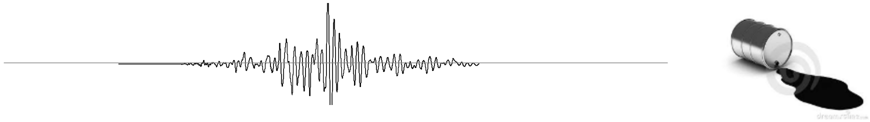
2nd World Congress on

Petroleum and Refinery

June 1-3 , 2017 Osaka, Japan



Seismic Isolation of elevated steel Storage Tanks by Sliding Concave Bearings

Fabrizio Paolacci

ROMA TRE
UNIVERSITÀ DEGLI STUDI

OUTLINE

- Premises
- Objectives of the work
- Discussion on seismic vulnerability reduction of tanks using PCT
- Definition of case study
- Seismic vulnerability of non isolated case
  - Implementation of a 3D numerical model
  - Probabilistic seismic response analysis and fragility evaluation
- Vulnerability-based design of CSBs
  - Numerical model
  - Probabilistic response and optimal selection of isolation period
- Conclusions

ACKNOWLEDGMENT

- The work presented herein has been partially funded by the Italian RELUIS consortium within the executive research program **DPC/ReLUIS 2015** and the **European Research Project INDUSE-2- SAFETY (Grant No. RFS-PR13056).**

OBJECTIVES

- Address the problem of the seismic vulnerability of storage tanks
- Define suitable passive control systems for the seismic protection of storage tanks
- Analyze the seismic fragility of an elevated tank collapsed during the 1999 Itzmit Earthquake by using a 3D simplified modes
- Optimal design of an isolation system based on Concave-sliding bearings by using fragility analysis

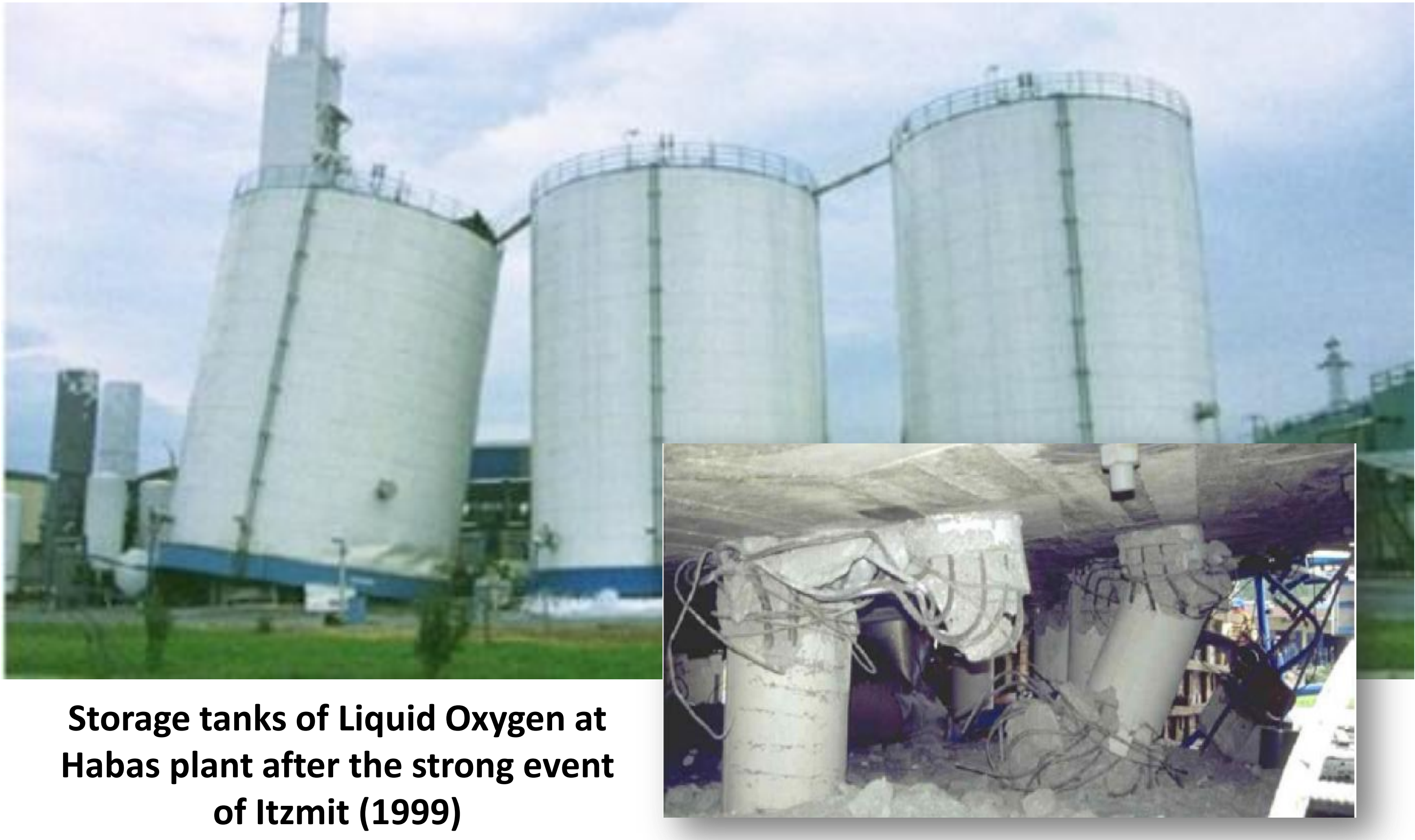
SEISMIC VULNERABILITY OF STORAGE TANKS

Earthquakes can cause damage to industrial liquid storage tanks resulting in loss of functionality, fires, explosions or environmental contaminations due to the leakage of hazardous materials.

Typical damages of tanks due to earthquakes are due essentially to:

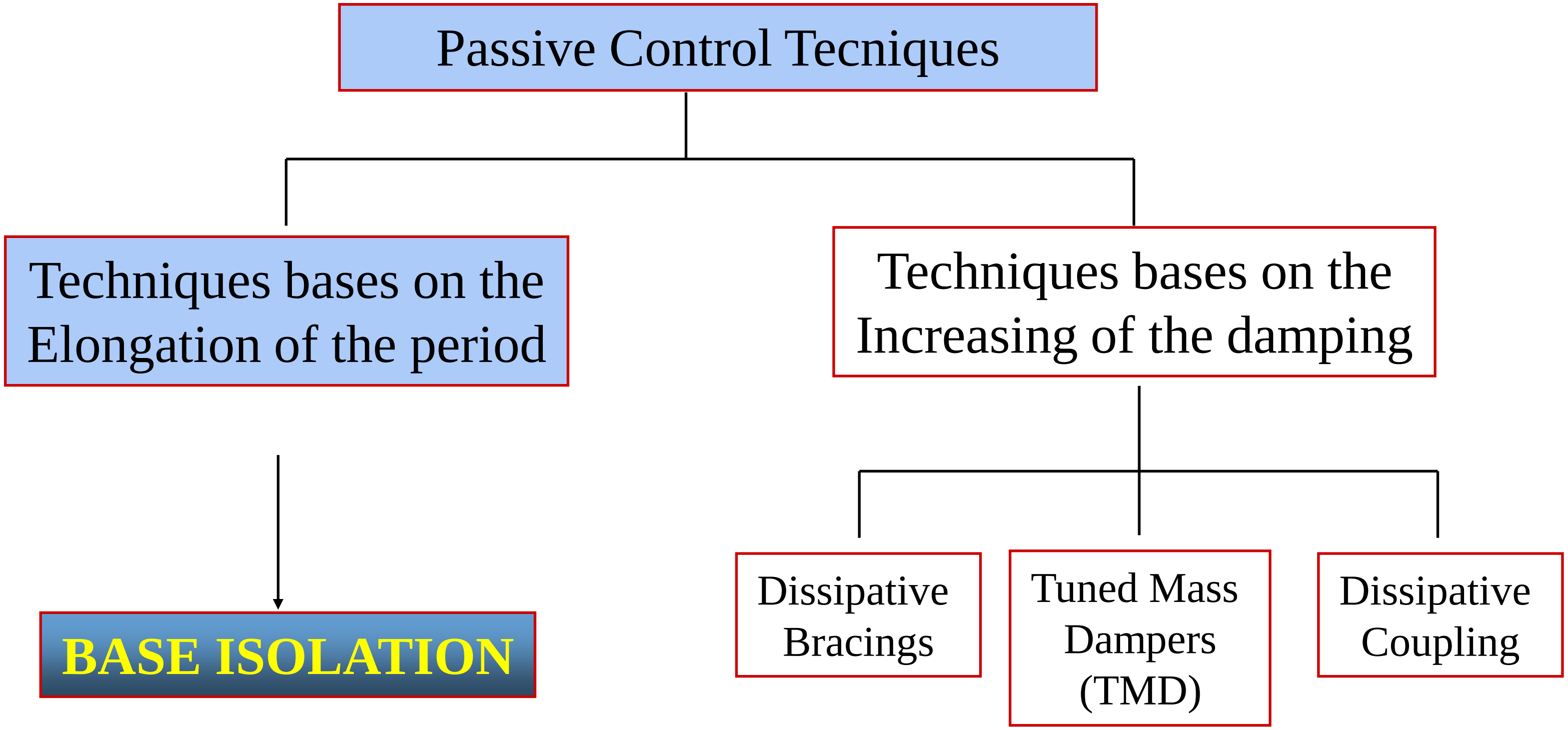
#	Failure mode
1	Overtopping
2	Elastic buckling
3	Sliding
4	Elasto-plastic buckling
5	Tank roof damage
6	Uplift
7	Anchor Bolts

SEISMIC VULNERABILITY OF STORAGE TANKS



Storage tanks of Liquid Oxygen at Habas plant after the strong event of Itzmit (1999)

Applicability of PCT



Passive Control Tecniques

Techniques bases on the Elongation of the period

Techniques bases on the Increasing of the damping

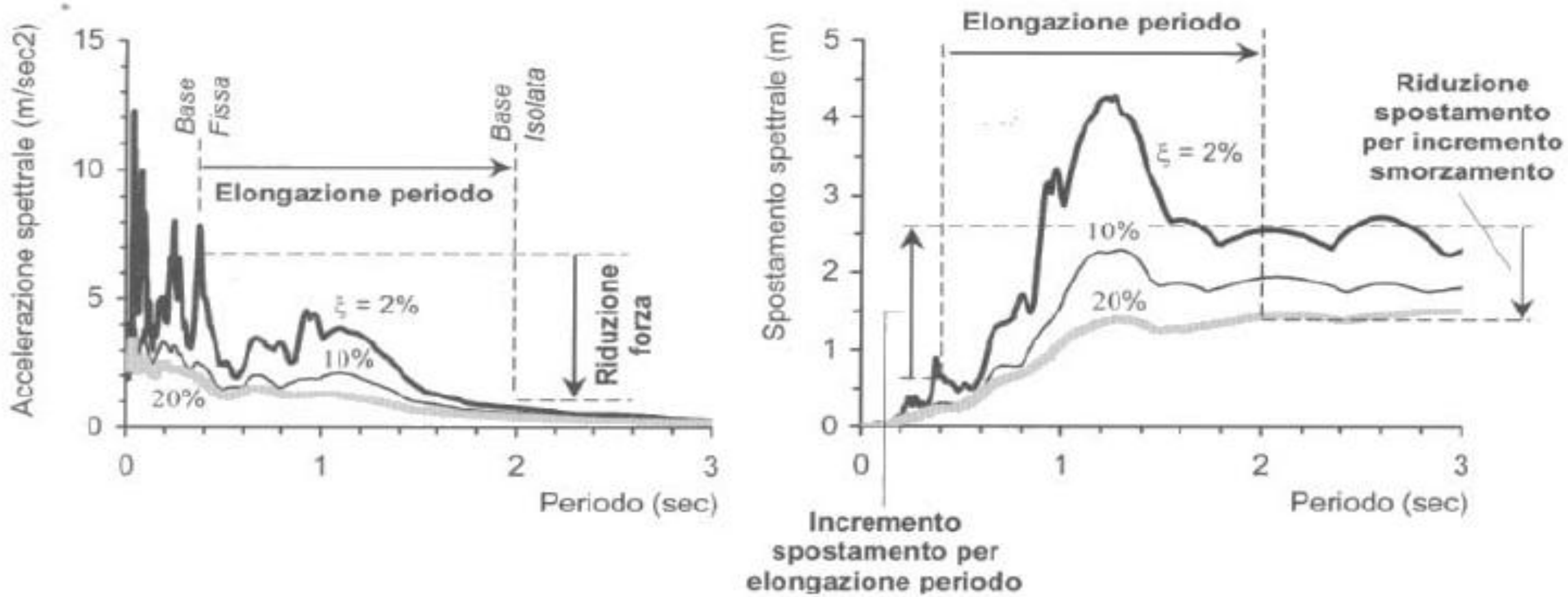
BASE ISOLATION

Dissipative Bracings

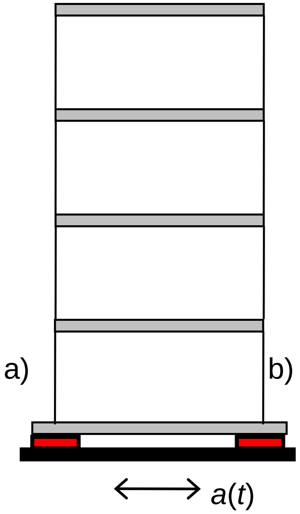
Tuned Mass Dampers (TMD)

Dissipative Coupling

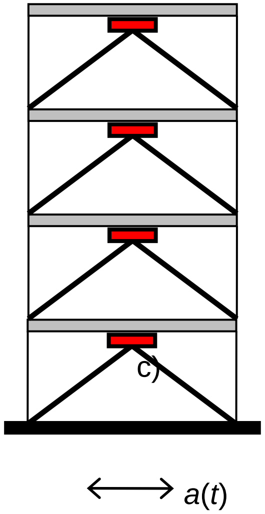
Applicability of PCT



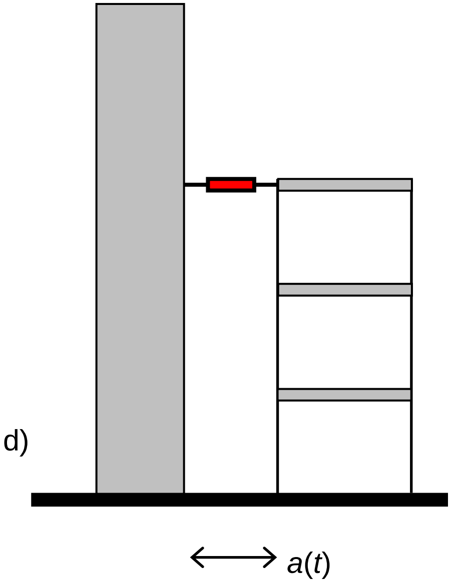
Applicability of PCT



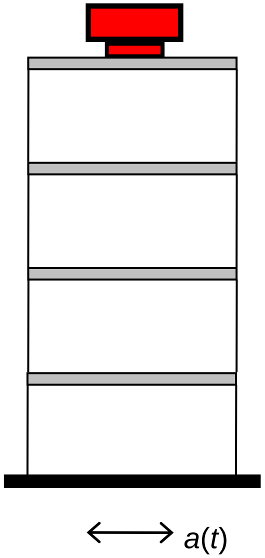
Base isolation



Dissipative bracings

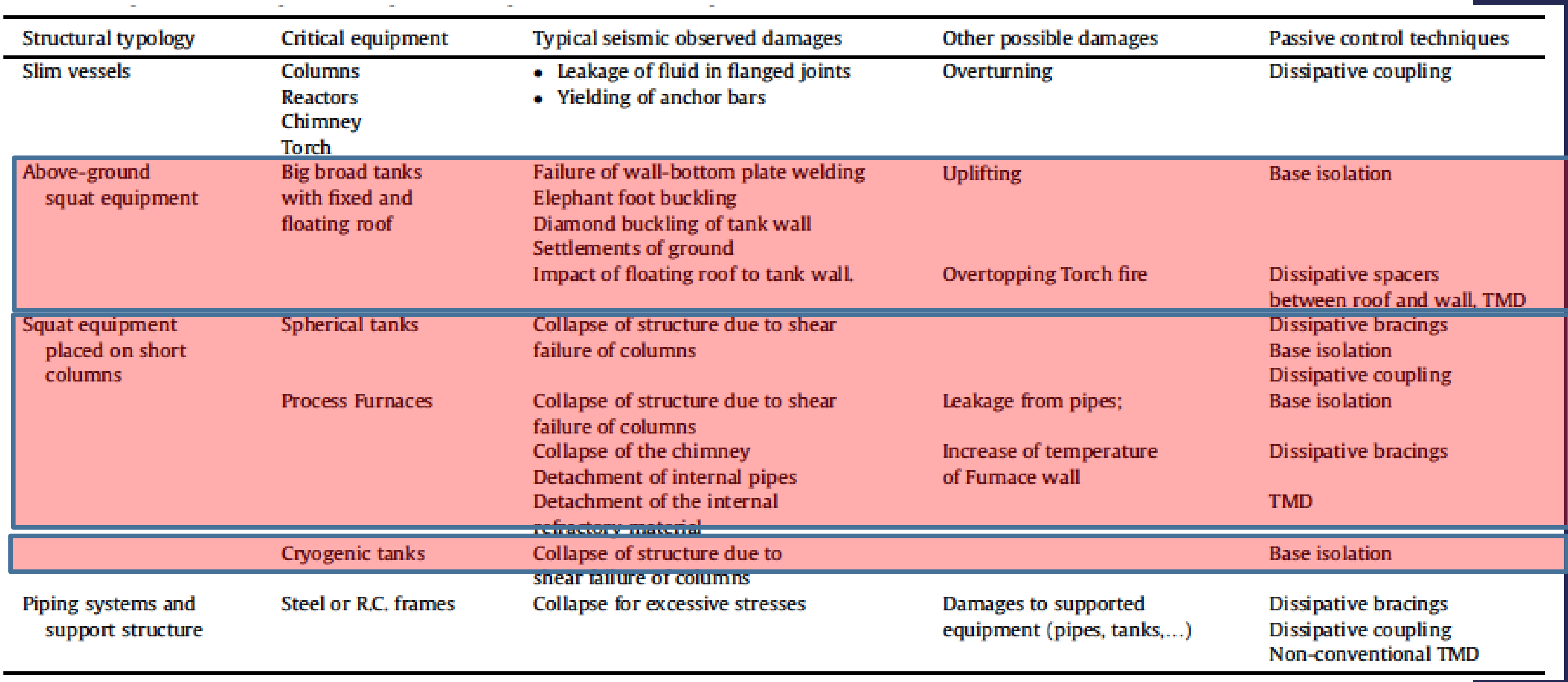


Dissipative coupling



Tuned mass dampers

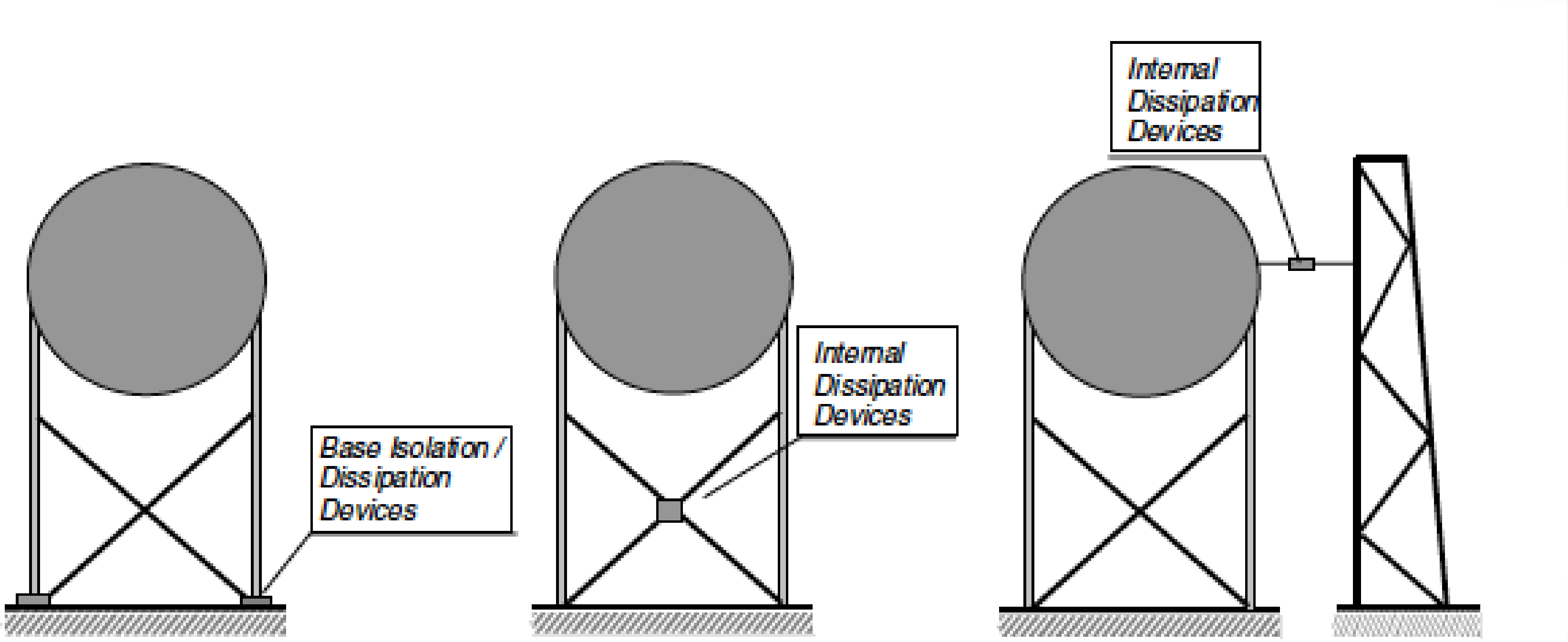
RETROFITTING SOLUTIONS FOR INDUSTRIAL COMPONENTS



Structural typology	Critical equipment	Typical seismic observed damages	Other possible damages	Passive control techniques
Slim vessels	Columns Reactors Chimney Torch	• Leakage of fluid in flanged joints • Yielding of anchor bars	Overturning	Dissipative coupling
Above-ground squat equipment	Big broad tanks with fixed and floating roof	Failure of wall-bottom plate welding Elephant foot buckling Diamond buckling of tank wall Settlements of ground	Uplifting	Base isolation
		Impact of floating roof to tank wall.	Overtopping Torch fire	Dissipative spacers between roof and wall, TMD
Squat equipment placed on short columns	Spherical tanks	Collapse of structure due to shear failure of columns		Dissipative bracings Base isolation Dissipative coupling
	Process Furnaces	Collapse of structure due to shear failure of columns	Leakage from pipes;	Base isolation
		Collapse of the chimney Detachment of internal pipes	Increase of temperature of Furnace wall	Dissipative bracings
		Detachment of the internal refractory material		TMD
	Cryogenic tanks	Collapse of structure due to shear failure of columns		Base isolation
Piping systems and support structure	Steel or R.C. frames	Collapse for excessive stresses	Damages to supported equipment (pipes, tanks,...)	Dissipative bracings Dissipative coupling Non-conventional TMD

Paolacci F., Giannini R., De Angelis M., (2013), Seismic response mitigation of chemical plant components by passive control systems, Journal of Loss Prevention in Process Industries, Volume 26, Issue 5, Pages 879-948 Special Issue: Process Safety and Globalization - DOI:10.1016/j.jlp.2013.03.003.

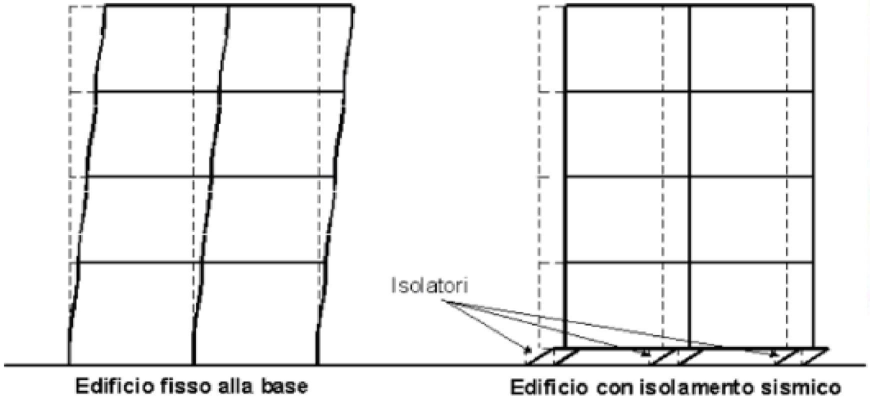
Applicability of PCT



POSSIBLE PASSIVE CONTROL SYSTEMS FOR ELEVATED STORAGE TANKS

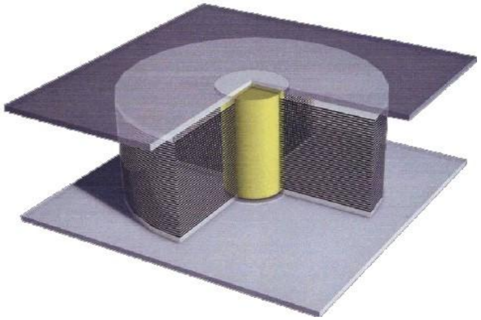
Typologies of base isolation

Deformata, sotto l'azione di un terremoto, di un edifcio tradizionale e di uno con isolamento sismico

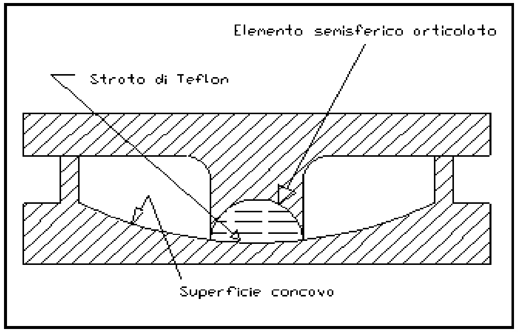


ISOLATORE ELASTOPLASTICO

ISOLATORE ELASTOMERICO



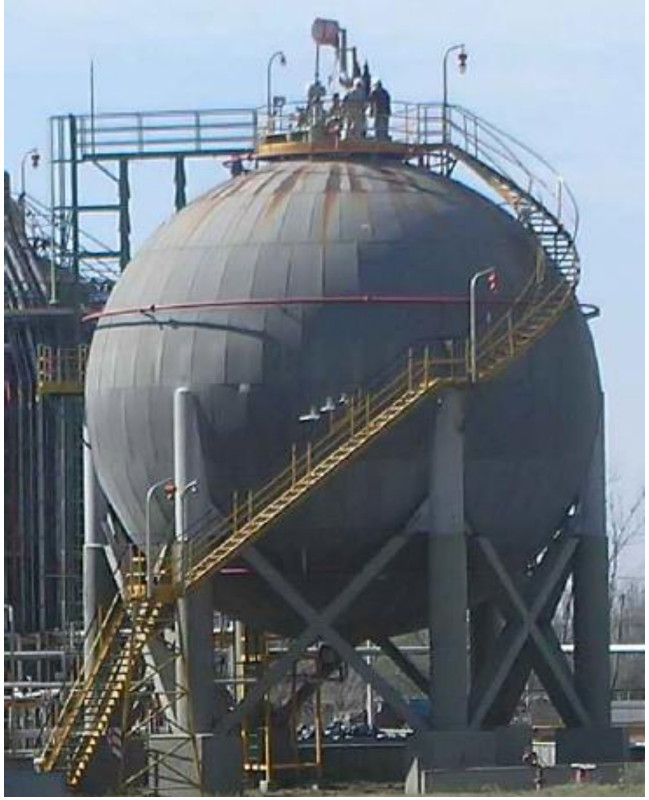
IS. ELAST. CON NUCLEO IN PIOMBO



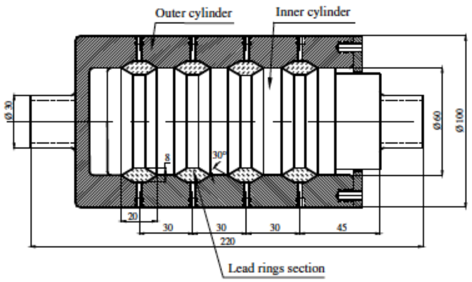
ISOLATORE FRICTION PENDULUM

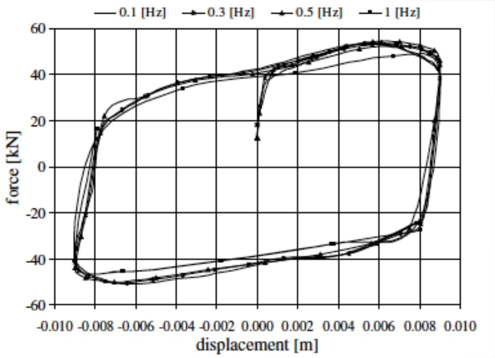
Applications of Passive Control

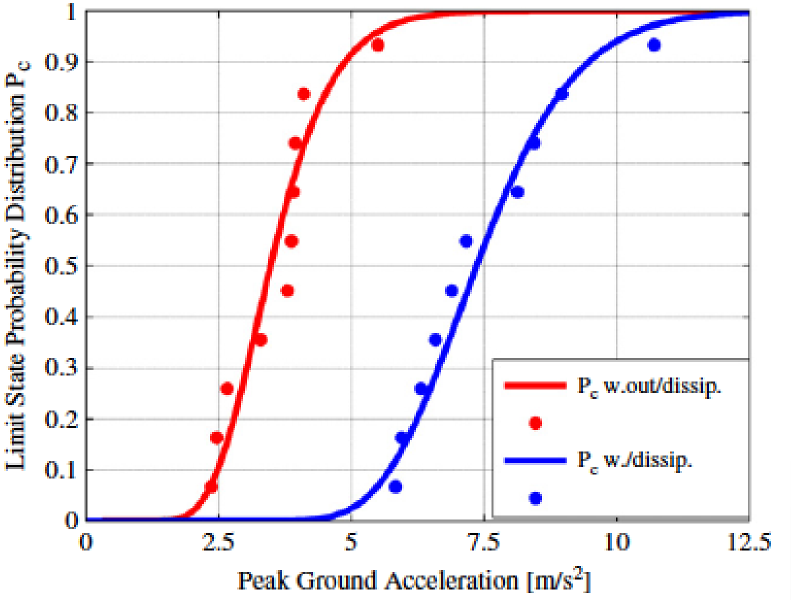
Energy Dissipation (Curadelli 2011)



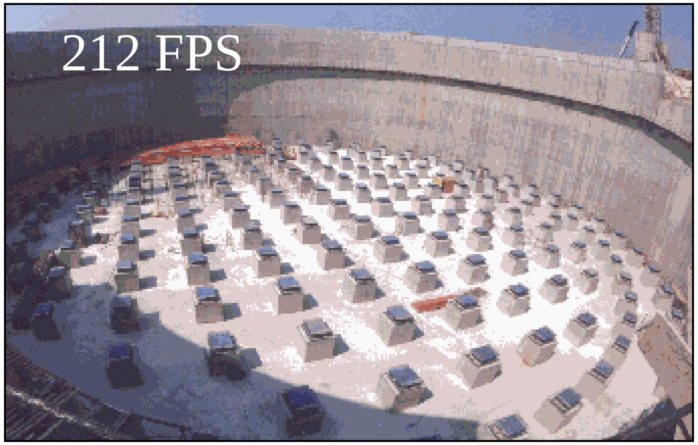
Controventamento dissipativo

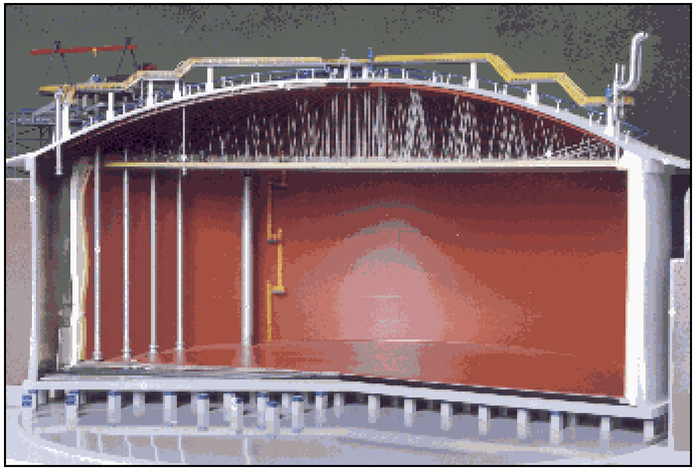


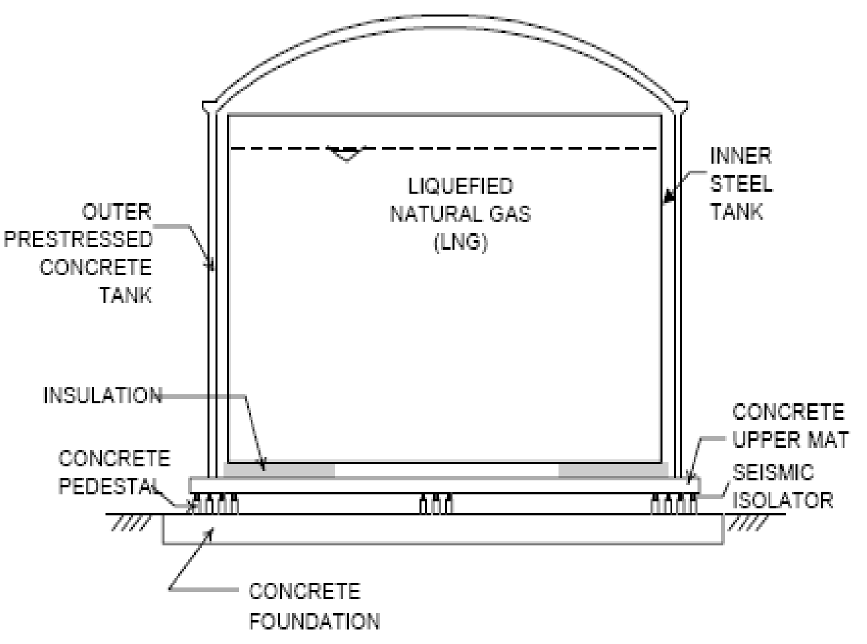




Applications of Passive Control







Base Isolation of LNG Tanks

Base Isolation by FPS

Revithoussa Island in Grecia

Applications of Passive Control

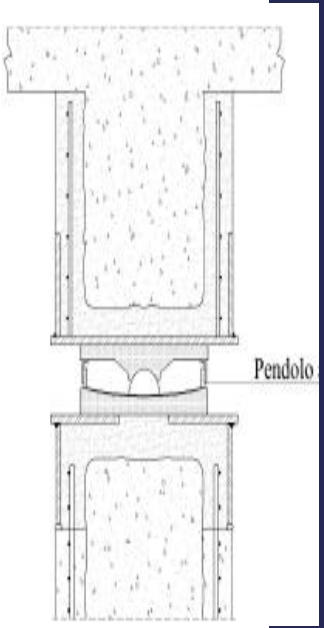
Base isolation of LNG tanks

Melchorita - Perù

Applications of Passive Control

Seismic retrofitting of a steel tank using 26 HDRB isolators Switzerland

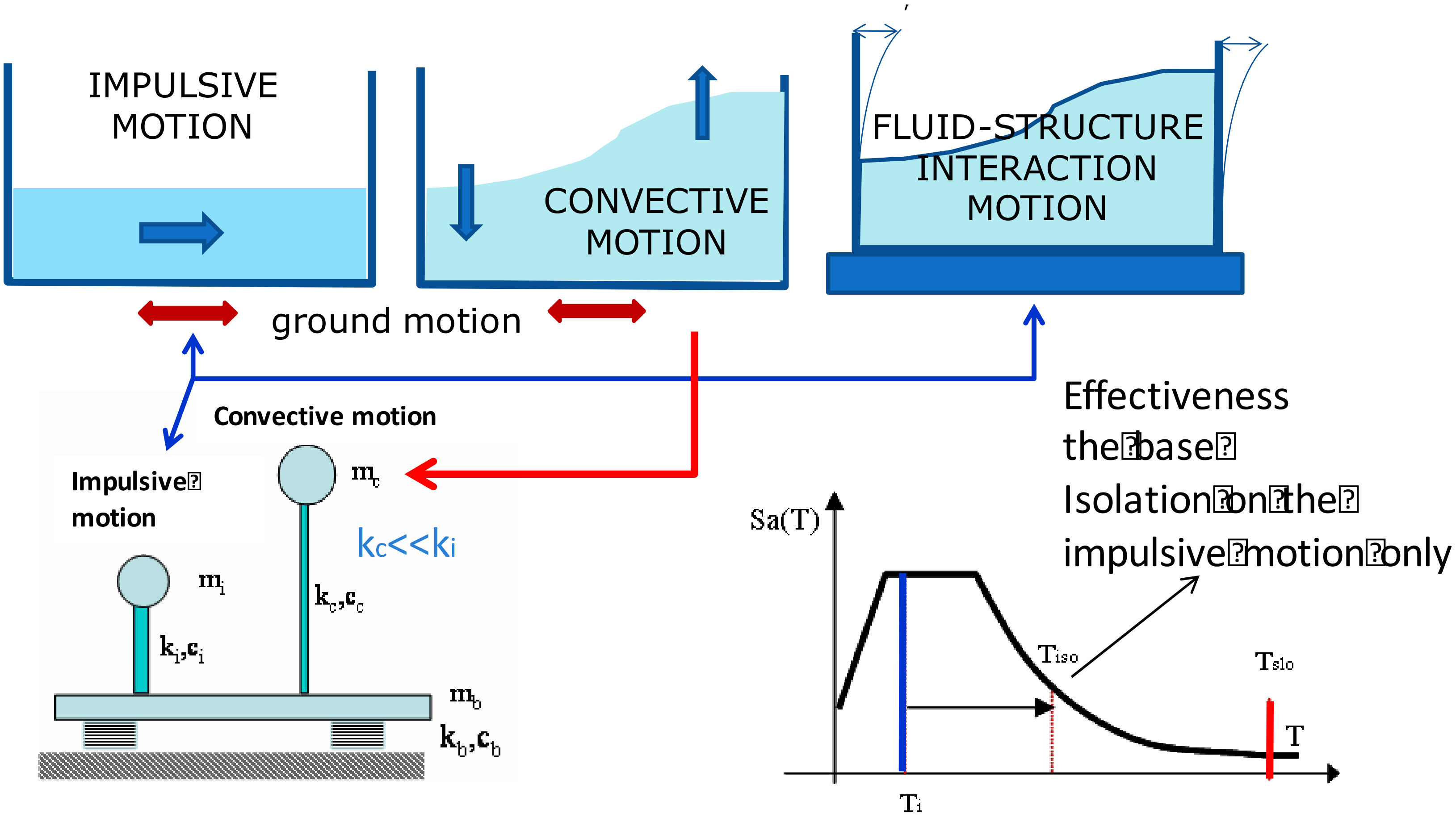
Applications of Passive Control



Seismic retrofitting of a steel tank using FPS
Petrolchimical pole of Siracusa
Priolo Gargallo (Sr) – Sicily

Which Isolation systems for storage tanks ??

Effectiveness of base isolation systems for tanks

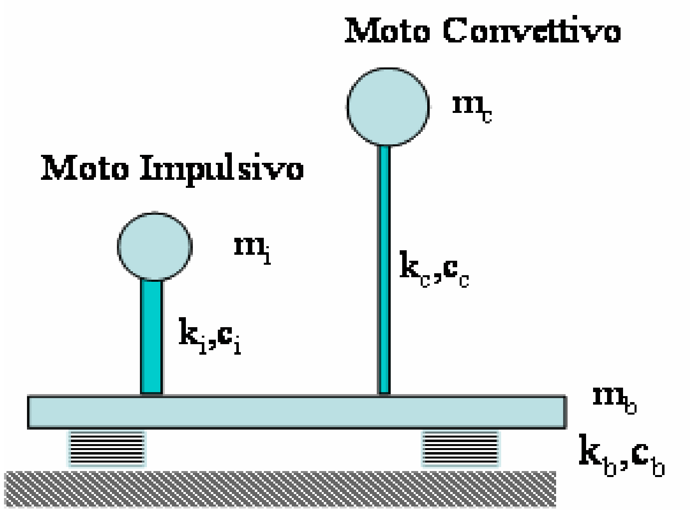


Effectiveness the base Isolation on the impulsive motion only

2DOF model

Design of base isolation systems for tanks

- A 2DOF model can be used for the dynamic response of tank
- For a preliminary design of the isolators it can be assumed the isolated mass as the impulsive mass, being the convective one naturally isolated
- Consequently, the stiffness of the base isolation can be easily determined using the following relation

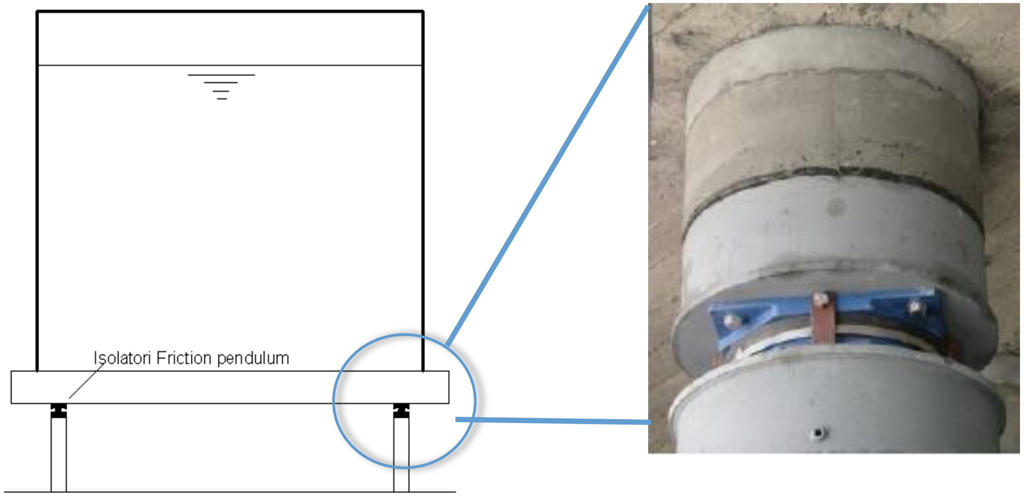


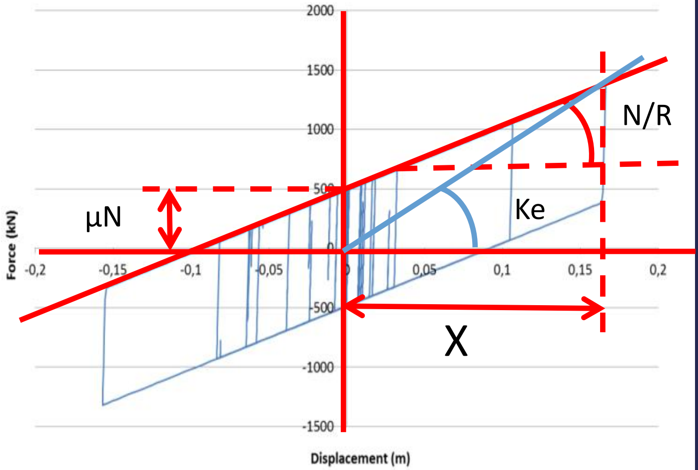
$$T_{iso} \approx 2\pi \sqrt{\frac{m_i + m_s + m_b + m_w}{k_{iso}}} = 2\pi \sqrt{\frac{m_{tot}}{k_{iso}}}$$

Period of the base isolated tank

Design of CSB isolation systems for tanks

DESIGN OF SLIDING CONCAVE BEARINGS





$$T_p=2\pi\sqrt{\frac{m}{k_e}}=2\pi\sqrt{\frac{m}{g\,m\,(\frac{1}{R}+\frac{\mu}{X})}}=2\pi\sqrt{\frac{1}{g\,(\frac{1}{R}+\frac{\mu}{X})}}$$

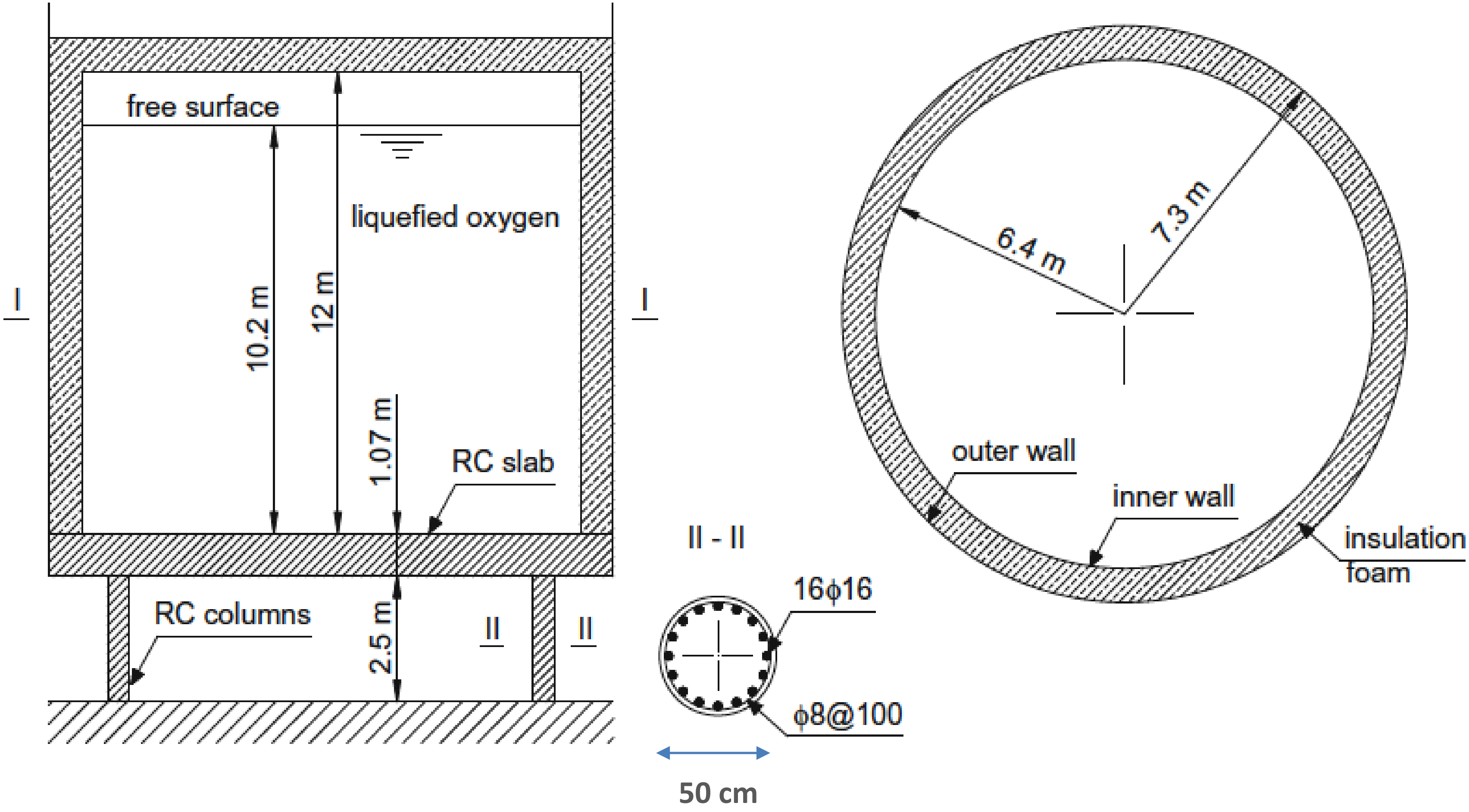
Vibration Period of base-isolated structure with FPS

$$\boxed{T_p=2\pi\sqrt{\frac{m}{k_e}}=2\pi\sqrt{\frac{m_{imp}+m_{ss}+m_{iso}}{g\,m_{tot}\,(\frac{1}{R}+\frac{\mu}{X})}}}$$

Vibration Period of base-isolated Tank with FPS

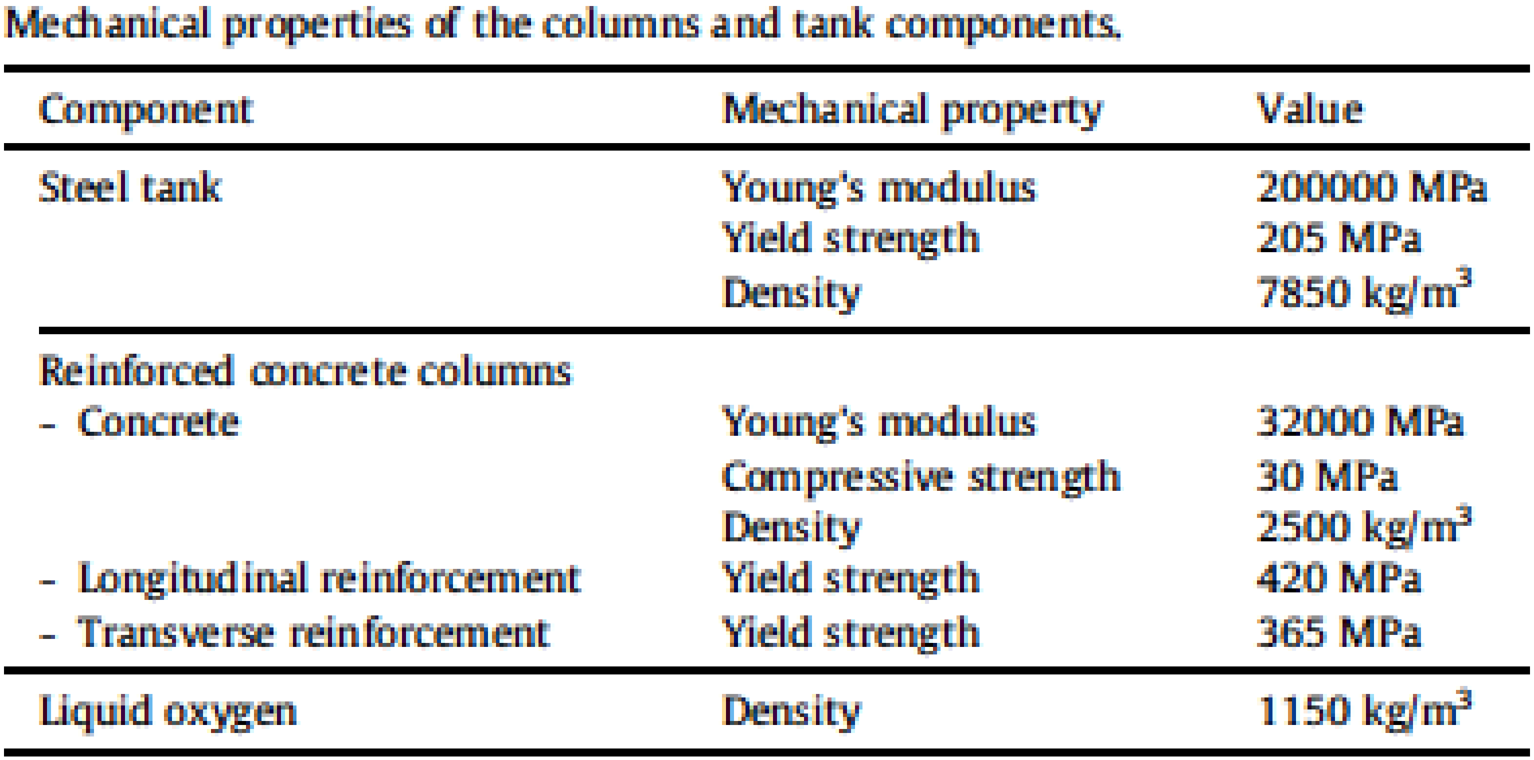
DEFINITION OF CASE STUDY

Main characteristics



DEFINITION OF CASE STUDY

Main characteristics

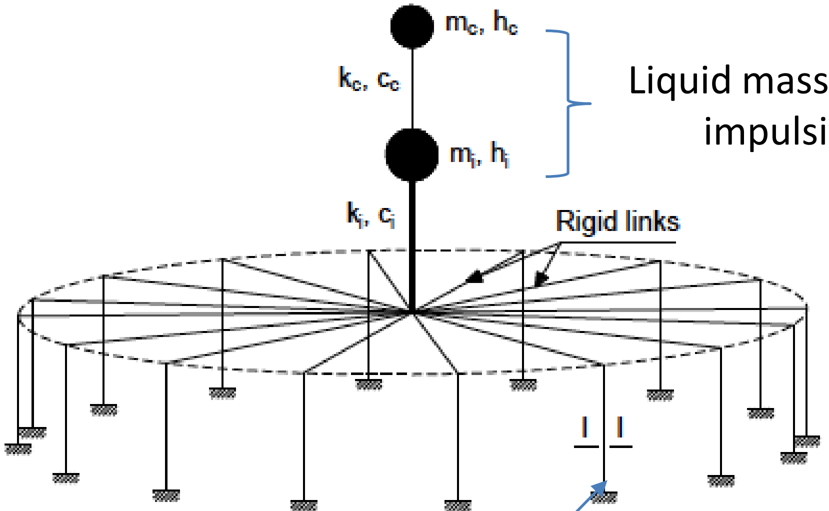


Mechanical properties of the columns and tank components.

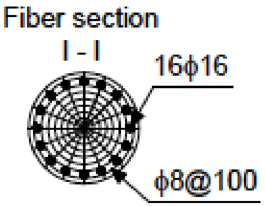
Component	Mechanical property	Value
Steel tank	Young's modulus	200000 MPa
	Yield strength	205 MPa
	Density	7850 kg/m^3
Reinforced concrete columns		
- Concrete	Young's modulus	32000 MPa
	Compressive strength	30 MPa
	Density	2500 kg/m^3
- Longitudinal reinforcement	Yield strength	420 MPa
- Transverse reinforcement	Yield strength	365 MPa
Liquid oxygen	Density	1150 kg/m^3

Numerical Modeling (non isolated tank)

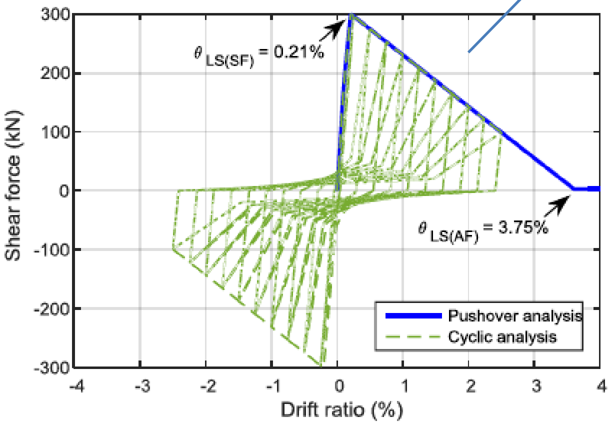
Sketch of 3D model (OPENSEES)



Liquid mass is lumped and subdivided into impulsive and convective masses.



RC columns are modeled using 3D nonlinear elements with fiber-defined cross-sections



Phenomenological Model for Shear

Table 1. Parameters of the liquid-tank model

Parameter / Component	Impulsive	Convective
Mass	m_i = 1,063 T	m_c = 447 T
Damping ratio	ξ_i = 2%	ξ_c = 0.5%
Natural time period	T_i = 0.14 s	T_c = 3.74 s
Height of mass	h_i = 5.52 m	h_c =7.54 m

Damage and limit states

Limit State (LS)	**Engineering Demand Parameter (EDP)**	**Damage Measure (DM)**	**LOC1 Continuous release from a 10mm hole**	**LOC2 Continuous release of the full content in 10 minutes**	**LOC3 Instantaneous release of full content**
Elephant Foot Buckling	Meridional Stress s	Buckling Limit s_{EFP}	Yes	No	No
Diamond Shape buckling	Hoop Stress H	Buckling limit E	Yes	No	No
Roof Damage	Max vertical displacement of liquid	Free-board height	Yes	Yes	No
Shear Damage columns	Story drift	Max shear drift	No	No	Yes

The Limit States of the tank itself can be quantified analytically using for the analytical formula provided by the current regulations.

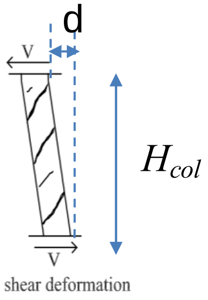
The limit states of support columns can be represented by the shear failure of the columns whose Damage Measure can be determined according to recent theories in which flexural-shear interaction in considered (MCF theory)

Damage and limit states

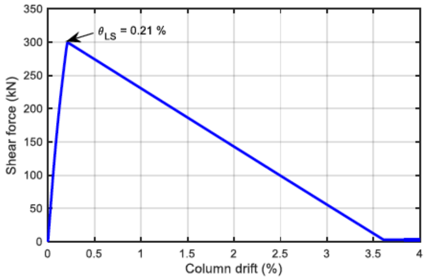
Engineering Demand Parameters (EDP)

Damage Measure (DM)

$$\theta = \frac{\delta}{H_{col}}$$



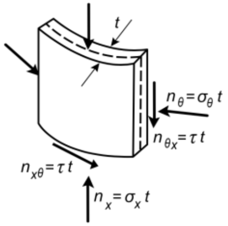
Max Column Drift



$$q_{LS} = 0.210\%$$

Shear Failure

$$\sigma_z = \frac{1}{t_s}\left(w_t\left(1+0.4a_{gv}\right)+1.273\frac{M_T}{D^2} \right)$$

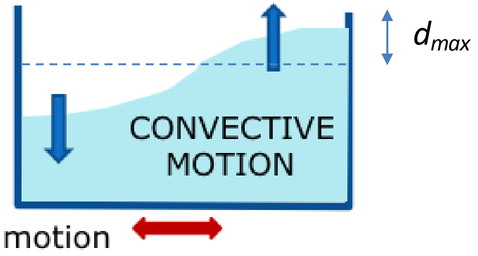


Max Meridional Stress

$$\sigma_{x,Rd} = \sigma_{x,Rk}/\gamma_{M1} = \left(\chi_x\sigma_y\right)/\gamma_{M1}$$

EEB 65.1 MPa

$$d_{\max} = 0.84RS_a\left(T_c\right)/g$$

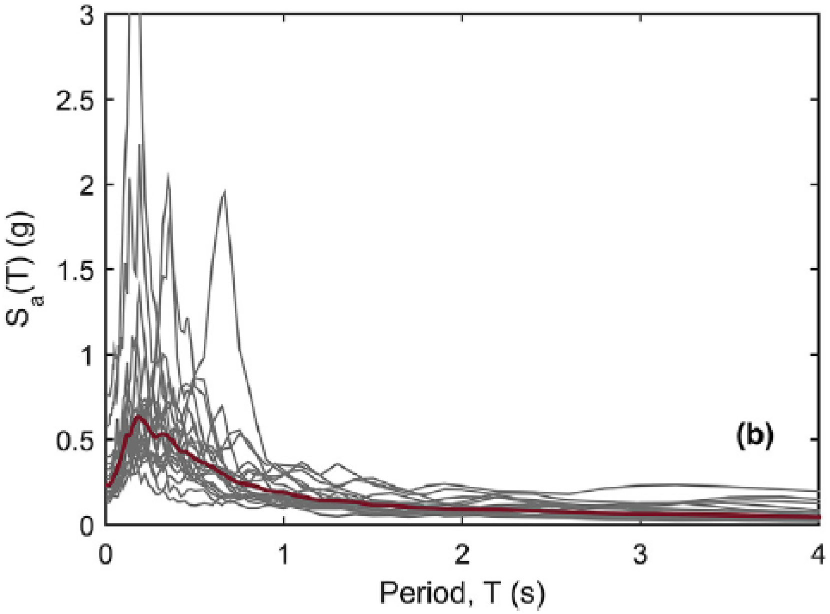


Max displacement

$$d_{LS} = H_{tank} - H_{liquid}$$ = 1.80 MPa

Free board jeight

Seismic Input definition



The seismic response analysis of the tank is conducted using 2 sets of **20 natural earthquake records**:
Near Fault Records (A) and Far Field (B)

This data set of records is selected from **Pacific Earthquake Engineering Research Center (PEER)** ground motion database

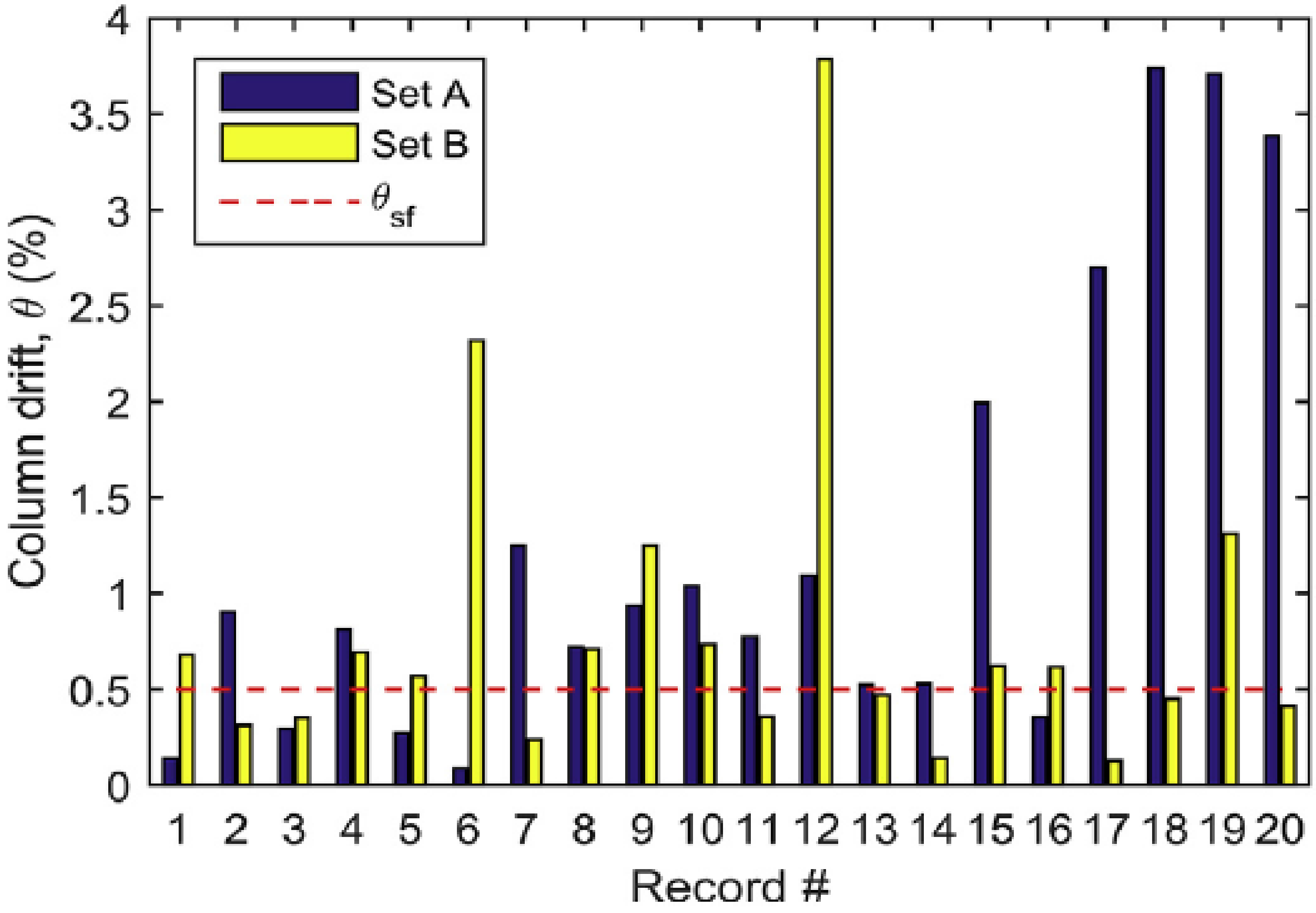
Hazard Conditions (from a PSHA)

Soil B (360 m/s < $V_{s,30}$ < 760 m/s)

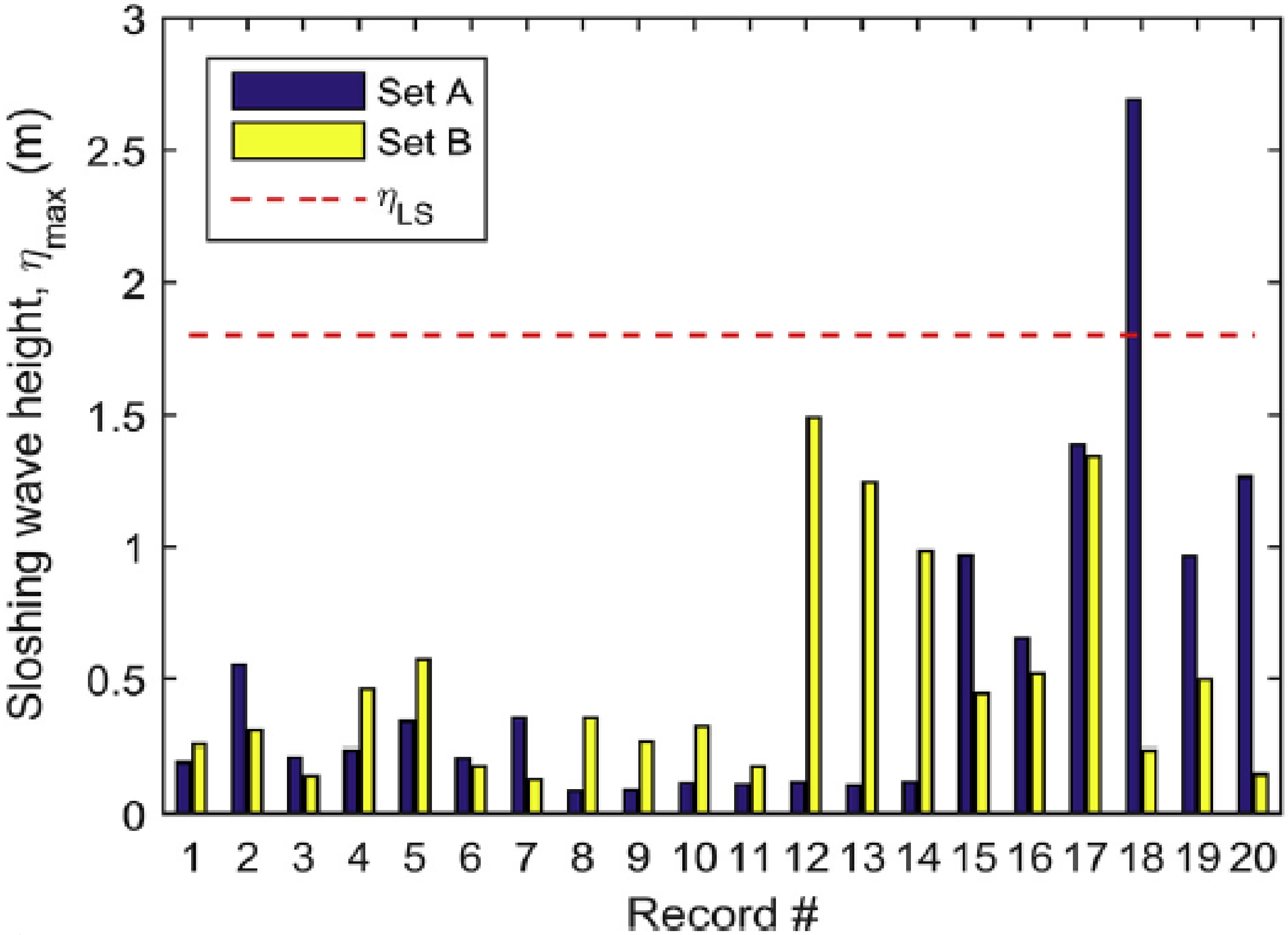
Moment magnitudes (M_w) between 5.1 and 6.9

Epicentral distances (ED) between 8.18 km and 19.73 km.

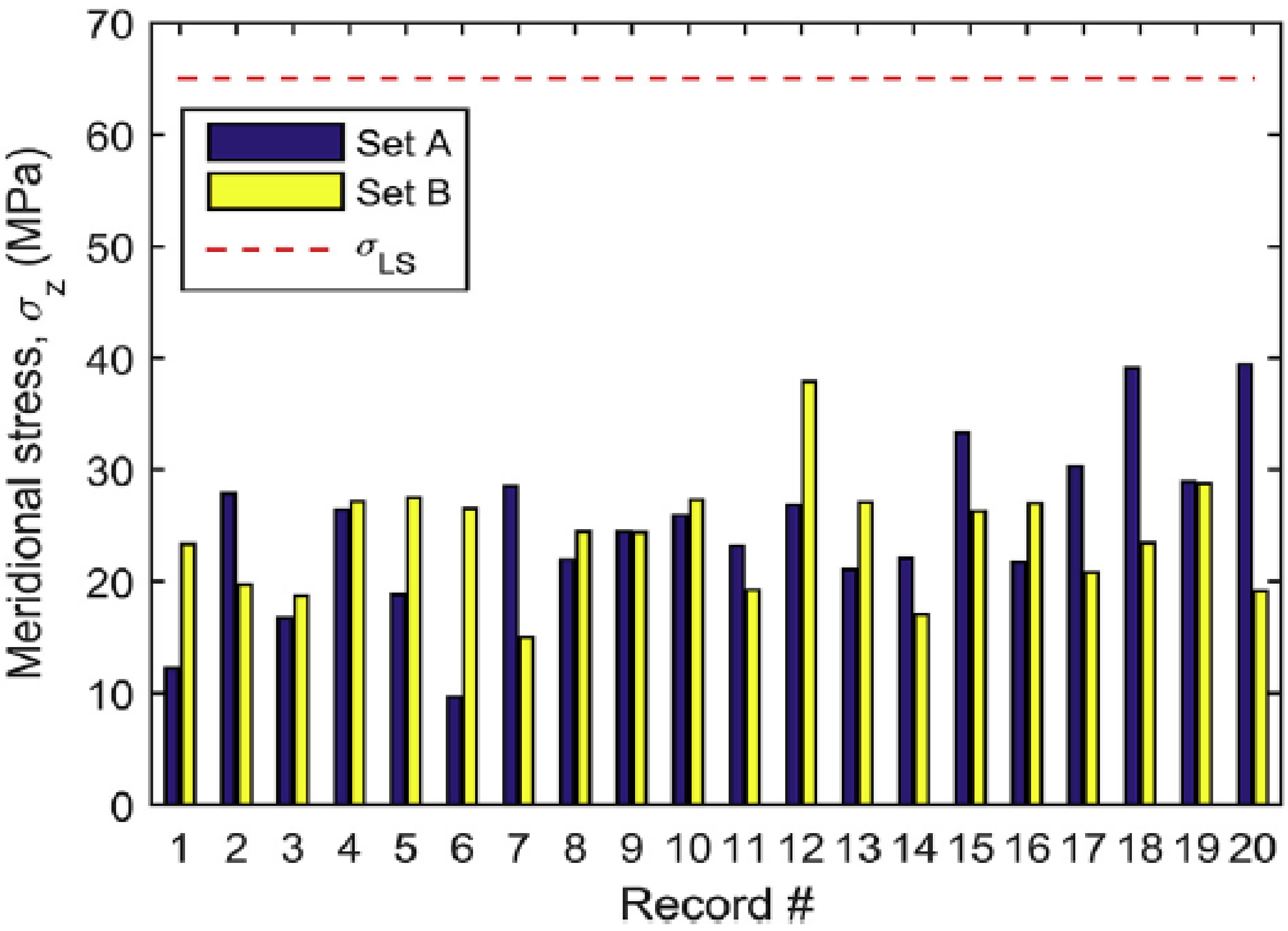
Seismic response analysis: Column Drift



Seismic response analysis: Sloshing Waves



Seismic response analysis: Meridional Stress



SEISMIC VULNERABILITY ASSESSMENT

Seismic Fragility analysis of the elevated tank

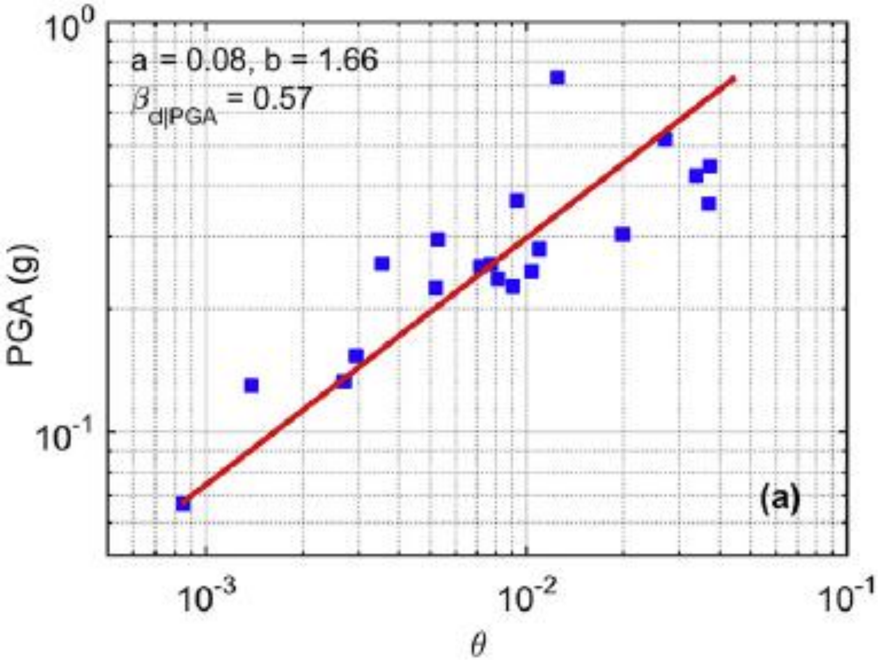
Cloud Analysis

$$D_m = a(IM)^b$$

Mean Value

$$\beta_{d|IM} = \sqrt{\frac{\sum_{i=1}^{n}\left[\ln(d_i) - \ln\left(aIM_i^b\right)\right]^2}{n-2}}$$

Standard Deviation



Linear Regression in the Log-Log plane

Fragility Curve

$$P\left[D_{EDP} > LS \mid IM\right] = 1 - \Phi\left(\frac{\ln(LS_m) - \ln(D_m)}{\sqrt{\beta_{d|IM}^2 + \beta_{LS}^2}}\right)$$

Seismic Fragility analysis of the elevated tank

Cloud Analysis

$$D_m = a(IM)^b$$

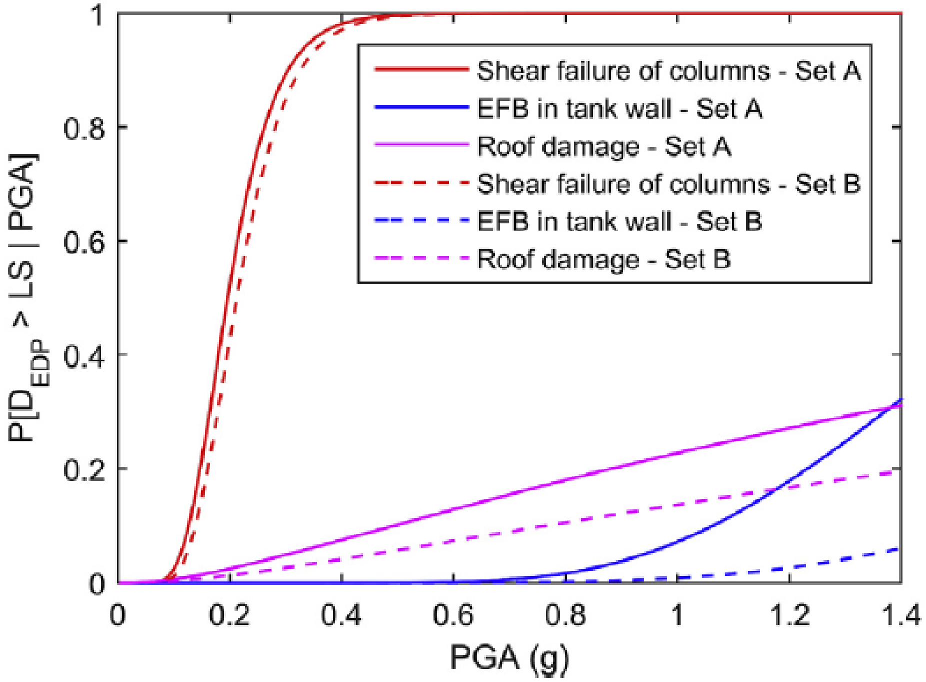
Mean Value

$$\beta_{d|IM} = \sqrt{\frac{\sum_{i=1}^{n}\left[\ln(d_i) - \ln\left(aIM_i^b\right)\right]^2}{n-2}}$$

Standard Deviation

Fragility Curve

$$P\left[D_{EDP} > LS \mid IM\right] = 1 - \Phi\left(\frac{\ln(LS_m) - \ln(D_m)}{\sqrt{\beta_{d|IM}^2 + \beta_{LS}^2}}\right)$$



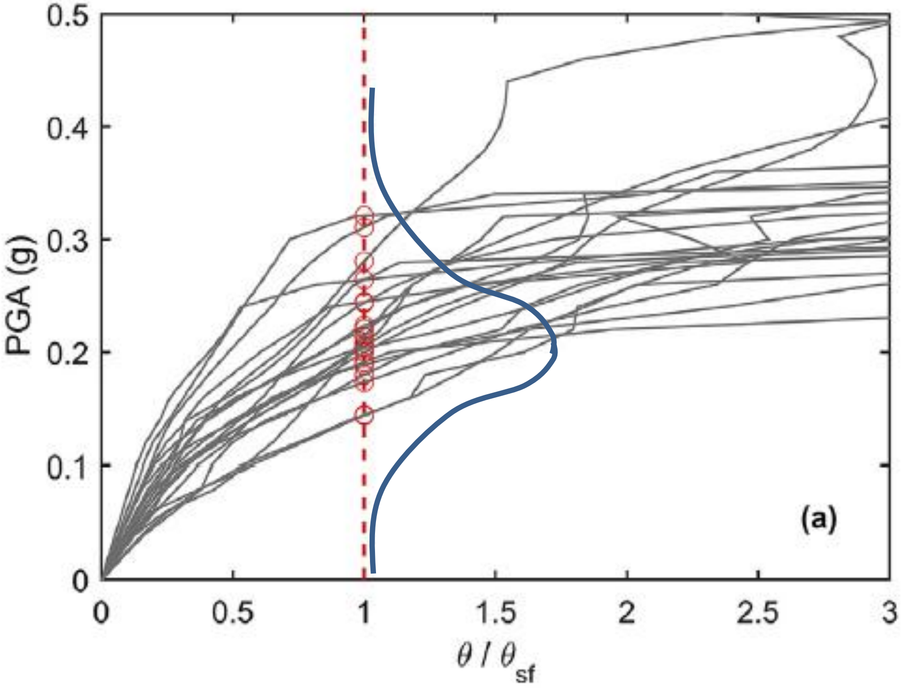
Seismic Fragility analysis of the elevated tank

Incremental Dynamic Analysis

The fragility function parameters, which include the mean and standard deviation, can be estimated using the method of moments estimator,

$$\ln\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} \ln IM_i$$

$$\hat{\beta} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (\ln(IM_i/\hat{\mu}))^2}$$



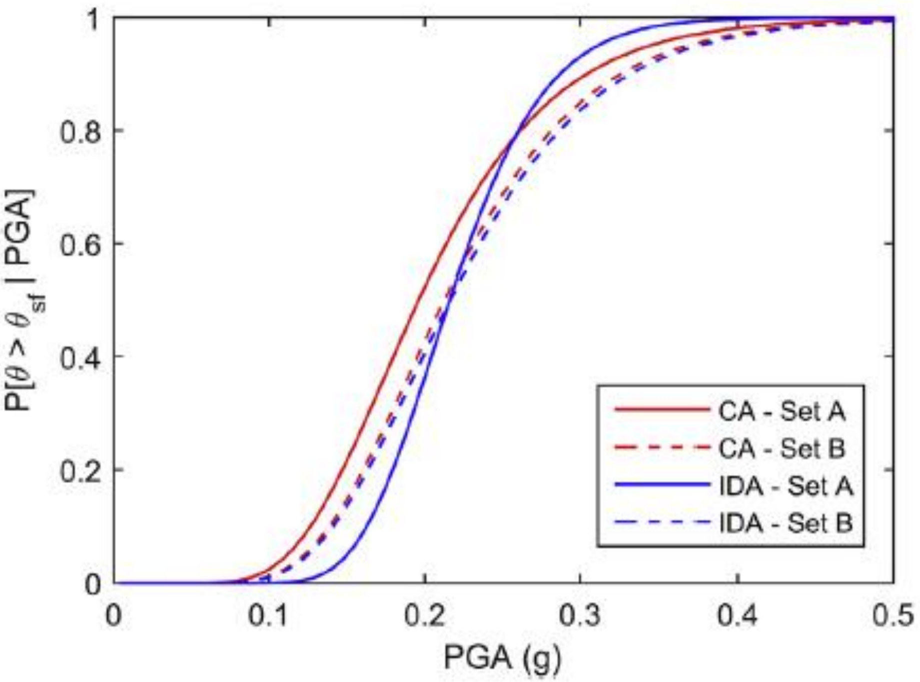
Seismic Fragility analysis of the elevated tank

Incremental Dynamic Analysis

The fragility function parameters, which include the mean and standard deviation, can be estimated using the method of moments estimator,

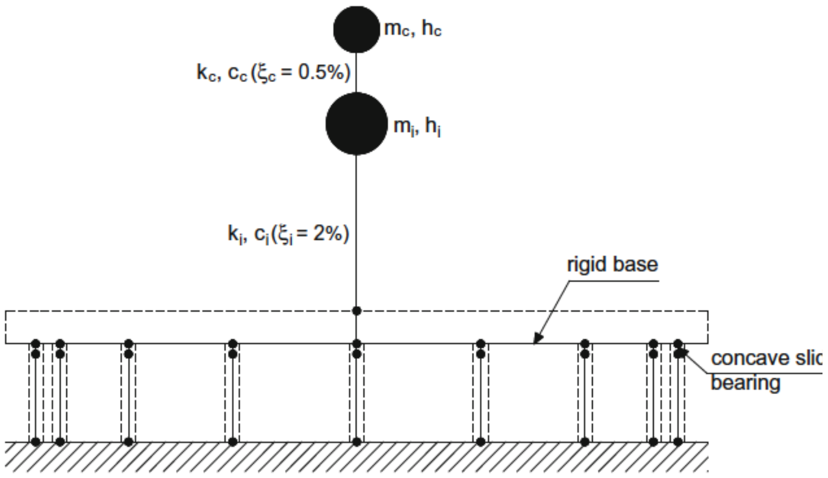
$$\ln\hat{\mu} = \frac{1}{n}\sum_{i=1}^{n} \ln IM_i$$

$$\hat{\beta} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n} (\ln(IM_i/\hat{\mu}))^2}$$

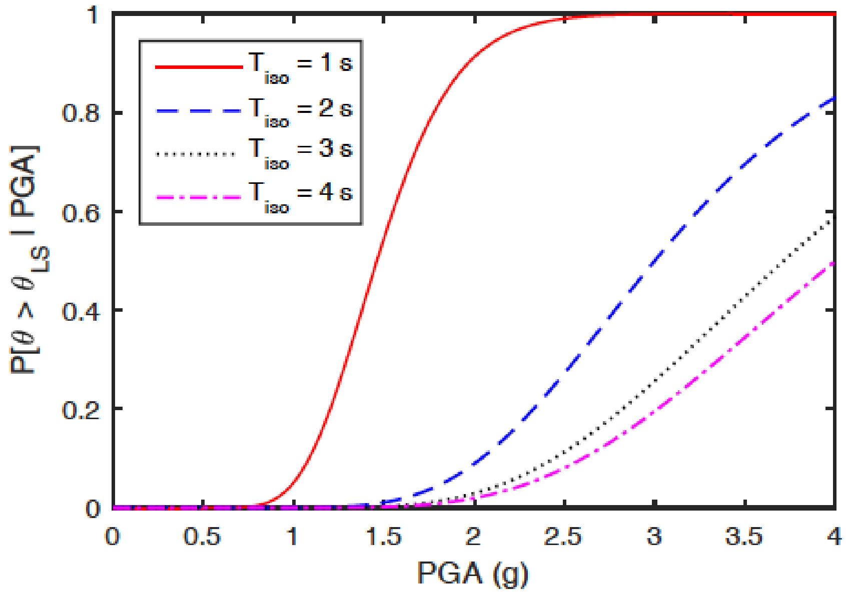


Base isolation design: Vulnerability-based approach

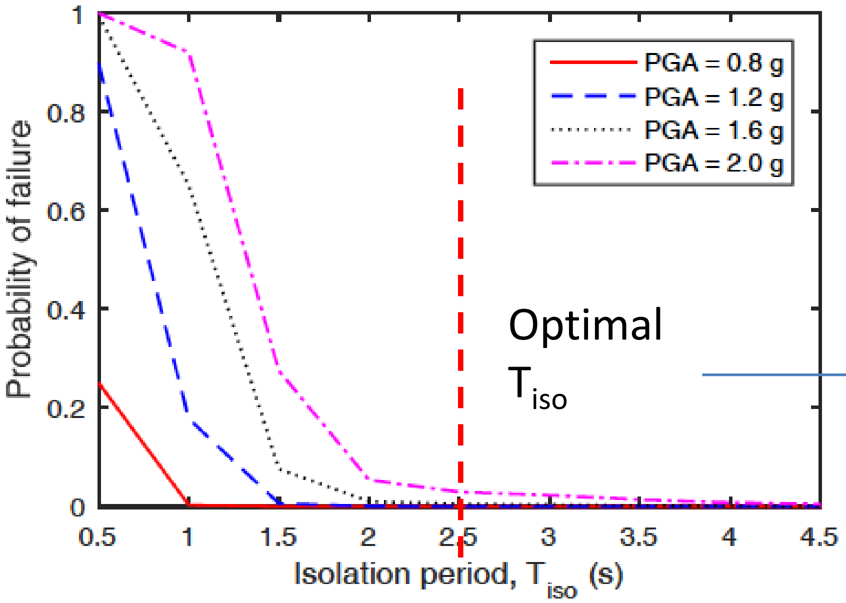
- ❑ For the selection of the optimal isolation period T_{iso} a fragility analysis has been adopted
- ❑ At this end, the model used for the non-isolated case has been modified by including the CSB modeled using the elemen “singleFPBearing” implemented in OPenSEES and proposed by Shellemberg with Columb model for the friction (friction coefficient constant =3%).
- ❑ The T_{iso} has been varied in the range 0.5 – 4 sec



Numerical model of isolated tank



Base isolation design: Vulnerability-based approach



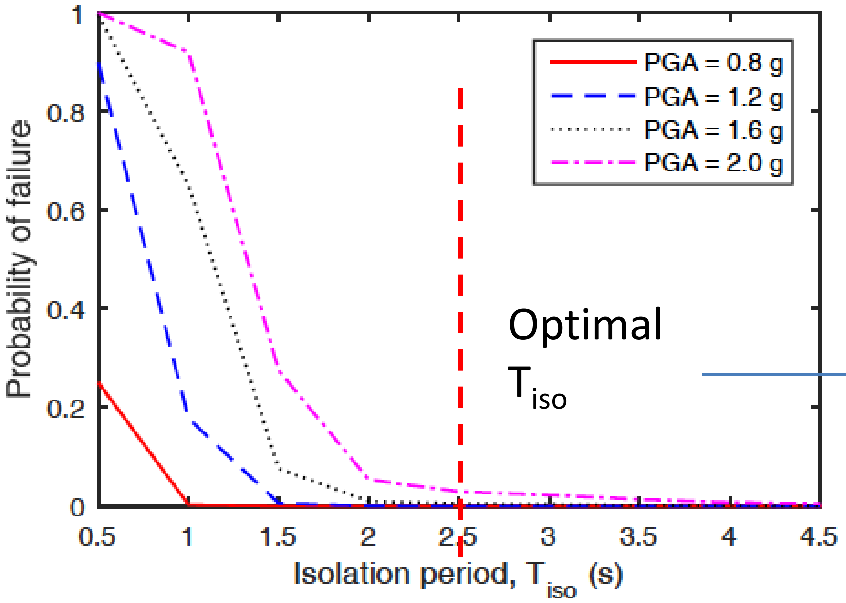
Optimal T_{iso}

It can be observed from the figure that the probability of failure is close to zero for the isolation periods from 2.5 s.

→ *The optimal Isolation period Tiso correspond to a minimization of the probability of failure of columns forr shear*

For the design purpose, the selection of Tiso = 2.5 s as an optimal period appears a good compromise for both effectiveness and feasibility. In fact, this value of isolation period is associated to the maximum probability reduction for any level of the seismic intensity and an acceptable level of the lateral displacement

Base isolation design: CSB



Optimal T_{iso}

It can be observed from the figure that the probability of failure is close to zero for the isolation periods from 2.5 s.

The optimal Isolation period Tiso correspond to a minimization of the probability of failure of columns forr shear

The remaining parameters of the bearings are then defined based on the designed isolation period. In detail, the **effective radius** and the **damping coefficient** of the bearings are calculated as **1,900 mm** and **12%**, respectively

Base isolation design: CSB

Concave Sliding Bearings (FPS)

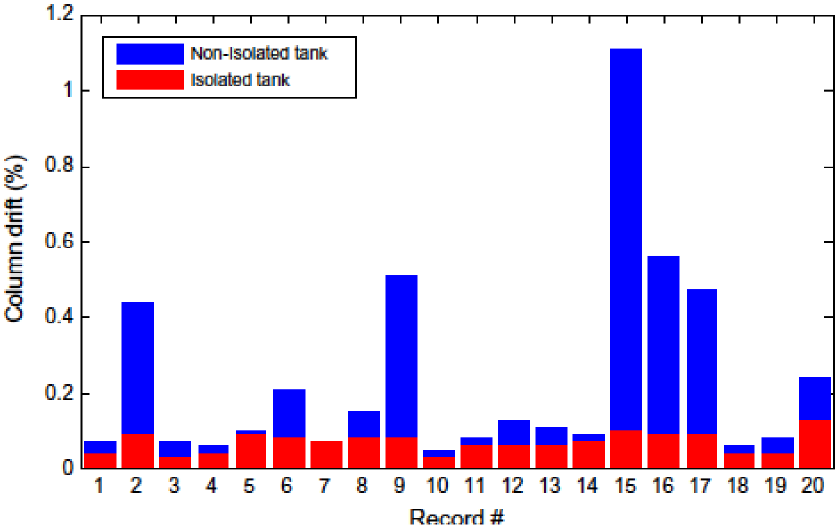
D_{iso}=49 cm

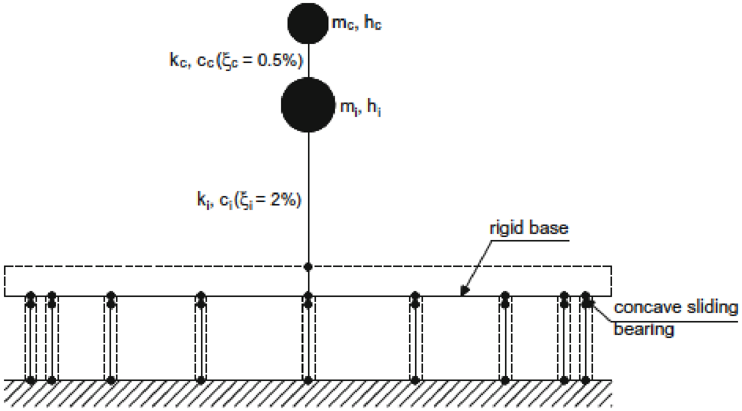
H_{iso}=11.4 cm

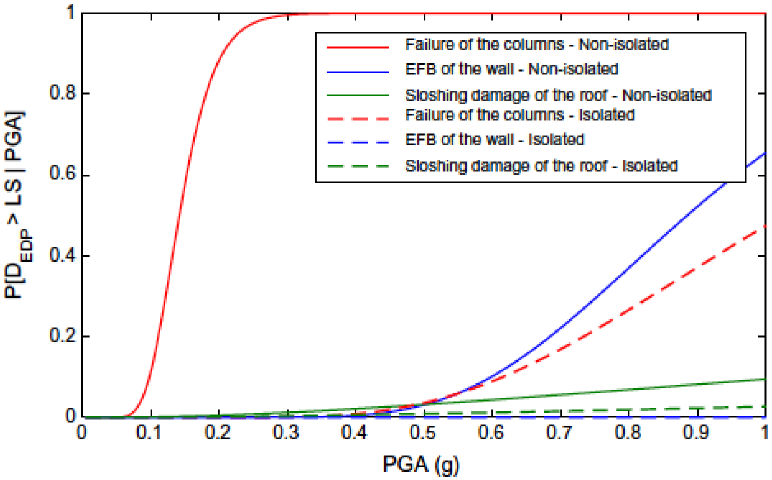
R=310 cm

Max Displ=22.5 cm

m=3%







CONCLUSIONS

- In this work, the vulnerability-based design of a CSB system for an elevated tank is performed by means of fragility analysis.

- An emblematic example of elevated tanks, which collapsed during the Kocaeli Earthquake (1999) at Habas Pharmaceutics plant in Turkey, is considered

- Seismic analyses conducted using a 3D lumped mass model and a set of 20 natural records demonstrate a high shear demand of the support columns. This is fully investigated by building the fragility curves

- The probability of collapse due to the failure in shear of the support columns is 100% at the PGA levels greater than 0.4 g, whereas the figures for shell failure due to EFB and roof sloshing damage are limited.

CONCLUSIONS

- The design of a CSB system is conducted based on Fragility Analysis performed by using the same 3D model in which non linear elements for isolator are employed.

- The oprimization of seismic performace of the isolated tank has been conducted by a Fragility analysis, which allowed to identfy the optimal value of the isolation period that minimize the probablity of shear failure of columns

Thank you very much for your attention

Questions?