Performance Based Seismic Design of T-Section and Box Girder Bridges

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Abstract - *In modern earthquake resistant bridge design, there is need of bridge design and technologies that are both sustainable and resilient; however, achieving both of these is difficult and challenging. Development of performance based seismic design methodologies for structures has become the main focus of recent researches. Performance Based Design is not only the extension of limit state design to cover the complex issues such as excessive displacement, rotation, damages and functionality etc. but also, it provides an insight to the expected performance of designed structure during an earthquake event. In its current form, it aims at achieving one or more predicted performance levels after pre-defined hazards, and is superior to force based methods in terms of structural performance. General promise of Performance Based Design is to produce engineered structures with predictable performance during future earthquakes. This paper signifies on the application of Performance Based Seismic Design to T- section Girder Bridge and Box Girder Bridge, using Indian codal provisions. The bridges are modelled, analyzed and designed using CSI Bridge 20. The response of bridges is estimated using both non-linear static and non-linear dynamic analyses. Different seismic parameters like fundamental time period, base moment in pier, percentage of reinforcement and base shear are obtained and compared.*

Key Words: Performance based seismic design, bridges, nonlinear analysis, and seismic design.

1. INTRODUCTION

Good and efficient transportation system is one of the key points of networking of any nation. Bridges are important and critical civil infrastructures for the transportation network of any country. Therefore proper and careful considerations are required while designing bridges particularly in seismic regions. The closure of important bridges due to damage or collapse in the event of earthquake can disrupt the total transportation network. IRC codes are used for bridge designing in our country, where working stress method is used. Recently IRC has prescribed the limit state design of various components of bridges, while considering the seismic force IRC has used same formula which is given in IS1893(part 3):2014. Bridges are generally divided into two categories: Normal (Ordinary) bridges and Important Bridges.

In this paper, a bridge is designed by IRC guidelines and analysis is done using non-linear static pushover analysis method to meet the given performance criteria as per ATC-40 guidelines. Bridge is designed considering Normal (Ordinary) and Important category. Considering different seismic parameter like response reduction factor, zone factor and soil conditions.

The literature shows considerable research in PBSD of bridges. Some of correlated works are discussed below:

[Kevin R. Mackie][1] This paper gives the modern seismic-resistant bridge design, there is a need for bridge designs and technologies that are both sustainable and resilient; however, quantifying both of these is challenging. Performance-based earthquake engineering as applied to typical highway bridges is presented in this paper. [Zhang. Qi & Alam, M. Shahria][2] This paper reviews the fundamentals and current practices of performance-based design for standard highway bridges covering the Canadian Highway Bridge Design Code (CHBDC), AASHTO and a number of jurisdictions.[Zhang. Qi & Alam, M. Shahria][3] This paper gives the idea about introduction of Performance-based design (PBD) in Canadian Highway Bridge Design Code (CHBDC) in 2014. Performance-based design is the design that meets multiple performance criteria under different earthquake hazards.[M. Neaz Sheikh & Frédéric Légeron][4] This paper correlates seismic performance objectives (both qualitative and quantitative) with engineering parameters, based on the data collected from published experimental investigations and field investigation reports of recent earthquakes.[Ghosh et al.][5] This paper examines the estimated performance of a three-span continuous bridge designed using a codal procedure for the site-specific design response spectrum. [Ying Suna et al.][6] In this paper, a simple and practical performance-based seismic design (PBSD) method for regular highway bridges is suggested. In the proposed PBSD method, the drift ratio of the bridge column is employed as quantitative indices of seismic performance.

2. IDIALIZATION OF METHODOLOGY

2.1 Performance Based Design

Performance based design is a process in which performance requirements are translated and integrated into a bridge design. Performance-based seismic design can be viewed as a process of system conception followed by an assessment procedure in which the performance of the structural system is evaluated and improved as needed to satisfy stated performance objectives. These criteria differ from traditional codes in that they correlate levels of damage noted in laboratory testing and real earthquake damage to quantifiable material properties and design parameters. PBSD is a modern design concept of earthquake resistant structure. PBD is a more general design philosophy in which the design criteria are expressed in terms of achieving stated performance objectives when the structure is subjected to stated levels of seismic hazard. Since, 1994 Northridge earthquake and other earthquakes around the world during the end of the 20th century were an eye-opener for the use of PBSD. Performance- based design (PBD) is a more general design philosophy which aims at achieving multiple performance objectives when the structure is subjected to stated levels of earthquake ground motion. Performance-based earthquake engineering (PBEE) comprises the design, evaluation, and construction of structures performing during design earthquakes and extreme earthquakes to the desires / needs of owners, user, society and environment. The general promise of performance based design is to produce engineered structures with predictable performance during future earthquakes. These days efficient method of assessing the capacity and demand of structures are developed. Moreover, due to advancement in research and test facilities, rapid development of structural analysis and design software, PBD is becoming more popular and efficient tool of design over the usual code methods.

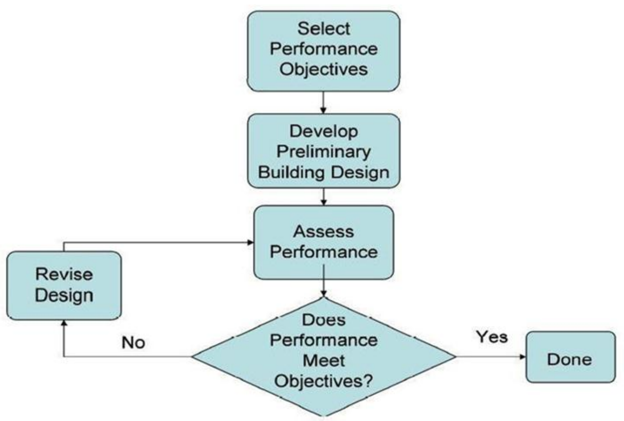

Fig.1: Flowchart of the Performance Based Design Process (FEMA 356)

PBSD is a systematic methodology for design of structures whose performance under seismic loads is predefined based on needs of the stakeholder.

2.2 Performance Objective

A performance objective is combination of Performance levels and Damage levels. PBD relates performance objectives with design process. Performance criteria can be based on any qualitative and quantitative response parameters such as strains and drifts. Performance objectives can be expressed in terms of specific damage states against prescribed probability demand levels.

2.2.1 Performance Levels

• **Immediate:** The Bridge shall be fully serviceable for normal traffic, and repair work does not cause any service disruption.
• **Limited:** The Bridge shall be usable for emergency traffic and be repairable without requiring bridge closure. At least 50% of the lanes, but not less than one lane, shall remain operational.
• **Service Disruption:** The Bridge shall be usable for restricted emergency traffic after inspection. The bridge shall be repairable. Repairs to restore the bridge to full service might require bridge closure.
• **Life Safety:** The structure shall not collapse and it shall be possible to evacuate the bridge safely. While it may not be possible for users to drive off the structure, they must be able to walk off safely.

2.2.2 Damage Levels

• **Minimal Damage:** The extreme fiber concrete and reinforcement steel limiting strains are $\epsilon_c \leq 0.004$ and $\epsilon_s \leq \epsilon_y$ (no yielding), respectively for concrete structures. Local or global buckling is not allowed in steel structures.
• **Repairable Damage:** Full dead plus live load carrying capability must be verified post-event. For concrete structures, limit has been changed to $\epsilon_s \leq 0.025$. No buckling of primary steel members is allowed. To ensure aftershock resilience, 90% seismic capacity has to be retained; full capacity has to be restored after repairs.
• **Extensive Damage:** Full dead load plus 50% live load carrying capability must be ensured post-event.
Extensive concrete spelling is allowed; however, the concrete core is not allowed to crush. To ensure aftershock resilience, 80% seismic capacity has to be retained; full capacity has to be restored after repairs.
• **Probable Replacement:** The bridge may be unusable and need replacement, but collapse must be prevented. The Code does not give concrete and steel reinforcement strains for this level. The bridge must be able to carry full dead load plus 30% live load without impact, including P-delta effects.

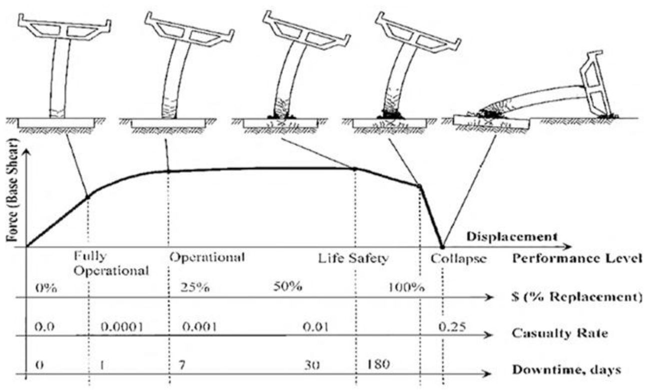

Fig. 2: Visualization of Performance Levels and Damage Levels

3. METHODS OF ANALYSIS

During the PBSD process, it is critical to accurately predict the structural response to earthquake ground motions. Depending on the geometry of the system and the extent of inelastic behavior, various methods of increasing complexity and refinement have been developed Fundamental to three of the analysis methods is some form of simplification from the most general and powerful, but time-consuming and complex methodology—full nonlinear static and dynamic response analysis.

3.1 Non-Linear Static Pushover Analysis

The pushover analysis is nonlinear static method which is used in a performance based analysis. The method is relatively simple to be implemented and provides information on strength, deformation and ductility of the structure and distribution of demands which help in identifying the critical members likely to reach limit states during the earthquake and hence proper attention can be given while designing and detailing. This method assumes a set if incremental lateral load over the height of the structure. Local nonlinear effects are modeled and the structure is pushed until a collapse mechanism is developed. This method is relatively simple and provides information on the strength, deformation and ductility of the structure and distribution of demands. These permits to identify the critical members likely to to reach limit states during the earthquake by the formation of plastic hinges. The formation of plastic hinges, stiffness degradation and lateral inelastic force versus displacement response for the structure is analytically computed. It gives an idea of the maximum base shear that the structure is capable of resisting and the corresponding inelastic drift. It also gives the global stiffness of the structure.

3.2 Non-Linear Dynamic Time History Analysis

Non-linear dynamic time-history analysis is by far the most comprehensive method for seismic analysis. The earthquake record in the form of acceleration time history is input at the base of the structure. The response of the structure is computed at each second for the entire duration of an earthquake. This method differs from response spectrum analysis because the effect of "time" is considered. That is, stresses and deformations in the structure at an instant are considered as an initial boundary condition for computation of stresses in the next step. Furthermore, nonlinearities that commonly occur during an earthquake can be included in the time-history analysis. The results are realistic and not conservative. All types of nonlinearities can be accounted for in this analysis. However, this method is very expensive and time consuming to perform. Seven Time Histories are taken from PEER Ground Motion Data Base.

4. STRUCTURAL MODELLING

4.1 Structural Modelling For Concrete T Section Girder Bridge

- Bridge Geometry

Type of bridge	Concrete T Beam Bridge
Span of the Bridge	30 m
Number of Lane	2
Lane width	3.6 m
Width of bridge	7.2 m
Centerline offset	1.8 m
Height of Bridge	8.5 m
Number of interior girder	3
Girder width	10.9 m
Slab thickness	0.305 m
Diaphragm thickness	0.3 m
Diaphragm depth	1 m
Pier Cap Section	(2.5 *1.2) m & length: 10 m.
Pier Section	1.2 m dia.
Abutment Section	(1.22*1.52) m & length: 9 m

- Material Properties

Concrete	M25 grade
Steel	Fe500

- Load Considerations

Dead Load	Girder + Deck Slab + Diaphragm
Super-imposed Dead Load	Crash Barrier + Wearing Coat
Live Load (IRC-6:2014)	Class A & Class 70R

- Seismic Properties (IS 1893(III):2014)

Importance Factor	1 (for Ordinary bridges)(O) 1.5 (for important bridges)(I)
Response Reduction Factor	3

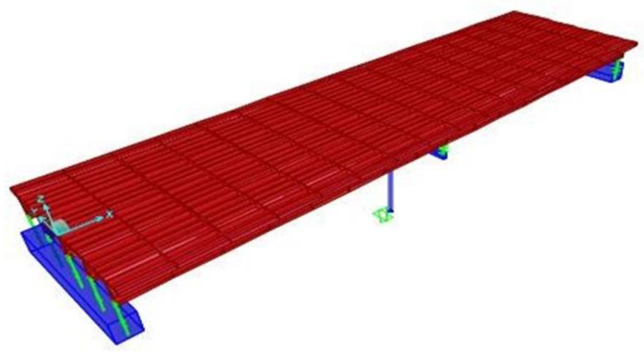

Fig. 3: 3d View of T-Section Girder Bridge

4.2 Structural Modelling For Concrete Box Girder Bridge

A Box girder bridge of 2 span having length 30m long is modelled. Bridge Deck is 10m wide. The bridge will support 2 lanes of traffic each of width 4.5m. The bridge is prestressed in concrete deck section.

- **Deck section properties:** Concrete box girder with vertical sides and 3 cells. It has a nominal depth of 1.5m. Vertical diaphragms are placed at the each end of bridge deck.
- **Abutment properties:** The abutments are of concrete rectangular sections of 2.5m deep and 1.3m wide. The bearing supports over the abutment of length 9.5m and which further rests over the foundation springs.
- **Bent properties:** One bent is provided in the middle of bridge.
- **Colum:** A circular concrete section with diameter of 1.5m, the length depends over the depth of substructure. 3 no of columns are used. The moment released at top and bottom of columns are fixed.
- **Bent cap:** It is a rectangular concrete cap with 9.5m length, 3m depth and 1.5m width. It should be integral with the column.
- **Tendon properties:** The tendons are of area 10 in^2 with parabolic variation and modeled as a load. The tendons are provided in all girders.
- **Material Properties:**

Concrete: M25 grade
Steel: Fe500

- **Load Considerations:**

Dead Load (Girder + Deck Slab + Diaphragm)
Super-imposed Dead Load (Crash Barrier + Wearing Coat)
Live Load as per IRC-6:2014 (Class A & Class 70R).

- **Seismic Properties (IS 1893(III):2014):**

Importance Factor: 1 (for Ordinary bridges) (O)
1.5 (for important bridges) (I)
Response Reduction Factor: 3

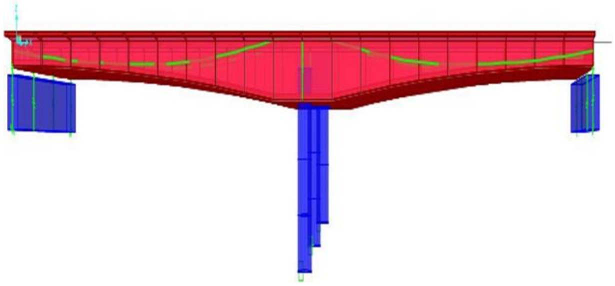

Fig. 4: Elevational View of Box Girder Bridge

5. RESULTS AND DISCUSSIONS

Performance based seismic design of T section Girder Bridge and Box Girder Bridge is carried out using CSI Bridge 20. Performance based seismic evaluation was carried out by non-linear static and dynamic process for the considered bridge sections, considering different soil types and seismic zone factors. Comparative study of results will be helpful in deciding the suitability and type of soil and other factor for the bridge structure.

5.1 T-Section Girder Bridge

A comparative study is carried out for T-section Girder Bridge considering different soil condition and different seismic zone condition. Number of checks are described in ATC-40, FEMA 356 and IS 1893:2014 are applied on output of analysis to verify whether performance objective of design is achieved or not. If Performance objective of design is not achieved then the design procedure is revised and again similar procedure is adopted for next iterations till performance objective are not achieved.

- **Time Period**

Time period of a bridge affects the overall response of the bridge. Figure 5 gives the variation of the fundamental time period with respect to the soil profile beneath the structure. It is observed that the maximum time period occurs for soil type 3 models.

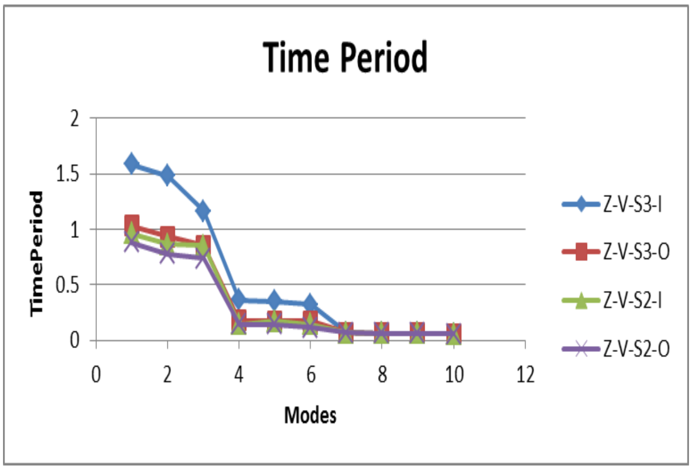

Fig. 5: Fundamental Natural Period for All Considered Base Models

- **Base Moment**

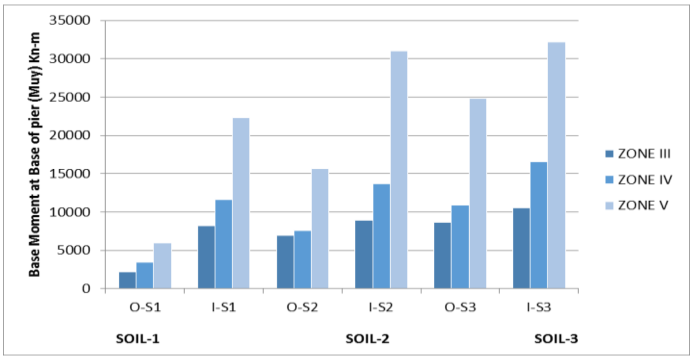

Fig. 6: Comparison of Base Moment at Base of Pier (MUY) KN-M

Moment at the base of pier for both Ordinary and important bridge is shown in Fig. 6. It is observed that moment in soft soil is relatively much more than in the hard soil.

- **Base Shear**

It is observed that base shear values for soft soil are much higher than the base shear values for hard soil. It also the indication that the base shear has played an important role in the seismic response of the bridge deck. It provides resistance to lateral load.

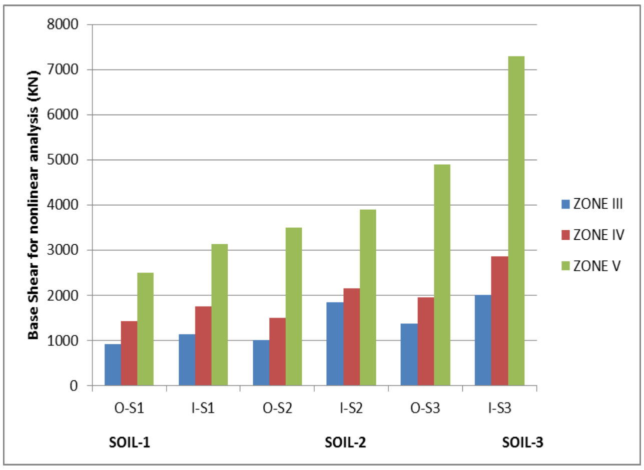

Fig. 7: Comparison of Base Shear for Nonlinear Analysis (KN)

- **Percentage Reinforcement in Pier**

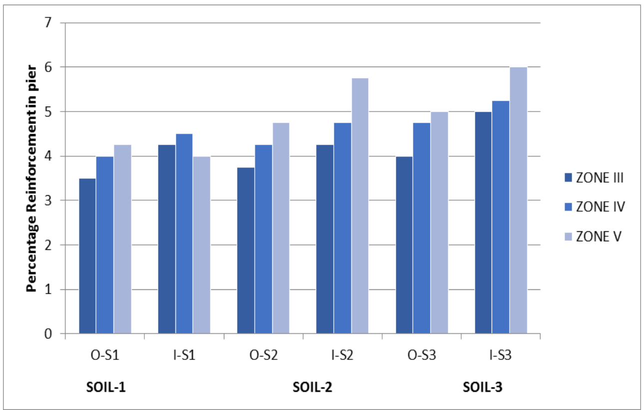

Fig. 8: Comparison of Percentage Reinforcement in Pier

- **Hinge results**

For nonlinear analysis, localized damage i.e. plastic hinge formation is due to the inelastic deformation capability of a bridge. In this particular case the hinge formation is up to the life safety level, beyond that there is no any hinge formation. The bridges were then designed to achieve the desired performance objective (LS). The plastic hinges developed are shown below. It can be confirmed that the hinges developed are within the limit and hence performance objective is achieved.

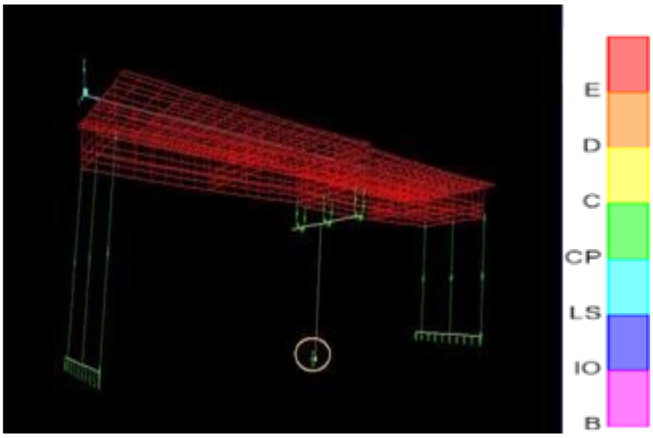

Fig.9: Hinge Formation in Bridge Model

5.2 Box Girder Bridge

A comparative study is carried out for Box Girder Bridge considering different soil condition and different seismic zone condition. Number of checks are described in ATC-40, FEMA 356 and IS 1893:2014 are applied on output of analysis to verify whether performance objective of design is achieved or not. If Performance objective of design is not achieved then the design procedure is revised and again similar procedure is adopted for next iterations till performance objective are not achieved.

- **Time Period**

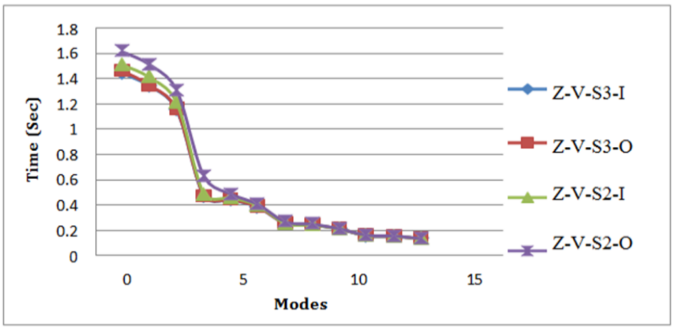

Fig. 10: Fundamental Natural Period for All Considered Base Models

- **Base Moments**

Moment at the base of pier for both Ordinary and important category box girder bridges are compared. It is observed that moment in soft soil is relatively much more than in the hard soil.

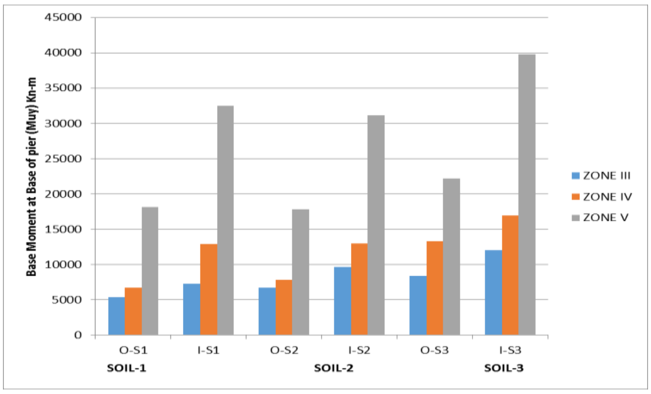

Fig. 11: Comparison of Base Moment at Base of Pier (Muy) KN-M

- **Base Shear**

It is observed that base shear values for soft soil are much higher than the base shear values for hard soil. It also the indication that the base shear has played an important role in the seismic response of the bridge deck. It provides resistance to lateral load. The values from the curves are noted and are taken for the analyzing purpose for the performance based design, where the performance point and target displacement are taken into account for the design purpose.

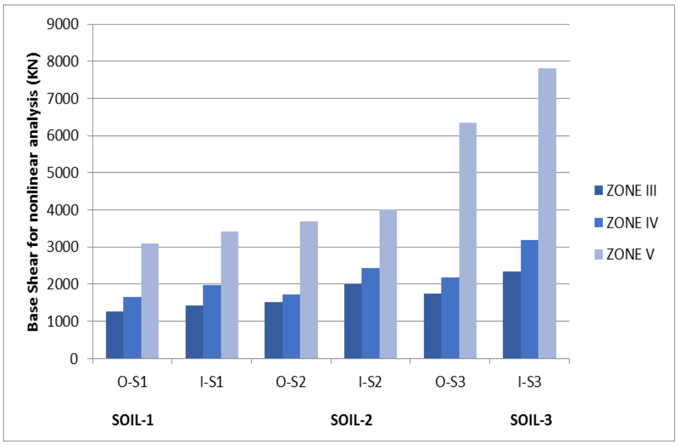

Fig. 12: Comparison of Base Shear for Nonlinear Analysis (KN)

- **Percentage Reinforcement in Pier**

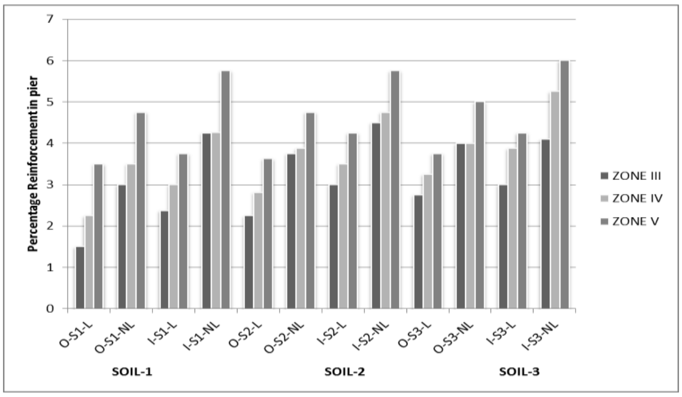

Fig. 13: Comparison of Percentage Reinforcement in Pier

- **Hinge results**

In this particular case the hinge formation is up to the life safety level, beyond that there is no any hinge formation. The bridges were then designed to achieve the desired performance objective (LS). The plastic hinges developed are shown below. It can be confirmed that the hinges developed are within the limit and hence performance objective is achieved.

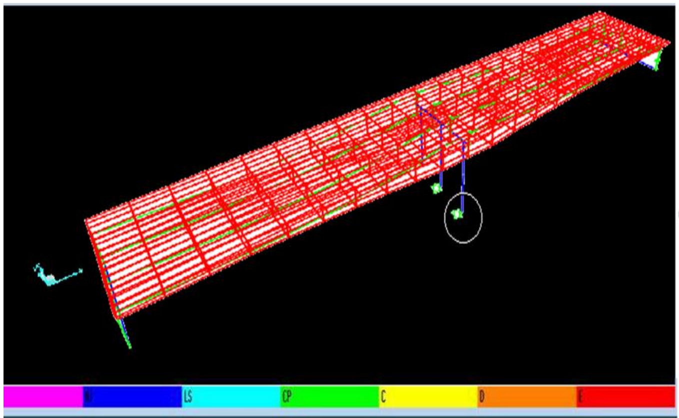

Fig.14: Hinge Formation in Box Girder Bridge Model

5. CONCLUSIONS

In this study Non-linear static and dynamic process is used for analysis of T-section Girder Bridge and Box Girder Bridge and design for life safety performance level incorporating different soil types and seismic zone conditions.

According to the results of investigation conducted the following are the salient conclusions obtained from the present study:

1. Performance based seismic design (PBSD) is an emerging trend and the procedure for performance based seismic design (PBSD) is explained effectively in the study.
2. The hinge result for all the considered models has been obtained and confirms the desired performance objective.

3. It is observed that moment at the base of pier in seismic zone-V is maximum. The value of moment for ordinary and important bridges differs by 40% to 82%.
4. Percentage of reinforcement I pier in seismic zone-V for soil type-III is maximum. Difference in percentage of reinforcement for linear and non-linear analysis is shown which indicates the need of Performance Based Seismic Design.
5. Base shear values are higher for important bridge category compared to ordinary bridge category. Base shear values are also higher for soil type-III. Base shear force is lowest in soil type-I
6. The current design practices in Bridge design are sufficient for normal ordinary bridges where the impact due to seismic activity is not serious. However for important bridges there is a definite need for improving the design process.

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