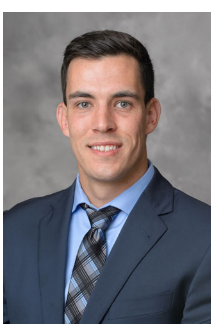
Improving the Seismic Performance of INDOT's Bridge Network

Corey Beck

INDOT Bridge Design

1

Introduction & Acknowledgements



Bridge Design Engineer

Email: CBeck1@indot.IN.gov

B.Sc. Purdue University (2017)

M. Sc. Purdue University (2020)

JTRP 4222 Members & Sponsors

- Dr. Shirley Dyke
- Dr. Julio Ramirez
- Dr. George Mavroeidis
- Leslie Bonthron
- Farida Mahmoud
- Alana Lund
- Xin Zhao
- Rebecca Orellana Montano
- Yenan Cao

2

2

Presentation Outline

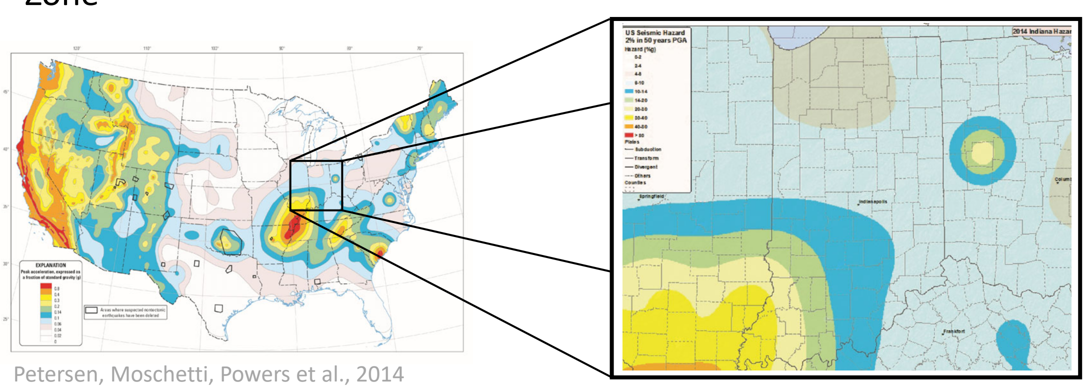
- Project Motivation
- *Contributions from Research:*
  - Development of INSAT
- *Ongoing Work:*
  - Data Collection
  - Tackling already-programmed bridges
- *Future Goal:*
  - Programming seismic retrofits

3

3

Project Motivation

- Increased seismic risk due to identification of Wabash Valley Seismic Zone



Petersen, Moschetti, Powers et al., 2014

4

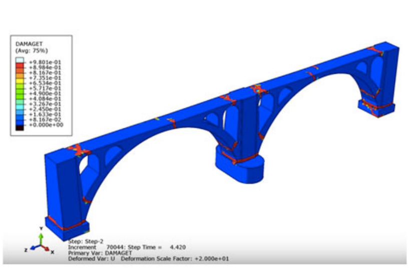
4

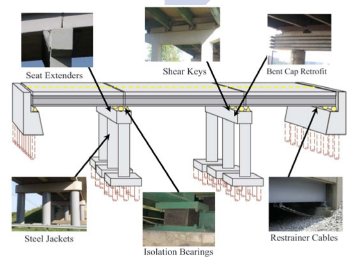
Contributions: JTRP 4222

Detailed Seismic Assessment of Representative Sample Set

Rapid Vulnerability Assessment of Bridges (INSAT)

Retrofit Strategies and Modeling



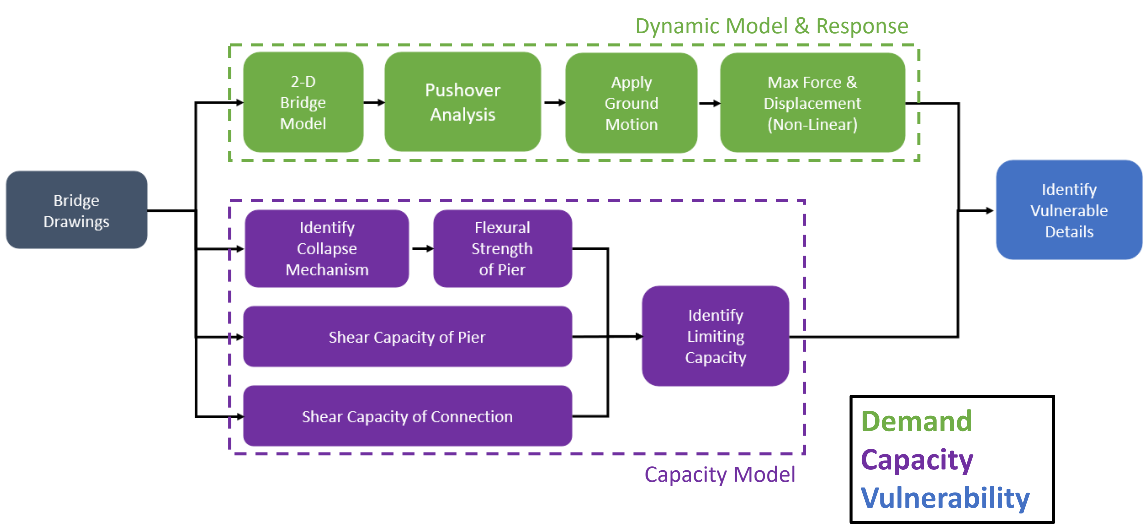


Bonthron, Beck, Lund et al., 2014

Contributions: 5

5

Detailed Seismic Assessment

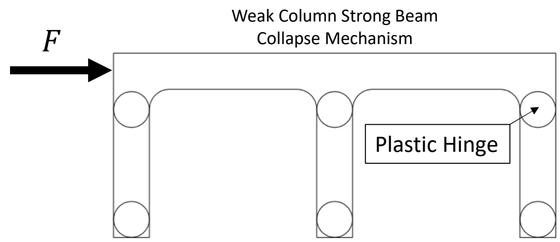


Contributions: 6

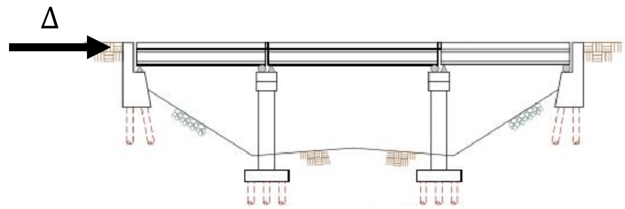
6

Pushover Analysis

- Incremental application of force (F) to: (i) Identify substructure's mechanism of hinge formation (collapse mechanism) & (ii) Ultimate displacement/rotation capacity



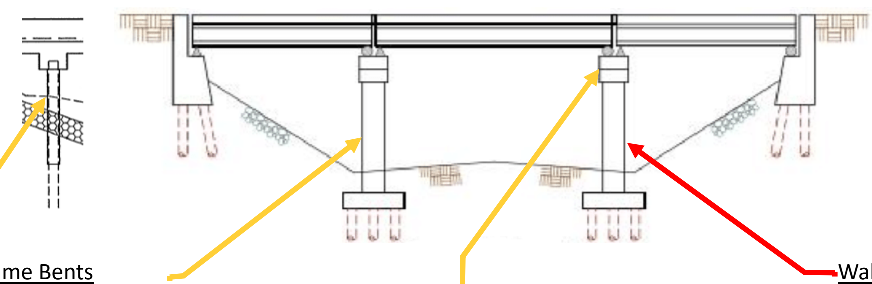
- Incremental application of displacement (Δ) to account for force redistribution due to non-simultaneous nonlinear response of piers



Contributions: 7

7

Identified Bridge Vulnerabilities



Pile-Type Frame Bents & Walls & Hammerheads & RC Frame Bents Formation of plastic hinges

RC Frame Bents Mechanism Formation (Strong Column Weak Beam)

Walls & Hammerheads Brittle Failure (low flexural reinforcement)

Not Vulnerable:
- Single Span Bridges Not on Rocker Bearings
- Single Span Bridges On Rocker Bearings + 60' Length or Less
- Bridges with Integral Abutments in Longitudinal Direction

Moderate Vulnerability
High Vulnerability

Contributions: 8

8

Identified Limit State Thresholds

- Identified trends between vulnerability levels (or limit states) and drift- and displacement-based values

	Transverse Direction		Longitudinal Direction		
	Drift-Based		**Displacement-Based**		
Structural Response	Formation of Plastic Hinge	Exceedance of Hinge Rotational Capacity	Formation of Plastic Hinge	Exceedance of Hinge Rotational Capacity	Brittle Failure
Rapid Assessment	Drift > 0.5%	Drift > 1.5%	Displacement > 1 in.	Displacement > 6 in.	Displacement > 0.1 in.
Additional Identifiers	Substructure Built After 1990	Substructure Built After 1990	Substructure Built After 1990	Substructure Built After 1990	Substructure Built Before 1990*
Corresponding Vulnerability Classification	Moderate Vulnerability	High Vulnerability	Moderate Vulnerability	High Vulnerability	High Vulnerability

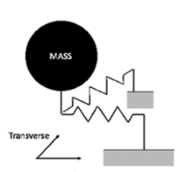
Contributions: 9

9

Rapid Vulnerability Assessment (INSAT)

- Simple SDOF Dynamic Model developed using bridge-specific information from BIAS + additional user-inputted details

Activated Mass

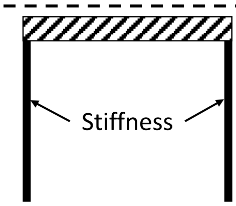


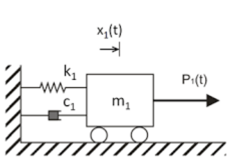
BIAS Items Utilized
- Structure length
- Deck out-to-out width

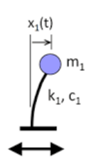
Trends Used
- Average mass per area

Substructure Stiffness

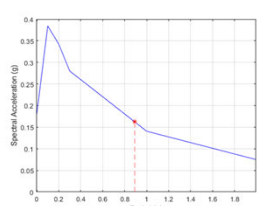
User-Inputted Info
- Substructure Dimensions
- Height Ratio Flag







+



→

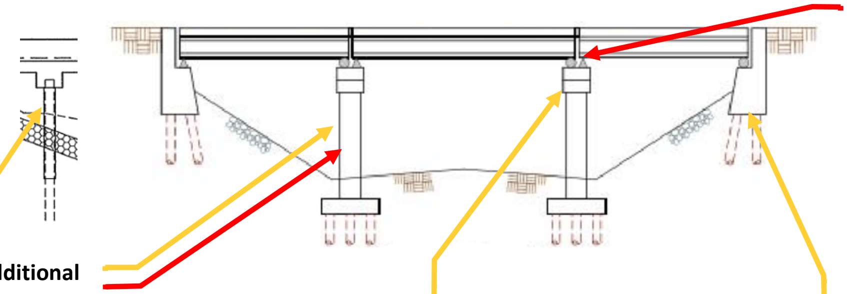
Compare spectral displacement (S_d) to Limit State Thresholds to Identify Vulnerable Bridges

Contributions: 10

10

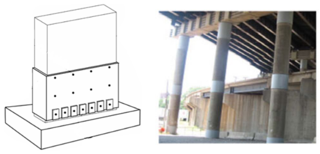
Identified Retrofit Strategies

Moderate Vulnerability
High Vulnerability



Seismic Isolation
Elastomeric Bearings (with or w/o lead core)

Provide Additional Confinement
-Steel Plate Encasement with Steel Anchors
-CFRP or Steel Jackets



Increase Capacity of Bent Cap
- External Post-tensioning
- Shear Reinforcement

Timothy, DesRoches, & Padgett, 2011

Additional Restraint
-Integral Abutments
-Restrainers

Contributions: 11

11

Ongoing Work: Next 3-5 Years

1. INDOT – Collecting Data Items necessary for conducting rapid seismic assessment
2. Identifying structures already programmed for rehabilitation which are worthy of seismic retrofit
   - **Projects which have already been programmed should consider seismic performance via INSAT when determining the scope**
   - Additional documentation published with PowerPoint presentation which outlines INSAT resources, best practices related to checking INSAT assumptions, identify possible retrofits, and details steps for preliminary retrofit assessment using information from INSAT

Ongoing Work: 12

12

Collecting Data Items

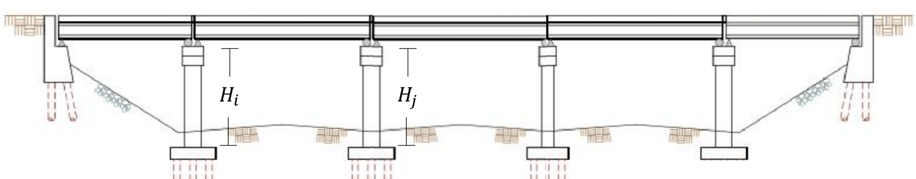
- Data recorded during regular inspection cycle

Data Item	Description	Impact
Substructure Type	Frame Bent; Hammerhead Wall; Wall; Other	Stiffness Equation for Dynamic Model
Abutment Type	Integral; Semi Integral; Non-Integral	Assumptions regarding longitudinal response
Number of Elements	Number of columns in single pier (1 for hammerhead and walls)	Stiffness of pier/bridge
Element Dimensions (Height; Width; Length)	Clear or unsupported height; dimension in transverse & longitudinal direction	Stiffness of pier/bridge
Height Ratio Flag	Identify piers in bridge with significantly differing heights	Identify bridges not suitable for simplified assessment
Deck Thickness*	Thickness of reinforced concrete deck	Mass

*Collected for all bridges – currently only used in mass calculations for reinforced-concrete slab deck bridges

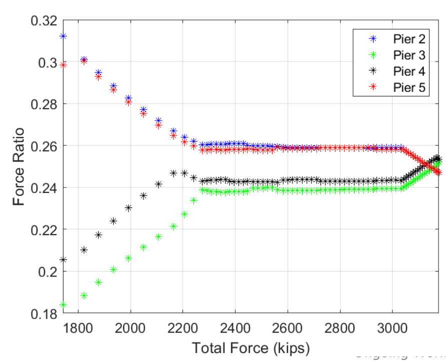
Height Ratio Flag

$H_i > H_j$



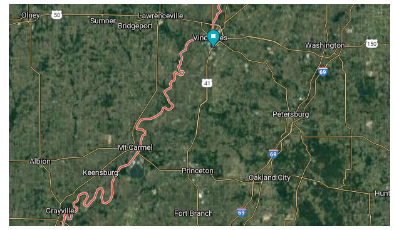
$$\frac{H_{Tall}}{H_{Short}} = \frac{H_i}{H_j} > 1.1 \quad \sim \quad \frac{K_{Tall}}{K_{Short}} < 0.7$$

- INSAT is incapable of accounting for:
  - Large variations in stiffness - cannot be captured using information from a single pier
  - Non-linear redistribution of forces



Sample Bridge Assessment Using INSAT

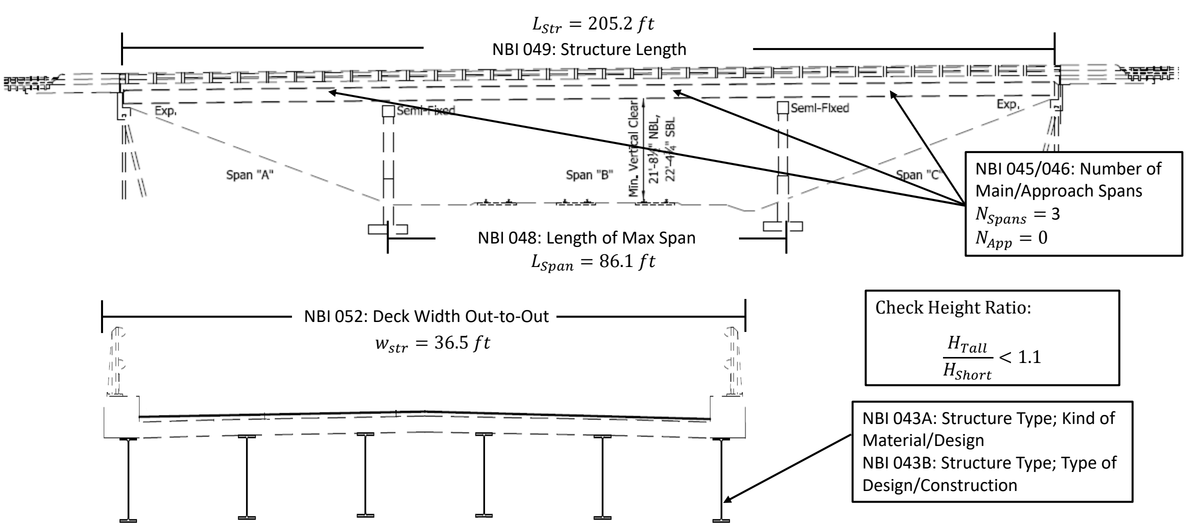
- NBI 14630
- Str. No: 041-42-02351 BNBL
- Built: 1967
- Rehabs:
  - 1986 – Bridge Deck Overlay
  - 2016 – Bridge Deck Overlay 2
- 3 Span Continuous Steel Beam Superstructure
- Supported by Multi-Column Piers



Ongoing Work: 15

15

NBI 14630 – Mass Data & Inputs



Ongoing Work: 16

16

NBI 14630 – Calculating Mass

$m_{Long} = m_{avg} * L_{Str} * w_{Str}$

$m_{Trans} = m_{Long} * \%_{act}$

Number of Spans	Percent of Mass Activated
2	50%
3	71.5%
4	80%
5	82.5%
6	85%

Variable	NBI	Definition
m_{avg}	-	Average weight – steel superstructure*
m_{Long}	-	Mass in Longitudinal Direction (Dir).
m_{Trans}	-	Mass in Transverse (Trans) Dir.
$\%_{act}$	-	Percent of Mass Activated – Trans Dir.*
N_{Spans}	045	No. Main Spans
N_{App}	046	No. Approach Spans
L_{Str}	049	Structure Length
w_{Str}	052	Deck Width Out-to-Out

*Determined through trend identification of detailed sample set

Additional INSAT checks:

$N_{Spans} \leq 6$; $L_{Str} \leq 1000\ ft.$; $N_{App} = 0$

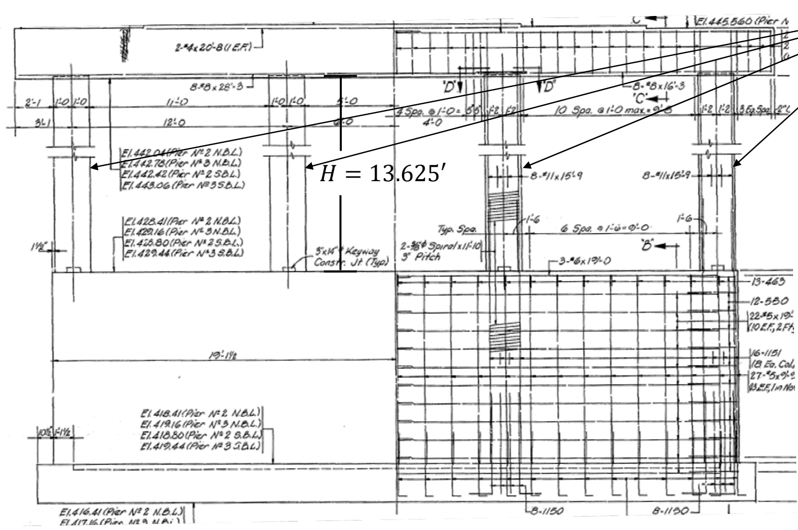
Rationale: Bridges with expansion joints require detailed assessment

Ongoing Work: 17

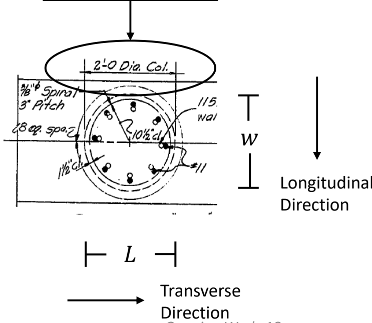
17

NBI 14630 – Stiffness Inputs

Number of Elements:
1 – Wall & Hammerheads
Columns – Multi-Column Bent
$N_E = 4$



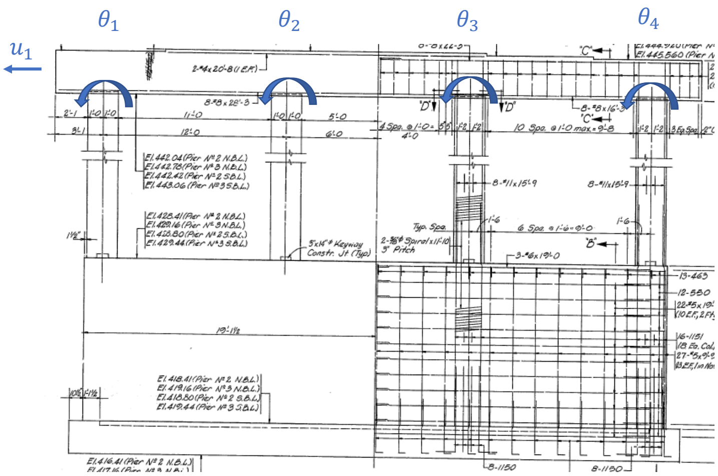
$w = L = 2' - 0"$



Ongoing Work: 18

18

NBI 14630 – Calculating Trans. Stiffness (K_T)



Modeling Stiffness – Stiffness Method

$$K = \begin{array}{c|cccc} & u_1 & \theta_1 & \theta_2 & \dots \\ u_1 & N_E * 12E_cI_T/H^3 & 6E_cI_T/H^2 & 6E_cI_T/H^2 & \dots \\ \theta_1 & 6E_cI_T/H^2 & \frac{4E_cI_T}{H} + 4E_cI_B/L_B & 2E_cI_B/L_B & \dots \\ \theta_2 & 6E_cI_T/H^2 & 2E_cI_B/L_B & \frac{4E_cI_T}{H} + 4E_cI_B/L_B & \dots \\ \dots & \dots & \dots & \dots & \dots \end{array}$$

$$F_{FB} = \frac{K_{Cond}}{K_{11}} = \frac{K_{Cond}}{N_C * 12E_cI_T/H^3}$$

Modeling Stiffness – INSAT

$$K_T = N_{Pier} * F_{FB} * N_E * \frac{12E_cI_T}{H_3}$$

N_{Pier}:	No. of Piers	I_T:	Moment of Inertia – Transverse Dir.
N_E:	No. of Elements	H:	Clear Height
E_C:	Concrete's Modulus of Elasticity	F_{FB}:	Frame Bent Factor
K_{11}:	1,1 Component of K Matrix	K_{Cond}:	Statically Condensed Stiffness

Ongoing Work : 19

19

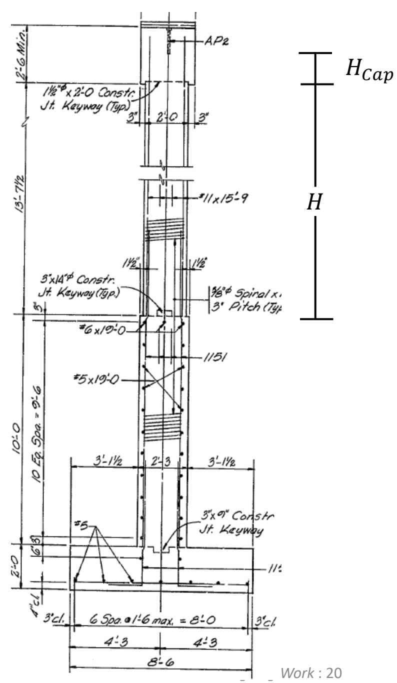
NBI 14630 – Long. Stiffness (K_L)

$$K_L = N_E * F_{Con} * \frac{E_cI_L}{H_L^3}$$

$$H_L = H + H_{Cap} = H + 18\ in.$$

F_{Con}	Superstructure Type
3	Steel
6	Prestressed Concrete
12	Reinforced Concrete

F_{Con}	Fixity of Connection	I_L:	Moment of Inertia – Longitudinal Direction
N_C:	No. of Columns	H_L:	Height of Element for Longitudinal Response
E_C:	Concrete's Modulus of Elasticity	H_{Cap}:	Estimated height of half the cap



Work : 20

20

NBI 14630 –Response & Demand (Transverse)

$$\omega_n = \sqrt{\frac{K_{Tr}}{m_{Tr}}} = \sqrt{\frac{1073.4\,\frac{kip}{in}}{1.94\,\frac{kip}{g}}} = 23.5\,\frac{rad}{s}$$

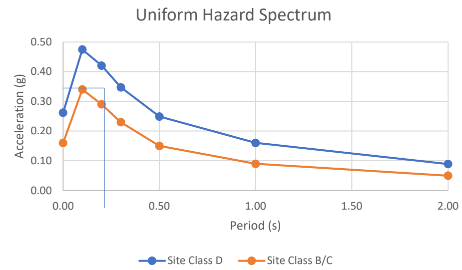
$$T = \frac{2\pi}{\omega_n} = \frac{2\pi}{23.5\,\frac{rad}{s}} = 0.27s$$

Site Class D (Hill, 2008)

$$SA_{Long} = 0.41\ g$$

$$\Delta_{Lin} = SD = \frac{\text{SA}}{\omega_n^2} = 0.41in$$

$$\%_{NL} = \frac{\sqrt{2}*\Delta_{Lin}}{\frac{H_{IP}}{2}} = \frac{\sqrt{2}*0.41in}{\frac{13.625'}{2}} = 0.5\%$$ (Sozen, 2003)



ω_n:	Circular Natural Frequency	SA:	Spectral acceleration
K:	Stiffness	SD:	Spectral displacement
m:	Activated Mass	Δ_{Lin}:	Linear displacement
T:	Structural period	$\%_{NL}$:	Non-linear disp.
H_{IP}:	Height of Element from Fixed End to Inflection Point		

*Displacement only amplified for substructures expected to be ductile

Ongoing Work : 21

21

NBI 14630 – Vulnerability

$\%_{NL_{Tr}} = 0.5\% \geq 0.5\%$

	Transverse Direction		Longitudinal Direction		
	Drift-Based		**Displacement-Based**		
Structural Response	Formation of Plastic Hinge	Exceedance of Hinge Rotational Capacity	Formation of Plastic Hinge	Exceedance of Hinge Rotational Capacity	Brittle Failure
Rapid Assessment	Drift > 0.5%	Drift > 1.5%	Displacement > 1 in.	Displacement > 6 in.	Displacement > 0.1 in.
Additional Identifiers	Substructure Built After 1990	Substructure Built After 1990	Substructure Built After 1990	Substructure Built After 1990	Substructure Built Before 1990*
Corresponding Vulnerability Classification	Moderate Vulnerability	High Vulnerability	Moderate Vulnerability	High Vulnerability	High Vulnerability

* Hammerhead walls and walls built before 1990 are expected to have insufficient flexural reinforcement

Ongoing Work : 22

22

NBI 14630 –Response & Demand (Longitudinal)

$$\omega_n = \sqrt{\frac{K_{Long}}{m_{Long}}} = \sqrt{\frac{111.46\frac{kip}{in}}{2.72\frac{kip}{g}}} = 6.40\frac{rad}{s}$$

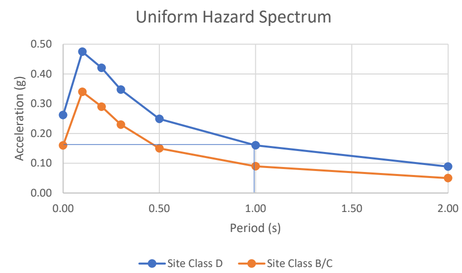
$$T = \frac{2\pi}{\omega_n} = \frac{2\pi}{6.40\frac{rad}{s}} = 0.98s$$

Site Class D (Hill, 2008)

$SA_{Long} = 0.164\ g$

$\Delta_{Lin} = SD = \frac{SA}{\omega_n^2} = 1.55$ in

$\Delta_{NL} = \sqrt{2} * \Delta_{Lin} = 2.18$in (Sozen, 2003)



ω_n:	Circular Natural Frequency	SA:	Spectral acceleration
K:	Stiffness	SD:	Spectral displacement
m:	Activated Mass	Δ_{Lin}:	Linear displacement
T:	Structural period	Δ_{NL}:	Non-linear disp.

*Displacement only amplified for substructures expected to be ductile

Ongoing Work : 23

23

NBI 14630 – Vulnerability

$\Delta_{NL_{Long}} = 2.18\ in \geq 1in$

Transverse Direction | Longitudinal Direction

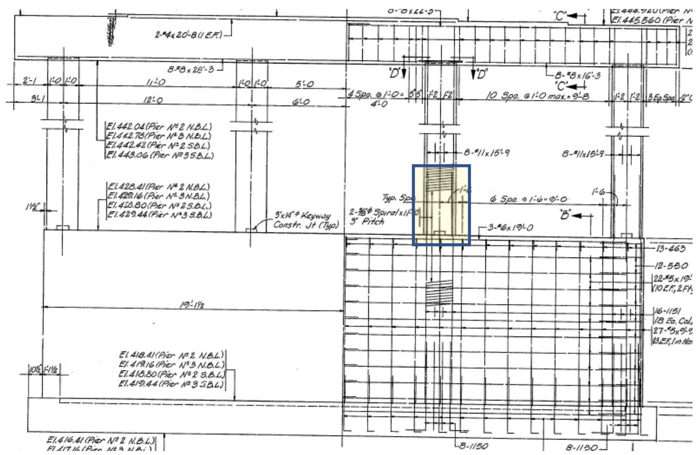
	Drift-Based		Displacement-Based		
Structural Response	Formation of Plastic Hinge	Exceedance of Hinge Rotational Capacity	Formation of Plastic Hinge	Exceedance of Hinge Rotational Capacity	Brittle Failure
Rapid Assessment	Drift > 0.5%	Drift > 1.5%	Displacement > 1 in.	Displacement > 6 in.	Displacement > 0.1 in.
Additional Identifiers	Substructure Built After 1990	Substructure Built After 1990	Substructure Built After 1990	Substructure Built After 1990	Substructure Built Before 1990*
Corresponding Vulnerability Classification	Moderate Vulnerability	High Vulnerability	Moderate Vulnerability	High Vulnerability	High Vulnerability

* Hammerhead walls and walls built before 1990 are expected to have insufficient flexural reinforcement

Ongoing Work : 24

24

NBI 14630 – Checking INSAT Assumptions



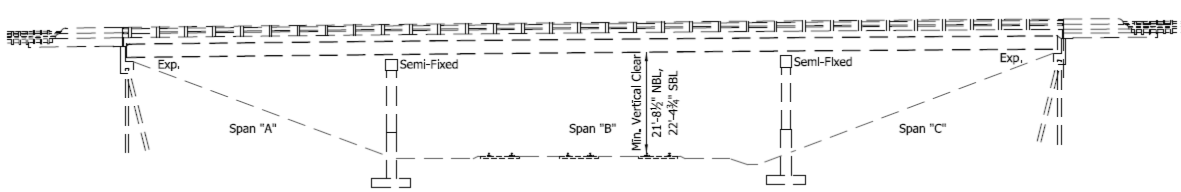
Assumption 1:

- Substructure capable of developing plastic hinge
  - Splice within plastic hinge region – poor seismic detail leading to reduced capacity & potential for longitudinal bar pullout

Ongoing Work : 25

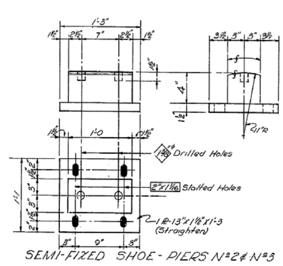
25

NBI 14630 – Checking INSAT Assumptions



Assumption 2:

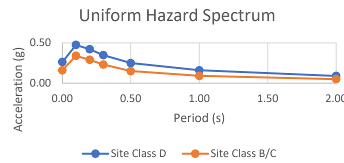
- Single fixed pier for steel superstructure bridges
  - Expansion bearings incapable of transferring significant force due to design
  - **NBI 14630 has two fixed shoes**



Ongoing Work : 26

26

NBI 14630 – Updated Model



Results using INSAT Assumptions

$$\omega_n = \sqrt{\frac{K}{m}} = \sqrt{\frac{111.46\frac{kip}{in}}{2.72\frac{kip}{g}}} = 6.40\frac{rad}{s}$$

$$T = \frac{2\pi}{\omega_m} = \frac{2\pi}{6.40\frac{rad}{in}} = 0.98s$$

$$SA = 0.164\ g \quad \& \quad \Delta_{Lin} = \frac{\text{SA}}{\omega_n^2} = 1.55\text{ in}$$

$$\Delta_{NL} = \sqrt{2} * \Delta_{Lin} = 2.18\text{in}$$

Results using Updated Assumptions

$$\omega_n = \sqrt{\frac{2K}{m}} = \sqrt{\frac{222.92\frac{kip}{in}}{2.72\frac{kip}{g}}} = 9.05\frac{rad}{s}$$

$$T = \frac{2\pi}{\omega_m} = \frac{2\pi}{6.40\frac{rad}{in}} = 0.69s$$

$$SA = 0.23\ g \quad \& \quad \Delta_{Lin} = \frac{\text{SA}}{\omega_n^2} = 1.06\text{ in}$$

$$\Delta_{NL} = \sqrt{2} * \Delta_{Lin} = 1.49\text{ in}$$

$\Delta_{NL} > 1\ in$ → Moderately Vulnerable

Ongoing Work : 27

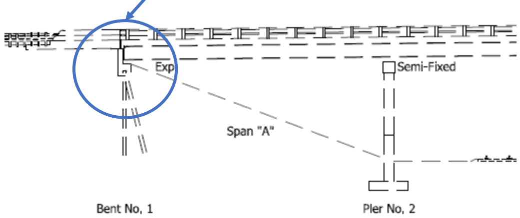
27

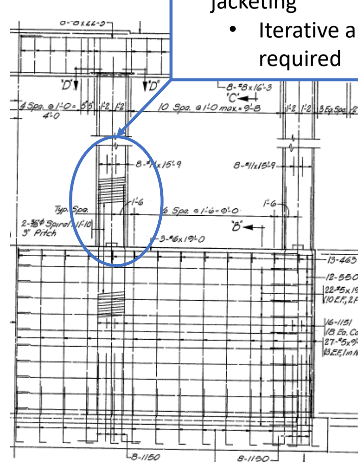
NBI 14630 – Possible Retrofits

- Ensure ductile response & full moment capacity via confinement using FRP
- Increase substructure capacity using steel/RC jacketing
  - Iterative analysis required

Converting abutment to semi-integral:
- Reduce inertial effects of superstructure mass thus reducing demand

Reduce superstructure displacement via restrainers



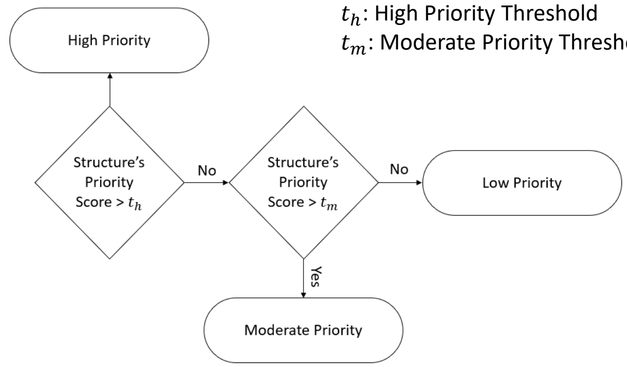


Ongoing Work: 28

28

Future Goal:

- INDOT programming structures for seismic retrofits during the scoping process



t_h: High Priority Threshold
t_m: Moderate Priority Threshold

Future Goal: 29

29

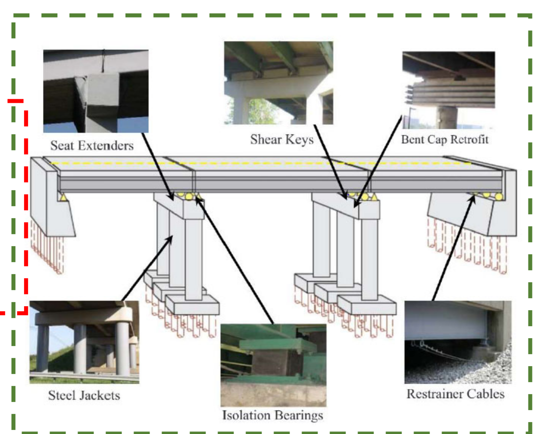
Identifying Critical Bridges

Provided by JTRP 4222

Vulnerability Assessment

Means for identifying ***critical bridges*** for retrofit prioritization

Retrofit Strategies



Future Goal: 30

30

FHWA Guidelines

Seismic Rating (V)

- Assess vulnerability of bridge using site-specific hazard curve and bridge details

Priority Index (S)

- Determine importance of bridge by considering socioeconomic factors

Critical Bridge

- Seismic performance greatly impacts the functionality & longevity of INDOT's transportation network

$$\text{Priority} = 0.4\text{V} + 0.6\text{S}$$

Future Goal: 31

31

Socioeconomic Factors

- The following socioeconomic factors should be considered:

Network configuration & redundancy

Bridge age & additional required rehabilitations

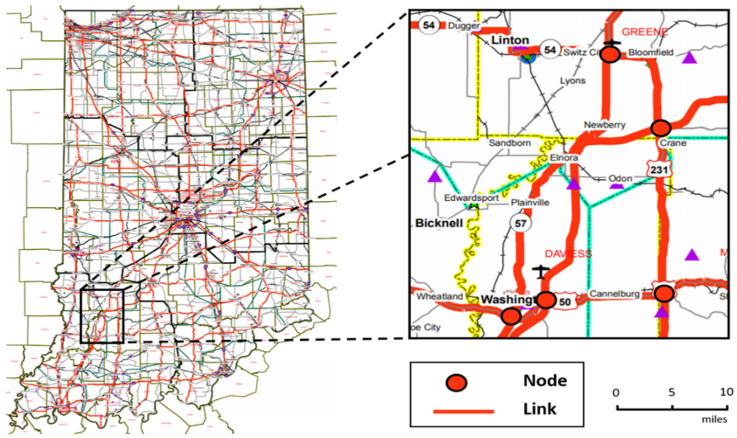
Economic Impact

Future Goal: 32

32

Modeling Transportation Network

- Link: Section of undisturbed roadway
- Node: Connections between links (major interchanges or intersections)



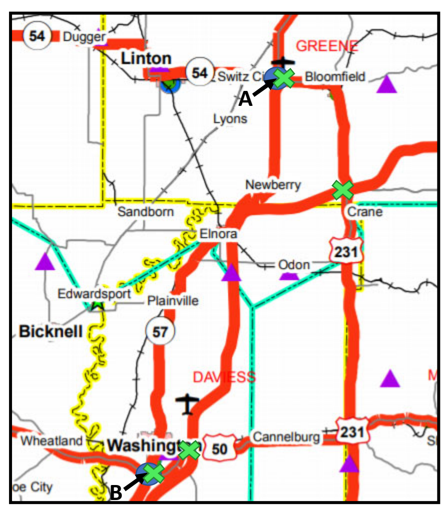
Beck, 2020

Future Goal: 33

33

Network Redundancy

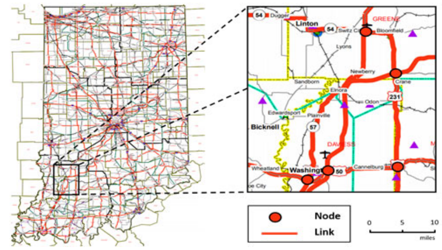
- Structural redundancy -> network redundancy
- More redundant routes between A and B -> less important is the primary route.
- Assess routes using:
  - Highway Capacity Manual
  - Travel Time
  - Seismic Sufficiency



Future Goal: 34

34

Network Configuration



- How does improving the performance of a single bridge improve the link?
- Weakest-link model
  - Link is only functional if all bridges within the link are passible

$$P_L(F|E_j) = 1 - \prod_{i=1}^{N} P_B(F^C|E_j)$$

$$I_{Retrofit} = P_L(F|E_j) - P_{L_R}(F|E_j)$$

Identify scenarios which maximize impact

F: Failure
F^C: Not failure
L: Link
B: Bridge
E_j: j^th earthquake to occur in design return period
L: Link with all bridges as-built
L_R: Link with seismically-retrofitted bridge

Future Goal: 35

35

Economic Impact

- What is the cost-benefit ratio (R_{CB}) of the seismic retrofit?
  - Assume retrofit programmed alongside additional work

$$R_{CB} = \frac{Cost_{Retrofit}}{Cost_{Damage} + Cost_{Social}}$$

Cost of retrofit applied pre-event

Cost to repair bridge post-event – related to level of vulnerability

Socioeconomic cost – accrued due to link closure for 'X' days to repair post-event

Future Goal: 36

36

References

- Beck, C. (2020). Robust Seismic Vulnerability Assessment Procedure for Improvement of Bridge Network Performance. Master's Thesis, Purdue University, IN.
- Bonthron, L., Beck, C., Lund, A., Zhang, X., Cao, Y., Dyke, S., Ramirez, J., Mavroeidis, G., Baah, P., & Hunter, J. (2020). *A Rapid Seismic Vulnerability Assessment Tool for Bridges in Indiana.* DesignSafe-CI.
- Bonthron, L., Beck, C., Lund, A., Zhang, X., Orellana Montano, R., Dyke, S., Ramirez, J., Cao, Y., & Mavroeidis, G. P. (In Press) (2020). Empowering the Indiana Bridge Inventory Database Toward Rapid Seismic Vulnerability Assessment. Rep. JTRP No. 4222, Purdue University, IN.
- Hill, J. (2008). Map of Indiana showing predicted responses of geologic materials to seismically induced ground shaking. *Indiana Geological Survey Report of Progress 35, Plate 1.*
- Mavroeidis, G., Cao, Y., Beck, C., Bonthron, L., Lund, A., Zhang, X., Dyke, S., Ramirez, J., Baah, P., Hunter, J. (2020). *Synthetic Ground-Motion Records for 100 Bridge Sites in Indiana.* DesignSafe-CI.
- Petersen, M. D., Moschetti, M. P., Powers, P. M., Mueller, C. S., Haller, K. M., Frankel, … Olsen, A. H. (2014). Documentation for the 2014 update of the United States national seismic hazard maps (USGS Open-File Report 2014-1091). Reston, VA: U.S. Geological Survey.
- Sozen, M. A. (2003). The Velocity of Displacement. *Seismic Assessment and Rehabilitation of Existing Buildings - NATO Science Series (NAIV)*, 29, 11-28.
- Timothy, W., Reginald, D., & Padgett, J. E. (2011). Bridge Seismic Retrofitting Practices in the Central and Southeastern United States. *Journal of Bridge Engineering*, 16(1), 82-92.