

Seismic Fragility Analysis of an Existing Bridge Pier

D.B. Sonowal^{1,*}, J. Pathak²

¹Department of Civil Engineering, Assistant Professor, Tezpur University, Tezpur, 784 028, India

²Department of Civil Engineering, Professor, Assam Engineering College, Guwahati, 781 013, India,

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Abstract

The main objective of this paper is to develop the fragility curves for an existing bridge having circular pier by static nonlinear analysis (Pushover Analysis). In this study, a cantilever circular bridge pier which is located in Assam, a highly seismic zone in India is considered for development of seismic fragility curve. Capacity of the bridge has been determined by Pushover analysis of bridge pier and demand parameter of the bridge were obtained by using ATC 40 Capacity Spectrum method and IS 1893:2016 (Part 1) along with IRC 6:2017. Civil Software SAP 2000 version 20 is used to analyze the bridge pier. The fragility curves of the pier have been constructed assuming a lognormal distribution. The evaluation results presented here describes the probabilistic seismic failure of the bridge pier and its capacity to meet the desired performance level.

Keywords: Pushover Analysis, Fragility curve, IS 1893:2016, SAP 2000, ATC 40

1. Introduction

Bridges are one of the most critical components of transportation systems that must remain functional even after the major earthquakes. Their damage and collapse may not only cause loss of life and property, but also obstruct post-earthquake aid and restitution activities. Recent observations of the damages caused to bridges in major earthquakes have raised questions about the safety of existing bridge structures constructed using previous design standards. Additionally, from investigation and analysis of the behavior and performance of structures in past earthquake events, various deficiencies have been identified in structures constructed during different time periods in the past. The extensive damage and huge economic loss due to earthquake damage to structures during 1994 Northridge and 1995 Kobe earthquakes, 1971 San Fernando as well as the 1989 Loma Prieta and 1991 Costarica and 2001 Bhuj earthquake of India give plenty of evidence to these observations. Therefore, it is important to quantify the related seismic risk and to calculate the possible damages that can be experienced by the bridge structures under seismic events. With this risk quantified, rational decisions can be made as to whether the bridge should be retrofitted or replaced, or to leave the bridge in the existing state. However, seismic reliability assessment of highway bridges in India using probabilistic methods is still in its infancy. Among the limited literature available, Goswami and Murty [8] have reviewed the seismic vulnerability of reinforced concrete (RC) bridge piers designed with IRC provisions.

Dealing with such present needs, this paper traces the seismic vulnerability of highway bridges using fragility

curves. Seismic vulnerability assessment and development of fragility curves for different structures (building, bridges etc.) are getting increased attention among the researchers in the recent years ((Banerjee & Shinozuka, 2007 [2]; Dutta & Mander,1998 [6]; Mander, 1999 [13]; Mander & Basoz, 1999 [14]; Shinozuka et al.,2000 [20]; Bhandari et al.,2019 [3]; Sharma et al.,2020 [18]; Sharma et al.,2020 [19]). These curves are conditional probabilistic statements which indicate the likelihood of bridge failure given the intensity of seismic shaking. In this study, seismic fragility curves are developed for a typical circular bridge pier for an existing three-span simply supported box girder bridge located in Assam, the high seismic zone (Zone V) by static nonlinear analysis (pushover analysis). Analytical method for development of fragility curves based on numerical simulation of seismic response of the pier and regression analysis of simulated response are presented.

2. Description of the Bridge

In the present study a sample bridge located in Assam has been considered for development of fragility curves for vulnerability assessment. The bridge consists of three simply supported spans, with spans of length 15.6 m and total bridge length of 47.4 m. The superstructures, consisting of concrete longitudinal T beam girders, cross beams and deck slab, are supported on two circular solid R.C. piers and abutments. Piers are of 4 m in height and supported on the pile foundation. Type of soil can be categorized as medium as per IS 1893 (Part-I), 2016 [11]. The nominal (i.e. design) concrete strength of the

*Corresponding author. Tel: +917896788844; E-mail address: bailung@tezu.ernet.in

substructure and superstructure is 20 MPa. The diameter of the column is 1.4 m and reinforced with 18 numbers of 36 diameter Fe 415 steel. The lateral seismic forces are determined as per different version of IRC [9,10]. The bridge lies in seismic Zone V and belongs to the seismic class of important bridges.

3. Modeling of the Bridge (Lumped Mass Model)

Priestly et. al.(1996) [15] observed that the response of the piers to be same as the response of overall bridge and suggested that a bridge can be represented by a single column with tributary mass from the two adjacent half spans of the superstructure. So, in this study, the seismic fragility of the case-study bridge is primarily dictated by the vulnerability of RC piers. The case-study bridge is modeled as 2D stick/beam-column element with superstructure mass lumped on the top of the bridge pier along with its self-weight. The pier section is modeled with the structural analysis program SAP 2000 (version 20) [5]. The pier is modeled by beam element whose nonlinear properties are determined by push over analysis. The additional flexibility caused by the formation of plastic hinges at bottom of the pier has been modeled by providing yield penetration length with additional nodes.

4. Static Non-Linear Analysis (Pushover Analysis)

Pushover analysis is a static nonlinear procedure in which the magnitude of the lateral load is increased monotonically maintaining a predefined distribution pattern along the height of the structure. Structure is displaced till the ‘control node’ reaches ‘target displacement’ or structural collapses. The sequence of cracking, plastic hinging and failure of the structural components throughout the procedure is observed. The relation between base shear and control node displacement is plotted for all the pushover analysis. Generation of base shear – control node displacement curve is single most important part of pushover analysis. This curve is conventionally called as pushover curve or capacity curve. The pushover analysis may be carried out twice: (a) first time till the collapse of the building to estimate target displacement and (b) next time till the target displacement to estimate the seismic demand [15].

4.1 Plastic Hinge

In pushover analysis, to account for the nonlinear behaviour of the structural elements a point-plasticity approach is considered for modelling nonlinearity, wherein the plastic hinge is assumed to be concentrated at a specific point in the structural member under consideration. In bridge structure hinges are assumed to be formed at pier i.e. hinge at pier should fail before superstructure or foundation failure. Properties of flexure hinges must simulate the actual response of reinforced concrete components subjected to lateral load. As per the IS 1893(part 3),2014 [12] the plastic hinge formation should be at pier instead of superstructure or substructure. In case of single pier, the hinge is at bottom near pier foundation only. In this work, the plastic hinge length (L_p) is calculated as per Seismic Retrofitting Manual of Highway Bridges (FHWA 2006) [17] which is given as,

$$L_p = 0.08 h + 9 D_b \tag{1}$$

Where h is the height of pier in mm and D_b is the diameter of longitudinal bar in mm

Static nonlinear analysis is carried out to obtain force displacement relationship at the top of the bridge pier. Since the bridge is located in high seismic zone V, the design response spectrum is considered with an acceleration coefficient of $PGA = 0.36g$. A 5%- damped response spectrum for accelerations is shown in Fig2.

The capacity curve for force displacement relationship at the top of the bridge pier has been developed using SAP 2000 (version 20) and performance point is calculated. The location of performance point for bridge is shown in fig 3. Based on Pushover curve: performance point of Base shear, displacement (V,D) as 176.495 kN,0.108 m, performance point of Spectral acceleration, spectral displacement (Sa, Sd) as 0.034g, 0.108 m, performance point of Effective time period, effective damping (Teff, Beff) as 3.582 sec, 0.243 respectively. Hence it is observed that the target displacement of performance point is 108 mm.

Target displacements were calculated for different performance level from the pushover capacity curve as shown in fig.4 and the target displacement values are tabulated in table no.1. The pushover capacity curve is the plot of the lateral force on the structure against the lateral deflection of the top of the structure. The location of hinges in various stages can be defined as immediate occupancy (IO, where the members just yielded and the extent of structure damage is much less), life safety (LS, where significant yielding of members led to severe damage to the structure) and collapse prevention (CP, where a significant loss of strength and stiffness in members led to large permanent deformations in the structure due to which it is at the verge of partial collapse) according to the FEMA 356, 2000 [7]. The target displacement is displacement demand for the structure subjected to the ground motion under consideration. In this study, capacity spectrum method (CSM) of ATC 40 [1] is used to calculate the target displacement.

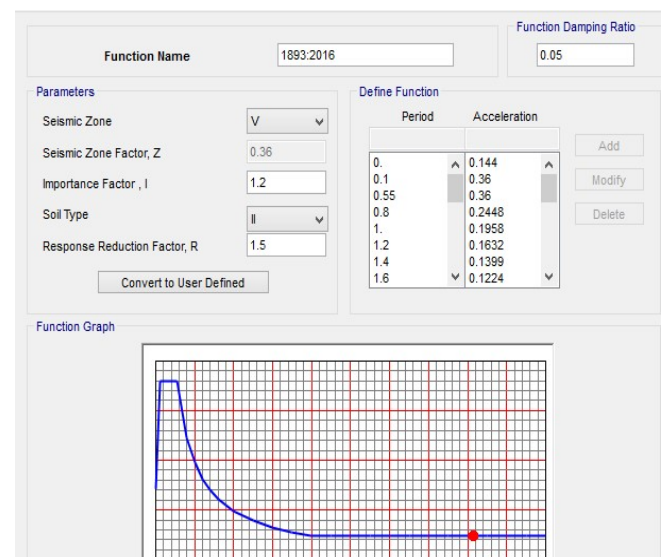


Fig.1. 5% damped response spectra as per IS 1893:2016 built in SAP 2000 (version 20)

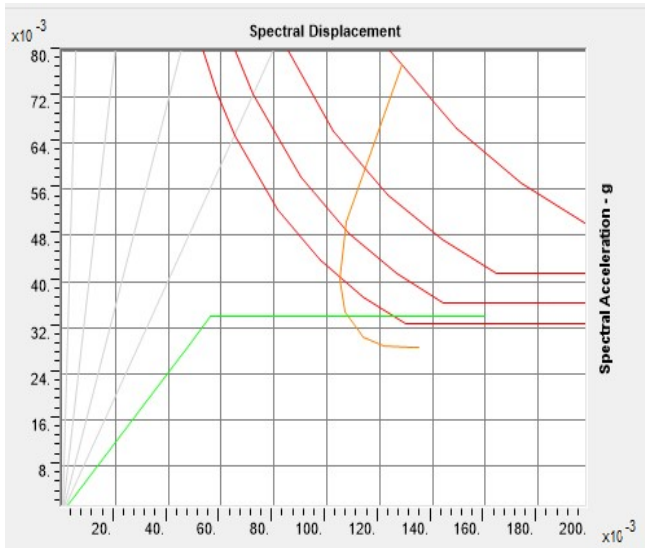


Fig.2.Location of Performance Point built in SAP2000(Version 20)

Table-1: Target Displacement Value at different Level

Performance Level	IO	LS	CP	Collapse
Displacement	56 mm	88 mm	104 mm	126 mm

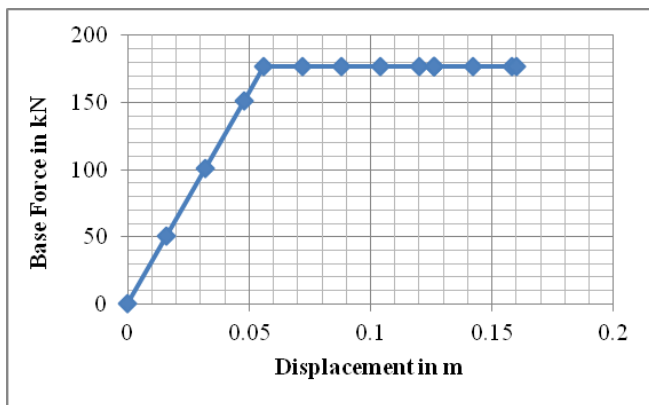


Fig.3. Pushover Capacity Curve of the sample bridge Pier

5. Fragility Curves

The inception of lifeline earthquake engineering in the early 1970s has influenced numerous researchers to develop and proposed a wide variety of seismic risk assessment methodologies for highway transportation systems (Billah & Alam, 2015) [4]. The fragility functions explicitly express the probability of meeting or exceeding the specific damage limit state for a specific intensity of seismic excitation. In this study, fragility curves are developed analytically with respect to spectral displacement for seismic damage assessment of the sample bridge. The capacity curve is converted from force-displacement (F-D) format into acceleration-displacement response spectra (ADRS) format (S_A-S_D) using ATC 40[8] capacity spectrum in SAP 2000 .To get the damage state median, in this study different damage states are defined in terms of the target displacement of the pushover capacity curve. The target displacements have been determined from the result of the pushover analysis using SAP 2000 and different damage states are mentioned in table no. 2.

Based on these data, fragility curves for the bridge piers are constructed assuming a lognormal distribution. For the cumulative probability $P(\geq \text{Capacity (C)})$ of occurrence of the damage equal or higher than level Capacity (C) is given as

$$P(DS \geq ds_i | S_d) = \Phi[1/\beta_{ds_i} \ln \{S_d(T)/S_{d, ds_i}\}] \tag{2}$$

S_{d, ds_i} : is the median value of spectral displacement at which the structure reaches the threshold of damage state ds_i
 β_{ds_i} : is the total uncertainty considered as 0.75 in this study as per FEMA 356, 2000 [7].

Table-2. Damage limit states for different damage levels

Damage State	Medians (Dutta and Mander, 1998) [6]
No Damage	Yield
Moderate Damage	2.5% of yield
Extensive Damage	5% of yield
Complete Damage	7.5% of yield

6. Results and Discussions

This study presents the assessment of seismic vulnerability of Highway Bridge located in Assam, India. To investigate the probability of failure of the bridge using seismic fragility, a representative case-study of simply supported girder bridge located in Assam, the highly seismic zone (zone V) is considered. The analytical fragility curves for all the damage levels have been developed using the parameters obtained from the Push over analysis of the bridge pier. The results obtained from Pushover Analysis shows that the bridge collapses before reaching the Target Displacement. As the bridge could not achieve the target displacement in any of the pushover cases it can be concluded that the bridge is not safe for any performance limit state under the seismic demand corresponding to Zone V. Fig.4 shows the analytical fragility curve for the sample bridge pier obtained from lumped mass model and it is observed that at the performance point the probability of the exceedance of damage is very high.

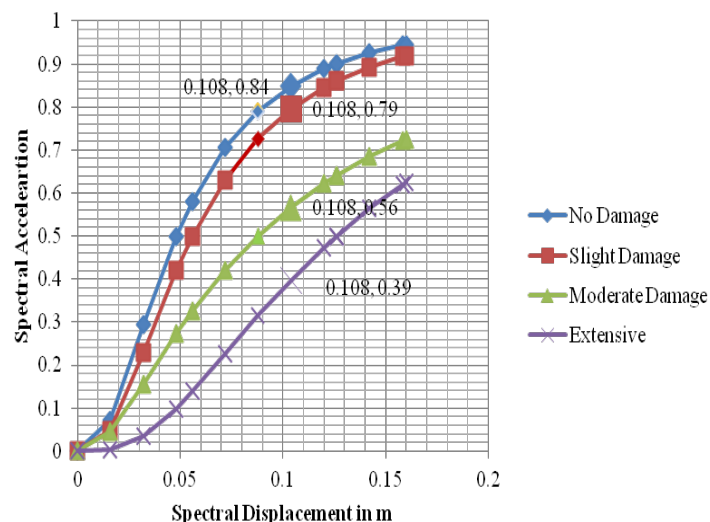


Fig.4.Fragility curves for bridge pier by lumped mass model

Disclosures

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