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Dynamic Response of Existing R.C. Bridges Against Earthquake Forces

Manasa J[1*], KodandaRamarao P [2], Srinivasulu A[3], and Reddy SRK[4]

[1]Village Surveyor, A.P. State Government, Vijayawada, India
[2]Vice Principal, Department of Civil Engineering, Seshadri Rao Gudlavalleru Engineering College, GUDLAVALLERU, A.P, India
[3]Head of the Department, Department of Civil Engineering, Seshadri Rao Gudlavalleru Engineering College, GUDLAVALLERU, A.P, India
[4]Adjunct Professor, Department of Civil Engineering, Seshadri Rao Gudlavalleru, Engineering College, GUDLAVALLERU, A.P, India

*Corresponding author: Manasa J, Village Surveyor, A.P. State Government, Vijayawada, India.

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Abstract

Performance of bridges against earthquake forces is different from buildings and other kind of structures as bridges are long and narrow, and support fleeting populace on highways or railways. Earthquakes with magnitude greater than 6.0 are capable of damaging or sometimes leading to even collapse of lifeline bridges, resulting in human and socio-economic losses. The extent of earthquake damage depends on the location of bridge close to the nearest seismic zone, structural configuration, ductility demand, age, and characteristics of the soil below foundation. Many failure examples during recent past earthquakes demand the scientific community and civil engineers, the importance of designing bridge structures against seismic forces; particularly when they built on loose soils. Vertical and lateral loads are resisted by the frame action of the superstructure and substructure of the bridge. Abutments and piers or supporting columns resist lateral forces in proportion to their relative stiffness. The vulnerability of any bridge during an earthquake is mainly due to the lateral displacements which cause large shear and flexure in pier or abutment and lead to failure at connections between the pier top and superstructure, or pier bottom and foundation. In the present study, an example of a two-lane and four spanned R.C. T-beam bridge across a canal, located in seismic zone III, is chosen for carrying out dynamic analysis against seismic forces and checked whether the bearing seat width provided at top of abutment and pier is safe or not, against the horizontal displacement of abutment and pier, obtained from the analysis due to seismic forces.

Keywords: Seismic Response, IS1893-(Part-3) 2014, Abutment & Pier, Time Period, Displacement and Base shear

Introduction

Any bridge, if damaged during an earthquake, can have serious impact on the transport system and also have tremendous consequences since bridges come under important transport infrastructure system. If the abutments and piers are built on soft soils, the ground motion gets amplified during an earthquake and if the soil below the foundation is sandy soil, sometimes it may lead to liquefaction failure. The seismic response of abutments and piers of a bridge depends on their capacity, mass and the dynamic resistance against backfill soil.

The bridges that were built twenty or thirty years back, when checked as per the present seismic code provisions, at least, some of them may be found vulnerable against strong or even moderate earthquakes.

The failure examples during recent earthquakes (figs. 1&2) have made people to think about the safety of existing bridges. To avoid the possibility of future damages, bridges that are at risk shall be identified, evaluated, and necessary retrofitting measures may be taken up.

K Andreas et.al. [1] investigated the effect of pile foundation stiffness on lateral displacements, the flexibility of the bridge, and the ductility demand of the pier. Araliya Mosleh et.al. [2] performed non-linear dynamic time-history analyses to identify the seismic vulnerability of typical pre-1990 bridges. Yuandong Wang et.al. [3] suggested seismic retrofit methods of a three-span R.C. bridge introducing Buckling–Restrained Braces (BRB) between bent columns which redistribute and dissipate energy in the transverse direction of the bridge.

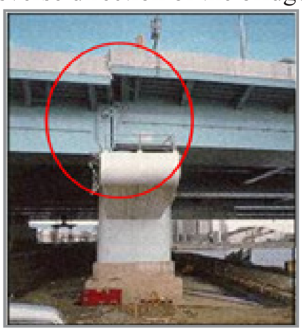

Figure 1: Lateral movement of pier due to soil liquefaction

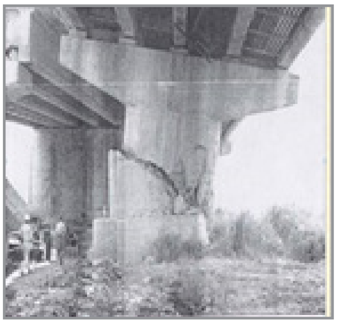

Figure 2: Failure of bridge pier during CHI-CHI, Taiwan earthquake, 1999

Objective

In the present study, the focus is made mainly on the structural behaviour of existing bridges, when they are subjected to earthquake forces. A thirty-year old R.C. T-beam bridge located in seismic Zone III, near Machilipatnam, a coastal town in the state of Andhra Pradesh, India, has been chosen for study, and the dynamic analysis is carried out for obtaining the response parameters like; time period, displacement and base shear of the bridge elements against earthquake loading.

Methodo

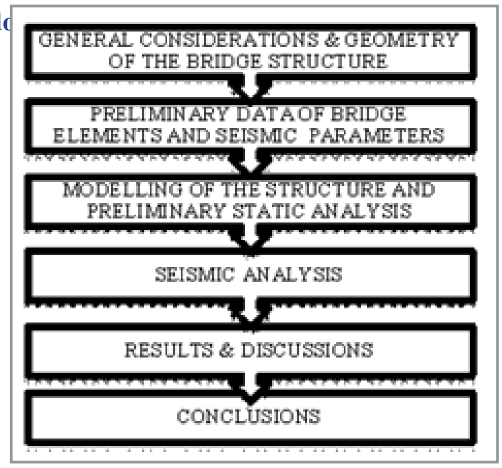

Figure 3

The basic dimensions of structural elements of the chosen bridge are assumed as per the provisions given in IRC-6, 2000 [4] and the seismic analysis is carried out as per IS 1893 (Part 1) 2016 [5] and IS 1893 (Part 3) 2014 [6]. The assumed dimensions are then assigned to the bridge and the analysis, when the bridge is subjected to both dead loads and live loads, is carried out as per IRC code provisions, and checked whether the assumed dimensions are safe or not. Earthquake analysis is carried out for obtaining the seismic parameters like; time periods, displacements and base shears. A cheek is also made whether the bearing seat widths provided at the top of abutment and pier, are safe or not.

General Considerations

Structure Details

- Preliminary sizes of the bridge components are calculated for dead load and live loads only.
- Though the ground vibrates in all directions during an earthquake, normally horizontal component of the ground motion is more predominant than that of vertical component.
- Hence, in the analysis, the horizontal component that acts in longitudinal direction of the bridge, is only considered for obtaining horizontal displacements of abutment and pier.
- For all structural elements of bridge, M25 grade concrete and Fe 415 grade steel are used and for abutments and piers M15 grade concrete is used.

The Geometry of Bridge Structure

The plan and cross-sectional view of the chosen bridge are s

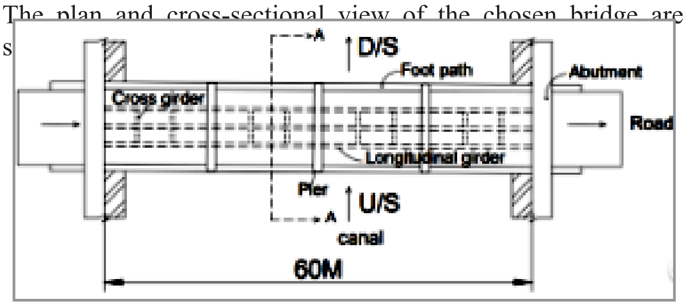

Figure 4: Plan of RC T-Beam Bridge

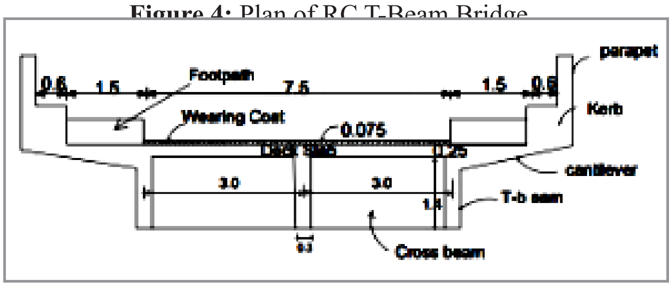

Figure 5: Cross-Section AA

Preliminary Data

- **Dimensions of Structural Elements of Bridge**

Table 1: Dimensions of structural members of bridge

Member	Dimensions
Length of the bridge	60m
Width of the bridge	11.7m
Clear Road Carriage width (Two-lane)	7.5m wide
Width of Kerb	600mm
Thickness of deck slab	250mm
Thickness of wearing coat	75mm

Span between end bearings	13.8m c/c
Overall span	15m
Foot path width	1.5m
Abutment height	3.4m
Abutment top & bottom widths	1.6m& 2.4m respectively
Pier height	3.4m
Length of the bridge	2m& 3m respectively

The details of various seismic parameters for carrying out the analysis are summarized in Table 2 below

Table 2: Seismic parameters

Seismic Parameter	Value / Reference
Unit weight of RCC	25 kN/m3
Unit weight of soil fill	20 kN/m3
Location	Machilipatnam (Seismic Zone III)
Earthquake load	As per IS-1893 (Part 1) – 2016
Type of soil	Type III as per IS:1893(Part-3) 2014
Zone Factor	0.16
Importance Factor	1.5
Response Reduction Factor	2.5

Design of Bridge Elements for Dead and Live Loads

- **Hydraulic Particulars of the Bridge**

Soil – Black cotton soil

MSL - -3.43m and MFL - +1.53m

The bridge deck slab and longitudinal T-beam girders are analysed for IRC class AA- loading and checked against IRC Class A-loading. Following the code provisions given in IS 456 (2000), [7] the thicknesses of deck slab as 250mm, the rib size of each longitudinal girder as 300x1400mm, and rib size of cross girder as 250x1400mm, are obtained. The final dead & live load moments and shear force values are calculated for both class AA and class A loadings and the values are presented in Tables 3 & 4.

Table 3: Design Moments

Type of girder	B.M Dead load (kN-m)	B.M live load (kN-m)	Total B.M (kN-m)
Outer girder	1335	1534	2869
Inner girder	1335	924	2259

Table 4: Design Shear forces

Type of girder	S.F dead load (kN)	S.F live load (kN)	Total S.F (kN)
Outer girder	365	204	569
Inner girder	365	123	488

For the above maximum B.M and S.F values, the sections of the T-beam girders are worked out as per the provisions given in IS 456 (2000) code and the assumed dimensions of T-beams are found satisfactory.

Design of Abutment

- **Active Earth Pressure on Abutment**

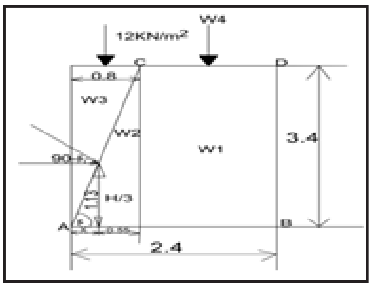

Figure 6: Forces acting on the abutment for active earth pressure

It is assumed that the bottom and top width of abutments as 2.4m and 1.6m respectively and the horizontal component of earth pressure is calculated.

To calculate the slanted slope of the abutment (β),
From fig 6, tanβ = $\frac{3.4}{0.8}$ = 76.45^{0}and α = 13.55^0

Coulomb's Active Earth Pressure for Cohesion-less Soils

$$P_a = \frac{1}{2} k_a \gamma H^2 \text{ ; Where } k_a = \frac{1-sin\emptyset}{1+sin\emptyset} = 0.33$$

$$P_a = \frac{1}{2} k_a \gamma H^2 = \frac{1}{2} \times 0.33 \times 20 \times (3.4)^2 = 38.15 \text{ KN}$$

$$P_H = P_a \cos(13.55^0) = 38.15 \cos(13.55^0) = 37.09 \text{ KN}$$

$$P_V = P_a \sin(13.55^0) = 38.15 \sin(13.55^0) = 8.94 \text{ KN}$$

- **Passive Earth Pressure on Abutment**

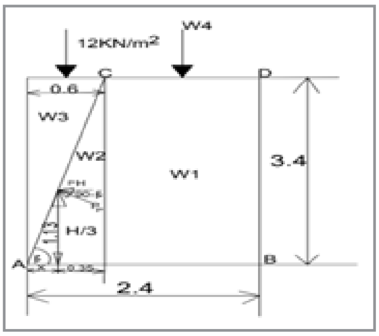

Figure 7: Forces on Abutment for passive earth pressur

Coulomb's Passive Earth Pressure for Cohesionless Soils from fig 7,

$$P_a = \frac{1}{2} k_a \gamma H^2$$

Where, $k_a \frac{1 + sin\emptyset}{1 - sin\emptyset} = 3$

$P_a = \frac{1}{2} k_a \gamma H^2 = \frac{1}{2} \times 3 \times 20 \times (3.4)^2 = 346.8$ KN

$P_H = P_a \cos(10.41^0) = 346.8 \cos(10.41^0) = 341.09$ KN

Pv $= P_a \sin(10.41^0) = 346.8 \sin(10.41^0) = 62.66$ KN

The stability analysis of the abutment is carried out and the check against sliding and no tension at the base is done and found safe.

Design of Pier

Reaction due to water pressure (buoyancy),

P =0.5h^{2}xDensity of water

= 0.5x $(2.8)^2$x 10 =39.2KN

To calculate the slanted slope of the pier,

From fig.8, tanβ $\frac{3.4}{0.8}$; and β = 81.38^0

α = 900 – β= 8.620

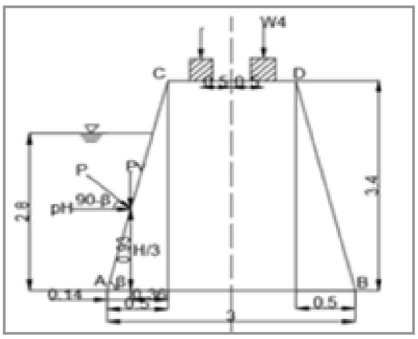

Figure 8: Forces acting on the pie

P_H = P cos (8.62^0) = 39.2cos (8.62^0) = 38.76 KN

P_V = P sin (8.62^0) = 39.2 sin (8.62^0) = 5.88KN

The stability analysis of the pier is carried out and the checks against sliding and no tension at the base are done and found safe.

Seismic Analysis

Seismic Analysis for Horizontal Displacement of Abutment

The vibration unit of abutment can be idealized as a single cantilever carrying the mass of bridge superstructure at top of abutment and supported by open foundation or piles with pile cap at the bottom and the fundamental time period against horizontal displacement at top is calculated as per clause 8.1 of IS 1893 (Part 3) 2014

$$T = 2\pi \sqrt{\frac{\delta}{g}}$$

Where δ – Horizontal displacement at top of abutment due to horizontal force (mg)

m – Lamped mass at top of the abutment transmitted from bridge superstructure

g – Acceleration due to gravity

It is assumed that abutment is fixed at foundation level and free at top. The load from bridge superstructure, assigned at the top of abutment is calculated considering the weights of deck slab, footpath, kerb, parapet, wearing coat, longitudinal & cross girders along with 70R live load.

Total weight obtained, W = 1745.0 kN

Mass 'm' at top of abutment = 1745/9.81= 77.9 kN-s^2 /m

M 15 grade concrete is assumed for abutment & pier for which $E_{c = 5000}$ √15 = 19365 N/mm2, say 19.4 x 10^6 kN/m^2

- **Time Period of Abutment**

Load from Bridge Superstructure Assigned at the Top of Abutment

DL due to deck slab = $\frac{15}{2}$x6.3x0.25x25 = 295.3 kN

DL due to cantilever slab = $\frac{15}{2}$x$\frac{2x2.7}{2}$x0.25x25 = 26.6 kN

DL due to Kerbs = $\frac{15}{2}$x2x0.6x0.5x25 = 112.5 kN

DL due to wearing coat = $\frac{15}{2}$x0.075x7.5x24 = 101.2kN

DL due to parapet = $\frac{15}{2}$x0.23x0.8x19.2 = 26.5kN

DL due to Long girders = $\frac{15}{2}$x3x0.3x1.4x25 = 236.3 kN

DL due to Cross girder = 2x2x1.4x0.25x25 = 35.0 kN

Total DL = 1044.5kN

Say total DL = 1045.0kN

Total LL = 700.0kN

Total Dead load & Live load, W = 1745.0kN

Mass at top of abutment,

$$m = \frac{W}{g} = \frac{1745}{9.81} = 177.9 kN\text{-}s^2/m$$

Horizontal force at top of abutment,
mg=1745KN

$$k = \frac{W}{\delta} = \frac{mg}{\delta}$$

Where k-stiffness of abutment

Case i: Treating the abutment as cantilever,

$$\delta = \frac{Wl3}{3EI} \text{ or } k = \frac{W}{\delta} = \frac{3EI}{L3}$$

Where L- abutment height =3.4m

$$I = \frac{1}{12} \times 11.7 \times 2.4^3 = 13.48 m^4$$

$$k = \frac{3x19.4x10^\wedge 6x13.48}{(3.4)^\wedge 3} = 20 \times 10^6 kN/m$$

$$\delta = \frac{W}{k} = \frac{1745}{20x10^\wedge 6} = 87.25 \times 10^{-6} m$$

Say, $\delta = 0.088$ mm

$$T = 2\pi\sqrt{\frac{\delta}{g}} = 2\pi\sqrt{\frac{87.25x10-6}{9.81}} = 18.74 \times 10^{-3} sec$$

$$T = 0.019 \text{ sec, Frequency, } f = \frac{1}{T} = \frac{1}{0.019} = 52.6 \text{ Hz}$$

Considering the location of bridge in seismic zone III
Z = 0.16, I = 1.2, R = 2.5 for abutment
From spectral curves given in IS1893 (part-3) 2014,

$\frac{Sa}{g}$ = 2.5 for loose soil

$$A_h = \frac{z}{2} \times \frac{I}{R} \times \frac{Sa}{g} = \frac{0.16}{2} \times \frac{1.2}{2.5} \times 2.5 = 0.096$$

To obtain total base shear at base of abutment,
W =Weight at top of abutment + weight of abutment,

$$W = 1745 + 11.7\,\frac{(2.4+1.6)}{2} x 3.4 x 24 = 3655 \text{ kN}$$

Base Shear at Foundation level of Abutment

$$V_B = A_h.\ W = 0.096x3655 = 350.9 \text{ kN}$$

Case ii) Horizontal Displacement of Abutment Due to Shear and Flexure,

$$\delta x = \frac{FH3}{3EcI} + \frac{1.2FH}{AGc}$$

Total horizontal force acting on abutment (F) is the summation of
a) Base shear against earthquake load
b) Active or passive earth pressure whichever is more and
c) Longitudinal load at 20% of class AA or class A loading whichever is more

F = 350.9+341.09+0.2(700) =1042 kN

$E_c = 19.4 \times 10^{6}$ kN/m²; μ = 0.2

$E_c = 2G_c (1+\mu)$ and $G_c = 8.08 \times 10^{6}$ kN/m²

I=13.48m⁴, A=11.7x2.4=28.08 m² and H=3.4m

Substituting these values in equation (1),δx= 0.07mm

From the above two cases, the maximum value of horizontal displacement of abutment is 0.088mm.

δx= 0.088mm

- **Time Period for Pier**

Load from Superstructure of Bridge Transferred to Top of the Pier

DL from two super structures =2x1045 = 2090kN

LL = 700kN
Total W = 2790kN

$$\text{Mass at top of pier, } m = \frac{W}{g} = \frac{2790}{9.81} = 284.4 kN\text{-}s^2/m$$

Case i) Considering pier as a Cantilever

Stiffness, $k = \frac{3EI}{L3}$

Where $I = \frac{1}{12} x 11.7 x 3.0^3 = 26.325\ m^4$
and L = 3.4m

$$k = \frac{3x19.4x10^\wedge 6x26.325}{3.4^\wedge 3} = 39.0 \times 10^6 kN/m$$

$$\delta = \frac{W}{k} = \frac{2790}{39x10^\wedge 6} = 71.5 \times 10^{-6} m = 0.0715 mm$$

$$\text{Time period, } T = 2\pi\sqrt{\frac{\delta}{g}} = 2\pi\sqrt{\frac{71.5x10-6}{9.81}}$$

$$T = 2\pi x 2.7 x 10^{-3} = 17 x 10^{-3} sec = 0.017 sec$$

$$\text{Frequency, } f = \frac{1}{T} = \frac{1}{0.017} = 58.8 \text{ Hz}$$

$$A_h = \frac{Z}{2} \cdot \frac{I}{R} \cdot \frac{Sa}{g}$$

From spectral curves of IS1893 (Part3) 2014,

$\frac{Sa}{g}$ = 2.5, Z = 0.16, I = 1.2 and R = 2.5 for pier

$$A_h = \frac{0.16}{2} x \frac{1.0}{2.5} x 2.5 = 0.096$$

Total weight W = weight at top of pier + self-weight of pier

$$W = 2790 + \left(\frac{3.0+2.0}{2}\right) 3.4 x 24 x 11.7 = 5177 \text{ kN}$$

Base shear at bottom of pier,

$$V_B = 0.096x5177 = 497 \text{ kN}$$

Case ii) Displacement of Pier Under the Action of Both Flexure and Shear

Total horizontal force acting on pier,

F=497.0+38.8+700(0.2) =675.8 kN

I= 11.7x 3.0^3 = 26.325m^4

A=11.7x3.0 = 35.1m^2

E_c= 19.4x10^6kN/m^3&G_c=10.42x10^6kN/m^2

Substituting above values in Eq. $\delta x = \frac{FH3}{3EcI} + \frac{1.2FH}{AGc}$

δx= 0.025mm

From above two cases, the maximum value of horizontal displacement at top the pier is 0.0715mm

The results of seismic analysis for both abutment and pier are presented in Table 4.

Table 4: Base Shears and Horizontal Displacements

Parameter	Abutment	Pier
Frequency	52.6 Hz	58.8 Hz
Base shear	350.9 kN	497.0 kN
Horizontal displacement	0.088 mm	0.0715 mm

However, as per provisions given in IS 1893 (Part 3) 2014, the minimum bearing seat width (SE) for abutment or pier as in fig 9, shall be

SE= (203+1.67L+6.66H) mm for seismic Zone III

Where

L - Length of superstructure to the adjacent expansion joint or to the end of bridge superstructure. (meters)

H - Average height of abutment or pier supporting the superstructure to the next expansion joint. (meters)

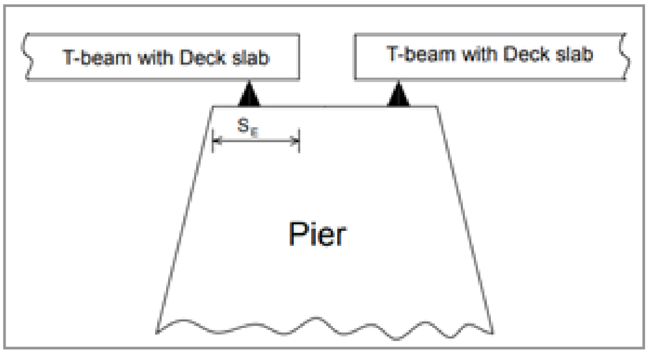

Figure 9: Arrangement of bearings on pier and minimum bearing seat width (SE)

Substituting L = 13.8 m & H = 3.4 m

S_E= 203+1.67(13.8) +6.66(3.4) = 248.7mm

For both abutment & pier,

$\delta_{Calculated} < \delta_{min} < \delta_{Provided}$

0.088mm < 248.7mm < 500mm

Hence the provided edge distance is safe.

Results and Discussions

From the above results, it is noticed that the variation in frequency components of abutment (52.6 Hz) and pier (58.8 Hz), is very less (12%).

It is also observed that the base shear due to earthquake motion in pier (497kN) is more compared to that of in abutment (350.9kN). This is mainly because the inertia force due to mass at top of pier is more than that of the mass at top of abutment.

The horizontal displacements obtained at top of both abutment and pier (0.088 mm) due to seismic forces are less and hence the provided bearing seat width both on top of abutment and pier are found safe.

Conclusions

During an earthquake, if the calculated displacement at top of abutment or pier is more than that of the minimum bearing seat width as per IS 1893(Part 3) 2014 code, the bridge is not safe.

Similarly, the displacement of slab both in longitudinal and transverse directions against seismic forces shall be within permissible limits.

In case, the provided bearing seat width at top of abutment and pier is not sufficient, retrofitting measures need to be taken up by increasing the top width on both sides in case of pier and on canal side only in case of abutment.

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