Evaluation of Seismic Health Monitoring System of Golden Horn Bridge

M.Sc. Thesis Defense

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Contents

Contents

Introduction: Overview

- Structural Health monitoring motivations;
  - Validating conditions of structure
  - Tracking long-term degradation of structures
  - Assessing fatigue of members
  - Assessing the post-event performance of structure

- Damage identification classification
  - Existance of damage in structure
  - Locating the damage
  - Quantification of damage
  - Forecasting the remaining life of structure

Objective

Seismic Use of Structural Health Monitoring System of Golden Horn Bridge;

- Development of system identification algorithms
- System identification of GHB
- Finite Element Modelling of GHB
- Performance Assessment of GHB

Introduction

Scope

System Identification algorithms

- Peak Picking
- Frequency Domain Decomposition
- Stochastic Subspace Identification

Implementation of System Identification Methods

- Experimental Studies
- Numerical Studies
- GHB

Performance Assessment of GHB

- Nonlinear Modelling of GHB
- Nonlinear Time History Analysis

Theoretical Background: Peak Picking

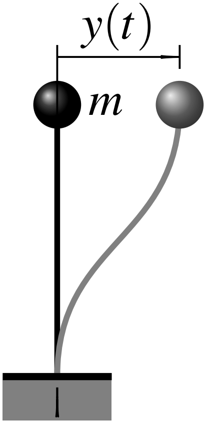
Requirements:

- Structure should behave as a linear system,
- Modes well separated and lightly damped,
- Structural Modes of interest significantly excited,
- Classical damping.

$$\mathbf{y}(t) = \mathbf{a}q(t)$$

$$\mathbf{R}(\tau) = E[y(t)y(t+\tau)^T] = \mathbf{a}E[q(t)q(t+\tau)]\mathbf{a}^{\mathrm{T}} = R_q(\tau)\mathbf{a}\mathbf{a}^{\mathrm{T}}$$

$$\mathbf{G}_y(f) = \mathbf{G}_q(f)aa^T$$



Theoretical Background: Frequency Domain Decomposition

- Enhancement on closely-spaced modes,
- Additional Singular Value Decomposition,
- Computationally Undemanding,

Computational Steps:

- Obtaining Fourier Transform of Measurents,
- Computing Power Spectral Density Matrix,
- Performing Singular Value Decomposition,
- Selecting Singular Values.

$$\mathbf{y}(t) = a_1 q_1(t) + a_2 q_2(t) + a_3 q_3(t) + \ldots = \mathbf{A}q(t)$$

$$\mathbf{R}_{\mathrm{y}}(\tau) = E[y(t)y^T(t+\tau)],$$

$$\mathbf{R}_{\mathrm{y}}(\tau) = \mathbf{A}E[q(t)q^T(t+\tau)]\mathbf{A}^{\mathrm{T}}$$

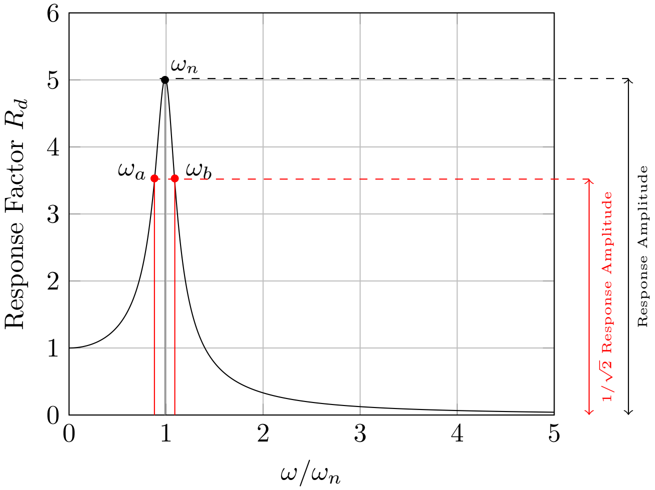
$$\mathbf{G}_{\mathrm{y}}(f) = \mathbf{A}[g_n^2(f)]\mathbf{A}^{\mathrm{H}}$$

$$\mathbf{G}_{\mathrm{y}}(f) = \mathbf{USU}^{\mathrm{H}}$$

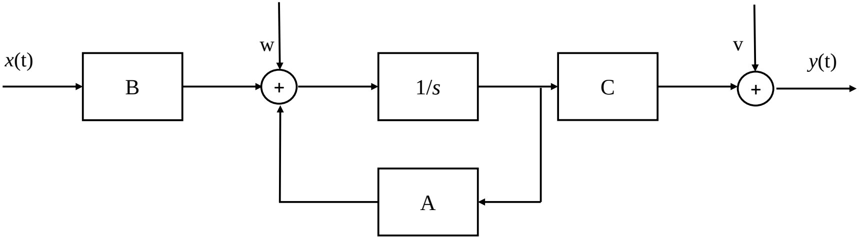
Damping Identification in Frequency Domain

$$2\xi = \frac{\omega_b - \omega_a}{\omega_n},$$

$$\xi = \frac{\omega_b - \omega_a}{2\omega_n} \quad or \quad \xi = \frac{f_b - f_a}{2f_n}.$$



Theoretical Background: Stochastic Subspace Identification



$$\dot{x}(t) = \mathbf{A}_c x(t) + \mathbf{B}_c u(t),$$

$$\mathbf{A}_c = \begin{Bmatrix} 0 & \mathbf{M}^{-1} \\ \mathbf{M}^{-1}\mathbf{K} & \mathbf{M}^{-1}\mathbf{C} \end{Bmatrix}, \qquad \mathbf{B}_c = \begin{Bmatrix} 0 \\ \mathbf{M}^{-1}\mathbf{K} \end{Bmatrix},$$

$$y(t) = \mathbf{C}_c x(t) + \mathbf{D}_c u(t).$$

Theoretical Background: Stochastic Subspace Identification

Computational Steps:

- Obtaining Hankel Matrix,
- Performing Singular Value Decomposition,
- Obtaining Kalman states and Observability matrix,
- Computing matrix **A** and **C**,
- Performing Eigenvalue Decomposition.

$$\mathscr{P}_{i-1} = \mathbf{Y}_f^- / \mathbf{Y}_p^+ = O_{i-1}\hat{\mathbf{X}}_{i+1}$$

$$\hat{\mathbf{X}}_{i+1} = O_{i-1}^{\dagger}\mathscr{P}_{i-1}$$

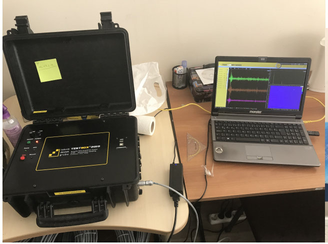
$$\begin{pmatrix} \hat{\mathbf{X}}_{i+1} \\ \mathbf{Y}_{i|i} \end{pmatrix} = \begin{pmatrix} \mathbf{A} \\ \mathbf{C} \end{pmatrix} \hat{\mathbf{X}}_i + \begin{pmatrix} \mathbf{W}_i \\ \mathbf{V}_i \end{pmatrix}.$$

$$\mathbf{A} = \mathbf{\Psi}\mathbf{\Lambda}_{\mathrm{d}}\mathbf{\Psi}$$

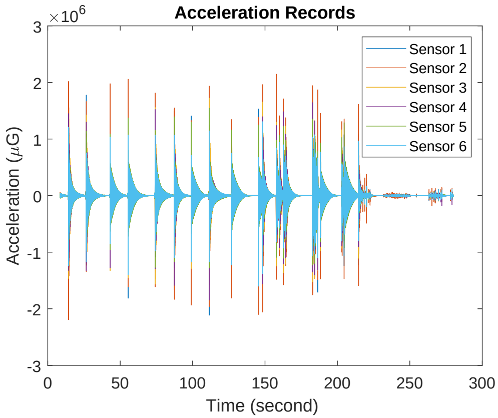
$$\mathbf{U} = \mathbf{C}\mathbf{\Psi}$$

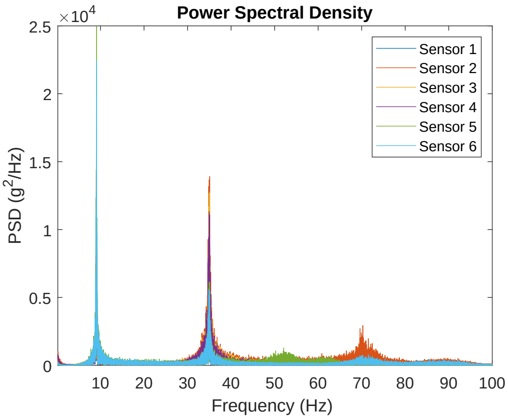
Contents

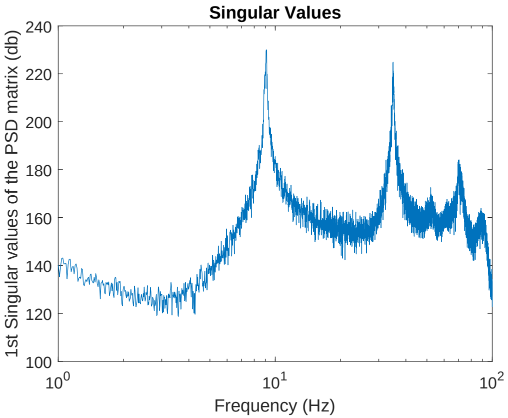
Experimental and Numerical Studies: Experimental Study

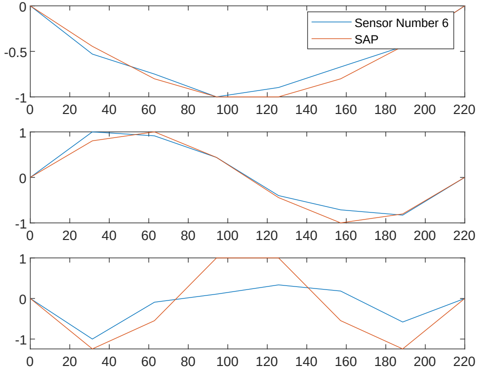


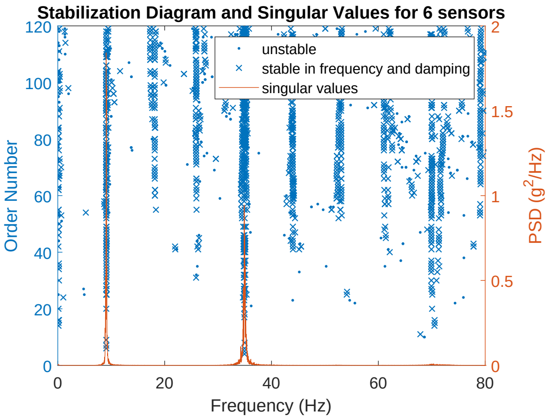
Experimental and Numerical Studies: Experimental Study

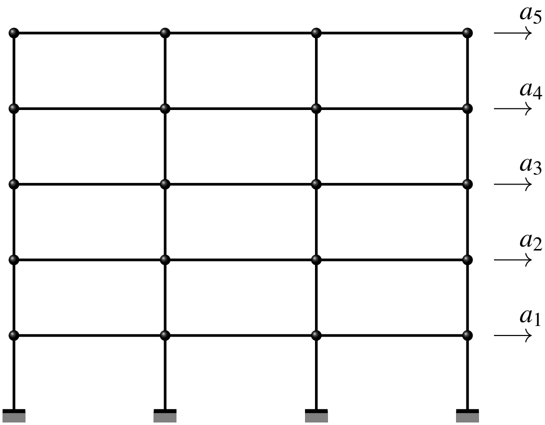


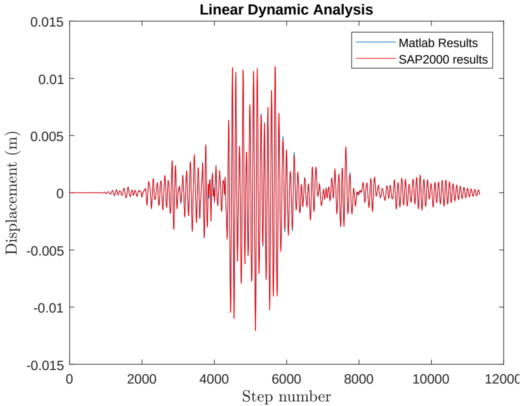



Singular Values
1st Singular values of the PSD matrix (db)
240
220
200
180
160
140
120
100
10^0
10^1
10^2
Frequency (Hz)


Sensor Number 6
SAP
0
-0.5
-1
1
0
-1
1
0
-1
0 20 40 60 80 100 120 140 160 180 200 220

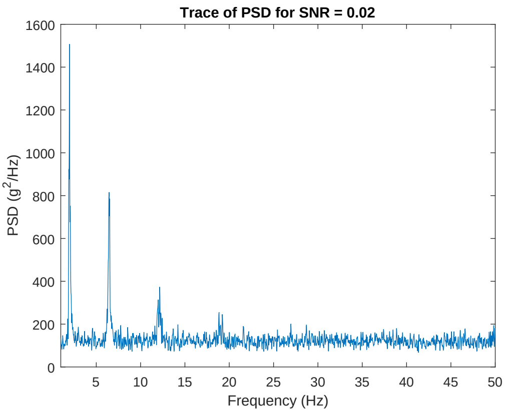

Stabilization Diagram and Singular Values for 6 sensors
Order Number
Frequency (Hz)
PSD (g^2/Hz)
unstable
stable in frequency and damping
singular values
0
20
40
60
80
100
120
0
20
40
60
80
0
0.5
1
1.5
2

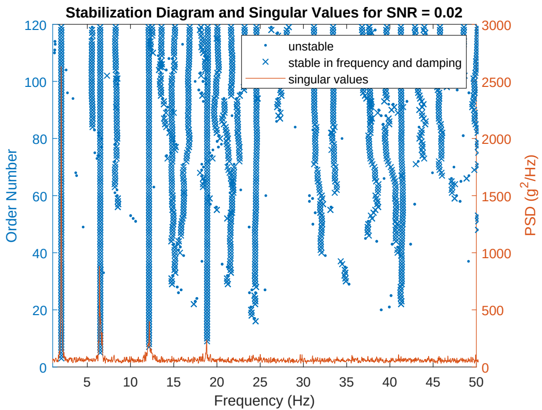




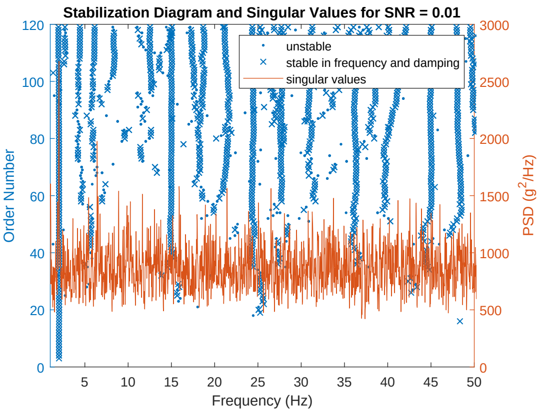
Numerical Model and linear time history analysis

Experimental and Numerical Studies: Numerical Study





Numerical Model and linear time history analysis



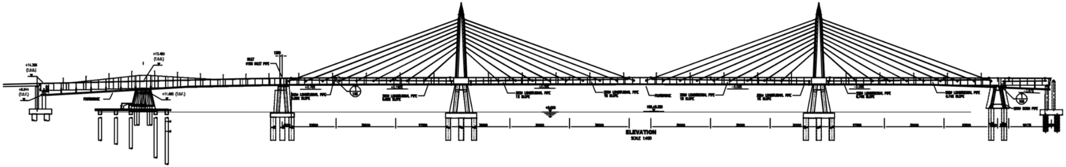
Numerical Model and linear time history analysis

Contents

System Identification of GHB: Structural Properties

System Identification of GHB: Structural Properties

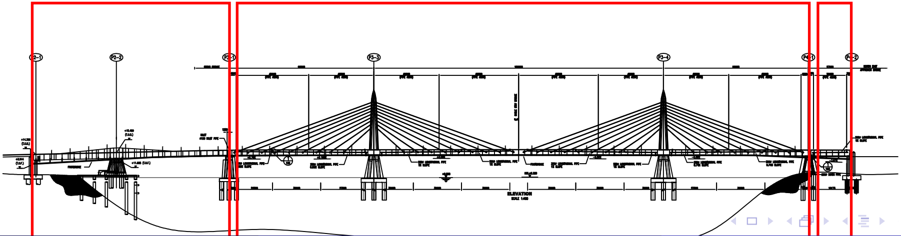
- Between Yenikapı and Taksim
- Cable-Stayed Bridge
- Construction begining: 2009
- Construction end: 2014
- Metro-Crossing



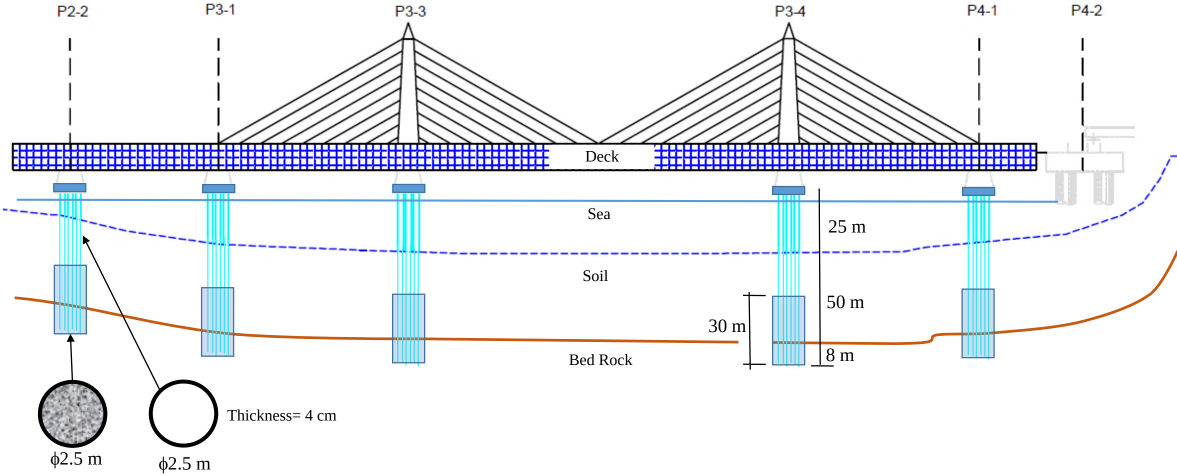
The parts of the GHB:

- North-East Approaching Bridge
- South-West Approaching Bridge
- Cable-Stayed Bridge
- Swing Bridge
- Single-Span Bridge

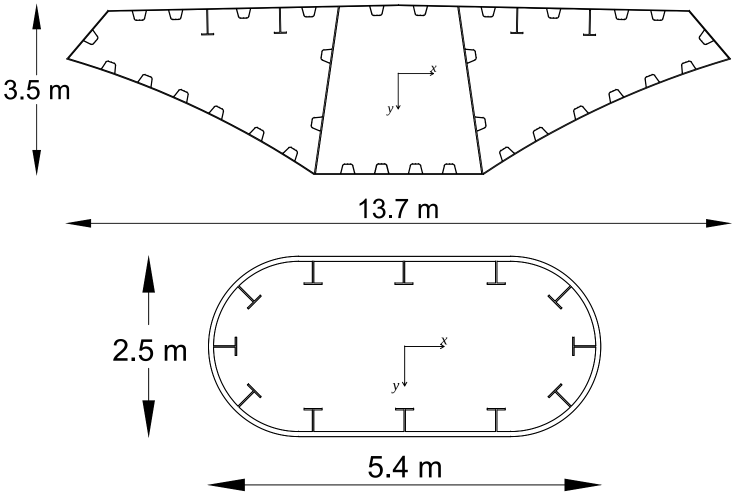
Swing Bridge Cable-Stayed Bridge Single-Span Bridge



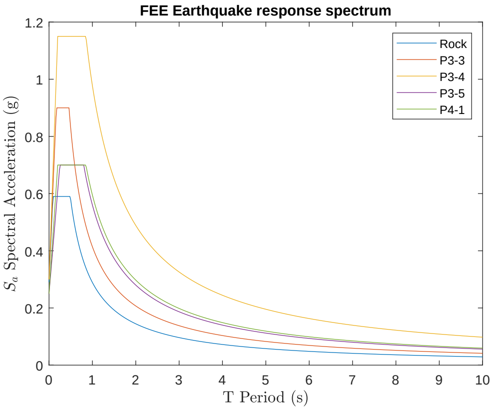
System Identification of GHB: Structural Properties

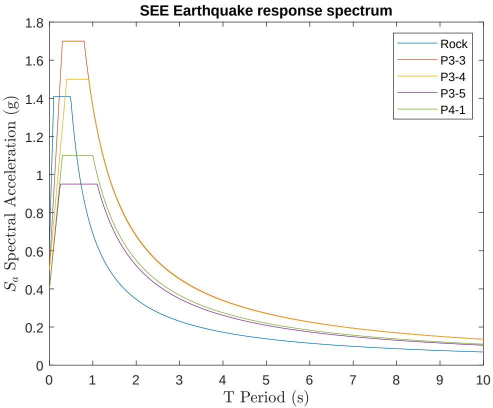


System Identification of GHB: Structural Properties



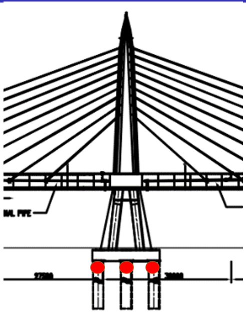
System Identification of GHB: Structural Properties





Response spectra

System Identification of GHB: Structural Properties

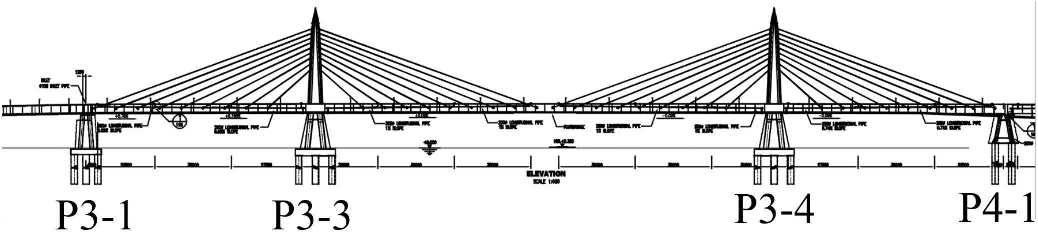


Ductility	Seismicity	
	72-year return period	2475-year return period
Normal	R= 1.0	R= 3.5
High	R= 1.5	R= 5.0

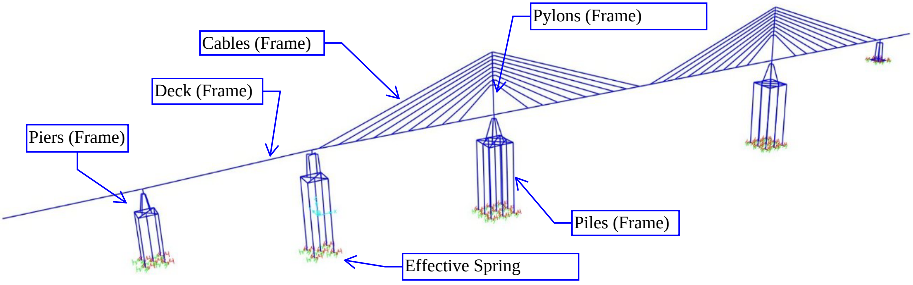
Plastic Hinge Locations and Seismicity

System Identification of GHB: Structural Properties

P3-1	P3-3	P3-4	P4-1
BackFill	Soft Clay	Very Soft Fill	Very Soft Fill
Soft Clay	Sandy Clay	Soft Clay	Soft Clay
Gravel			
Bed Rock (depth 50 m below ground)			

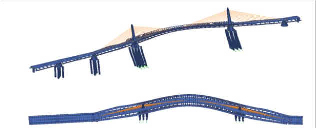


System Identification of GHB: Finite Element Model of GHB

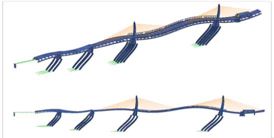


SAP2000 Model of GHB

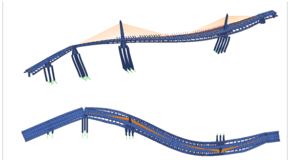
System Identification of GHB: Finite Element Model of GHB



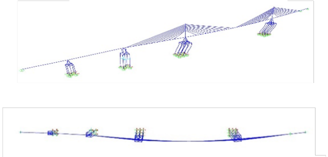
1st Mode: 2.475 s
(VCE: 2.00 s)



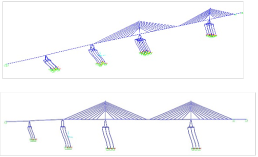
2nd Mode: 2.188 s



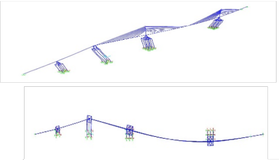
3rd Mode: 1.730 s



1st Mode: 2.955 s



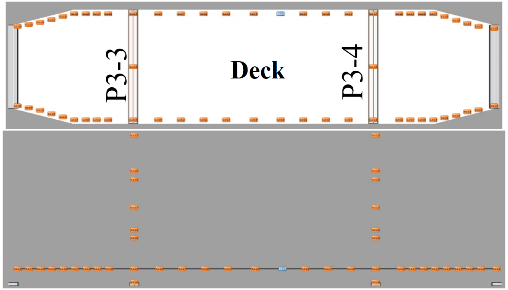
2nd Mode: 2.589 s

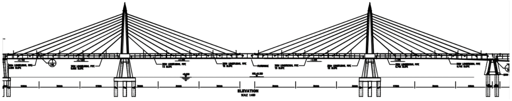


3rd Mode: 2.441 s

SAP2000 Mode Shape Comparison

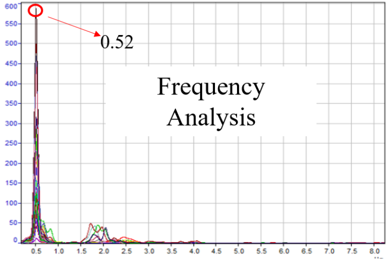
System Identification of GHB: Initial Measurements by VCE

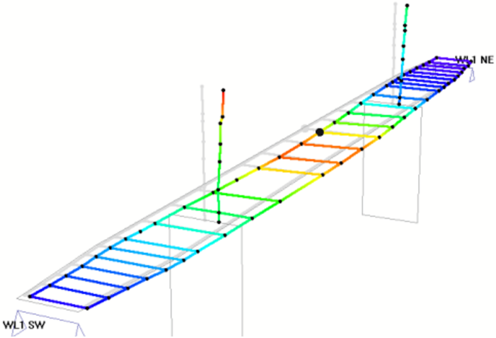




	Sensor Number
CSB Deck	80
CSB Pylons	14

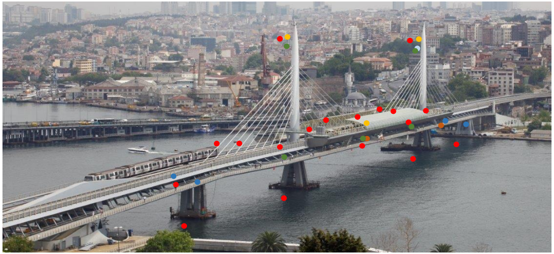
Structural Health Monitoring System of GHB: Initial Measurements by VCE





Eigen-frequencies	Vibration mode (Kind of loading)	BRIMOS Measurement [Hz]	FE Model [HZ]	Deviation [%]
1	1st bending mode	0,52	0,49	7,4
2	2nd bending mode	0,63	0,55	13,8
3	1st torsional mode	1,08	-	-
4	3rd bending mode	1,26	1,08	16,3
5	4th bending mode	1,82	-	-
6	2nd torsional mode	3,02	-	-
7	5th bending mode	4,23	-	-
mean deviation				**12,5**

System Identification of GHB: Permanent System by VCE



Acceleration (32)
Meteorological (4)
Str. Temp. (12)
Tilt (5)
Displacement (4)
GPS (4)

Interval = 0.05 s

TOTAL = 61

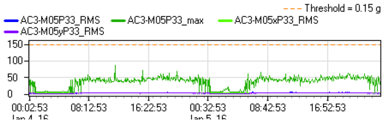
VCE

Raw Data

METRO İSTANBUL

Internet Web Browser + Report

- Max (5 mins)
- RMS (5 mins)

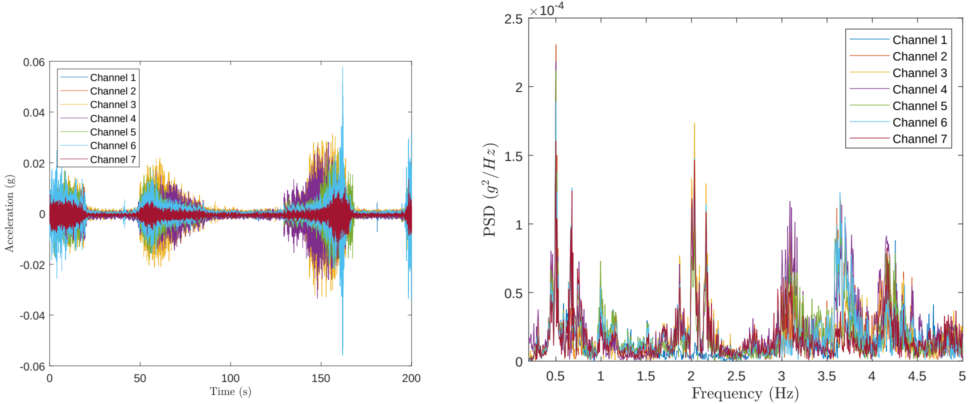


Structural Health Monitoring

This part is not available yet!

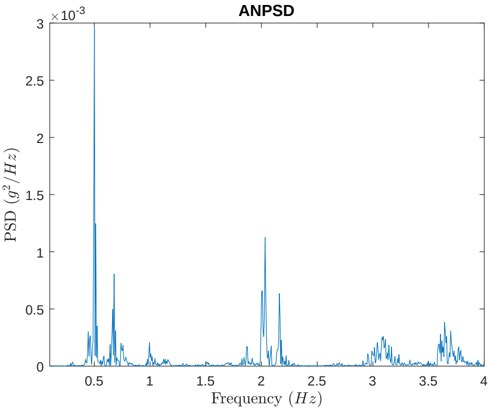
System Identification of GHB: Measurements

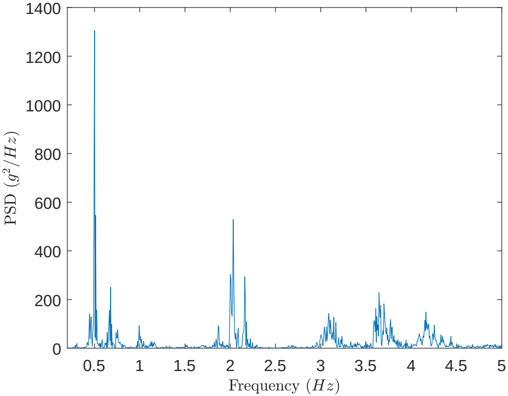
System Identification of GHB: Measurements



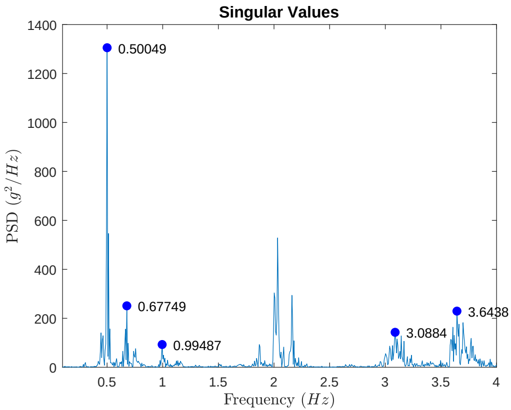
Measurements and their PSD

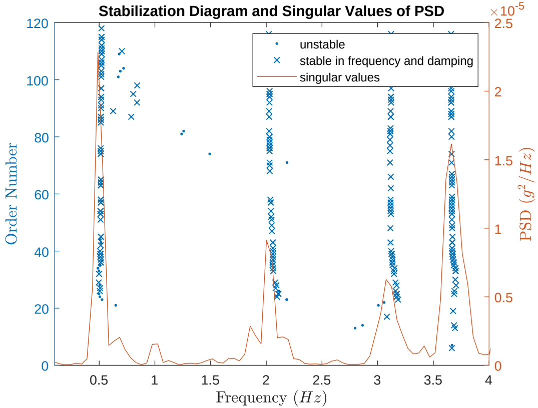
System Identification of GHB: Measurements





ANPSD and Trace of PSD





Singular Values and Stabilization Diagram

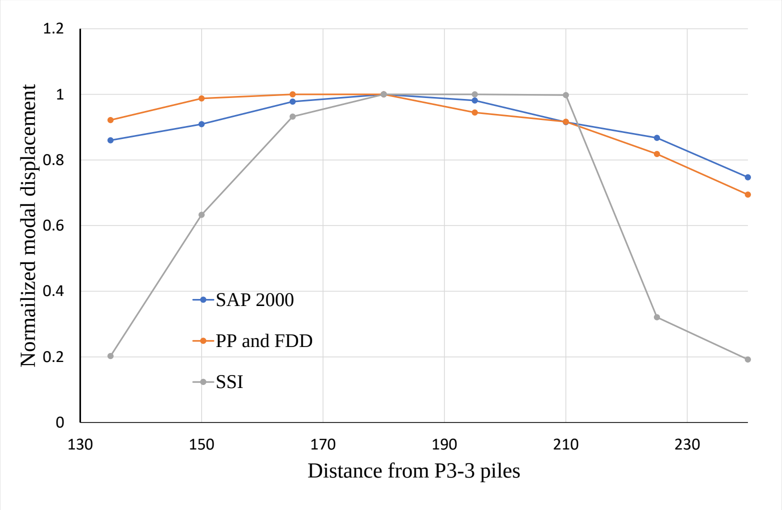
System Identification of GHB: Measurements

SI method	1st Mode	2nd Mode	3rd Mode	4th Mode	5th Mode
PP	0.50	0.68	0.99	3.09	3.64
FDD	0.50	0.68	0.99	3.09	3.64
SSI	0.52	-	-	3.12	3.66

SI method	MAC (%)	ξ (%)
PP	99.75	4
FDD	99.75	4
SSI	84.00	2.45

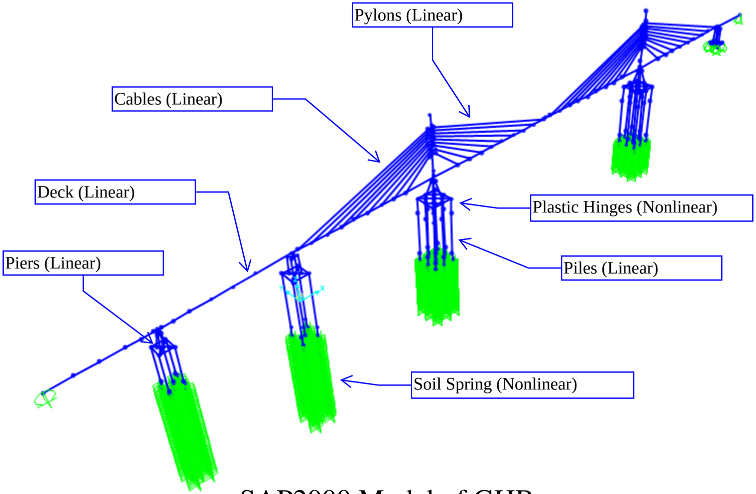
System identification results

System Identification of GHB: Measurements



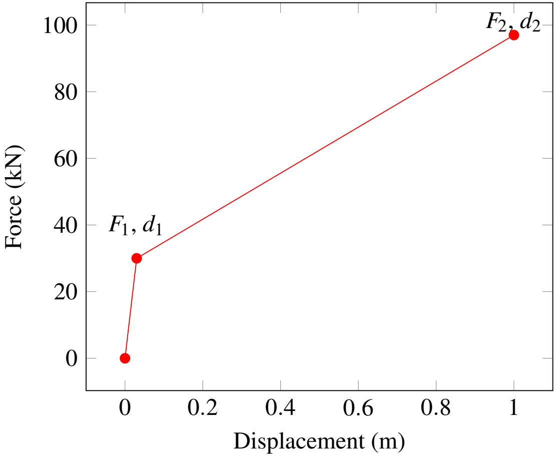
Contents

Performance Assessment: Nonlinear Model of GHB



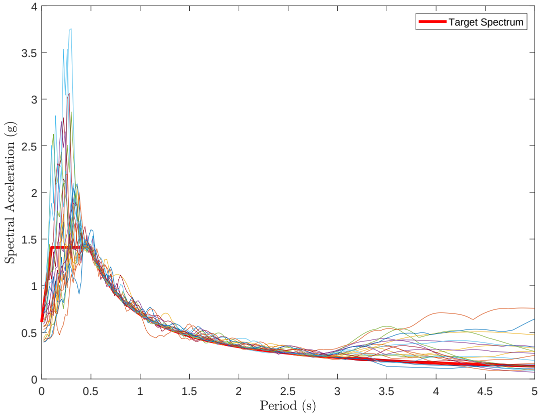
SAP2000 Model of GHB

Performance Assessment: Nonlinear Model of GHB



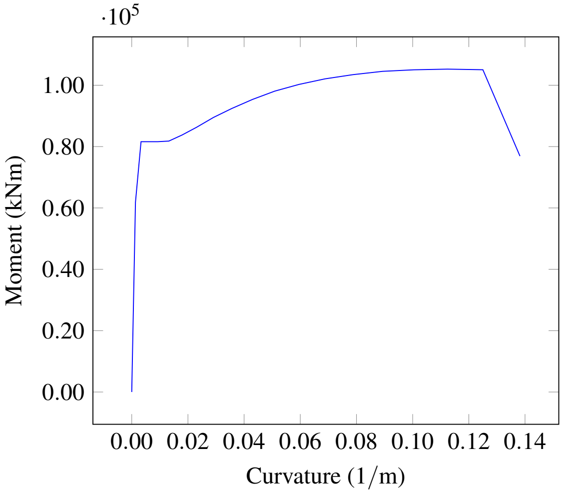
Soil spring model

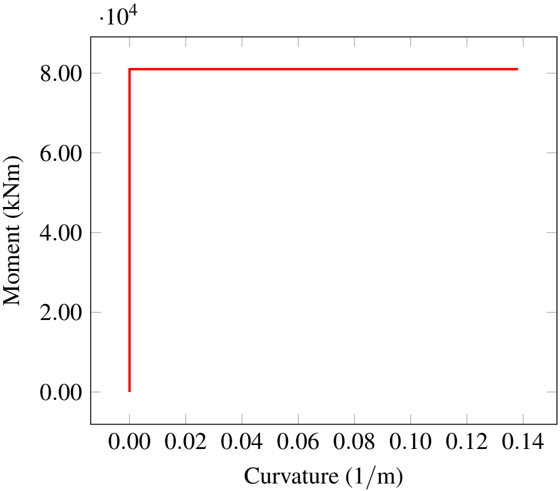
Performance Assessment: Nonlinear Model of GHB



Matched Spectrum for earthquake data

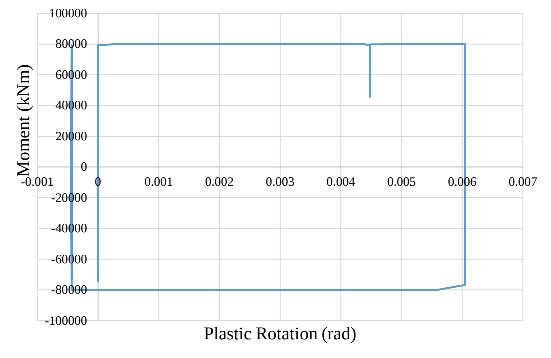
Performance Assessment: Nonlinear Model of GHB

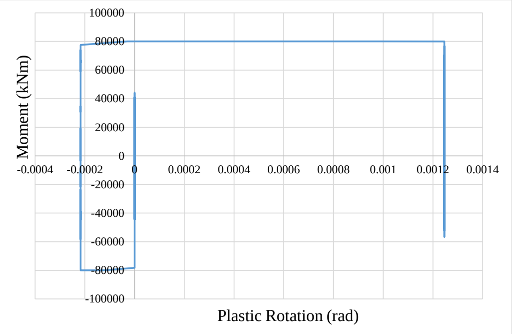




Moment-Curvature relationship of piles and rigid-plastic hinge.

Performance Assessment: Nonlinear Time History Analysis





Moment-Plastic rotation of elements of piles P3-3 and P3-4

Performance Assessment: Nonlinear Time History Analysis

Element	θ_{max}	θ_y	Performance level
1	0.006	0.07	IO
2	0.0012	0.07	IO

For colums $P/P_{CL} < 0.20$	IO	LS	CP
Criteria	$1\theta_y$	$6\theta_y$	$8\theta_y$
	0.07	0.42	0.56

Performance assessment and FEMA 356 Acceptance Criteria

Results

- System identification algorithms used in this study, are useful up to considerable amount of noise. Furthermore, number of the sensors significantly affects the capturing the mode shapes. The sensor number to be used should be chosen considering probable mode shapes of the structure specifically.
- It was noticed that many sensors produces bad data in the permanent structural health monitoring system of GHB. The modal properties of the GHB could not be obtained using the existing sensors.
- Measured acceleration of the bridge deck, mode frequencies were obtained and these results are compatible with those extracted from the initial measurements. Although, mode shapes belonging to the higher frequencies could not be acquired.
- As a result of this study, the necessary modifications of structural health monitoring system of GHB concerning seismic aspect were understood.

Recommendation

- For the seismic use of structural health monitoring system, the number of sensors should be increased to capture the higher frequency mode shape with a high spatial resolution. Increasing resolution provides more information about mode shapes and the accuracy of damage identification is improved. Furthermore, sensors on the bridge are need to be maintained.
- The sensors deployed on free field or ground which provides information about seismic excitation are necessary, since under the known seismic excitation, performance of GHB can be assessed more accurately with the measured response. Therefore, the performance assessment of GHB can be realized real-time after an earthquake, and decision may be made about the structural health of GHB.

Teşekkürler

Thank You