

Resilient Structures for Buildings and Infrastructure in High Seismic Zones



提供建设领域一体化服务

CHINA HARBOUR
July 28, 2025

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Worldwide High Seismic Zones

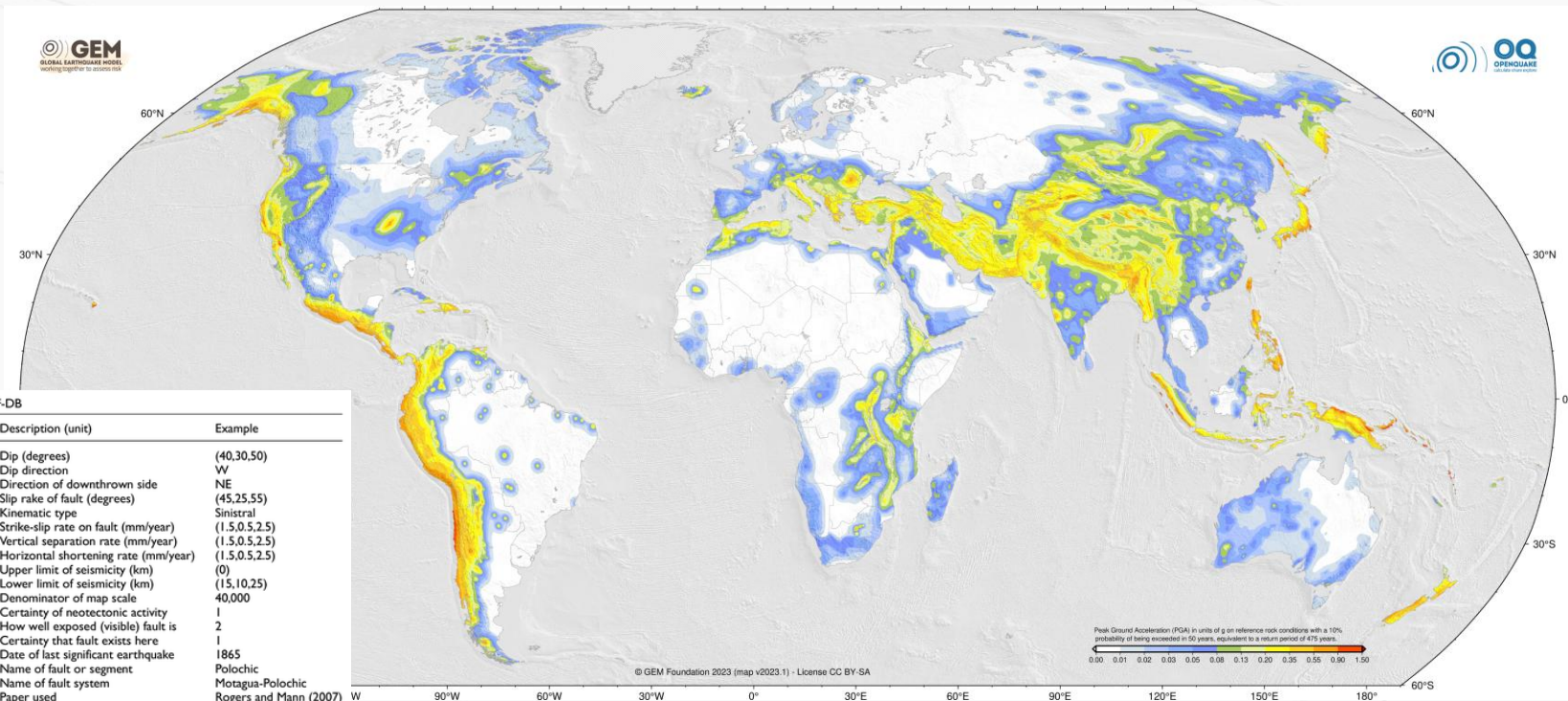
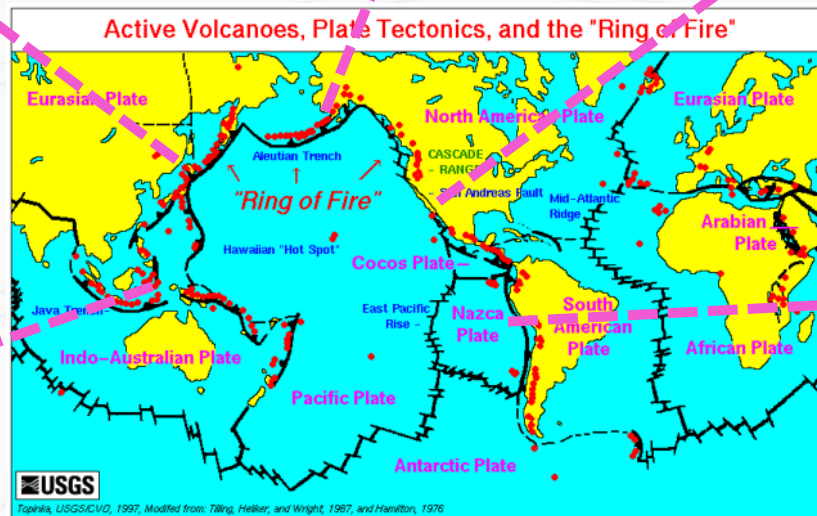
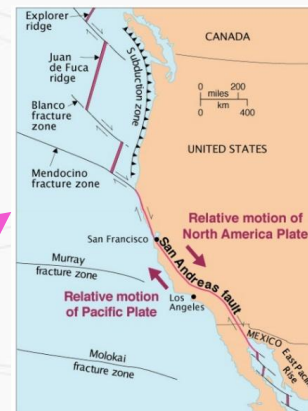
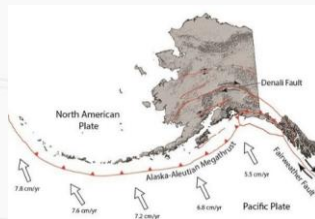
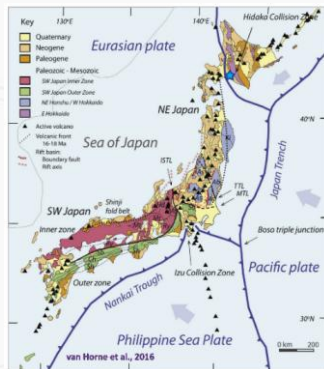


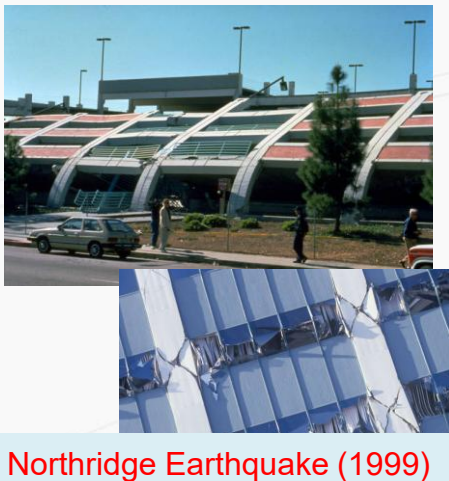
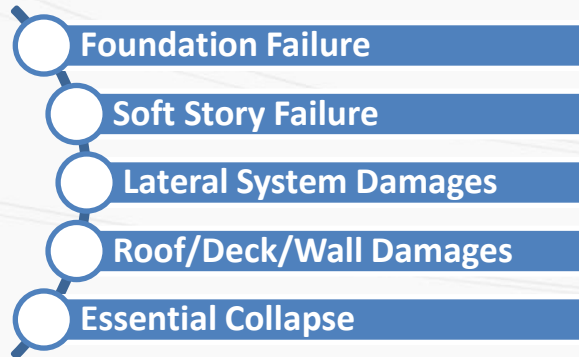
Table 1. Fault parameters in the GAF-DB

Attribute	Data type	Description (unit)	Example
Dip	Tuple	Dip (degrees)	(40,30,50)
dip_dir	String	Dip direction	W
downthrown_side_id	String	Direction of downthrown side	NE
average rake	Tuple	Slip rake of fault (degrees)	(45,25,55)
slip_type	String	Kinematic type	Sinistral
strike_slip_rate	Tuple	Strike-slip rate on fault (mm/year)	(1.5,0.5,2.5)
vert_sep_rate	Tuple	Vertical separation rate (mm/year)	(1.5,0.5,2.5)
shortening_rate	Tuple	Horizontal shortening rate (mm/year)	(1.5,0.5,2.5)
upper_seis_depth	Tuple	Upper limit of seismicity (km)	(0)
lower_seis_depth	Tuple	Lower limit of seismicity (km)	(15,10,25)
Accuracy	Integer	Denominator of map scale	40,000
activity_confidence	Integer	Certainty of neotectonic activity	1
exposure_quality	Integer	How well exposed (visible) fault is	2
epistemic_quality	Integer	Certainty that fault exists here	1
last_movement	String	Date of last significant earthquake	1865
name	String	Name of fault or segment	Polochic
fs_name	String	Name of fault system	Motagua-Polochic
reference	String	Paper used	Rogers and Mann (2007)
notes	String	Any relevant info	May be creeping
ogc_fid	Integer	ID used by GIS	8
catalog_id	String	Global ID	CCARA_8

❑ Pacific Rim Seismic Zone: World's highest earthquake risk areas

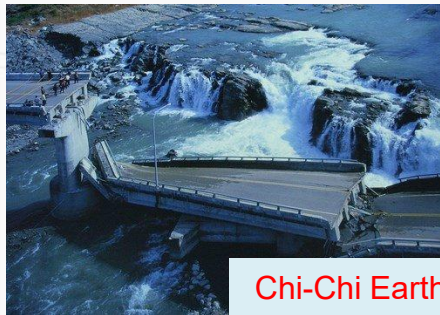


❑ Typical Building Structural and Foundation Damages



❑ Typical Bridge Structural and Foundation Damages

● Foundation Failure ● Unseating ● Deck Damages ● Pier Shear ● Framing Collapse



□ Typical Port Structural and Foundation Damages

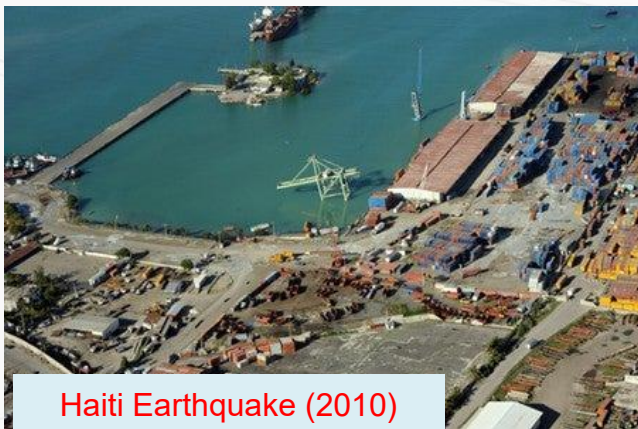
● Foundation Failure

● Quay Wall Damages

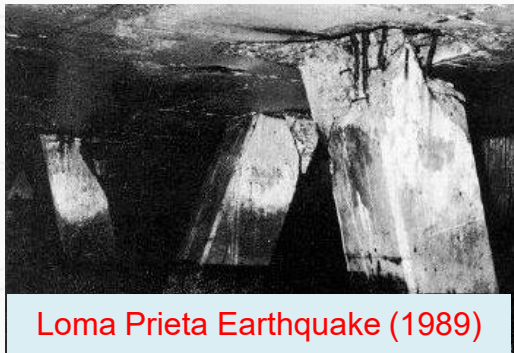
● Facility Instability

● Revetment Failure

● Tsunami and others



Haiti Earthquake (2010)



Loma Prieta Earthquake (1989)



Tohoko Earthquake (2011)



Boulanger



Boulanger

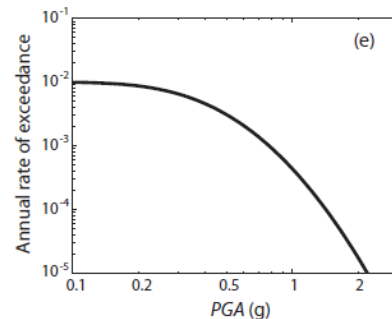
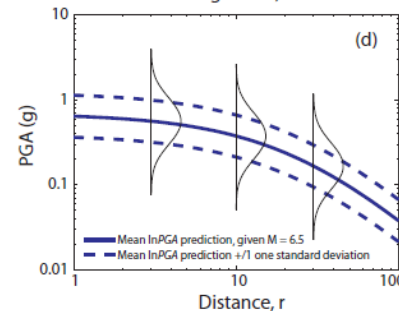
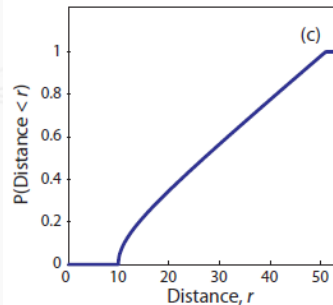
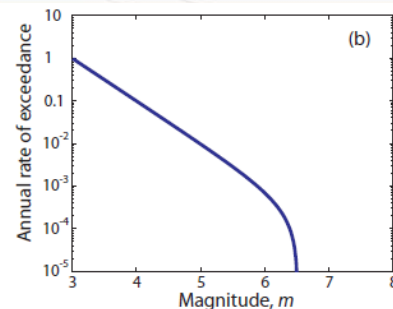
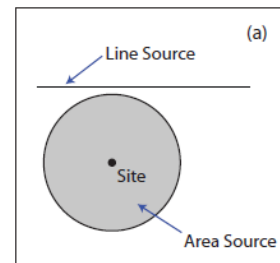


Kobe Earthquake (1995)

Harder

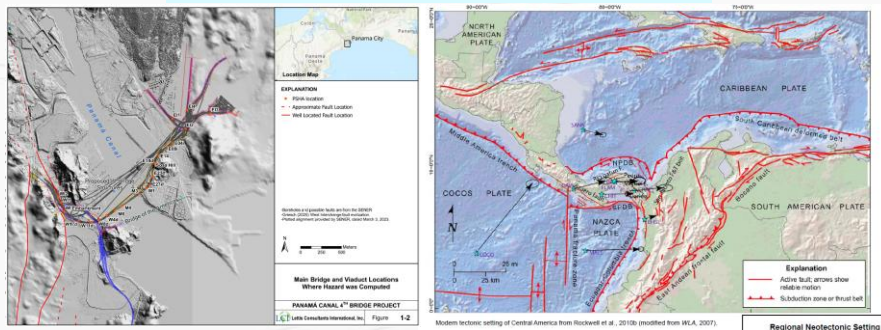
□ Probabilistic Seismic Hazard Assessment

- Identify all earthquake sources producing ground motions.
- Evaluate the occurrence of earthquakes of different magnitudes at each source.
- Evaluate the distribution of distances from the source to site.
- Use appropriate seismic motion models to quantify the ground motion intensity as a function of magnitude, distance, etc.
- Predict the uncertainties and use total probability theory to determine the earthquake risk and uniform risk response spectrum.

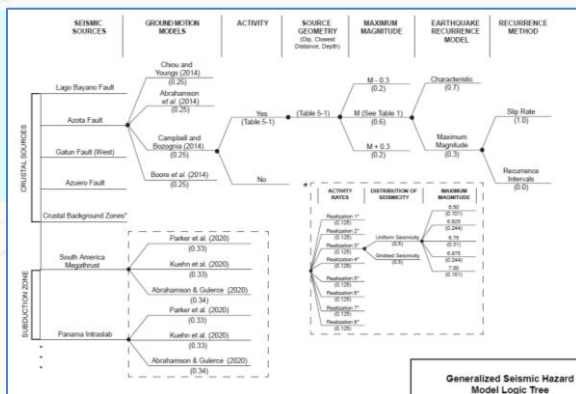


❑ Probabilistic Seismic Hazard Assessment (PSHA) - Panama Canal 4th Bridge as Example

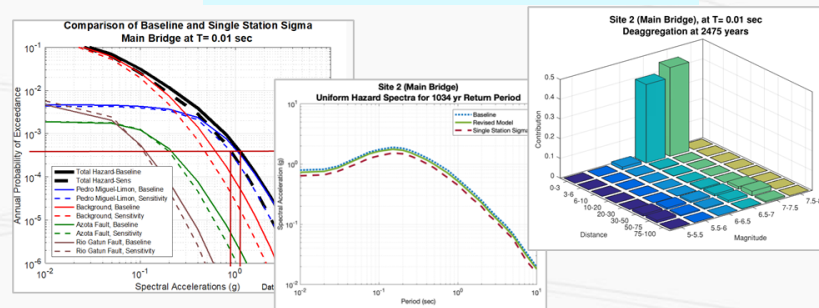
Potential Seismic Sources



SSC and GMPE, Logic Tree Approach

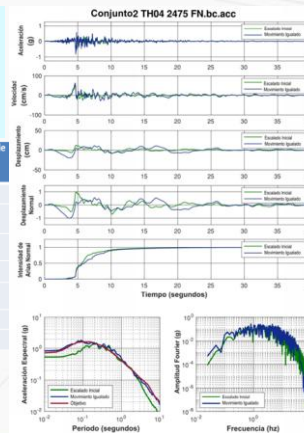


URS and Deaggregation



Bedrock Ground Motion as Design Input

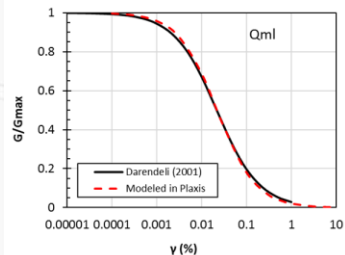
ID	Earthquake Name	Station Name	Record Sequence Number	Tp-Pulse Period (sec)	S-95% Duration (sec)	Arias Intensity (m/sec) (unscaled)	Year	Magnitude
04	Loma Prieta	Gitroy Array #3	767	2.639	11.4	2.1	1989	6.93
05	Loma Prieta	San Jose-Santa Teresa Hills	801	Not a pulse	10.1	1.3	1989	6.93
06	Northridge-01	La Sepulveda VA Hospital	1004	0.931	8.5	7.0	1994	6.69
09	Hector Mine	Hector	1787	Not a pulse	11.7	1.9	1999	7.13
10	Cape Mendocino	Centerville Beach, Naval Fac	3746	1.967	10.6	1.6	1992	7.03
12	Niigata, Japan	NIGH11	4228	1.799	12.2	2.2	2004	6.61
14	Duzce, Turkey	Bolu	1602	0.882	9.0	3.7	1999	7.14



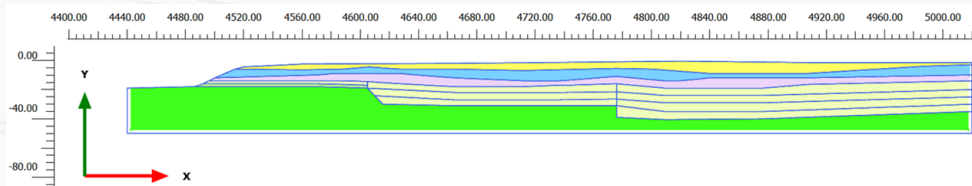
Seismic Hazard

□ Site Response Analysis (SRA) - Panama Canal 4th Bridge as Example

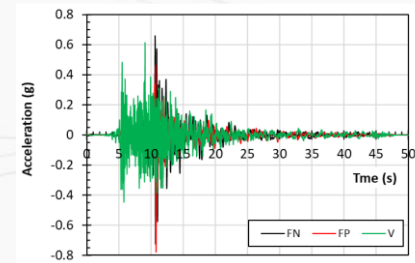
- 2D Nonlinear FEA is used to fully consider the influence of soil dynamic nonlinearity, complex soil layer distribution, and complex terrain on seismic wave propagation



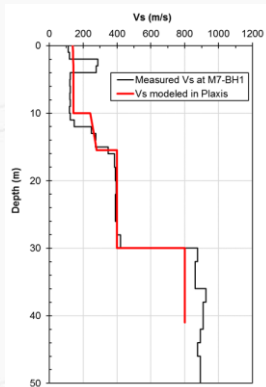
Shear Modulus Degradation Curve



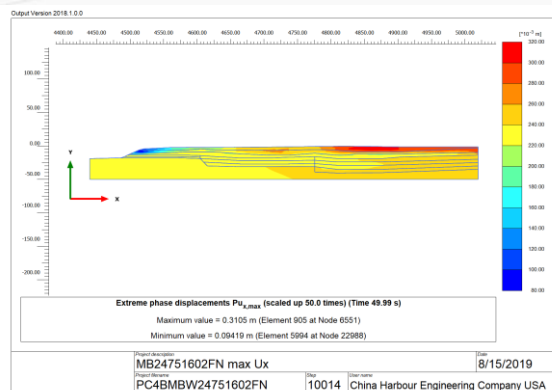
PLAXIS 2D Soil Field Model



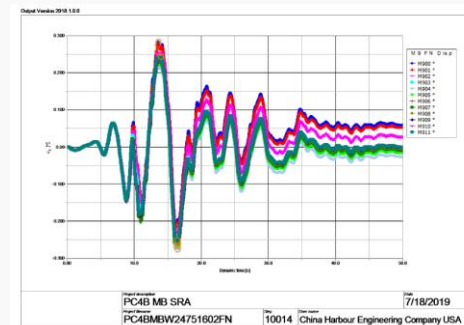
Ground Motion Input



Soil Vs Profile per Depth



Horizontal Displacement Diagram

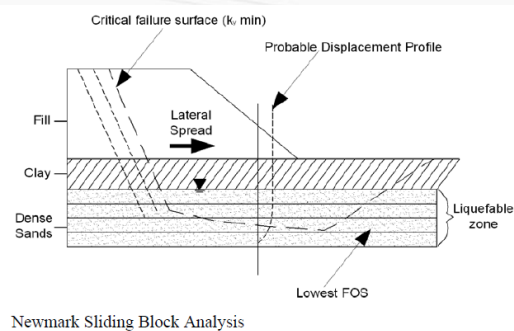


Displacement Time Histories at Multiple Depths

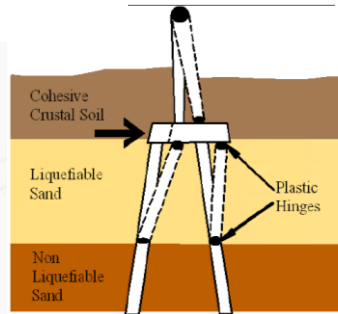
□ Geotechnical Earthquake Engineering

➤ Geotechnical Seismic Hazard:

- Liquefaction and lateral spreading
- Slope instability and movement
- Differential settlement
- Near-fault surface rupture



Widely used
to mitigate
liquefaction



g Road Bridge Lateral Spread (after Berrill et al., 1997)

➤ Typical Ground Improvement Measures

Table A-1 Ground Improvement Methods (after Cooke and Mitchell, 1999)

Method	Principle	Suitable Soil Types	Treated Soil Properties	Relative Costs
Compaction Grout	Highly viscous grout acts as spherical hydraulic jack when pumped under high pressure resulting in densification.	Compressible soils with some fines	Increased D_r SPT: $(N_1)_{60}$ 25 to 30 CPT: $q_{cl}=80$ To 150 tsf (Kg/cm ²)	Low material cost; high injection cost.
Particulate Grouting	Penetration grouting fills soil pores with cement, soil or clay.	Clean, medium to coarse sand and gravel	Cement-grouted soil: high strength	Lowest of grouting systems
Chemical Grouting	Solutions of two or more chemicals react in soil pores to form a gel or solid precipitate.	Sands and Silts	Low to high strength	High to very high
Jet Grouting	High-speed jets at depth excavate, inject and mix stabilizer with soil to form column or panels	Sands, silts, and clays	Solidified columns and walls	High
Vibro-Compaction	Densification by vibration and compaction of backfill at depth.	Sand (<20% passing No. 200 sieve)	D_r : up to 85+% SPT: $(N_1)_{60}$ 25 to 30 CPT: $q_{cl}=80$ To 150 tsf (Kg/cm ²)	Moderate
Vibro-replacement/Stone Columns	Densely compacted gravel columns provide densification, reinforcement, and drainage	Sands and silts	Increased D_r SPT: $(N_1)_{60}$ 25 to 30 CPT: $q_{cl}=80$ To 150 tsf (Kg/cm ²)	Moderate to high
Drains: Gravel Sand Wick	Drains relieve excess pore water pressure to prevent liquefaction and intercept and dissipate excess pore water pressure plumes from adjacent liquefied soil.	Sands and silts	Improved drainage	Low to moderate
Mini-Piles	Piles carry loads through liquefiable soils to firm stratum.	All soils		High

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Seismic Hazard

Earthquake-Resistant Buildings

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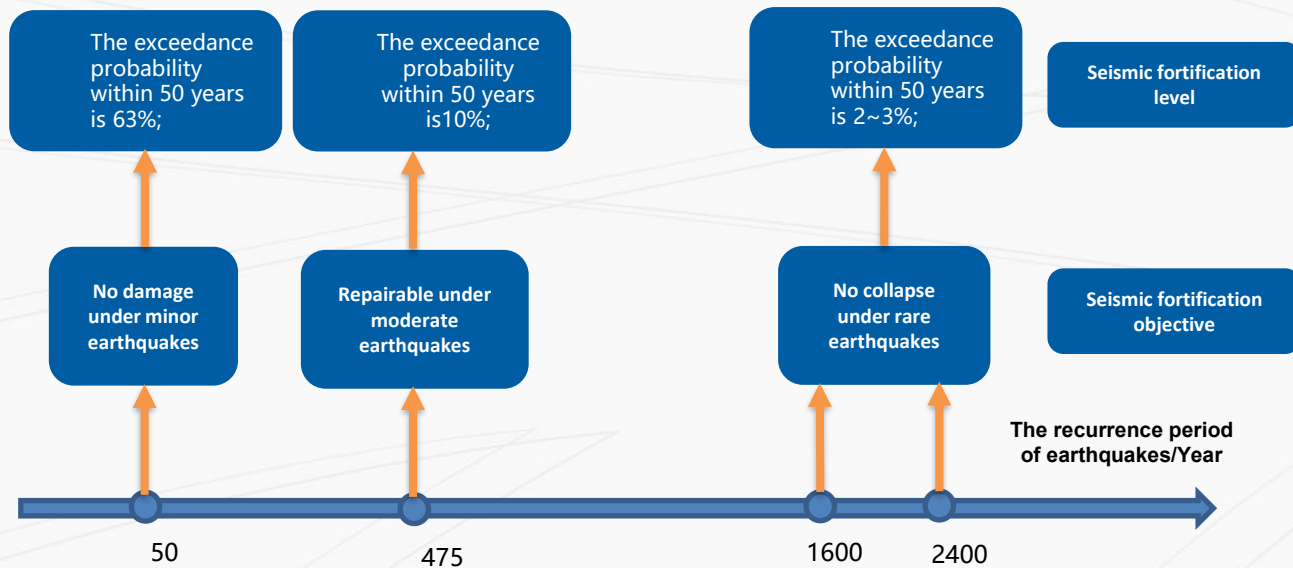
Q & A

Earthquake-Resistant Buildings

□ Seismic Design of New Buildings

➤ The Seismic Fortification Level and Objective

Three-level fortification and the fortification objective is "no damage under minor earthquakes, repairable under moderate earthquakes, and no collapse under major earthquakes".



The seismic fortification level and objective

Earthquake-Resistant Buildings

➤ Two-stage Seismic Design Method

- Verification of bearing capacity and elastic deformation under Minor earthquakes;
- Verification of elastoplastic deformation under rare earthquakes.

Building Type	First Stage (Minor earthquakes)	Second Stage (Rare earthquakes)
General building\Buildings with special requirements other than the eight categories in the two zones, shall undergo checking calculations under Major earthquakes	General buildings only need to check the structural resistance and deformation under minor earthquakes.	General buildings do not require verification; only buildings with special requirements need to undergo verification.
Eight types of buildings including emergency command centers, schools, hospitals, etc. in high-intensity areas and earthquake monitoring and defense zones	Not only check structural resistance and deformation under minor earthquakes, but also under moderate ones.	The structural deformation under rare earthquakes shall be verified.

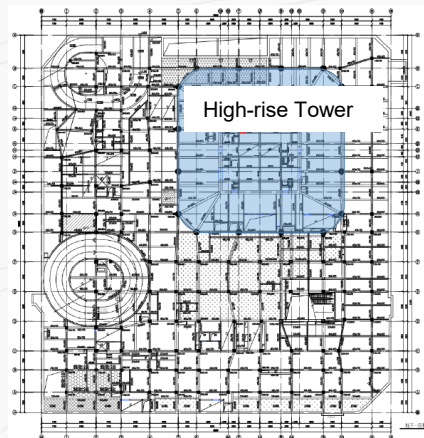
Earthquake-Resistant Buildings

➤ Design Example of A New Building Project

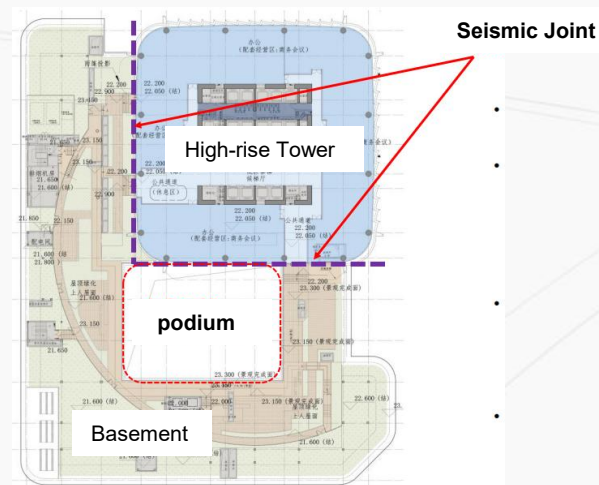
- This project is located within the Lize Financial Business District in Beijing, consisting of one super high-rise tower and one attached podiums. The tower stands at a height of 178.95 meters, and there are four basement floors. The structure system adopted is steel frame (concrete-filled circular tubular columns) + reinforced concrete core tube structure.
- In the seismic design of this project, structural capacity and deformation checking are carried out under both Minor and Rare earthquakes, while key structure components were designed elastically under Moderate Earthquakes.



Architectural design rendering



Structural layout plan



Layout drawing of seismic joints

Earthquake-Resistant Buildings

➤ Design Process for Seismic design of Existing Buildings

The check indexes for the three-level fortification are as follows:



Three-level
fortification

Minor earthquakes	Check index				
	Structural resistance	Displacement ratio	Floor shear bearing capacity ratio	Lateral stiffness ratio of floors	Elastic interlayer displacement angle
	√	√	√	√	√

Moderate earthquakes	Adopt seismic measures to ensure.
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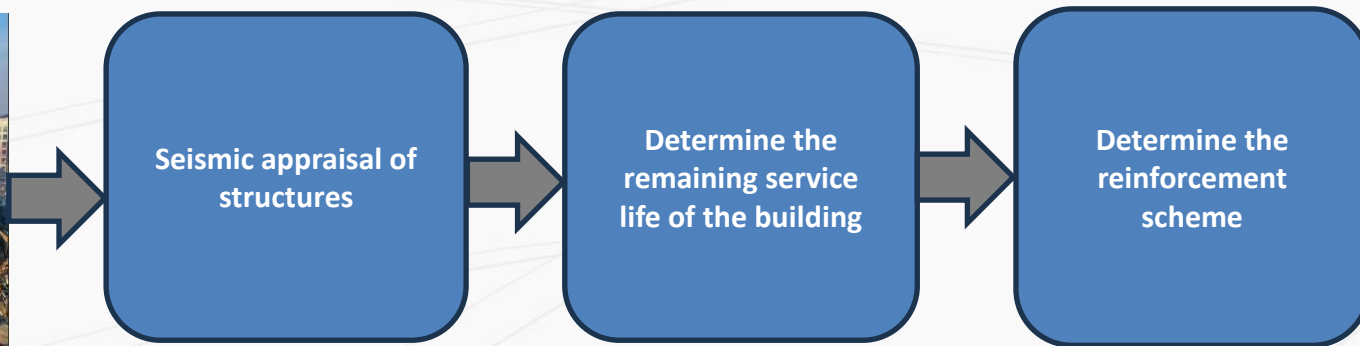
Rare earthquakes	Check index				
	Structural resistance	Displacement ratio	Floor shear bearing capacity ratio	Lateral stiffness ratio of floors	Plastic interlayer displacement angle
	/	/	/	/	√

Earthquake-Resistant Buildings

❑ Seismic Strengthening Design of Existing Buildings

➤ Design Process for Seismic Strengthening of Existing Buildings

- For seismic strengthening of existing buildings, seismic behavior evaluation is usually carried out first.
- Based on the evaluation results, determine the remaining service life of the building and determine the retrofit scheme.
- Determine the final strengthening design considering performance, constructability and cost.



Design process for seismic strengthening of existing buildings

Earthquake-Resistant Buildings

➤ Seismic Strengthening Scheme for Existing Structures

- Strengthening by changing the structural lateral force-resisting system.
- Strengthening of structural components.
 - 1) Strengthening structural components by the section enlargement method.



Bracing reinforcement method with Buckling-Restrained Braces (BRBs)



Strengthening method by adding shear walls to frame structures



Section enlargement strengthening method for frame columns



Masonry wall reinforcement method using reinforced concrete, mortar overlays



Masonry wall reinforcement method using high-toughness fiber-reinforced concrete overlays

Earthquake-Resistant Buildings

2) External bonded steel section strengthening method for structural components.



External bonded steel section strengthening method for concrete walls



External bonded steel section strengthening method for frame columns



Bonded steel plate reinforcement for cast-in-place slab

3) Bonded fiber cloth strengthening method for structural components.



Externally bonded fiber sheet strengthening method for frame columns



Fiber cloth bonding reinforcement method for frame beams



Bonded fiber cloth reinforcement for cast-in-place slab

Earthquake-Resistant Buildings

➤ Project Example of Existing Building Strengthening

A case of house reinforcement after the 2008 Wenchuan earthquake . After seismic inspection and appraisal, it was identified that the residential building had insufficient stiffness. To enhance the lateral resistance capacity of the structure, a reinforcement method involving modifying the structural lateral force-resisting system was adopted, specifically by adding inter-column braces.



A residential building after the 2008 Wenchuan earthquake



Support reinforcement node

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Bridge Seismic Design and Examples

❑ Performance-Based Design

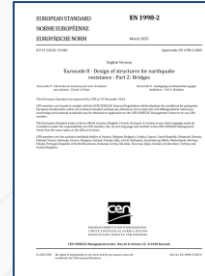
➤ Design Philosophy (per US Standards):

- Small-to-moderate earthquakes (Functional Evaluation Earthquake, FEE): within the elastic range of the structural components without significant damage.
- Moderate-to-large earthquakes (Safety Evaluation Earthquake, SEE): No collapse of all or part of the bridge and reparable damages.

BRIDGE CATEGORY	SEISMIC HAZARD EVALUATION LEVEL	EXPECTED POST EARTHQUAKE DAMAGE STATE	EXPECTED POST EARTHQUAKE SERVICE LEVEL
Ordinary	SEE	Major	No Service
Essential (Recovery)	SEE	Moderate	Limited Service-weeks
	FEE	Minimal	Full Service
Critical (Important)	SEE	Minimal to Moderate	Limited Service-days
	FEE	None to Minimal	Full Service

➤ International Seismic Design Standards:

- AASHTO LRFD Bridge Design Specifications
- AASHTO Guide Specifications for LRFD Seismic Bridge Design
- AASHTO Guide Specifications for Seismic Isolation Design
- AASHTO Guidelines for Performance-Based Seismic Design of Highway Bridges, 1st Edition (2023)
- Eurocode 8 (EN 1998) Part 2 Seismic Design of Bridges

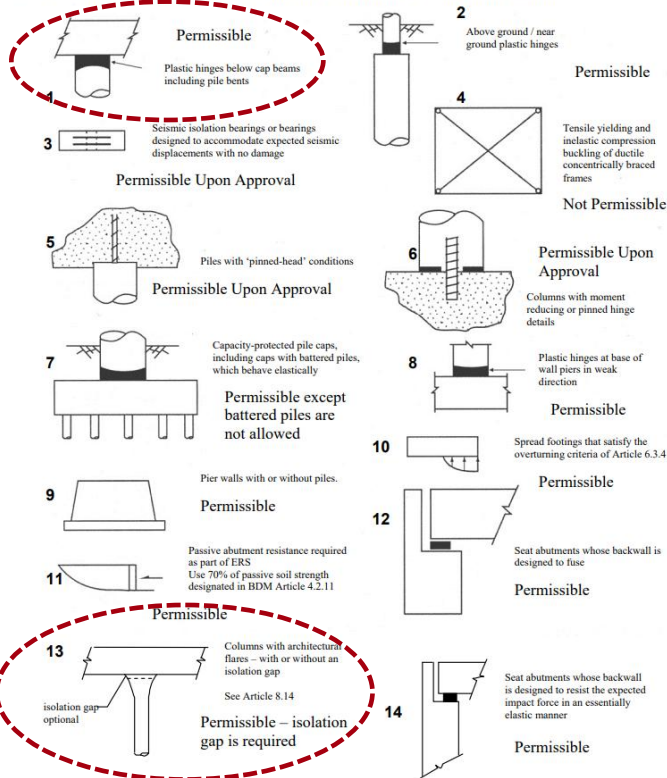


Bridge Seismic Design and Examples

Performance-Based Design

Earthquake-Resistant Structural Systems (ERS):

BDM Figure 4.2.2-2 Figure 3.3-1b Permissible Earthquake-Resisting Elements (EREs)



Design Approach (SDC C for example):

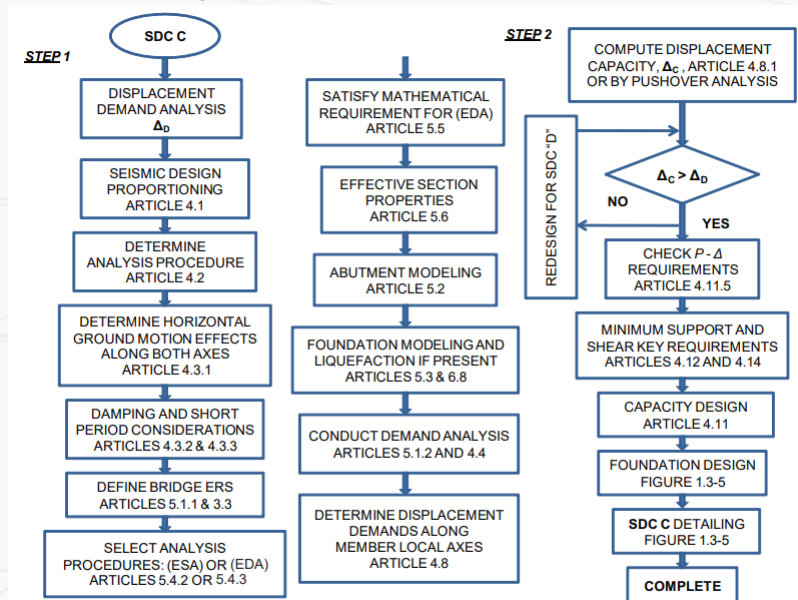


Figure 1.3-3—Seismic Design Procedure Flowchart for Bridges in SDC C

Seismic Design Category (AASHTO)

Value of $S_{D1} = F_V S_1$	Seismic Design Category (SDC)
$S_{D1} < 0.15$	A
$0.15 \leq S_{D1} < 0.30$	B
$0.30 \leq S_{D1} < 0.50$	C
$0.50 \leq S_{D1}$	D

Decide inelastic structural mechanism under the earthquake

Design the elements to continue to resist applied loading with ductility.

Develop a complete load path with other components for capacity-protected design.

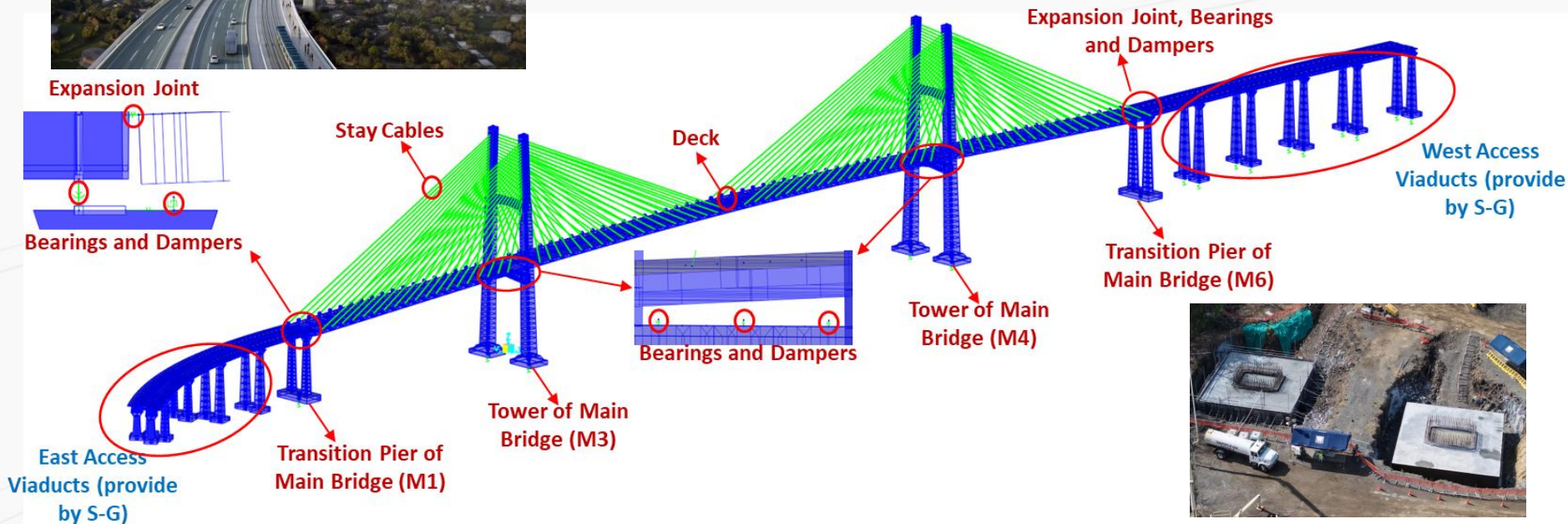
Bridge Seismic Design and Examples

❑ CHEC Project Example - Panama Canal 4th Bridge



Design (Left View) and FE Analysis Model Fundamentals

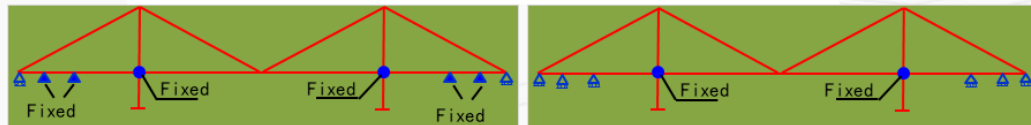
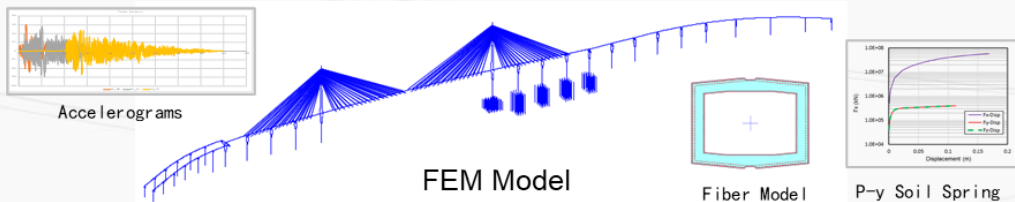
Nonlinear finite element models consisting of the main bridge structure are established, consisting of towers and piers, east access viaducts, west access, cable stays, superstructure/deck, bearings, expansion joints, dampers and pile-caps.



Bridge Seismic Design and Examples

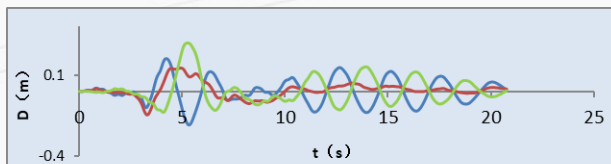
The tower-beam-pier consolidation system and design method for dual-purpose cable-stayed bridges in strong earthquake zones were proposed, which solved the technical problems of large longitudinal expansion and contraction deformation and asynchronous lateral movement of the main and approach bridges under earthquake action, and improved the static and dynamic stress performance of the cable-stayed bridge.

ERS

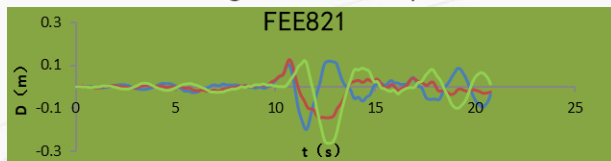


All Fixed Piers

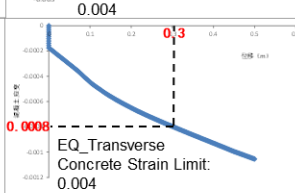
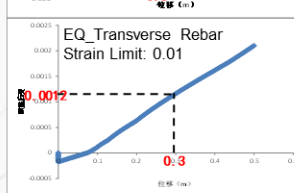
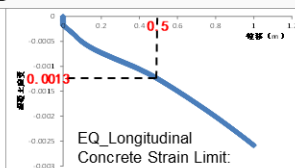
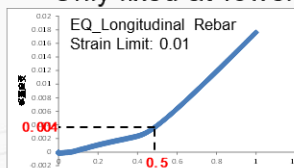
Only fixed at Towers



Longitudinal Disp



Longitudinal Deformation - FEE



Performance Levels – Steel and Concrete Strain

➤ The consolidation system can better control the seismic displacement of the structure, and has the conditions

- The main beam has a large mass, and the large inertial force under earthquakes requires a high scale of seismic isolation measures
- The flexible structure of typical high piers and towers has a certain seismic isolation capacity
- Under SEE earthquakes, towers and piers are allowed to enter plasticity

Conclusions

➤ Recommended ERS

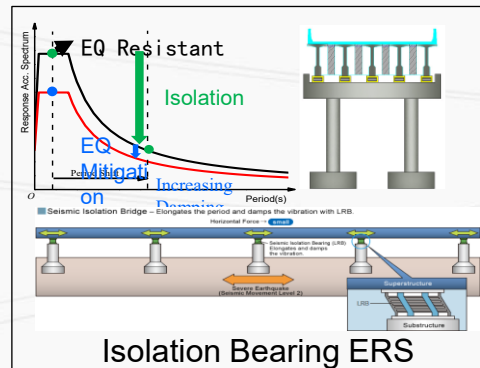
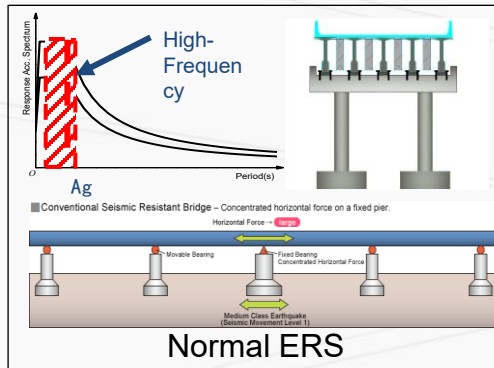
- FEE earthquake: the longitudinal expansion and contraction deformation of the main bridge end $\leq \pm 400\text{mm}$
- FEE earthquake: all components of the cable-stayed bridge are intact and do not need to be repaired or replaced
- SEE earthquake: the strain of steel bars ≤ 0.01 , and the strain of concrete ≤ 0.004

Analysis Results

Bridge Seismic Design and Examples

Anisotropic seismic isolation system suitable for long-span continuous girder bridges to solve the challenges of large differences in longitudinal and lateral dynamic characteristics as well as complex structural stress distributions, hence improve the structural seismic performance.

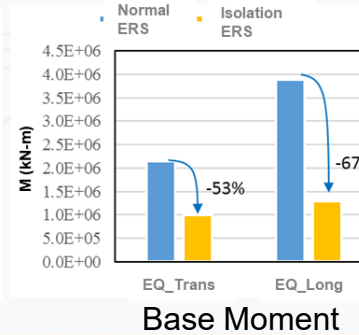
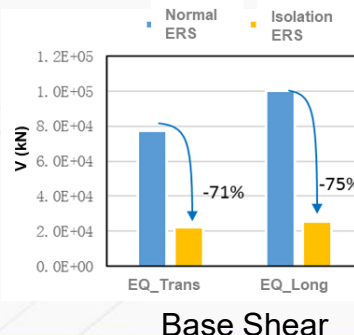
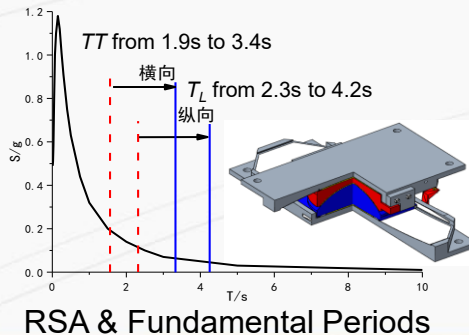
ERS



➤ Performance-based isolation system:

- Challenges for sufficient strength resisting inertia force in high seismic zone. Conventional fixed piers to limit seismic load through plastic hinges
- Significant differences in longitudinal and lateral dynamic characteristics
- Isolation system, extending the natural vibration period, avoiding the strong earthquake frequency range, and reducing shock energy consumption

Analysis Results



C o n c l u s i o n s

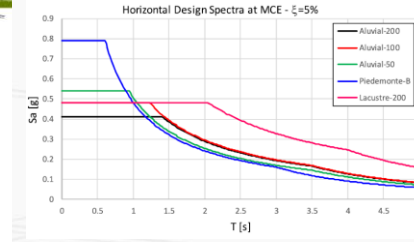
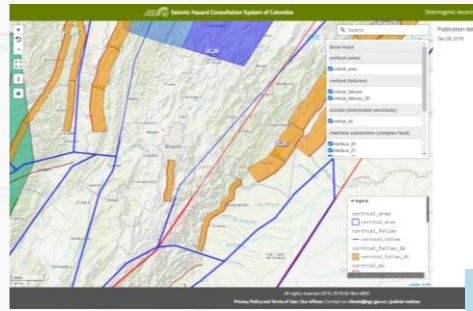
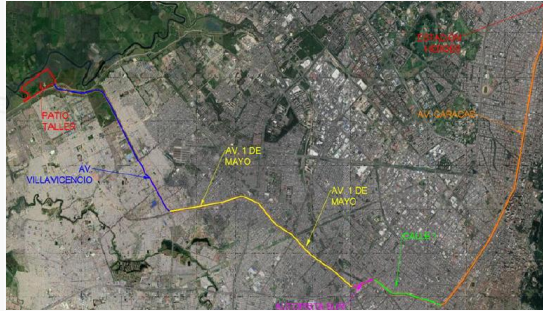
➤ Anisotropic seismic isolation system

- T longitudinal from 2.3s to 4.2s, T transverse from 1.9s to 3.4s.
- Seismic force demands reduced by up to 50%.
- Smaller RC members to improve the economic efficiency.

Bridge Seismic Design and Examples

❑ CHEC Project Example – Bogota Metro Line 1

➤ Project Layout and Seismic Design Basics:



MCE Design Spectra (1000 YR-RP)

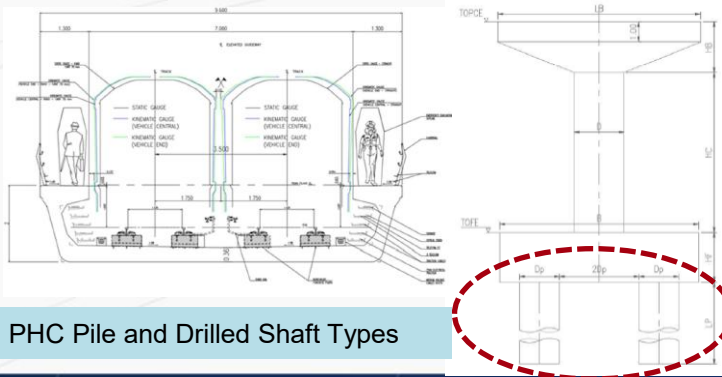
Tabla 23 – Factores de Modificación de Respuesta - Subestructuras

Estructura de Viaducto	Categoría Operacional Esencial
Pila-pilotes de concreto reforzado con pilotes verticales únicamente	2.0
Pila-pilotes de concreto reforzado con pilotes inclinados	1.5
Columnas Individuales	2.0
Pórticos con múltiples columnas	3.5

Fuente: Adaptado de LRFD-CCP-14

Response Modification Factor

➤ Aerial Viaduct Design and Actual Photos



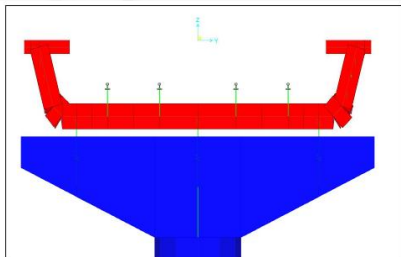
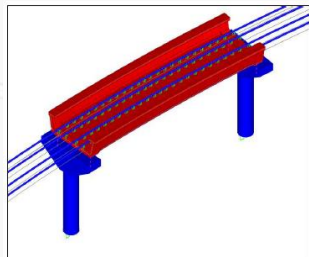
PHC Pile and Drilled Shaft Types



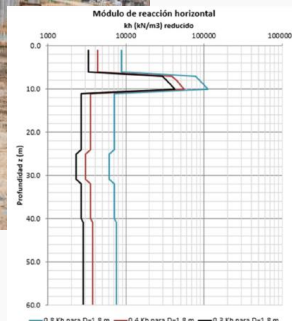
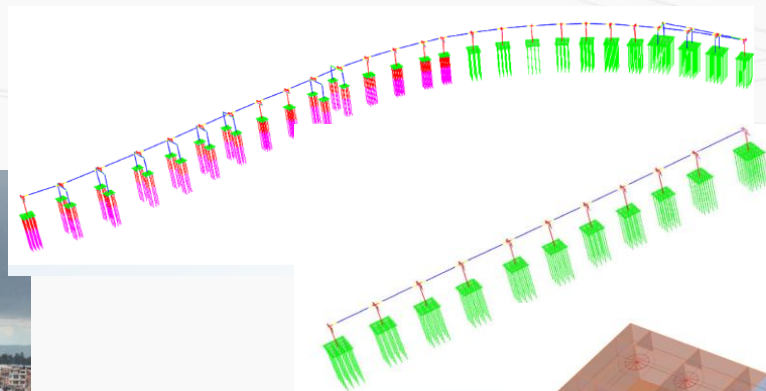
Bridge Seismic Design and Examples

❑ Aerial Viaduct Structure and Foundation Analysis

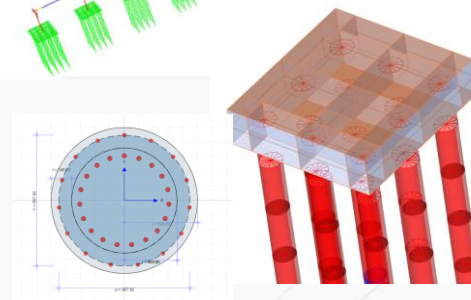
- Aerial Viaduct Modelled in SAP2000 / CSiBridge: Soil-Pile interaction using soil springs



CSiBridge Modeling for Detailed Girder and Pier Design



Pile Lateral Reaction



SAP2000 Modeling for Detailed Pile Cap and Foundation Design

Bridge Seismic Design and Examples

❑ CHEC Project Example – Bogota Metro Line 1



Bridge Seismic Design and Examples

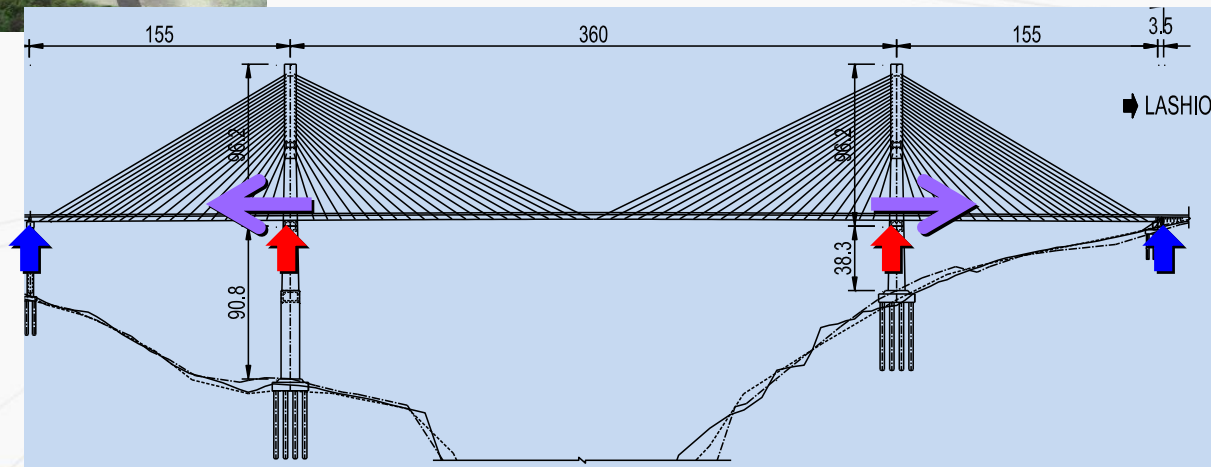
❑ CHEC Project Example - GOTE HTEIK BRIDGE



Design (Left View) and FE Analysis Model Fundamentals

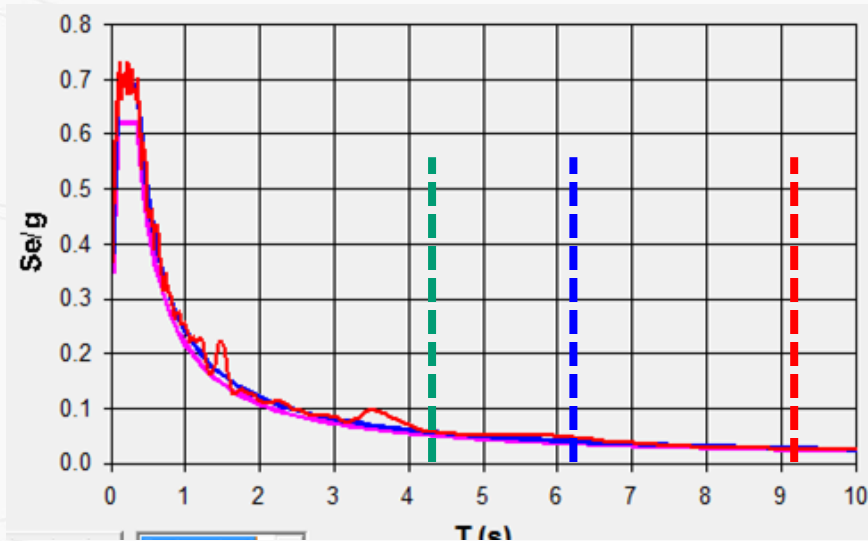
Nonlinear finite element models consisting of the main bridge structure are established, consisting of pylons, piers, superstructure/deck, cables, bearings, dampers and pile foundation.

- Pot rubber bearings used as the vertical support at the pylon and pier.
- Viscous hydraulic damper used as the longitudinal dampers at the pylon
- Elastoplastic steel damper used as the lateral dampers at the pylon

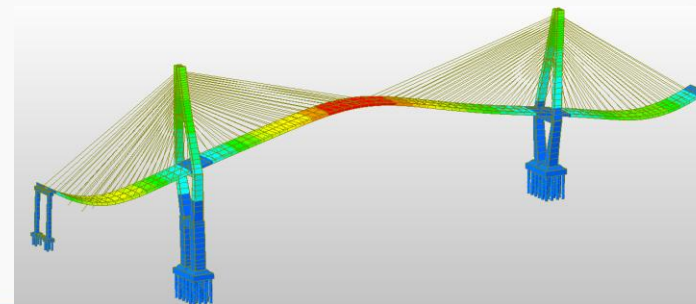
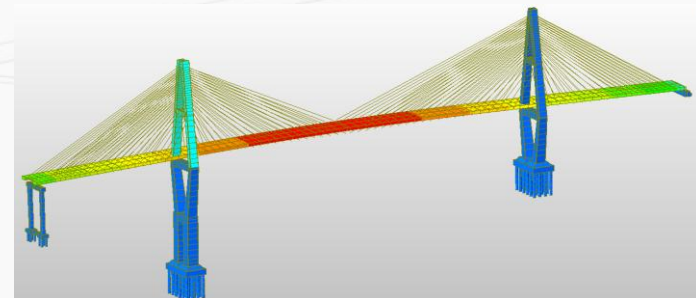
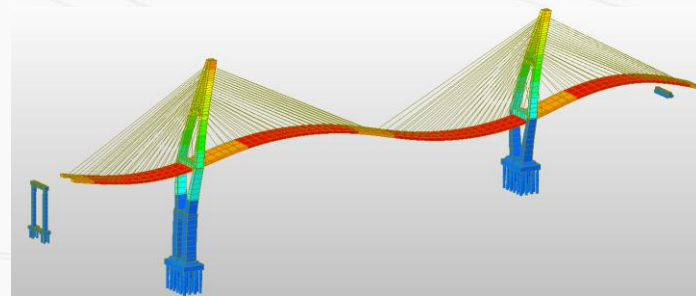


Bridge Seismic Design and Examples

❑ Proposed Project - GOTE HTEIK BRIDGE

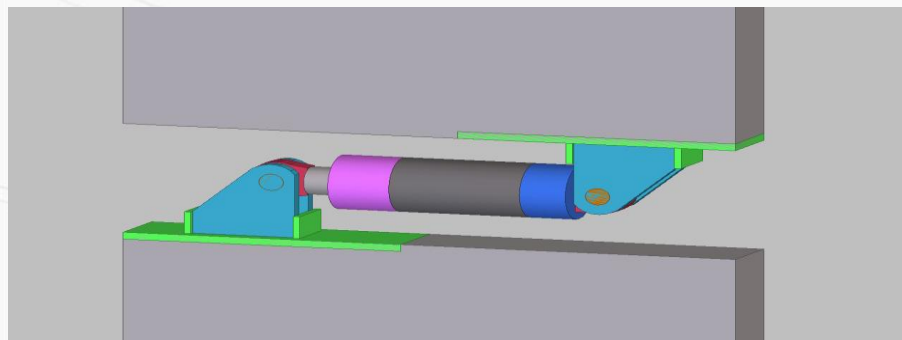


Mode	Cycle (T,s)	Vibration mode description
1	9.095	Longitudinal floating
2	6.220	One-order symmetric side bending+No.8 pylon side bending
5	4.096	One-order symmetric vertical bending



Bridge Seismic Design and Examples

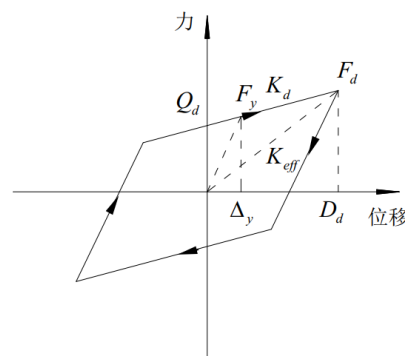
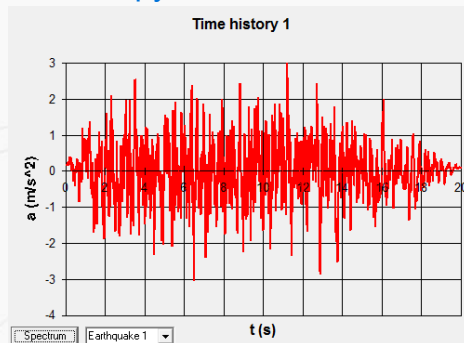
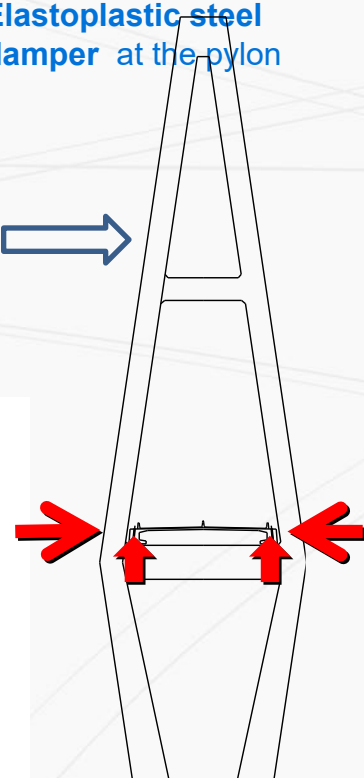
❑ Proposed Project - GOTE HTEIK BRIDGE **Dampers used to restrict bridge displacement**



Longitudinal direction **Viscous hydraulic damper** at the pylon



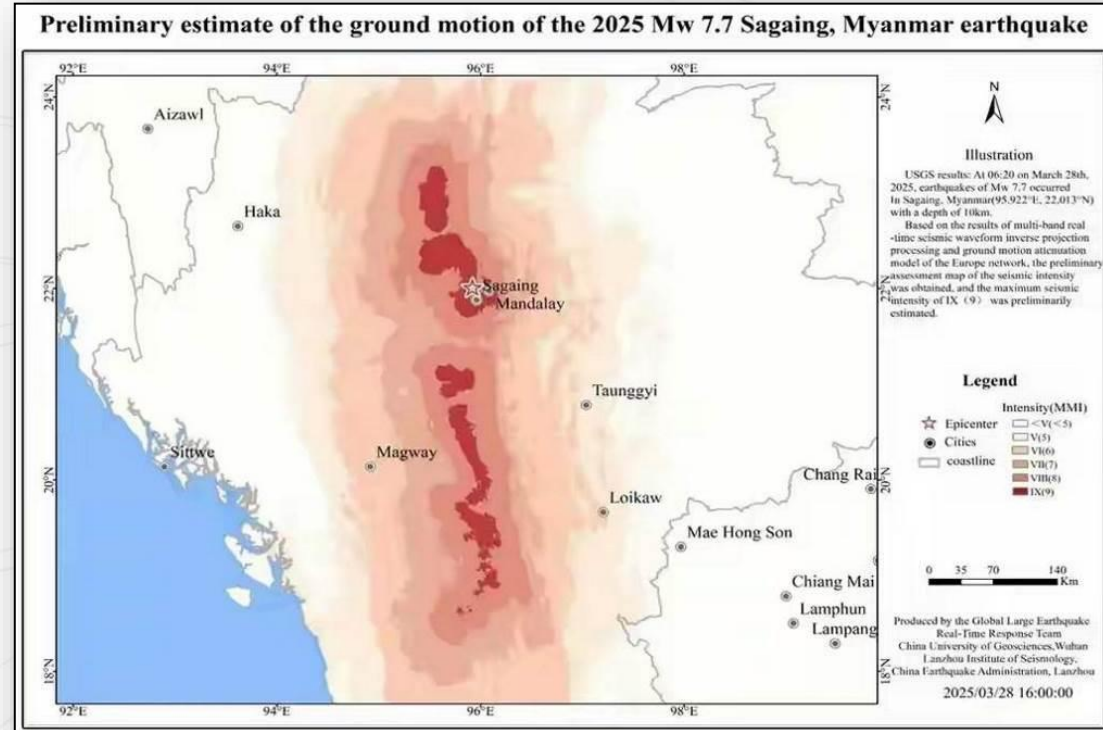
Lateral direction **Elastoplastic steel damper** at the pylon



Bridge Seismic Design and Examples

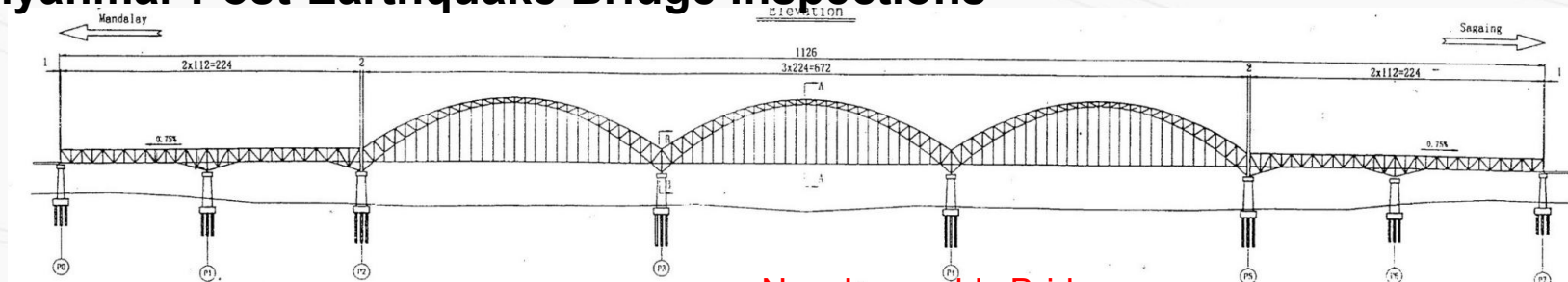
❑ Myanmar Post-Earthquake Bridge Inspections

- The Mw7.7 Mandalay earthquake on Mar 28, 2025 has the epicenter as shallow as 10 degrees, and multiple after-shocks in the same area. Severe infrastructure damages observed in Sagaing, Mandalay, Naypyidaw, and other regions.
- CHEC formed and led a professional team with CCCC-IMG, visiting the disaster area to conduct damage investigations, assessments, and treatment recommendations for infrastructure, providing professional opinions for retrofit or reconstruction work.
- In this earthquake, many infrastructure such as bridges and buildings suffered significant damages, which will provide some reference for the seismic design of subsequent infrastructure.



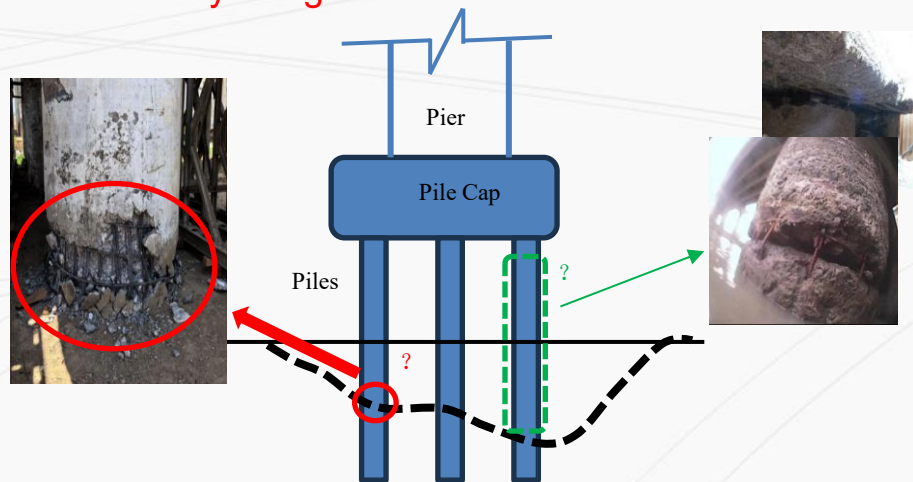
Bridge Seismic Design and Examples

❑ Myanmar Post-Earthquake Bridge Inspections



Failure mode of steel truss arch bridge components

New Irrawaddy Bridge



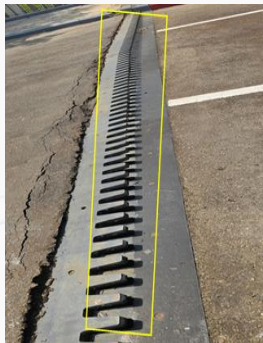
Hidden Damages

Bridge Seismic Design and Examples

❑ Myanmar Post-Earthquake Bridge Inspections



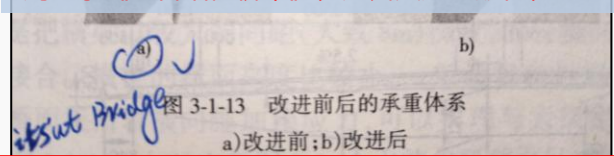
Failure modes of beam bridge components



What are the goals and significance of design optimization?



刘玉擎《组合结构桥梁》，人民交通出版社，2005



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Seismic Hazard

Earthquake-Resistant Buildings

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Summary

Q & A

□ Performance-Based Design

➤ Design Philosophy (per US Standard ASCE 61-14):

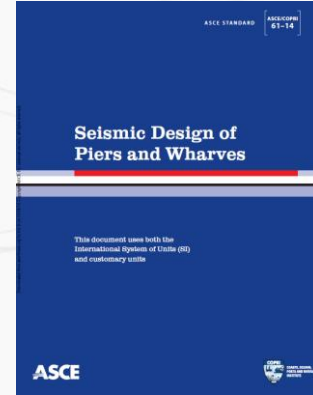
- Operational Level Earthquake, OLE: No significant structural damage, minimal or no interruption to wharf operations.
- Contingency Level earthquakes CLE: Controlled inelastic structural behavior and limited deformations. Only temporary or short-term loss of operations.
- Design Level Earthquake: Safeguards life and guards against major structural failures.

Table 2-1. Minimum Seismic Hazard and Performance Requirements

Seismic hazard level and performance level						
Operating level earthquake (OLE)			Contingency level earthquake (CLE)		Design earthquake (DE)	
	Ground motion probability of exceedance	Performance level	Ground motion probability of exceedance	Performance level	Seismic hazard level	Performance level
High	50% in 50 years (72-year return period)	Minimal damage	10% in 50 years (475-year return period)	Controlled and repairable damage	Design earthquake per ASCE 7 (2005)	Life safety protection
Moderate	N/A	N/A	20% in 50 years (224-year return period)	Controlled and repairable damage	Design earthquake per ASCE 7 (2005)	Life safety protection
Low	N/A	N/A	N/A	N/A	Design earthquake per ASCE 7 (2005)	Life safety protection

➤ International Seismic Design Standards and References:

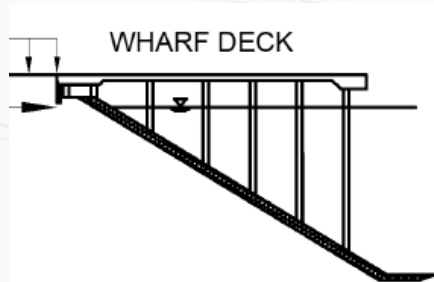
- ASCE 61: Seismic Design of Piers and Wharves
- PIANC Seismic Design Guidelines for Port Structures (2001)
- Eurocode 8 (EN 1998) Part 2 and 5 Seismic Design of Bridges, Foundations



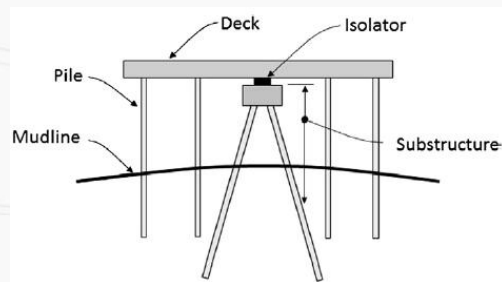
Port Seismic Design and Examples

Performance-Based Design

Earthquake-Resistant Structural Systems (ERS):



Vertical Piles considering inelastic performance



Battered Piles combined with isolation system

Most Popular - Pile Hinge Mechanism:

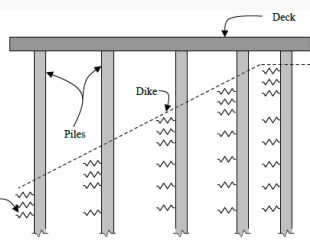
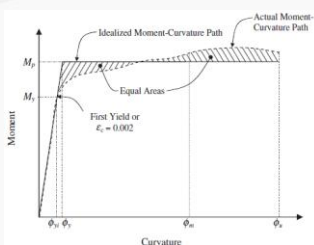
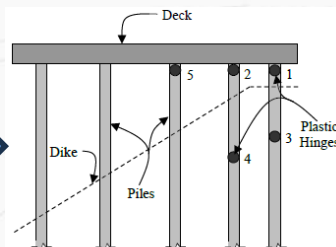
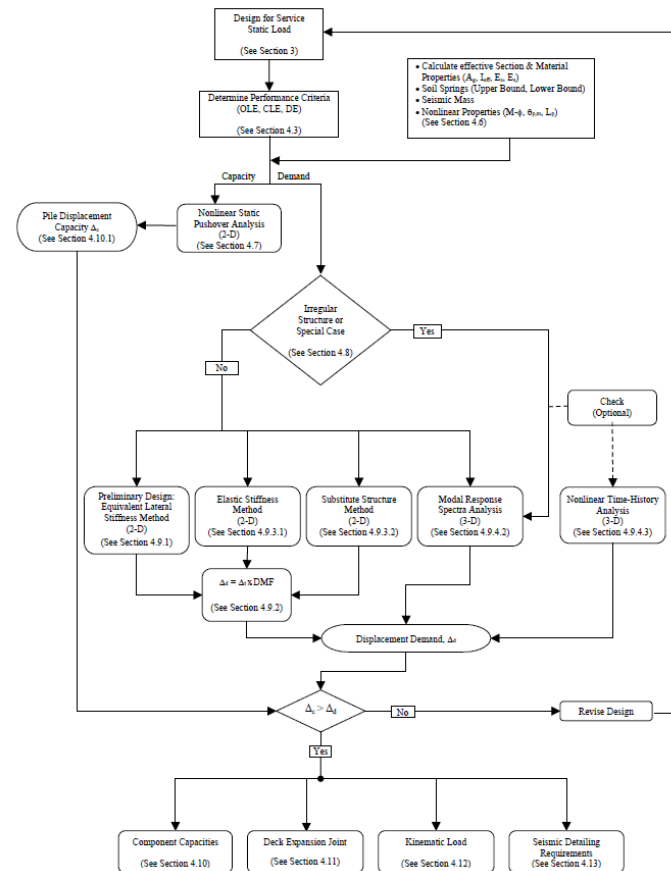


Figure 4-14: Pushover Model with p-y Springs



b) Example of Plastic Hinge Sequence

Design Approach (POLB WDC, 2021):



Port Seismic Design and Examples

□ Performance-Based Design

➤ Limit State Definitions for Pile Supported Wharves:

Table 3-1. Strain Limits for “Minimal Damage” per Section 2.4.3

Pile type	Component	Hinge location		
		Top of pile	In ground	Deep in ground (>10D _p)
Solid concrete pile	Concrete	$\epsilon_c \leq 0.005$	$\epsilon_c \leq 0.005$	$\epsilon_c \leq 0.008$
	Reinforcing steel	$\epsilon_s \leq 0.015$		
	Prestressing steel		$\epsilon_p \leq 0.015$	$\epsilon_p \leq 0.015$
Hollow concrete pile ^a	Concrete	$\epsilon_c \leq 0.004$	$\epsilon_c \leq 0.004$	$\epsilon_c \leq 0.004$
	Reinforcing steel	$\epsilon_s \leq 0.015$		
	Prestressing steel		$\epsilon_p \leq 0.015$	$\epsilon_p \leq 0.015$
Steel pipe pile	Steel pipe		$\epsilon_s \leq 0.010$	$\epsilon_s \leq 0.010$
	Concrete	$\epsilon_c \leq 0.010$		
	Reinforcing steel	$\epsilon_s \leq 0.015$		

^aIf the interior of the hollow pile is filled with concrete, all strain limits shall be the same as for solid piles.

Table 3-2. Strain Limits for “Controlled and Repairable Damage” per Section 2.4.2

Pile type	Component	Hinge location		
		Top of pile	In ground	Deep in ground (>10D _p)
Solid concrete pile	Concrete	$\epsilon_c \leq 0.005 + 1.1\rho_s \leq 0.025$	$\epsilon_c \leq 0.005 + 1.1\rho_s \leq 0.008$	$\epsilon_c \leq 0.012$
	Reinforcing steel	$\epsilon_s \leq 0.6\epsilon_{smd} \leq 0.06$		
	Prestressing steel		$\epsilon_p \leq 0.025$	$\epsilon_p \leq 0.025$
Hollow concrete pile ^a	Concrete	$\epsilon_c \leq 0.006$	$\epsilon_c \leq 0.006$	$\epsilon_c \leq 0.006$
	Reinforcing steel	$\epsilon_s \leq 0.4\epsilon_{smd} \leq 0.04$		
	Prestressing steel		$\epsilon_p \leq 0.020$	$\epsilon_p \leq 0.025$
Steel pipe pile	Steel pipe		$\epsilon_s \leq 0.025^b$	$\epsilon_s \leq 0.035$
	Concrete	$\epsilon_c \leq 0.025$		
	Reinforcing steel	$\epsilon_s \leq 0.6\epsilon_{smd} \leq 0.06$		

^aIf the interior of the hollow pile is filled with concrete, all strain limits shall be the same as for solid piles.

^bIf the steel pipe pile is infilled with concrete, a value of 0.035 may be used.

Table 3-3. Strain Limits for “Life Safety Protection” per Section 2.4.1

Pile type	Component	Hinge location		
		Top of pile	In ground	Deep in ground (>10D _p)
Solid concrete pile	Concrete	No limit	$\epsilon_c \leq 0.005 + 1.1\rho_s \leq 0.012$	No limit
	Reinforcing steel	$\epsilon_s \leq 0.8\epsilon_{smd} \leq 0.08$		
	Prestressing steel		$\epsilon_p \leq 0.035$	$\epsilon_p \leq 0.050$
Hollow concrete pile ^a	Concrete	$\epsilon_c \leq 0.008$	$\epsilon_c \leq 0.008$	$\epsilon_c \leq 0.008$
	Reinforcing steel	$\epsilon_s \leq 0.6\epsilon_{smd} \leq 0.06$		
	Prestressing steel		$\epsilon_p \leq 0.025$	$\epsilon_p \leq 0.050$
Steel pipe pile	Steel pipe		$\epsilon_s \leq 0.035^b$	$\epsilon_s \leq 0.050$
	Concrete	No limit		
	Reinforcing steel	$\epsilon_s \leq 0.8\epsilon_{smd} \leq 0.08$		

^aIf the interior of the hollow pile is filled with concrete, all strain limits shall be the same as for solid piles.

^bIf the steel pipe pile is infilled with concrete, a value of 0.050 may be used.

OLE – Minimal Damage

CLE – Controlled & Repairable Damage

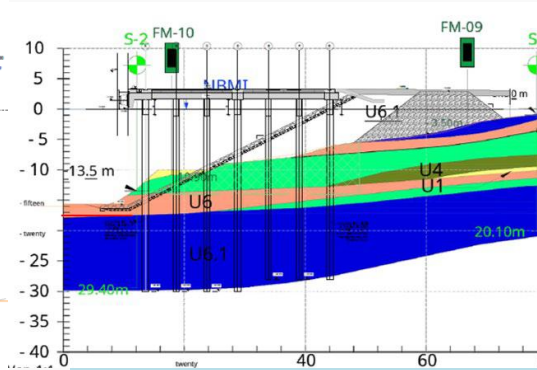
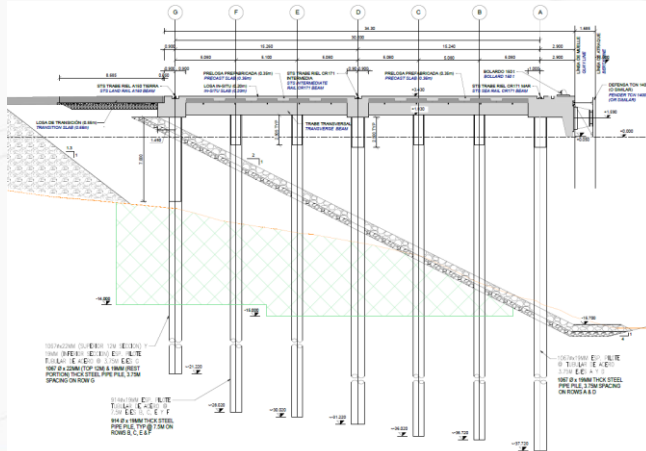
DE – Life Safety Protection

Port Seismic Design and Examples

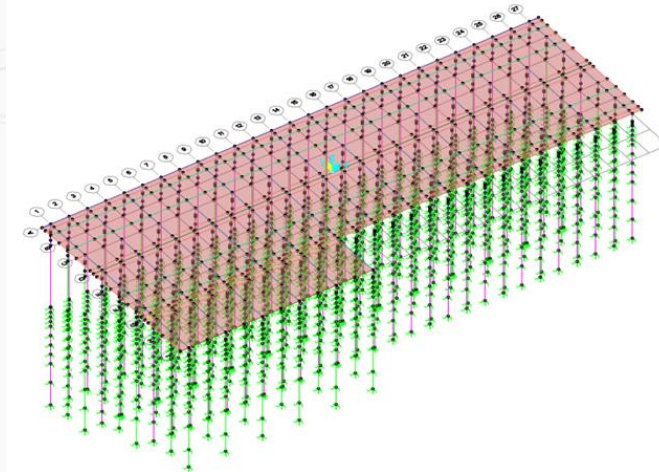
❑ CHEC Project Example – Mexican Ensenada Hutchinsonson Port Project

Design Element	Main standard	
	Static Situation	Seismic Situation
Geotechnical Pile design	AASHTO 2020 – ASCE 61	AASHTO 2020 – ASCE 61
Global stability	ASCE 61	ASCE 61
Structural design of piles	API RP 2A (Steel Pipe) ACI 318-19 (RC Pile plug)	PoLB WDC, ACI 318-19 (RC Pile plug)
Superstructure design	ACI 318-19	ASCE 61 - ACI 318-19
Seismic design spectrum	-	CFE Design Manual. Seismic Design (2015)

- LRFD Static Load Analysis
- Displacement-based Seismic Design



Example Geotechnical Profile

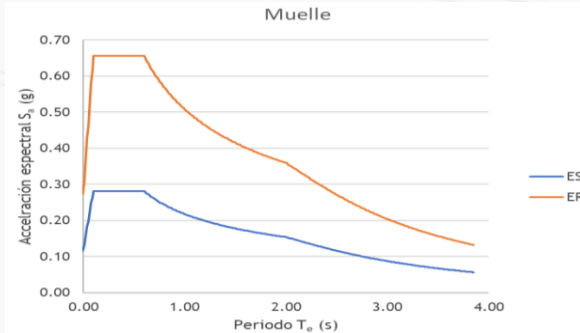


3D FEM Model in SAP2000
(Module 1 as example)

Port Seismic Design and Examples

❑ CHEC Project Example – Mexican Ensenada Hutchinsonson Port Project

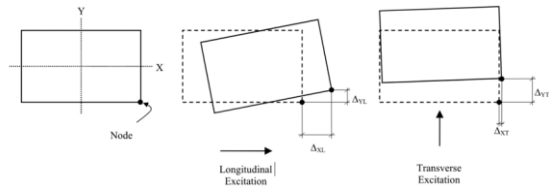
- Response Spectrum Analysis (RSA) is performed in SAP2000 to obtain seismic displacement demand of the quay structure per ASCE 61-14 and PoLB v5.0



Design Spectrum

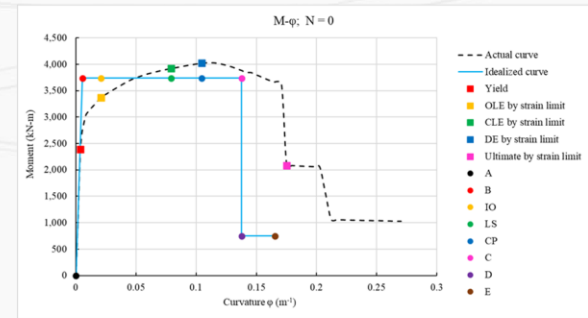
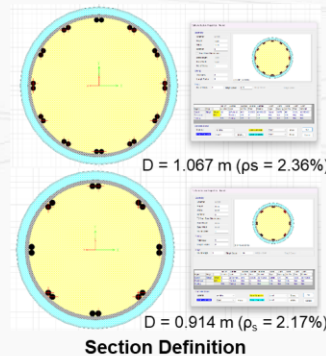
$$\Delta_{X1} = \Delta_{XL} + 0.3\Delta_{XT} \quad \Delta_{X2} = 0.3\Delta_{XL} + \Delta_{XT} \quad \Delta_d = \max\left(\sqrt{\Delta_{X1}^2 + \Delta_{Y1}^2} \text{ or } \sqrt{\Delta_{X2}^2 + \Delta_{Y2}^2}\right)$$

$$\Delta_{Y1} = \Delta_{YL} + 0.3\Delta_{YT} \quad \Delta_{Y2} = 0.3\Delta_{YL} + \Delta_{YT}$$

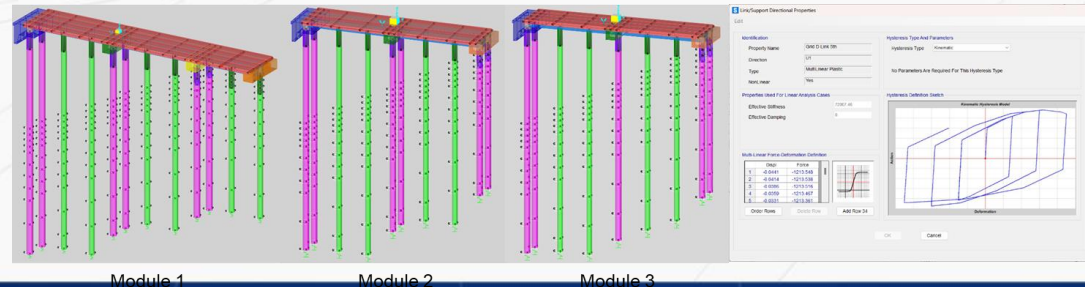


Directional Combination

- Moment-curvature curve of the RC plug hinge is determined per the Method B in ASCE 61-14, and the idealized plastic moment capacity is calculated from Caltrans method. Pushover analysis was conducted to obtain capacity.



Representative M- ϕ Curve of the Plastic Hinge (RC Pile Plug)

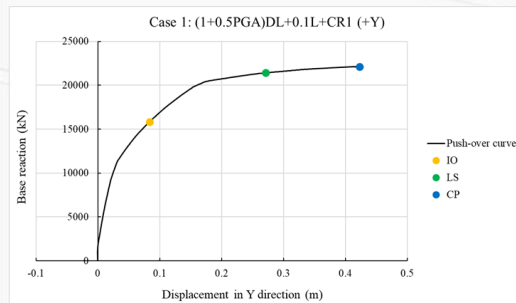


Port Seismic Design and Examples

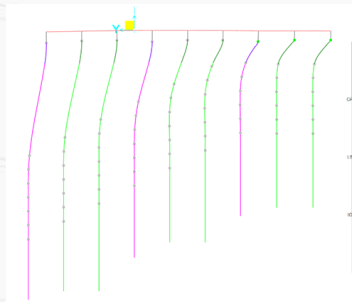
❑ CHEC Project Example – Mexican Ensenada Hutchinsonson Port Project

➤ Pushover Analysis Results and Check Against Demand

➤ Kinematic Load Case



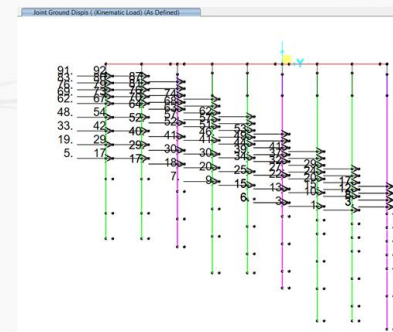
Example Pushover Curve Result (Module 1, UB)



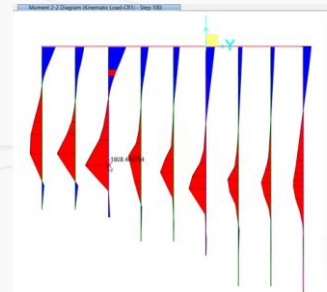
Example Pushover Deformation (Module 1, UB)

Pushover Resistance Check Results for Steel Piles (UB, Flexure and Compression, Module 1)

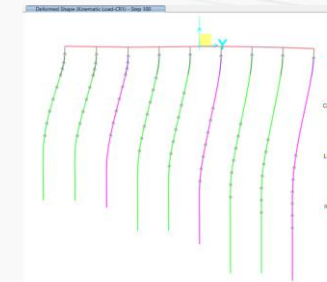
UB Gridline	P_r kN	M_r kN-m	P_c kN	M_c kN-m	P_r/P_c	M_r/M_c	Capacity ratio
A	3481.45	1764.65	14608	6580	0.238	0.268	0.48
B	2002.08	1415.36	12480	4917	0.160	0.288	0.37
C	1159.29	1804.29	13777	4917	0.084	0.367	0.41
D	1131.76	2914.25	18269	6580	0.062	0.443	0.47
E	1080.01	2932.14	16055	4917	0.067	0.596	0.63
F	1266.36	3457.27	16951	4917	0.075	0.703	0.74
G	2664.31	6793.12	23917	7751	0.111	0.876	0.93
H	2521.87	4303.17	17798	4917	0.142	0.875	0.95
J	2684.12	4295.82	17798	4917	0.151	0.874	0.95



Kinematic Load Displacement



Moment Distribution on Piles



Pile Deformation and Hinge Status

- The representative load demands on steel piles, as well as the visualized plastic hinge status, indicate that all steel piles are within elastic stage under kinematic loads. Not control!

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Summary

- ❑ As one of the greatest disasters, earthquake-induced damages are the reflection of geological hazard of active faults, seismic wave propagation and site responses, structural and foundation failures, etc. It is crucial to follow reasonable design philosophies like performance-based design and adopt viable methods for seismic analyses.
- ❑ Performance-Based Design strategies are fundamentally similar among building, bridge and marine field with different mechanisms and focuses. Typical seismic design follows the approach: PSHA → SRA → Soil-Foundation Interaction → structural seismic analysis (static or dynamic) → Foundation and Structural detailing.
- ❑ In this presentation, comprehensive studies in fields of building, bridge and port were summarized to cover the key aspects: design standards; ERS with inelastic hinges or isolations; seismic input; foundation risk and ground improvement; structural modeling and analysis with soil-structure interaction; detailed design, etc.
- ❑ Selected CHEC Projects are presented here as illustration of above-mentioned performance-based design and real applications to enhance the resilience of structures under earthquake hit.
- ❑ Advanced analysis tools (software and hardware) allows the seismic studies of more complex foundation and structural system using dynamic methods, and help to determine more effective and efficient earthquake resistance structures.



CHINA HARBOUR