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Real-Time Structural Damage Evaluation of Bridges from Seismic Monitoring Records Using Machine Learning and Sparse Representation

機械学習とスパース推定法を利用した地震応答モニタリング記録からの橋梁のリアルタイム損傷検知

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Research Background

- Performance of isolated bridge depends on performance of isolators.
- In the past earthquakes, there were cases where isolators failed to function properly because side stopper were locked. As a result, deck was not isolated completely, and unexpected load redistribution occurred.
- Monitoring system can be used to evaluate isolation bearing condition and prevent the failure.

免震支承，ゴム支承では支承が地震時に期待通りの挙動（性能）を発揮するかがキー.
事実，支承が地震で破損する例が非常に多い.
下の写真にあるように，サイドブロックが支承の橋軸方向の動きを拘束するケースが間々ある.
地震応答モニタリングが支承が地震時に想定通り動いているかを判断できるか？

side stopper unlocked with isolator bearing

side stopper locked with isolator bearing

Research Objectives

- Develop a structural monitoring system to detect isolation bearing malfunction directly from seismic records using machine learning and sparse representation.
- Implement the detection system to full-scale monitoring of multi-span continuous girder isolated bridge using wireless sensor network.

- 地震応答記録から支承の挙動を判断できるシステムを実記録から，応答シミュレーションから機械学習を使って構築する.

Methodologies 応答記録のウェーブレット変換を基本に

- **Continuous Wavelet Transform (CWT)** : to detect shifts in the vibration frequency of accelerations by extracting the instantaneous frequency (IF) from the continuous wavelet time-frequency map (Grossmann and Morlet 1984).

$$W(a,b) \cong \frac{1}{2a}\int_{-\infty}^{\infty} \Lambda_x(t)\Lambda_\psi\left(\frac{t-b}{a}\right) e^{i\left[\phi_x(t)-\phi_\psi\left(\frac{t-b}{a}\right)\right]}dt$$

- **Discrete wavelet transform (DWT) (4th Order Daubechies wavelet)** : to detect irregularities in the high frequency of acceleration. By sparse representation analysis the irregularities are associated with the change in the detail component (Di) caused by stiffness characteristics of isolation bearing.

$$x(t) = A_i + \sum_j^i D_j$$

- ***K*-means Clustering Algorithm (Machine Learning)** (Arthur & Vassilvitskii 2007)**:** to perform partition of data space (CWT & DWT results) into clusters associated with normal and malfunction bearing via data training and pattern recognition. Euclidean metric is computed to determine the distance between the clusters:

$$Dist(U,V) = \|U-V\| = \sqrt{\sum_{i=1}^{n}(u_i - v_i)^2}$$

Flowchart of Analysis　研究の流れ

Seismic records from Wireless Sensor Network → Data Preprocessing (Selection, cleansing, & removal of traffic effect)

Continuous Wavelet Transform Analysis

- Determination of Morlet wavelet parameters
- Response Evaluation based on Wavelet Time-Frequency Map
- Machine Learning-based K-Cluster Classification based on Instantaneous Frequency (IF) criteria

Discrete Wavelet Transform Analysis

- Sparse Representation Analysis & Discrete wavelet Decomposition
- Machine Learning-based K-Cluster Classification of Details wavelet Components (Di)

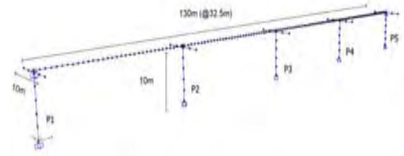
Evaluation of Isolation Bearing Condition

Finite Element Simulation

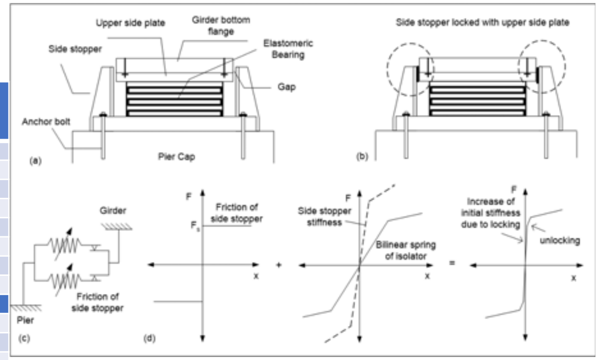
FEMによる数値解析モデルの構築　5径間連続，ゴム支承

- Condition of locked (malfunction) bearing is simulated numerically by Finite Element model using nonlinear structural dynamics.
- Locked bearing is model by changing the hysteresis model of isolator with added friction.

- 3D-Continuous girder isolated bridge with 5 piers.
- Model made in SAP 2000.
- Input : Various-scale 1995 Kobe Earthquake Takatori.



Structural Element	Cross Section Area(m^2)	Cross Section Moment of Inertia $[I_{xx}, I_{yy}, I_q]$ (m^4)
Girder	5.80	[14.48, 2.26, 5.9]
Pier	3.00	[0.57,1.00, 1.215]
Bent	1.44	[0.18,0.18,0.292]
Bearing Properties	Mid Pier	End Pier
Initial stiffness (kN/m)	3000	5000
Post Yield Stiffness ratio	0.2	0.2
Yield Strength (kN)	312.5	312.5
Ultimate Disp. (m)	0.15	
Stiffness of Side Stopper		
Initial stiffness (ton/m)	30000	
Post Yield Stiffness ratio	0.2	
Yield Force (ton)	15000	

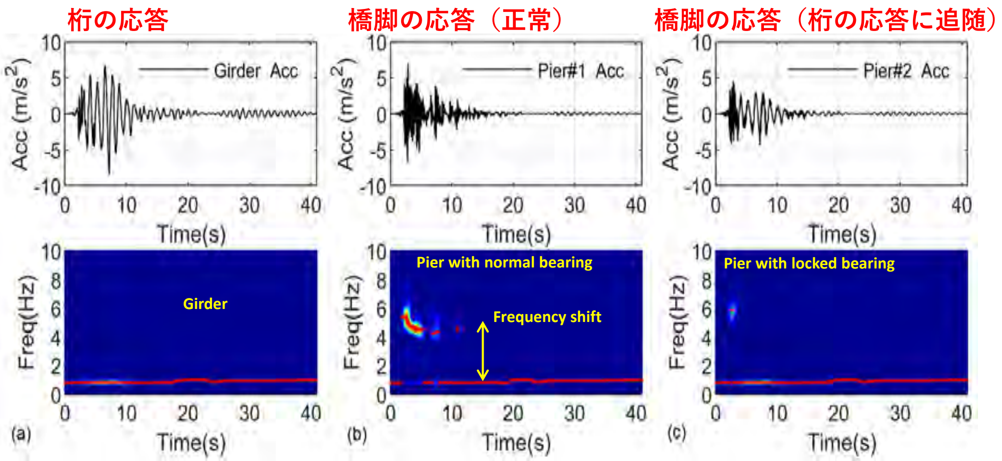


Simulation of Hysteretic Isolation Bearing condition in the case of Locked Bearing

Results of Finite Element Simulation

Results of simulation show that bearing malfunction can be detected from

1. Pattern of Instantaneous Frequency Shift from Continuous Wavelet Transform.

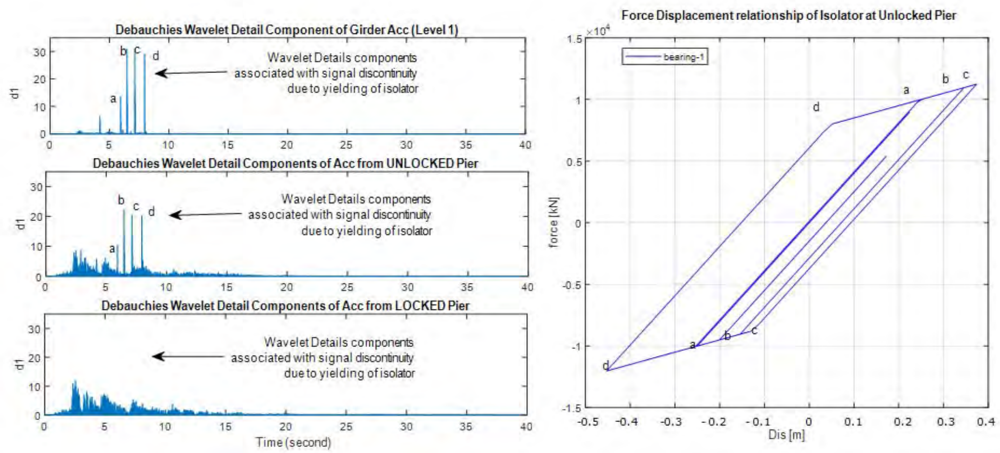


正常：免震効果が発揮　　一時，支承がロック　　支承が完全にロック状態

Results of Finite Element Simulation

Results of simulation show that bearing malfunction can be detected from

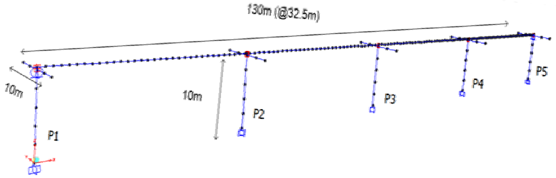
1. Pattern of shift in Instantaneous Frequency from CWT.
2. Pattern of Large spikes on the High-frequency detail function from DWT.



ウェーブレット変換からの支承の挙動の把握

Finite Element Simulations for Locked Bearings

ロックされた支承の挙動把握　FEM応答シミュレーションより



Damage scenarios (32 cases):　32ケース

1. All bearings function normally. (No)　すべて正常
2. One pier with locked bearings (P1,P2,..P5) = 5 cases.　一つの橋脚がロック
3. Two piers with locked bearings (P12, P13,..P45) = 10 cases. 2つの橋脚がロック
4. Three piers with locked bearings(P123, P124,… P345) =10 cases 3つの橋脚がロック
5. Four piers with locked bearings (P1234,…,P1345) =5 cases 4つの橋脚がロック
6. All bearings at five piers locked (All)すべての橋脚がロック

For each case:

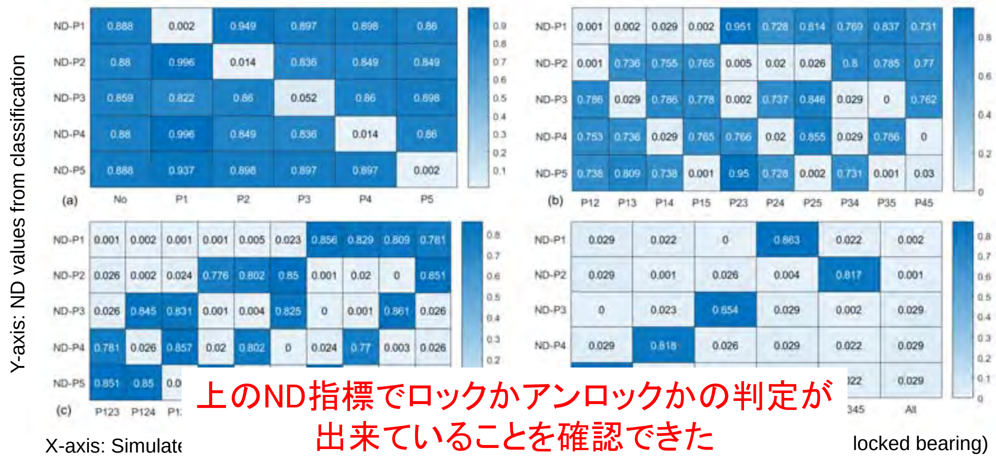
1. Nonlinear seismic response calculated.
2. CWT & DWT Analysis conducted.
3. K-means Clustering analysis is performed

K-means Clustering of FE Simulation - CWT Results

- The distance between two clusters of instantaneous frequencies (U_{c1}, U_{c2}) is normalized with the absolute difference between the pier freq (ω_p) and girder frequency (ω_g) in each case, called the normalized distance (ND):

$$ND(U_{c1}, U_{c2}) = \left| \frac{(\overline{U_{c1}} - \overline{U_{c2}})}{\omega_p - \omega_g} \right| \qquad \begin{array}{l} ND \rightarrow 1 \ \text{(normal bearing)} \\ ND \rightarrow 0 \ \text{(locked bearing)} \end{array}$$

Result of Bearing Classification based on CWT & *K*–means Clustering



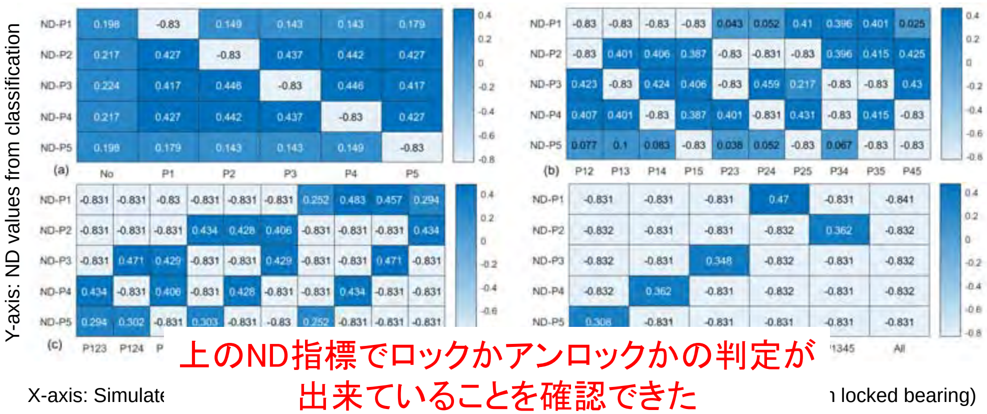
上のND指標でロックかアンロックかの判定が
出来ていることを確認できた

K-means Clustering of FE Simulation - DWT Results

- The distance between the cluster of normalized D_1 to the threshold value is computed for the interval time of peak excitation.
- The normalized distance (ND) between the cluster's centroid of detail components DWT (Uc) and the threshold value ($\tilde{U}$) are used to define condition of isolation bearing.

$$ND(U_c, \tilde{U}) = \frac{\overline{U}_c - \tilde{U}}{\tilde{U}} \qquad \begin{array}{l} ND \ > 0 \ \text{(normal bearing)} \\ ND \ < 0 \ \text{(locked bearing)} \end{array}$$

Result of Bearing Classification based on DWT & *K*–means Clustering



上のND指標でロックかアンロックかの判定が
出来ていることを確認できた

Implementation on Katsuta Bridge

勝田高架橋 (平成13年完成)

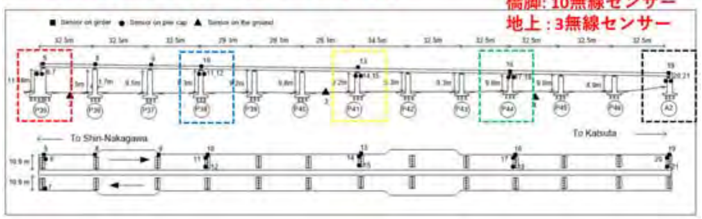
- 茨城県ひたちなか市に位置する
  12径間連続非合成鋼鈑桁橋
- 橋長L=383m
- すべりゴム支承（P35，A2）
  積層ゴム支承　（P36～P46）を使用

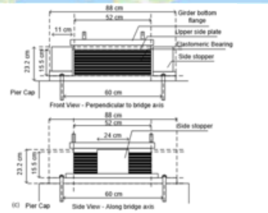
Wireless sensor node

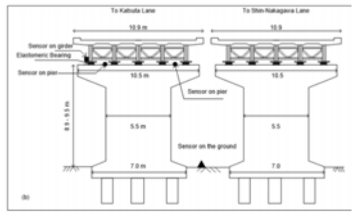
（Google マップより）

勝田橋の無線センサーネットワーク (20)

桁：7 無線センサー
橋脚: 10無線センサー
地上：3無線センサー







Earthquake List Recorded on Katsuta Bridge (2018-2020)

- List of earthquakes recorded on Katsuta Bridge between 2018-2020.
- The seismic responses were recorded from Wireless Sensor Network (WSN)

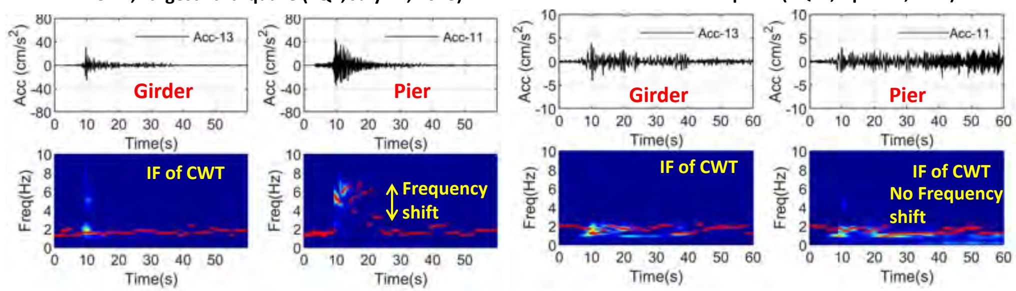
EQ	Date	Epicenter	Depth (km)	Magnitude (M)	Distance (km)	PGA (cm/s2)
EQ1	7/17/2018	36.43N,140.7E	52	M4.8	15	143.7
EQ2	6/17/2019	36.50N,140.6E	80	M5.1	16	137.4
EQ3	3/30/2018	36.44N,140.6E	56	M5.1	11	121.8
EQ4	6/4/2020	36.4N,140.7E	50	M4.7	14	116.6
EQ5	1/21/2020	36.4N,140.7E	50	M4.3	14	61.38
EQ6	4/12/2020	36.2N,140.0E	50	M5.1	53	42.48
EQ7	6/1/2020	36.2N,140.4E	100	M5.3	22	31.64
EQ8	1/14/2020	36.1N,139.9E	50	M5.0	66	26.78
EQ9	9/5/2018	36.4N,141.3E	60	M5.5	72	25.02
EQ10	2/1/2020	36.0N,140.1E	70	M5.3	57	23.57
EQ11	8/4/2019	37.7N,141.7E	50	M6.4	181	16.03
EQ12	5/17/2018	36.35N,140.6E	52	M5.3	75	10.4
EQ13	6/18/2019	38.6N,139.5E	10	M6.8	266	9.51
EQ14	7/7/2018	35.3N,140.6E	70	M6.0	118	7.98
EQ15	4/18/2020	27.2N,140.7E	50	M6.9	1018	2.48

15の地震からの地震記録

Characteristics of Instantaneous Frequency of CWT and Details Components of DWT from Seismic Records on Katsuta Bridge

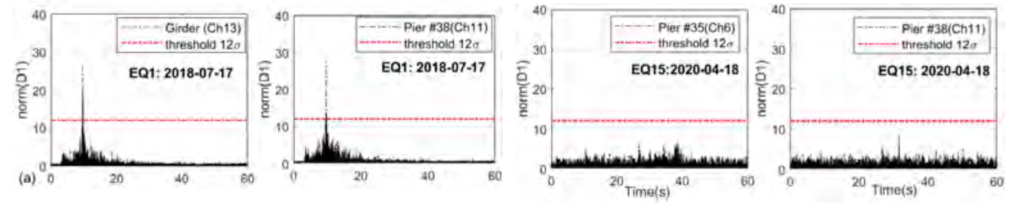
CWT, Largest Earthquake (EQ1, July 17, 2018)

Smallest Earthquake (EQ15, April 18,2020)



DWT, Largest Earthquake (EQ1, July 17, 2018)

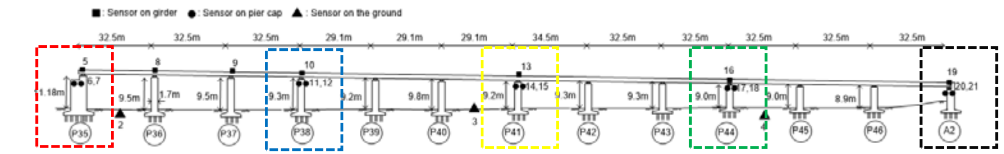
DWT, Smallest Earthquake (EQ15, April 18,2020)



Large earthquake → Large spike on detail components of DWT crosses the threshold value

Small earthquake → Detail components of DWT are below the threshold value

Assessment of Bearing Condition by *K*-means Clustering based on CWT Results



Normalized Distance

	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7	EQ8	EQ9	EQ10	EQ11	EQ12	EQ13	EQ14	EQ15
ND-P35	N.A	0.705	0.844	0.786	0.645	0.715	0.697	0.654	0.679	0.942	0.739	0.09	0.567	0.065	0.157
ND-P38	0.999	0.981	0.863	0.941	0.762	0.899	0.948	0.95	0.971	0.96	0.874	0.579	0.107	0.047	0.15
ND-P41	0.938	0.93	0.876	0.802	0.733	0.876	0.806	0.889	0.936	0.925	0.825	0.677	0.114	0.056	0.157
ND-P44	0.785	0.848	0.722	0.708	0.6	0.802	0.7	0.761	0.602	0.811	0.74	0.101	0.111	0.274	0.152
ND-AB2	0.863	0.894	0.893	0.754	0.746	0.873	0.958	0.872	0.984	0.558	0.952	0.426	0.093	0.138	0.156

Earthquakes

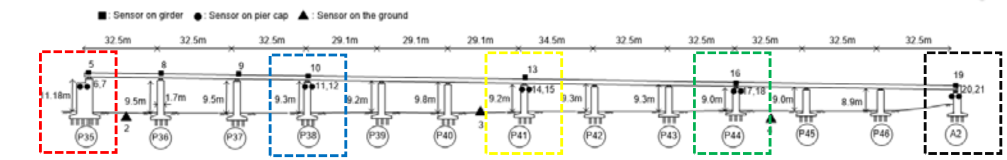
Largest Earthquake

Smallest Earthquake

ND → 1 (normal bearing)
ND → 0 (locked bearing)

実応答データにおいてもND指標でロックかアンロックかの判定が出来ていることを確認できた

Assessment of Bearing Condition by *K*-means Clustering based on DWT Results



Normalized Distance

	EQ1	EQ2	EQ3	EQ4	EQ5	EQ6	EQ7	EQ8	EQ9	EQ10	EQ11	EQ12	EQ13	EQ14	EQ15
ND-P35	N.A.	0.098	0.43	0.097	0.828	0.028	0.519	0.203	0.305	0.32	-0.89	-0.945	-0.948	-0.958	-0.948
ND-P38	0.346	0.894	0.205	0.483	0.949	0.683	0.231	0.272	0.152	0.156	0.201	0.176	-0.955	0.302	-0.946
ND-P41	0.096	0.398	0.125	0.991	0.295	0.808	0.586	0.253	0.137	0.05	-0.935	-0.956	-0.955	-0.958	-0.964
ND-P44	0.178	0.346	0.091	0.545	0.058	0.121	0.085	0.179	0.184	0.088	-0.916	-0.954	-0.946	-0.95	-0.945
ND-AB2	0.619	0.28	0.361	0.338	0.202	0.203	0.076	0.171	0.217	0.108	-0.946	-0.963	-0.954	0.158	-0.956

Earthquakes

Largest Earthquake

Smallest Earthquake

ND > 0 (normal bearing)
ND < 0 (locked bearing)

実応答データにおいてもND指標でロックかアンロックかの判定が出来ていることを確認できた

Conclusions

- Continuous and Discrete Wavelet with Sparse representation techniques were employed to detect malfunction of isolation bearing directly from seismic response. Classification of bearing condition is made by machine-learning based K-cluster technique.
- The techniques were verified in the finite element simulation and implemented on a Katsuta Bridge, a continuous multi-span girder bridge using seismic responses from 15 earthquakes recorded by wireless sensor network.
- Results show that isolation bearings have functioned properly without observed locked bearing during large (PGA>100cm/s^2) and moderate (10 cm/s^2 < PGA < 100 cm/s^2) earthquakes. Possible locked bearing was observed during small earthquakes (PGA<10cm/s^2) because the isolation mechanism has not been initiated due to the small amplitude of excitation.

ゴム支承の高架橋を対象に，支承が地震時にロック（機能不全）かアンロック（機能）かを橋脚の地震応答のウェーブレット解析からの正規化指標から判定できることを，シミュレーションならびに，ワイヤレスセンサーで2年ほど地震計測している勝田高架橋（茨城県）の実応答データから明らかにした.