Structural Health Monitoring and Rapid Post–Event Assessment of Civil Infrastructures through Digital Twins

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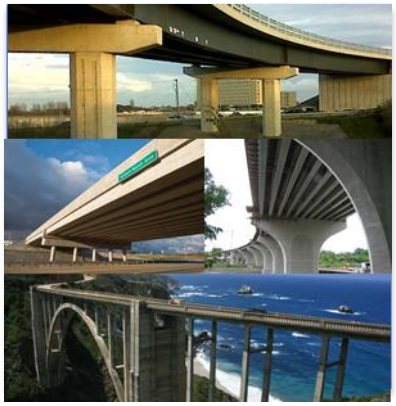
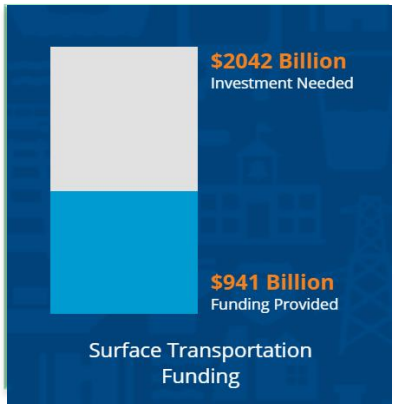
Why Bother?



Emergency Response

Asset Management

Retrofit & Upgrading



ASCE

Visual Inspection

Maintenance Inspection

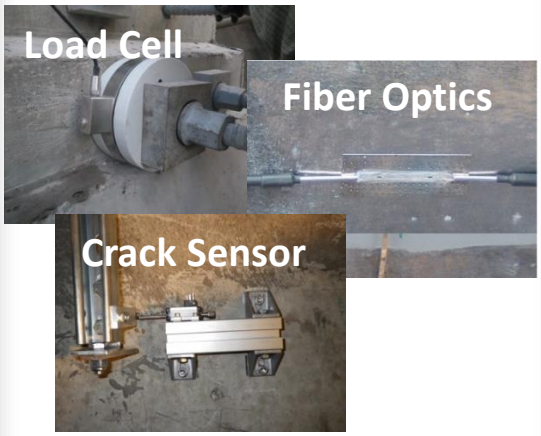
- Costly
- Periodic
- Subjective
- No system-level insight
- Hidden damage

Post-Earthquake Inspection

- # of bridges × inspection time × chaos = ?
- Intensity-based metrics can be inaccurate!
- Inspection complexity
- Hidden damage
- No system-level insight

SHM – NDE

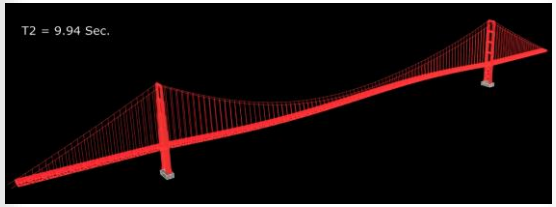
Point Monitoring



Shortcomings?

- Data not information
- Limited damage detection, and quantification capability
- Require large number of sensors
- Maintenance and installation cost
- No system-level insight

Modal-Based Linear Damage Identification

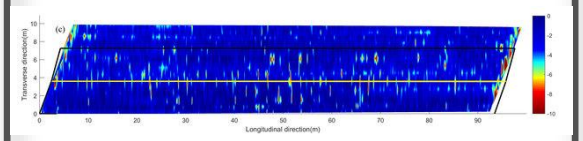


Shortcomings?

- Not sensitive to local damage
- Based on limiting assumptions (broad band excitations, etc.) – inaccuracy and lack of robustness

NDE

Source: FHWA SHRP2 Solutions



(Source: DOI 10.1115/JRC2014-3782)

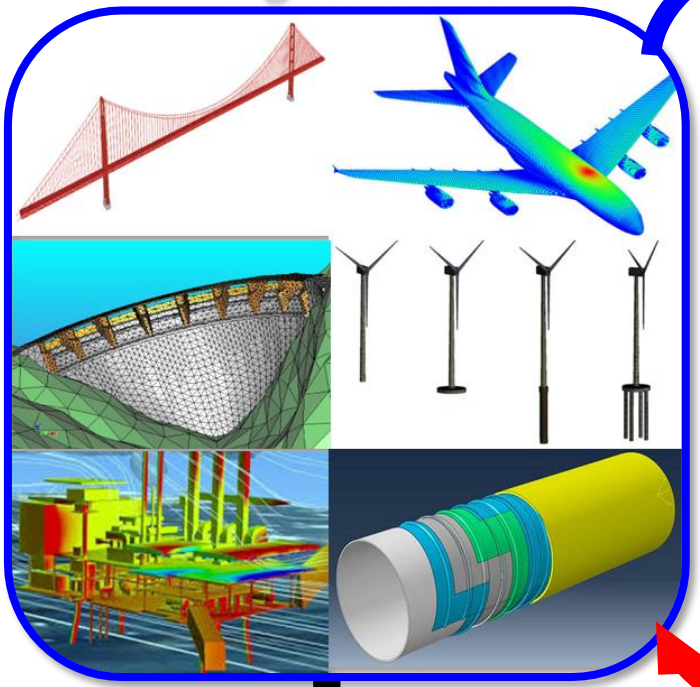
Shortcomings?

- Traffic interruption
- Cost
- Access limitations
- No system-level insight

Integration of Mechanics–Based Models with Data

Forward Simulation

Digital World



Real World

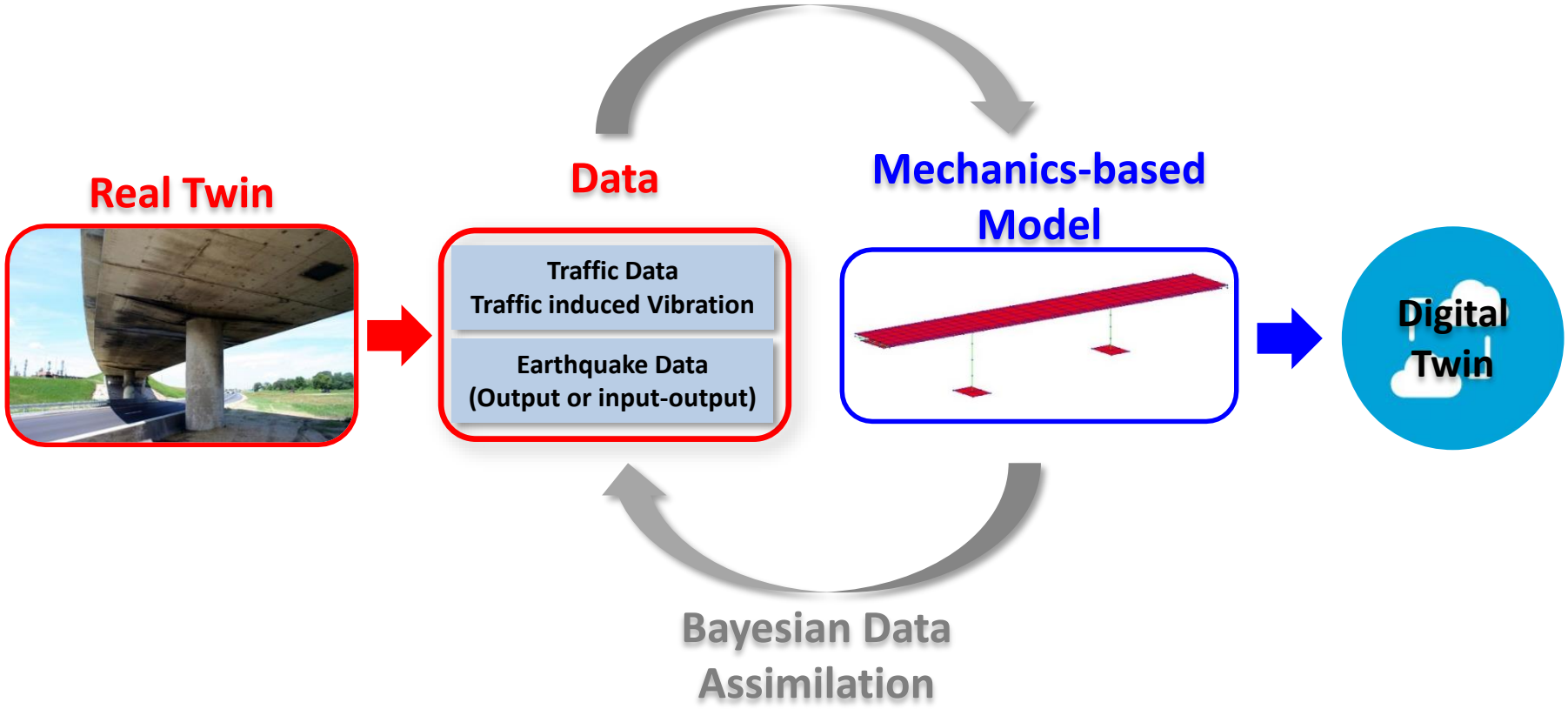
- Model Parameter Uncertainties
- Unknown Inputs

- **Estimate Model Parameters**
- **Estimate Input Forces**

Model Updating / training

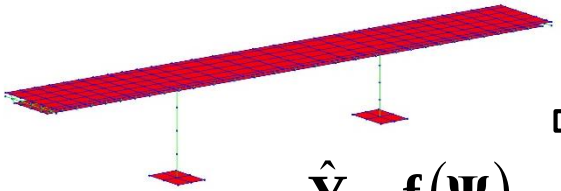
Mechanics-based damage diagnosis at refined spatial resolution

Digital Twins



Bayesian Data Assimilation

Linear/Nonlinear FE Model

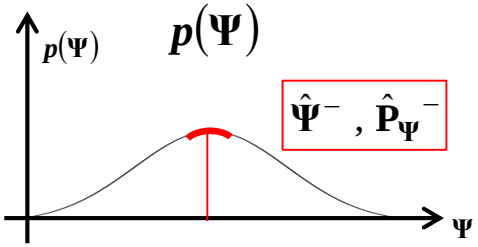


$$\hat{\mathbf{Y}} = \mathbf{f}(\boldsymbol{\Psi})$$

Measurement

$$\mathbf{Y} = \mathbf{y}$$

Prior Information

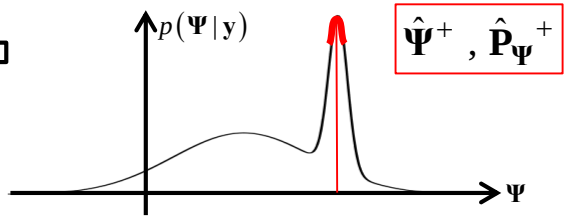


Likelihood Function

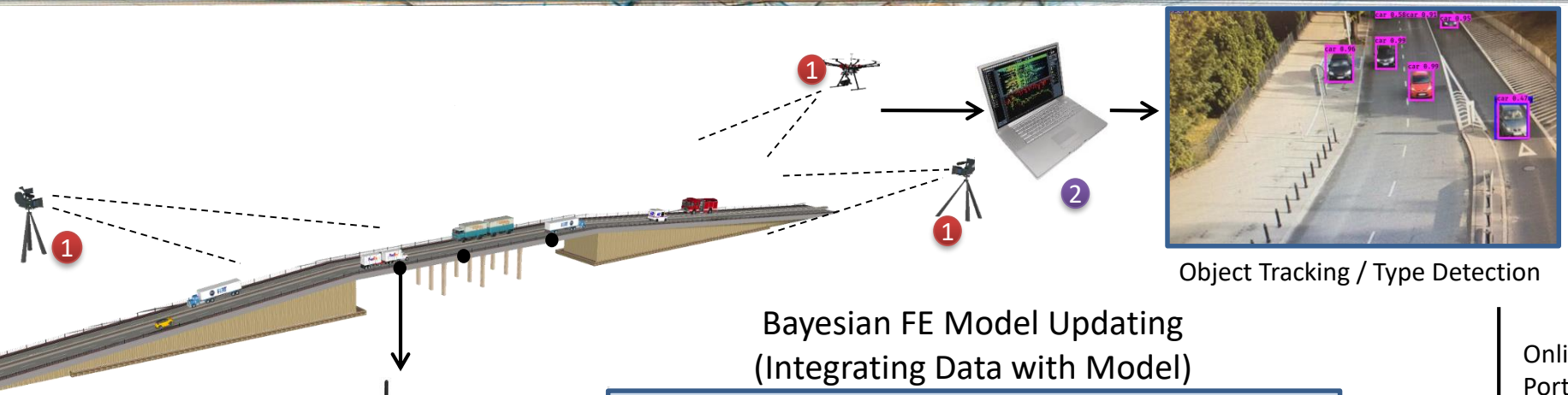
$$p\left(\mathbf{Y} = \mathbf{y} \middle| \boldsymbol{\Psi}\right) \sim N\left(\mathbf{0}, \mathbf{R}\right)$$

Bayesian Updating

$$p\left(\boldsymbol{\Psi} \middle| \mathbf{y}\right) = \frac{p\left(\mathbf{y} \middle| \boldsymbol{\Psi}\right)\ p\left(\boldsymbol{\Psi}\right)}{p\left(\mathbf{y}\right)}$$



Digital Twins for Operational Monitoring and Management



Bayesian FE Model Updating
(Integrating Data with Model)

Online Portal

Permanent/temporary sensors

Acceleration THs

Online Portal

Stochastic Filtering

Mechanics-based FE Model

P_1 P_2 ... P_n

Vehicle Locations

Predictions

+

-

Estimate jointly the model parameters and vehicular loads

Measurements

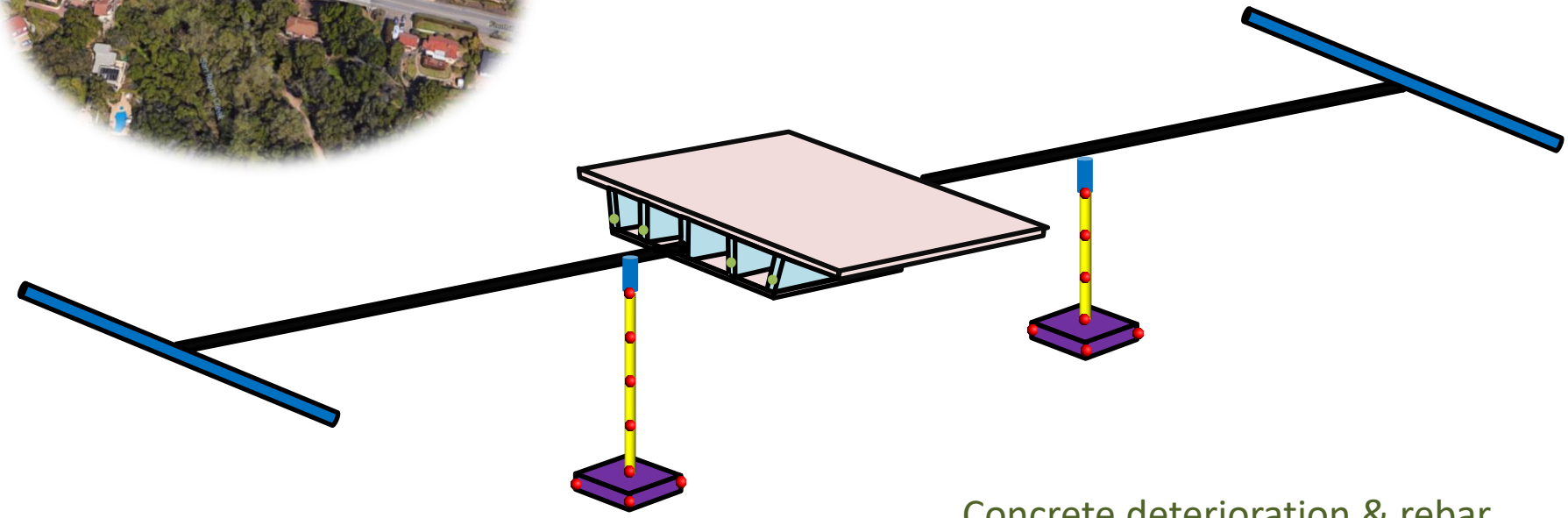
Digital Twin

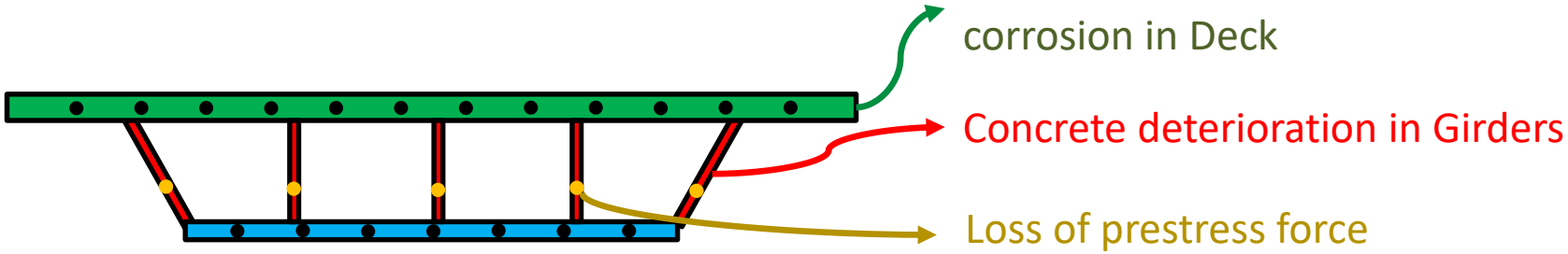
Share Information with Stakeholders

1 Regular camera system (tripod or drone mounted)
2 On-site laptop
3 Office/server computer

Box–Girder Bridge Case Study

- San Roque Canyon Bridge
- Typical prestressed cast-in-place RC box girder

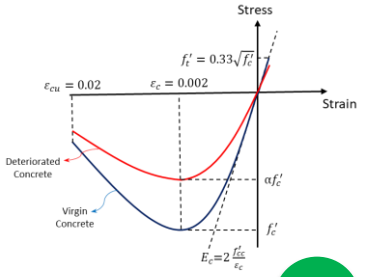


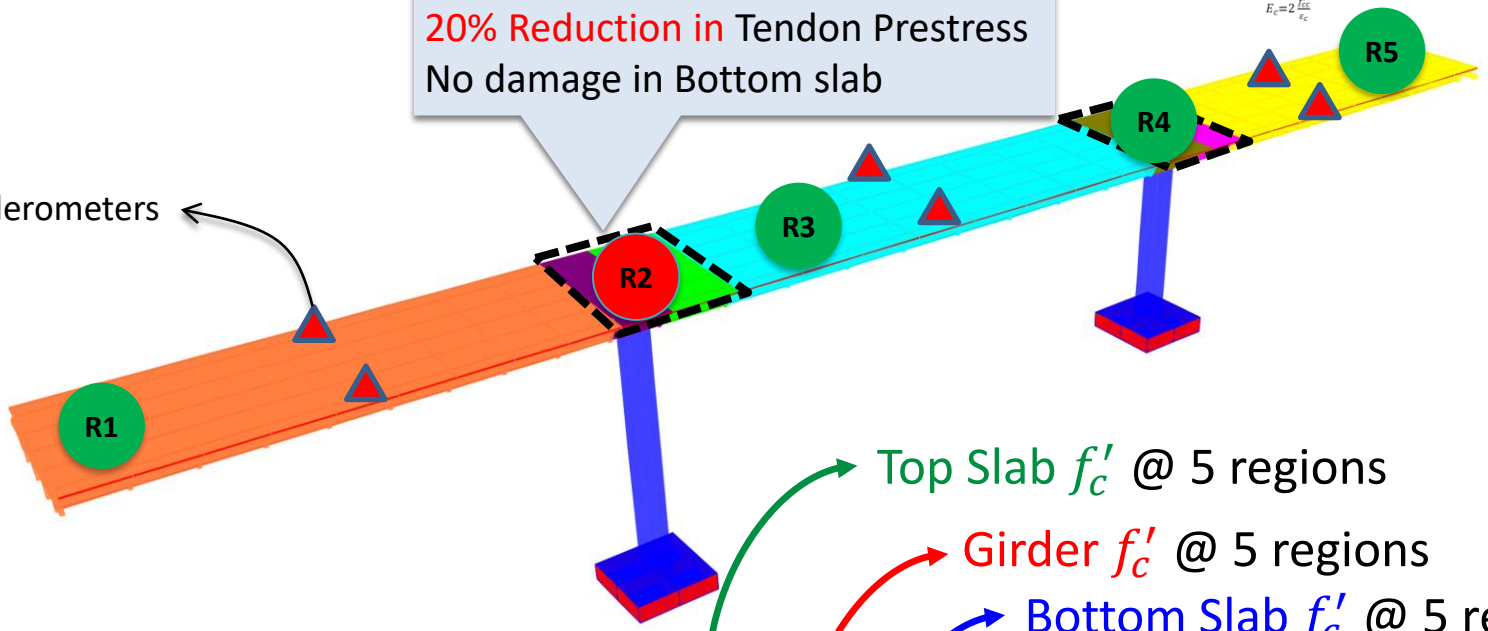


Verification Study

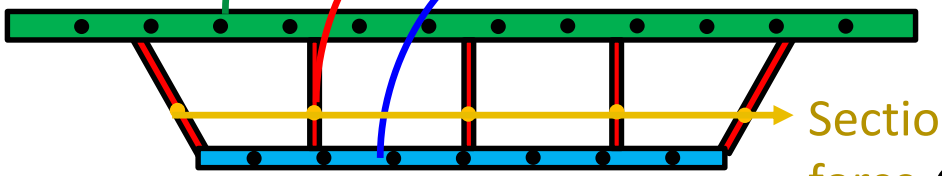
- Verification using numerically simulated data
- Poor condition in R2

40% Reduction in Top slab f_c'
20% Reduction in Girder f_c'
20% Reduction in Tendon Prestress
No damage in Bottom slab





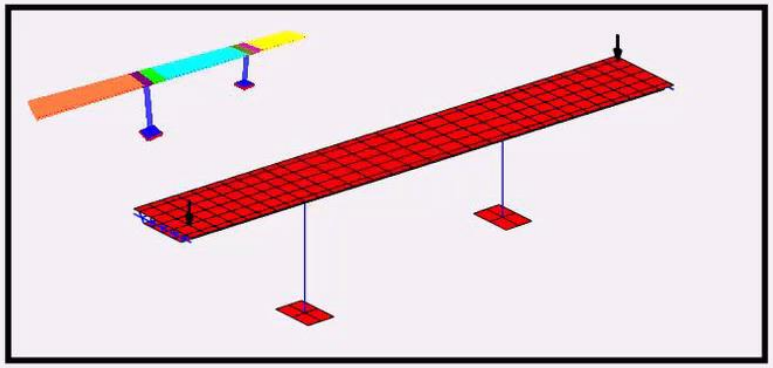
Top Slab f_c' @ 5 regions
Girder f_c' @ 5 regions
Bottom Slab f_c' @ 5 regions

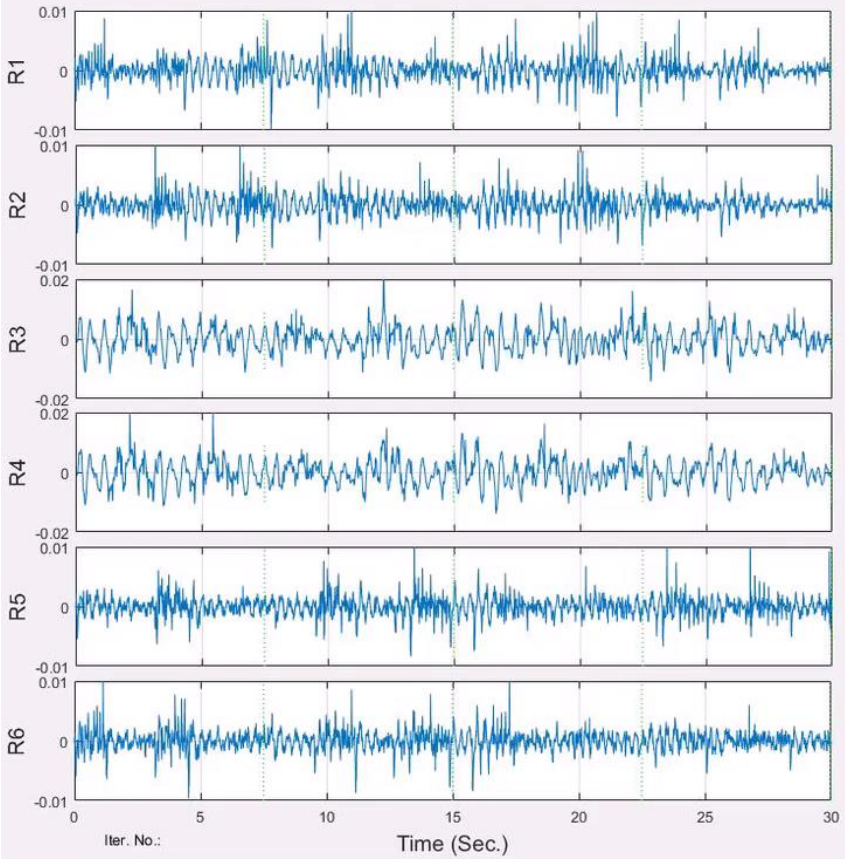


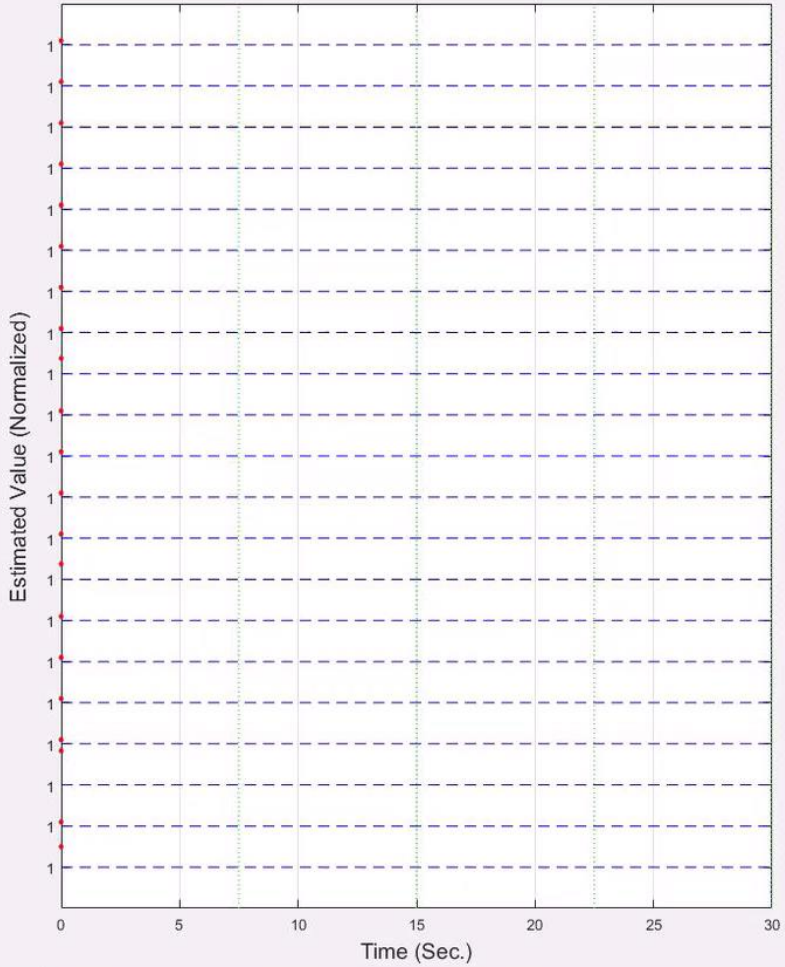
Section prestress force @ 5 regions

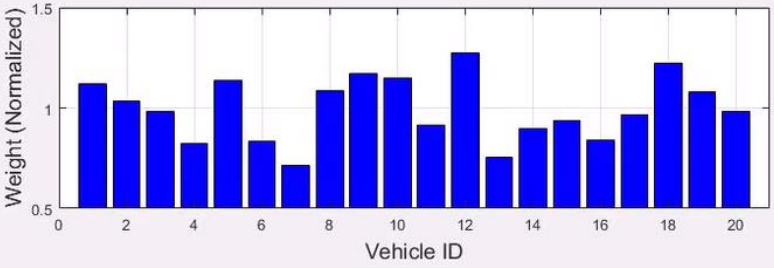
- 20 unknown material parameters + Rayleigh damping parameters + Vehicular loads

Verification Study

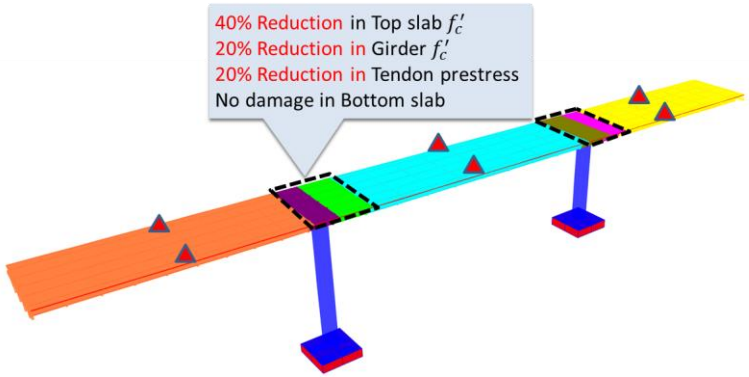


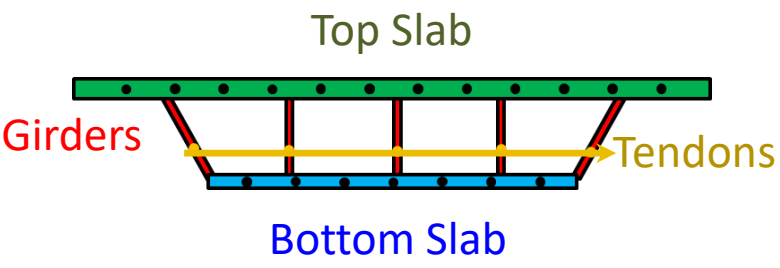




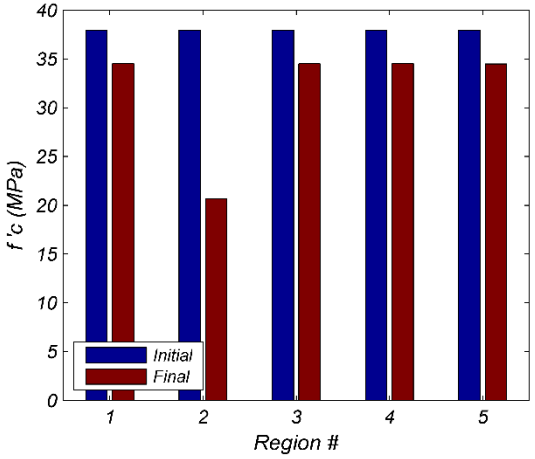


Damage Diagnosis

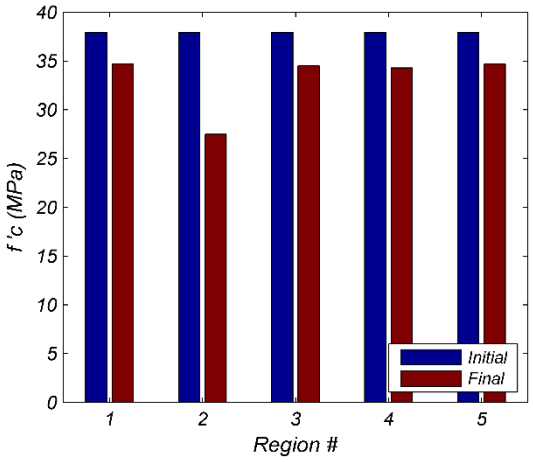




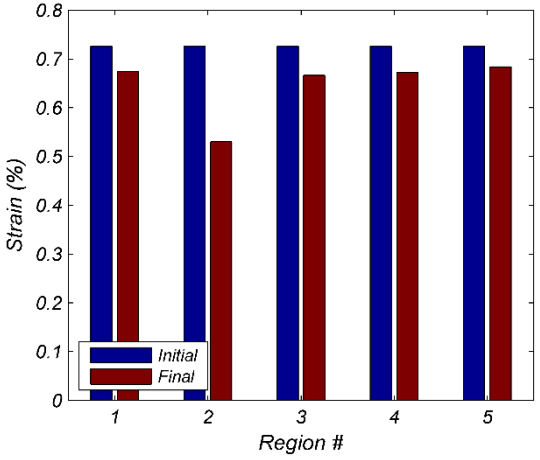
Top Slab f_c'



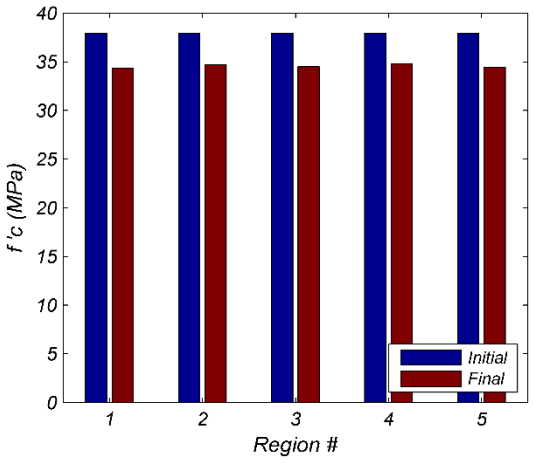
Girders f_c'



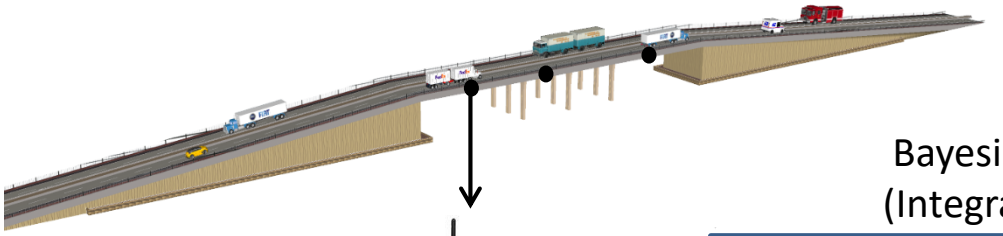
Tendon Prestress Strain



Bottom Slab f_c'

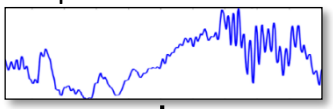


Digital Twins for Post-Earthquake Assessment



Permanent Sensors

Output Acceleration THs



Online Portal

Measurements

Bayesian FE Model Updating
(Integrating Data with Model)

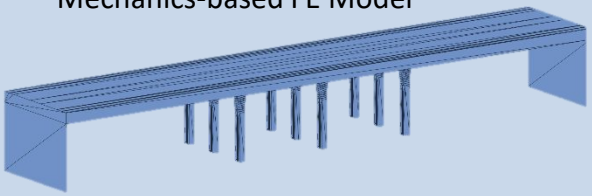
Stochastic Filtering

Predictions

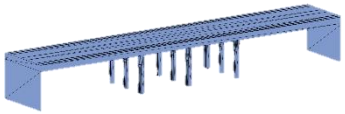
+

-

Mechanics-based FE Model



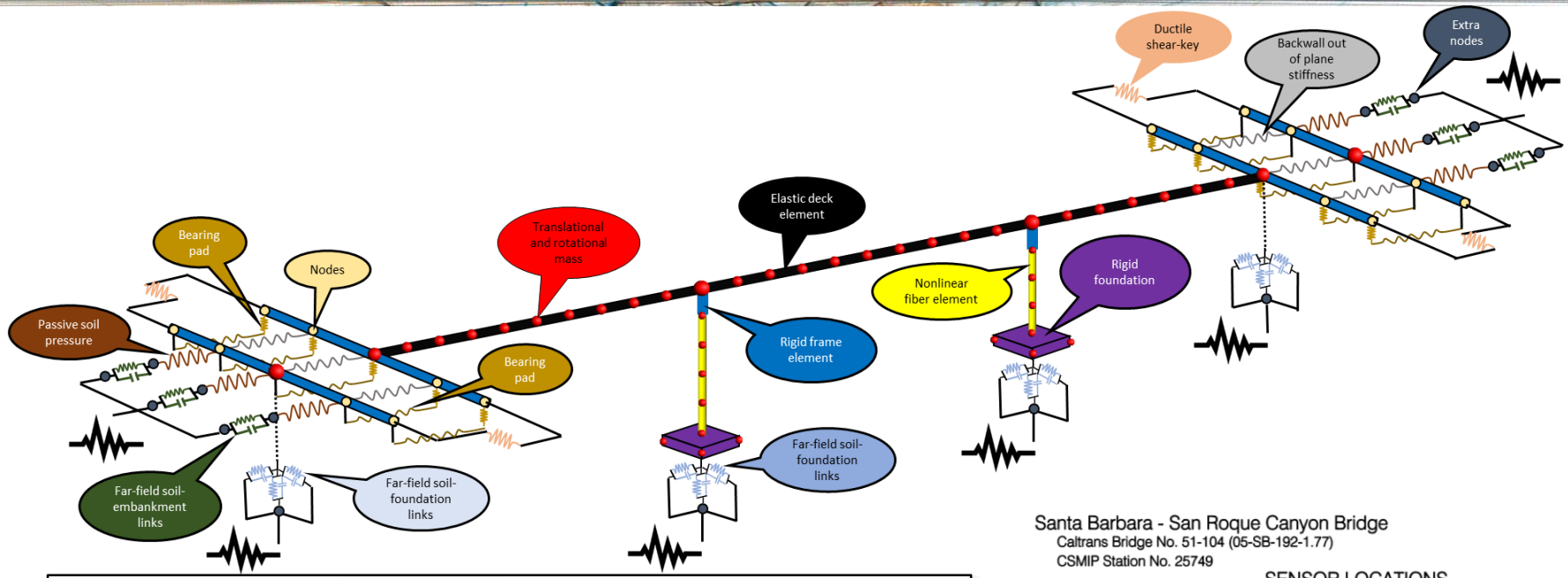
Estimate jointly the model parameters and foundation input motions (FIMs)



Digital Twin

Share Information with Stakeholders

Box–Girder Bridge Case Study



CESMD Strong-Motion Data Set

Home | Archives | Search | Earthquake/Station Maps | About

Search

5 records match the following search parameters

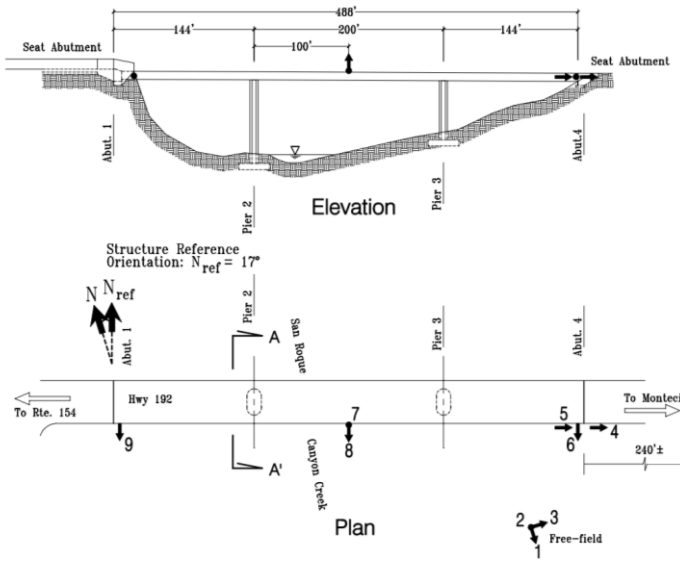
Station (City, Name or No): san roque
Site Class: Any
PGA (g): Any

Station type: Any
Epicentral Dist. (km): Any

StaNo	Station	Network	Distance (km)		Horiz Apk (g)		Earthquake	View	Download
			Epic	Fault	Ground	Struct.			
25749	Santa Barbara - San Roque Canyon Bridge	CGS	27.2	--	0.016	0.047	IslaVista 09May2004		
	"		187.0	--	0.015	0.045	SanSimeon 22Dec2003		
	"		18.0	--	0.041	0.152	islavista 29may2013_15350729		
	"		9.5	--	0.022	0.046	Montecito 23Apr2017_37865280	--	
	"		67.9	--	0.016	0.058	SantaCruzIsEend 05Apr2018_37908735		

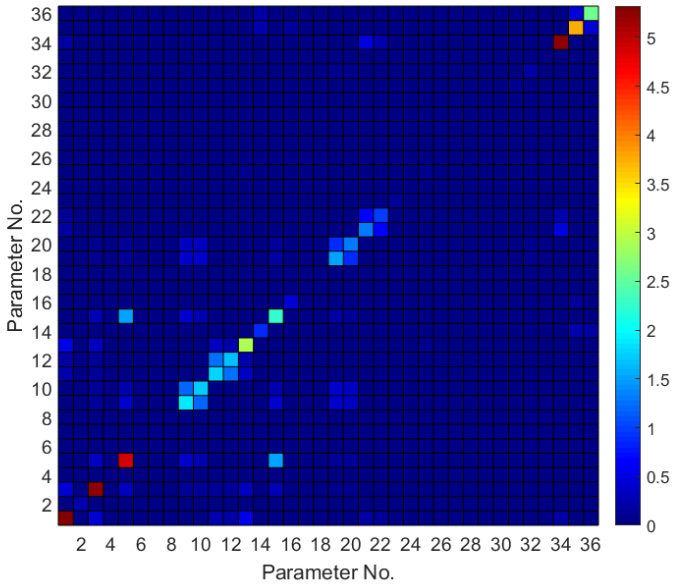
Santa Barbara - San Roque Canyon Bridge
Caltrans Bridge No. 51-104 (05-SB-192-1.77)
CSMIP Station No. 25749

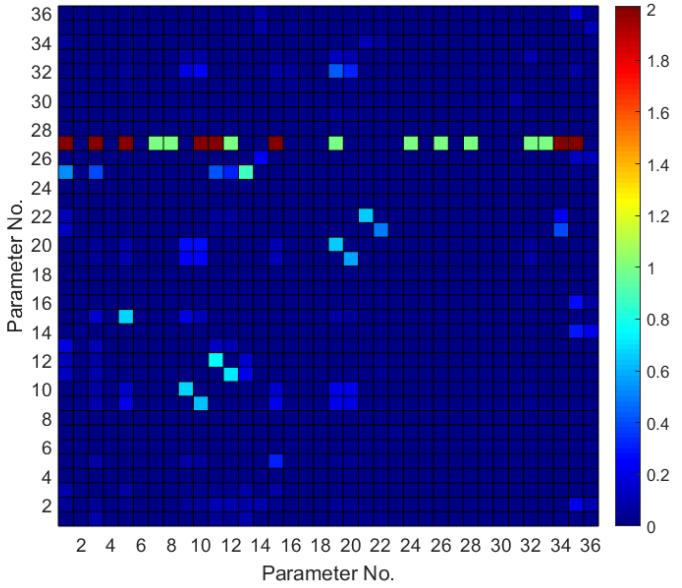
SENSOR LOCATIONS



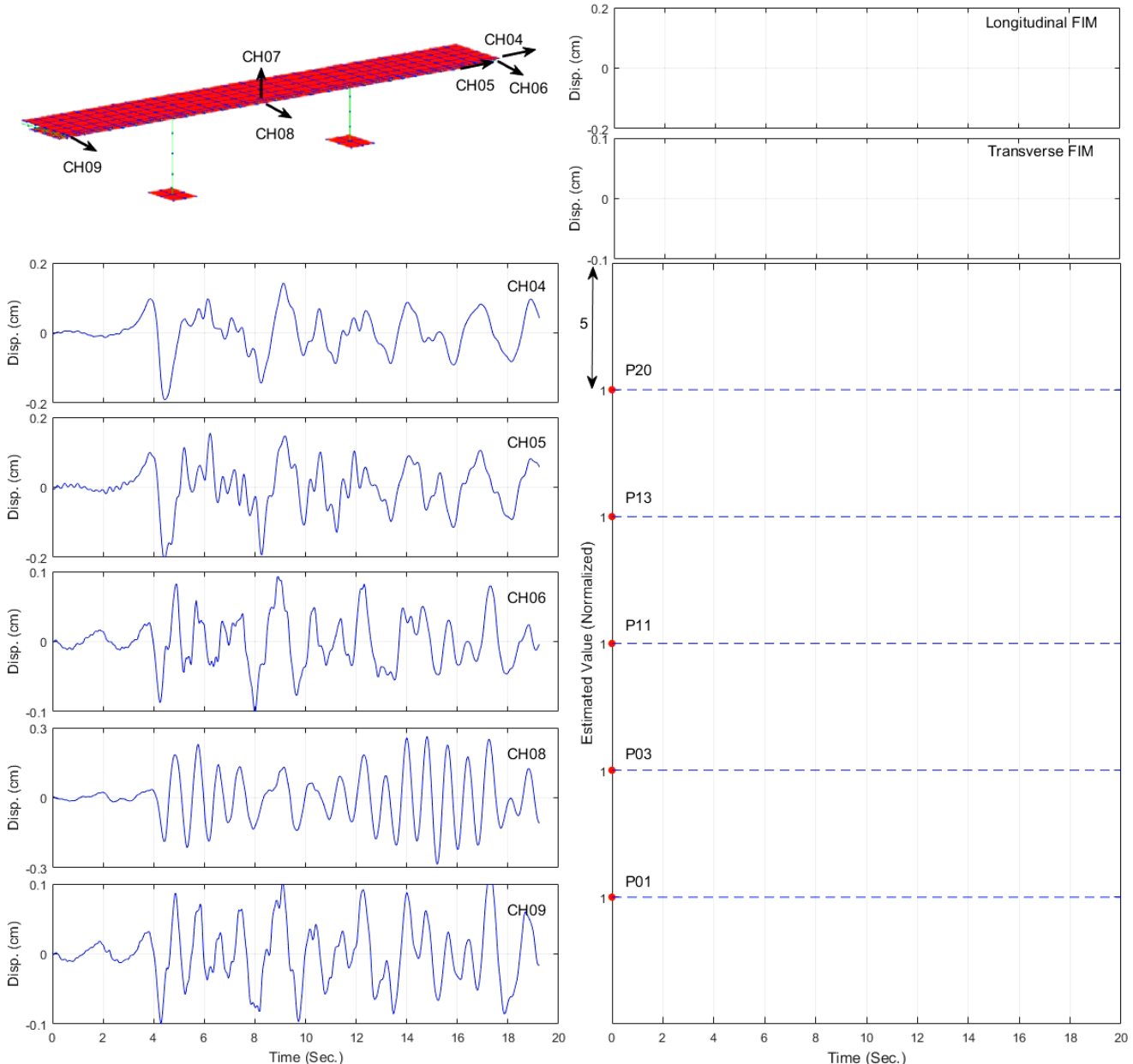
Identifiability Analysis

No.	Description	No.	Description
1	Modulus of elasticity of the concrete (deck)	19	Longitudinal soil-foundation stiffness (abutment)
2	compressive strength of the concrete (columns)	20	Longitudinal soil-foundation damping (abutment)
3	Initial modulus of elasticity of the concrete (columns)	21	Transverse soil-foundation stiffness (abutment)
4	Modulus of elasticity of the bearing pad	22	Transverse soil-foundation damping (abutment)
5	Shear stiffness of the bearing pad	23	Vertical soil-foundation stiffness (abutment)
6	Mass of the embankment-abutment	24	Vertical soil-foundation damping (abutment)
7	Vertical soil-foundation stiffness (piers)	25	Rotational soil-foundation stiffness about the longitudinal axis (abutment)
8	Vertical soil-foundation damping (piers)	26	Rotational soil-foundation damping about the longitudinal axis (abutment)
9	Longitudinal soil-foundation stiffness (piers)	27	Rotational soil-foundation stiffness about the vertical axis (abutment)
10	Longitudinal soil-foundation damping (piers)	28	Rotational soil-foundation damping about the vertical axis (abutment)
11	Transverse soil-foundation stiffness (piers)	29	Far-field soil-embankment stiffness in the longitudinal direction
12	Transverse soil-foundation damping (piers)	30	Far-field soil-embankment radiation damping in the longitudinal direction
13	Rotational soil-foundation stiffness about the longitudinal axis (piers)	31	Far-field soil-embankment material damping in the longitudinal direction
14	Rotational soil-foundation damping about the longitudinal axis (piers)	32	Initial stiffness of the soil-backwall stiffness in the longitudinal direction
15	Rotational soil-foundation stiffness about the transverse axis (piers)	33	Ultimate strength of the soil behind the backwall
16	Rotational soil-foundation damping about the transverse axis (piers)	34	Initial stiffness of the shear-key
17	Rotational soil-foundation stiffness about the vertical axis (piers)	35	Mass-proportional damping coefficient
18	Rotational soil-foundation damping about the vertical axis (piers)	36	Stiffness-proportional damping coefficient

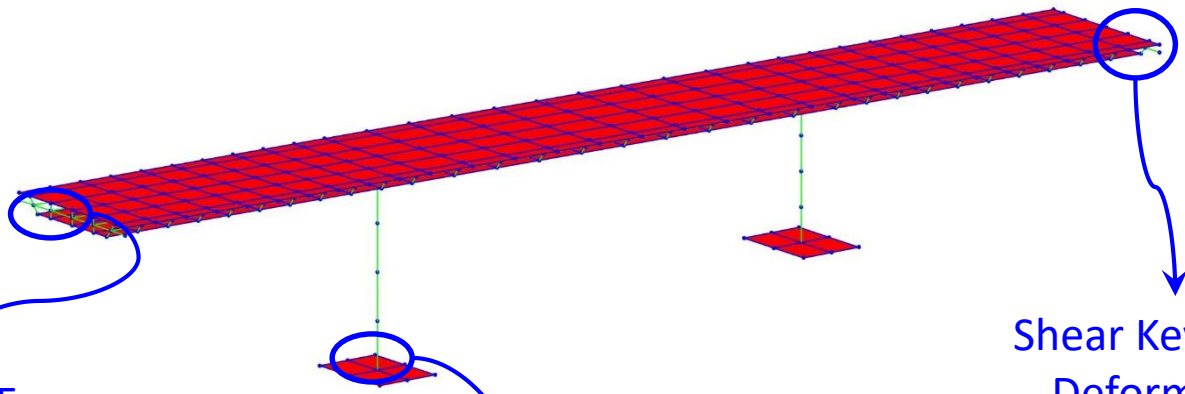




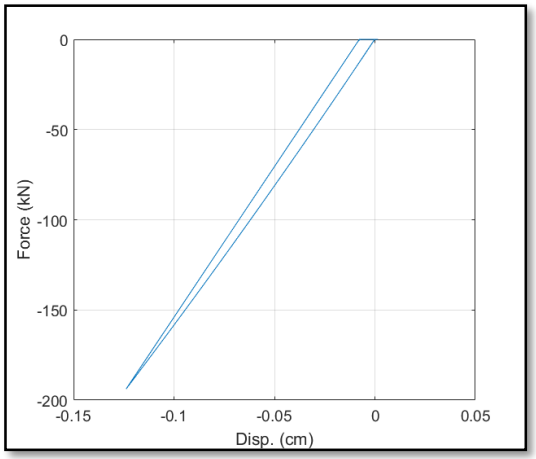
Validation Study – Santa Cruz 2018 Eq.



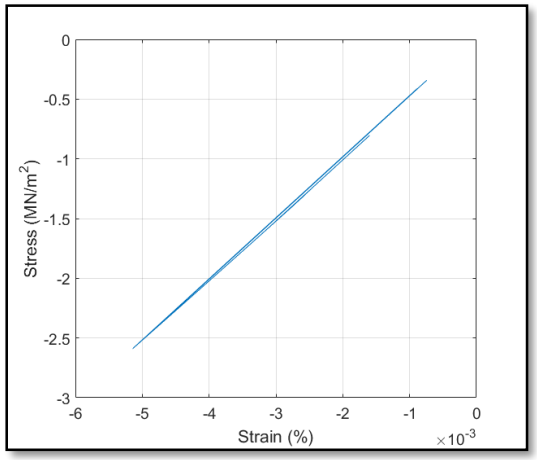
Damage Diagnosis



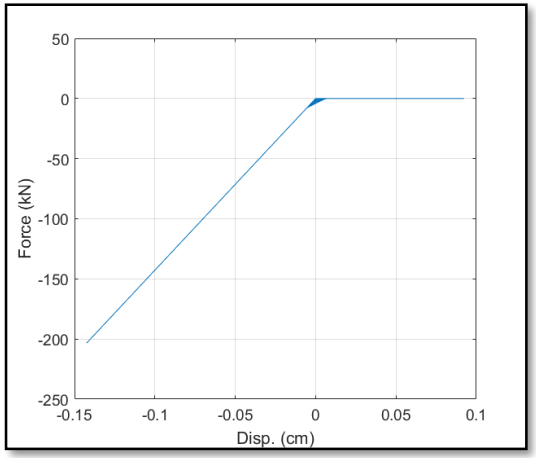
Passive Soil Force-Deformation



Concrete Fiber Material Response



Shear Key Force-Deformation



Acknowledgements

- U.S. DOT - SBIR Program Grant # 6913G618P800109
- Caltrans Contract # 65A0642
- My colleagues at SC Solutions, Inc.

Thank you
for your attention!