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Seismic Evaluation Of T-Girder Concrete Bridges- A Performance-Based Approach

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ABSTRACT: In Indian structural codes, Performance-based earthquake engineering (PBEE) methodology has not been implemented yet. It is widely developed during the past two decades, and has become a key approach for seismic analysis and design in most developed countries. Therefore, further research is required to develop a domestic approach for Indian applications. In this paper, the seismic capacity of a typical T girder concrete highway bridge designed as per Indian Standards is evaluated througha probabilistic method as well as nonlinear static analysis (pushover analysis). Two different types of substructures, single-column and multi-column bents are considered separately. Fragility curves are developed and used for evaluation purposes. This paper presents the method as well as the results in the form of vulnerability and structural reliability relations based on two damage functions.

Keywords: concrete bridge,damage limit state, evaluation, fragility curve, incremental dynamic analysis

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I. INTRODUCTION

Considering the high randomness of return period and shaking intensity of earthquakes, they remain one of the most unpredictable natural hazards. In response to this, the extensive research on performance-based approaches in structural engineering during the last two decades has brought about the invention of performance-based earthquake engineering (PBEE) methods. However, as discussed by Cornell and Krawinkler (2000), it should not be forgotten that PBEE methods are not essentially developed for predicting structural performance or estimating seismic losses; they are established to ultimately contribute to the effective reduction of seismic losses and improvement of structural safety [1].

It is known that the seismic performance of transportation systems plays key role for the post earthquake emergency management [2]. Hence, it is necessary to be evaluated both physical and functional aspects of bridge structures. The physical aspects of the seismic performance of bridges are evaluated with the seismic fragility functions. A fragility curves represent the probability of structural damage due to various ground shakings [3,4]. They describe a relationship between ground motion and level of damage.

In this paper, the seismic performance of a typical six span T-girder concrete highway bridge is studied. For this purpose, a three-dimensional analytical model of the bridge is created, which encompasses all the bridge major components. It is noteworthy to mention that this analytical model was developed for generalised concrete T-girder bridges and not for a specific bridge. The bridge is first analysed using nonlinear static analysis (pushover analysis) by SAP2000 [5] for substructure type of single-column and multi-column bents separately. The seismic performance and overall seismic capacity of the bridge are then investigated through incremental dynamic analyses (IDA) by developing IDA curves [6] using IDARC2D software [7]. Nonlinear dynamic analysis is applied to simulate the earthquake loads over the analytical model. A set of ten Indian ground motions is selected. Fragility and hazard survival curves are generated to define the damage limit states and probability of survival of the structure.

II. GEOMETRIC DESCRIPTION AND DESIGN DETAILS

In this study typical Indian T-girder six span concrete bridge is considered with span length of 24m. The bridge is analysed using nonlinear static analysis (pushover analysis) by SAP2000 for substructure type of single-column and multi-column bents separately. Both substructure types are designed as per provisions of IS 456, IS 1893 and IS 13920 for 1.5(DL+EQ) i.e. load of 5500kN acting at C.G. of bent cap. Finite element model for both the bridges with different substructure types are shown in figure below. For abutments and connections of super-structure with sub-structure, elastic bearing springs are provided.

2.1 Super-structure details

Interior slab thickness 305mm, Exterior overhang slab thickness 205mm, T-Girder interior web thickness 305mm, T-Girder base thickness 460mm, centre to centre girder distance 2.2m, overhang slab portion 1.1m, horizontal length of chamfer 460mm and vertical length of chamfer 150mm.

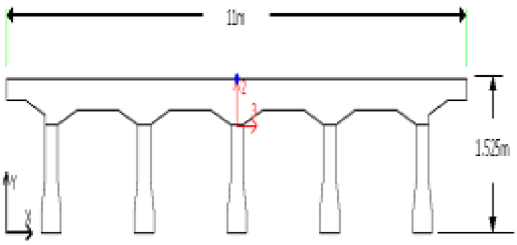


Fig.1 deck cross-section

2.2 Sub-structure details

Cross-section of bent-cap used is 1.8m×2.0m which is kept constant for both the bents.

Following column cross sections are used for 8m height single column bent and multi column bent respectively. For outer concrete, Mander unconfined concrete model is used and for core concrete, Mander confined concrete model is used. For steel reinforcement Park model is used. M30 grade of concrete and Fe415 grade of steel is used.

Table 1. Details of column cross-sections for single and multi-column bents

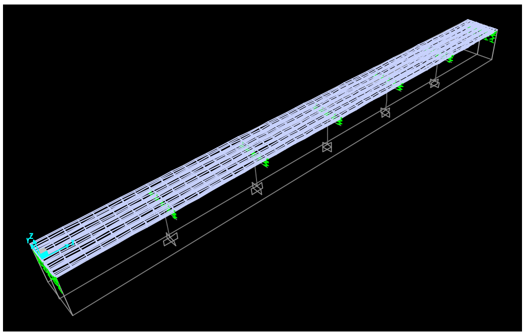
Type of bent	Size of column	Longitudinal reinforcement	Shear reinforcement
SCB	2m	Φ32mm 44no.	Φ16mm with 250mm c/c spacing
MCB	1.2m	Φ32mm 22no.	Φ16mm with 250mm c/c spacing

III. METHODOLOGY

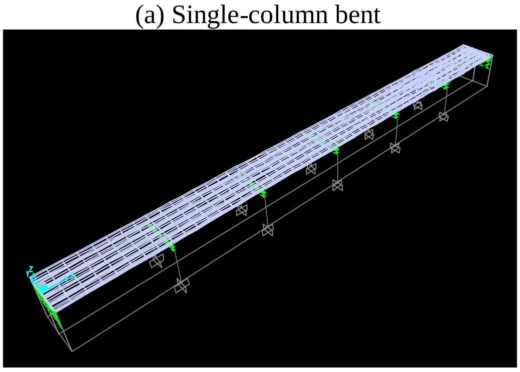
3.1. Finite element modeling

A simplified analytical modelling is utilized which allows for more economical analysis time when a large number of simulations are required. The analytical bridge model was established in SAP2000 analysis software. The modelling was performed consistent with Nielson's [8] findings on typical bridge properties and modelling assumptions. The bridge superstructure consists of six symmetric spans. The superstructure is supported by two seat-type pile abutments at its two ends and two multi-column piers in the middle which are supported by footings and pile caps at the columns bases. The bearing system is provided by an elastomeric rubber pad and two steel dowels under girder's end over the headstocks. Normally, the superstructure does not dominate the overall seismic response of a concrete highway bridge system because composite deck sections are much stiffer than other bridge components. This means that the concrete girders and slab behave like rigid elements and are expected to remain linearly elastic under seismic loads. Therefore, the superstructure is modelled using elastic beam elements by calculating the section properties of each span. The columns and headstock of the piers are however modelled by displacement column elements to reflect the nonlinearities in steel and concrete materials and P-Δ effects. The analytical model of the bridge bearings consists of an elastic material with no hardening ratio as of the elastomeric rubber pad, in parallel with a hysteretic material which represents the behavior of the two steel dowels [9].

Finite element model for the bridge with different substructure types are shown in Fig.2. For abutments and connections of super-structure with sub-structure, elastic bearing springs having translational and rotational stiffnesses based on their cross sectional and material properties are provided.



(a) Single-column bent



(b) Multi-column bent

Fig.2 finite element model for six span bridges

3.2. Selection of Ground Motion Records

For seismic performance assessment of civil structures and infrastructure in a specific area, it is particularly important to have a representative suit of ground motion time-histories recorded from earthquake sources at the area. A set of ten ground motion records is selected randomly from 20 Indian ground motion records used by Maniyar and Khare [10] to consider maximum ground motion parameters and its effect on seismic performance.

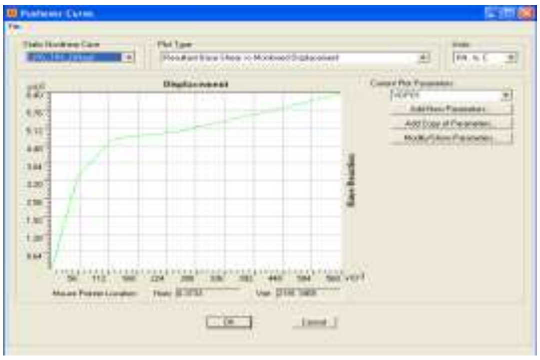
Table 2. Indian Earthquake records adopted for IDA

Record Id	**Event**	**Year**	**Station**	**Φ*1**	**M*2**	**R*3 (km)**	**PGA (g)**
1	Uttarkashi	1991	GHANSIALI	Longitudinal	6.5	38.0	0.118
2	Uttarkashi	1991	GHANSIALI	Transverse	6.5	38.0	0.117
3	Uttarkashi	1991	UTTARKASHI	Longitudinal	6.5	32.5	0.242
4	Uttarkashi	1991	UTTARKASHI	Transverse	6.5	32.5	0.309
5	Chamoli	1999	JOSHIMATH	Longitudinal	6.4	32.3	0.091
6	Chamoli	1999	UKHIMATH	Longitudinal	6.4	32.3	0.091
7	Chamoli	1999	UKHIMATH	Transverse	6.4	32.3	0.097
11	Uttarkashi	1991	SRINAGAR	Longitudinal	6.5	57.9	0.067
13	Chamoli	1999	GHANSIALI	Transverse	6.4	73.8	0.083
14	Chamoli	1999	GHANSIALI	Longitudinal	6.4	73.8	0.073

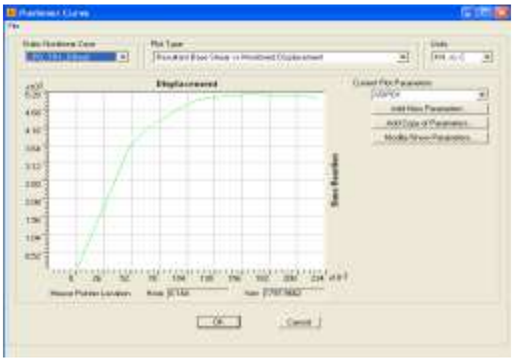
[1] Component [2] Moment Magnitudes [3] Closest Distances to Fault Rupture
Source: Department of Earthquake Engineering, IIT, Roorkee

3.3. Pushover analysis

Under the Nonlinear Static Procedure, i.e. Pushover Analysis, the mathematical model of the bridge is subjected to monotonically increasing lateral forces or displacements until either a target displacement is exceeded or the bridge collapses. The target displacement is intended to represent the maximum displacement likely to be experienced during the design earthquake. The goal of the static pushover analysis is to evaluate the overall strength, typically measured through base shear Vb, yield, and maximum displacement i.e. δY and δu, as well as the ductility capacity μc of the bridge structure. The pushover analysis can examine the sequence of limit states, formation of plastic hinges, and redistribution of forces throughout the structure, with the increment of the lateral loads or displacement demand. The pushover curve (force vs. deformation) of the bridge also allows identifying any softening behavior of the entire structure due to material strength degradation or P-Δ effects (Fig. 3 and 4).

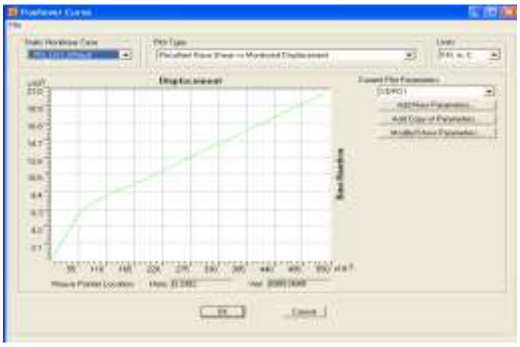


(a) Single column bent

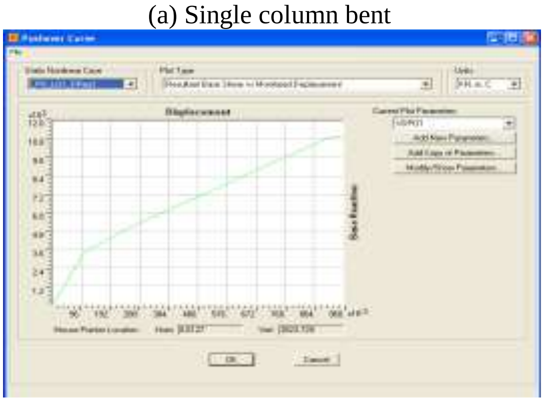


(b) Multi column bent

Fig.3 pushover curves in transverse direction



(a) Single column bent



(b) Multi column bent

Fig.4 pushover curves in longitudinal direction

The results of pushover analysis are tabulated in Table 3.

Table 3.Results of Pushover Analysis

Base shear direction	Design Base shear kN	Base Shear Capacity kN		Displacement Ductility at LS		D/C Ratio	
		SCB	MCB	SCB	MCB	SCB	MCB
TR	1485	4641.183	5118.891	2.283	2.043	0.250	0.763
LG	1485	8092.447	4471.161	1.659	1.672	0.351	0.363

Values of vulnerable PGA (g) are shown in Tables 4 and 5 which are calculated from the obtained base shear capacities using equation given below.
V = Ah*W; (Ah = Z*I/R*Sa/g)

where V is design base shear, Ah is seismic coefficient, W is seismic weight, Z is maximum considered earthquake in terms of PGA(g), I is importance factor, R is response reduction factor and Sa/g is spectral acceleration.

Table 4. Base shear capacities and vulnerable PGA (g) for transverse direction at different performance level from pushover analysis

Push Step	Base Shear capacity kN		Displacement mm		PGA (g) From Base Shear Capacity		Damage State
	SCB	MCB	SCB	MCB	SCB	MCB	
1	3410.144	3642.958	52.736	51.215	0.41	0.44	No Damage (Immediate occupancy)
2	3849.595	4433.01	75.109	81.348	0.46	0.53	Yield of steel (Life safety)
3	4289.092	5031.102	97.482	122.091	0.51	0.60	Spall of concrete (Collapse prevention)
4	4641.183	5118.891	115.406	154.913	0.56	0.62	Crushing of concrete (Damage)
5	4764.142	5123.179	132.159	157.941	0.57	0.62	Complete collapse (cracking of steel)

Table 5. Base shear capacities and vulnerable PGA (g) for longitudinal direction at different performance level from pushover analysis

Push Step	Base Shear capacity kN		Displacement mm		PGA (g) From Base Shear Capacity		Damage State
	SCB	MCB	SCB	MCB	SCB	MCB	
1	5553.115	3049.549	52.763	91.796	0.67	0.36	No Damage (Immediate occupancy)
2	7098.413	3865.26	85.587	145.776	0.86	0.46	Yield of steel (Life safety)
3	7595.431	4168.214	100.744	173.54	0.92	0.50	Spall of concrete (Collapse prevention)
4	8092.447	4471.161	115.902	201.304	0.98	0.54	Crushing of concrete (Damage)
5	8637.866	5031.773	132.535	255.523	1.0	0.60	Complete collapse (cracking of steel)

At the completion of the analysis phase, the pushover curve is obtained, as shown in Fig. 3 and 4, where the total base shear and displacement capacity of the bridge are determined. A quick check of the base shear values should be conducted to verify the results of the pushover analysis using seismic design codes

3.4. Incremental Dynamic Analysis

This research adopts nonlinear transient (time-history) analysis to simulate the earthquake loads acting on the analytical bridge model. As said before, the sources of nonlinearity were the nonlinear materials and bridge components behaviors. The ground motions were applied at the nodes representing the pile caps and abutments, in which the main horizontal component was acting along the longitudinal direction and the orthogonal component was applied along the transverse direction. The time-history analyses were performed by a time step of 0.05s which was half of the synthetic accelerograms' time step. Nevertheless, where required the analysis time step was decreased until numerical convergence was achieved. Moreover, the dynamic analyses were conducted using 5% Rayleigh damping. The damping coefficient was calculated deterministically such that the 5% damping occurs in the first two modes of vibration for the bridge analytical model, as calculated by the eigenvalue analysis. Incremental dynamic analysis (IDA), was performed to investigate the seismic performance and loading capacity of the highway bridge. For this purpose, each single ground motion record should be scaled to form different ground shaking levels. Consequently, an IDA curve was constructed using a set of ground motion records which demonstrates the bridge's decaying under increasing ground shaking level. According to Vamvatsikos and Cornell [5], the seismic capacity performance level is reached on the IDA curve where the local tangent reaches 20% of the elastic slope.

Among the recorded seismic responses, the columns' curvature ductility (μc), longitudinal deformations in the fixed and expansion bearings, and active and passive deformations in the abutments were nominated as the seismic demand parameters for performance assessment of the bridge system, since they have been reported to be determinant in evaluating the seismic capacity of highway bridges [11] IDA results are tabulated in Table 6. Fig. 5 shows the developed IDA curves for bridge components.

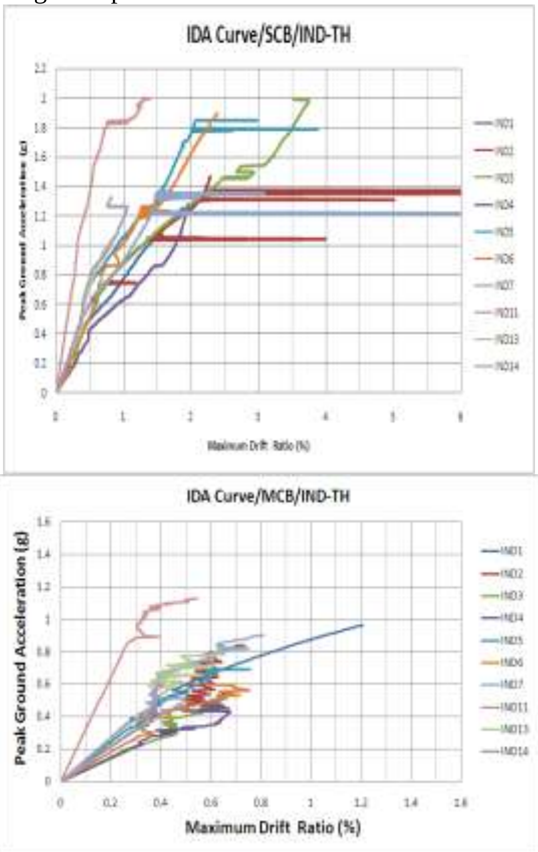


Fig.5 IDA curves of T-girder bridges for transverse direction

Table 6. IDA Result Summary for Set of Time Histories

Degradation Condition	Damage States	Single-column bent (SCB)		Multi-column bent (MCB)	
		Range of PGA(g)	Range of % Drift Ratio	Range of PGA(g)	Range of % Drift Ratio
Moderate	At-Yield	0.445 to 1.54	0.414 to 2.836	0.275 to 0.855	0.268 to 0.50
	At-Collapse	1.04 to 2.0	0.817 to 6.104	0.49 to 1.13	0.407 to 1.207

3.5.Fragility analysis results

These fragility curves represent the probability of structural damage due to various ground shakings. They also describe a relationship between ground motion and level of damage.

Fragility curves can be used for evaluating the total risk of infrastructures [12]. These curves indicate the probable level of damage for a specific class. Fragility curves can be expressed in the form of two parameters (median and log-standard deviation) lognormal distribution functions. Fragility curves (FC) are constructed with respect to PGA (g). The damage indices of the bridge piers are obtained from a non-linear dynamic response analysis. Then using the damage indices and the ground motion indices, the fragility curves for the single column and multicolumn bents are constructed as shown in Fig. 6. The results are tabulated in Table7.

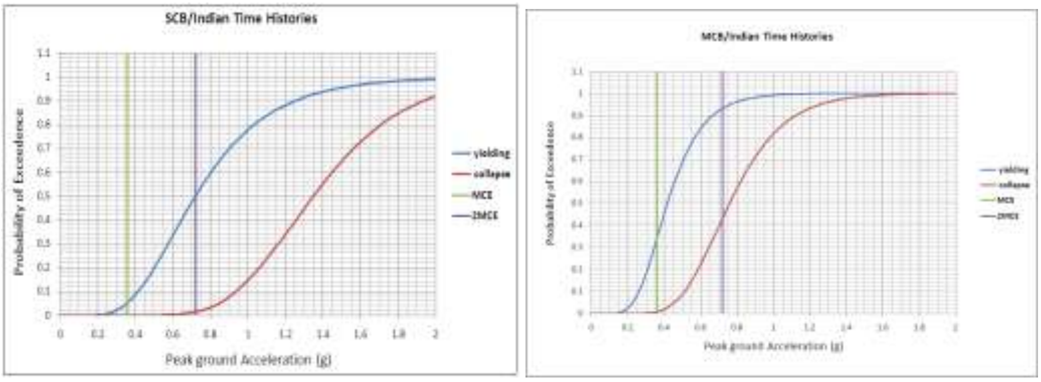


Fig.6 fragility curves of t-girder bridges for transverse direction

Table 7. Fragility Results for IND Time Histories

Degradation Condition	Type of Earthquake	PGA(g) of Earthquake	Probability of Damage (%)			
			At Yield		At Collapse	
			SCB	MCB	SCB	MCB
Moderate	MCE	0.36	4	34	0	0
	2MCE	0.72	50	93	2	42

3.6. Hazard survival results

Hazard survival curve (HS) is a plot of probability of survival versus return period. Probability of survival is equal to one minus probability of yielding or collapse at respective damage state. Return period is calculated using the equation defining relation between PGA of Serviceability Earthquake (SE), Design Basis Earthquake (DBE), MCE and their annual probability of occurrence in Indian perspective [13]. The results are tabulated in Table 8 and curves are constructed as shown in Figure 7.

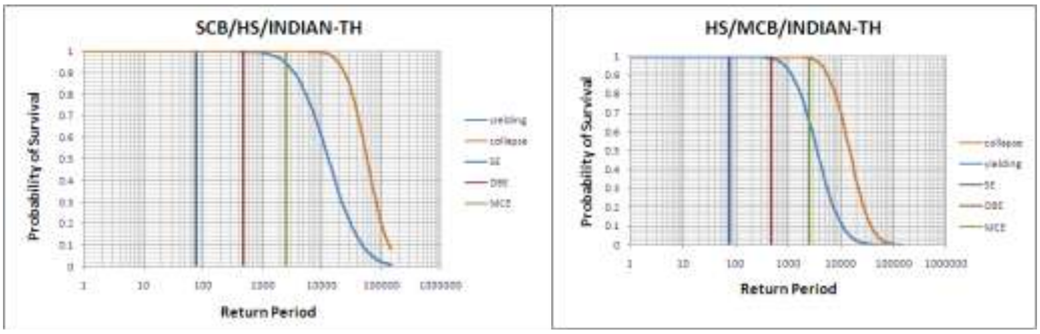


Fig.7 hazard survival curves of T-girder bridges for transverse direction

Table 8. Hazard Survival Results for IND Time Histories

Degradation Condition	Type of Earthquake	Return period in Years	Probability of Survival			
			At Yield		At Collapse	
			SCB	MCB	SCB	MCB
Moderate	SE	75	100	100	100	100
	DBE	475	100	100	100	100
	MCE	2475	96	66	100	100

IV. DISCUSSION OF RESULTS

In the study for six span bridges it is observed that in longitudinal direction strength increases as stiffness increases due to increase in number of spans. As transverse direction is critical for six and more span bridges results for the same are discussed here. Single column bent has over strength in transverse direction indicated by demand-capacity ratio. Displacement ductility is adequate for both the column bent. The value of vulnerable PGA(g) for collapse prevention is 0.51 which is low. These results show inadequacy of

Indian seismic design code as recent earthquakes experienced worldwide has intensity range of 0.8 to 1.0 PGA(g).

A methodology based on IDA is developed to determine the structural performance, damage levels, fragility and hazard-survival probability of the representative T-girder bridges. The seismic performance of the sample bridges is quantified in terms of yield and collapse capacities in terms of various ground motion indices, which are derived from IDA curves. The yield capacity of the structure is defined as the level of PGA (g) (i.e. Intensity Measure) at which the IDA curve leaves the linear path. Similarly, the collapse capacity is defined as the PGA (g) level at which the IDA curve becomes horizontal. Results of IDA with the 10 ground motion records are used to assess the record-to-record randomness of response. Fragility curves defined as the probability of exceeding a damage level (yielding/collapse) at various levels of PGA (g) are then plotted for these two damage levels. The fragility curves for yielding and collapse damage levels are developed by statistically interpreting the results of the time-history analyses. Hazard-survival curves are generated by changing the horizontal axis of the fragility curves from ground motion intensities to their annual probability of exceedance using the log-log linear ground motion hazard model. Probabilistic seismic performance assessment of the sample concrete bridge in this study reveals the following key findings:

- From IDA results, it is observed that the drift capacities are acceptable for T-girder bridges.
- The hazard survival curve clearly shows the acceptable performance level against SE (Serviceability Earthquake) and DBE (Design Base Earthquake) as per Indian seismic code.
- The chance of survival of T-girder bridges of 24m span is 66% against yield and 100% against collapse under probable MCE ground motions.
- From this study, it is observed that time period of the column bents structures plays an important role in seismic performance levels of concrete bridges. For higher value of the time period single column structures are more vulnerable and for lower value multicolumn bents are more vulnerable.
- These results show inadequacy of Indian seismic design code as recent earthquakes experienced worldwide has intensity range of 2MCE.

V. CONCLUSION

This paper focuses on the importance of Performance-based earthquake engineering (PBEE) methodology as a key approach for seismic analysis and design. Yet such approach has not been implemented in Indian structural codes

The seismic capacity of a typical T-girder concrete highway bridge designed as per Indian Standards is evaluated through a probabilistic method for substructure type of singlecolumn and multi-column bents separately. Fragility curves are developed and used for evaluation purposes. The results express at a glance the probabilities of yielding and collapse against various levels of ground motion intensities. The results of this study can be further employed for developing performance-based seismic design of typical Indian T-girder concrete bridges.

REFERENCES

[1]. C.A.Cornell, and H. Krawinkler,Progress and Challenges in Seismic Performance Assessment, PEER Center News, 2000,pp. 1-3.

[2]. MCEER. Seismic Retrofitting Manuals for Highway Systems, Volume II: Seismic Evaluation and Retrofitting Manual for Highway Bridges. Multidisciplinary Center for Earthquake Engineering Research, Buffalo, New York, 1999b.

[3]. J.B.Mander, Fragility Curve Development for Assessing the Seismic Vulnerability of Highway Bridges, MCEER Highway Project/FHWA National Institute of Building Sciences (NIBS), 1999, 1-10.

[4]. W.I.Liao, and C.H.Loh, Preliminary Study on the Fragility Curves for Highway Bridges in Taiwan,Journal of the Chinese Institute of Engineers, 27(3), 2004, 367-375.

[5]. SAP2000, Integrated Software for Structural Analysis and Design, Version14.0. Computers & Structures, Inc., Berkeley, California, 2013

[6]. D. Vamvatsikos, and C.A.Cornell, Incremental dynamic analysis, Earthquake Engineering and Structural Dynamics,31(3), 2002,491–514.

[7]. IDARC-2D-7.0 Computer Program, Department of Civil Engineering, The State University of New York at Buffalo, 2009.

[8]. B.G.Nielson,Analytical Fragility Curves for Highway Bridges in Moderate Seismic Zones, PhD Thesis, Georgia Institute of Technology, GA, USA, 2005.

[9]. E. Choi,Seismic Analysis and Retrofit of Mid-America Bridges, PhD Thesis, Georgia Institute of Technology, GA, USA, 2002.

[10]. M.M.Maniyar, and R.K. Khare, Selection of ground motion for performing incremental dynamic analysis of existing reinforced concrete buildings in India, Current Science, 100(5), 2011, 701-713.
[11]. B.G.Nielson, and R. DesRoches, Seismic fragility methodology for highway bridges using a component level approach,Earthquake Engineering & Structural Dynamics, 36(6), 2007, 823–839.
[12]. S.H.Kim, and M. Shinozuka, Development of fragility curves of bridges retrofitted by column jacketing,Journal of Probabilistic Engineering Mechanics, 19, 2004, 105-112.
[13]. R.P. Dhakal, R. K. Khare, and J. B. Mander, Economic Payback of Improved Detailing for Concrete Buildings with Precast Hollow-Core Floors, UC Research Repository of Civil and Natural Resources Engineering,University of Canterbury, 2006.

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