Građevinski materijali i konstrukcije
Building Materials and Structures
journal homepage: www.dimk.rs

http://doi.org/10.5937/GRMK2500003I

Technical paper

Seismic fragility curves for integral concrete bridge in Bulgaria

Alexander Iliev*[1)], Dimitar Stefanov[1)]

[1)] *National Institute of Geophysics, Geodesy and Geography (Bulgarian Academy of Sciences)*

Article history

Received: 05 February 2025
Received in revised form: 09 April 2025
Accepted: 22 April 2025
Available online: 19 May 2025

Keywords

Bridge seismic capacity,
Integral bridge,
Capacity spectrum method (CSM),
Seismic fragility curves

ABSTRACT

The determination of seismic behavior is a major issue concerning civil engineers nowadays. The development of computer systems has led to an increasing use of various analytical approaches for determining the seismic response of buildings and structures.
This study employs the Capacitive Spectrum Method (CSM) as an indirect approach to calculate fragility curves. In it, the capacity of the structure is represented by the so-called capacity curve which shows the relationship between force and displacement and thus represents the expected response for a given seismic load.In this procedure, the seismic excitation is represented by the 5% elastic response spectrum for the respective location and return period of the seismic input.
The Capacitive Spectrum Method (CSM) is based on a direct graphical comparison of the structural capacity (capacitive curve) with the required reduced elastic demand spectrum.
In the current paper, the seismic capacity and fragility curves for the integral bridge case study were developed.
The so-called fragility models and the relative probabilities of reaching four levels of damage are defined. These curves are used to develop loss models of the built environment. The discrete damage probabilities can be used as input data for determining and estimating various losses and damages in structures.

1 Introduction

Today's engineering practice primarily uses numerical analyses to calculate the seismic capacity of civil structures. There are different options for representing both the structural model and the seismic motion/load. In this study, the structure of a reinforced concrete road integral bridge was analyzed using the “Finite Element Method” (FEM) and a group of nonlinear static analyses, taking into account the interaction with the ground base. The nonlinear static analysis gives a good idea of the failure mechanism (plastification zones) of structures loaded with horizontal loads. Its advantage over dynamic analysis is the significantly reduced computational time due to ignoring the dynamic part of the equation of motion. This type of analysis estimates the ultimate limit capacity of the structure well, but it fails to represent the development of damage at a different time from the seismic input.

More advanced methods need detailed analyses and better models, take more time, and are used to calculate individual structures, usually after simpler methods like screening procedures or for potentially dangerous facilities. They are not suitable for large earthquake projects where many structures need to be calculated.. Although fragility curves and probability damage matrices have traditionally been derived using observed data, recently there have been proposals to compile them using computational analyses. In this way, some of the shortcomings of empirical methods are overcome.

The Capacity Spectrum Method (CSM) is a modern method for determining the seismic behavior of a given structure for earthquakes of different intensities. Its use is increasingly gaining ground among practicing engineers due to a number of advantages it possesses. With the help of this method, the nonlinear behavior of structural elements in a given structure is more easily described. The method was first introduced in the document ATC-40 [1], and was subsequently slightly modified in FEMA-440 [2]. By means of the corresponding procedures, the response of a structure during a seismic action can be represented in a simple way. The Capacitive Spectrum Method (CSM) is based on a direct graphical comparison of the structural capacity (capacitive curve) with the required reduced elastic demand (seismic) spectrum.

This method assumes that the total maximum number of movements (both elastic and inelastic) of a complex system can be figured out by looking at the elastic response of a simpler system with just one degree of freedom, even though this simpler system has a different period and damping than the original. For the calculation of the effective damping β_{eff}

* Corresponding author:
E-mail address: eng.alexander.iliev@gmail.com

and appropriate reduction factors, it is necessary to represent the capacitive curve by its bi-linear approximation. Following the procedure from [1], the so-called “behavior point” of the studied structure for the selected seismic action is calculated.

In analytical methods, the development of damage in structural elements is obtained through static or dynamic nonlinear analysis.

The present study is a continuation of the previously calculated capacity curves [7] for the same reinforced concrete integral bridge. In the original work, nonlinear static analysis of the case study bridge were analyzed and push over curves based on different procedures in both horizontal directions were developed. In the present paper, the previously published results [7] are transformed in spectral displacement/acceleration format and a response assessment is made for a given seismic excitation.

2 Description of the case study concrete bridge

The case-study is a girder reinforced concrete frame bridge in straight and unsloped direction. The bridge consists of 3 spans and a total length of 40 m, Fig. 1. In the transverse direction, the bridge is 8.8 m in size, Fig. 2. The average height

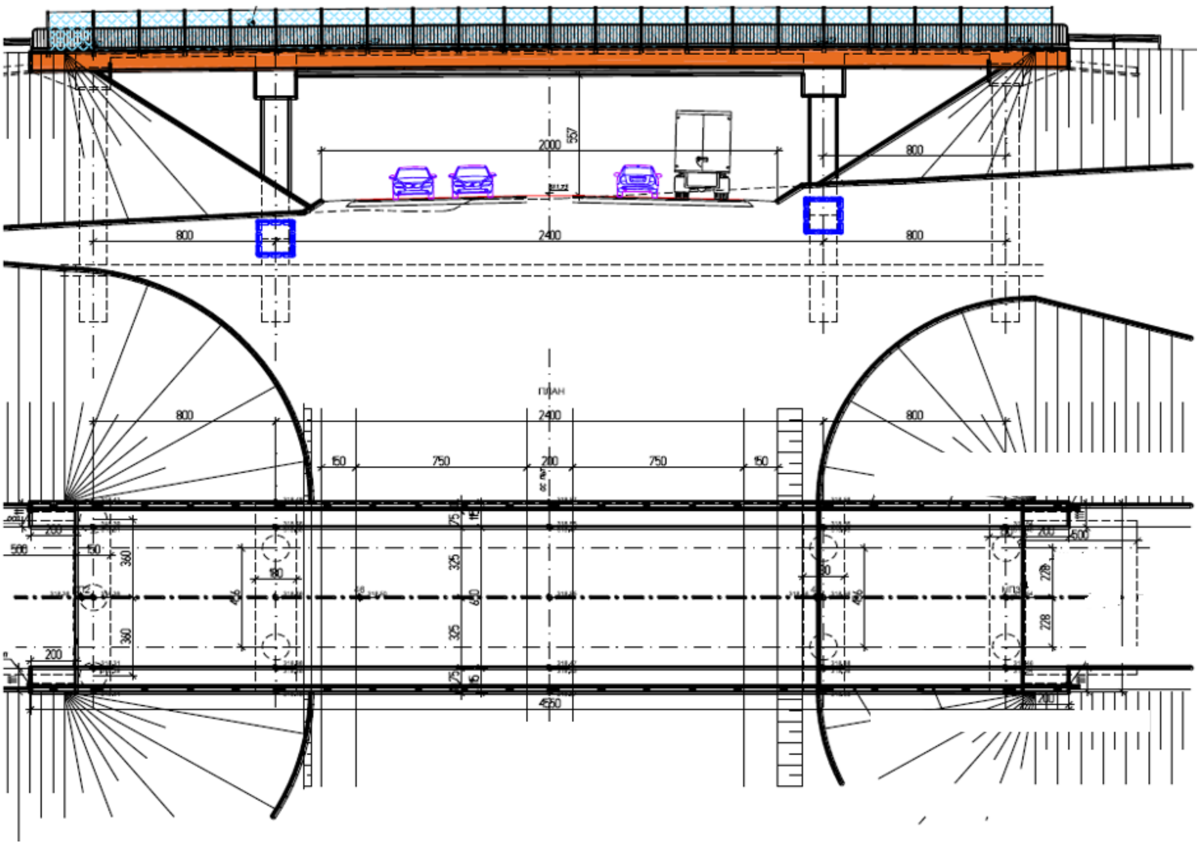

Fig. 1. Longitudinal and plan view of the bridge

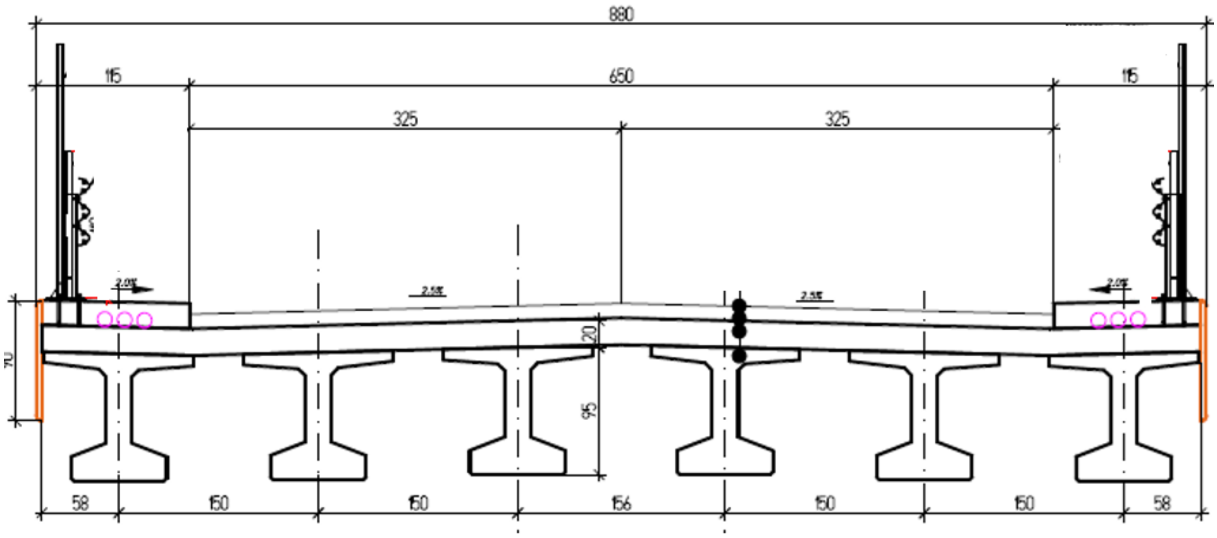

Fig. 2. Cross section of the middle span superstructure

of the columns is 6 m, and their diameter is 1.2 m. In the middle span (24 m) the longitudinal beams of the superstructure are prestressed. They are of the GT type and are 95 cm high. In the end spans, the superstructure is slab-shaped. A cross-section in the middle span of the overpass is shown in Fig. 2. The foundation is in a type C soil foundation, using cast-in-place piles with a diameter of 120 cm and a length of 22 m. The structure is designed with a significance factor of 1.4 and a behavior factor of 1.5. For loading from moving traffic, the LM1 load model [8] was adopted.

3 Assessment of the seismic response

To determine the seismic behavior (so-called performance point), it is necessary to present the capacitive spectrum and the demand (seismic) spectrum in the same format. The original nonlinear static push-over curve (Figure 3) was converted into the spectral displacement - spectral acceleration format. This transformation is done using the previously determined dynamic characteristics of the structure under study.

The intersection of the two spectra gives the so-called "performance point", which represents the response of the structure under study to the perceived seismic input (demand/seismic spectrum) - Fig. 4. In this case, the response of the structure is represented by the spectral displacement parameter - S_d .Subsequently, the fragility model is given for PGA earthquake parameter, since it gives a better applicability ("sense") for further risk assessments. The numerical calculation of reduction coefficients in ATC-40 [1] is performed using formulas (1) and (2).

$$SR_A = \frac{3.21 - 0.68\ln(100\beta_{eff})}{2.12} \quad (1)$$

$$SR_V = \frac{2.31 - 0.41\ln(100\beta_{eff})}{1.65} \quad (2)$$

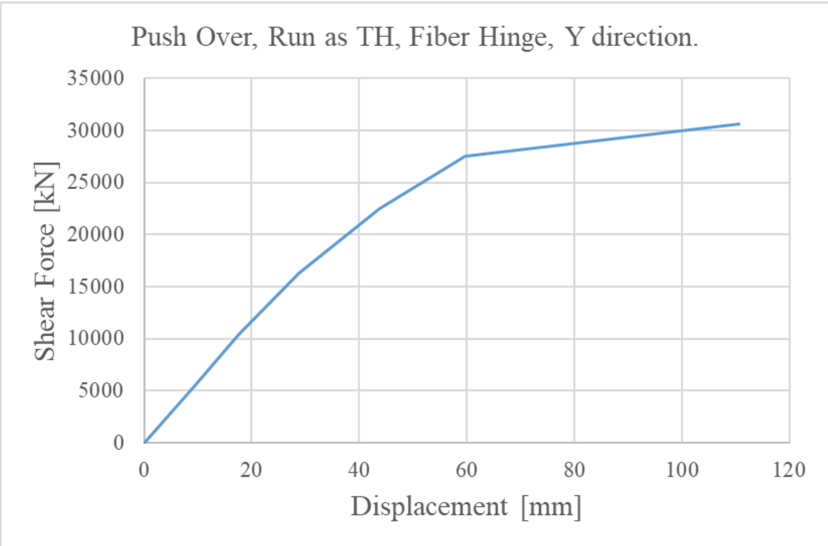

Fig. 3. Previously calculated push-over curve [7]

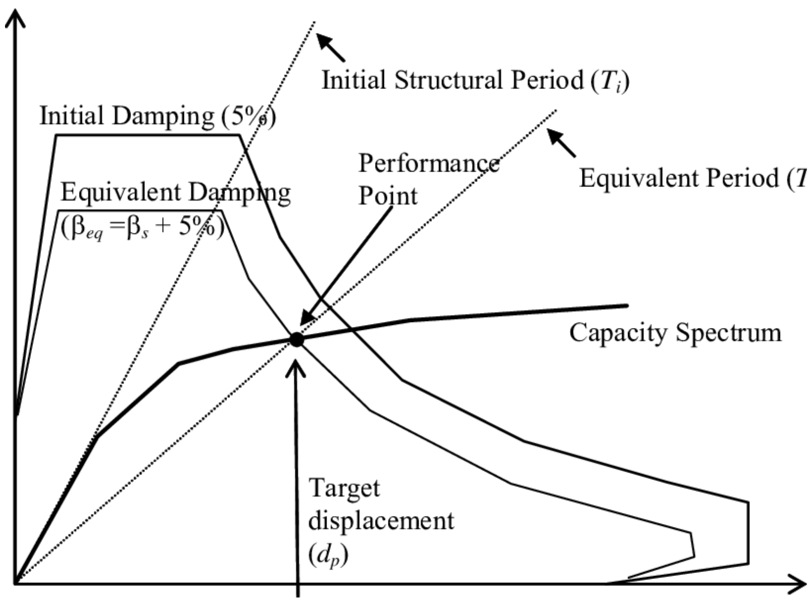

Fig. 4. Assessment of the performance point with CSM

For the initially selected point and the corresponding values for a_y, d_y, a_{pi} d_{pi} a β_{eff} value of 18% has been calculated. This corresponds to reduction factors $SR_A=0.59$ and $SR_V=0.69$, which reduce the initial demand elastic spectrum of the seismic action. Its intersection with the bi-linear capacity curve gives the temporary "behavior point" $a_{,int}/d_{,int}$– Fig. 5.

After lowering the demand (seismic) spectrum and intersecting it with the capacity spectrum, it should be determined whether the initially accepted behavior point a_p/d_p and the calculated behavior point a_{int}/d_{int} fulfill the convergence conditions. The initial point $a_{,p1}/d_{,p1}$ is considered suitable if it fulfills the criterion $0.95d_{,pi}<d_{int}<1.05d_{,pi}$. In this case, this requirement is not met, which is why a second iteration was performed with $a_{,p2}=1.81g/d_{,p2}=0.04m$, Fig. 6.

4 Definition of "Damage States"

Subsequently, for the purpose of determining conditional probabilities, the so-called "Damage States" are defined. They represent a discrete and qualitative description of the overall damage to structural and non-structural elements. Five damage levels are most commonly used: DS0 - No damage, DS1 – Light (Minor cracks or superficial damage to non-structural elements, such as surface coatings), DS2 – Medium (Noticeable structural damage, such as moderate cracking in critical components, slight deformation, or reduced functionality), DS3 –Severe (Significant structural compromise, including major cracks, deformation, or partial failure of key components, leading to restricted use) and DS4 – Destruction (Complete structural failure or collapse, rendering the bridge unusable and requiring full reconstruction).

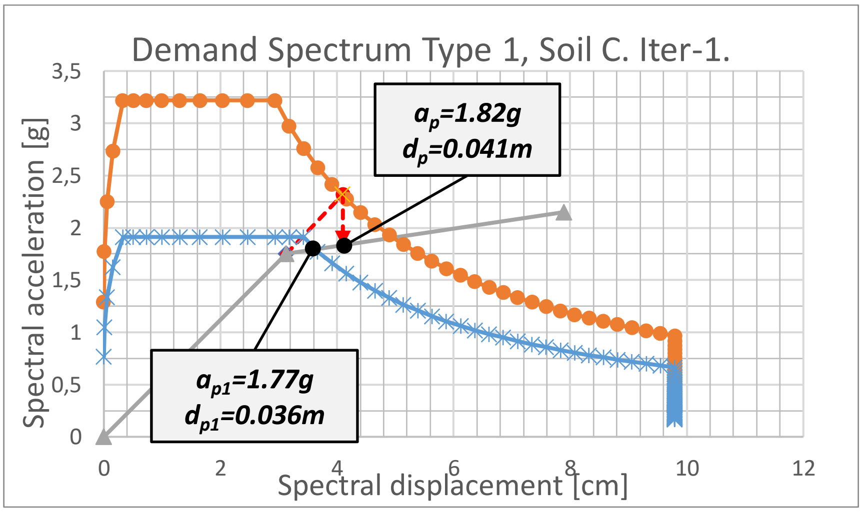

Fig. 5. Assessment of the initial performance point for PGA=0,8g (pointa_{pi}/d_{pi})

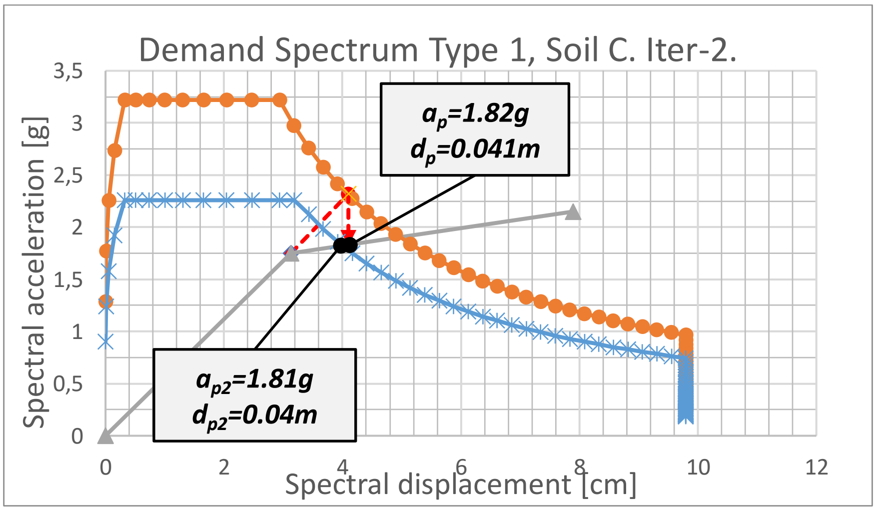

Fig. 6. Assessment of the performance point for PGA=0,8g (point a_{pi}/d_{pi}). Second iteration

The definition of damage levels (Table 1) can be done using the displacement values based on the capacity curve of the structure, [6].

Table 1. Definition of Damage States[6]

	Damage State	Limits of the spectral displacements
0	No damage	$D < 0.7^*D_y$
1	Light	$0.7^*D_y < D < D_y+1/3^*(D_u-D_y)$
2	Medium	$D_y+1/3^*(D_u-D_y) < D < D_y+2/3^*(D_u-D_y)$
3	Severe	$D_y+2/3^*(D_u-D_y) < D < D_u$
4	Destruction	$D > D_u$

5 Definition of fragility curves

The fragility model of a given structure (Fig. 7) consists of a group of fragility curves defining the conditional probability of reaching P[D=ds] or exceeding a certain level of damage P[D>ds].

Each fragility curve is defined by a median value of an impact parameter (spectral displacement) that corresponds to the limit of a given damage level and to the variability of the damage level. For example, the spectral displacement S_d, which defines the limit for a given level (ds), is calculated by the formula:

$$S_d = S_{d,ds} \times \varepsilon_{ds} \tag{3}$$

where:

$S_{d,ds}$ is the median value of the spectral displacement for the damage level, ds;

ε_{ds} is a lognormically distributed random variable with median value and logarithmic standard deviation, β_{ds}.

From the fragility curves thus defined and the calculated performance points for the respective seismic excitation (represented by a spectral displacement response parameter) the conditional probabilities for reaching or exceeding the respective damage level can be calculated.

For a given typology, the conditional probability of reaching a given level “DS” is represented by a cumulative lognormal function with respect to the spectral displacement at the corresponding "performance point".

$$P(DS|S_d) = \phi\left[\frac{1}{\beta_{DS}}\ln\left(\frac{S_d}{S_{d,DS}}\right)\right] \tag{4}$$

The fragility curves represent the distribution of damage at several levels of damage: Light, Medium, Severe and Destruction. For each given value of the spectral response, discrete probability values such as the difference of the cumulative probabilities of reaching or exceeding successive/related damage levels are calculated. The probability of reaching or exceeding different levels of damage for a given seismic level is 100%. Discrete probabilities of failures can be used for the determination and valuation of various losses and damages in structures.

There are different approaches for the treatment of uncertainties in the determination of seismic fragility. The most accurate results should be obtained when analyzing uncertainties using statistical methods for generating random samples of parameter values from a multidimensional distribution. The sampling method is often used to design computer experiments. This approach is quite laborious and requires handling large amounts of data. For this reason, tables with defined values of the relevant uncertainties for different types of structural typologies are presented in a number of manuals and documents.

Determining uncertainties in structural modeling is of primary importance for the probabilistic definition of seismic vulnerability. There are various sources of uncertainty, but the greatest importance should be given to uncertainties in the dissipation of input energy, uncertainties in the strengths of materials, as well as model uncertainties. Most often, uncertainties are described by normally distributed “Gaussian” functions, since they often give a very good representation of the distribution of the studied quantities.

One approach to determine the variability (uncertainties) of fragility curves is by applying f-li (5). In this, the variability is given as a function of the ductility of the structure under study. This approach has been implemented in the RISK-UE

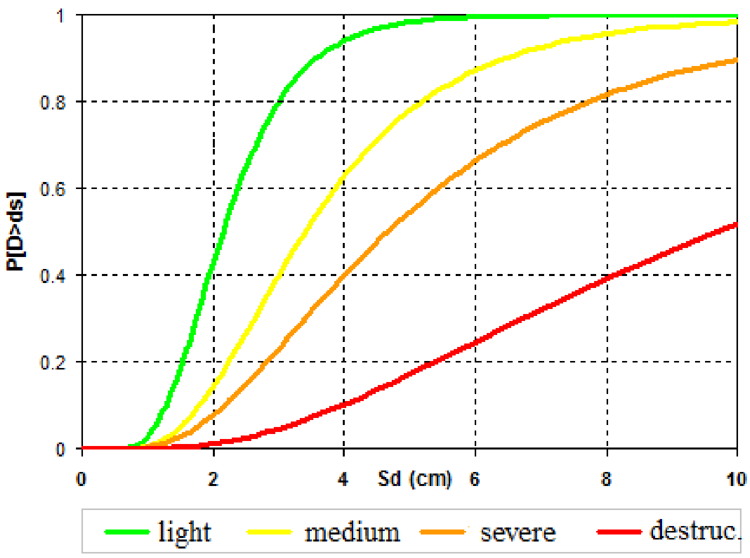

Fig. 7. Fragility model of given structure (fragility curves)

project [4] and provides a quick and easy way to calculate uncertainties in fragility curves through nonlinear static analysis.

$$\begin{aligned} &\beta 1=0.25+ 0.07 \ln \mu(u)\\ &\beta 2=0.2+ 0.18 \ln \mu(u)\\ &\beta 3=0.1+ 0.4 \ln \mu(u)\\ &\beta 4=0.15+ 0.5 \ln \mu(u) \end{aligned} \quad (5)$$

Subsequently, the numerical values necessary to define the damage levels for the studied structure are determined.

Sd,0<0.7*Sdy=0.7*0.0313 m=0.0125 m=>Sd,0<2,19 cm
Sd,1>0.7*Sdy=0.7*0.0313 m=0.0125 m=>Sd,1>2,19 cm
Sd,2=Sdy+1/3(Sdu-Sdy)=3,13+1/3(7,9-3,13)=4,72 cm
Sd,3=Sdy+2/3(Sdu-Sdy)=1.79+2/3(7,9-3,13)=6,30 cm
Sd,4=Sdu=0.079 m=7,9 cm

After defining the fragility model (the group of curves), specific discrete values of the probabilities of damage occurrence due to a given seismic impact can be determined. In this case, the probabilities of reaching damage to the reinforced concrete bridge for a seismic input with a maximum ground acceleration PGA=0.8g have been determined. An input with such intensity corresponds to a spectral displacement of 4.0 cm. Fig. 8 presents the obtained relative probabilities of reaching the four levels of damage (light, medium, severe, destruction), through uncertainties determined by formulas (5).

To have a better understanding and applicability for risk assessment purposes, the fragility model is also calculated in PGA format. This is more convenient in certain cases as PGA gives a direct understanding of the earthquake event.

The performance point is calculated with a certain simplification for the damping (β_{eff}) value to 5% (elastic response) for different earthquake levels (demand spectra). In reality, for higher earthquake scenarios, due to dissipation of the structure due to damage, the damping value will be higher.Its intersection with the bi-linear capacity curve gives the"behavior point" for four seismic levels (damage states)$a_{,int}/d_{,int}$– Fig. 9.

Finally, the fragility model is calculated for four damage levels in terms of PGA values, Fig. 10.

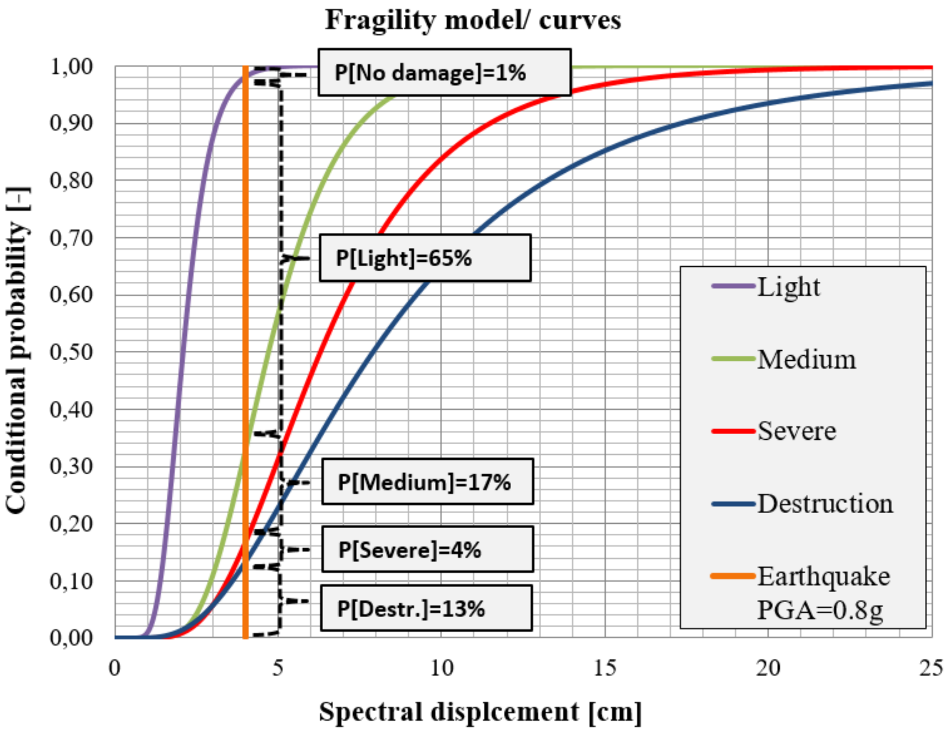

Fig. 8. Fragility model giving the relative probabilities of damage

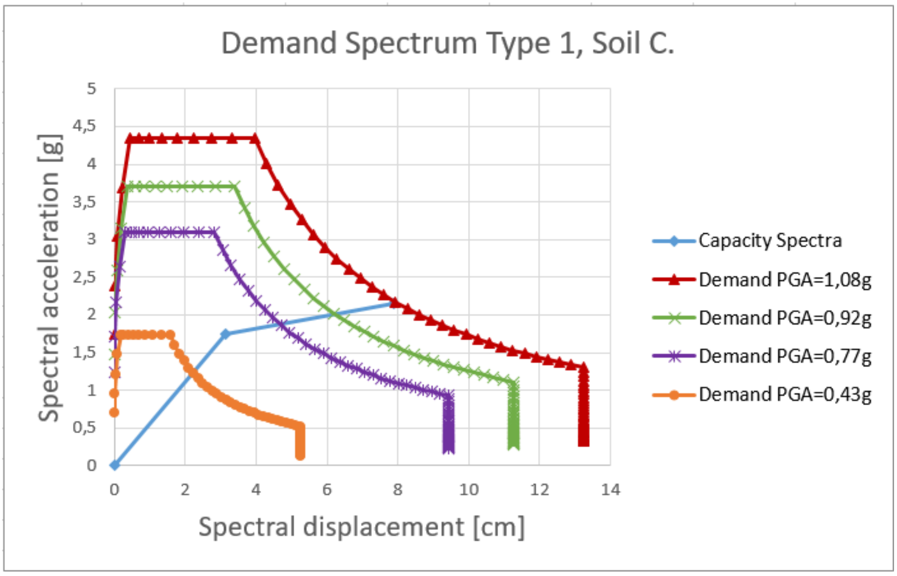

Fig. 9. Assessment of the performance point for different PGA levels (seismic events)

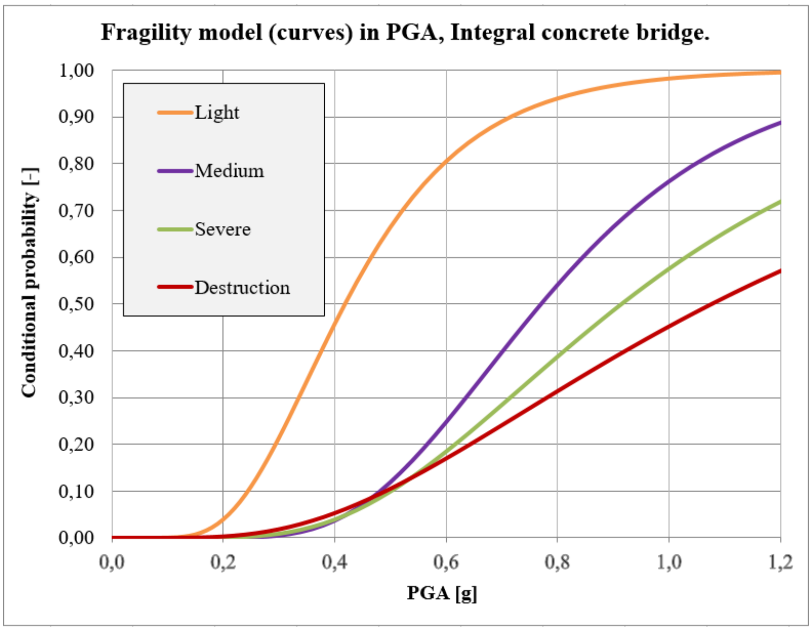

Fig. 10. Fragility model giving the relative probabilities of damage (in PGA)

6 Conclusions

In this study, the seismic response of a reinforced concrete integral bridge structure is analyzed using the Capacity Spectrum Method, taking into account the soil-structure interaction (SSI) through seismic spectra for soil class C and elastic springs for piles, calculated based on [9]. Its advantage over dynamic analysis is the significantly reduced computational time due to ignoring the dynamic part of the equation of motion. This type of analysis estimates the ultimate limit capacity of the structure well, but it fails to represent the development of damage at a different time from the seismic input.

The estimated failure scenarios are presented along with the accumulated damage and deformations in the structure. Subsequently, the so-called fragility model and the conditional probabilities for reaching four levels of damage are defined. For the studied seismic excitation (catastrophic earthquake) with a maximum peak ground acceleration PGA = 0.8 g, it is most likely that "light" to "medium" damage will occur in the structure. This indicates the very good seismic capacity of the newly designed facilities according to current modern regulatory documents (Eurocode). Discrete damage probabilities can be used as input data for the determination and valuation of various losses and damages in the structures.

CRediT authorship contribution statement

Alexander Iliev: Writing- original draft, Formal Analysis, Resources, Visualization, Methodology.

Dimitar Stefanov: Writing-review & editing, Conceptualization, Resources, Validation, Supervision.

Declaration of competing interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This study was conducted without any external support.

Literature

[1] AppliedTechnology Council(ATC-40), Seismic Evaluation and Retrofit of Concrete Buildings, California, U.S.A, 1996.

[2] Applied Technology Council (FEMA-440). Improvement of Nonlinear Static Seismic Analysis Procedures,California, U.S.A, 2005.

[3] Grünthal G., Cahiers du Centre Européen de Géodynamique et de Séismologie: Volume 15 – European Macroseismic Scale 1998. European Center for Geodynamics and Seismology, Luxembourg, 1998.

[4] RISK- EU, The European Risk-Ue Project: An Advanced Approach to Earthquake Risk Scenarios (2001-2004) www.risk-ue.net.

[5] Federal Emergency Management Agency(HAZUS), Earthquake Loss Estimation Methodology - Technical and User Manuals., Washington, D.C, 1998.

[6] Ioannis F. Moschonas, Andreas J. Kappos, Panagiotis Panetsos, Vissarion Papadopoulos, Triantafyllos Makarios, Pavlos Thanopoulos - Seismic fragility curves for Greek bridges: methodology and case studies, Bull Earthquake Eng, 2009.

[7] A.Iliev, D.Stefanov, P.Nikolov- Nonlinear Static (Push-Over) Analysis of Integral Concrete Bridge. Scientific Journal 'Mechanics Transport Communications', Issue: 2 / 2024.

[8] EN 1998-2, Eurocode 8: Design of structures for earthquake resistance, Part 2: Bridges.

[9] Priestley, M.J.N, Seible F and Calvi G.M., Seismic Design and Retrofit of Bridges, John Wiley & Sons, p.465, 1996.