The Integration of Models, Data, and Virtual Computing for Operational Monitoring and Post-Disaster Emergency Response Management

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Why Bother?

- Aging Infrastructures
- Threats
- Limited Resources
- Retrofit & Upgrading

Emergency Response
Asset Management

Retrofit & Upgrading

ASCE

$2042 Billion
Investment Needed

$941 Billion
Funding Provided

Surface Transportation Funding
Visual Inspection

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

Maintenance Inspection

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

**Point Monitoring**
- Load Cell
- Fiber Optics
- Crack Sensor

**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

**Shortcomings**?
- Data not information
- Limited damage detection, and quantification capability
- Require large number of sensors
- Maintenance and installation cost
- No system-level insight
Integration of Mechanics-Based Models with Data

Forward Simulation
- Model Parameter Uncertainties
- Unknown Inputs

Model Updating / Training
- Estimate Model Parameters
- Estimate Input Forces

Digital World
- Mechanics-based damage diagnosis at refined spatial resolution

Real World
Digital Twins

Real Twin

Data
- Traffic Data
  - Traffic induced Vibration
- Earthquake Data
  (Output or input-output)

Mechanics-based Model

Bayesian Data Assimilation

Digital Twin
Bayesian Data Assimilation

\[ Y = y \]

\[ \hat{Y} = f(\Psi) \]

Prior Information

\[ p(\Psi) \]

Likelihood Function

\[ p(Y = y | \Psi) \sim N(0, R) \]

Bayesian Updating

\[ p(\Psi | y) = \frac{p(y | \Psi) \cdot p(\Psi)}{p(y)} \]
Digital Twins for Operational Monitoring and Management

1. Permanent/temporary sensors
2. Acceleration THs
3. Online Portal

Object Tracking / Type Detection

Bayesian FE Model Updating (Integrating Data with Model)

- Stochastic Filtering
- Mechanics-based FE Model
- Vehicle Locations
- Estimate jointly the model parameters and vehicular loads

Share Information with Stakeholders

Digital Twin

Regular camera system (tripod or drone mounted)
On-site laptop
Office/server computer
Box–Girder Bridge Case Study

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

Concrete deterioration & rebar corrosion in Deck

Concrete deterioration in Girders

Loss of prestress force
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

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

Accelerometers

Top Slab $f'_c$ @ 5 regions
Girder $f'_c$ @ 5 regions
Bottom Slab $f'_c$ @ 5 regions
Section prestress force @ 5 regions
Verification Study
Damage Diagnosis

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 $f'_c$

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
  - Mechanics-based FE Model
  - Predictions
  - Estimate jointly the model parameters and foundation input motions (FIMs)
- Digital Twin
- Share Information with Stakeholders

Bayesian FE Model Updating
(Integrating Data with Model)

Measurements

Stochastic Filtering

Predictions

Mechanics-based FE Model

Digital Twin

Share Information with Stakeholders
Box-Girder Bridge Case Study

CESMD Strong-Motion Data Set

Search

5 records match the following search parameters

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

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SENSOR LOCATIONS

Santa Barbara - San Roque Canyon Bridge
Cahns Bridge No. 51-104 (SB-192-1.77)
CSMIP Station No. 25749
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<th>No.</th>
<th>Description</th>
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<tr>
<td>1</td>
<td>Modulus of elasticity of the concrete (deck)</td>
<td>19</td>
<td>Longitudinal soil-foundation stiffness (abutment)</td>
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<td>2</td>
<td>Compressive strength of the concrete (columns)</td>
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<td>Longitudinal soil-foundation damping (abutment)</td>
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<td>3</td>
<td>Initial modulus of elasticity of the concrete (columns)</td>
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<td>Transverse soil-foundation stiffness (abutment)</td>
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<td>4</td>
<td>Modulus of elasticity of the bearing pad</td>
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<td>Shear stiffness of the bearing pad</td>
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<td>Vertical soil-foundation stiffness (abutment)</td>
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<td>Mass of the embankment-abutment</td>
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<td>Vertical soil-foundation damping (abutment)</td>
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<td>Rotational soil-foundation stiffness about the longitudinal axis (abutment)</td>
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<td>Far-field soil-embankment material damping in the longitudinal direction</td>
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<td>Initial stiffness of the soil-backwall stiffness in the longitudinal direction</td>
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<td>Rotational soil-foundation stiffness about the transverse axis (piers)</td>
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<td>Ultimate strength of the soil behind the backwall</td>
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<td>Initial stiffness of the shear-key</td>
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<td>Mass-proportional damping coefficient</td>
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<td>Rotational soil-foundation damping about the vertical axis (piers)</td>
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<td>Stiffness-proportional damping coefficient</td>
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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
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Thank you for your attention!