An Optimization Technique for Uniform Damage Distribution in Inelastic Shear Buildings Considering Soil-Structure Interaction Effects

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SUMMARY

In the present paper, through intensive nonlinear dynamic analyses of shear-resistant buildings with consideration of soil-structure interaction (SSI) subjected to a group of artificial earthquakes, and using the uniform distribution of damage over the height of structures as the criterion an optimization technique for seismic design of inelastic shear-buildings incorporating SSI effects is developed. The effects of several parameters including fixed-base fundamental period, number of stories, soil flexibility, and building aspect ratio on optimum lateral load pattern are investigated. Results indicate that the influence of SSI through changing the dynamic characteristics of structures can significantly affect damage distribution along the height of structures in inelastic range of response. Moreover, it is shown that the seismic performance of the structures designed in accordance with the proposed optimization technique is superior to those designed by code-compliant or fixed-base optimum load patterns.

***Keywords**: Uniform damage, Soil-Structure Interaction, shear buildings, inelastic behaviour, seismic code*

1. INTRODUCTION

The primary design of common building structures are generally based on equivalent lateral forces that are mainly based on elastic structural behaviour of fixed-base structures and account for inelastic behaviour in a somewhat indirect manner. The height-wise distribution of these lateral load patterns from various standards such as EuroCode 8 (CEN, 2003), NEHRP 2003 (BSSC, 2003), ASCE/SEI 7-05 (ASCE, 2005) and International Building Code, IBC 2009 (ICC, 2009) depends on the fundamental period of the structures and their mass. They are derived primarily based on elastic dynamic analysis of the corresponding fixed-base structures without considering soil-structure interaction (SSI) effect. The efficiency of using the code-specified lateral load patterns for fixed-base building structures have been investigated during the past two decades (Anderson et al., 1991; Gilmore and Bertero, 1993; Chopra, 1995, Leelataviwat et al. 1999; Mohammadi et al. 2004,; Ganjavi et al., 2008, Hajirasouliha and Moghaddam, 2009). Leelataviwat et al. (1999) evaluated the seismic demands of mid-rise moment-resisting frames designed in accordance to UBC 94. They proposed improved load patterns using the concept of energy balance applied to moment-resisting frames with a pre-selected yield mechanism. Lee and Goel (2001) also proposed new seismic lateral load patterns by using high-rise moment-resisting frames up to 20-story with the same concept which Leelataviwat et al. (1999) used. Their proposed load pattern fundamentally follows the shape of the lateral load pattern in the code provisions (i.e., UBC 1994, 1997) and is a function of mass and the fundamental period of the structure. In a more comprehensive research, Mohammadi *et al.* (2004) investigated the effect of lateral load patterns specified by the United States seismic codes on drift and ductility demands of fixed-base shear building structures under 21 earthquake ground motions, and found that using the code-specified design load patterns do not lead to a uniform distribution and minimum ductility demands. Ganjavi et.al (2008) investigated the effect of equivalent static and spectral dynamic lateral load patterns specified by the major seismic codes on height-wise distribution of drift, hysteretic energy and damage subjected to severe earthquakes in fixed-base reinforced concrete buildings. More recently, several studies have been conducted by researchers to evaluate and improve the code-specified design lateral load patterns based on the inelastic behavior of the structures (Park and

Medina, 2007; Hajirasouliha and Moghaddam, 2009; Goel et al., 2010). However, all studies have been concentrated on the different types of structures with rigid foundation, i.e., without considering SSI effects. In fact, nothing has been done yet on optimum seismic design of buildings with consideration of SSI effects. For the first time, Ganjavi and Hao (2012a) through performing intensive analyses of 7200 shear-buildings with SSI subjected to a group of 30 earthquakes recorded on alluvium and soft soils investigated the adequacy of IBC-2009 code-complaint lateral loading patterns for elastic and inelastic soil-structure systems. They concluded that using the code-specified load pattern leads to nearly uniform (optimal) ductility demands distribution for structures having short periods and within the elastic range of response. For structures with longer periods, however, it loses its efficiency as the number of stories and soil flexibility increase especially for the cases of severe SSI effects and high inelastic behaviour. In another study, the authors (Ganjavi and Hao, 2012b) developed a new optimization algorithm for optimum seismic design of elastic shear-building structures with SSI effects. The adopted method is based on the concept of uniform damage distribution proposed by Moahammadi et al. (2004) and Hajirasouliha and Moghaddam (2009) for fixed-base shear building structures. Based on numerous optimum load patterns derived from numerical simulations and nonlinear statistical regression analyses, a new load pattern for elastic soil-structure systems with shallow foundation has been proposed. They showed that using the proposed load pattern could lead to a more uniform distribution of deformations over the height of structures. The designed structures also experience up to 40% less structural weight as compared with the code-compliant or aforementioned optimum patterns proposed for fixed-base structures (Ganjavi and Hao, 2012b).

In the present study, optimization algorithm developed by Ganjavi and Hao (2012b) for elastic soil-structure systems is modified to incorporate the inelastic behavior. By performing intensive numerical simulations of responses of inelastic soil-structure shear buildings with various dynamic characteristics and SSI parameters, the effects of fundamental period of vibration, ductility demand, the number of stories, soil flexibility and structure aspect ratio (slenderness ratio) on the optimum lateral load pattern of soil-structure systems are investigated.

2. SUPERSTRUCTURE MODELING AND GROUND MOTIONS

The well-known shear-beam model which is one of the most frequently used models that facilitate performing a comprehensive parametric study is utilized here as superstructure model (Mohammadi et al., 2004; Hajirasouliha and Moghaddam, 2009; Ganjavi and Hao, 201ba and 2012b). In the MDOF shear-building models, each floor is assumed as a lumped mass to be connected by elasto-plastic springs. Story heights are 3 m and total structural mass is considered as uniformly distributed along the height of the structure. A bilinear elasto-plastic model with 2% strain hardening in the force-displacement relationship is used to represent the hysteretic response of story lateral stiffness. However, the effect of different post yield behaviours is also investigated. This model is selected to represent the behaviour of non-deteriorating steel-framed structures of different heights. In all MDOF models, lateral story stiffness is assumed as proportional to story shear strength distributed over the height of the structure, which is obtained in accordance to the different lateral load patterns. Five percent Rayleigh damping is assigned to the first mode and the mode in which the cumulative mass participation is at least 95%. In this investigation, an ensemble of 21 earthquake ground motions with different characteristics recorded on alluvium and soft soil deposits are compiled. The selected ground motions are components of six earthquakes including Imperial Valley 1979, Morgan Hill 1984, Superstition Hills 1987, Loma Prieta 1989, Northridge 1994 and Kobe 1995. All the selected ground motions are obtained from earthquakes with magnitude greater than 6 having closest distance to fault rupture more than 15 km without pulse type characteristics. To be consistent, using SeismoMatch software (SeismoMatch, 2011) these seismic ground motions are adjusted to the elastic design response spectrum of IBC-2009 with soil type *E*. The ground motions utilized in the present study have the predominant period ranging from 0.5 to 1.35 sec, recorded on sites with shear wave velocity from 90 to 350 m/s, which are approximately consistent to the IBC-2009 elastic response spectrum of soil type *E*.

3. SOIL-STRUCTURE MODEL AND KEY PARAMETERS

The soil-foundation element is modelled by an equivalent linear discrete model based on the cone model with frequency-dependent coefficients and equivalent linear elastic properties (Wolf, 1994). Cone model based on the one-dimensional wave propagation theory represents circular rigid foundation with mass m_f and area moment of inertia I_f resting on a homogeneous half-space. The simplified cone model can be used with sufficient accuracy in engineering practice (Wolf, 1994). A typical 10-story shear building model of fixed-base and flexible-base systems used in this study is shown in Fig. 1. The sway and rocking DOFs are defined for translational and rotational motions of the foundation, while the vertical and torsional movement of the foundation are neglected. The stiffness and energy dissipation of the supporting soil are modelled by springs and dashpot, respectively. Soil material damping is assumed as commonly used viscous damping so that more intricacies in time-domain analysis are avoided. All coefficients of springs and dashpots for sway and rocking motions used to define the soil-foundation model in Fig. 1 are summarized as follows:

$$k_h = \frac{8\rho v_s^2 r}{2-\upsilon}, \qquad c_h = \rho v_s A_f \;, \quad k_\varphi = \frac{8\rho v_s^2 r^3}{3(1-\upsilon)}, \qquad c_\varphi = \rho v_p I_f \tag{1}$$

where k_h, c_h, k_φ and c_φ are sway stiffness, sway viscous damping, rocking stiffness, and rocking viscous damping, respectively. Equivalent radius and area of cylindrical foundation are denoted by r and A_f. Besides, ρ, υ, v_p and v_s are respectively the specific mass density, Poisson's ratio, dilatational and shear wave velocity of soil. To consider the soil material damping, ζ_0, in the soil-foundation element, each spring and dashpot is respectively augmented with an additional parallel connected dashpot and mass.

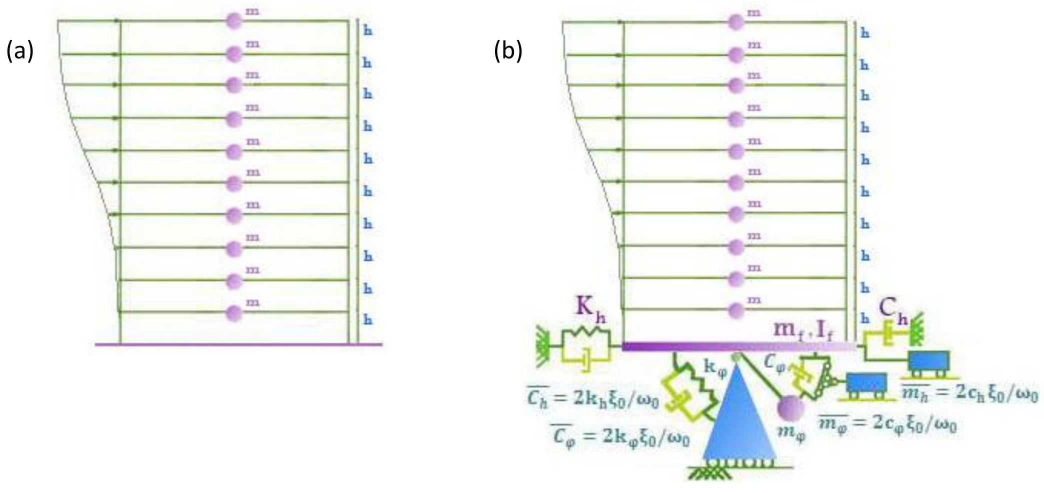

Figure 1. Typical 10-storty shear building models (a) fixed-base model and (b) flexible-base model

For a specific earthquake ground motion, the dynamic response of the structure can be interpreted based on the property of the superstructure relative to its underlying soil. It has been shown that the effect of these factors can be best described by some dimensionless parameters (Veletsos, 1977). In this study, dimensionless frequency $a_0 = \omega_{fix} \bar{H} / v_s$, and aspect ratio $\bar{H}/r$ are two key parameters which define the main SSI effect. ω_{fix} is the natural frequency of the fixed-base structure; v_s is the shear wave velocity of soil; r is the equivalent foundation radius, and $\bar{H}$ is the effective height of the structure. Other parameters, having less importance, may be set to some typical values for conventional buildings (Veletsos and Meek, 1974; Wolf, 1994). In the present study, the foundation mass ratio is assumed to be 0.1 of the total mass of the MDOF buildings. The Poisson's ratio is considered to be 0.4 for the alluvium soil and 0.45 for the soft soil. Also, a damping ratio of 5% is assigned to the soil material.

4. OPTIMIZATION TECHNIQUE FOR UNIFORM DAMAGE DISTRIBUTION

Based on the optimization technique adopted by Mohammadi et al., (2004), and Hajirasouliha and Moghaddam (2009) for fixed-base shear-building structures, Ganjavi and Hao (2012b) proposed a new algorithm for optimum seismic design of soil-structure systems in elastic range of response. In this section, the optimization algorithm adopted by Ganjavi and Hao (2012b) for optimum elastic shear-strength distribution of soil-structure systems is modified to take into account for the inelastic behaviour of the structure. In this approach, the structural properties are modified so that inefficient material is gradually shifted from strong to weak parts of the structure. This process is continued until a state of uniform deformation is achieved. In the present study, the seismic demand parameter used to quantify the structural damage is the inter-story displacement ductility ratio (μ). The following step-by-step optimization algorithm is proposed for shear-building soil-structure systems to estimate the optimum inelastic lateral force distribution:

1. Define the MDOF shear-building model depending on the prototype structure height and number of stories.
2. Assign an arbitrary value for total stiffness and strength and then distribute them along the height of the structure based on the arbitrary lateral load pattern, e.g., uniform pattern. As mentioned earlier, the lateral story stiffness is assumed as proportional to the story shear strength distributed over the height of the structure.
3. Select an earthquake ground motion.
4. Consider a presumed set of aspect ratio, $\bar{H}/r$, and dimensionless frequency, a_0, as the predefined key parameters for SSI effects.
5. Select the fundamental period of fixed-base structure and scale the total stiffness without altering the stiffness distribution pattern such that the structure has a specified target fundamental period. The following equation is used for scaling the stiffness to reach the target period by just one step:

$$(\sum_{i}^{n} K_{j+1})_{i+1} = (\frac{T_i}{T_t})^2 . (\sum_{i=1}^{n} K_j)_i \qquad (2)$$

   where K_j, T_i and T_{target} are story stiffness in the *j*th story, fixed-base period in the *i*th step and the target fixed base period, respectively. Refine effective height of the structure, $\bar{H}$ based on the fundamental modal properties of fixed-base MDOF structure.
6. Select a target ductility ratio and Perform dynamic analysis for the soil-structure system subjected to the selected ground motion and compute the total shear strength demand, $(V_s)_i$. If the computed ductility ratio is equal to the target value within the 0.5% of the accuracy, no iteration is necessary. Otherwise, total base shear strength is scaled (by either increasing or decreasing) until the target ductility ratio is achieved. To do this the following equation is proposed:

$$(V_s)_{i+1} = (V_s)_{\mathrm{i}} (\frac{\mu_{\max}}{\mu_t})^{\beta} \qquad (3)$$

   where $(V_s)_i$ is the total base shear strength of MDOF system at *i*th iteration; μ_t and $\mu_{\max}$ are respectively the target ductility ratio and maximum story ductility ratio among all stories. Parameter β is an iteration power which is more than zero. Ganjavi and Hao (2012a) showed that for elastic MDOF shear-building structures a very fast convergence, i.e. less than 5 iterations, can be obtained for β equal to 0.8. For Inelastic state ($\mu_t > 1$) β value, depending on the fundamental period, can be approximately defined as:

$$\begin{array}{ll} \beta = 0.05 - 0.1 & T_{fix} \le 0.5 \\ \beta = 0.1 - 0.25 & 0.5 < T_{fix} < 1.5 \\ \beta = 0.25 - 0.4 & T_{fix} > 1.5 \end{array} \tag{4}$$

7. Calculate the coefficient of variation (COV) of story ductility distribution along the height of the structure and compare it with the target value of interest which is considered here 0.02. If the value of COV is less than the presumed target value, the current pattern is regarded as optimum pattern. Otherwise, the story shear strength and stiffness patterns are scaled until the COV decreases below or equal to the target value.
8. Stories in which the ductility demand is less than the presumed target value are identified and their shear strength and stiffness are reduced. To obtain the fast convergence in numerical computations, the equation proposed by Hajirasouliha and Moghaddam (2009) for fixed-base systems is revised for soil-structure systems as follows:

$$[S_i]_{q+1} = [S_i]_q . [\frac{\mu_i}{\mu_t}]^{\alpha} \tag{5}$$

where $[S_i]_q$ = shear strength of the *i*th floor at *q*th iteration, μ_i =story ductility ratio of the *i*th floor and α = convergence parameter that has been considered equal to 0.1- 0.2 as the acceptable range by Hajirasouliha and Moghaddam (2009) for elastic and inelastic fixed-base structures. Nevertheless, the authors showed that for elastic fixed-base and soil structure systems, the value of 0.8 generally leads to the fastest convergence (i.e., less than 5 iterations) (Ganjavi and Hao, 2012b). Based on intensive analyses performed in the present study for soil-structure systems in inelastic range of response, it has been concluded that opposed to elastic state, α can be dependent on earthquake excitation characteristics, soil flexibility and dynamic properties of structures. It is found that α value is generally more dependent on respectively damping model, earthquake excitation, fundamental period of the structure and the level of inelasticity, and less dependent on damping ratio, strain hardening, the number of stories and soil flexibility. Very lower values of α need to be utilized for convergence problem in inelastic response in comparison with elastic one. Results of this study show because of the nature of the nonlinearity, considering a constant value may not guaranty achieving the fastest convergence for all cases of soil-structure systems. Based on intensive nonlinear dynamic analyses on shear-building structures in which the Rayleigh-type damping is used for the damping modelling, α= 0.07 for $\mu_t \le 3$ and α= 0.1 for $\mu_t > 3$ are approximately proposed for convergence problem of soil-structure systems in inelastic response.
9. Control the current maximum story ductility ratio ($\mu_{\max}$) and refine the total base shear strength of soil-structure systems if $\mu_{\max}$ is not equal to the target value within the 0.5% of the accuracy based on Eqs. 3 and 4 of step 6. Otherwise, go to the next step.
10. Control the current fixed-base period and modify it if it is not equal to the target value within the 1% of the accuracy based on Eq. 2 of step 5. Otherwise, go to the next step
11. Control the current Rayleigh-type damping coefficients and modify them if they are not equal to the previous values within the 1% tolerance. Otherwise, go to the next step
12. Convert the optimum shear strength pattern to the optimum lateral force pattern.
13. Repeat steps 6–12 for different target ductility ratio.
14. Repeat steps 5–13 for different presumed target periods.
15. Repeat steps 4–14 for different sets of $\bar{H}/r$ and a_0 .
16. Repeat steps 3–15 for different earthquake ground motions.
17. Repeat steps 1–16 for different number of stories.

To show the efficiency of the proposed method for optimum seismic design of soil-structure systems in inelastic range of response the above algorithm is applied to the 10-story shear building with T_{fix} = 1.5 sec, $\bar{H}/r$ = 3, and $a_0 = 2$ subjected to Kobe (Shin Osaka) simulated earthquake. Figure 2a illustrates a comparison of IBC-2009 load pattern with the optimum patterns of fixed-base and soil-structure systems. As seen, there is a significant difference between the optimum pattern of soil-structure systems and the other two patterns. These three patterns are applied to the same 10-story building with consideration of SSI effect and then the height-wise distribution of story ductility demand resulted from utilizing these lateral load patterns are computed and depicted in Fig. 2b. It can be seen that while using the SSI optimum pattern results in a completely uniform distribution of the deformation, using both the code-specified and fixed-base optimum patterns lead to a very non-uniform distribution of ductility demand (damage) along the height of the soil-structure systems in inelastic range of response. The COV of story ductility demand distributions resulted from applying IBC pattern, the fixed-base optimum pattern and SSI optimum pattern are 0.94, 0.64 and 0.003, respectively. Similarly, the values of 0.226, 0.196 and 0.003 were obtained for the same earthquake and structure model in previous study for elastic response (Ganjavi and Hao, 2012b). This indicates that SSI phenomenon through changing the dynamic characteristics of structures can more significantly affect damage distribution along the height of structures in inelastic range of response when compared to that of the elastic state. Therefore, utilizing fixed-base optimum load pattern may not result in an optimum seismic performance of soil-structure systems and, thus, a more adequate load pattern accounting for both SSI effects and inelastic behaviour should be defined and proposed for soil-structure system.

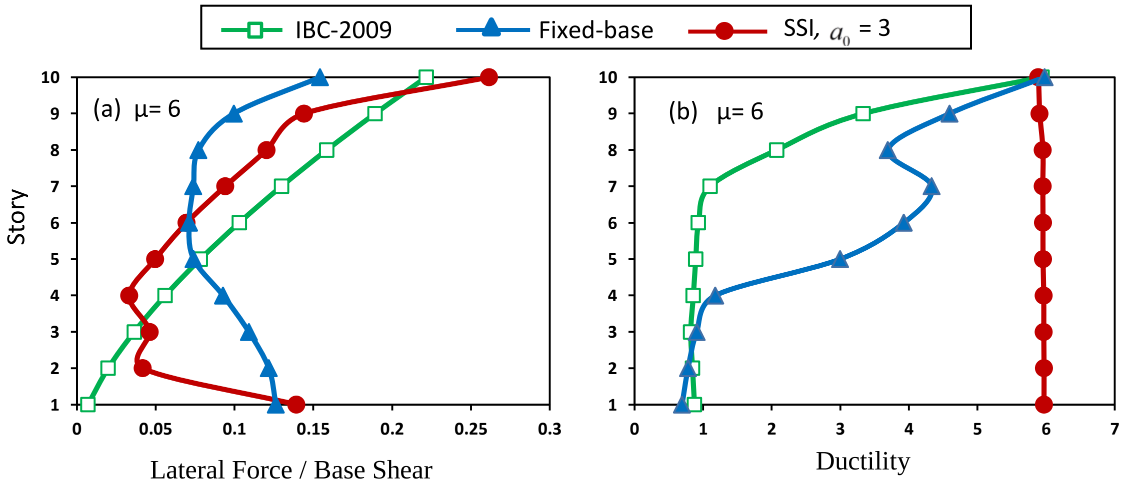

Figure 2. Comparison of IBC-2009 and fixed-base optimum load patterns with optimum designed models of soil-structure system: (a) lateral force distribution; (b) story ductility pattern, 10-story shear building with T_{fix} = 1.5 sec, $\bar{H}/r$ =3, Kobe (Shin Osaka) simulated earthquake

5. EFFECT OF STRUCTURAL DYNAMIC CHARACTERISTICS AND KEY PARAMETERS

5.1. Effect of Fundamental Period and Target Ductility Demand

To study the effect of fundamental period on optimum load pattern of inelastic soil-structure systems, the 10-story building models with $\bar{H}/r$ = 3 and a_0 = 2 having fixed-base fundamental periods of 0.5, 1, 2 and 3 sec are considered. The results are shown for μ = 6 representing the high level of inelasticity. For this case, the optimum load patterns are derived for the 21 matched earthquake ground motions and the average results are plotted in Fig. 3a. As seen, in high level of nonlinearity (i.e., μ= 6) increasing the fundamental period is generally accompanied by increasing the lateral shear force at both top and bottom stories for all cases, which is more pronounced in bottom stories than top stories. Previous studies carried out by Hajirasouliha and Moghaddam (2009) on fixed-base shear-building structures showed that increasing the fundamental period is only accompanied by increasing the shear strength in top stories. Comparing the results indicates that SSI can affect the optimum distribution of load pattern in different way when compared with fixed-base patterns.

Figure 3b shows the effect of target ductility demand on averaged optimum load pattern of soil-structure systems in inelastic response subjected to 21 matched ground motions. For this purpose, the

10-story shear-building models with $\bar{H}/r$ = 3 and a_0 = 2 having fixed-base fundamental period of 2 sec target ductility demands of 1, 2, 4 and 6 have been considered. As seen, the average optimum lateral load patterns are significantly dependent on the target ductility demand while nearly in all code-specified seismic load patterns for both fixed-base and soil-structure systems this parameter is not considered. It can also be seen that for soil-structure systems increasing the target ductility demand leads to decreasing and increasing the story shear strength in top and bottom stories, respectively.

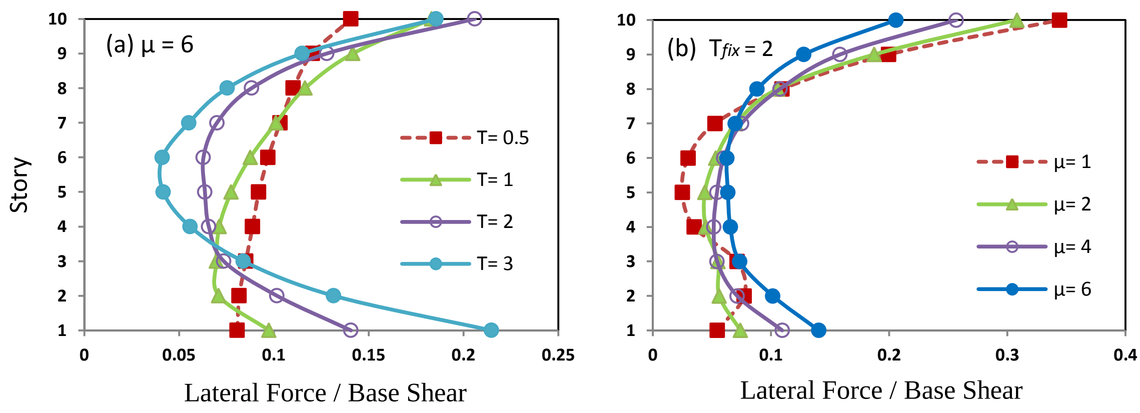

Figure 3. Effect of (a) fundamental period and (b) target ductility demand on averaged optimum lateral force profile for soil-structure systems with $\bar{H}/r$ =3 and a_0 = 2: 10-story building (average of 21 earthquakes)

5.2. Effect of Number of Stories

To examine the effect of number of stories on the optimum distribution profile, the proposed optimization algorithm is applied to the 5-, 10-, 15- and 20-story soil-structure models with T_{fix} = 1.5, $\bar{H}/r$ = 3 and a_0 = 2 subjected to the 21 matched earthquake ground motions. The average results are depicted in Fig. 4. In order to compare the averaged optimum patterns corresponding to different number of stories, the normalized lateral loads are plotted. In Fig. 4, the vertical and horizontal axes are relative height and normalized lateral load divided by base shear strength, respectively. From this figure, it can be concluded that the optimum load patterns are almost independent of the number of stories. This finding is also consistent with that by Hajirasouliha and Moghadam (2009) for fixed-base shear-building structures and Ganjavi and Hao (2012b) for elastic soil-structural systems.

5.3. Effect of Dimensionless Frequency and Aspect Ratio

Figure 5 shows the effect of dimensionless frequency, a_0 on averaged optimum load pattern of soil-structure systems subjected to 21 matched ground motions. As sated before, aspect ratio and dimensionless frequency are two key parameters that can affect the response of the soil-structure systems subjected to earthquake excitation. The results are plotted for the 10-story shear building with two fundamental periods of 0.5 and 2 sec respectively representing the rigid and flexible structures, and $\bar{H}/r$ =3 corresponding to three values of dimensionless frequency (a_0 =1, 2, 3) in comparison with fixed-base structure. It can be observed that in both rigid and flexible structures, dimensionless frequency can significantly affect the averaged optimum load pattern in inelastic range of response. For rigid model (i.e., T_{fix} = 0.5) increasing the value of dimensionless frequency results in increasing the lateral load at top stories and decreasing the load in lower stories while for flexible structures increasing the dimensionless frequency is accompanied by increasing the lateral load at bottom and top stories, and decreasing the load in middle stories . This phenomenon could be again due to the effect of higher mode effect as a result of increasing the fundamental period of the soil-structure systems.

Figure 6 shows the effect of aspect ratio on averaged optimum load pattern of soil-structure systems. The results are for the 10-story shear building with T_{fix} =1.5 sec, ductility demand of 4, two dimensionless frequencies (a_0 =1, 3), representing the insignificant and severe SSI effect, respectively and three values of aspect ratio ($\bar{H}/r$ = 1, 3, 5) representing respectively squat, average and slender buildings subjected to 21 matched ground motions. As seen, for the case of insignificant SSI effect (i.e., Fig. 6a), increasing aspect ratio will not change the optimum load profile remarkably. However, by increasing the dimensionless frequency and, therefore more significant SSI effect, the aspect ratio will significantly affect the averaged optimum load pattern. In sever SSI effect, the trend is to some extent similar to that of the dimensionless frequency discussed in the previous section such that increasing the value of aspect ratio is accompanied by increasing the lateral load at bottom and top stories, and decreasing the load in the middle stories, which is more pronounced for slender building (i.e. $\bar{H}/r$ = 5). It can be concluded that SSI effect on optimum lateral load pattern will become more significant for the case of slender building with larger dimensionless frequency. Nearly the same conclusion has been reported by writers (Ganjavi and Hao, 2012b) for the elastic soil-structure systems.

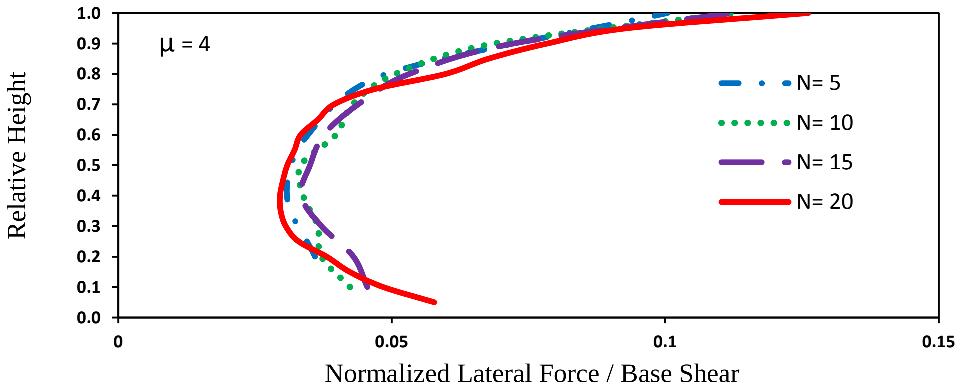

Figure 4. Effect of the number of stories on averaged optimum lateral force profile for soil-structure systems with $\bar{H}/r$ =3 and a_0 = 2: T_{fix} = 1.5 sec. (average of 21 earthquakes)

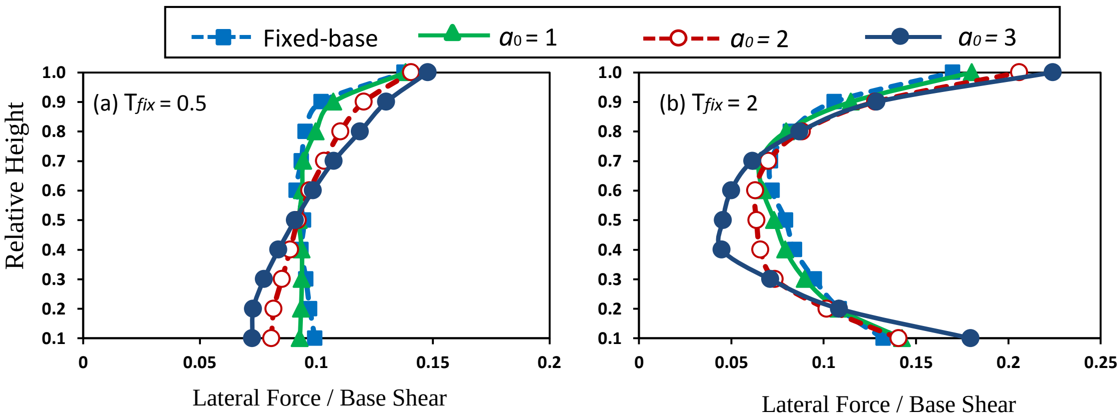

Figure 5. Effect of dimensionless frequency on averaged optimum lateral force profile for 10-story soil-structure systems with $\bar{H}/r$ =3, μ= 6: (a) T_{fix} = 0.5 sec.: (b) T_{fix} = 2 sec.

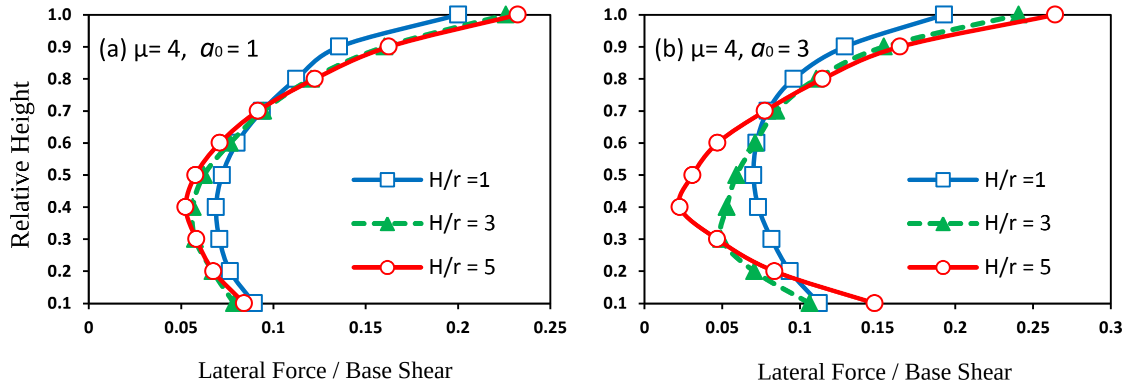

Figure 6. Effect of aspect ratio on averaged optimum lateral force profile for a 10-story soil-structure system with T_{fix} = 1.5 sec, μ= 4 (average of 21 earthquakes)

6. CONCLUSIONS

An optimization technique for uniform (optimum) damage distribution along the height of the inelastic shear-buildings considering SSI effects has been developed in the present study. The effects of fixed-base fundamental period, number of stories, dimensionless frequency, and building aspect ratio on optimum lateral load pattern are investigated. It was demonstrated that the seismic performance of the structures designed in accordance with the proposed optimization technique is superior to those designed by code-compliant or fixed-base optimum load patterns. This study provides a fundamental step towards the development of the more rational seismic design methodology that explicitly account for the complex phenomenon of soil-structure interaction and presumed level of damage in inelastic range of response. More research works for more complex structural configurations and behaviour are deemed necessary for developing a practical methodology applicable to design and analysis of structures exposed to earthquake ground motions. In addition, a more adequate load pattern accounting for both SSI effects and inelastic behaviour should be defined and proposed for soil-structure systems. Such a course of study is being carried out by the authors and would be reported in the near future.

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