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EARTHQUAKE PERFORMANCE EVALUATION OF TYPICAL BRIDGE STRUCTURES WITH SEISMIC ISOLATION AND SOIL STRUCTURE INTERACTION IN THE PHILIPPINES

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ABSTRACT

The current seismic code for bridges in the Philippines adopts concepts from the American Association of State Highway and Transportation Officials' (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications, 2012. It utilizes the Force-Based Design (FBD) approach, which has been applied in bridge seismic design since the 1990 Luzon Earthquake. However, AASHTO recently recommends the use of Displacement-Based Design (DBD) as an alternative approach in defining seismic performance levels. The study attempts to adopt the concept from DBD to investigate the effects of seismic isolation together with soil-structure interaction (SSI) towards typical bridge structures in the Philippines. The approach for evaluating the structure's limit state and seismic performance was conducted following the provisions of the Japan Road Association Specifications for Highway Bridges (JRASHB), 2012. The application of isolation bearings on structures with distinctive natural periods was evaluated based on its effectivity and applicability. The earthquake response analysis was also performed to analyze its influence on the structure to develop a more accurate representation of its seismic response. Furthermore, the effects of the individual and combined contribution from the parameters were evaluated on its significance in affecting seismic performance.

Keywords: Seismic Isolation, Soil-Structure Interaction, Displacement Based Design.

1. INTRODUCTION

The current seismic code for bridges in the Philippines adopts concepts from the American Association of State Highway and Transportation Officials' (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications, 2012. It utilizes the Force-Based Design (FBD) approach, which has been applied in bridge seismic design since the 1990 Luzon Earthquake. However, AASHTO recently recommends the use of Displacement-Based Design (DBD) as an alternative approach in defining seismic performance levels.

The study of Panaligan (2019) investigated the seismic performance of a typical bridge in the Philippines designed using FBD and evaluated by the alternative approach – DBD. One of the main conclusions was strengthening the pier's sectional properties by increasing the column diameter from 1000 mm to 1500 mm and increasing the amount of longitudinal reinforcements. The revised section enhanced the original performance point to satisfy the limit state requirements of the Capacity Spectrum Method (CSM). However, it inadvertently increases the substructure's stiffness, causing a shorter fundamental natural period, which consequently amplifies the earthquake response towards the structure. This study aims to reduce the seismic demand brought by the heightened stiffness using seismic isolation.

The bridge is located on alluvial ground and is supported by deep pile foundations a depth of 30 m. The soil condition's influence was beyond the scope of Panaligan's study. Therefore, the effects of Soil-Structure Interaction (SSI) was not considered. It depicts that the initial assumption on the

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foundation condition could not portray the structure's actual seismic behavior. The influence of SSI could also inadvertently affect the applicability of seismic isolation as it is much dependent on the natural period of the structure. This study aims to accommodate soil amplification and soil spring effects brought by local soil conditions to develop a more accurate representation of the structural seismic behavior. Furthermore, the attributes introduced by SSI and seismic isolation are expected to produce large displacements; therefore, using the DBD approach is advantageous in addressing the heightened parameter. This method is regarded as a more accurate representation of damage; hence it provides a more reliable measure to depend upon than the FBD approach.

2. BRIDGE STRUCTURE AND MODEL

The target structure is a typical bridge that is being widely used in the Philippines. It is a two-lane, three-span prestressed concrete girder (PSCG) bridge supported by two-column bent piers. It was designed by the Department of Public Works and Highways (DPWH) in accordance with the Design Guidelines, Criteria, and Standards (DGCS) 2004 Edition, and the Bridge Seismic Design Specifications (BSDS) 2013 Edition. The seismic design utilizes the FBD method or more commonly known as the R-factor method. The bridge's design was recently evaluated through the DBD method in the study of Panaligan (2019). This study utilizes the same bridge structure, although applying both the original and revised column sections to investigate SSI and seismic isolation effects.

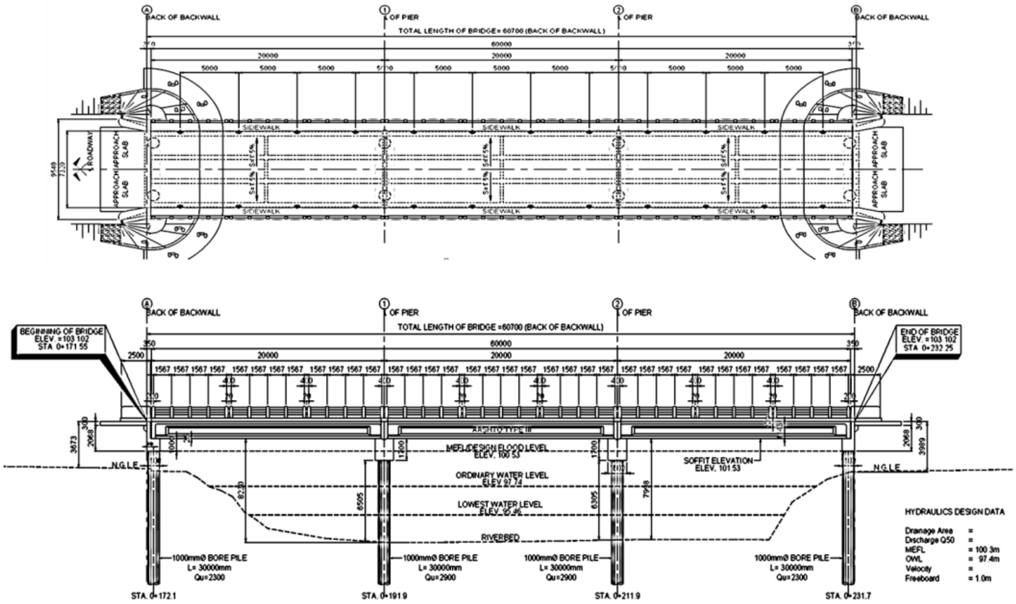
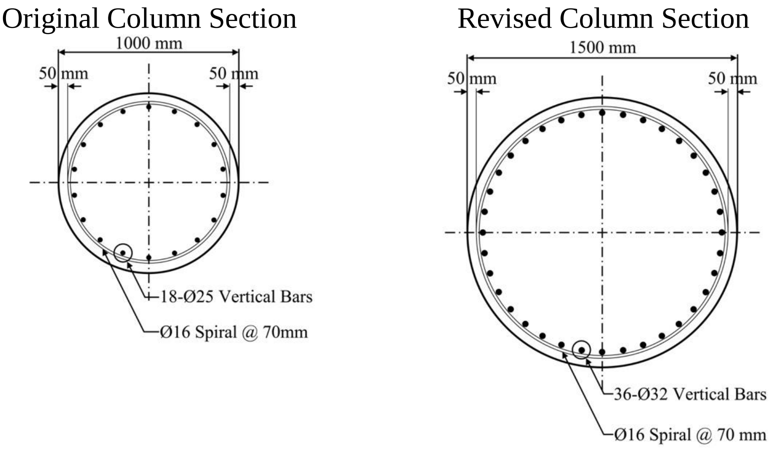


Figure 1. General plan and elevation of the bridge.


Original Column Section

Revised Column Section

Figure 2. Original and revised column sections.

3. METHODOLOGY

The study focuses on two main parameters, which are the foundation condition and seismic isolation. These parameters are investigated as individual and combined components on their respective influence towards the bridge structure's seismic performance. Afterward, seismic response analyses were performed, such as the static capacity spectrum method (CSM) analysis and the dynamic nonlinear response history analysis (RHA).

Several geophysical tests can obtain the low-strain shear modulus of soil either in the laboratory or in situ. The most convenient method in obtaining this parameter is defined in as a function of the soil's bulk density and shear wave velocity. However, this relationship represents the first tangent shear modulus, where it is at its maximum and can only be found in normal conditions or low strain circumstances. The soil properties alter when considering high-strain situations found in strong ground motion. Various cyclic tests have shown that soil stiffness is directly dependent on the strain amplitude and the number of loading cycles. Therefore, in conducting seismic analysis, the reduced soil parameters are considered to account for this phenomenon. This study adopts the Hardin-Drnevich Model as the numerical soil model.

The seismic performance of seismically isolated bridges depends primarily on the energy absorption capacity coming from its isolation bearings. Therefore, it is necessary to define an adequate nonlinear hysteric model that best represents the isolation system's attributes. Typically, isolators and dampers work together to achieve seismic isolation based on hysteric and viscous damping theories to improve the overall damping performance of the structure. This study utilizes Lead Rubber Bearing (LRB) as the seismic isolation bearing.

4. RESULTS AND DISCUSSION

Three analyses were conducted towards the structure. First, an eigenvalue analysis to obtain the fundamental natural period of the structure. Second, a static analysis to determine the structure's performance point. Third, a dynamic analysis to verify the results from the static analysis. Furthermore, these analyses were conducted along two orthogonal directions – longitudinal and transverse. The three analyses considered the individual and combined effects of the parameters on the structure and each other.

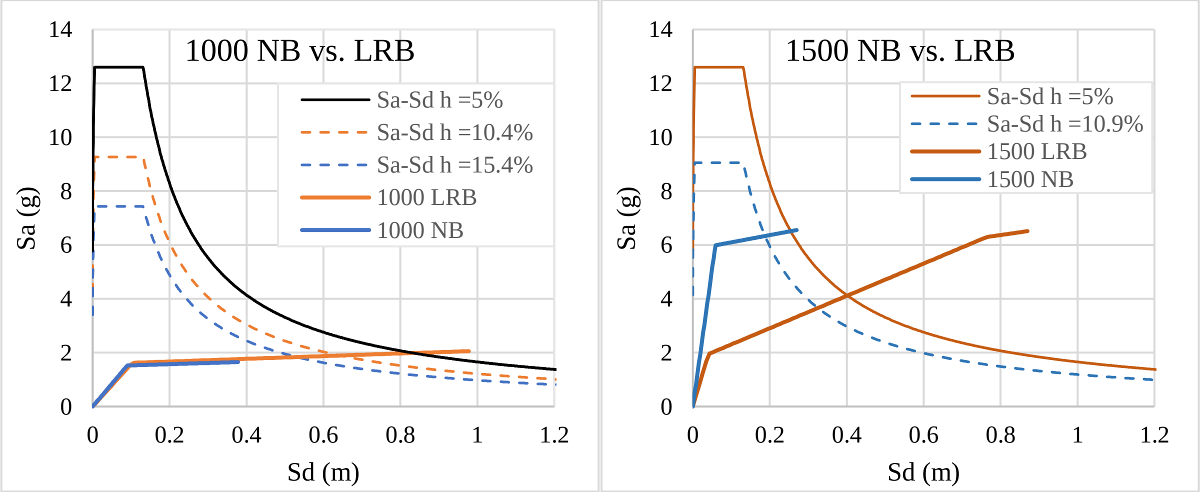
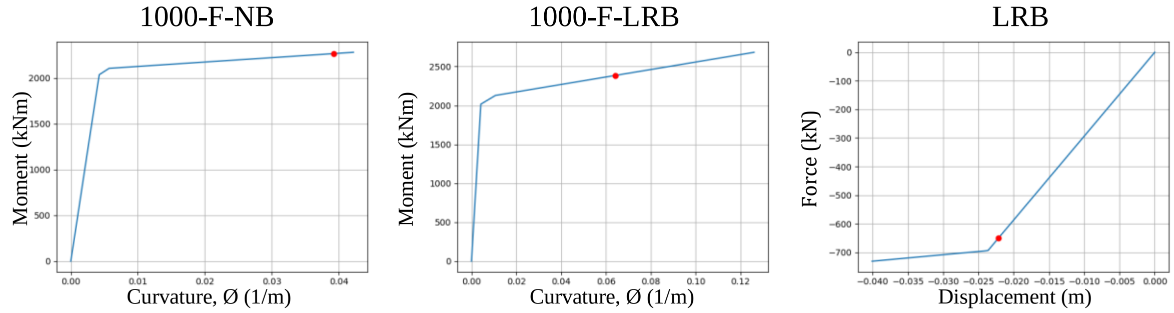


Figure 3. Capacity curve vs. Demand spectrum of the two column sections on fixed support with and without seismic isolation along the longitudinal direction.

It is observed in the Figure below that the 1000 NB model's capacity curve does not generate an intersection point. The structure had been pushed up to the allowable limit displacement of 378 mm to incur minimal or repairable damages according to its seismic performance level. If the structure were to be displaced further, the limit displacement would not be satisfied, and subsequently, neither will the seismic performance level. On the other hand, when introducing LRB towards the structure, the limit displacement is theoretically increased due to the additional limit displacement capacity of the isolation bearing. However, it is observed that the capacity curve indicated by the 1000 LRB and 1000 NB models are seemingly identical. Furthermore, there is no noticeable change in stiffness between the two models indicating that there is no significant contribution from the isolation bearing.

It can be noticed that there is a significant change between the capacity curves of the 1500 NB and 1500 LRB models shown in the Figure above. The 1500 NB model's yield point of the capacity curve indicates that the member starts to yield at the plastic hinge location. In the case of 1500 LRB, the yield point occurs much lower and continues to reach the target spectrum without any reduction factor. The lower yield point is assumed to be caused by the introduction of the isolation bearing. However, to verify this assumption, the F-D relationship of the structural members and the isolation bearings needs to be investigated.

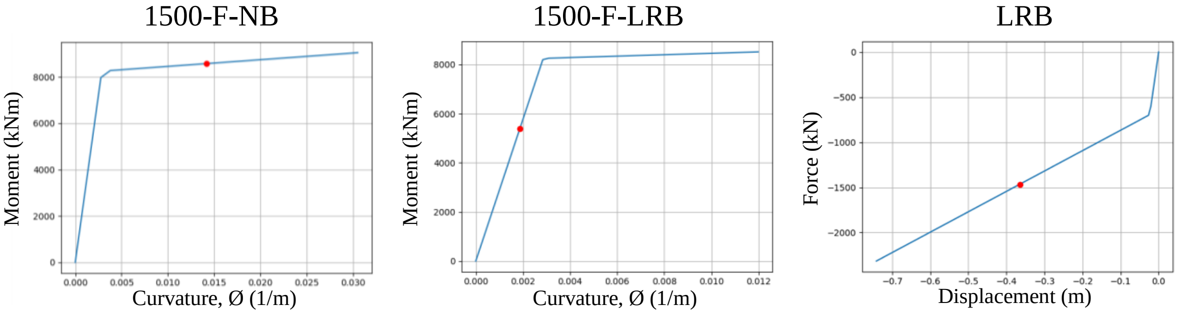
The left figure below shows the F-D behavior of the column at the plastic hinge. It can be seen that the performance point, indicated by the red dot, is under yielding. It should be noted that this point has not reached the intersection point of the capacity spectrum. However, this point defines the limit displacement of the section with respect to the seismic performance. Further displacing this point would not satisfy the limit state requirements of Seismic Performance Level 2. The center figure shows the F-D behavior of the 1000 LRB model at the same location. Notice that the performance point is still under yielding. It also indicates that the point has surpassed the allowable limit state, thereby not satisfying seismic performance requirements. Also, the Right figure illustrates the F-D relationship of the LRB. Notice that the performance point has occurred during the isolator's initial stiffness and concludes that the LRB is not functioning for the original section when applying CSM analysis.


1000-F-NB

1000-F-LRB

LRB

Figure 4. F-D relationship from CSM of the 1000-F-NB and 1000-F-LRB models along the longitudinal direction.


1500-F-NB

1500-F-LRB

LRB

Figure 5. F-D relationship from CSM of the 1500-F-NB and 1500-F-LRB models along the longitudinal direction.

Figure 5 shows the original section's F-D relationship on fixed-support subjected to 2011 Great East Japan earthquake ground motion. The left figures show the column is incurring some damages from the earthquake, and it can be seen, that the column is behaving nonlinearly through the Takeda-Model relationship. It is also noted that all three earthquake ground motions did not surpass the limit curvature of the original column section. The center figures show the F-D relationship of the column when the model is incorporating isolation bearings. It shows a minimal change from the previous model due to the linear behavior from the isolation bearings, as shown in the right figures. The LRB does not exhibit any bilinear deformation and therefore was not able to dissipate any seismic energy.

The RHA results from the revised section on fixed supports generated parallel results when comparing to the static analysis results. The left figures show the F-D relationship of the 1500 section with no isolation bearing. It can be seen that the column is experiencing some damages indicated by the Takeda-Model relationship. In applying LRB towards the model, the behavior significantly changes. The column section does not show any yielding and is kept in the linear region. The deformation was accommodated by the LRB, indicated in the right figures. It can be observed that the LRB is performing its function as it shows the bilinear deformation relationship. It can be said that the functionality of the LRB was achieved as it maintained the linear behavior of the column section.

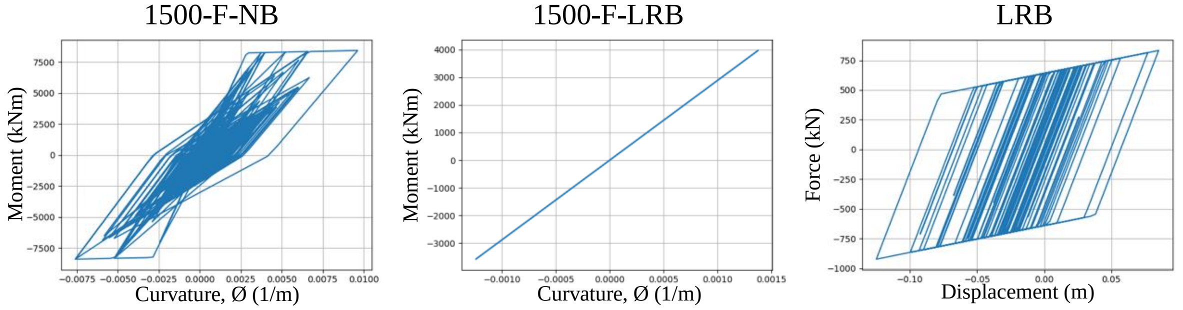


Figure 6. F-D relationship from RHA of the 1500-F-NB and 1500-F-LRB models using the 2011 Great East Japan Eq along the longitudinal direction.

The results of the RHA on pile foundations closely resemble the results from the fixed-support models. However, in carefully comparing the maximum attained curvatures, the pile foundation models yielded higher values than the fixed-support models. It could be attributed to the soil amplification as well as the soil-structure interaction. The seismic forces may have potentially increased due to the difference in support conditions. Furthermore, the inertial forces from a more flexible structure may have caused an increase in the members' deformation. It can also be verified by comparing the maximum deformation of the isolation bearings from the pile foundation models to the fixed support models shown in Figure 7. It illustrates the amplified displacements caused by the pile foundations through the rocking and swaying motion of the structure. Furthermore, it consistently shows that the maximum attained deformation is indeed higher than that of the fixed-support models. Therefore, the inertial forces occurring from the superstructure is higher than the fixed-support models.

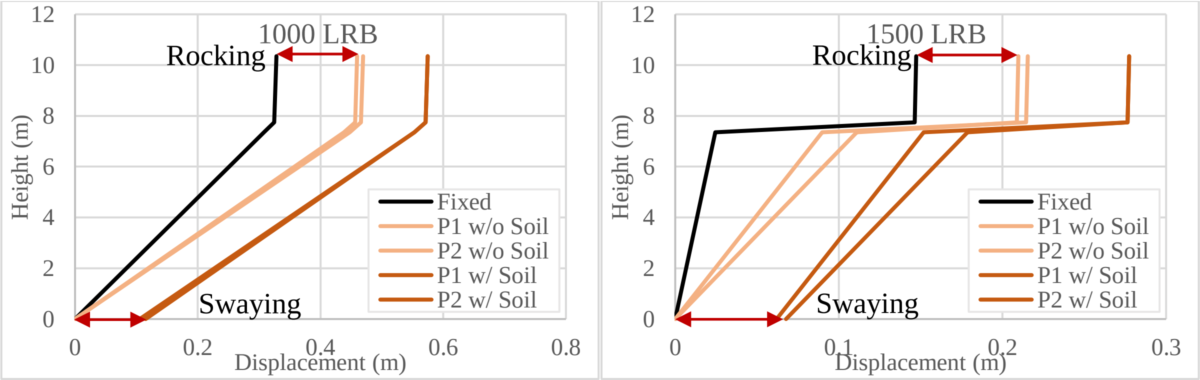


Figure 7. Longitudinal horizontal displacements of the 1000-LRB and 1500-LRB models from the 2011 Great East Japan Earthquake.

5. CONCLUSIONS

The study was attempted to investigate the effects of seismic isolation together with soil-structure interaction towards typical bridge structures in the Philippines. The displacement-based method for evaluating the structure's limit state and seismic performance was conducted and is considered as a more convenient approach to investigate the effects of seismic isolation and soil-structure interaction. The limit displacements were determined in reference to the JRASHB, 2012.

Two types of analysis were performed in the study: a static analysis from the capacity spectrum method and dynamic analysis from the response history analysis. The static and dynamic analyses generated parallel results and are in good agreement with each other. The conclusions from the seismic analyses are summarized as follows:

1. The seismic isolation bearings exclusively functioned when applied to the revised column section. This section having a shorter natural period is a more rigid structure for which the LRB could effectively function.
2. The soil-structure interaction amplified the effects of the ground motion through the swaying and rocking motions of the structure, which inadvertently increased horizontal displacement responses. This displacement, however, was lowered when effectively introducing isolation bearings.
3. The LRB continued to function towards rigid structures with pile foundations despite the increased natural period and added flexibility at the pier.
4. The maximum and residual displacements at the top of the superstructure remained within practical design limits. The response displacement is accounted for by providing sufficient clearances for the functionality of the isolation bearings.
5. Installment of expansion joints that can accommodate the horizontal displacement should confirm not hindering the isolation bearing’s functionality and maintaining safe traffic conditions during the bridge’s service state.
6. The revised column section satisfies the current seismic code of the Philippines. Since the R-factor was recently revised in the BSDS from 5 to 3.5 for the same bridge with an operational category as ‘Essential’, it confirms the revised section has higher strength capacity than the required.
7. The transverse direction is sufficient to maintain a linear response from strong ground motions. The ramen-type pier together with superstructure’s lateral stiffness contributed in resisting the lateral force demand.

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