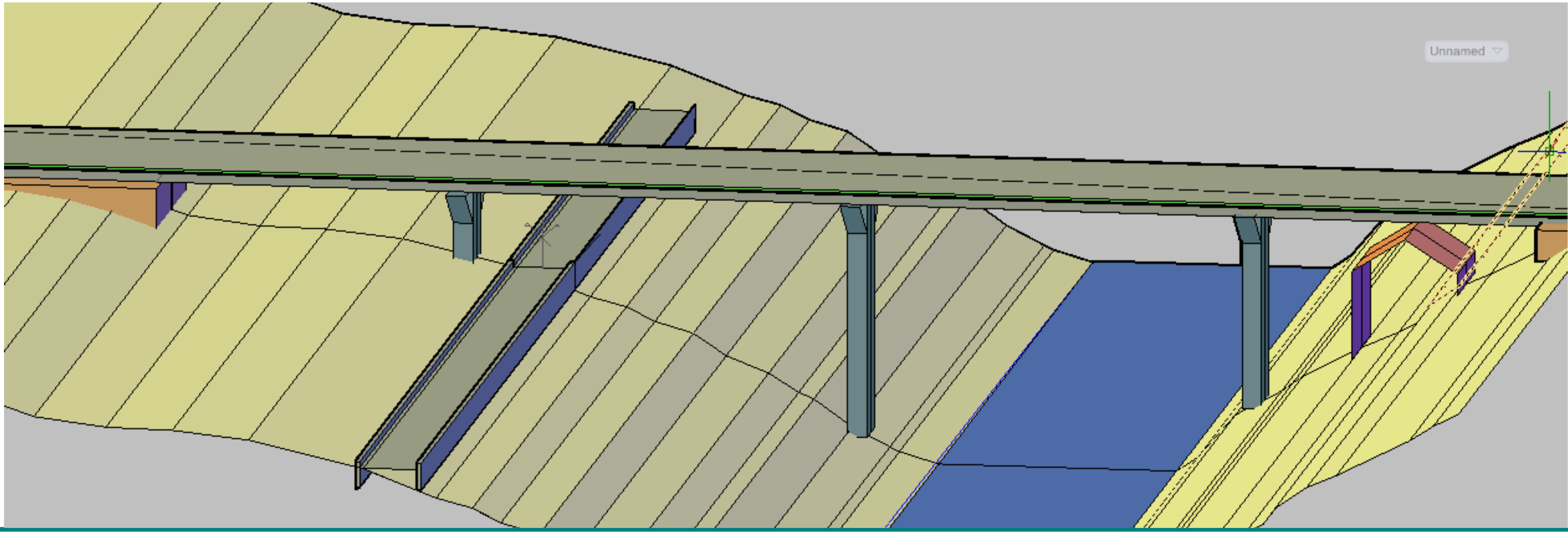
Categorization of bridges according to dynamic behavior and definition of a framework for optimization

Applying evolutionary algorithms as tools for structural optimization

Vítor Teixeira Camacho – PhD student at Instituto Superior Técnico (IST)
Prof. Mário Lopes – thesis supervisor (IST)
Prof. Carlos Sousa Oliveira – thesis co-supervisor (IST)



Presentation layout

- Thesis objectives
- Categorization of bridges and choice of design variables
- Structural seismic optimization framework
- Case studies

Thesis objectives

Thesis objectives

To develop a seismic design methodology for RC bridges, inserted in an optimization and stochastic framework

This methodology has the aim to standardize optimization/normalization solutions for bridges according to the deck and pier length and bridge regularity

Work developed so far

Optimization algorithm developed in tcl/tk for structural optimization associated to seismic design

Bridge model generator developed with OpenSees

Optimization and normalization methodology framework initiated, bridge categories defined

A couple of case studies analysed

MCS of bridge geometry and multi-modal linear analysis

Introducing two indicators:

RSI - Relative Stiffness index

$$RSI = \frac{Ks}{\sum Kp} = \frac{384 \cdot E_S \cdot I_S}{5L_S^3} \Big/ \sum \frac{12 \cdot E_P \cdot I_P}{H_P^3}$$

RP - Regularity Parameter

$$RP = \sqrt{\frac{\sum_{j=1}^{n} \left(\left(\phi_j^T \Big/ \sqrt{\phi_j^T [M] \phi_j} \right) \cdot [M] \cdot \left(\psi_j^T \Big/ \sqrt{\psi_j^T [M] \psi_j} \right) \right)^2}{n}}$$

How does bridge geometry influence these indexes and what do they mean?

Can these indexes be related to the Transverse Horizontal Deck Displacement Profile (THDDP) of the bridge?

To answer these questions:

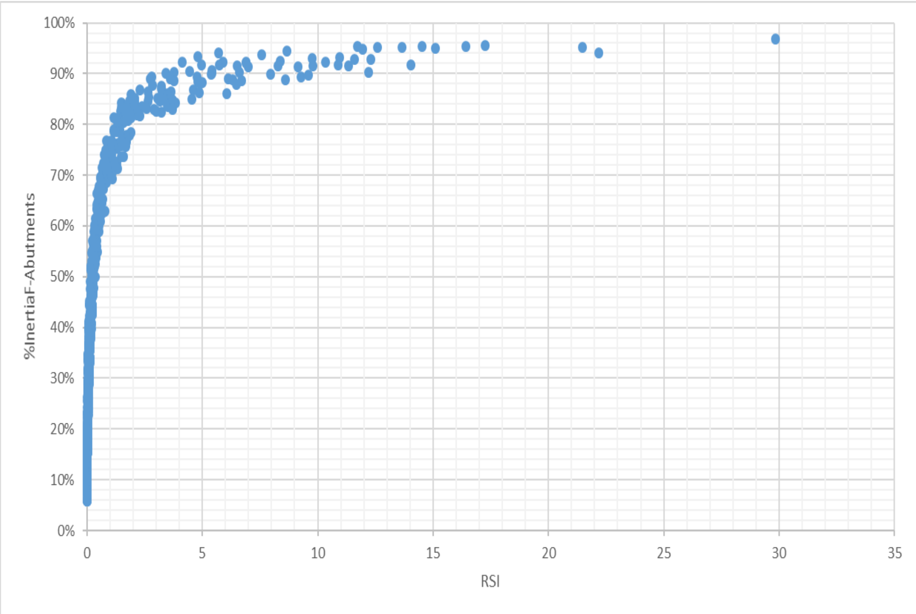
Monte Carlo Simulations, where a set of bridges with varying geometry are randomly generated and subjected to elastic multi-modal analysis

MCS 1 – Regular bridges – only to test RSI parameter

MCS 2 – Irregular bridges – to test also RP parameter

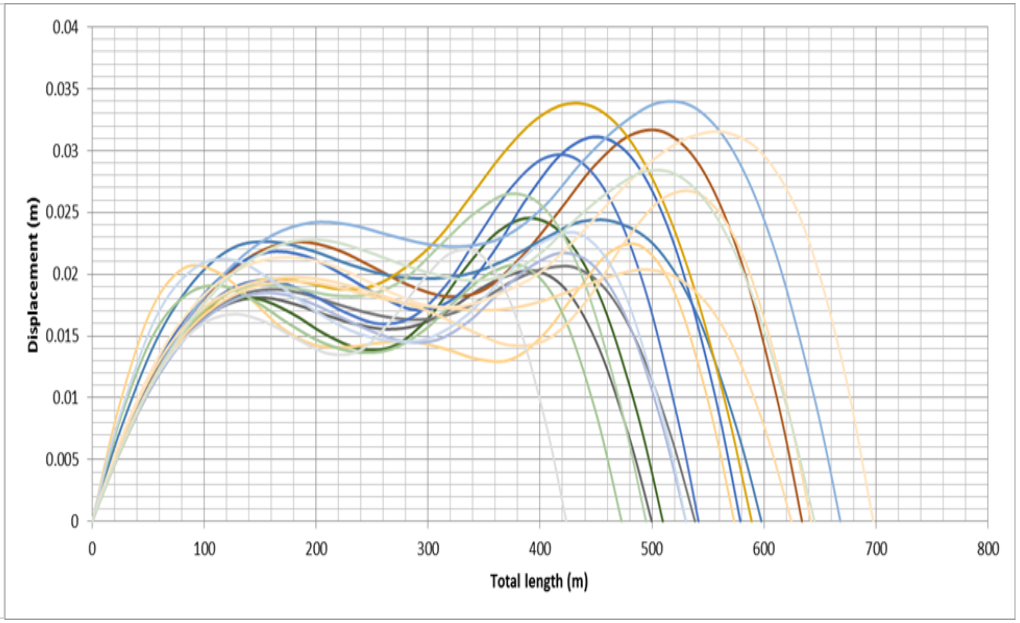
MCS of bridge geometry and multi-modal linear analysis

MCS 1 – Regular bridges



Relationship between RSI and % of inertia force transmitted to abutments

MCS 2 – Irregular bridges

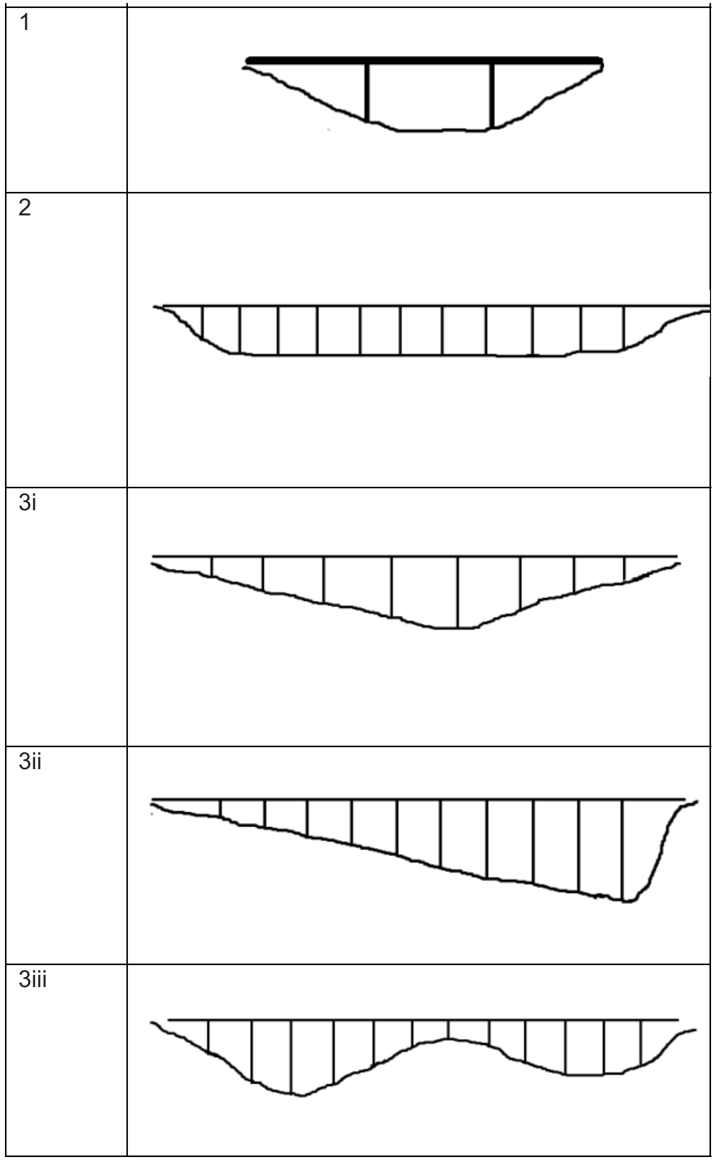


Influence of different irregularity patterns on the transverse horizontal displacement profile of the deck

Categorization of the bridges and choice of design variables

Three categories were defined:

1. Short bridges
2. Long regular bridges
3. Long irregular bridges
   i. Shorter piers near the ends and longer piers at the center
   ii. Shorter piers on one half and longer piers on the other half
   iii. Shorter piers at the center and longer piers near the ends



Structural seismic optimization: optimization and normalization

Optimization – two criteria:

1. Costs
2. Execution time

- Material quantities minimization
- Normalization

Normalization reduces labour costs and execution time

Structural seismic optimization: optimization and normalization

Challenging aspects of bridge optimization:

- There are no universal criteria for the transversal direction
- In some groups the best solution individually for longitudinal and transversal direction may not be compatible

Methodology:

- Subdivide bridges in groups of similar dynamic behavior
- Develop recommendations for each group

Normalization formats

- A normalization format is a collection of design recommendations that have the objective of standardizing the design
- These design recommendations are related to the dynamic behavior and the geometry of the bridge

Short bridge - example

All piers designed with the same cross-section

Either built-in or pinned connections

Long Irregular bridge - example

Piers divided in two or three groups according to length and position

Pier cross-section is different for each group

Short piers either with pinned or rolled connections. Long piers either built-in or pinned

Optimization methods. Multi-objective optimization

An optimization problem with many variables is a multi-objective optimization. To solve such a problem, traditional gradient-based methods aren’t ideal

Traditional optimization methods -> only one optimal solution; not good with discrete variables

Multi-objective optimization methods -> set of optimized solutions, i.e., Pareto set

Evolutionary algorithms

Case Studies - Objectives

Two case studies were developed and analysed. Both are regular bridges
Dynamic non-linear analyses in both directions with recorded ground-motion pairs.

Objectives:

- Determine the influence of the design variables on the seismic resistance of the bridge
- Determine the shape of the rupture surface, associated with the design variables
- Determine the importance of the dynamic behaviour for each direction in the overall dynamic behaviour

Case Study 1 – Regular bridge

Four 35-meter long spans and three 10-meter high piers. Total length 140 meters

Normalization format:

All piers have same cross-section and same connection to superstructure.

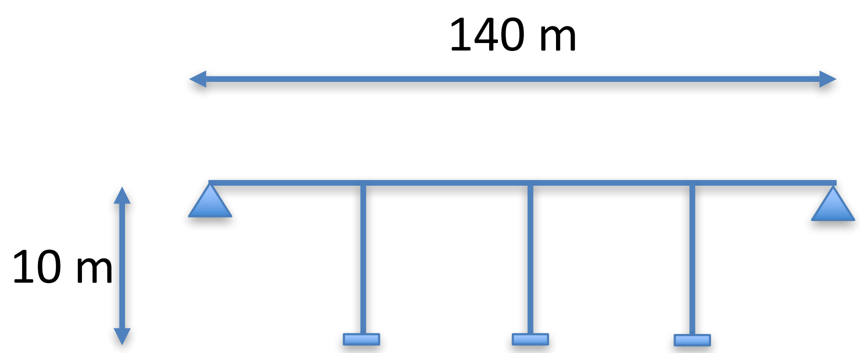
Fixed Variables:

C30/37 concrete

A500 steel

Pier-deck connections – built-in

Φ16//10 transverse reinforcement



Optimization variables:

X1 - Cross-section diameter

X2 - Steel ratio

Case Study 1 – Regular bridge

Application of evolutionary algorithms with dynamic analysis using 4-pairs of Time-History signals.

Two objective variables (pier cross-section):

Diameter (m) Y-axis

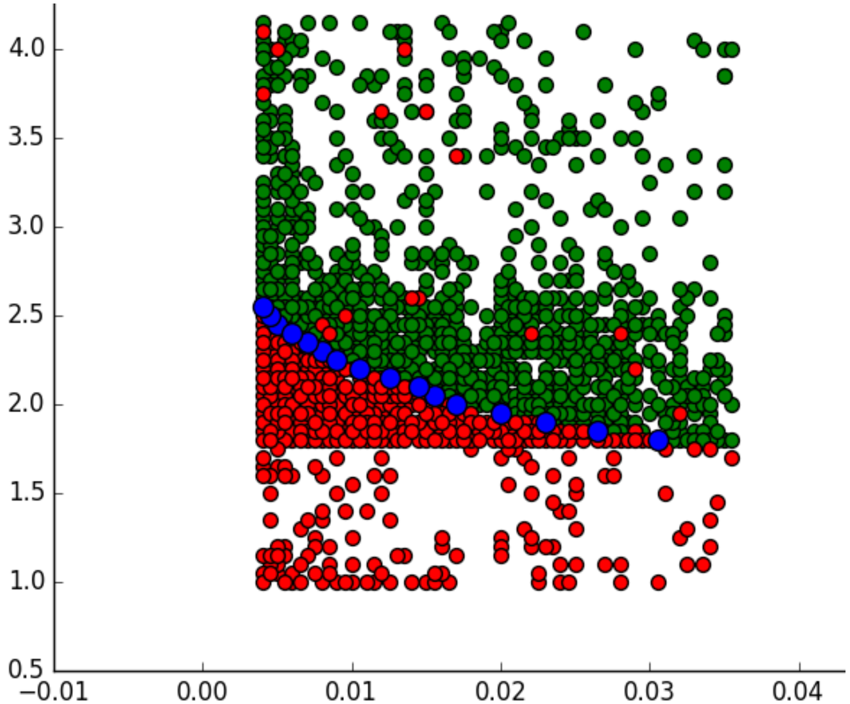
Longitudinal steel ratio X-axis

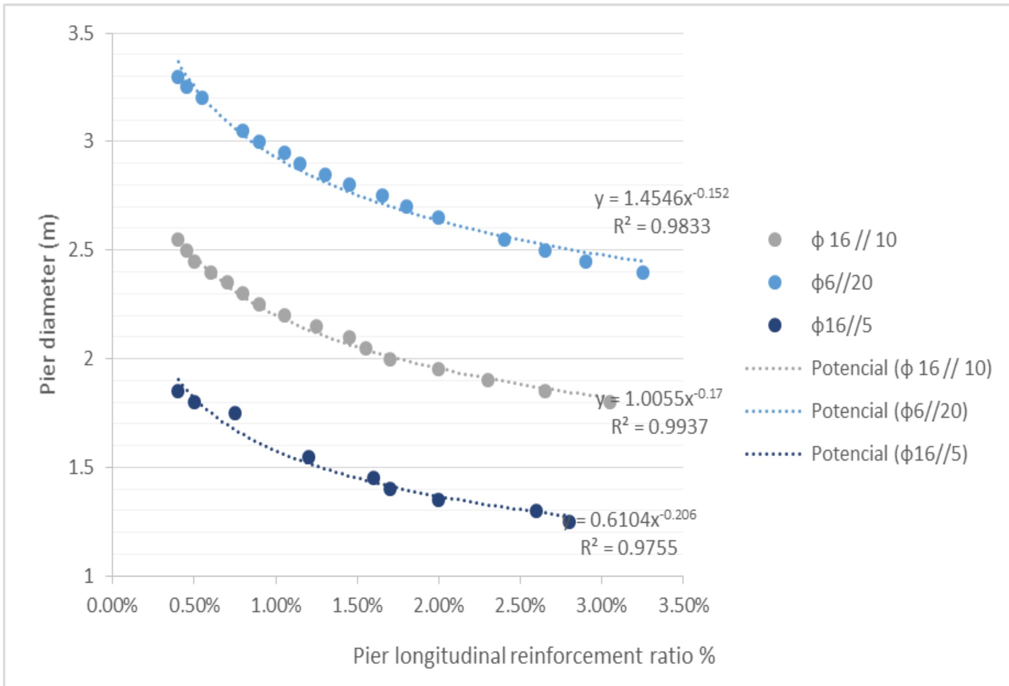
What is the use of this?

Influence of each variable on the Pareto set -> delimits the feasible and unfeasible region – rupture curve

Below:

Influence of different confinement amounts on the rupture curve





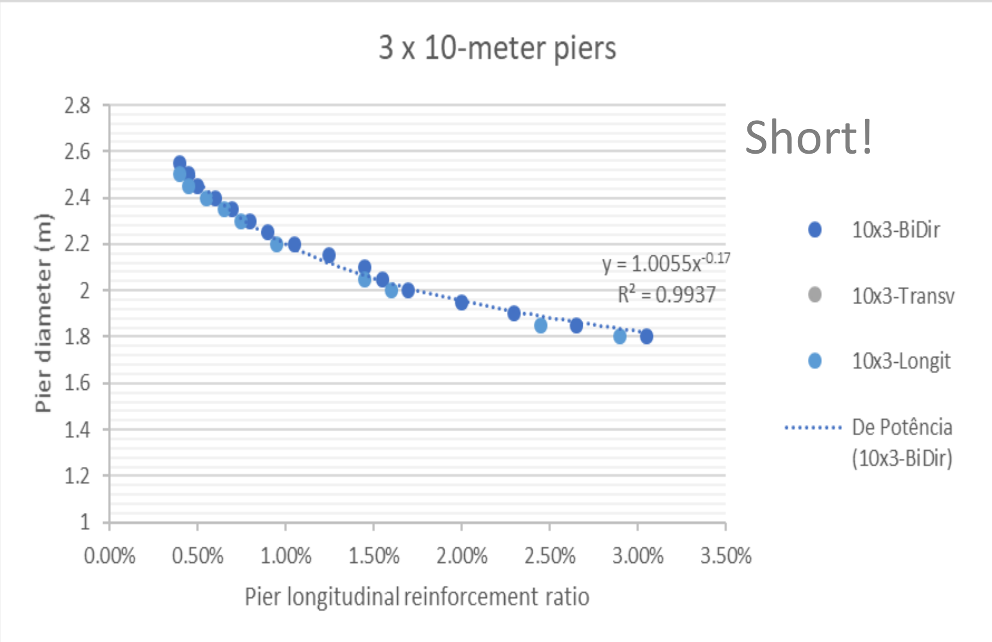
Case Study 1 and 2

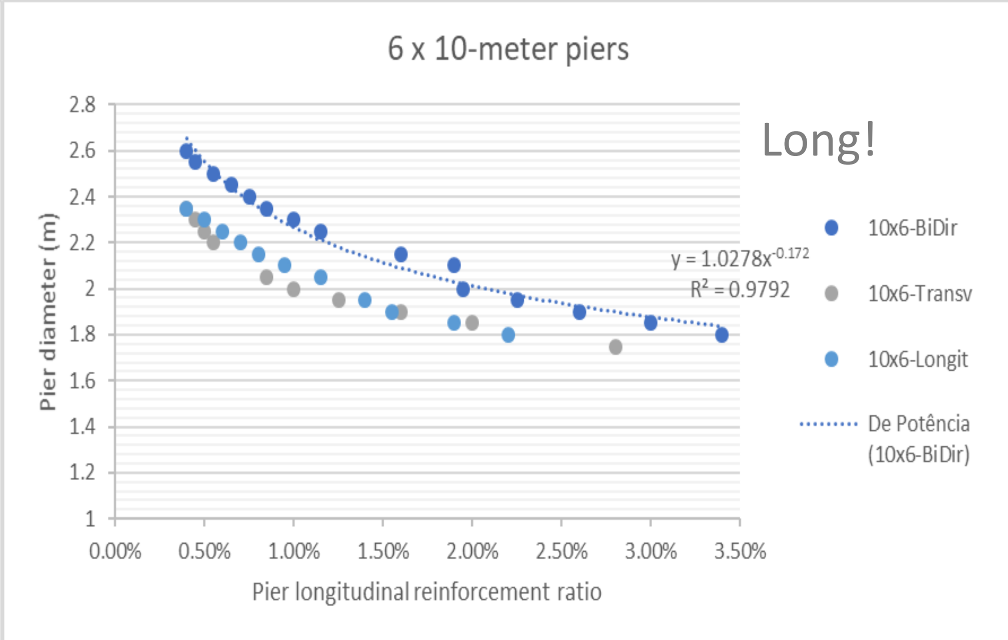
Case study 1 – regular (short or long?)

Another use of the results from the optimization method is characterizing the bridge as short or long, since the optimization can be done individually for each direction

Case study 2 – regular (short or long?)

The same as case study 1 but with 7 spans instead of 4. Total length 245 meters





Analysis and first conclusions of case studies

- So far, only regular bridges have been analysed. Two cases were presented with the purpose of illustrating a short regular bridge and a long regular bridge

- The main variables for seismic design of RC (circular) piers are dimension of cross-section, longitudinal steel ratio and transverse steel ratio. The influence of each of these variables is obtained through these analysis showing the impact of each one on the rupture curve (Pareto set)

- These results obtained from this optimization process are important to aid the development of the normalization formats and design methodology

Future Work

- Monte-Carlo simulations with stochastic definition of the material properties (already being done)
- Deriving and testing different normalization formats for the irregular bridge groups
- Definition of a design procedure for each bridge group, according to the normalization formats, for practical use of project engineer

Thank you for your attention!

Analytic model (Question slide)

OpenSees software was used to execute the analysis:

- Deck – Linear elastic beam element
- Piers – Non-linear force-based fiber elements divided into 3 sub-elements, and each sub-element divided into 5 integration sections:
  - The constitutive relation for steel follows Menegotto-Pinto's model
  - The constitutive relation for concrete follows a uniaxial Kent-Scott-Park concrete material object with degraded linear unloading/reloading stiffness
  - The definition of the confined concrete model variables is done according to EC8 part 2 regarding confined concrete stress-strain model

Pushover vs Dynamic (Question slide)

Dynamic analysis was chosen over pushover analysis for two main reasons:

1. The inability to obtain, through pushover methods, credible results for analysis in both directions simultaneously
2. The unreliability of the simpler, less time-consuming, pushover methods for the study of irregular bridges (Kappos et al. 2012, figure below)

Type of bridge	Single-mode methods	Multi-mode methods		Nonlinear response history analysis
		Non-adaptive	Adaptive	
Response is governed predominantly by one mode, which does not considerably change: Short bridges on moderate to stiff soil, pinned at the abutments, and not supported by very short columns.	X			
The influence of higher modes is limited and their shape does not considerably change when the seismic intensity is increased: Short bridges pinned at the abutments, supported by short side and long central columns.	X	X		
Considerable influence of higher modes, that do not significantly change the shape: Long bridges without very short central columns		X	X	
Considerable influence of one or a few number of modes, which significantly change the shape: Short bridges with roller supports at the abutments			X	
Considerable influence of higher modes, which significantly change their shape when the seismic intensity is changed: Short or long bridges supported by very short central and higher side columns.				X

Time-History Signals

Recorded time-history signals selected to match the EC8 spectrum type 1, zone 2, soil C – Portuguese National Annex (PGA 0.285g)

Respected criteria:

- the mean of the zero period spectral response acceleration values calculated from the individual time histories should not be smaller than the value of ag S for the site under study, being ag the design ground acceleration on rock and S the soil parameter
- In the meaningful range of frequencies, 0.2 T1 and 2.0 T1, no value of the mean 5% damping elastic spectrum, calculated from all time histories, should be less than 90% of the corresponding value of the 5% damping elastic response spectrum.