# Effect of Nonlinear SSI on Seismic Response of Low-Rise SMRF Buildings

**Prishati Raychowdhury and Poonam Singh**

**Abstract** Nonlinear behavior of soil-foundation system may alter the seismic response of a structure by providing additional flexibility to the system and dissipating hysteretic energy at the soil-foundation interface. However, the current design practice is still reluctant to consider the nonlinearity of the soil-foundation system, primarily due to lack of reliable modeling techniques. This study is motivated toward evaluating the effect of nonlinear soil-structure interaction (SSI) on the seismic responses of low-rise steel moment-resisting frame (SMRF) structures. In order to achieve this, a Winkler-based approach is adopted, where the soil beneath the foundation is assumed to be a system of closely spaced, independent, nonlinear spring elements. Static pushover analysis and nonlinear dynamic analyses are performed on a 3-story SMRF building, and the performance of the structure is evaluated through a variety of force and displacement demand parameters. It is observed that incorporation of nonlinear SSI leads to increase in story displacement demand and reduction in base moment, base shear, and inter-story drift demands significantly, indicating the importance of its consideration toward achieving an economic yet safe seismic design procedure.

**Keywords** Soil-structure interaction • Winkler modeling • Nonlinear analysis • Seismic response

## 1 Introduction

Nonlinear behavior of a soil-foundation interface due to mobilization of the ultimate capacity and the consequent energy dissipation during an intense seismic event may alter the response of a structure in several ways. Foundation movement can increase

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the period of a system by introducing flexibility, nonlinear behavior and hysteretic energy dissipation at the soil-foundation interface may reduce the force demand to the structure, and foundation deformations may alter the input ground motion. However, till date, current design practice is reluctant to account for the nonlinear soil-structure interaction (SSI), primarily due to the absence of reliable nonlinear modeling techniques and also in anticipation that consideration of SSI generally leads to more conservative design.

In the past few decades, a number of analytical and experimental studies have been conducted to understand the effect of SSI on the seismic behavior of structures [1, 6, 7, 9, 12, 13, 16–18, 21, 23]. These studies indicated that the nonlinear soil-foundation behavior under significant loading has considerable effect on the response of structure-foundation system. Design and rehabilitation provisions (e.g., [2, 3, 8, 14]) have traditionally focused on simplified pseudo-static force-based or pushover-typeprocedures, where the oil-foundation interface is characterized in terms of modified stiffness and damping characteristics. However, the above-mentioned approaches cannot capture the complex behavior of nonlinear soil-foundation-structure systems, such as hysteretic and radiation damping, gap formation in the soil-foundation interface and estimation of transient and permanent settlement, and sliding and rotation of the foundation.

In this chapter, the seismic response of a ductile steel moment-resisting frame (SMRF) building [adopted from Gupta and Krawinkler [11]] has been evaluated considering nonlinear SSI through a beam-on-nonlinear-Winkler-foundation (BNWF) approach, where the soil-foundation interface is assumed to be a system of closely spaced, independent, inelastic spring elements [12, 15]. The details of the modeling technique, soil and structural properties considered, and analysis procedures adopted are discussed below.

## 2 Numerical Modeling of Nonlinear SSI

The BNWF model is an assembly of closely spaced, independent, nonlinear spring elements (Fig. 1). Vertical springs (q-z elements) distributed along the length of the footing are intended to capture the rocking, uplift, and settlement, while horizontal springs (t-x and p-x elements) are intended to capture the sliding and passive resistance of the footing, respectively. The constitutive relations used for the q-z, p-x, and t-x mechanistic springs are represented by nonlinear backbone curves that were originally developed by Boulanger [4], based on an earlier work of Boulanger et al. [5], and later on calibrated and validated by Raychowdhury [15] for more appropriate utilization toward shallow foundation behavior modeling. Details of the BNWF modeling technique along with its predictive capabilities to achieve experimentally observed soil-foundation behavior can be found in Raychowdhury [15], Raychowdhury and Hutchinson [16, 17], and Gajan et al. [9]. The initial elastic stiffness and vertical capacity of the soil springs are calculated based on Gazetas [10] and Terzaghi [22], respectively. Springs are distributed at a spacing of 1%

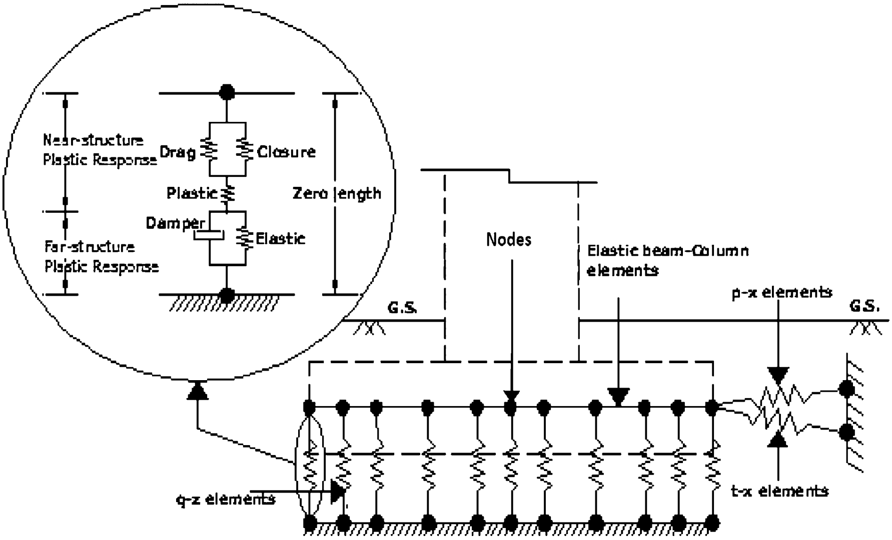


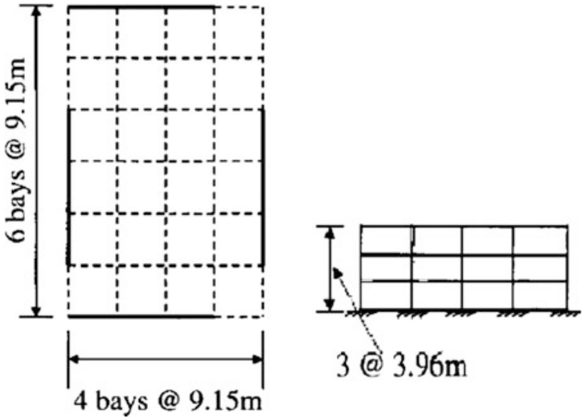
**Fig. 1** Idealized BNWF model

of the footing length at the end region and of 2% of the footing length at the mid-region. The end region is defined as high stiffness region extending 10% of footing length from each end of the footing, while the mid-region is the less stiffer middle portion. This variation in the stiffness distribution is provided based on the recommendations of ATC-40 [3] and Harden and Hutchinson [12] in order to achieve desirable rocking stiffness of the foundation.

## 3 Selection of Structure, Soil Properties, and Ground Motions

A 3-story, 4-bay steel moment resisting frame (SMRF) building adopted from Gupta and Krawinkler [11] is considered for the present study. The building is designed based on the weak-beam strong-column mechanism, with floor area of 36:6 × 36:6 m and four bays at an interval of 9.15 m in each direction (Fig. 2). The section properties and geometric details of the structure have been taken from Gupta and Krawinkler [11]. The columns of the building are assumed to be supported on mat foundation resting on dense silty sand of Los Angeles area (site class-D, NEHRP), with the following soil properties: cohesion 70 kPa, unit weight 20 kN = m3, shear modulus 5.83 MPa, and Poisson's ratio 0.4. The effective shear modulus is obtained by reducing the maximum shear modulus (corresponding to small strain values) by 50% to represent the high-strain modulus during significant earthquake loadings. The foundation is designed in such a way that it has a bearing capacity three times of the vertical load coming to it (i.e., a static vertical factor of safety of 3). More details can be found in Singh [19]. Nonlinear dynamic analysis

**Fig. 2** SMRF structure considered in the study (Adapted from Gupta and Krawinkler [11])



is carried out using SAC ground motions [20] representing the probabilities of exceedance of 50, 10, and 2% in 50 years, with return periods of 72 years, 475 years, and 2,475 years, respectively. In this chapter, these three sets of ground motions are denoted as 50/50, 10/50, and 2/50, respectively, for brevity. A 2% Rayleigh damping is used in the dynamic analysis.

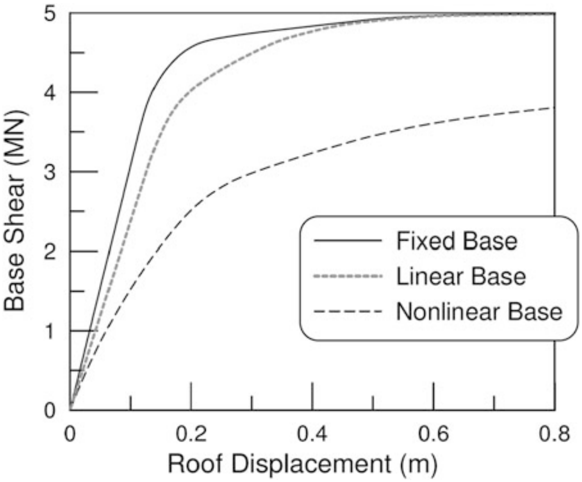
## 4 Results and Discussion

Before performing the dynamic analysis, eigenvalue analysis and static pushover analysis were carried out and compared with that obtained by Gupta and Krawinkler [11]. It has been observed that when the building is considered fixed at its base (i.e., ignoring the SSI effects), the fundamental period is obtained as 1.03 s, which is in accordance with the period obtained by Gupta and Krawinkler [11]. However, when the base flexibility is introduced, the fundamental period is observed to be 1.37 s, indicating significant period elongation (~33%) due to SSI effects.

The static pushover analysis shows the effect of SSI on the force and displacement demands of the structure in an effective way (Fig. 3). It can be observed that when the soil-foundation interface is modeled as linear, the global response of the system is altered only slightly from that of a fixed-base case. However, when the soil springs are modeled as nonlinear, the curve becomes softer, resulting in lower yield force and higher yield displacement demands (Table 1), which may be associated with yielding of the soil beneath the foundation.

Figures 4, 5, 6, and 7 provide the statistical results of the various force and displacement demands obtained from the nonlinear dynamic analysis using 60 ground motions mentioned earlier. The maximum absolute value of each response parameter (such as story displacement, moment, and shear) is considered as the respective demand value. Before incorporating the nonlinear SSI effects, the

**Fig. 3** Global pushover curves for different base conditions



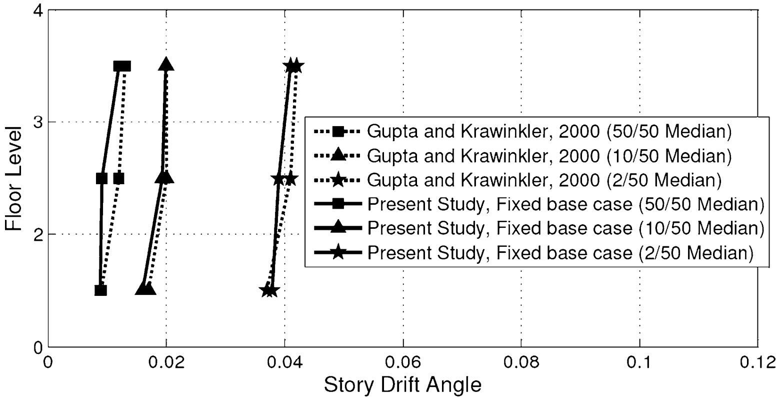


**Fig. 4** Median values of inter-story drift demands: comparison of fixed-base case with Gupta and Krawinkler [11]

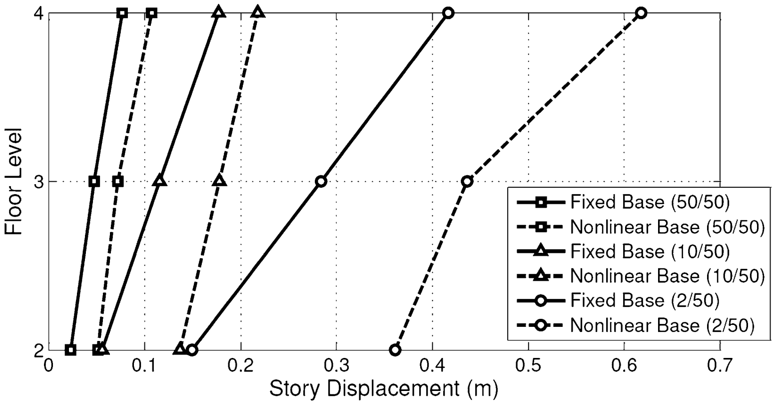


**Fig. 5** Median values for story displacement demands

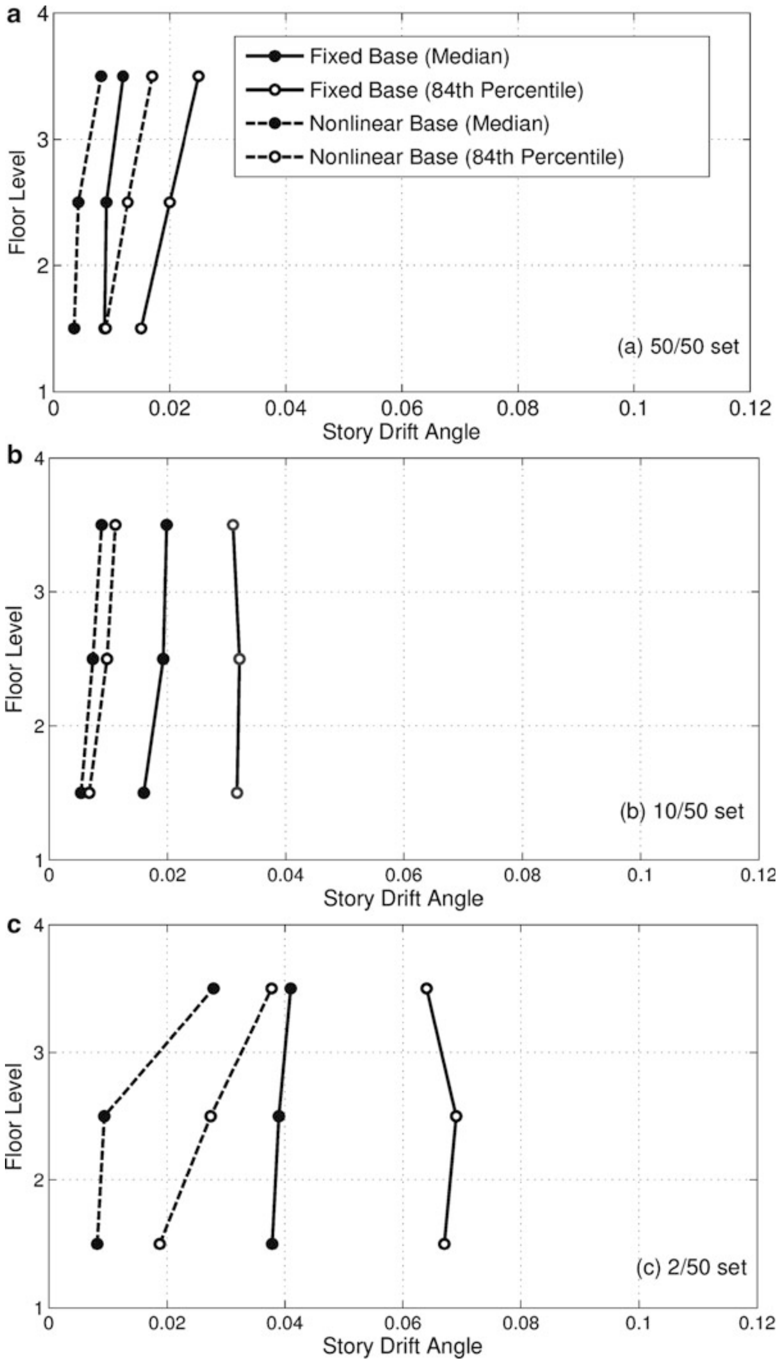


**Fig. 6** Statistical values of inter-story drift demands for ground motions: (**a**) 50% in 50 years, (**b**) 10% in 50 years, and (**c**) 2% in 50 years hazard levels

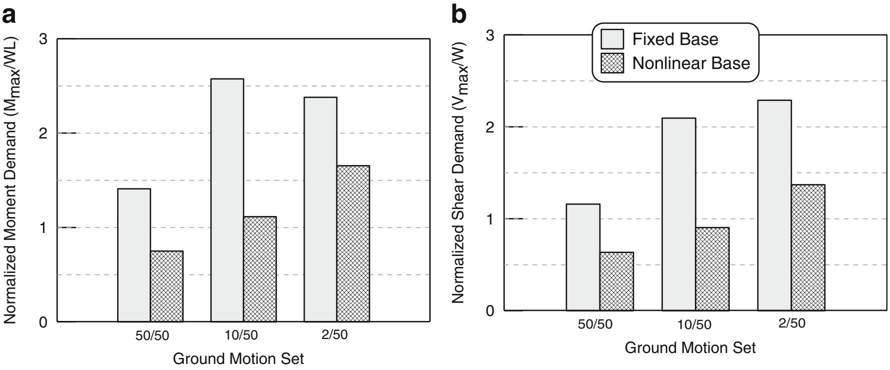


**Fig. 7** Median values for (**a**) normalized base moment demand and (**b**) normalized base shear demand (*W* weight of the building, *L* length of the footing)

**Table 1** Pushover analysis results

| Base condition | Yield displacement(m) | Yield force (MN) |
|---|---|---|
| Fixed Base | 0.19 | 4.53 |
| Linear Base | 0.25 | 4.28 |
| Nonlinear Base | 0.28 | 2.86 |

response of the fixed-base structure is compared with that obtained by Gupta and Krawinkler [11]. It has been observed that response of the fixed-base case is in accordance with that of Gupta and Krawinkler [11] with minor deviation in second story for 50/50 set of motion (Fig. 4). Figure 5 shows the median values of the story displacements considering fixed-base condition and nonlinear SSI. It can be observed that consideration of nonlinear SSI increases the story displacement demand significantly (more than 100%) for each set of ground motion and at each floor level. This indicates that neglecting the nonlinear SSI effects during the structural design may lead to an unconservative estimation of story displacement demands. However, when the inter-story drift demands are compared, it is observed that the inclusion of base nonlinearity reduces the same (see Fig. 6). Moreover, this reduction is significant and consistent for each floor level and each set of ground motion. Since inter-story drift demand is an important parameter for designing individual structural members, it is very likely that the members will be designed over-conservatively if the SSI effects are neglected. Similar observations are also made from comparison of force demands, where median values of both base moment and base shear are observed to decrease 25–50% when nonlinear SSI is introduced at the foundation level (Fig. 7). Note that since the pushover analysis indicated that linear assumption of SSI does not have significant effect on the response of a structure, the dynamic analysis results are provided for the fixed and nonlinear base conditions only.

# 5 Conclusions

The present study focuses on the effect of foundation nonlinearity on various force and displacement demands of a structure. A medium-height SMRF building adopted from Gupta and Krawinkler [11] has been used for this purpose. The nonlinear behavior of soil-foundation interface is modeled using a Winkler-based model concept. Static pushover analyses and nonlinear dynamic are carried out using SAC ground motions of three different hazard levels provided by Somerville et al. [20]. The following specific conclusions are made from the present study:

- Pushover analysis results indicate that the global force demand of a structure reduces with incorporation of SSI, whereas the roof displacement demand decreases with the same. Further, this alteration is much significant when inelastic behavior of soil-foundation interface is accounted for.
- It is observed from the dynamic analysis that the story displacement demands increase significantly when base nonlinearity is accounted for. However, the inter-story drift angle is observed to decrease, indicating lower design requirement for the structural members.
- The global force demands such as base moment and base shear of the columns are also observed to get reduced as much as 50% with incorporation of nonlinear SSI, indicating the fact that neglecting nonlinear SSI effects may lead to an inaccurate estimation of these demands.

Finally, it may be concluded from this study that the soil-structure interaction effects may play a crucial role in altering the seismic demands of a structure, indicating the necessity for incorporation of inelastic foundation behavior in the modern design codes to accomplish more economic yet safe structural design.

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