International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 2, February - 2014

Review Paper - Seismic Vulnerability Assessment of Bridge using Pushover Analysis

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***Abstract*— Bridge failure problems have been rapidly increasing worldwide. Therefore it is important to evaluate existing bridges and suggest design and retrofit schemes. Pushover analysis is an effective tool to evaluate the expected non-linear behavior and consequent failure pattern in different components of the bridge. Bridges extends horizontally with its two ends restrained and that makes the dynamic characteristics of bridges different from building. This paper reviews the different methods of pushover analysis of bridges. The different methods are Response spectrum analysis, Transverse and longitudinal analysis, standard pushover analysis, Capacity spectrum analysis, Modal pushover analysis, time history analysis. Finally the future of pushover analysis development in bridges is envisioned briefly.**

Keywords*— Bridge, Modal analysis, Pushover, Higher mode effect.

I. INTRODUCTION

India has had a number of the world's greatest earthquakes in the last century. In fact, more than fifty percent area in the country is considered prone to damaging earthquakes. There is a nation-wide attention to the seismic vulnerability assessment of existing buildings comparatively existing bridges have less. However, bridges are very important components of transportation network in any country. The bridge design codes, in India, have very limited seismic design provision at present. A large number of bridges are designed and constructed without considering seismic forces. Therefore, it is very important to evaluate the capacity of existing bridges against seismic force demand. There are presently no comprehensive guidelines to assist the practicing structural engineer to evaluate existing bridges and suggest design and retrofit schemes. In order to address this problem, the present paper reviews different methods of pushover analysis.

Although elastic analysis provides a useful overview of the expected dynamic response of a bridge, in general it cannot predict the failure mechanisms or the redistribution of forces that follow plastic hinge development during strong ground shaking. Nonlinear pushover analysis on the other hand, is a widely used analytical tool for the evaluation of the structural behavior in the inelastic range and the identification of the locations of structural weaknesses as well as of failure mechanisms. Nevertheless, the method is limited by the assumption that the response of the structure is controlled by its fundamental mode. In particular, the structure is subjected to monotonically increasing lateral forces with an invariant spatial distribution until a predetermined target displacement is reached at a monitoring point. As a result, both the invariant force distributions and the target displacement, do not account for higher mode contribution, which can affect both, particularly in the inelastic range, thus limiting the application of the approach to cases where the fundamental mode is dominant.

In pushover analyses, both the force distribution and target displacement are based on a very restrictive assumptions, i.e. a time-independent displacement shape. Thus, it is in principle inaccurate for structures where higher mode effects are significant, and it may not detect the structural weaknesses that may be generated when the structure´s dynamic characteristics change after the formation of the first local plastic mechanism. One practical possibility to partly overcome the limitations imposed by pushover analysis is to assume two or three different displacements shapes (load patterns), and to envelope the results, or using the adaptive force distribution that attempt to follow more closely the time-variant distributions of inertia forces.

II. DEVELOPMENT OF PUSHOVER ANALYSIS

The available literatures on pushover analysis of RC bridges are very limited whereas we can get a number of published literatures in pushover analysis of buildings. Hence the review of various papers are presented here of past 15 years which shows that research on the motivation behind researchers into Earthquake induced damage phenomenon and associated mitigation options.

The use of the nonlinear static analysis (pushover analysis) came in to practice in 1970's but the potential of the pushover analysis has been recognized for last 10-15 years. This procedure is mainly used to estimate the strength and drift capacity of existing structure and the seismic demand for this structure subjected to selected earthquake. This procedure can be used for checking the adequacy of new structural design as well. The effectiveness of pushover analysis and its computational simplicity brought this procedure in to several seismic guidelines (ATC 40 and FEMA 356) and design codes (Eurocode 8 and PCM 3274) in last few years.

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a) Estimates of force and displacement capacities of the structure. Sequence of the member yielding and the progress of the overall capacity curve.

b) Estimates of force (axial, shear and moment) demands on potentially brittle elements and deformation demands on ductile elements.

c) Estimates of global displacement demand, corresponding inter-storey drifts and damages on structural and non-structural elements expected under the earthquake ground motion considered.

d) Sequences of the failure of elements and the consequent effect on the overall structural stability.

III. METHODS OF PUSHOVER ANALYSIS USED FOR BRIDGES

Advanced nonlinear analysis methods with classical engineering principles to evaluate the global dynamic behavior of the bridge system and he local response of individual components was presented in Dameron's paper in 1997. Linear and nonlinear time-history analysis, with Out-of-phase ground motions including incoherency effects, and linear-response-spectrum analysis, in order to determine the critical responses for the bridge was performed in this Damerons paper. To obtain an estimate of the single maximum value of a response quantity, response-spectrum analysis (RSA) was used. While the RSA results were not used directly in the design calculations, the RSA drifts of critical elements were used as a check on the NTHA results. Author then plotted the results of 90 pier walls and explained the various parameters as follows:

1) Effect of pushover direction.
2) Effect of bridge skew angle.
3) Effect of wall pier type.
4) Effect of wall pier pile/ foundation type.
5) Effect of wall & footing reinforcement steel ratio.
6) Effect of bearing type.
7) Effect of regular pier wall height.

Standard' pushover analysis (SPA)

In 2006 KAPPOS paper, A fundamental mode-based ('standard') pushover analysis was first performed, to serve as the reference (i.e. the least demanding procedure) for assessing the inelastic response of the bridge studied. It is worth noting that unlike the case of buildings, wherein the pushover curve is generally defined in terms of base shear vs. top displacement (in the direction under consideration), in bridges the shape of the pushover curve depends on the pier on which the monitoring point is located (particularly when piers are of unequal height, as in the bridge studied). The displacement of the monitoring point is used not only as a parameter of the

This was judged to be an important consideration since NTHA was performed with only one earthquake time history. For RSA, 5% damped spectra were used so the RSA solution assumes 5% damping for all modes. For time-history analysis, an additional requirement arises when direct integration of the equations of motion is performed; namely, the need for an explicitly-defined damping matrix. Since it is impractical to estimate the magnitude of damping coefficients c, for the entire structure, the use of damping matrices which are mass and stiffness proportional is convenient. In physical terms, mass-proportional (external) damping varies geometrically with frequency and affects, primarily, low-frequency components, whereas stiffness-proportional (internal) damping has a linear relationship with frequency from virtually no damping at low frequencies to high damping for high-frequency components.

Transverse and longitudinal pushover analyses; A transverse pushover analysis is one in which a slowly increasing horizontal acceleration is applied to the bridge superstructure perpendicular to the span of the bridge; a longitudinal pushover analysis is one in which the acceleration is applied parallel to the span of the bridge. These directions were chosen because they correspond closely with the predominant vibrational directions of the first (longitudinal) and second (transverse) modes of the bridges. In 2005, Bignell performed both analysis. In this paper Eighty-seven of the 90 bridge models were subjected to both of these pushover analyses. Three of the models were only subjected to a longitudinal pushover analysis, to avoid duplicating results obtainable from transverse pushover analyses already performed. Thus, from the 90 models a total of 177 pushover analyses were performed. Before performing the nonlinear pushover analyses, failure measures ("limit states") were defined for each of the major bridge components. These failure measures were organized into the following groups: bearing/seat failures, wall pier failures, footing/pile cap failures, pile failures. capacity curve, but also to establish the seismic demand along the structure at the estimated peak displacement.

Modal pushover analysis (MPA)(Ref)

After obtaining a clear overview of the main aspects of the expected inelastic response using the 'standard' pushover analysis, the MPA method described in the previous section was implemented. The dynamic characteristics required within the context of the MPA approach, were determined using standard Eigen value analysis. Fig. 2.2 illustrates the first four transverse mode shapes of the bridge, together with the corresponding participation factors and mass ratios, as well as the locations of the equivalent SDOF systems for each mode. It is seen that the modal mass participation factors of higher transverse modes are much lower than that of the fundamental transverse mode, a fact that could be primarily attributed to the curvature of the bridge in plan. Consideration of these four modes assures that more than 90% of the total mass is considered. Applying the modal load pattern of the *n*th mode in the transverse direction of the bridge, the corresponding pushover curve, involving the displacement of the central pier (M6) top was constructed and then idealized as a bilinear curve. These curves were then converted to capacity curves.

Non-linear Time history analysis (NL-THA)

In line with most previous studies, it was deemed necessary to compare results of the 'standard' and modal inelastic pushover approaches with those from nonlinear Time History Analysis (NL-THA), the latter assumed to be the most rigorous procedure to compute seismic demand. To this effect, a set of NL-THA's was performed in 2006 KAPPOS paper using 5 artificial records compatible with the EAK2000 elastic spectrum and generated with the use of the computer code ASING [24]. The classical Newmark integration method was used (γ=0.5, β=0.25), with time step Δt=0.002s and a total of 10000 steps (20s of input). Since this analysis is considered as the most refined and accurate, it was of particular interest to compare the maximum displacements of the deck calculated from time-history analysis with those corresponding to the target displacement defined through the SPA and the MPA approach.

A methodology was proposed for Modal Pushover Analysis (MPA) of bridges, and its feasibility and accuracy were investigated in 2006 KAPPOS paper by applying it to an actual long and curved bridge, designed to modern seismic practice. By analyzing the structure using inelastic 'standard' (SPA) and modal (MPA) pushover analysis, as well nonlinear time history analysis (NL-THA), KAPPOS paper concluded that:

- At least for the studied structure, which is complex but properly designed, all three methods yield similar maximum pier top inelastic displacements although their pattern is rather different.
- The SPA method predicts well the displacements only in the central, first mode dominated, area of the bridge. On the contrary, MPA provides a significantly improved estimate with respect to the maximum displacement pattern, reasonably matching the results of the more refined NL-THA analysis, even for increasing levels of earthquake loading that trigger increased contribution of higher modes.
- On the basis of the results obtained for the studied bridge structure, MPA seems to be a promising approach that yields more accurate results compared to the 'standard' pushover, without requiring the high computational cost of the NL-THA, or of other proposals involving multiple eigenvalue analyses of the structure to define improved loading patterns in the inelastic range.
- Further work is clearly required, to further investigate the effectiveness of MPA by extending its application to bridge structures with different configuration, degree of irregularity and dynamic characteristics, especially in terms of higher mode significance, since MPA is expected to be even more valuable for the assessment of the actual inelastic response of bridges with significant higher modes.

The seismic evaluation of the bridge was performed using the FHWA Seismic Retrofitting Manual for Highway Bridges Part 1 - Bridges published by the Multidisciplinary Center for Earthquake Engineering Research (MCEER) in 2009 Shatarat's paper. He used Two methods of analysis:The first method is a linear elastic force based method of evaluation named Method C, which is used to find out the elastic demand. The second method of analysis is a non-linear static pushover analysis named Method D2 in the seismic retrofitting manual, which is used to find out the nonlinear plastic capacity of the structure. The Capacity/Demand ratios are then calculated for all relevant components, such that a Capacity/Demand ratio value less than one indicates a potential need for seismic retrofit of a structural element.

For bridges with regular configuration multimode elastic response spectrum analysis is recommended. Time-history analysis is recommended for irregular bridge configuration; however the MCEER manual recommends that the multi-mode elastic response spectrum analysis could be used as minimum as well. Using this method the following components are to be investigated: seats, connections, columns, walls and footings. The elastic response spectrum function used to find the demand is based on a 475-year design level earthquake with 5 percent damping. AASHTO LRFD is used to construct the spectrum function with 0.3g Peak Ground Acceleration (PGA) and 1.2 site coefficient.

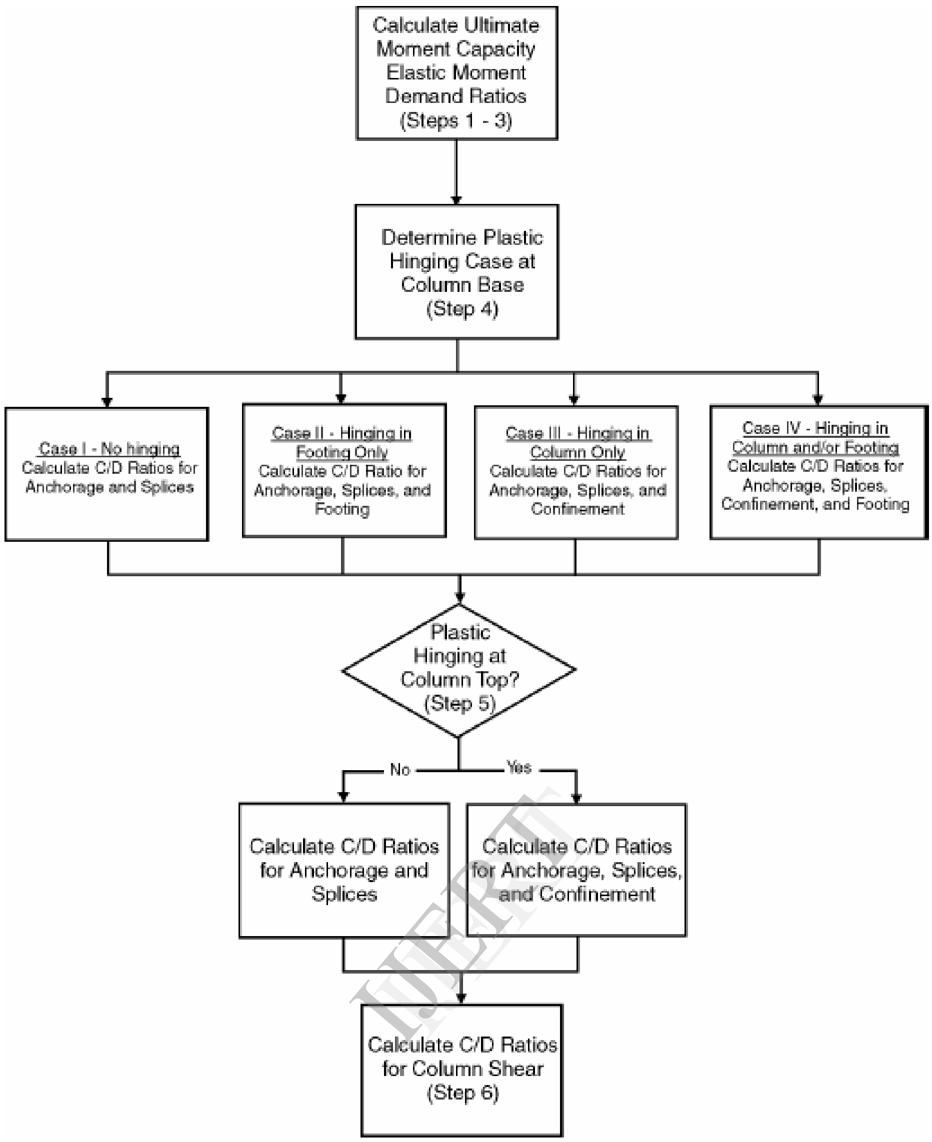


Fig. 2.3: Method C Column Analysis Flow Chart, Adapted from Seismic Retrofitting Manual for Highway Bridges

Nonlinear methods of analysis that are capable of realistically predicting the deformations imposed by earthquakes on structures are needed. In response to this need, new nonlinear static analysis procedures have appeared in national resource documents such as the ATC-40 report 1996 on seismic evaluation and retrofit of concrete buildings and the FEMA-356 (2000) pre standard on seismic rehabilitation of buildings. The Capacity Spectrum Method, originally developed by Freeman in 1978 is one of the more frequently utilized methods of nonlinear static analysis and is the principasl method described in the ATC-40 report. As described by Shattarat in 2007, the Capacity Spectrum Method begins with a nonlinear statics pushover analysis which results in a graphical depiction of the global force–displacement relation for the structure. The demand on the structure is then represented graphically by elastic spectra with equivalent viscous damping.

The Displacement Coefficient Method in FEMA 356 (2000) represents demand via inelastic displacement spectra which are obtained from the elastic displacement spectra using a number of correction factors, which in principle are expected to be more accurate than elastic spectra with equivalent viscous damping. Regarding the nonlinear static analysis methods used in the Shattarat's study(2007), the Capacity Spectrum Analysis method is well known and the seismic demand can be readily determined. For the Inelastic Demand Spectrum method, the seismic demand is much more difficult to define unless a simplified inelastic design spectrum is utilized.

The approach to converting the pushover curve to the capacity curve when gravity loads produce initial displacements needs further investigation. Herein, it is suggested that the performance point should be identified in the absence of any dead load effect and the influence of dead loads accounted for in the transformation from the SDOF modal domain back to the MDOF physical domain. For the bridge structure examined herein, the Capacity Spectrum Analysis method and the Inelastic Demand Spectrum Analysis method led to different predictions of displacement demand. However, neither method is regarded as producing correct results due to a number of simplifications inherent in the methods. In spite of such shortcomings, inelastic static analysis methods remain attractive to practicing engineers due to their explicit consideration of inelastic response and due to the graphical nature of the seismic performance evaluation.

IV. DIFFERENT BRIDGES USED FOR ANALYSIS

In 2005, Bignell's paper , he assessed the seismic vulnerability of wall pier supported bridges, the second most prevalent bridge type found on Illinois priority emergency routes, through a similar program of nonlinear pushover and dynamic analyses. Three general categories of wall piers exist within southern Illinois, namely hammerhead, regular, and flexible (Fig. 2.4), with hammerhead and regular wall pier bridges making up the vast majority. Most of the bridges were built during the 1950's, 60's, and early 70's, and they were typically either not skewed or had low skew angles. This paper presented typical details of southern Illinois wall pier supported bridges, describes construction of the three-dimensional finite element models (including nonlinear modeling assumptions), and summarizes results from the nonlinear pushover analyses.

For the case of the Coronado Bridge, In 1997 dameron's paper described significant nonlinearities, particularly in the foundations, and delineates the approach taken to model nonlinear foundation behavior. A vulnerability study of the San Diegdoronado Bay Bridge was conducted by ANATECH in 1995. The study combined the use of advanced nonlinear analysis methods with classical engineering principles to evaluate the global dynamic behavior of the bridge system and the local response of individual components. From late 1995 through 1996, the design phase of the seismic retrofit of the bridge has been underway. The retrofit design, also commissioned by Caltrans, is being headed by a joint venture between McDaniel Engineering and J. Muller International, San Diego, with ANATECH retained as the lead structural analyst.

For the purpose of modal pushover analysis,In 2006, kappos selected the Krystallopigi bridge, a twelve span structure of 638m total length (Fig. 2.5) that crosses a valley in northern Greece. The curvature in plan (radius equal to 488m) of the bridge adds to the expected complexity of its dynamic behavior. The deck consists of a 13m wide prestressed concrete box girder section (see insert in Fig. 2.5). He investigated the accuracy and also the practicality of the proposed procedure it was deemed appropriate to apply it on an actual bridge structure, whose complexity hints to increased contribution of higher modes.

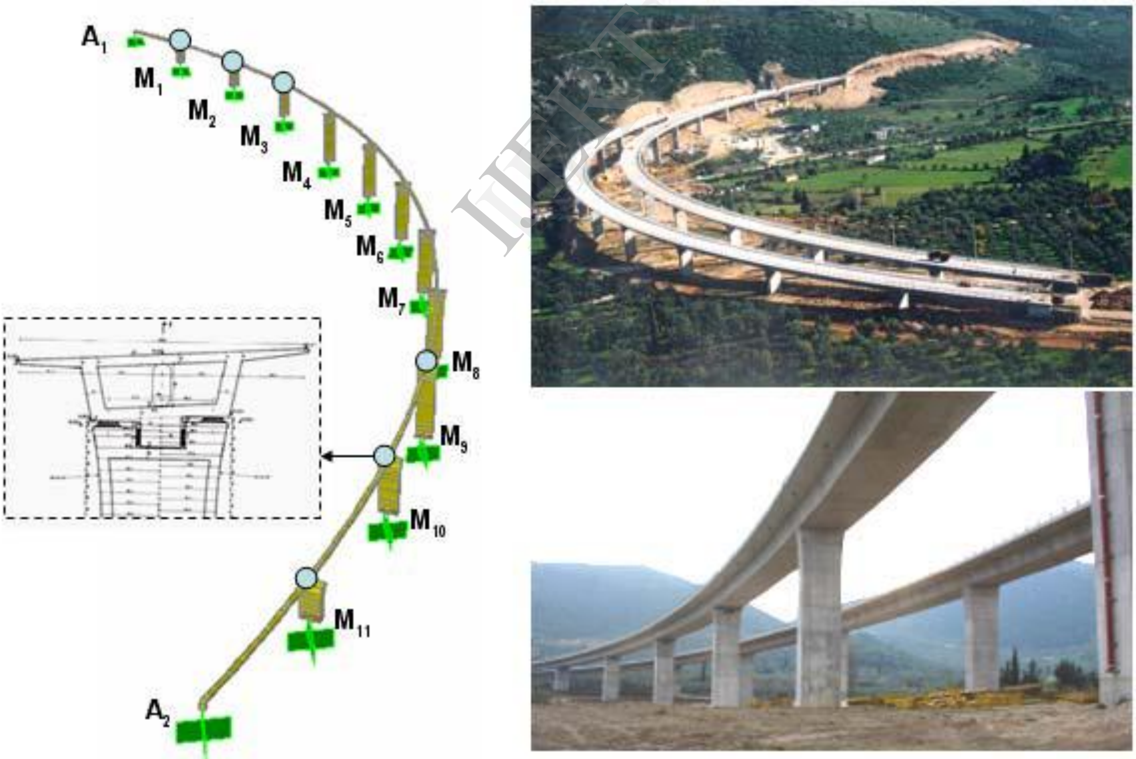


Figure 2.5: Layout of the bridge configuration and finite element modeling

In 2008, Shattarat's paper, The bridge consists of a two-span continuous, post-tensioned, reinforced concrete box girder with a three-column integral bent, and spread footings (see Fig. 2.6) and was selected for investigation based on its similarity to typical highway bridges in the state of Washington. Author considered Two different support configurations. In the Basic Support Configuration, the bridge has seat-type abutments which allow limited longitudinal movement of the superstructure due to the gap between the superstructure and the abutment back wall. The support provided by the abutment is assumed to be fixed against translation in the vertical and transverse directions and fixed against rotation about the longitudinal axis while the column bent footings are considered to be fixed against both translation and rotation. In the Spring Support

Configuration, the bridge has stub wall abutments which are restrained in the longitudinal and transverse directions due to end diaphragm and wing wall interaction with the soil, respectively. The support provided by the abutment is assumed to be fixed against translation vertically, fixed against rotation about the longitudinal axis of the superstructure and has translational springs in the longitudinal and transverse directions while the column bent footings were supported on translational and rotational springs in each orthogonal direction to account for soil flexibility.

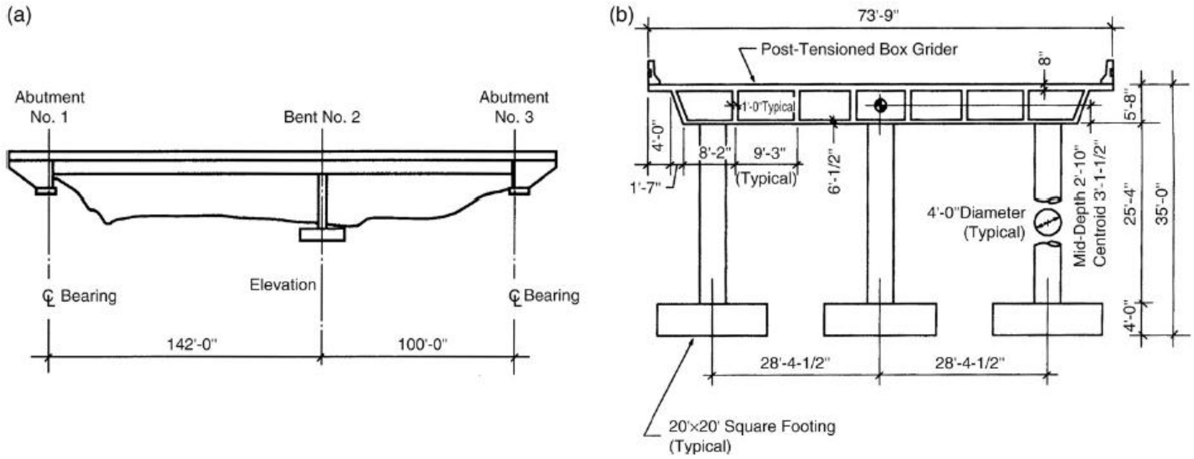


Fig.2.6. Elevation and cross-section of bridge.

In 2007,wang's paper selected the bridge to study is a replica from a quake-stricken river crossing highway bridge in central Taiwan. Built in 1984, it covers eleven intermediate spans of 35 m long deck, plus two end spans of 13 m long deck leading to abutments embedded in earth banks alongside the river. Fig.2.7 shows a few segments near the south end. Each deck span is made up of a 200 mm thick concrete slab cast onto five pre-stressed concrete T-girders laterally jointed by diaphragm ribs at intervals of one-third length. The girders, each of depth 2000 mm in longer spans, and 1000 mm in end spans, are supported on piers and abutments with rubber bearings. Each pier, consisting of a cap beam and vertical column, is fixed to a caisson foundation that sinks into a firm stratum of sandy rocks.

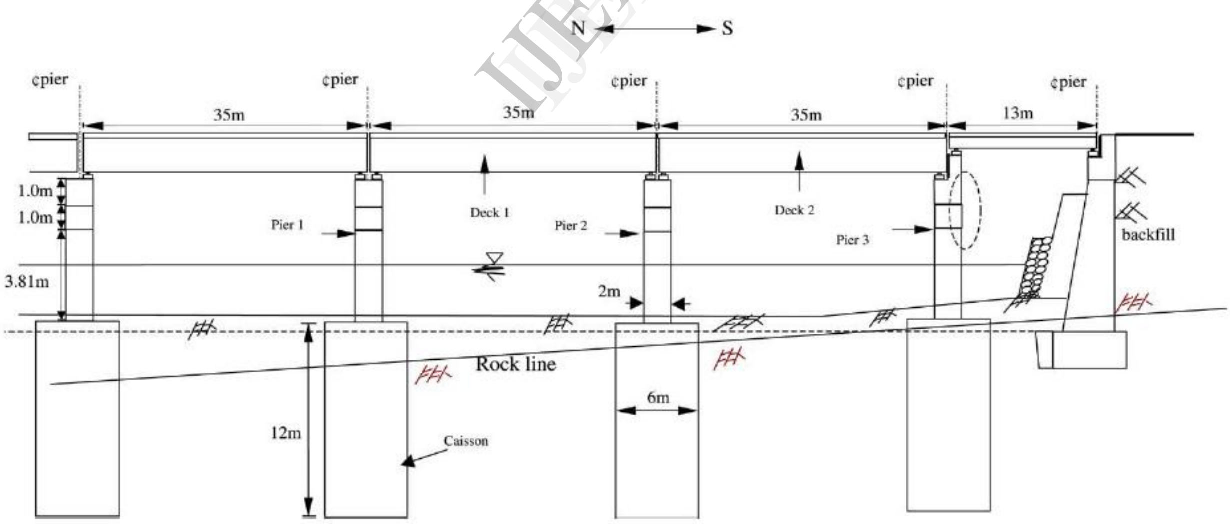


Fig.2.7. Elevation view of 4 segments at south end; the bridge has 13 segments in total: 13 m + 11@35 m + 13 m.

In 2004, Zhihao Lu's paper, Two upper-deck steel arch bridges are adopted for case studies (see Fig.2.8), referred to as Bridge I andBridge II hereafter in this paper. The two bridges were designed using the Seismic Coefficient Method recommended in the Japanese Codes for seismic consideration according to a moderate earthquake intensity level. Bridge I is mainly composed of reinforced concrete (RC) deck slab, steel girders and single-span steel arch ribs, as shown in Fig. 2.8(a). Bridge II mainly consists of RC deck slab, steel girders, arch ribs and RC piers, as shown in Fig. 2.8(b).

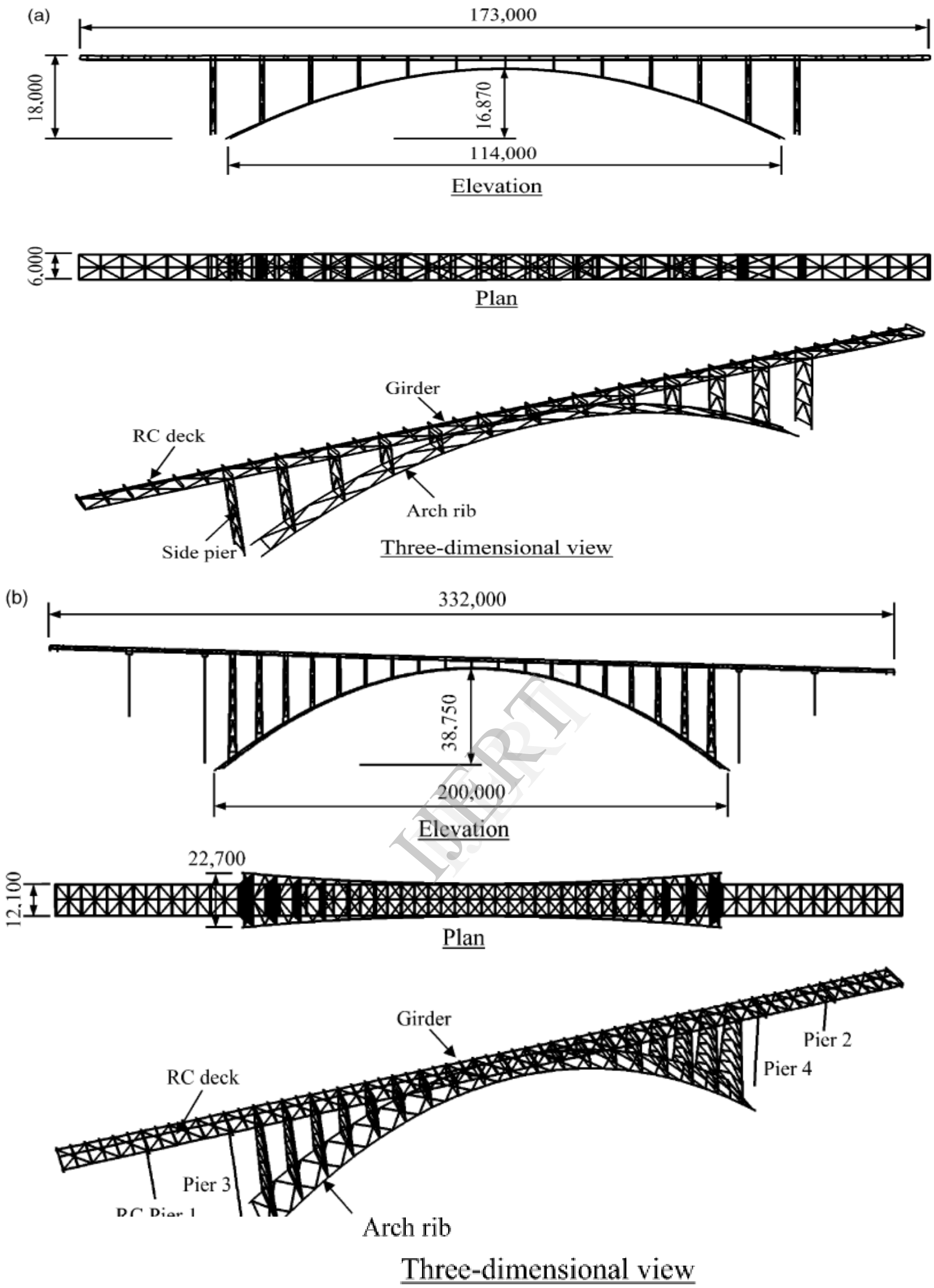


Fig.2.8. Structure models (a) Bridge I (b) Bridge II.

Similarly many author performed pushover analysis on various bridges like I-5 Ravenna bridge (Tehrany in 2011), I-155 bridge across the Mississippi River between permiscot country (Capro in 2007) and many more.

Results obtained in various methods:

In 2005, Bignell's paper, From his analysis he concludes that Pushover direction has a large impact on the types of failures encountered and the ultimate load attained. Wall bending and ductility failures were more prevalent in the longitudinal direction and bearing failures were more prevalent in the transverse direction. The ultimate load attained was greater in the longitudinal pushover cases.

A brief comparison of results with and without nonlinear foundation modeling is shown in Fig. . The top plot shows longitudinal tower top displacements and the bottom plot shows transverse pile-cap displacements.

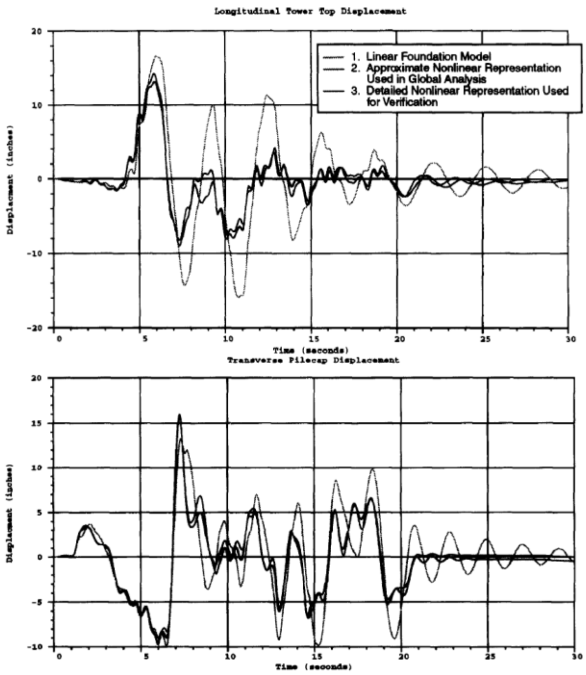
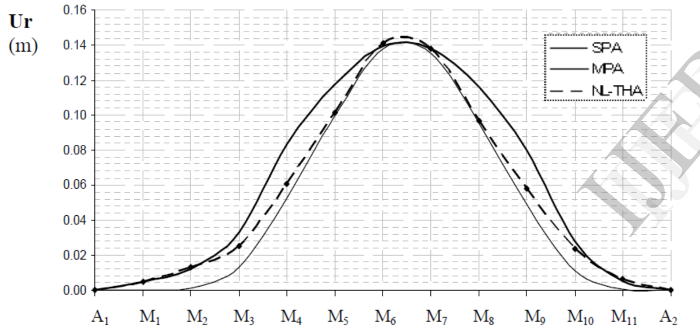
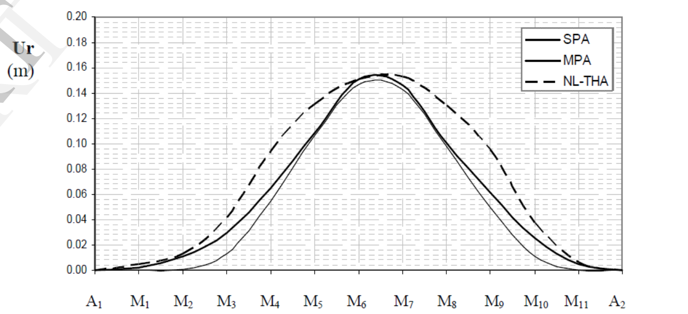


Fig. 15. Comparison of tower top and pile-cap level-displacement response predicted by nonlinear and linear foundation representations.

Kappos plotted the results of Standard pushover analysis , Modal pushover analysis and Time history analysis Method are as follows,

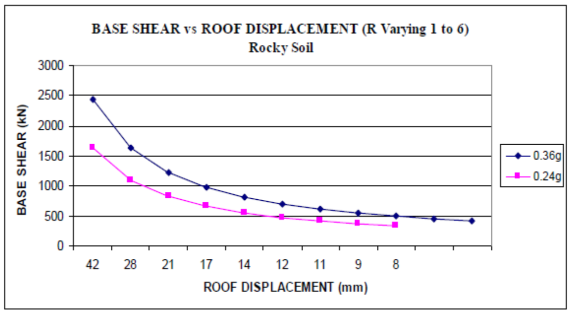


Pier top displacements calculated from SPA, MPA and THA, for elastic behavio



Pier top displacements by SPA, MPA and NL-THA. (transverse direction only), for the design earthquake intensity.

Isaković used Three typical pushover methods to analyze the bridge: a) The N2 method as a standard single-mode pushover method, b) the MPA method as a typical non-adaptive multimode pushover method, and c) the IRSA method as a typical adaptive multimode pushover method. For all considered methods the displacement shapes correlated with the experiment quite well when the lower intensity levels were considered. The N2 method was less effective in the case of higher intensity levels since it was not able to take into account qualitative changes of the deck rotations.



ss Figure Base Shear vs Roof Displacement (Ground Acceleration Varies)

Parimal godase obtained the relations between Base shear and roof displacement from linear static analysis and is presented in Figure. For the Pier model, by varying R base shear reduces but at the same time Ductility of material in terms of roof displacement varies in 25-30%. For the different Earthquake ground motion for particular type of soil, it is observed that as R value increases the roof displacement reduces considerably. As R value increases there is corresponding reduction in the base shear also relative to particular earthquake intensity.

V. CONCLUSION:

This paper has presented a general review of seismic vulnerability assessment of bridges using pushover analysis. Unlike the elastic analysis in past, the non linear pushover analysis has been proposed. Various Nonlinear pushover analysis methods have been described with emphasis on innovations. Bridges extends horizontally with its two ends restrained and that makes the dynamic characteristics of bridges different from buildings. And hence advanced pushover analysis is applicable to bridges is explained in this paper.

This paper demonstrate that the nonlinear pushover analysis created a great interest amongst researcher since last few years. There is need for investigating in order to make a generalized evaluation procedure for bridge structures with different configurations. More research is needed as the failure of bridges due to earthquake is increasing. Finally the Advanced pushover analysis methods should be seriously studied in terms of higher mode effect.

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