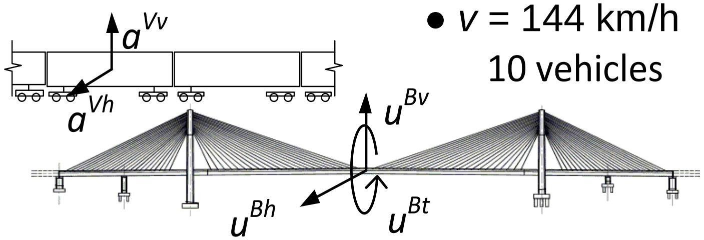
# case studies and results

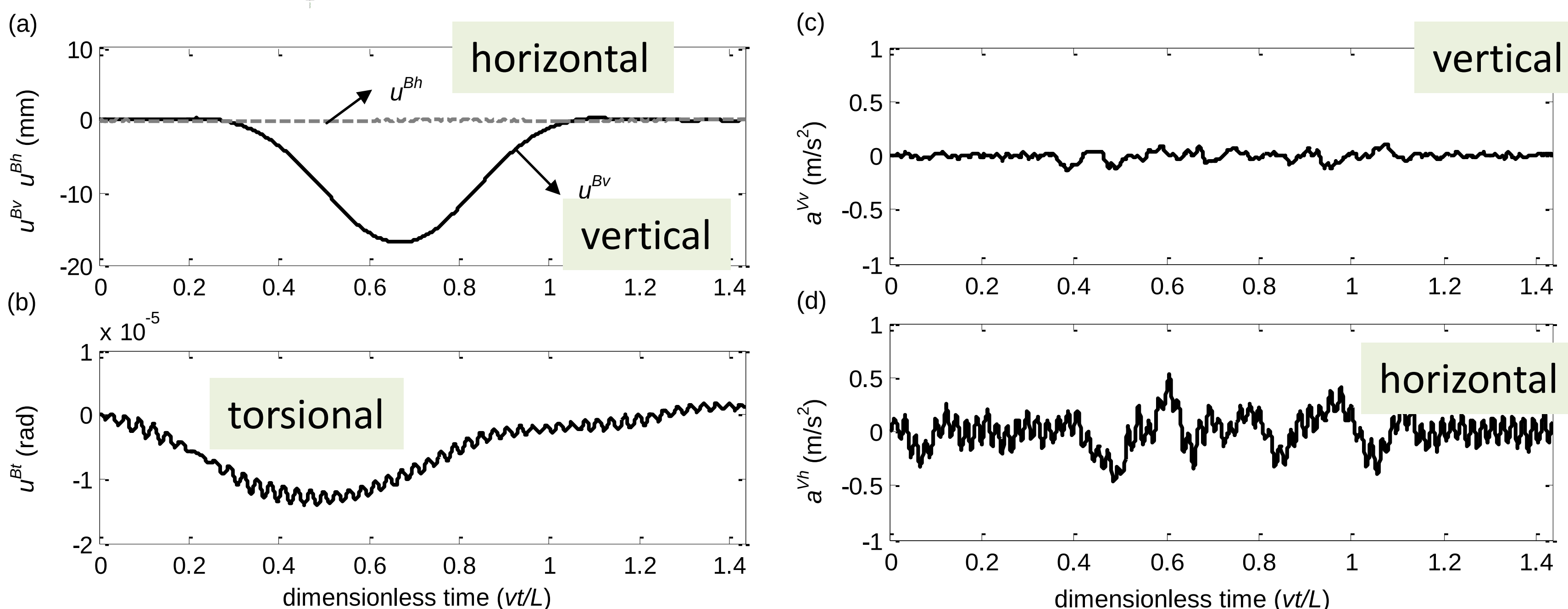
## cable-stayed bridge with the passage of MTR

- (a) and (b) bridge midpoint **vertical horizontal** and **torsional displacements**
- (c) and (d) vehicle **vertical** and **horizontal accelerations**

- $L$ = 750 m
- $v$ = 144 km/h

10 vehicles



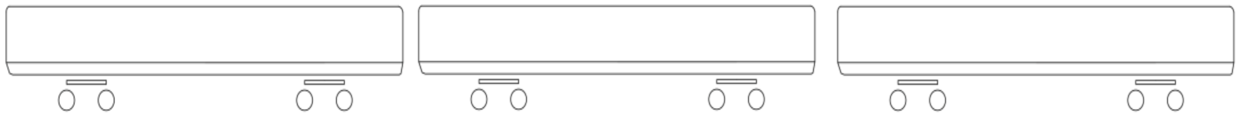



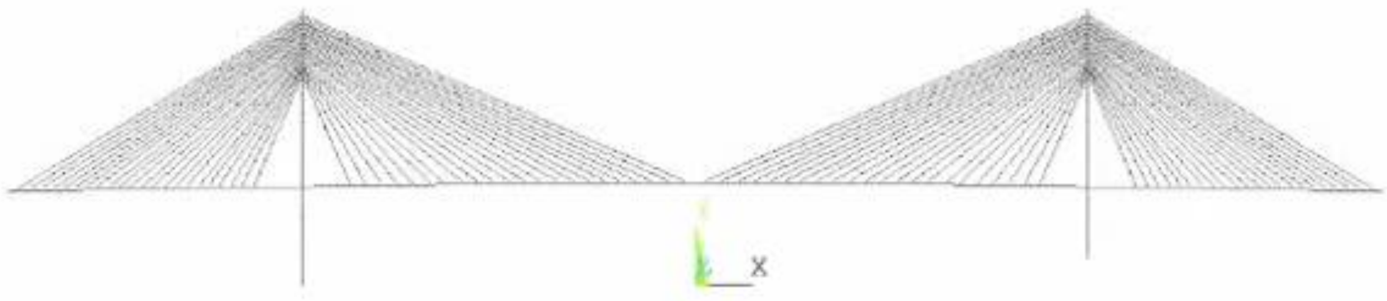

bridge displacement

vehicle acceleration

# case studies and results

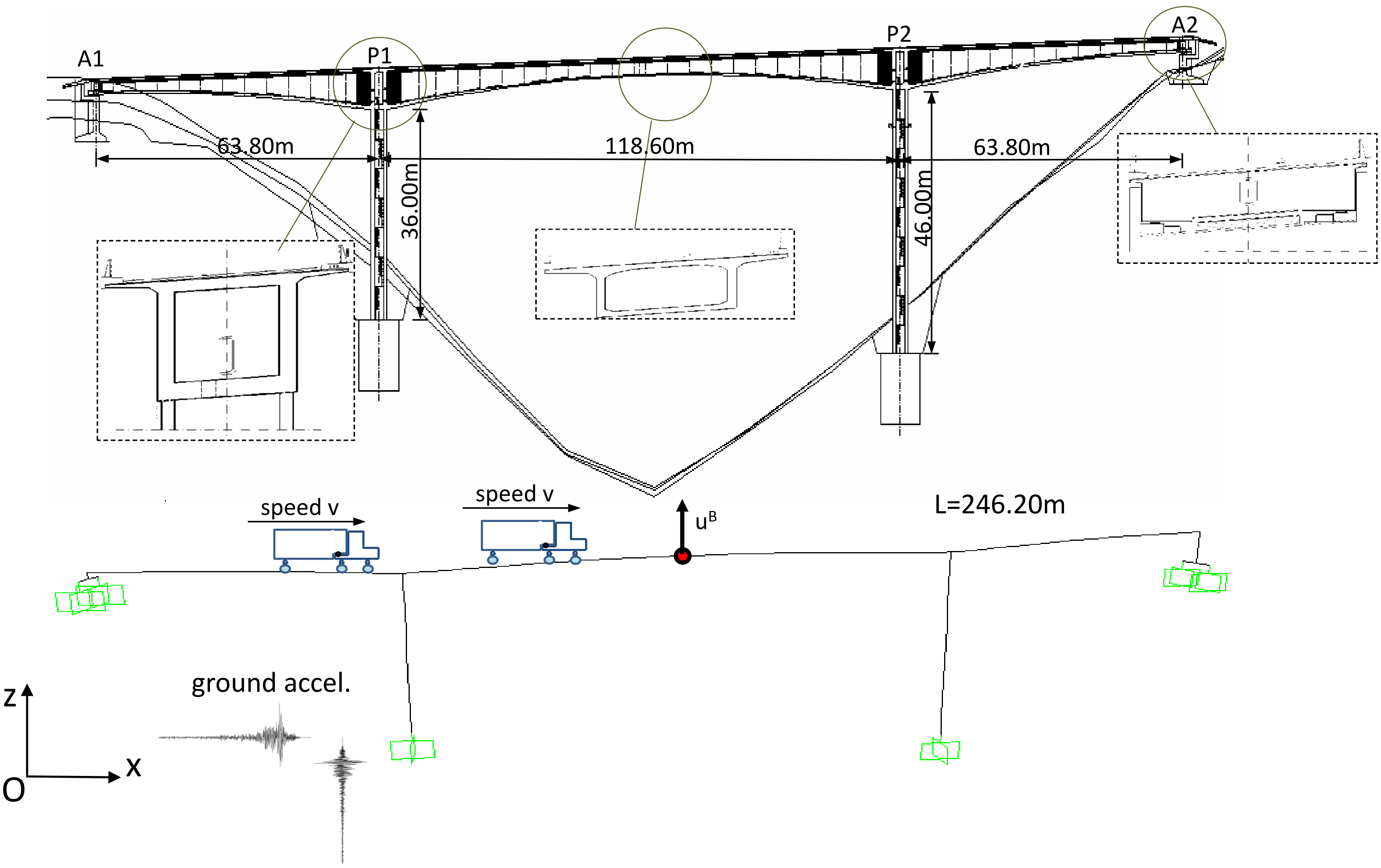
## cable-stayed bridge with the passage of MTR





# case studies and results

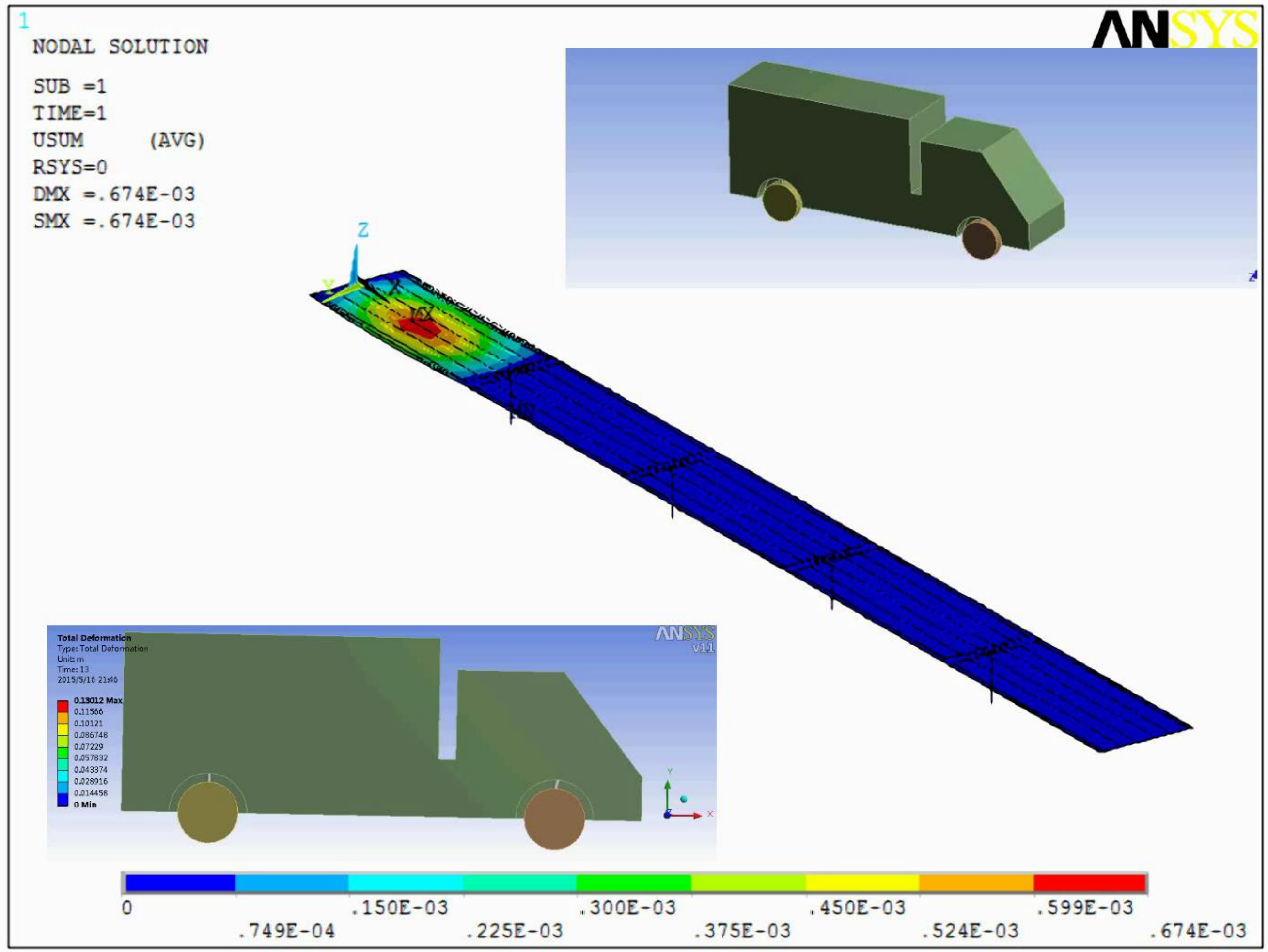
## straight highway bridge



# case studies and results

## 5-span highway continuous bridge with the passage of trucks

- deformed shape of the whole bridge and the vehicle
- 1 vehicle: speed of truck = 80 km/h



# case studies and results

## 5-span highway continuous bridge with the passage of trucks

- deformed shape of the whole bridge
- 5 vehicle: speed of truck = 80 km/h