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A REVIEW ON PERFORMANCE BASED SEISMIC DESIGN OF RC STRUCTURE CONSIDERING SOIL STRUCTURE INTERACTION

Rahul S. Patel[1], Maulik Kakadiya [2]

[1]*M.Tech. student, Civil Engineering Department, CGPIT*
[2]*Assistant Professor, Civil Engineering Department, CGPIT*

Abstract *—As the coming generation of seismic design methodology, performance-based seismic design (PBSD) method requires a structure satisfy multiple preselected performance levels under different hazard situations. Optimal PBSD methods give different strategies to design the multiple variables, including strength, stiffness and ductility of each structural element. The overall objective of this study is to develop a new optimal PBSD method for multi-story RC moment frames. Traditional design practice for dynamic loading assumes the structure to be fixed at their bases. Whereas, in reality, supporting soil medium allows movement to some extent due to their natural capability to distort which reduce the overall lateral stiffness of the structure. This paper presents the effect of Soil Structure interaction on seismic performance of the structure is considered and designed the structure for Life safety performance ideal. Ten story RC structure with and without considering soil-structure interaction (SSI) has been modelled for the analysis. These structures are modelled, designed as per IS 456:2000 and analyzed using ETABS software under two different boundary conditions, namely fixed-base and considering soil-structure interaction. There are four types of models have been made for the analysis and comparison-(1) NSSI-Fixed base model with no soil structure interaction, (2) HSSI-Rigid footing rest on hard soil with considering SSI, (3) MSSI-Rigid footing rest on medium Soil with considering SSI, (4) SSSI-Rigid footing rest on soft soil with considering SSI. Performance analysis was carried out and results obtained using Soil structure interaction. A relative study is done between HSSI, MSSI, SSSI models with fixed base model (NSSI). The output results of story drift ratio, story shear and natural period is considered for the comparison. After that design is carried out for asked performance objective. It was found that soil-structure interaction can alter the seismic performance of the structure in terms of seismic force demands and deformations.*

Keywords*-Performance based seismic design, Soil structure interaction, R.C. structure, ETABS software, Time history analysis, Story drift ratio*

I. INTRODUCTION

Over the last few years, strong earthquakes have occurred all over the world and caused great economic loss. Therefore, resilient city and building under earthquake have gradually become an important research focus in recent years. The resilience is firstly defined by sustainability committee, which refers to the ability to suffer less damage and recover rapidly from adverse events.

1.1 General

In the past decades, disaster due to earthquake gave the picture of failures of structures even though it was designed as per force-based approach. It significantly shows incapability to give minimal performance of structure under design earthquake. In the traditional method of designing a structure for seismic forces, a successive seismic base shear is calculated based on the estimated fundamental period of the structure and an elastic response spectrum that is representative of the seismicity of the position. The design base shear value depends on the height (period), type, location and significance of the structure as well as on the nature of foundation soil. The shear is adapted to take into account the ductility capacity of the structure and its anticipated over-strength. An elastic analysis is carried out next to find the element forces and the elements are designed for similar forces. Eventually, the inelastic inter-story drifts produced by the design forces are attained from the calculated elastic drifts and are checked against specified displacement limits.

1.2 Performance based seismic design

The current trend in seismic design is the performance-based seismic design which designs the structure for a number of performance levels defined by a pair of seismic intensity and damage level. It is a procedure of designing new buildings or seismic up-gradation of existing buildings, which includes a specific intent to achieve defined performance objectives in future earthquakes. Different performance levels are computed based on non-structural and structural limit values in terms of inter-story drift ratio (IDR), plastic rotation (θ_{pl}) and ductility (μ) account for. Values of (IDR), (θ_{pl}) and (μ) can be found in EC 8 part-3, SEAOC and FEMA 356. Different performance objectives are operational (O), immediate occupancy (IO), life safety (LS) and collapse prevention (CP) as shown in figure 1. PBSD is carried out in two steps, first for strength satisfaction under the design basis earthquake to account for life safety (LS) performance level and second for the displacement satisfaction. According to FEMA 356, Life safety is the major focus to reduce the threats to the life safety.

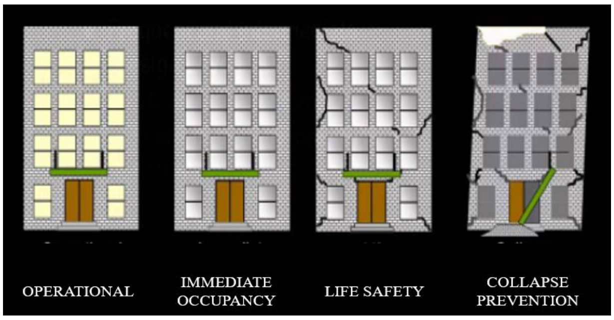

Figure-1 Performance levels

In performance-based design approach, performance levels are expressed in terms of displacement rather than forces. Displacement is considered in performance levels because it expresses the damage in proper way. This is based on the idea that performance objectives can be related to the damage level of the structure, which in term can be related to displacement and drift. Figure 2 shows the typical process of design is to be followed.

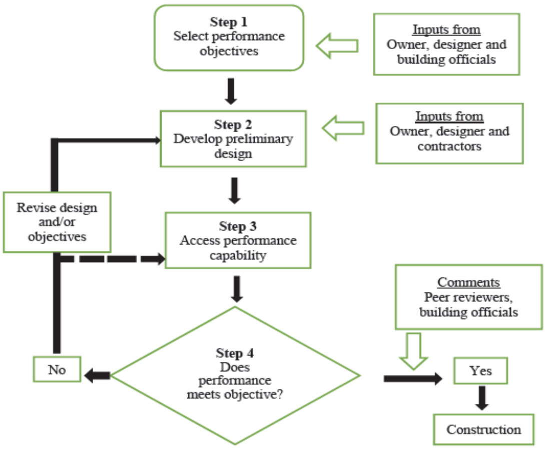

Figure-2 Typical process of PBSD

1.3 Soil structure interaction

In the seismic analysis of a structure constructed on ground, the ground motion passes through the base of structure. The response of the structure is dependent on the response of the foundation system and also vice versa, which is called dynamical soil-structure interaction (SSI). The dynamic response of tall structure is greatly affected by the properties and conditions of the soil-foundation system.

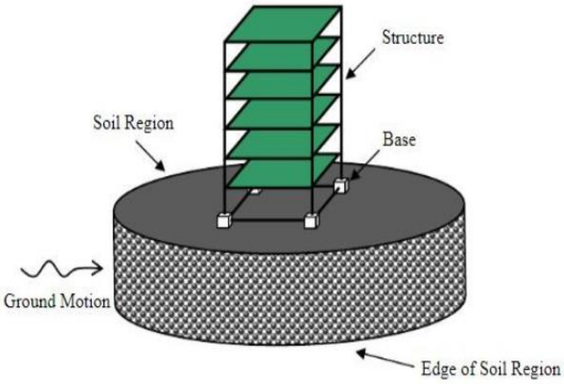

Figure-3 Soil structure interaction model

The response of tall structure during an earthquake is different when the structure is analyzed on deformable soil conditions as opposed to assuming fully rigid soil and foundations. Typically, structures tend to be modelled in practice assuming fixed-base conditions. However, it is fact that the actual behavior of soil-foundation-structure conditions are not well captured by assuming a rigid soil system, especially when buildings are constructed on soft soils.

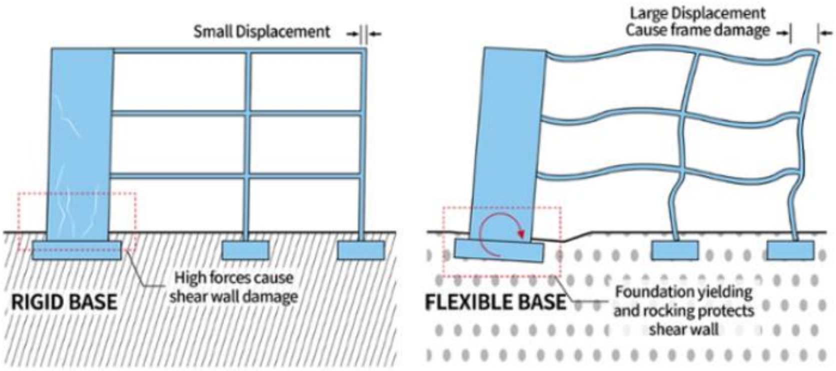

Figure-4 Response of structure with rigid and flexible base

The interaction between soil (ground) and a structure can be described by Soil-structure interaction (SSI). The process in which the response of the soil influences the motion of the structure and the motion of the structure influences the response of the soil is termed as soil-structure interaction.

II. LITERATURE REVIEW

2.1 Smail kechidi, Aires Colaco, "Modeling of soil-structure interaction in Open sees: A practical approach for performance-based seismic design." (ScienceDirect-ELSEVIER, 2021) studied the effect of soil structure interaction on Performance based seismic design. A Monkey-tail fundamental lumped parameter model has been made for the simulation of dynamic soil-structure interaction (SSI) based on numerical tool. The proposed model has been created in finite element software, Open Sees where the input parameters are simply function of the soil properties. Furthermore, two 5-storey moment-resisting frame buildings have been investigated to know the influence of the SSI and local soil conditions on the seismic response. The results indicate the importance of these two geotechnical aspects on the structural seismic response. It was observed that peak floor displacements and inter-story drifts considering the SSI are larger in the lower stories than those of the fixed base case. Furthermore, the output results show that the fundamental period of vibration, seismic intensity level and soil stiffness are dependent on the soil amplification factor which are not taken into account by the current European design codes.

2.1.1 Introduction

Throughout history, several civilizations have developed along sedimentary basins of soft soils, particularly along the alluvial ones. These geotechnical formations, which are mainly sought after due to the richness of their soil for agriculture, pose today serious concerns with regards to earthquake losses since they are densely populated areas. In addition, structures supported by shallow foundations are subjected to inertial loads due to earthquake ground motion and eventually the foundation might undergo sliding, settling and rocking movements. If the design of the foundation is changed, the soil-foundation interface would dissipate significant amount of vibrational energy resulting in a reduction in the structural force demand. This energy dissipation and force demand reduction may enhance the overall performance of the structure, provided that potential consequences such as excessive tilting, settlement or bearing failure are accounted for in the formulation of the corresponding numerical models.

2.1.2 Soil structure Interaction modelling

The consideration of the SSI in nonlinear dynamic analyses of structures. Seismic actions creates additional complexities. The mathematical background of the analysis methodology is shown in this section. Methods for the incorporation of the SSI can be achieved by simplified approaches as for example the lumped-parameter formulation. A lumped parameter model represents the frequency dependent SSI of a massless foundation. The model has been created for the dynamic behavior of the ground by a range of spring and dashpots-masses with lumped values. All the lumped values represents the stiffness, inertial effect and damping generated from the SSI phenomenon. The "monkey-tail" model is a four-parameter model. It contains parameter K, *i.e.*, the static stiffness, has a physical meaning, since the remaining three are adjusted parameters obtained in order to have a good fitting of the dynamic stiffness as function of the frequency. Five coefficients (K_s, C_s0, C_s1, M_s0 and M_s1) have been implemented for each DOF, as depicted in figure. The spring coefficient K_s

represents the static stiffness of the soil. In this study, the Open Sees FE software has been acquired to implement the above expressed lumped-parameter model.

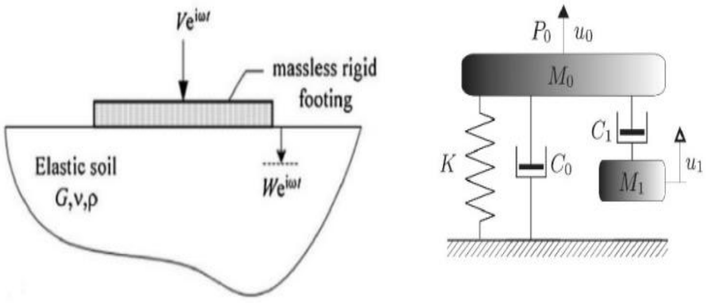

Figure-5 Monkey tail model: (a) problem description and (b) structural system

As it can be seen, there is a connection between MATLAB and Open Sees software, where the Soil structure interaction force is calculated in MATLAB then saved as an input file for Open Sees nonlinear dynamic analyses.

2.1.3 Case study

The aim of present study is to assess the influence of the SSI and local soil conditions (*i.e.*, site effect) on the seismic response of two 5-storey MRF buildings. The seismic analysis is focused on a strictly regulatory perspective, following the requirements set out in EC8. The comparison has been made between the obtained results and the existing legal provisions. As shown in figure, three different methodologies of analyses are considered in this study. The first one is a typical structural analysis, where the SSI is neglected and the site effects are incorporated in the ground motion record selection. The second analysis incorporates the SSI effects and the ground motion records are selected following the same way as in the first approach. In the last analysis, along with the incorporation of the SSI, the site effects are taken into account in the assessment of the building seismic response.

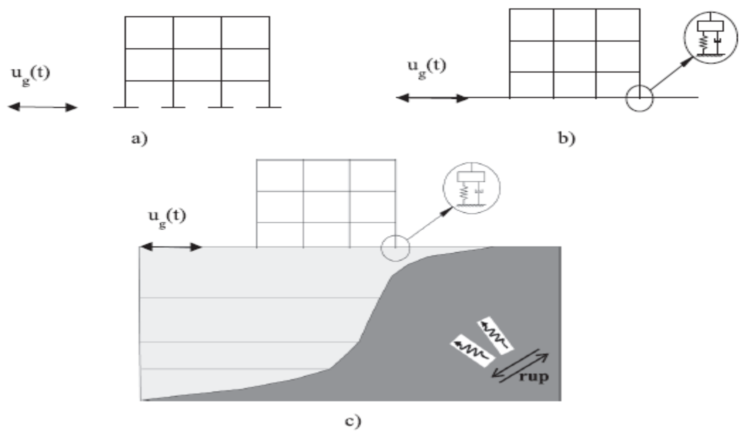

Figure-6 Schematic representation of different approach

2.1.4 Summary and conclusion

Using lumped-parameter models can be seen as a good option because it compromises accuracy of the solution and reduction of the computational cost. To investigate and extend the validation of the proposed tool in different geotechnical formations for the further studies are encouraged. Drifts when considering the SSI are even larger in the lower stories than those of the fixed base case which is due to the fact that the foundation movement causes flexibility in the structural system and results in additional deformations at lower stories. When a building is overlying on soft soil, soil stratification is a applicable therefore, a local geotechnical study is recommended in order to determine its geotechnical profile in order not to underestimate the demand on the structure.

2.2 Edmond V. Muho, Jiang Qian, "Modal behavior factors for the performance-based seismic design of R/C wall-frame dual systems and infilled-MRFs." (ScienceDirect-ELSEVIER, 2019) studied the behavior factors for the performance-based seismic design of R/C wall-frame dual systems and infilled-MRFs. In this research, strength reduction factors q_k for the performance-based seismic design of plane reinforced concrete wall-frame dual systems and infilled moment resisting frames are proposed. Instead of using a single and constant behavior (strength reduction) factor q (R) as all modern seismic design codes do, herein are proposed different such factors for the first few significant modes of the structure. Moreover, these q_k are constructed as functions of period, different deformation targets and soil types and thus, they are suitable for a performance-based seismic design in a force-based design scheme. Followed by linear analysis, an elastic acceleration response spectrum with its ordinates divided by q_k provides a design base shear. Base shear can produce seismically designed frames which account for both strength and deformation requirements. On the contrary to the code-based seismic design procedure which is accomplished in two steps, i.e., first for strength and second for deformation satisfaction, the proposed method eliminates the second step due to its deformational dependent q_k. The proposed method is illustrated and validated with realistic design examples, which shows its advantages over the force-based design method of Eurocode 8.

2.3 Edmond V. Muho, George A. Papagiannopoulos, "Deformation dependent equivalent modal damping ratios for the performance-based seismic design of plane R/C structures." (ScienceDirect-ELSEVIER, 2018) studied damping ratios for the performance-based seismic design of plane R/C structures**.** A performance-based seismic design method is preferred for three types of plane R/C structures, i.e., moment resisting frames, infilled moment resisting frames and wall-frame dual systems. It uses the concept of the equivalent viscous damping ratio ξ to account for inelastic energy dissipation instead of that of the behavior factor q (or R). Equivalent modal damping ratios ξ_k defined for the equivalent linear multi-degree-of-freedom system has been used to the original non-linear multi-degree- of-freedom system. This equivalent system consists same mass and the elastic stiffness of the non-linear one. Besides, these equivalent modal damping ratios ξ_k are constructed as functions of the periods of the structure, soil type, the non-structural and structural deformation. Thus, the proposed method is more sensible and leads to more accurate results in one step than code-based design methods. The proposed method is illustrated and validated by numerical examples which demonstrate its advantages over the Eurocode 8 seismic design method.

2.4 Sejal P. Dalal, Purvang Dalal, "Strength, Deformation and Fragility assessment of Reinforced Concrete Moment Resisting frame designed by Force Based Design and the Performance Based Plastic Design method for Seismic loads."(ScienceDirect-ELSEVIER, 2021) studied regarding the Strength, Deformation and Fragility assessment of Reinforced Concrete Moment Resisting frame. A 20 storied Reinforced Concrete (RC) Moment Resisting Frame (MRF) has been analyzed and designed by Force Based Design (FBD) method and the Performance Based Plastic Design (PBPD) method. The PBPD frames have been designed for different performance levels namely Immediate Occupancy, Life safety and Collapse Prevention of the basic safety objective. The Indian Standard codes along with established principles of design have been followed in the study. The fragility assessment was carried out in terms of Spectral displacement. It was obtained from the pushover analysis results for different specified damage states. Results shows that PBPD method is recommended compared to the FBD method, both in terms of seismic performance and fragility.

2.5 R. Allahvirdizadeh, M. Khanmohammadi, "Probabilistic comparative investigation on introduced performance-based seismic design and assessment criteria" (ScienceDirect-ELSEVIER, 2017) compared introduced performance-based seismic design and assessment criteria. A variety of recommendations were proposed in the paper which can be classified into two general groups, i.e. at section level or at story level. In this article, these two groups regarding each other, their relation and reliability of proposed recommendations have been analyzed. In this regard, diversity of outcomes related to the employed analysis method, type of the subjected ground motion record, building's height and desired performance level is reported. Contrarily, key parameters such as the influence of allowed percentage of elements to exceed from local limits on maximum experienced inter-story drift and amount of reserved capacity at components when global criteria control the performance are investigated. The probability of exceeding local threshold at any desired inter-story drift/performance level and their safety indices are taken into the consideration. To evaluate reliability of presented conclusions, the outcomes and conventional safety levels have been used. Thus, it can be said that the global criteria controls performance of the building at all levels. Therefore, it seems essential for global thresholds to be revised in development of PBSD to make it more compatible with its objectives.

2.6 Zhipeng Zhai, Wei Guo, "An improved performance-based plastic design method for seismic resilient fused high-rise buildings" (ScienceDirect-ELSEVIER, 2019) studied performance-based plastic design method for seismic resilient fused high-rise buildings. The performance-based plastic design (PBPD) method follows the nonlinear response of equivalent elastic-plastic single degree of freedom system. It is not able to achieve the design of three performance objectives simultaneously and may not consider the high mode effect of structure. A trilinear force-displacement model indicating three prescribed performance objectives at three seismic hazard levels is acquired to improve the PBPD method. The proposed PBPD method is derived considering multiple degrees of freedom system. Seismic resilient fused high-rise buildings can be designed by PBPD. A novel dual system has been implemented in steel energy-dissipative column. Moment resisting frame (MF) is taken for application of the proposed method. The fuse members of dual system have been decoupled from the gravity-resisting system. The performance-based design of this system is discussed and its application for high-rise buildings are also considered. A 20-story EDC-MF structure system is designed to demonstrate the effectiveness of the proposed method using improved PBPD method. Then detailed numerical model of the designed

EDC-MF system is developed and nonlinear dynamic response analyses at different seismic intensities have been performed to verify the actual structure performance. Results reveal that the designed structure can achieve the prescribed yielding mechanism and performance objectives at three seismic hazard levels, and the EDC-MF system is capable for applying to high-rise building as a seismic resilient fused structure.

2.7 Fei-Fei Sun, Jia-Qi-Yang, "An adaptive viscous damping wall for seismic protection: Experimental study and performance-based design" (ScienceDirect-ELSEVIER, 2021) did experimental study on an adaptive viscous damping wall for seismic protection. In this paper, a novel adaptive viscous damping wall (A-VDW) system was generated. The aim of creating system was to achieve a two-stage seismic mitigation. A viscous damping wall has been combined with lead dampers through working gaps in A-VDW. The A-VDW provides only damping but it is not able to provide extra stiffness for moderate or minor earthquakes, while for severe earthquakes, both stiffness and energy dissipation are provided. A numerical model which captures the displacement—force relation features at different working stages was proposed for the A-VDW. Dynamic tests on a scaled A-VDW under different loading frequencies and amplitudes have been conducted to verify the proposed physical configuration and numerical model. The two-stage seismic mitigation effect of the proposed A-VDW is evaluated in single-degree-of-freedom (SDOF) systems. Finally, a performance-based design method considering velocity exponent was proposed and also validated.

III. CONCLUSION

After scrutinizing all listed literature, it can be stated that Seismic analysis and design is demanding more and more precise procedure like Performance based seismic design method. According to the results of listed literature the following are the salient conclusions obtained.

1. When a structure is subjected to ground motion, coupling action takes place at the foundation and overturning of structure occurs, and thus changes the motion of the ground. By considering soil-structure interaction, makes a structure more strengthening and thus, increasing the natural period of the structure compared to the corresponding rigidly supported structure.
2. The natural time period of the structure with the fixed base is lower than the flexible base. It is also shown that natural period for the no soil structure interaction model and rigid footing rest on hard soil model is near about same.
3. Inter story drift increases as soil sub grade modulus decreases. Inter story drift increasing for lower story.
4. The pre-selected yielding mechanism can be achieved by the performance based seismic design method.
5. It was observed that percentage of displacement increases with decreasing sub grade modulus.
6. The effect of soil structure interaction has to consider especially for lower sub grade modulus of soil at higher seismic intensities.
7. As efficiency is of concern, a gradient based optimization is adopted. Which follows a design procedures to achieve particular performance level.

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