VULNERABILITY FUNCTIONS FOR BRIDGES IN SEISMIC REGIONS OF EGNATIA MOTORWAY IN NORTHERN GREECE

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Abstract

A methodology for the evaluation of vulnerability curves for Civil Engineering Structures under seismic excitation, and especially for bridges, is presented. The methodology combines the static pushover procedure and the capacity spectrum method and is applied in order to obtain the fragility curves for bridges in Egnatia Motorway, Northern Greece.

KEY WORDS: Computational Mechanics, Earthquake Civil Engineering, Fragility Curves of Bridges.

- **OUTLINE**

- **1. Introduction**
- **2. Methods for assessing structural vulnerability**
- **3. Two cases of Egnatia Motorway bridges with seismic stoppers**
- **4. Conclusions**

1. Introduction

- Fragility curves for Civil Engineering Structures, such as buildings and especially bridges, are a useful tool for the assessment of the damage they may sustain for a certain level of earthquake shaking.
- Bridges with aseismic stoppers: **Inequality Problem.**
- Double discretization, in space by the **Finite Element Method** and in time by a **direct-time integration scheme**, and **optimization methods** are used. Thus, by piecewise linearization of the interface unilateral contact laws, at each time-step a **nonconvex linear complementarity problem** of the following matrix form with reduced number of unknowns is finally solved:

$$v \geq 0 , \quad A\,v + a \leq 0 , \quad v^T . (A\,v + a) = 0 .$$

- So, the nonlinear Response Time-History (RTH) for a given seismic ground excitation can be computed.

2. Methods for assessing structural vulnerability

- The vulnerability functions, required for the fragility curves, are expressed in terms of a Lognormal cumulative probability function in the form of next eq.:
-

$$P_f\left(DP \geq DP_i \mid S\right) = \Phi\left[\frac{1}{\beta_{tot}} \cdot ln\left(\frac{S}{S_{mi}}\right)\right]$$

- Here *Pf (·)* is the probability of the damage parameter *DP* being at, or exceeding, the value *DPi* for the i-th damage state for a given seismic intensity level defined by the earthquake parameter *S* (here the Peak Ground Acceleration-PGA or Spectral Displacement-Sd), *Φ* is the standard cumulative probability function, *Smi* is the median threshold value of the earthquake parameter *S* required to cause the i-th damage state, and *βtot* is the total lognormal standard deviation. Thus, the description of the fragility curve involves the two parameters, *Smi* and *βtot*, which must be determined.

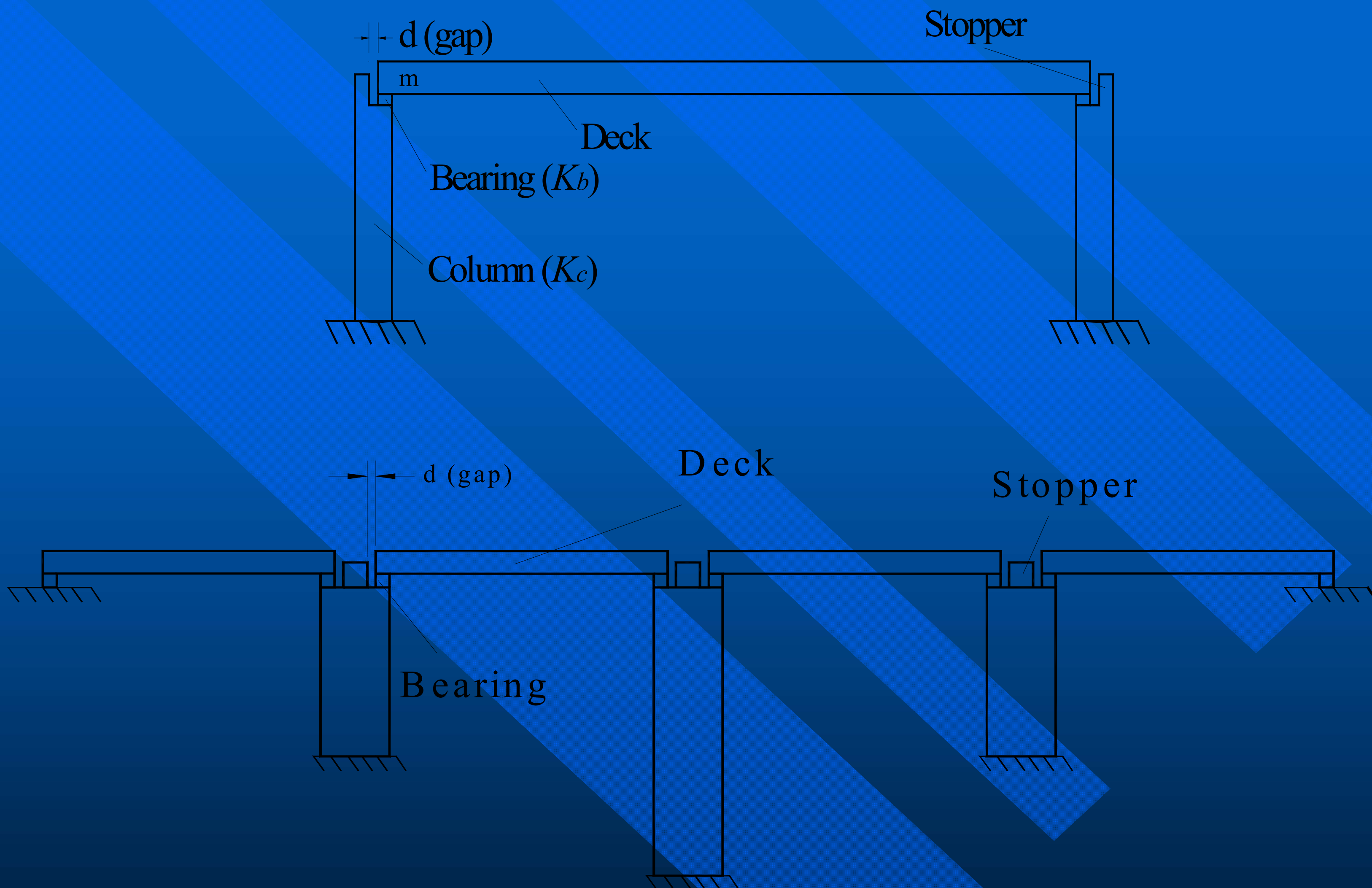

Figure 1: Schematic diagram of (a) single span bridge and (b) multi span bridge.

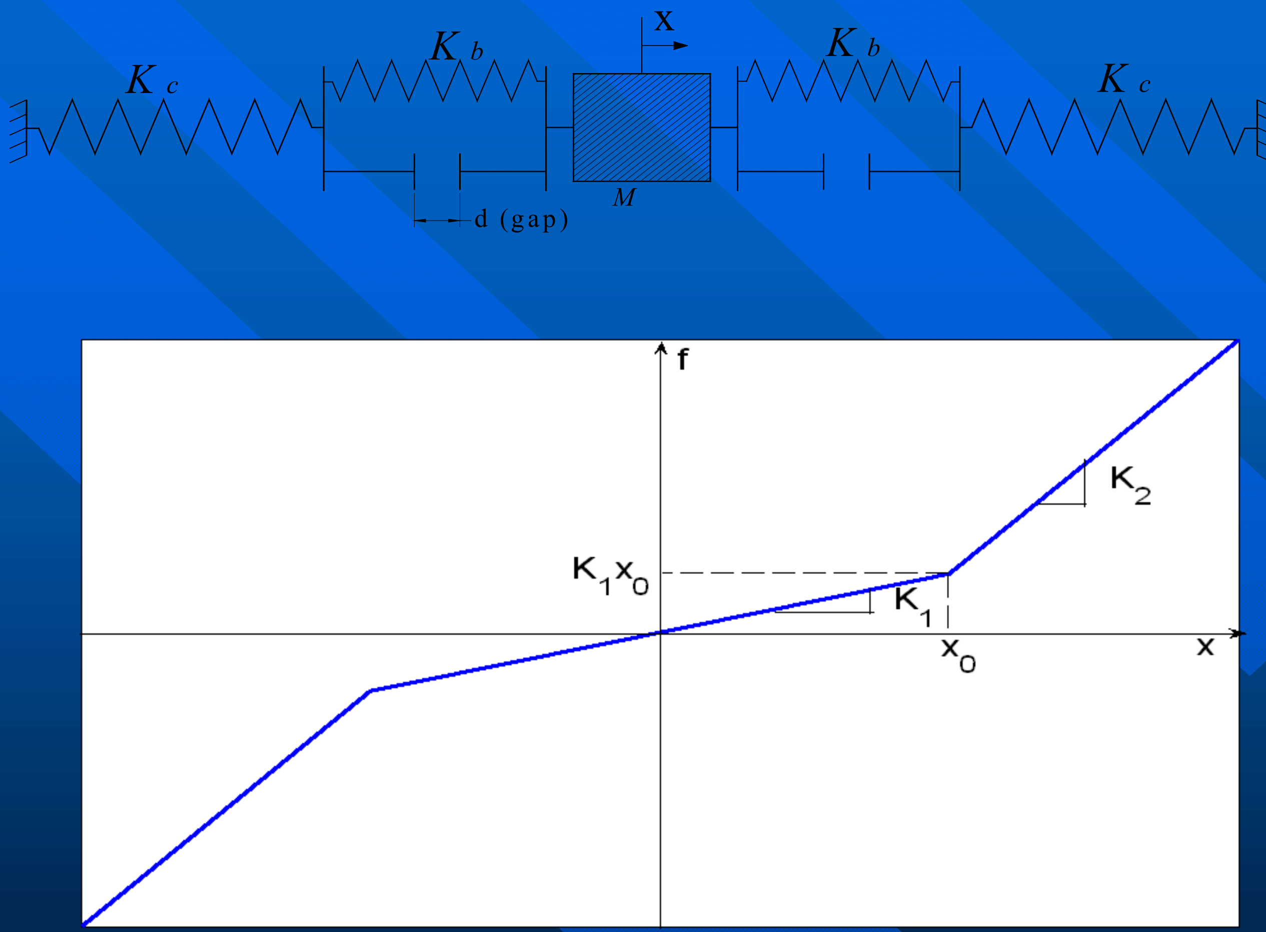

Figure 2: (a) Simplified SDOF system with bilinear stiffness and (b) elastic force-displacement relationship.

Proposed simplified methodology for the calculation of the vulnerability curves of bridges in the presence of seismic stoppers:

- This methodology is based on a modal pushover nonlinear static analysis and on a capacity demand spectrum approach, instead of a time consuming non-linear dynamic based vulnerability analysis.
- Briefly, the proposed methodology comprises the following main steps:
- (a) Due to elastomeric bearings, the system of the deck and prestressed reinforced concrete (r/c) beams is moving horizontally up to the existed gaps of spans will close. Here, the shear stiffness of the system of elastomeric bearings is quite active.
- (b) A Finite Element Model of the bridge is constructed using linear elements and lumped plastic hinges, for the end sections of the piers, the bents, the continuity slabs and the abutment's ballast walls.

(c) The structural elements possess suitable effective flexural stiffness.
(d) The structural critical sections are analyzed in order to calculate the bilinear moment-curvature (M-C) diagram, as well as the moment-axial force diagram up to the yielding point by using a suitable material law for confined concrete.
(e) Transformations of bilinear diagrams M-C in bilinear diagrams M-R (moments-rotations) using a suitable length of each plastic hinge.
(f) The first translational mode-shape distribution of external static seismic lateral forces is considered in the nonlinear static pushover analysis, for both horizontal principal axes, which represent adequately the dynamic response of the bridge.
(g) The gravity loads of the system are in action.
(h) Static pushover procedure and capacity spectrum method are performed.
(i) The damage levels of the bridge are defined and finally the statistical lognormal function of probability distribution is used.

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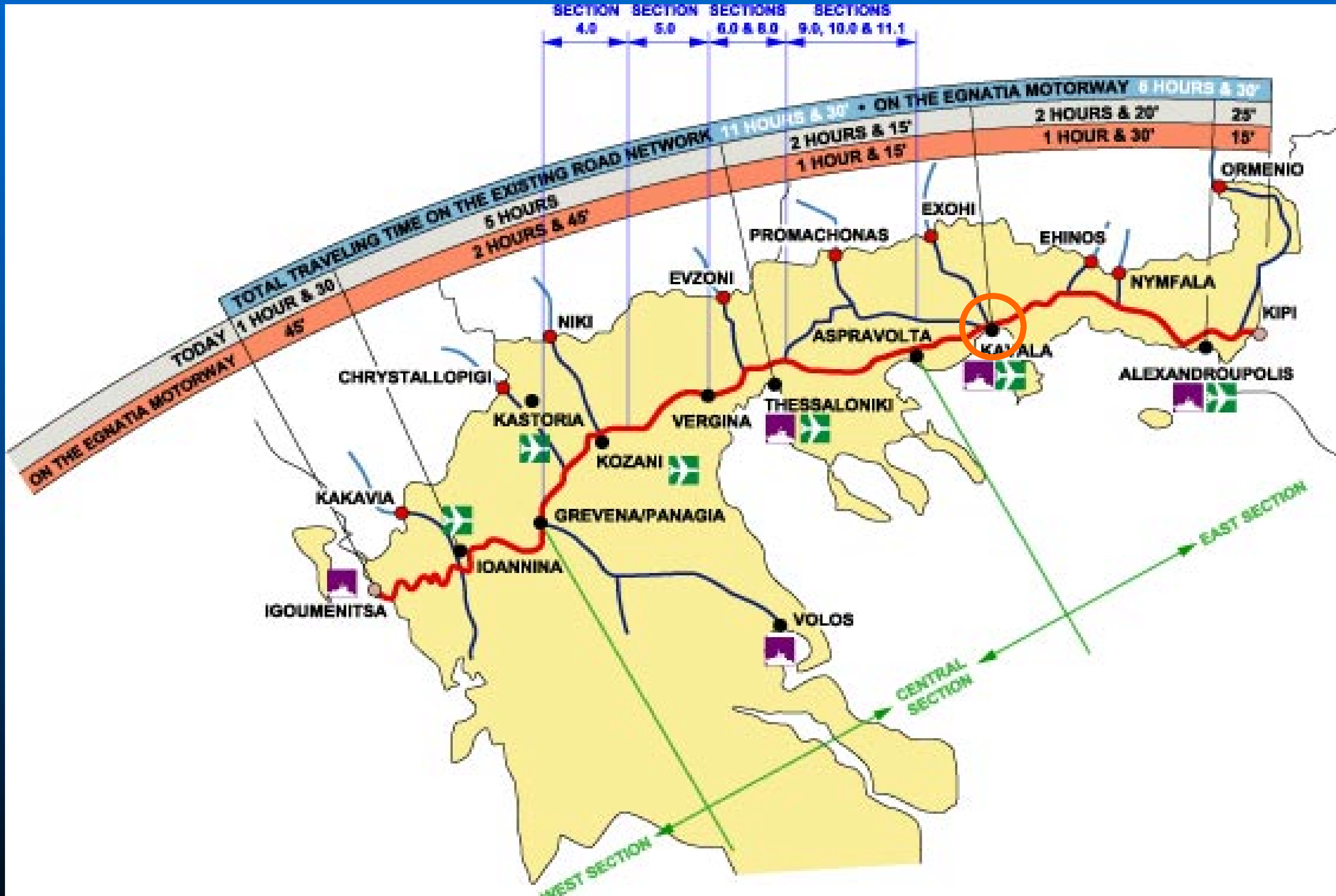
Egnatia Odos Motorway
670 Km
Plus 300 Km vertical axis

The Egnatia Motorway, Greece



PROJECT IDENTITY

■ AXIS LENGTH:	670 km (From Igoumenitsa through to Kipi)
■ TECHNICAL FEATURES:	Dual carriageway with a central reserve. Two traffic lanes per carriageway plus a hard shoulder.
■ STANDARD CROSS -SECTION:	24.5 m
■ MAIN ENTRANCE – EXIT JUNCTIONS:	50
■ OVERBRIDGES / UNDERPASSES:	353
■ SERVICE ROADS	720 km
■ TOTAL BRIDGE LENGTH :	2x40 km
■ TOTAL TUNNEL LENGTH :	2x50 km

TECHNICAL CHARACTERISTICS

- TUNNELS
- BRIDGES

Technical Characteristics - TUNNELS

LONG TUNNELS ON THE EGNATIA MOTORWAY

Region	Tunnel Name	Length (m)
Epirus	Dodoni	3,350
Epirus	Driskos	4,590
Epirus	T8	2,635
Epirus	Krimnos	1,080
Epirus	Neo Anilio	2,135
Epirus	Metsovo	3,550
Thessaly	Panagia	2,700
Western Macedonia	Syrto	1,500
Western Macedonia	Koiloma	1,080
Central Macedonia	S10	2,240
Central Macedonia	Paggaio	1,100

Technical Characteristics - BRIDGES

Region	Structure Name	Carriageway length/up to 6m span	Height (m)
Epirus	Aracthos	1.000/142	80
Thrace	Nestos	450/40	10
Macedonia	Greveniotikos	920/100	40
Epirus	Krystallopigi	850/55	30
Epirus	Metsovitikos	540/235	100
Epirus	Votonosi	490/230	53
Epirus	Megalorema	480/45	28
Macedonia	G12 (section Polymylos-Lefkopetra)	465/110	90
Thrace	Lissos	450/45	15
Epirus	Mesovouni	260/100	30

1650 bridges of total length 80 km

Construction Methods Employed

Balanced Cantilever
max span: 235m
max pier height: 105m

Incremental Launching
max span: 45.5m
max pier height: 27m

EPIRUS: VOTONOSI BRIDGE

Bridge Network of Egnatia Odos

1856 Highway Structures

650 Bridges

2 x 40 km New established Bridge Network

Design life of 120 years,

access for periodical inspection

maintenance cost saving

Requirements

Seismic risk & aftershock management

3. Two cases of Egnatia Motorway bridges with seismic stoppers

Photos 1,2 : The G2/**Kristallopigi bridge** on Egnatia Motorway.

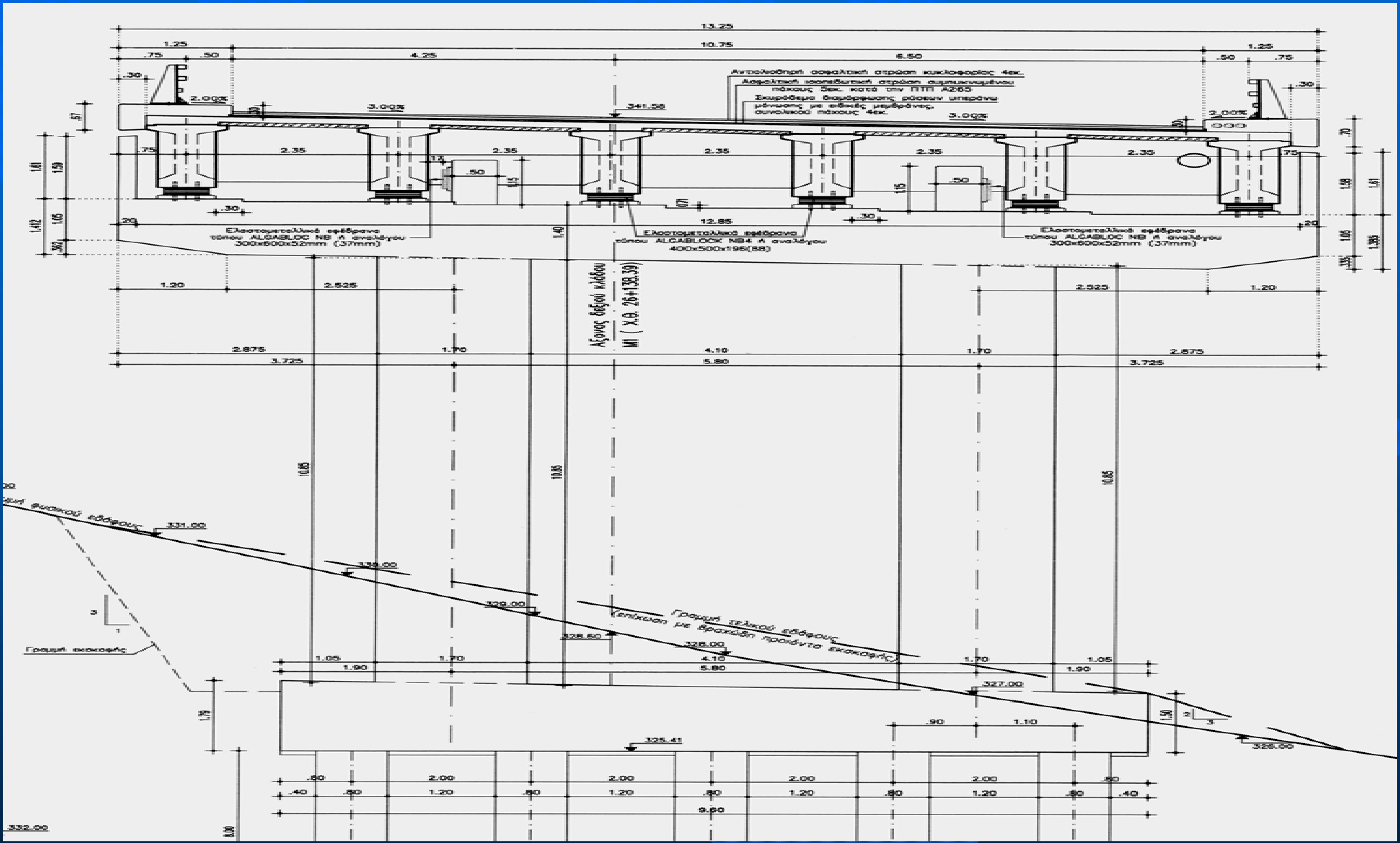


Figure 3: Transverse section of the piers

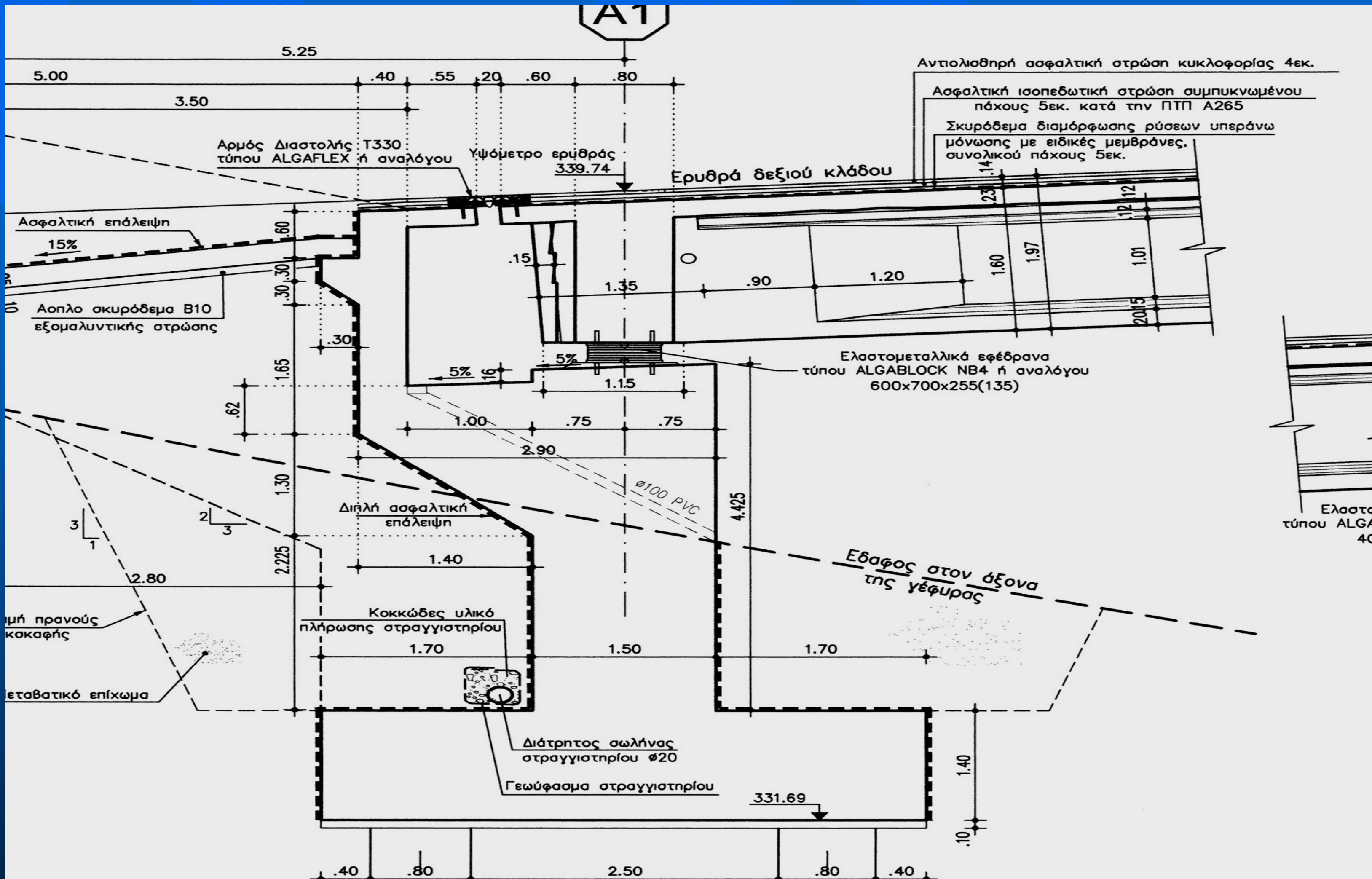
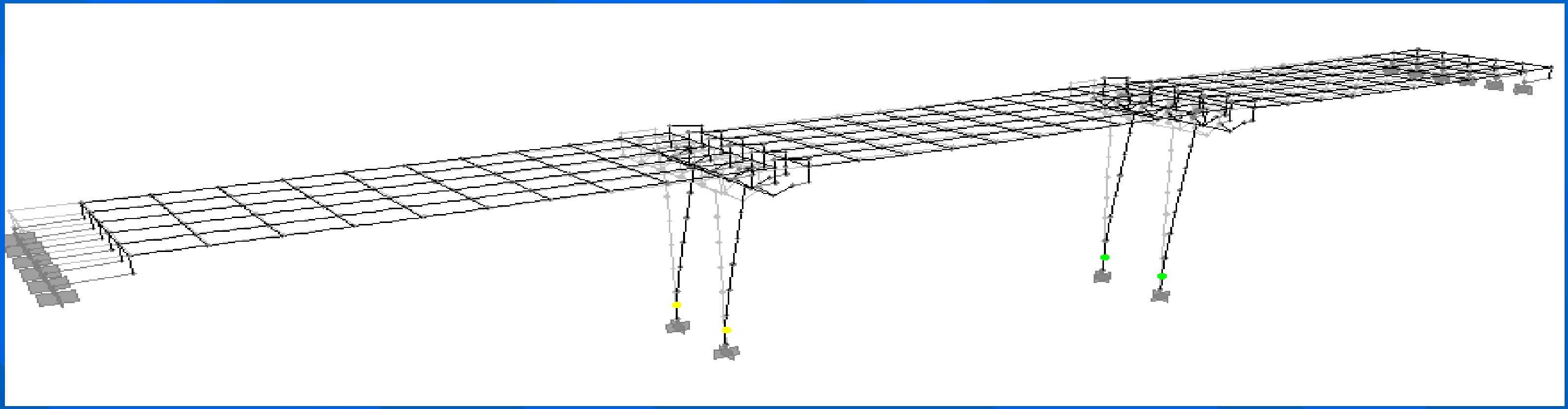


Figure 4: Abutment gallery and expansion joint gap.



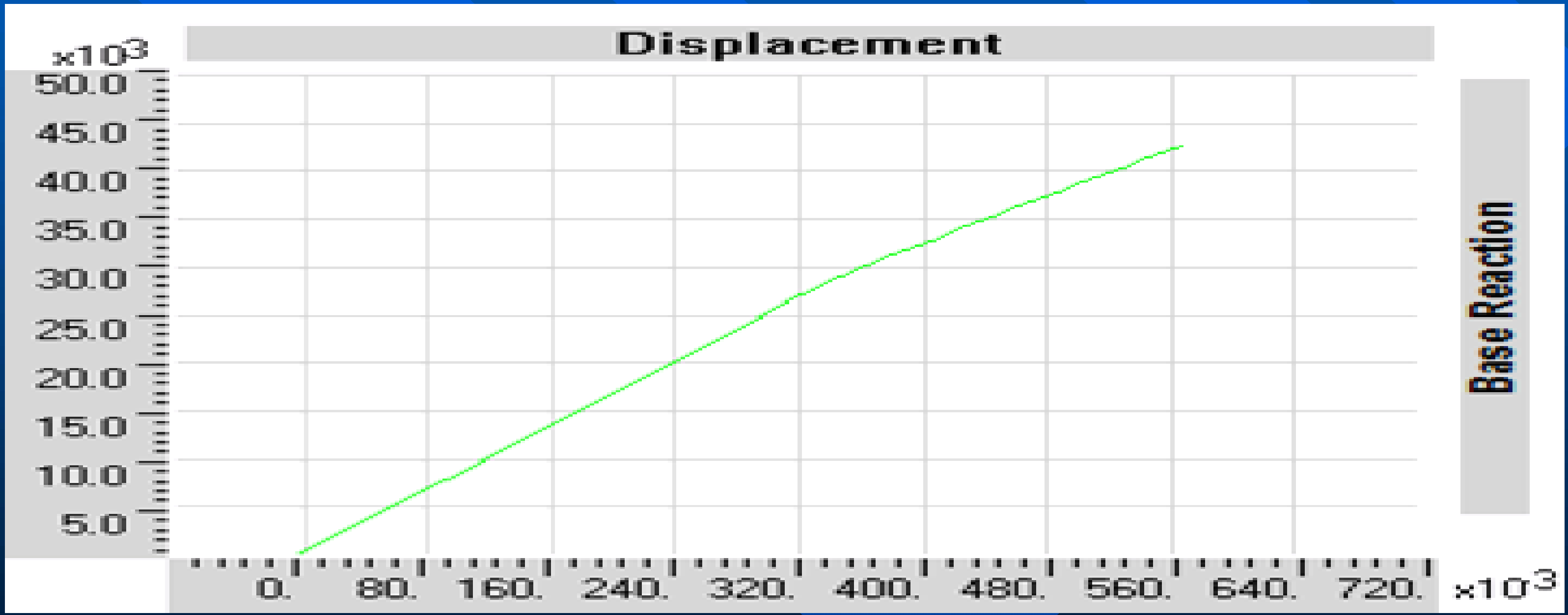


Figure 5: G2 bridge, longitudinal direction : (a) FEM model
(b) pushover curve (no gap closure)

Table 1: Definition of damage states

i	Damage state	Necessary repair interventions	Duration of interventions	Damage ratio $D_i=\delta_i/\delta_y$
0	No damage	None	---	<0.7
1	Minor damage	Small-scale repairs	<3 days	>0.7
2	Moderate damage	Repair of structural elements	<3 weeks	>1.5
3	Extensive damage	Reconstruction of structural parts	<3 months	>3
4	Collapse	Reconstruction of bridge	>3 months	$>\mu_u$

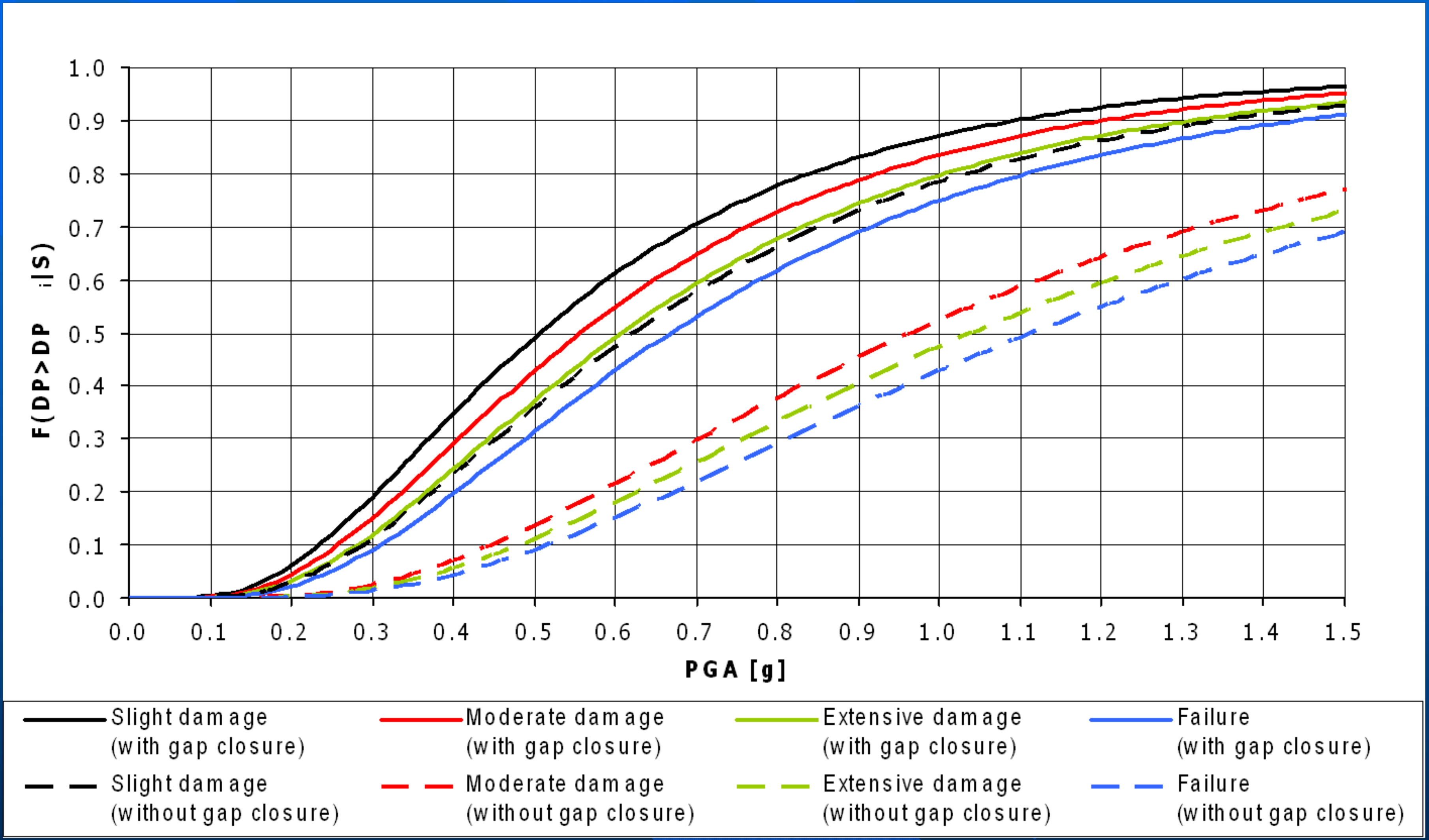


Figure 7. Fragility curves of the G2 Kristallopigi bridge:
(a) Longitudinal direction

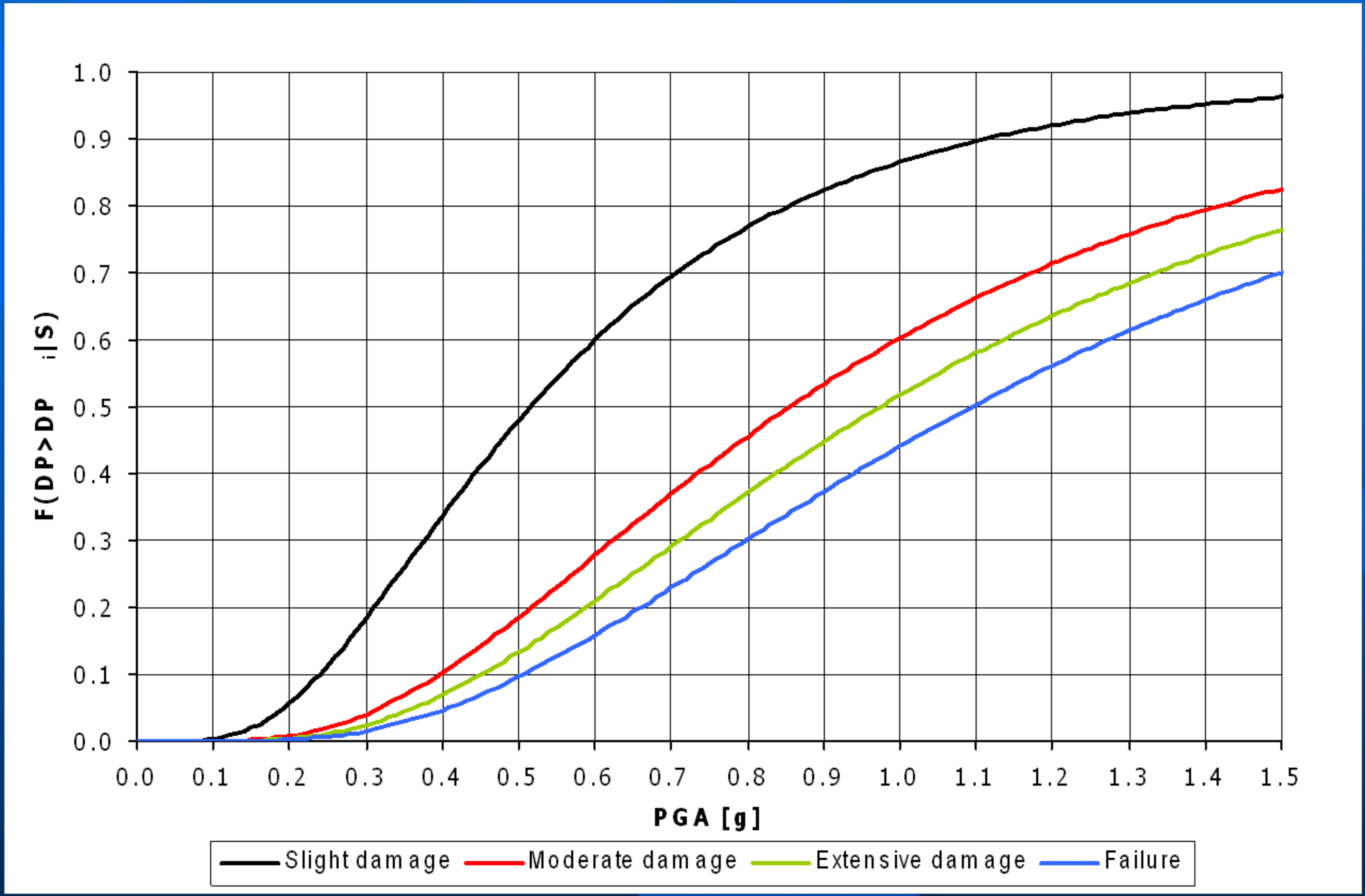
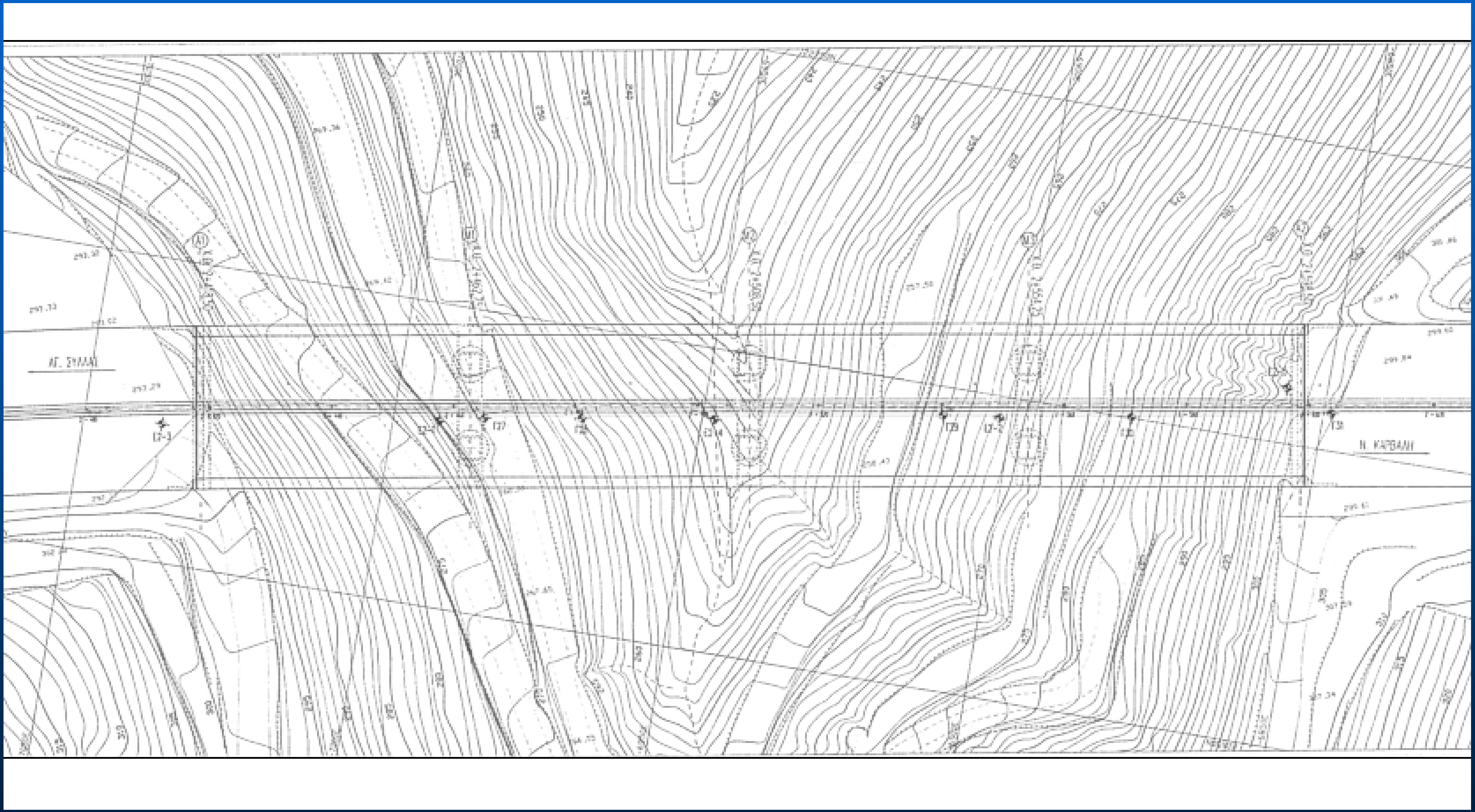


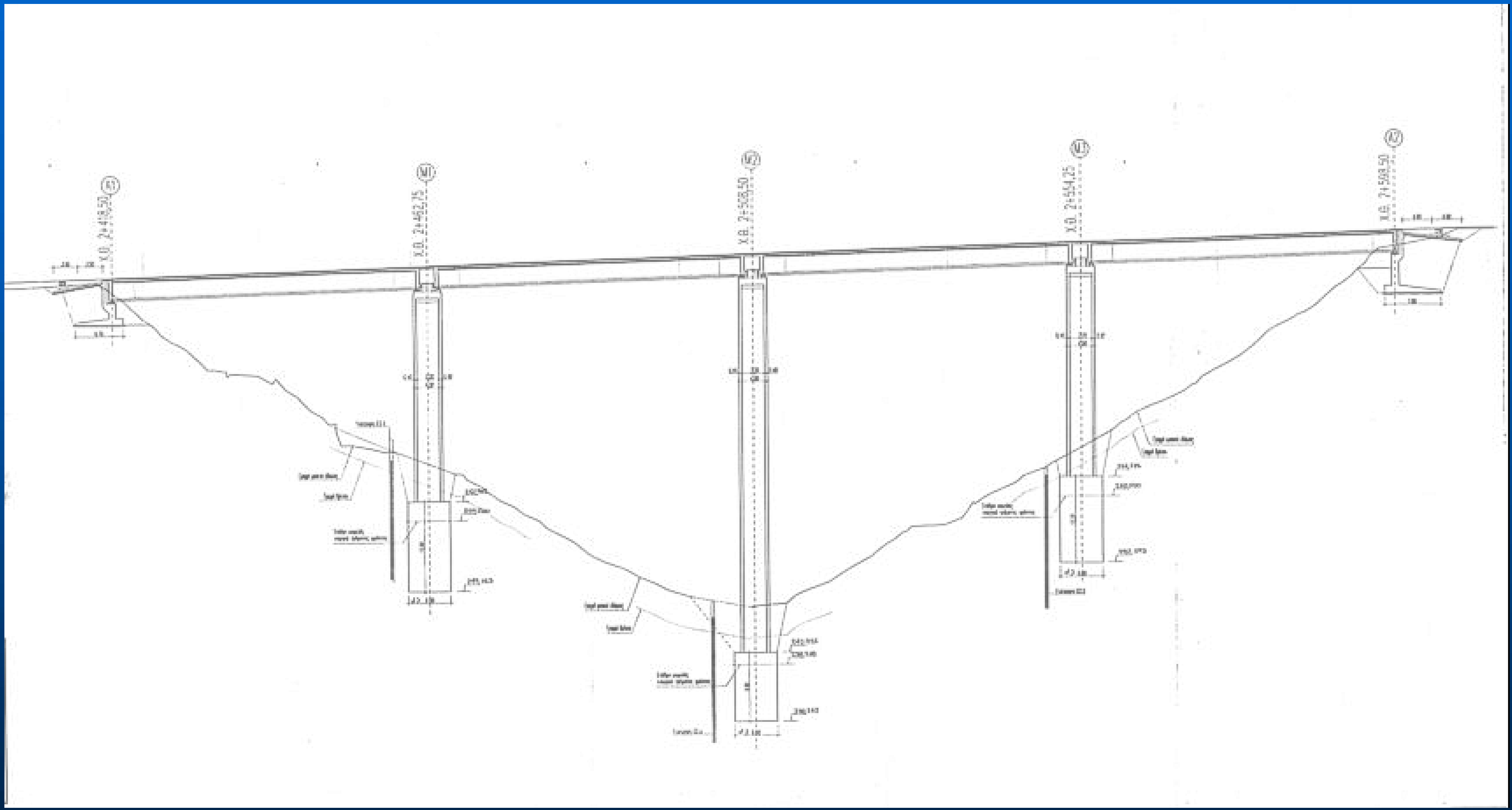
Figure 7. Fragility curves of the G2 Kristallopigi bridge:
(b) Transverse direction

2nd Kavala bypass ravine bridge

2nd Kavala bypass ravine bridge



2nd Kavala bypass ravine bridge



2nd Kavala bypass ravine bridge

2nd Kavala bypass ravine bridge

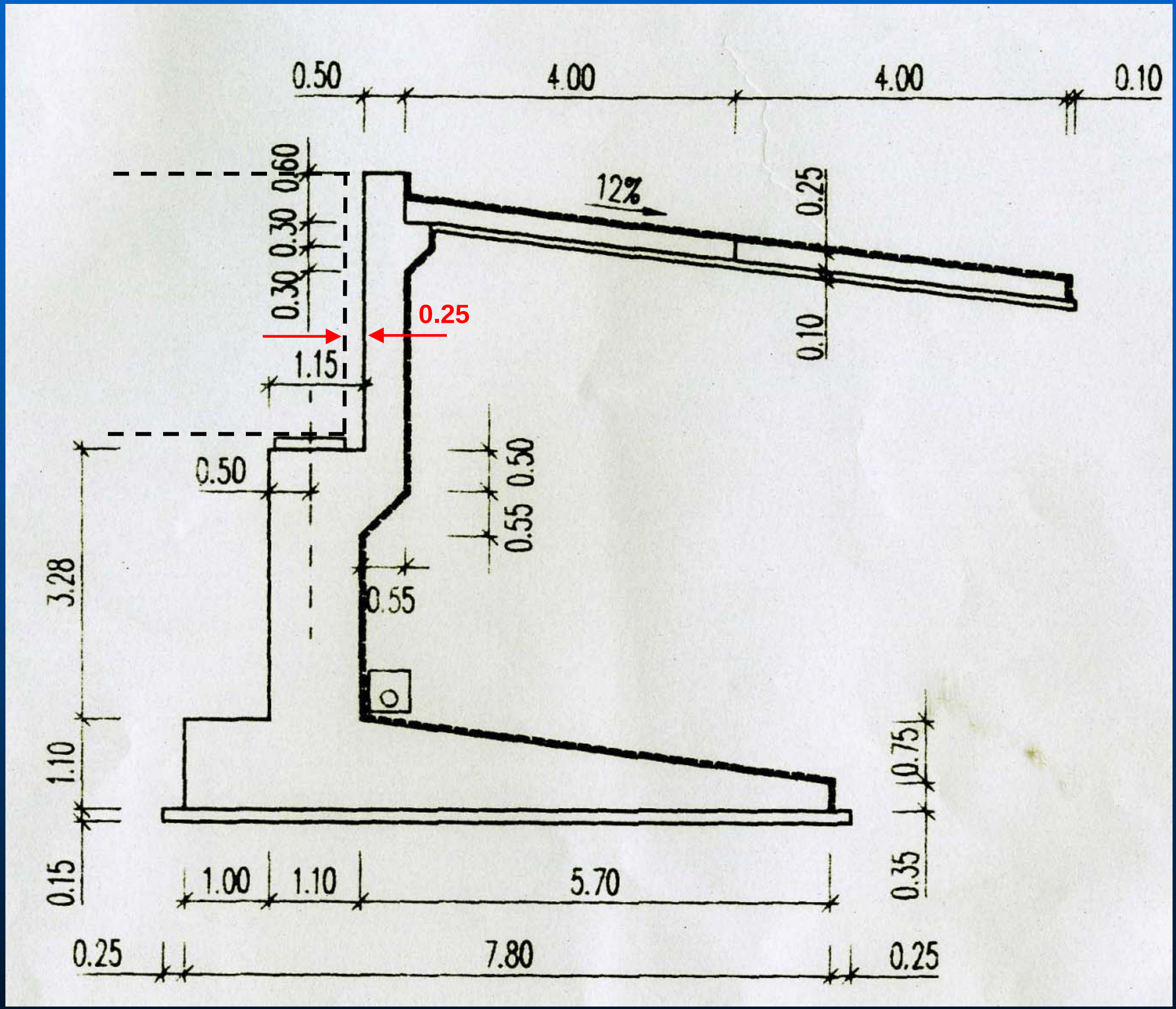
2^{nd} Kavala bypass ravine bridge

Typical shear key (top of pier)

5 cm horizontal gap at both directions at shear keys

2nd Kavala bypass ravine bridge

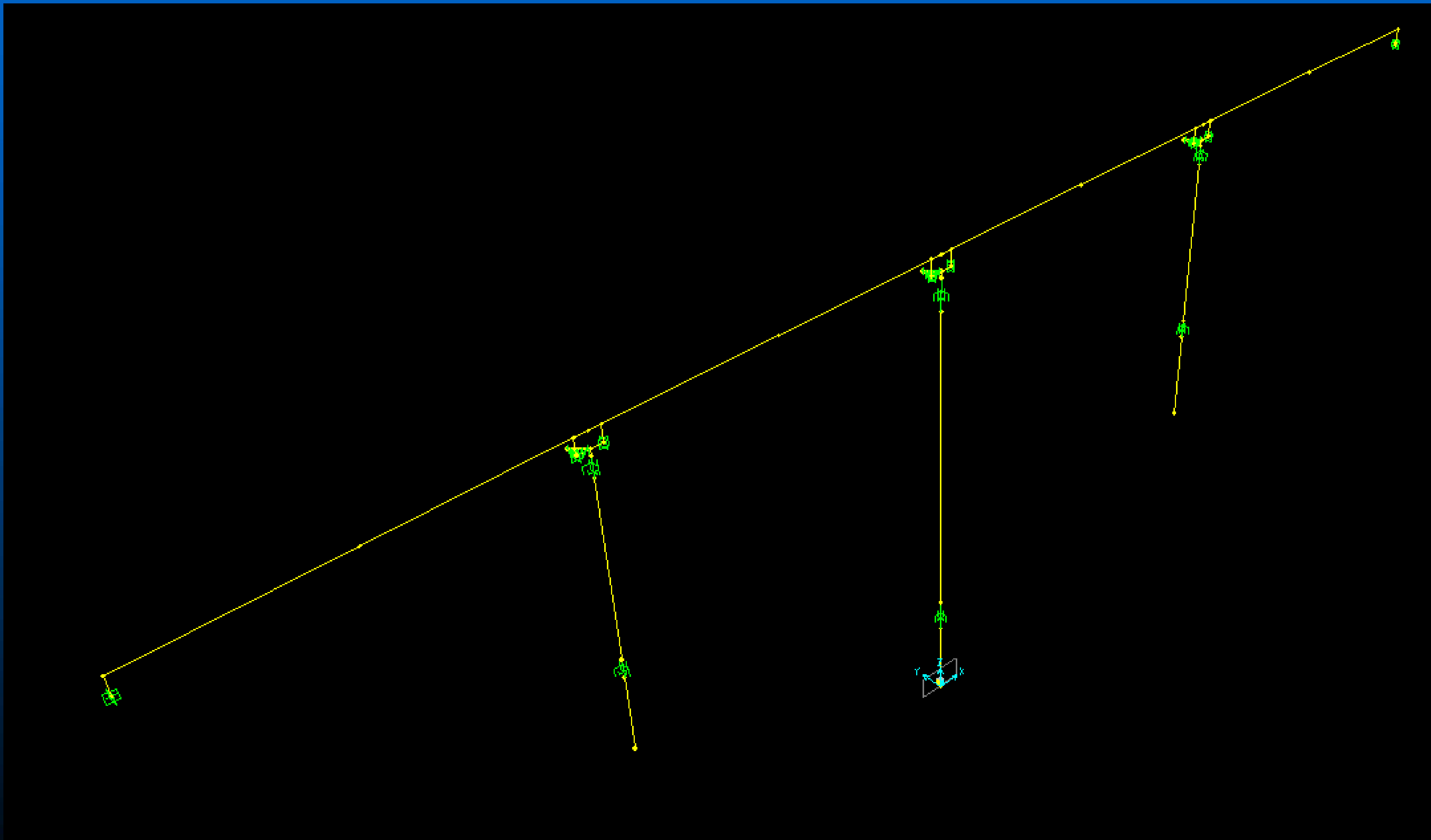
Abutments



No shear connections at the abutments (25 cm gap)

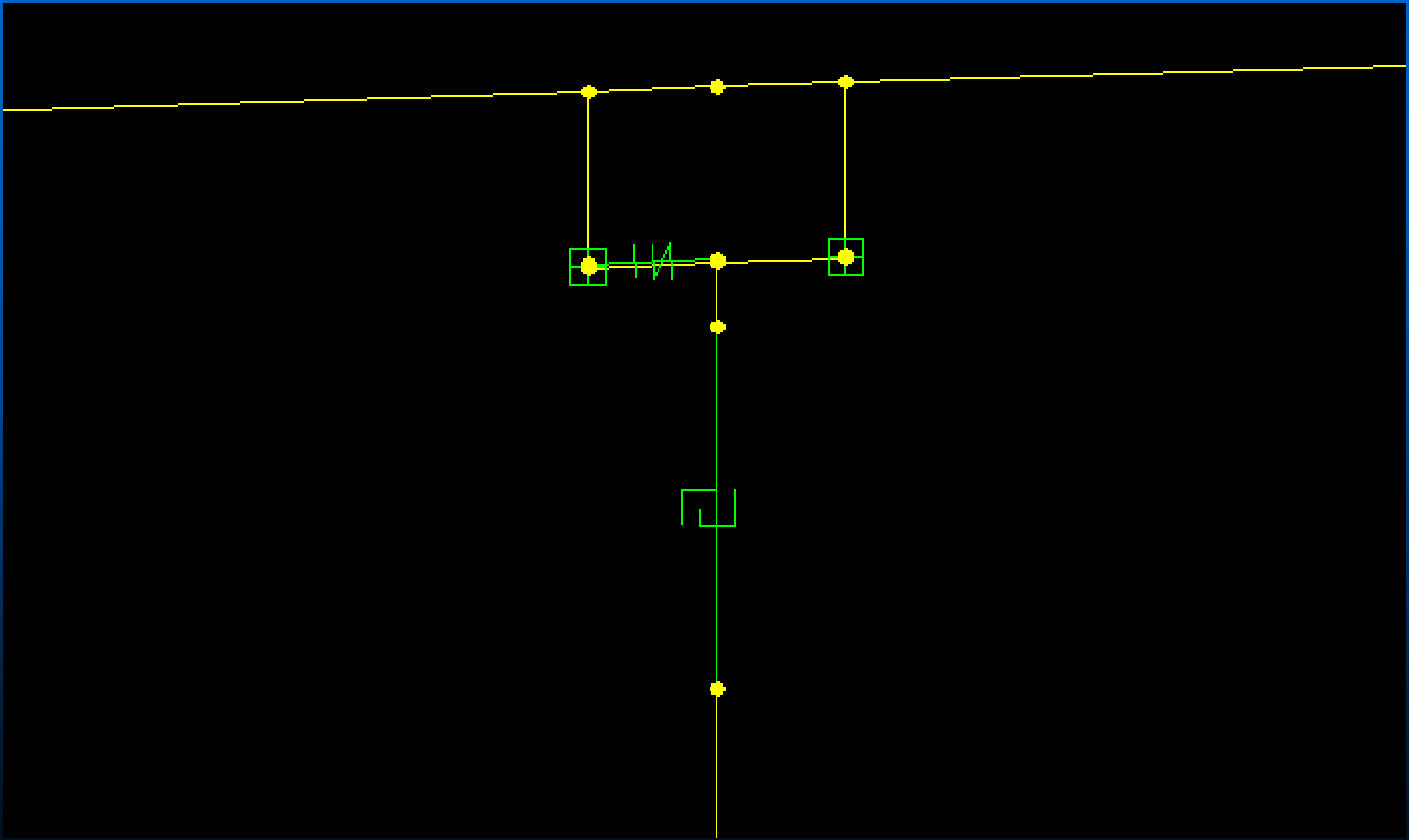
2nd Kavala bypass ravine bridge

F.E. model for Pushover Analysis



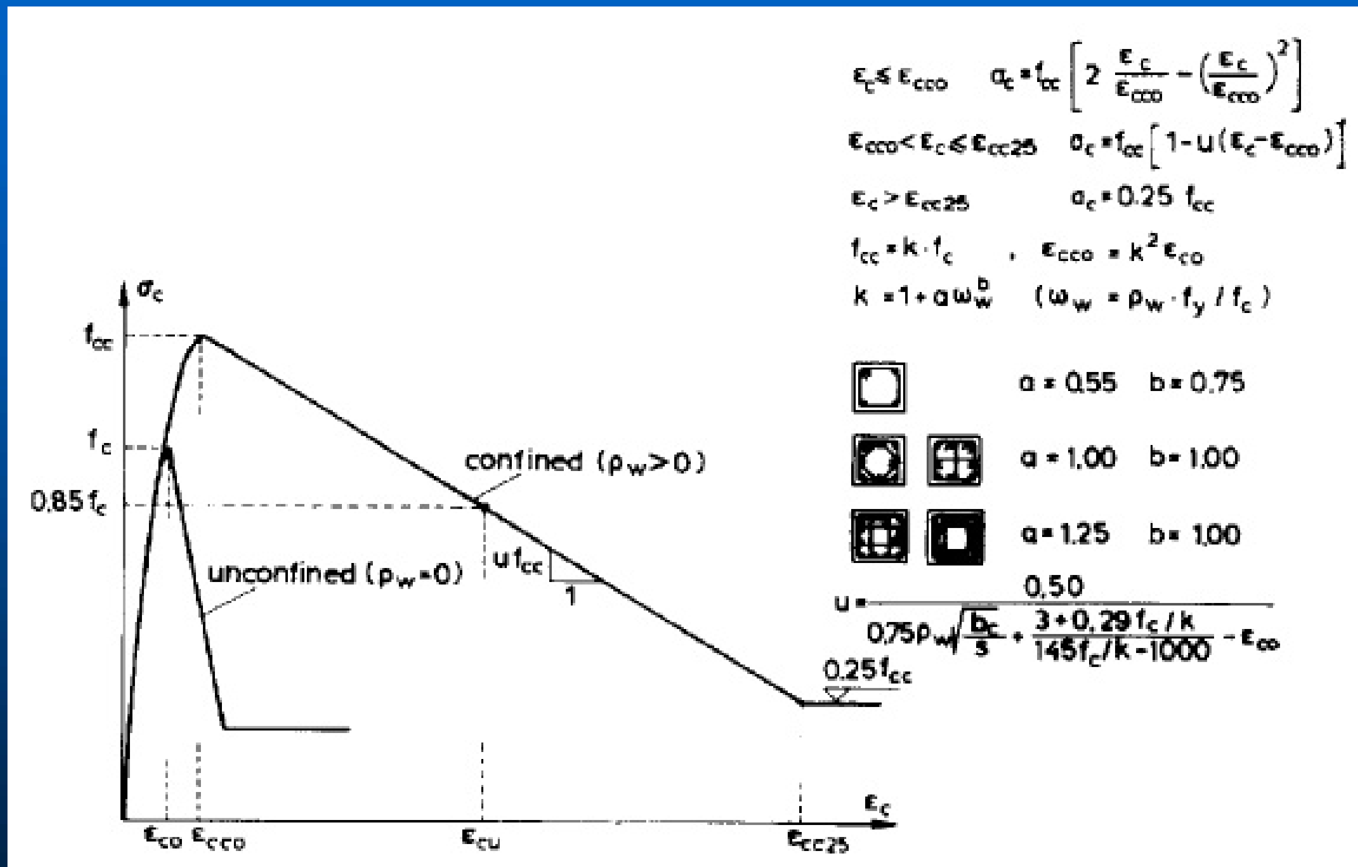
2^{nd} Kavala bypass ravine bridge

F.E. model for Pushover Analysis



2^{nd} Kavala bypass ravine bridge

Evaluation of plastic hinges (M – φ / XTRACT)



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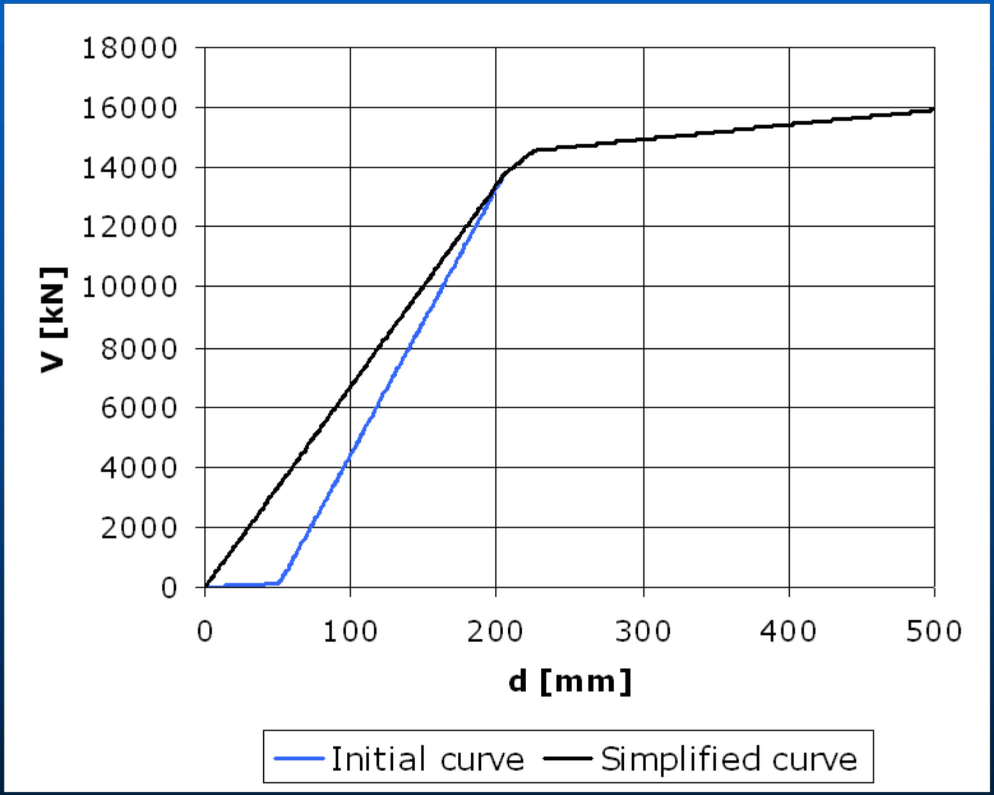
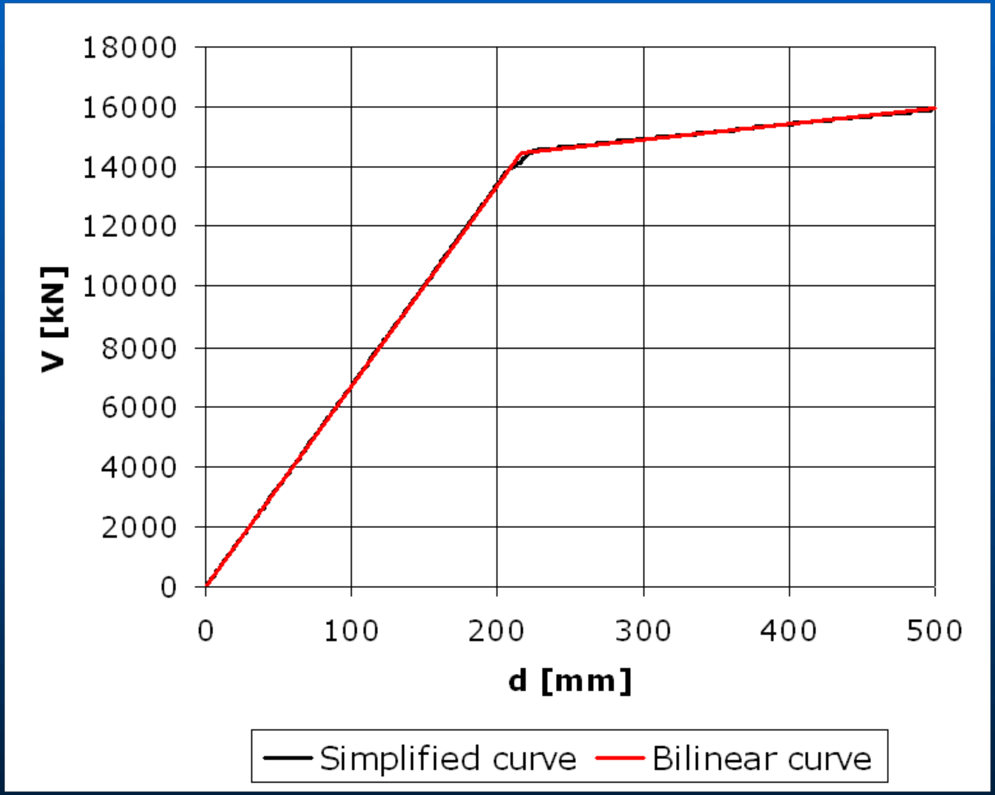
2nd Kavala bypass ravine bridge

Pushover Analysis
x-direction (longitudinal)

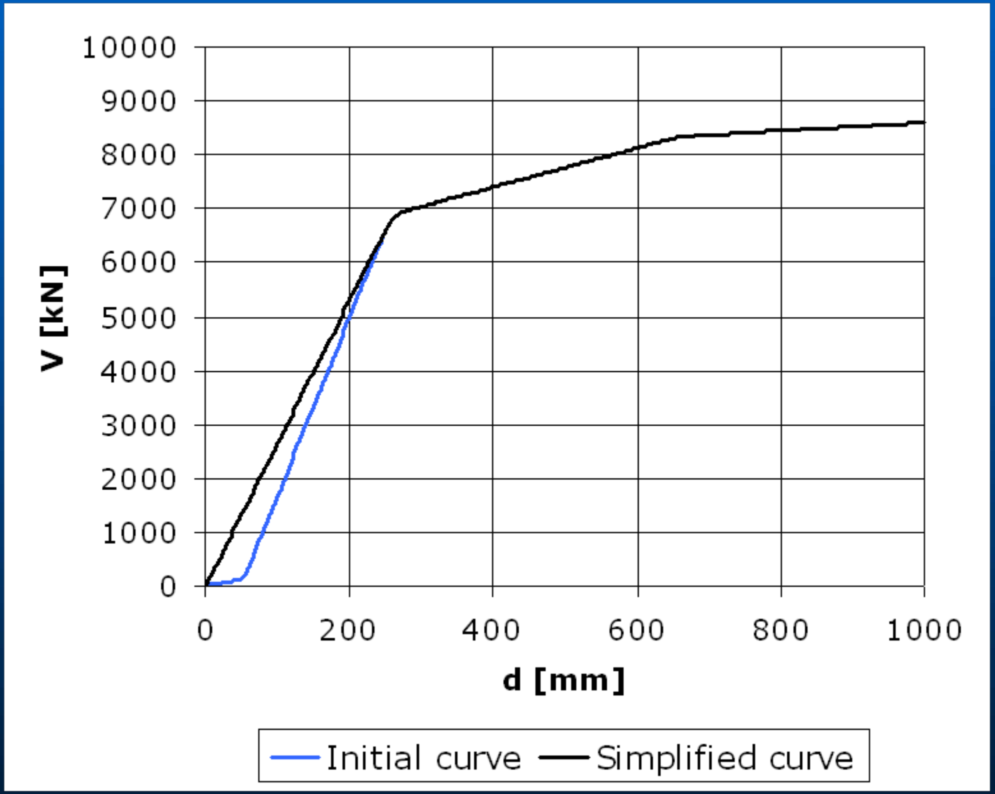


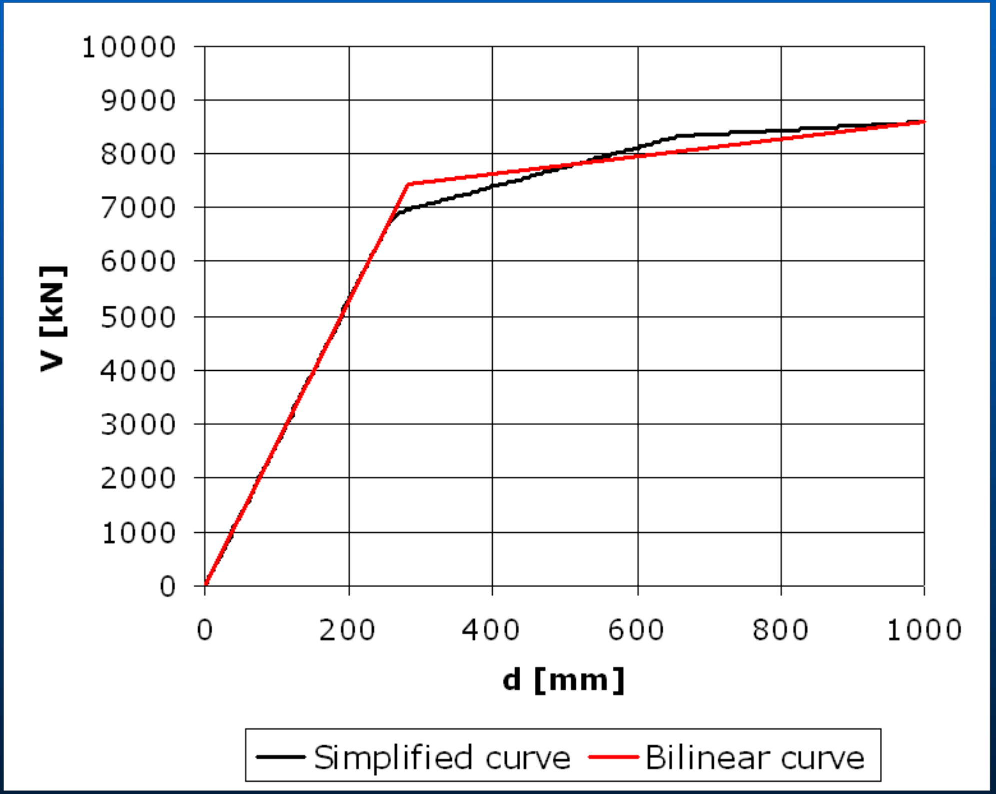


Initial pushover curve is a three-linear type curve due to elastomeric bearings

2nd Kavala bypass ravine bridge

Pushover Analysis
y-direction (transverse)

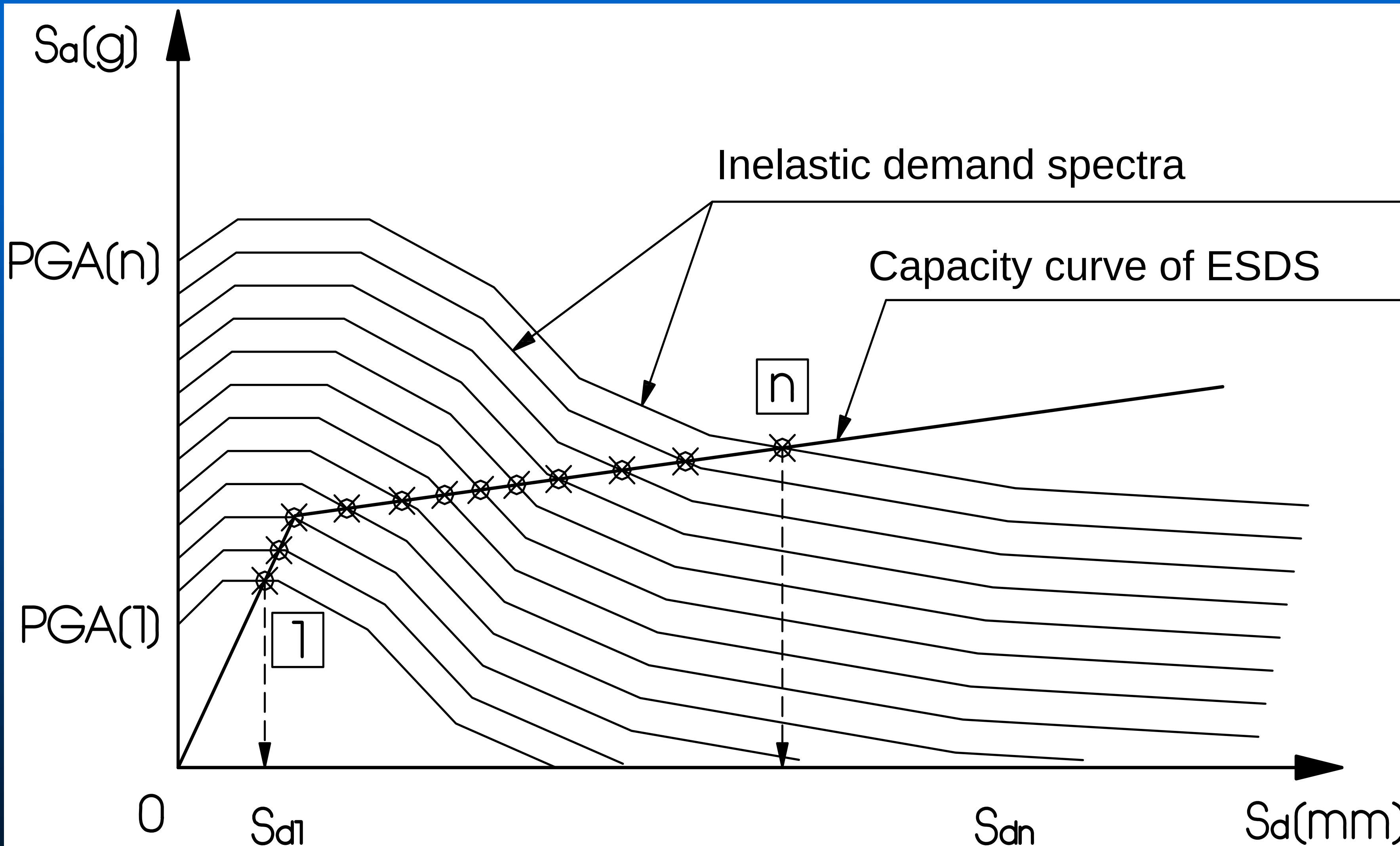




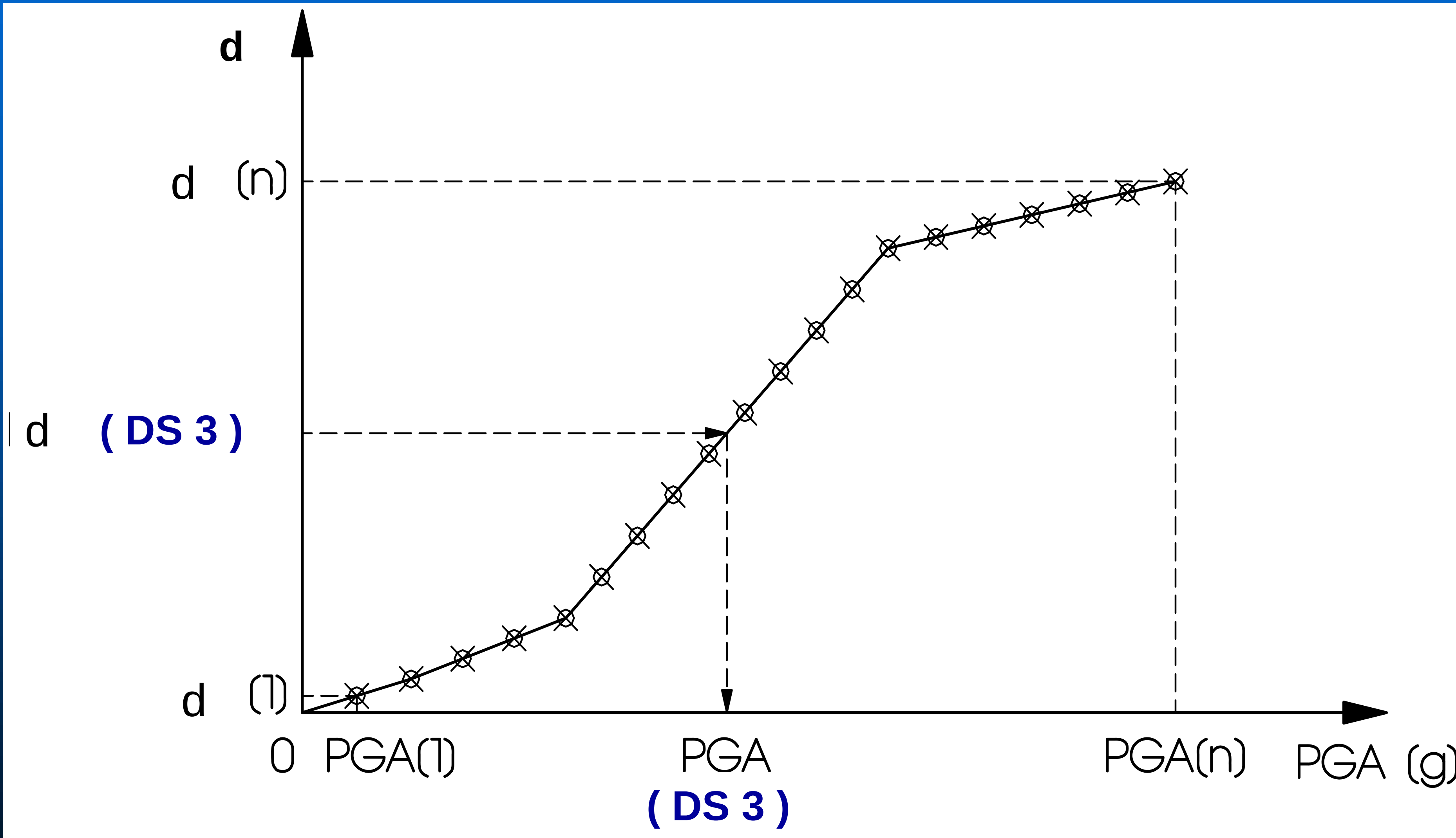
Definition of damage states

i	Damage state	Necessary repair interventions	Threshold values d	
			Longitudinal derection	Transverse direction
DS0	No damage	None	$\leq \min\{0.7 \cdot d_y, d_{gap}\}$	$\leq 0.7 \cdot d_y$
DS1	Minor damage	Small-scale repairs	$> \min\{0.7 \cdot d_y, d_{gap}\}$	$> 0.7 \cdot d_y$
DS2	Moderate damage	Repair of structural elements	$> \min\{1.5 \cdot d_y, d_y + (1/3) \cdot (d_u - d_y), 1.1 \cdot d_{gap}\}$	$> \min\{1.5 \cdot d_y, d_y + (1/3) \cdot (d_u - d_y)\}$
DS3	Extensive damage	Reconstruction of structural elements	$> \min\{3.0 \cdot d_y, d_y + (2/3) \cdot (d_u - d_y), 1.2 \cdot d_{gap}\}$	$> \min\{3.0 \cdot d_y, d_y + (2/3) \cdot (d_u - d_y)\}$
DS4	Destruction	Reconstruction of bridge	$> \begin{cases} d_u, \text{ if } d_u < 1.1 \cdot d_{DS3} \\ max\{a \cdot d_u, 1.1 \cdot d_{DS3}\} \end{cases}$	$> d_u$

The capacity spectrum method

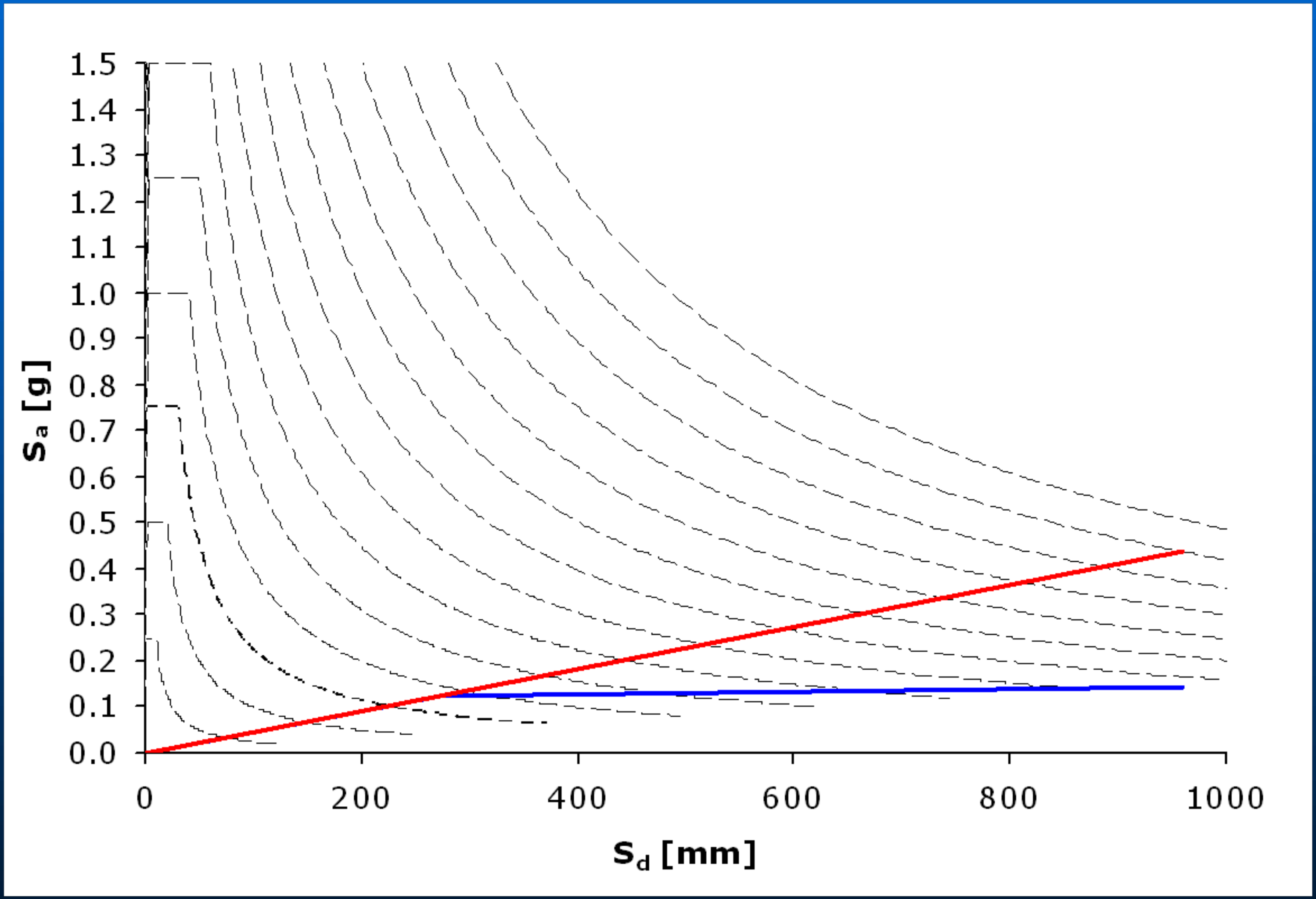


The capacity spectrum method



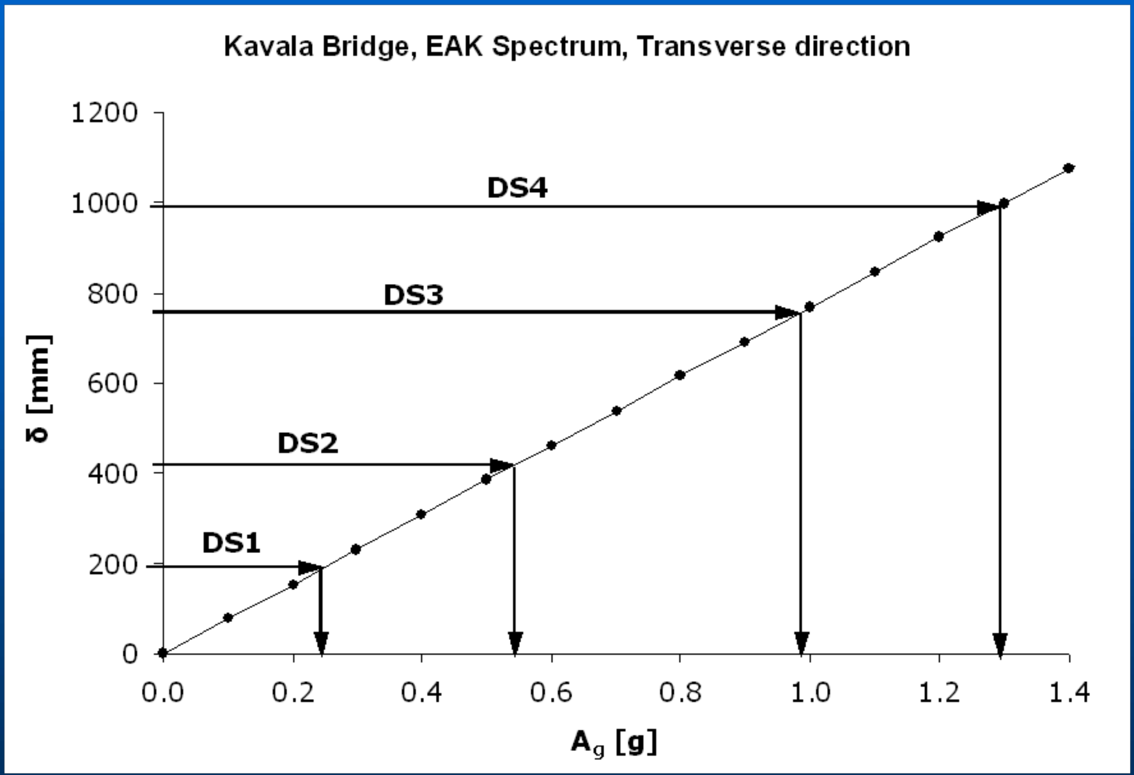
The capacity spectrum method

Elastic EAK spectrum, transverse direction



Long-period range (> 0.6sec) → Use of elastic spectra

Evaluation of mean value PGA_{mi} corresponding to the i-th damage state threshold value



Kavala Bridge, EAK Spectrum, Transverse direction		
Damage State	d [mm]	PGA_{mi} [g]
DS1 Minor damage	197.8	0.258
DS2 Moderate damage	423.9	0.552
DS3 Extensive damage	760.7	0.991
DS4 Destruction	999.8	1.302

Use of two demand spectra for evaluation of PGA_{mi} :

(a) mean elastic demand spectrum from representative sample of Greek earthquakes

(b) the Greek Seismic code (EAK) compatible spectrum

Representative sample of Greek earthquakes

- Criteria for selecting acceleration time histories:
  - $M_w > 5.0$, and epicentral distance $R < 100$ km.
  - PGA $\geq$ 0.10g and/or strong motion having caused damage in the neighborhood of the recording site.
  - Sufficient geotechnical data to classify existing soil conditions at the recording site according to the soil categories of Greek seismic code (EAK).

- In total, 71 records were selected, from 26 strong earthquakes in the last 25 years, recorded at 27 stations of the permanent accelerograph network of the Institute of Engineering Seismology and Earthquake Engineering (ITSAK) (6 records from 3 stations of Institute of Geodynamics – National Observatory of Athens).

Evaluation of fragility curves

The fragility curves can then be evaluated for different PGA values assuming a lognormal cumulative damage probability function

$$F = (D \geq D_i | PGA) = \Phi\left[\frac{1}{\beta_{tot}} \ell n\left(\frac{PGA}{PGA_{mi}}\right)\right]$$

where :

F is the probability that damage ratio D is equal or greater than the threshold value of Di for damage state i

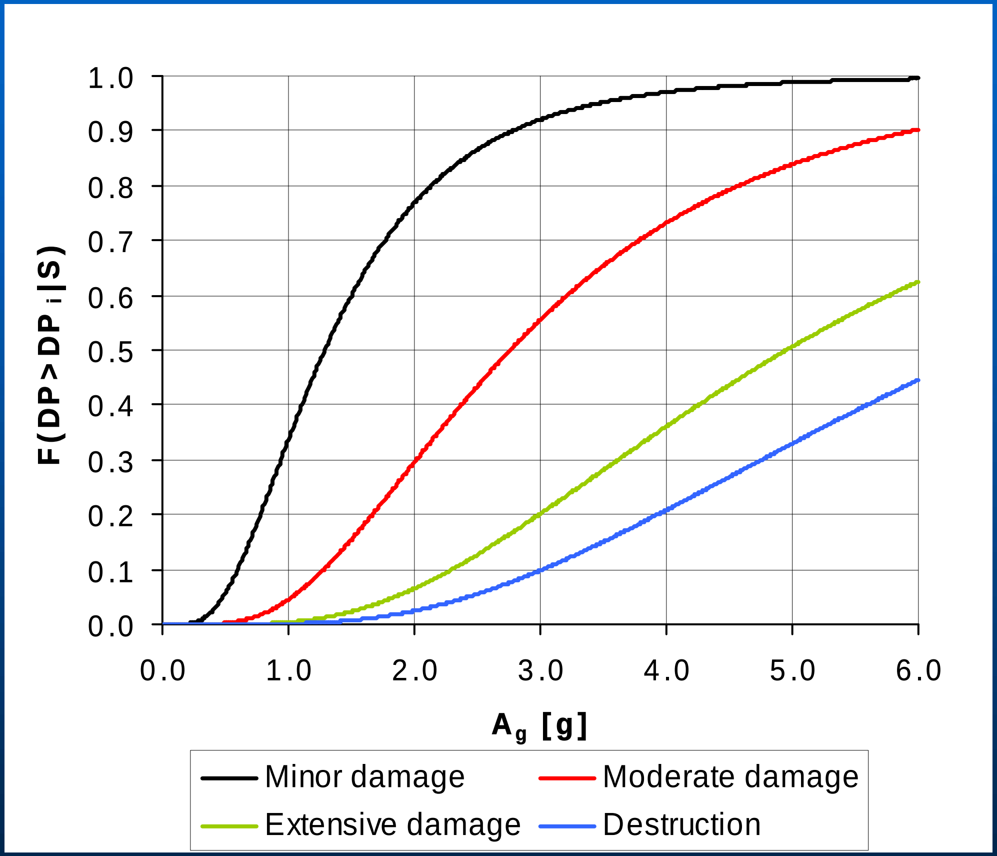
Φ is the standard lognormal cumulative probability function

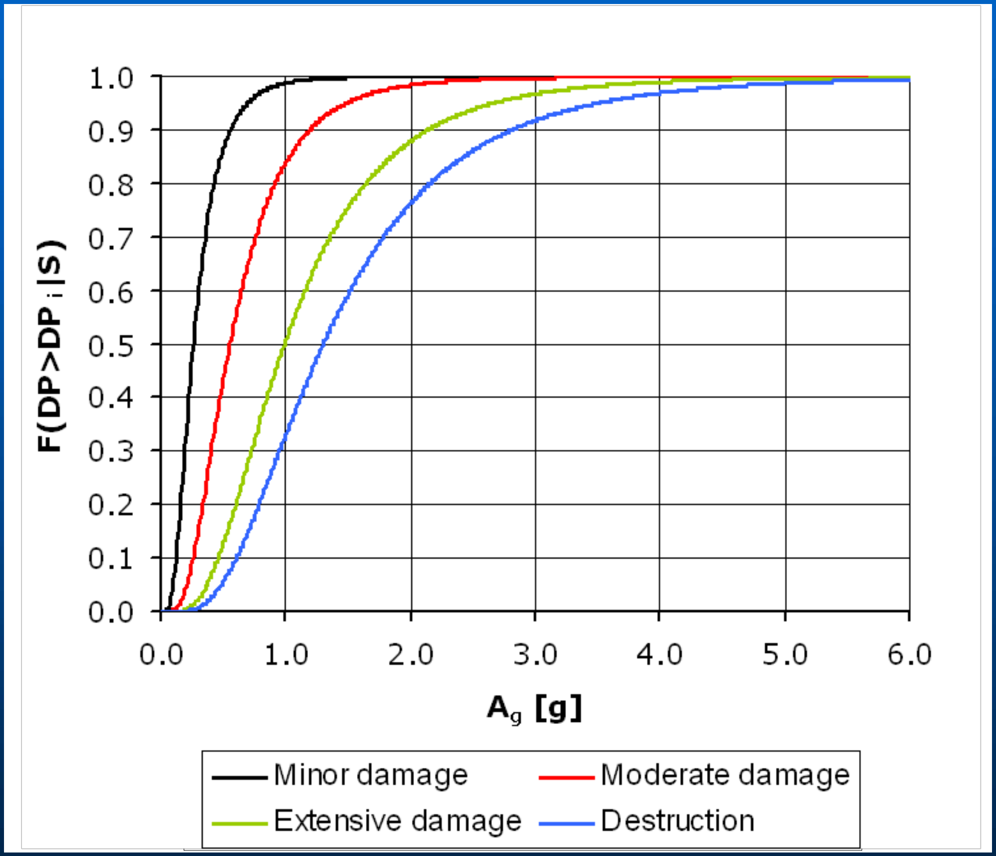
PGA is the peak ground acceleration and PGA_{mi} is the median threshold value that corresponds to damage state i

β_{tot} is the typical lognormal standard deviation.

The lognormal standard deviation β_{tot} incorporates the uncertainties in the seismic demand, the response and the capacity of the bridge, but also in the definition of the damage index and damage states. If no explicit calibration is performed, a value of β_{tot}=0.60 is proposed

Fragility curves for Kavala bridge
y -direction (transverse)

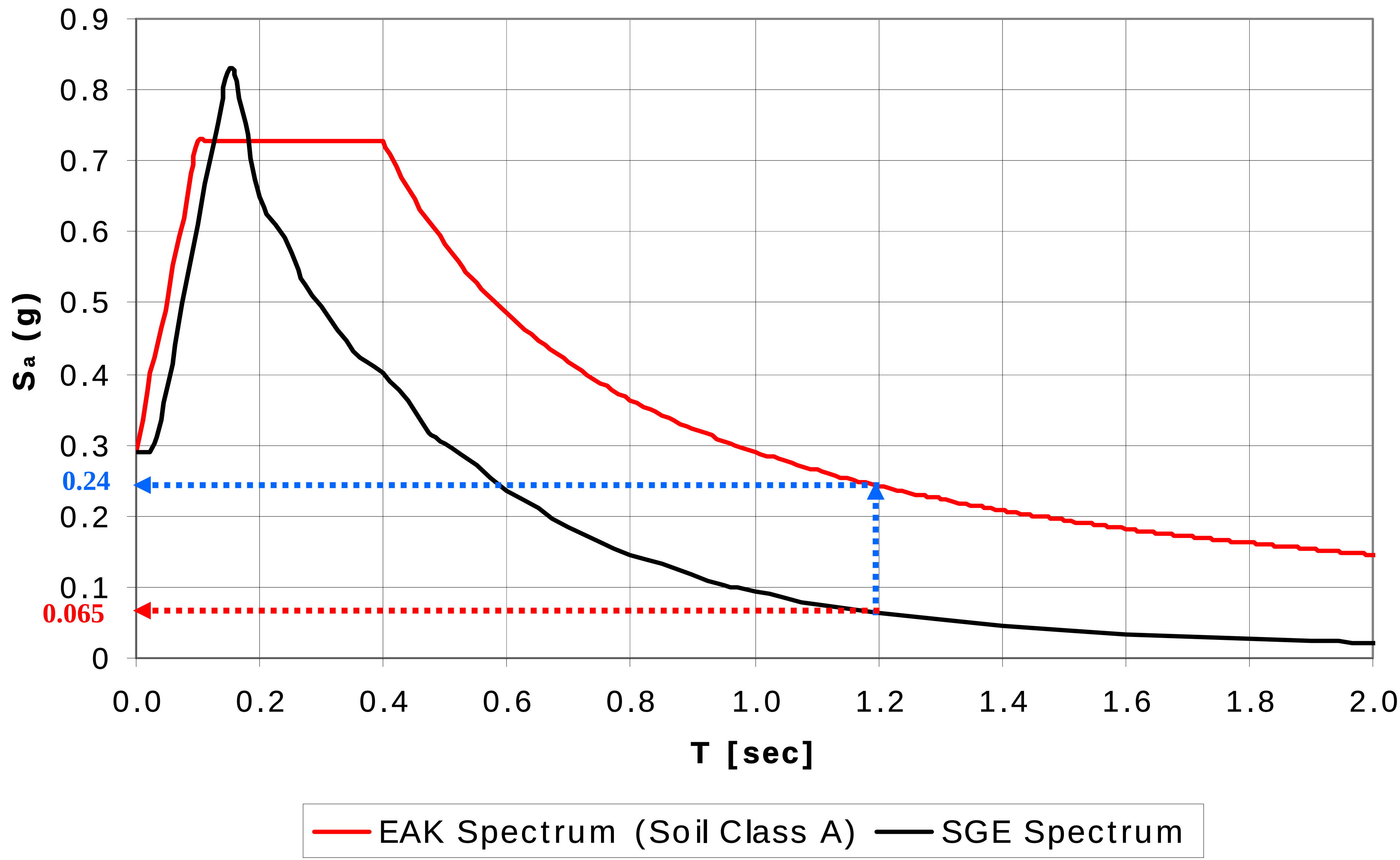




Mean elastic demand spectrum from Greek Earthquakes sample

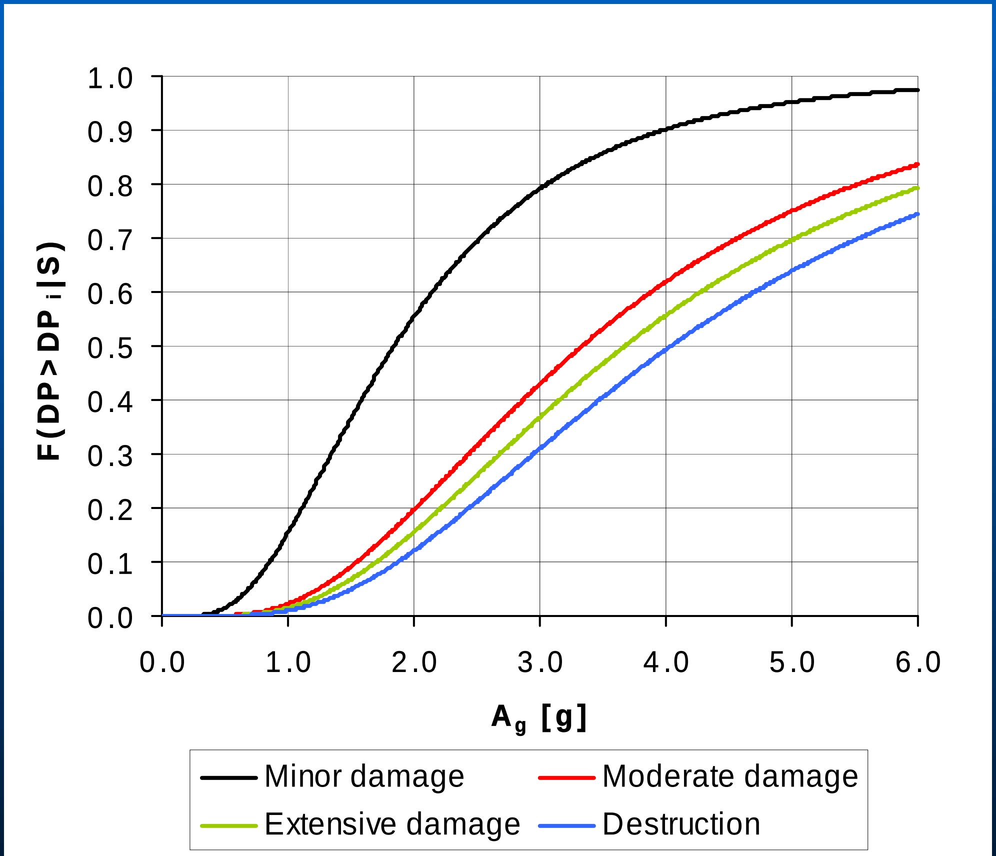
Elastic demand spectrum of Greek Seismic Code (EAK)

Elastic demand spectra

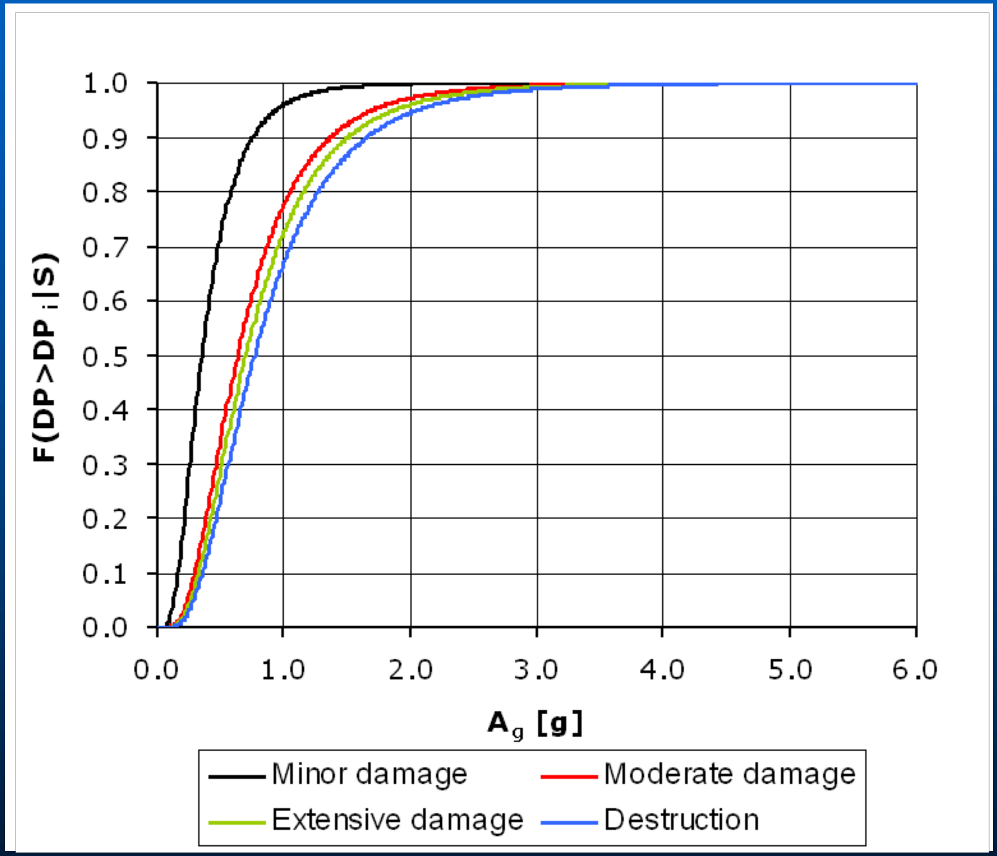


Fragility curves for Kavala bridge
x – direction (longitudinal)

Mean elastic demand spectrum from Greek Earthquakes sample



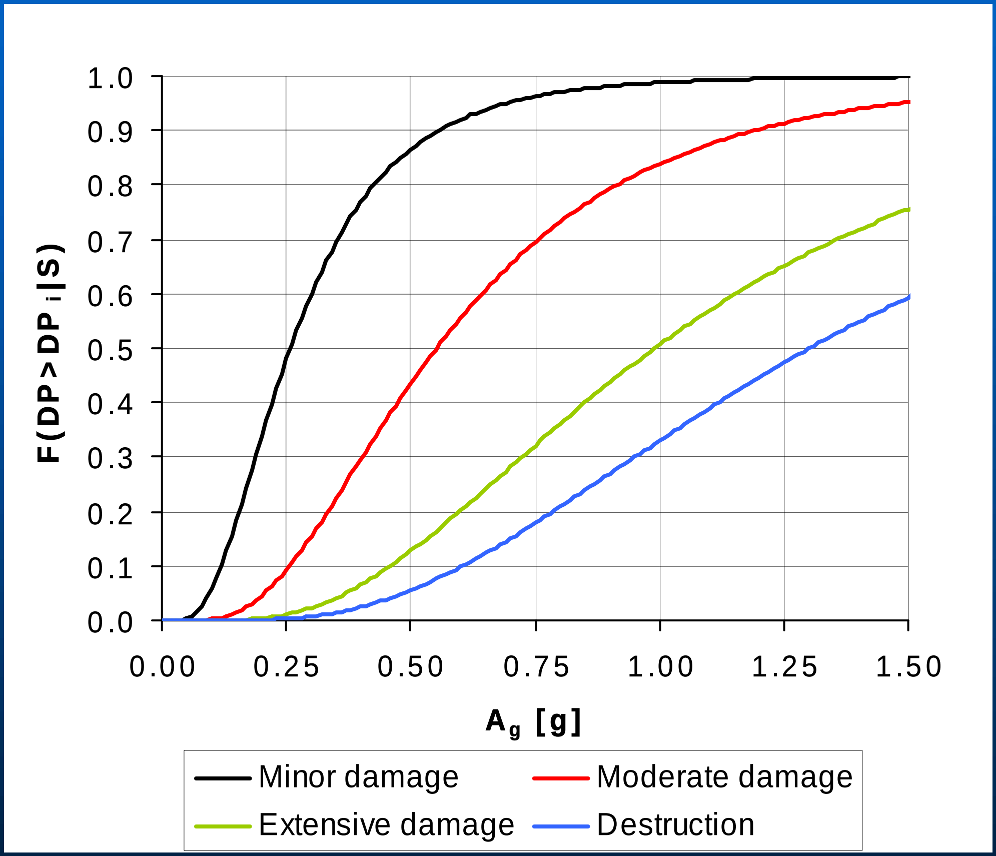
Elastic demand spectrum of Greek Seismic Code (EAK)



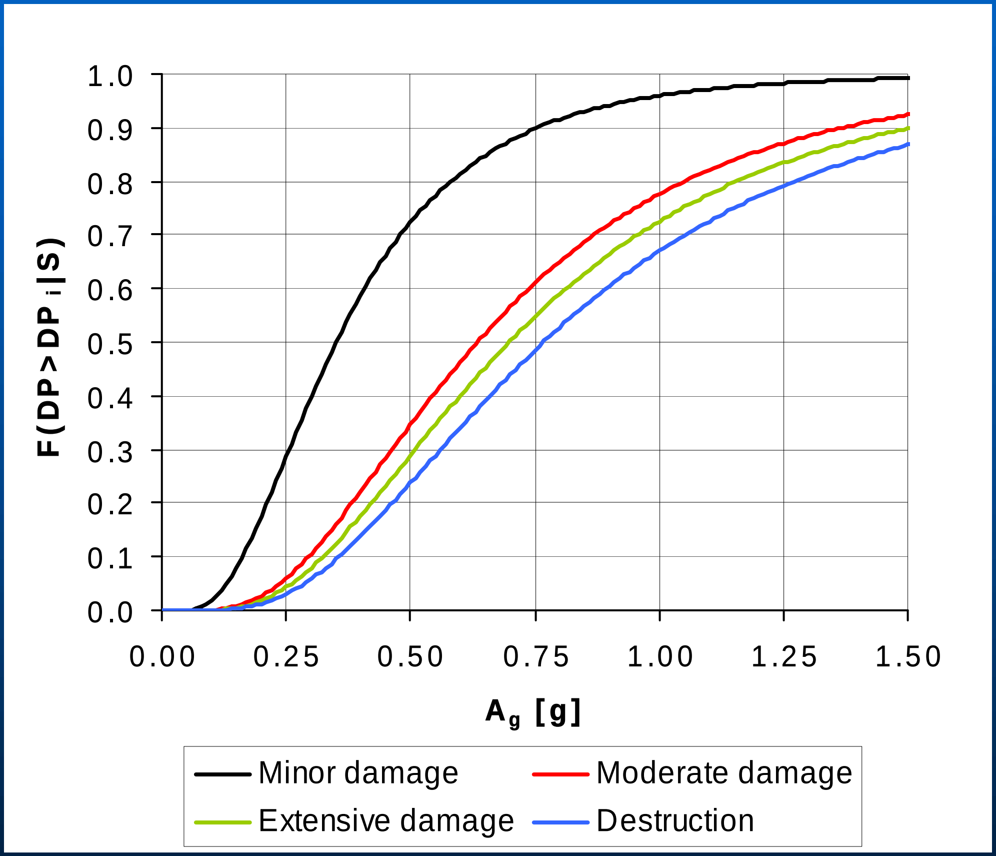
In the longitudinal direction the damage of the abutment – backfill system is critical, since it takes place before the failure of the piers

Fragility curves for Kavala bridge

Elastic demand spectrum of Greek Seismic Code (EAK)



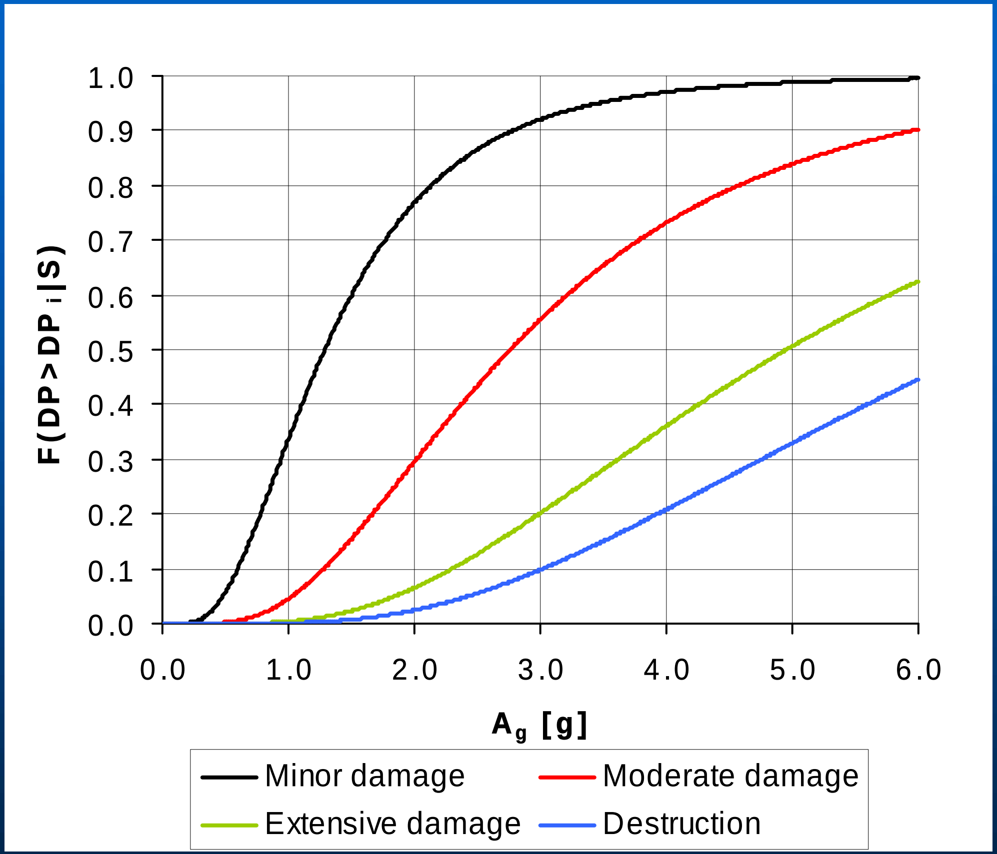
y -direction (transverse)



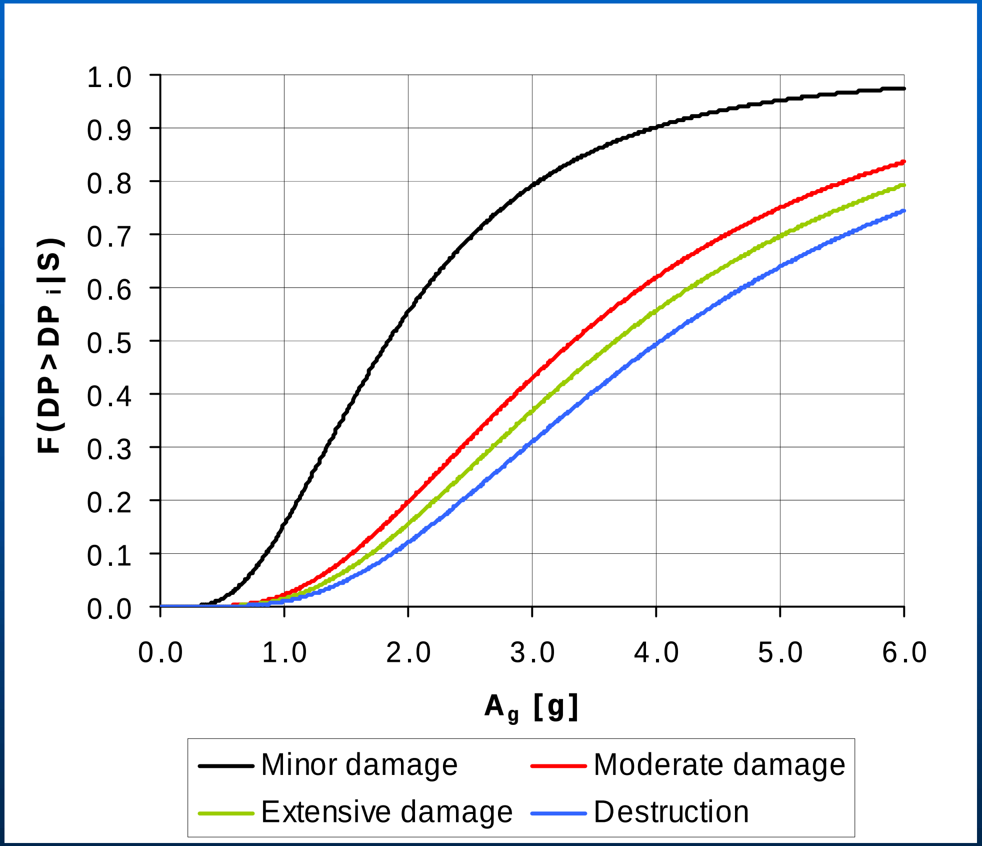
x -direction (longitudinal)

Fragility curves for Kavala bridge

Mean elastic demand spectrum from Greek Earthquakes sample

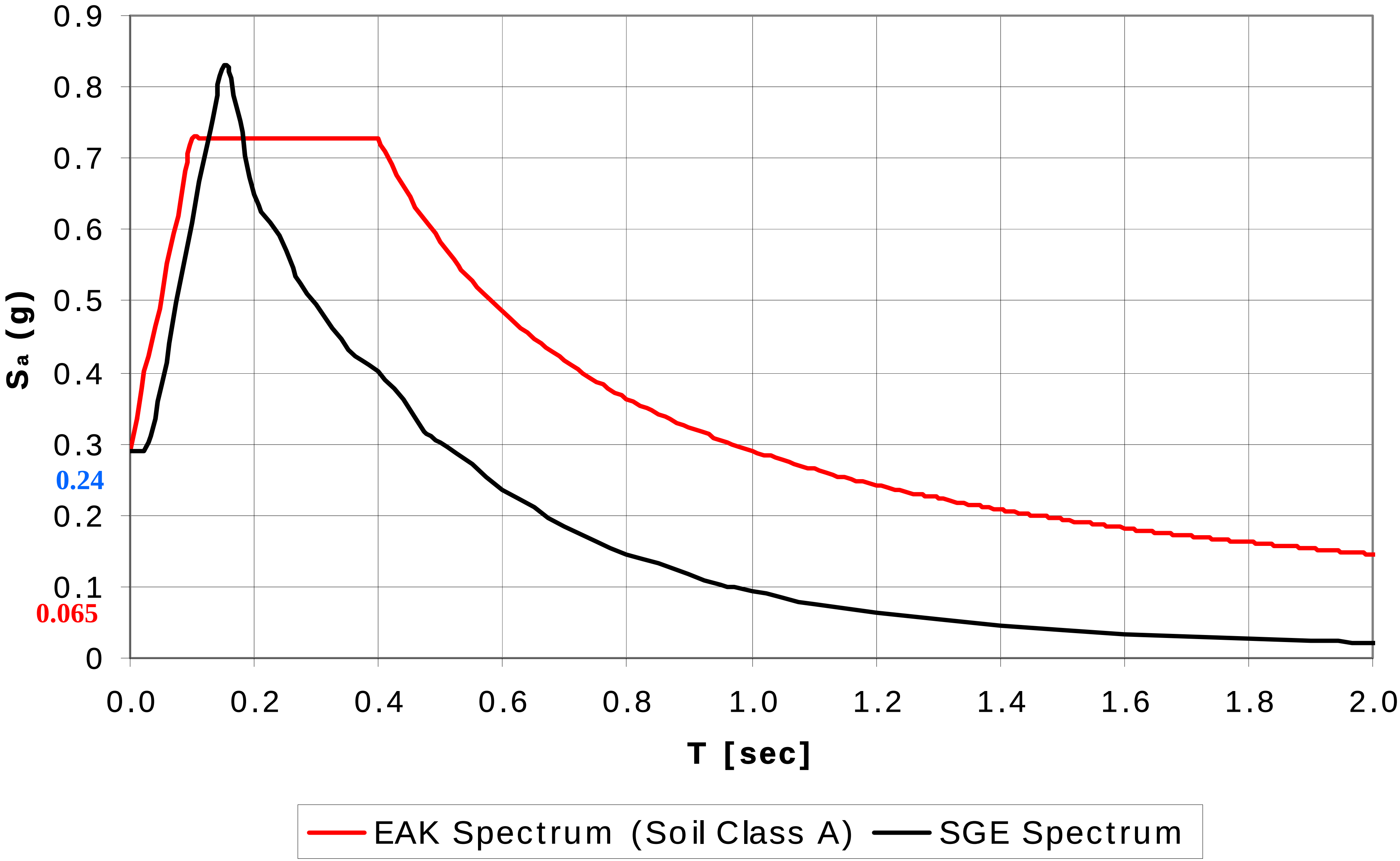


y -direction (transverse)



x -direction (longitudinal)

Elastic demand spectra



Conclusions

- A recently proposed methodology for the evaluation of vulnerability curves for bridges was applied for the case of Kavala Bridge on Egnatia Motorway in Northern Greece.
- Analysis was carried out for both horizontal directions of the bridge, a necessary choice since the most vulnerable direction was not immediately evident.
- For comparison purposes, analysis was carried out for two demand spectra, one based on a representative set of Greek earthquakes, and one derived from the elastic design spectrum proposed in the recent Greek Seismic Code.
- The proper choice of the demand spectrum is essential for the derivation of fragility curves that reliably predict the vulnerability of the bridge under examination.
- The proposed methodology is computationally straightforward, and can thus be easily implemented for the derivation of fragility curves for bridges of different structural types, thus providing highway managing authorities with more reliable means for the evaluation of seismic risk in their structures.

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Acknowledgements

This research effort was co-funded by the

Greek Secretariat of Research and Technology

and the

European Community Fund

through the EPAN program framework under grant DP15

(Seismic Protection of Bridges - ASPROGE **research project)**

Thank you !!!