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A novel formulation for Ductility Strength Reduction Factor of Structures Considering Kinematic and Inertial Soil-Structure Interaction

1st Author

Morvarid Hajian, Ph.D. Candidate, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran. Email: hajian.m@ut.ac.ir, ORCID number: 0000-0003-3742-4520

2nd Author

Reza Attarnejad (Corresponding Author)

Professor, School of Civil Engineering, College of Engineering, University of Tehran, Tehran, Iran. Email: attarnjd@ut.ac.ir, ORCID number: 0000-0003-3742-4520

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Abstract:

The strength reduction factor presented in design codes has been examined disregarding the influence of soil-structure interaction (SSI). However, it has been proved that SSI can significantly affect structural responses. Most recent studies evaluating the strength reduction factors have primarily focused on single-degree-of-freedom soil-structure systems, potentially overlooking the behavior of multi-degree-of-freedom systems. Furthermore, there is a lack of research, concerning the suggestion of a proper relationship to estimate the strength reduction factor of multi-story buildings considering SSI. Therefore, this paper focused on investigating the SSI effects on ductility strength reduction factor (R_μ) and presenting a simplified expression to practically estimate R_μ, including inertial and kinematic interactions. To obtain reliable results, several nonlinear multi-story structures with different ductility ratios subjected to earthquake ground motions on soft soils were analyzed. Unlike other studies that utilized simple spring methods to model the soil, this research represented the soil as a continuous medium. Consequently, this study addressed the limitations of modeling found in comparable research and, building on this, introduced a novel relationship for application in design codes. By comparing with the literature review, it was noted that the suggested formula could provide a fairly accurate estimation of the strength reduction factor.

Keywords: Soil-structure interaction (SSI), Strength Reduction Factor, MDOF systems, nonlinear dynamic analysis, Soft soils.

1. Introduction

During intense earthquake ground motions, structures will display nonlinear behavior. Seismic design codes have recommended using seismic strength design method which relies on ductility strength reduction factors, R_μ. R_μ is a factor determining the structural resistance needed to maintain the structure within the elastic range based on a specific level of ductility. Ductility strength reduction factor is defined as the ratio of the elastic strength demand to the inelastic strength demand, as **Eq. 1**.

$$R_\mu = \frac{F_y(\mu = 1)}{F_y(\mu = \mu_t)} \tag{1}$$

Where $F_y(\mu = 1)$ is the lateral yielding strength required to maintain the system elastic and $F_y(\mu = \mu_i)$ is the lateral yielding strength required to maintain the displacement ductility demand μ less or equal to a predetermined target ductility ratioμ_t.

Recent studies have shown that soil-structure interaction (SSI) can greatly impact structural dynamic responses. The research showed that SSI effect could enhance system's period and flexibility, leading to lower base shear force and higher structure displacement response. systems (Abtahi *et. al*., 2020**;** Mourlas *et. al*., 2020; Rofooei and Seyedkazemi, 2020; Vaseghiamiri *et. al*.; 2020; Maharjan and Bahadur, 2021; Nguyen and Shin, 2021; Requena *et. al*., 2022; Ali *et. al*., 2023; Xiong *et. al*., 2023; El Janous and El Ghoulbzouri, 2024). Additionally, the impacts of supporting soil on inelastic displacement ratios were examined in studies by Hassani *et al*. (2018) and Avci and Yazgan (2022). It was also revealed that soil dynamic characteristics such as shear modulus ratio could influence the peak ground acceleration and seismic input for structures (Li and Li, 2023). Razzouk *et. al*. (2023) investigated the impact of SSI on the seismic behavior of reinforced concrete buildings on four types of soil and offered important methods for selecting the optimal bracing type for structures of various heights.

It was also determined that in general, SSI could change the strength reduction factors of SDOF (Ghannad & Jahankhah, 2007; Halabian and Erfani, 2013). For instance, Ghannad & Jahankhah (2007) analyzed a SDOF system underlying a soil medium modeled by cone spring method. They found out that SSI reduced both the elastic and inelastic demand of structures, yet they did not propose a simplified expression to estimate the strength reduction factor. Elsadany *et. al*. (2024) determined the response factor for RC structures with various irregularities by pushover analysis using SAP2000. The soil represented by vertical springs, failing to capture the actual behavior of soil. They concluded that irregular buildings had lower inelastic seismic capacities compared to regular buildings.

Strength reduction factors outlined in design codes were formulated based on fixed-base structures. Utilizing the *R* values from design codes for soil-structure systems leads to inaccurate inelastic strength demands. Consequently, it is crucial to design structures based on their actual strength demands (ASCE7,2022). Generally, minimal attention has been given to the strength reduction factor and ductility demand in soil-structure systems (Miranda, 1993; Eser *et. al*. 2011; Marzban *et. al*., 2014; Ghandil and Behnamfar; 2017; Shi *et. al*., 2023). One study, such as that conducted by Talebi and Derakhshani (2022), examined the impact of group piles on the strength reduction factor using continuum soil modeling and enhanced p-y curves. However, their research did not account for the effects of soil-structure interaction (SSI) on the soil-pile reduction factor. Studies conducted by Veda and Manchalwar (2021), Anand and Kumar (2021) and Wani, et. al, (2022) investigated the effect of soil-structure interaction in the response reduction factors of structures using a series of nonlinear time history analysis. In their studies, soil medium was modeled by simplified spring method. They figured out that the strength reduction factors of soft soils or flexible base case was lower than those for hard soil or fixed base case, without presenting a new formulation to calculate *R* factor. According to the research by Nguyen and Shin (2021), an increase in shear wave velocity led to an increase in ductility capacity. Aydemir and Ekiz (2013) observed that the strength reduction factors for MDOF structures with soil-structure interaction were less than the design factors outlined in existing seismic design codes.

The studies referenced, solely analyzed the impact of SSI on the *R* factor without offering calculation relationships to use in design codes. To address this problem, only a limited number of studies were conducted to suggest a mathematical formula for estimating the strength reduction factor of soil-structure system, while further extensive research was carried out to suggest simplified equations for the strength reduction factor of fixed-base structures (Krawinkler, *et.al*. 1991; Miranda, 1993; Garcia *et. al*., 2024). Certainly, these investigations cannot capture the impacts of soil-structure interaction on seismic strengths and dynamic responses.

Among limited studies for soil-structure systems, Karatzetzou and Pitilakis (2018) and Ahmadi (2019) proposed an expression based on single-degree-of-freedom (SDOF) modeling of structures. For instance, Ahmadi (2019) investigated the effects of inertial and kinematic interactions on the ductility strength reduction factor of nonlinear SDOF models with various ductility ratios situated soft soil. The author suggested an inclusive expression that incorporated ductility ratio, fixed-base period, embedment ratio, aspect ratio and base flexibility level. In this research, soil medium was represented as a single spring, which cannot accurately simulate actual soil behavior.

Certainly, these investigations were conducted solely SDOF systems and the results cannot be applied to actual multi-story structures. Therefore, some scientists presented additional equations to predict the strength reduction factor of soil-structure systems on multi-degree-of-freedom (MDOF) structures (Ganjavi and Hao, 2014; Lu *et. al*., 2016). In these investigations, MDOF models were used in the time domain for nonlinear dynamic analysis. In the study by Lu *et al*. (2016), the soil medium was analyzed using the simplified cone model method, and Ganjavi and Hao (2014) utilized springs and dampers in their research. The studies introduced a formula dependent on slenderness ratio, number of stories, ductility ratio and structure to soil stiffness. Modeling using vertical independent springs may not accurately simulate actual soil behavior. The soil exhibits a shear behavior that is absent in spring modeling. Thus, there is a necessity to enhance the formulations by advancing in modeling.

Due to the notable influence of soil-structure interaction on structural response, modifications to design criteria are required. The strength reduction factor is one the key parameter in structural design. Design standards currently do not provide a solution for incorporating the strength reduction factor in soil-structure systems. As stated earlier, limited research investigated the dynamic behavior of MDOF systems considering soil-structure interaction and complete soil modeling, which failed to present a precise formula to estimate the strength reduction factor of such systems. Therefore, the primary goal of this article to propose a formulation grounded on full modeling of soil environment and applicable to multi-story building, which was not mentioned in the earlier research. This study aims to acquire a novel formula for predicting the ductility strength reduction factor (R_μ) of soil-structure systems. The analysis was focused on multi-story structures and improved soil modeling compared to earlier research. In this research, wherever strength reduction factor was mentioned, it referred to ductility strength reduction factor R_μ.

2. Methodology

A set of two-dimensional numerical simulations was carried out to develop a new formula for the strength reduction factor (R_μ) of multi-story buildings with flexible base condition. The calculation process was displayed in **Fig. 1**. The structures consisted of 3, 5, 10, and 15 story buildings on elastic plane-strain soil and underwent nonlinear dynamic analysis using Open System for Earthquake Engineering Simulation (OpenSees) software. The numerical models were considered both inertial and kinematic interaction according to **Sections 2.1** and **2.2**. For each model, the strength reduction factor was obtained by calculating the inelastic and elastic strength demand values under dynamic analyses.

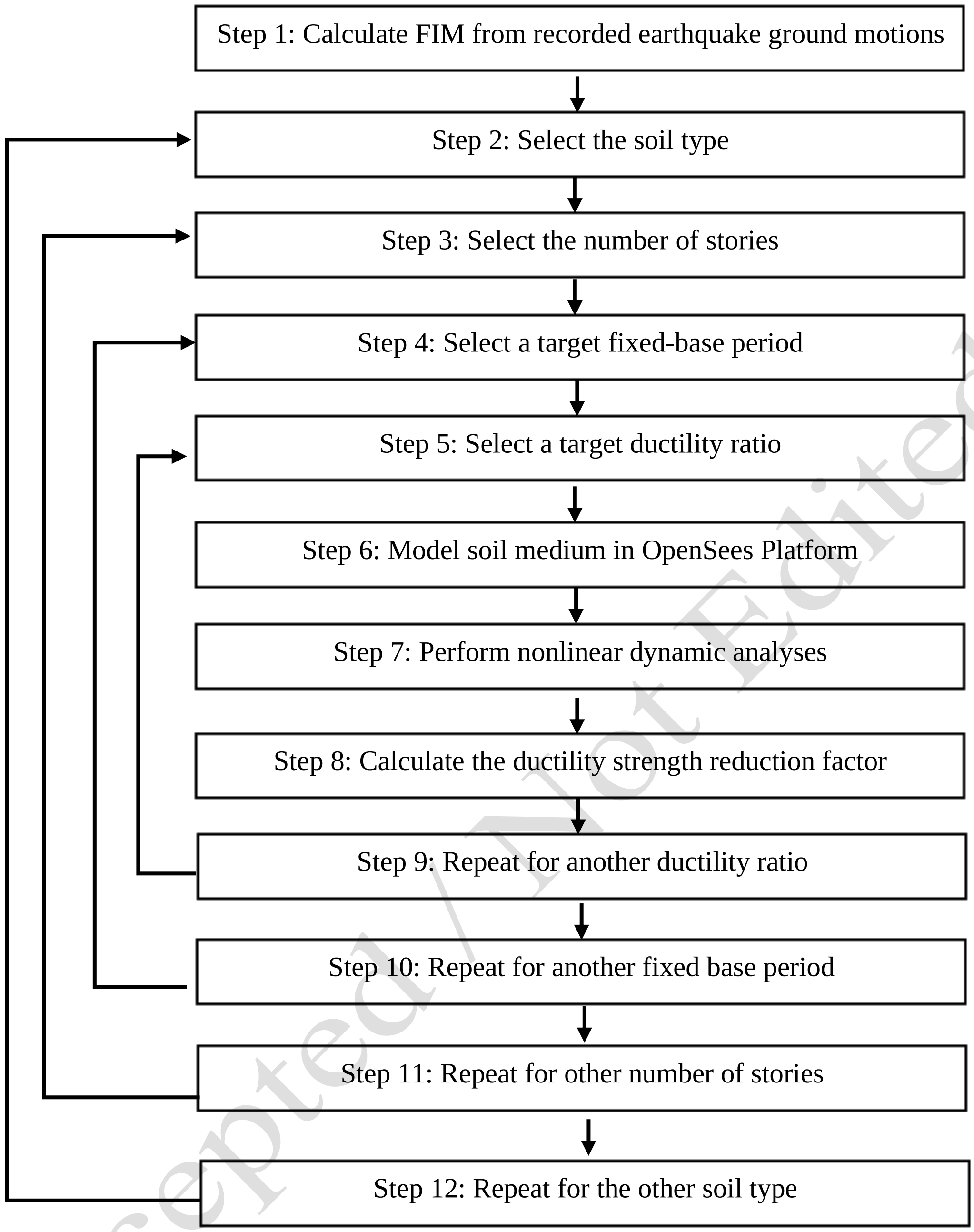


Fig. 1. The diagram of creation the process of the new strength reduction factor formula

According to the previous studies, the seismic response of the soil–structure system was dependent on the characteristics of the superstructure, soil, and input motion. The ductility demand ratio, structural fixed-base period, number of superstructure stories, the slenderness ratio, the foundation embedment ratio and soil flexibility defined by shear wave velocity and shear modulus, were found to be the parameters influencing the strength reduction factor. The equations for strength reduction factors found in existing literature were used as a guide to verify the correctness of the new formulation.

2. 1. Numerical models

Various structural models with different periods and level of ductility ratios were subjected to two-dimensional nonlinear analyses using OpenSees software. The height and ductility ratios of buildings with 3, 5, 10 and 15 stories varied in their structural designs, with a fixed base period ranging from 0.1 to 3 seconds. The strain hardening parameter for the lateral stiffness of the structure was considered to be 5%. The ductility ratios chosen were 2, 4 and 6 and Foundation embedment ratio (e/r) were 0.5, 1 and 2. r was the foundation equivalent radius, which was calculated according to **Eq. 2**.

$$r = \sqrt{\frac{BL}{\pi}} \tag{2}$$

Where B and L represented the width and length of the foundation.

Initially, the models were created assuming the shear structure's behavior based on **Fig. 2** in a fixed base case, through trial and error to achieve target ductility ratios of 2, 4 and 6, using nonlinear pushover analysis. The aim of this paper was to examine the strength reduction factor for typical buildings ranging from short to high-rise. Hence, several models were assumed as 3, 5, 10 and 15-story buildings with the story height of 3 meters and typical dead and live load. The structures were planned with three different aspect ratios $(H/r = 1.3.5)$ to address the slenderness ratios of typical buildings. As the R_{μ} factor is influenced by design ductility, three typical ductility ratio were selected (2, 4, 6). To design the structures, the defined steel sections in **Table 1** were initially utilized, followed by modifications to the mass and stiffness of the structures to achieve the target ductility ratio and encompass all the multi-story buildings. The structures were designed as a fixed-base models. The shear yield strengths of fixed-base structures were determined and applied as a yield point for the nonlinear behavior of flexible-base structures. After reaching the yield strength, the stiffness was altered due to a strain hardening of 5%.

Afterward, the designed structures were placed on soft soil surface and subjected to nonlinear dynamic analysis. The soil medium was described as an elastic shell element experiencing plane-strain conditions to address the gap in modeling found in literature reviews. As seen in **Fig. 3**, the soil medium was considered to be 30 meters deep with a width 7 times the length of the foundation. The soil's dimensions are taken into account to ensure they do not influence the structure's behavior beyond that point. The softer the soil, the greater the effect of soil-structure interaction, thus two types of soft soils were considered as **Table 2**.

Table 1.
Assumption of beam and column sections for initial trial

Model	Number of stories	Column Section	Beam Section
3-story	1,2,3	BOX 300x25	W300x10-200x15
5-story	1,2,3	BOX 350x25	W300x10-240x15
	4,5	BOX 300x25	W300x10-200x15
10-story	1,2,3,4	BOX 400x25	W350x10-300x15
	5,6,7,8	BOX 350x25	W300x10-300x15
	9,10	BOX 300x25	W300x10-200x15
15-story	1,2,3,4	BOX 500x25	W400x10-350x15
	5,6,7,8	BOX 450x25	W400x10-350x15
		BOX 400x25	W400x10-240x15
		BOX 300x25	W300x10-240x15

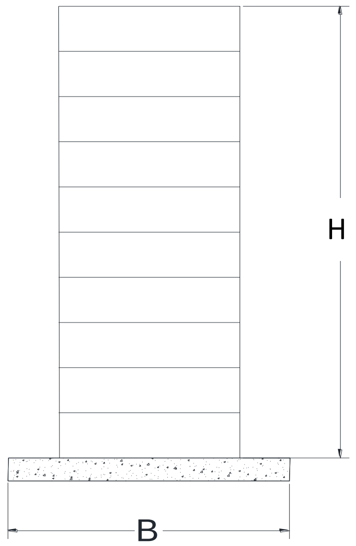


Fig. 2. Structural models

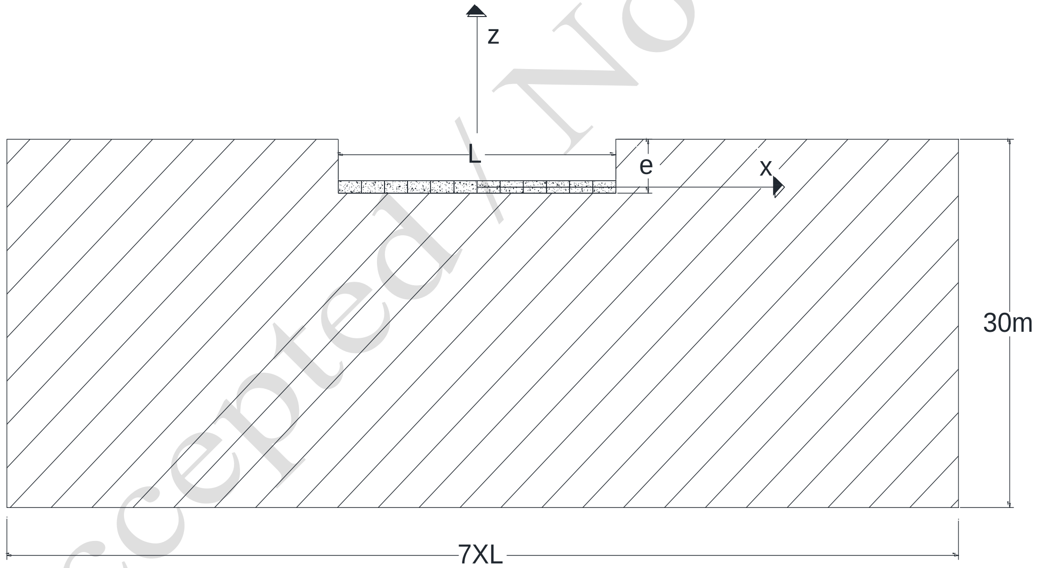


Fig. 3. Soil Geometry

2. 2. Kinematic Interaction

The literature stated that in an embedded foundation, the kinematic interaction not only altered the horizontal excitation but also generated a rotational component in the foundation input excitation. Various methods exist to consider the kinematic interaction and calculate the input excitation to the foundation. Transfer functions were employed in these techniques to determine the horizontal components and the period of the input excitation at the base. To determine the foundation input excitation in the time domain, these transfer functions acquired in the frequency domain need to be used through a series of steps.

1- Using the Fourier transform, the record of the free field motion was obtained in the frequency domain.
2- The transfer functions were calculated and multiplied in the free field excitation in the frequency domain and resulted in the FIM components in the frequency domain.
3- By using the inverse of the Fourier transform, the time history of the horizontal and rotational components of the foundation input motion were calculated.

This research utilized Elsabee *et al*.'s transfer functions, one of the most popular methods. The transfer functions developed by Elsabee *et al.* (1977) for a foundation with embedded depth *e* subjected to vertical shear waves to determine the horizontal and rocking components of the input excitation in the frequency domain, were as follows:

$$u_{FIM} = H_u(\omega) u_g \tag{3}$$

$$H_u(\omega) = \frac{u_{FIM}}{u_g} = \begin{cases} cos\left(\frac{\omega e}{V_s}\right) & \omega \leq 0.7\frac{\pi}{2}\frac{V_s}{e} \\ 0.453 & \omega > 0.7\frac{\pi}{2}\frac{V_s}{e} \end{cases} \tag{4}$$

$$\theta_{FIM} = \frac{2u_g}{L} \times H_\theta(\omega) \tag{5}$$

$$H_u(\omega) = \frac{\theta_{FIM} L}{2u_g} = \begin{cases} 0.257\left[1 - cos\left(\frac{\omega e}{V_s}\right)\right] & \omega \leq \frac{\pi}{2}\frac{V_s}{e} \\ 0.257 & \omega > \frac{\pi}{2}\frac{V_s}{e} \end{cases} \tag{6}$$

In the above relations, ω was the earthquake wave frequency in radians per second, V_s was the shear wave velocity, L was the foundation's length along the excitation direction, u_{FIM} and θ_{FIM}were the horizontal and rocking components of the foundation input motion, respectively and u_g was the free field motion of the ground (FFM). Then $H_u(\omega)$ and $H_u(\omega)$ were transfer functions of the horizontal and rocking components of FIM, respectively.

2. 2. Soil characteristics

Two varieties of soft soil with soil flexibility effects were utilized in the research, both with a shear wave velocity under 600 m/s. The main features of the selected soils were outlined in **Table 2**. To implement boundary conditions in the soil environment, viscous Lysmer absorbent boundaries were applied in accordance with **Eqs. 7-8**. **Eq. 7** represented the damping value of the dampers perpendicular to the face (t_n) while **Eq. 8** represented the damping in the tangential direction (t_s) (Lysmer and Kuhlemeyer, 1969).

$$t_n = \rho C_p A \tag{7}$$

$$t_s = \rho C_s A \tag{8}$$

Where ρ, A, C_p and C_s were the soil density, the cross-sectional area of the soil environment, the compression wave velocity and the shear wave velocity, respectively.

Table 2.
Geotechnical Characteristics of the Soil

Soil Type (ASCE 7-22)	**Shear Wave Velocity** (m/s)	**Poisson's Ratio**	**Soil Density** (kg/m^3)	***C'*** (kg/m^2)	**f'** (Degree)
D	200	0.4	1800	0	30
E	150	0.45	1700	5	25

2. 3. Earthquake Ground Motions

In accordance with the peer ground motion database, a set of 22 earthquake ground motions recorded on soft soil deposits (soil type D and E) were chosen and utilized in the nonlinear dynamic time history analyses. Information about the chosen ground movements was documented in **Tables 3-4**. Every earthquake selected had a magnitude exceeding 6 on the Richter scale. It should be pointed out that the chosen earthquake records were considered as free field ground motions.

The strength reduction factor (R_μ) was computed once, excluding kinematic interaction and utilizing FFM data. Next, using transfer functions, the foundation input motion was determined and R_μ was calculated using updated data.

Table 3.
Selected ground motions recorded at site Class D

No.	**Earthquake Name**	**Year**	**Magnitude**	**Recording Station Name**	**Vs (m/s)**	**PGA(g)**
1	Imperial Valley	1979	6.53	"Parachute Test Site"	348.69	0.11267
2	Imperial Valley	1979	6.53	"El Centro Array #13"	249.92	0.11796
3	Whittier Narrows-01	1987	5.99	"Downey - Co Maint Bldg"	271.9	0.20451
4	Whittier Narrows-01	1987	5.99	"LA - 116th St School"	301	0.27251
5	Landers	1992	7.28	"Yermo Fire Station"	353.63	0.24452
6	Loma Prieta	1989	6.93	"Palo Alto - 1900 Embarc."	209.87	0.12694
7	Loma Prieta	1989	6.93	"Dumbarton Bridge West End FF"	238.06	0.13837
8	Loma Prieta	1989	6.93	"Richmond City Hall"	259.9	0.12563

9	Northridge-01	1994	6.69	"Lakewood - Del Amo Blvd"	267.37	0.13327
10	Northridge-01	1994	6.69	"Downey - Birchdale"	245.06	0.14268
11	Morgan Hill	1984	6.19	"APEEL 1E - Hayward"	219.8	0.0409

Table 4.
Selected ground motions recorded at site Class E

No.	Earthquake Name	Year	Magnitude	Recording Station Name	Vs (m/s)	PGA(g)
192	Imperial Valley	1979	6.53	"Westmorland Fire Sta"	193.67	0.07605
174	Imperial Valley	1979	6.53	"El Centro Array #11"	196.25	0.36681
732	Loma Prieta	1989	6.93	"APEEL 2 - Redwood City"	133.11	0.27441
759	Loma Prieta	1989	6.93	"Foster City - APEEL 1"	116.35	0.12694
780	Loma Prieta	1989	6.93	"Larkspur Ferry Terminal (FF)"	169.72	0.12563
962	"Northridge-01"	1994	6.69	"Carson - Water St"	160.58	0.09145
452	"Morgan Hill"	1984	6.19	"Foster City - APEEL 1"	116.35	0.04295
760	Loma Prieta	1989	6.93	"Foster City - Menhaden Court"	126.4	0.10977
2473	"Chi-Chi_ Taiwan-03"	1999	6.2	"CHY047"	169.52	0.05419
1228	"Chi-Chi_ Taiwan"	1999	7.62	"CHY076"	169.84	0.07001
808	Loma Prieta	1989	6.93	"Treasure Island"	155.11	0.10026

The acceleration time history of the free field ground motion of Imperial Valley earthquake and its Fourier spectrum were shown in **Figs. 4-5**. Then, utilizing MATLAB, the Fourier transform was computed for all data sets and the time-domain signals were extracted using the Fourier inverse. An illustration of the horizontal and rocking foundation input motion of Imperial Valley earthquake can be seen in **Fig. 6**.

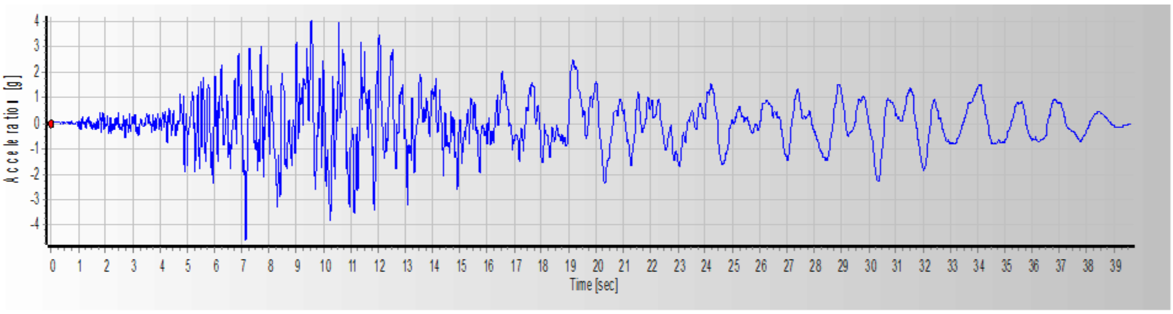


Fig. 4. Acceleration time history of Imperial Valley earthquake ground motion

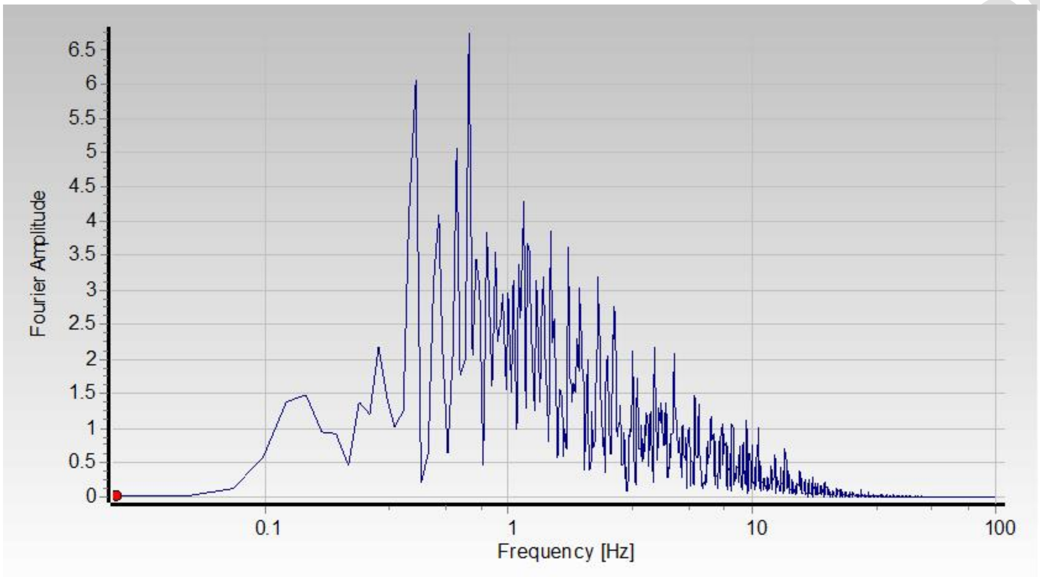
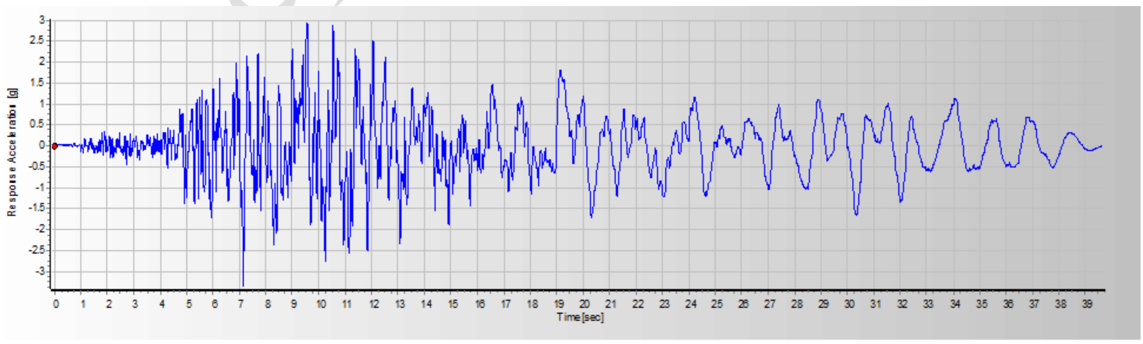


Fig.5. Fourier spectrum of Imperial Valley earthquake ground motion

(a)



(b)

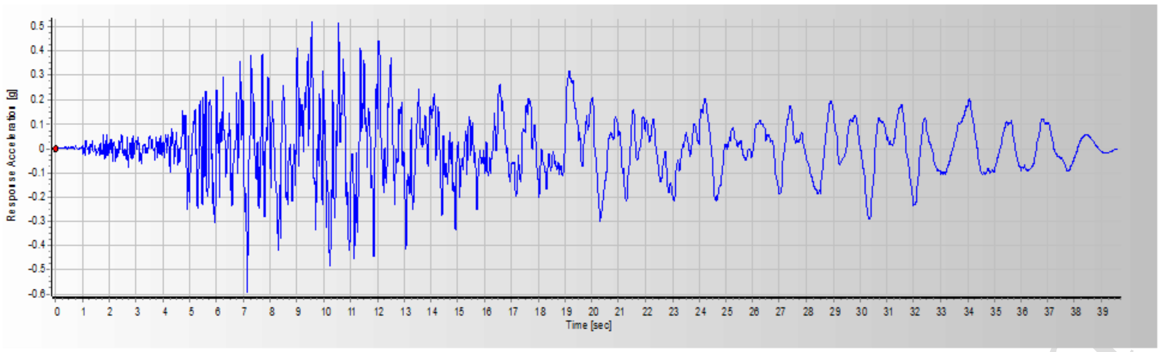


Fig. 6. Foundation input motion for Imperial Valley earthquake, (a) horizontal motion, (b) rocking motion

3. Effects of Soil-Structure Interaction on Strength Reduction Factor

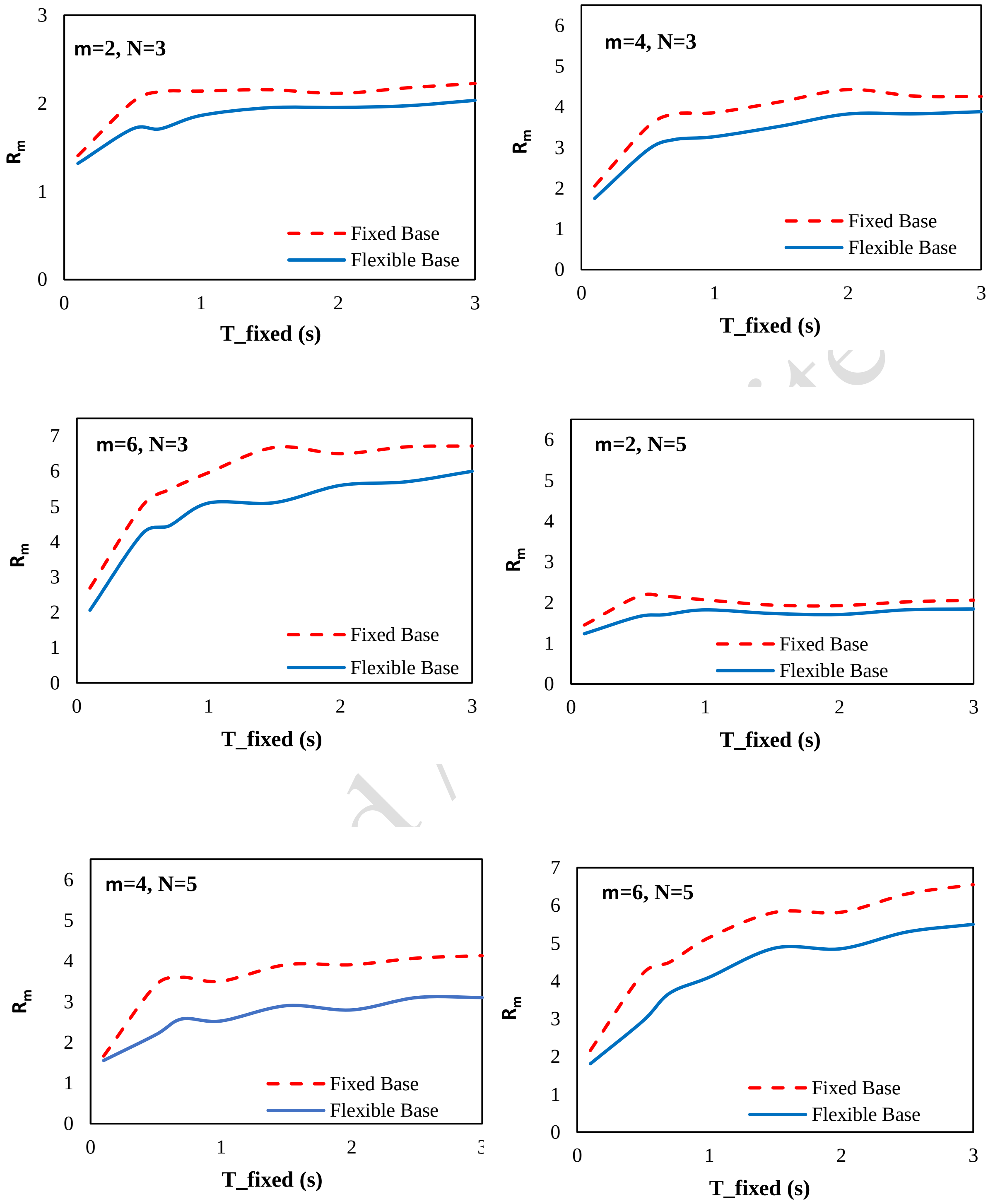
To derive a novel calculation expression for the ductility strength reduction factor applicable to multi-story buildings on soft soil, it was essential to first analyze how the key parameters influence this factor. Thus, This part looked at how SSI affects R_μ values for the selected buildings. As mentioned before, several dynamic time history analyses are used to figure out the elastic and inelastic strength demands of designated structures. The number of stories a building had determined its classification. In every group, the fixed-base time period varied from 0.1 to 3 seconds, with ductility ratios of 2, 4, and 6. The analysis of each model was conducted using 22 specific ground motions, and the outcomes were determined based on the average of all the analyses. According to the outcomes of this section, the design expressions for calculating R_μ were determined in **Section 4**.

3.1. Fixed-base and Flexible-based conditions

Based on **Fig. 7** analysis, it was found that in general, SSI could reduce the values of R_μ. The research indicated that the strength reduction factor declines with softer soil conditions. The cause of this was evident in **Fig. 8**. Soil-structure interaction lowered the strength required to achieve a desired level of ductility, in both elastic (F_e) and inelastic conditions (F_y). This diagram illustrated that the decrease in strength was greater in the elastic range compared to the inelastic range. Therefore, in **Eq. 1**, the numerator got smaller than the denominator, causing a decrease in strength demand compared to a rigid base. In this case, the use of the strength reduction factors of fixed base case state, proposed in the design codes, will lead to an underestimation of the strength demand of the soil-structure systems. Similar to the findings of Mourlas *et al*., it was discovered that the predicted base shear for a two-story RC plane frame decreased by 20-30% when compared to a fixed-base model.

In simpler terms, the soil-structure system's inelastic strength for the specific level of ductility, will be reduced compared to the actual strength. As a result, this leads to the development of ductility that exceeds the desired level in the building's structure. So, it would result in a non-conservative design of the structure. Particularly in short periods, the structure becomes more susceptible due to its inflexibility.

After analyzing the data, it can be inferred that the impact of soil flexibility rises with the number of stories and, as a result, R_μ decreases even more when the ductility ratio is increased. The reduction of R_μ was more pronounced in situations where ductility ratios were high, as opposed to the fixed base condition. Additionally, in buildings with a low ductility ratio ($\mu = 2$), the variations in the strength reduction factor were not strongly connected to the height of the building or the fixed period of the building. The outcome indicates that the greater ductility required, based on the force-displacement diagrams of a structure, the elastic force rises to level the surface under both elastic and inelastic diagrams, necessitating a further decrease in the elastic force and an increase in the ductility strength reduction factor.


m=2, N=3
m=4, N=3
m=6, N=3
m=2, N=5
m=4, N=5
m=6, N=5
Fixed Base
Flexible Base
R_m
T_fixed (s)

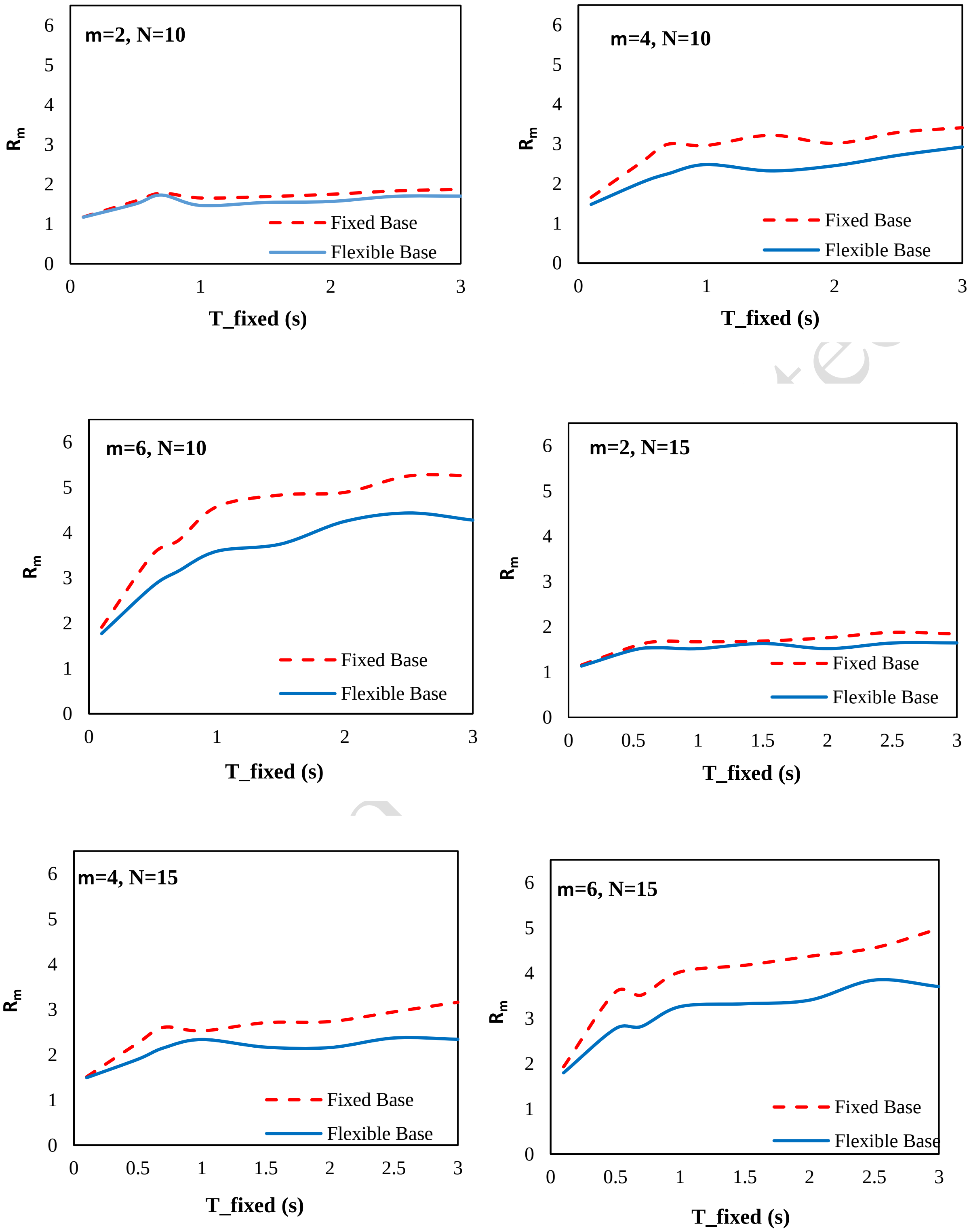


Fig. 7. Strength reduction factor of fixed-base case and flexible-base case for 3, 5, 10 and 15 story structures on soil type D

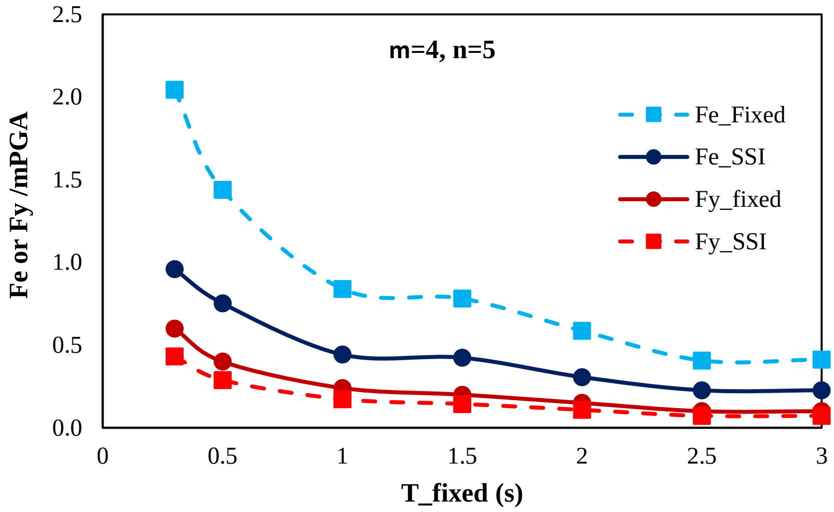


Fig. 8. Elastic and inelastic strength spectrum of the soil-structure system on soil D compared to fixed-base condition

As stated, according to Fig. 8, the strength demand of the structure was reduced in the soft base condition compared to the fixed-base case. This decrease occurred because of the extra horizontal movements generated at the bottom of the structure and transferred to the floors, resulting in diminished strength during large deformations

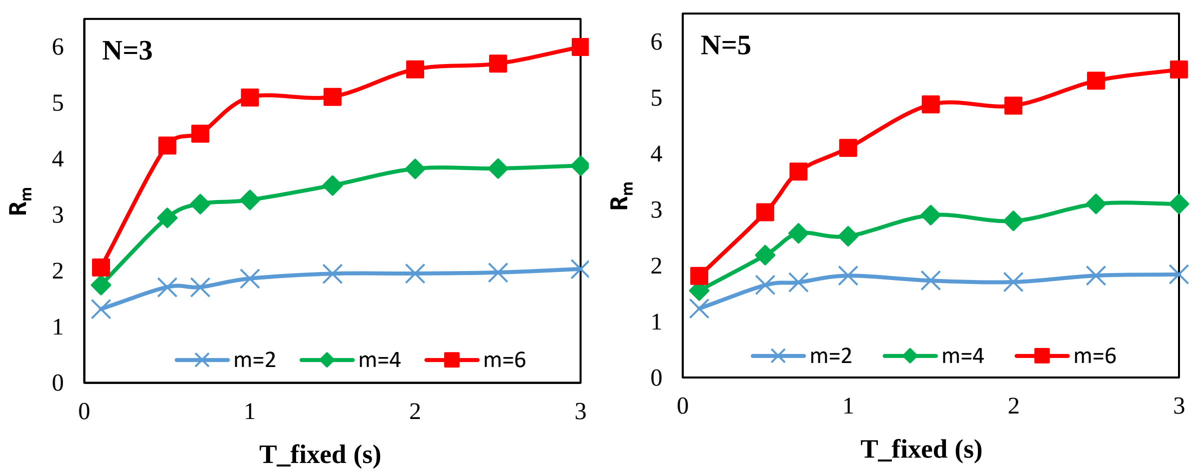
3.2. Target Ductility Ratio

Fig. 9 illustrated the differences in the average strength reduction factor among all buildings designed to reach a specific level of ductility. According to the findings, it can be deduced that R_μ and μ were directly related. These figures showed that regardless of the number of stories, the higher the target ductility ratio (μ), the greater the strength reduction factor R_μ. This means that as the structure required more flexibility, the ratio of elastic strength to inelastic strength demand increased. As noted previously, this event was linked to the rise in elastic force required to balance the surface beneath both elastic and inelastic graphs, causing an increase in the ductility strength reduction factor.

As the level of inelastic response rose, the influence of SSI on the ductility strength reduction factor became more significant, leading to a simultaneous decrease in R_μ values as the soil-structure interaction effect intensifies. This problem was highlighted in section 3.3, where the impact of soil softness was analyzed.

Moreover, upon viewing the charts, it was clear that, in general, as the fixed base period grew, there was an increase in the strength reduction factor for shorter periods, whereas for longer periods, it either varied slightly with a slight upward trend or stayed close to zero. This outcome indicates that rigid structures with shorter periods are more sensitive to substrate flexibility.

Based on these graphs, it was evident that as the design's ductility ratio increased from 2 to 4 (low to medium ductility), the decrease in the strength reduction factor was greater than for higher ductility ratios. In simpler terms, the decrease in the strength reduction value comparing to fixed base structure, remained stable in highly ductile ranges and was not affected by the substrate's flexibility. This outcome indicated that in stiff buildings situated on a soft soil where experiencing a higher demand of ductility, the decrease in R_μ values and the impact of the SSI were more evident. As a result, the seismic design outcomes based on the guidelines may not accurately portray the actual performance of the structure.



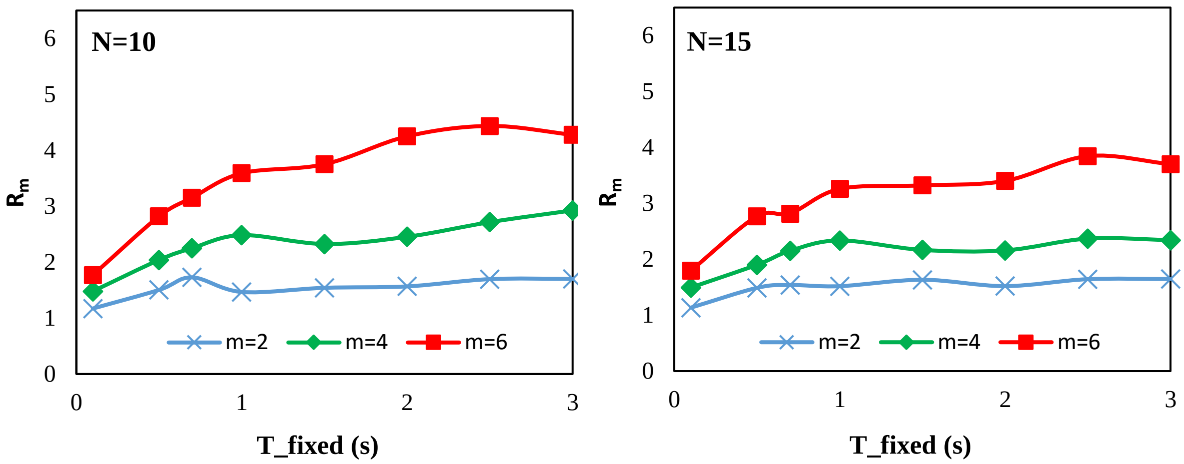
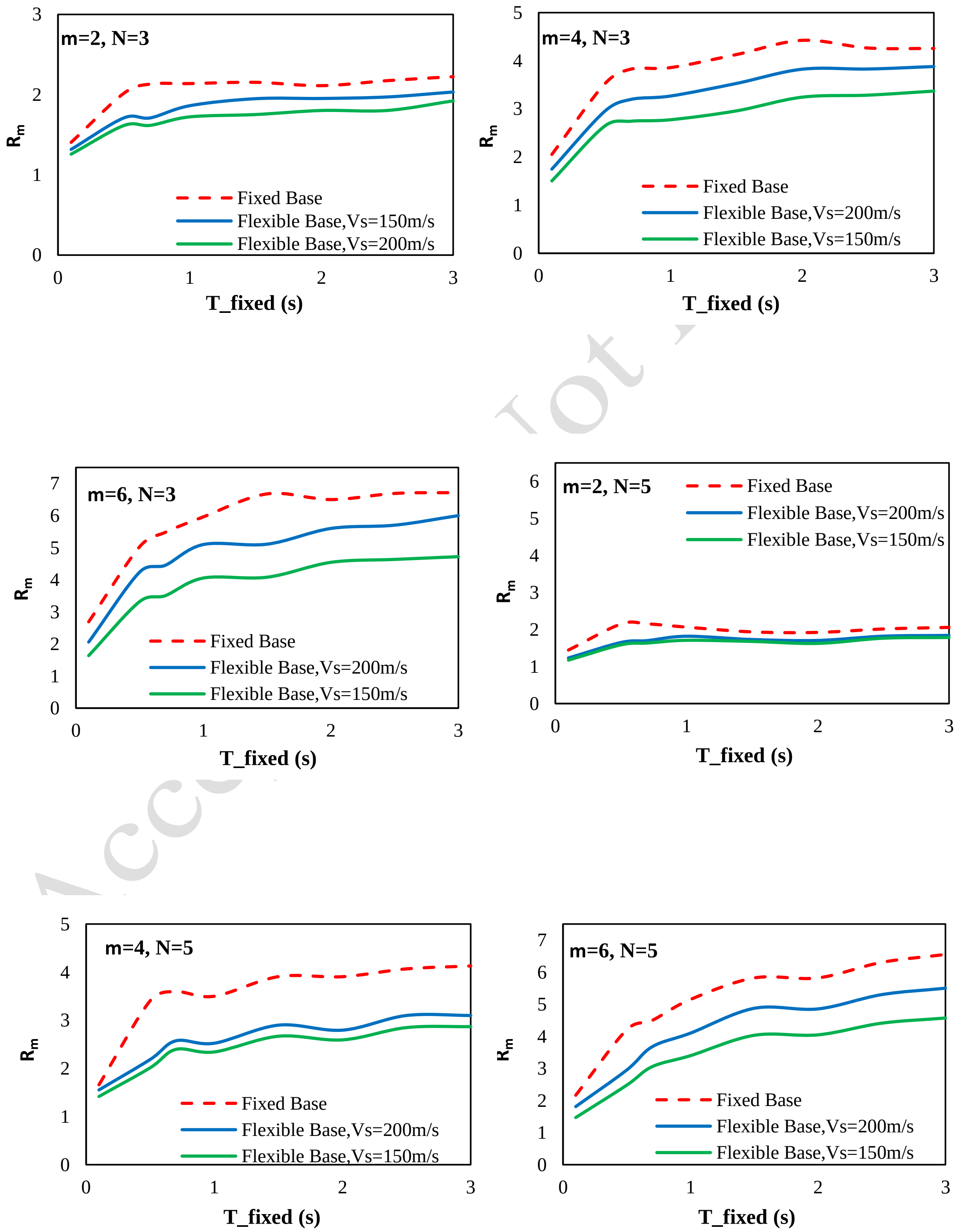


Fig 9. The effect of ductility demand ratio on Ductility Strength reduction factor for 3, 5, 10 and 15 story structures on soil type D

3.3. Effects of Soil Type

The results for both soil types were shown in **Fig. 10** in comparison to the fixed base case. Comparing the graphs revealed that the soil-structure system had a lower strength reduction factor than the fixed-base structure. Additionally, a comparison of the strength reduction factor results of soil D and E revealed that higher soil softness, as indicated by lower shear wave velocity, led to increased effects of soil-structure interaction. This resulted in a decrease in the ductility strength reduction factor R_{μ}. It means that, since the soil-to-structure stiffness is low, the system's flexibility increases, leading to a greater impact of SSI on seismic response of structures. Consequently, due to the extra foundation displacement, the base shear reduces, and the strength reduction factor lessens compared to that of rigid soil or a fixed-base case.

On the other hand, the design code's strength reduction factors were based on a fixed base assumption, which may not be appropriate for real structural situations, especially if a stiff structure is built on soft ground. In this case, the design strength reduction factor will underestimate the actual value, leading to non-conservative design outcomes. Therefore, it is essential to consider the soil in structural modeling and evaluate the outcomes of the entire system when soil-structure interaction effects are significant. As a result, the main goal of this paper is highlighted, which is to develop a way for calculating the strength reduction factor of soil-structure systems.



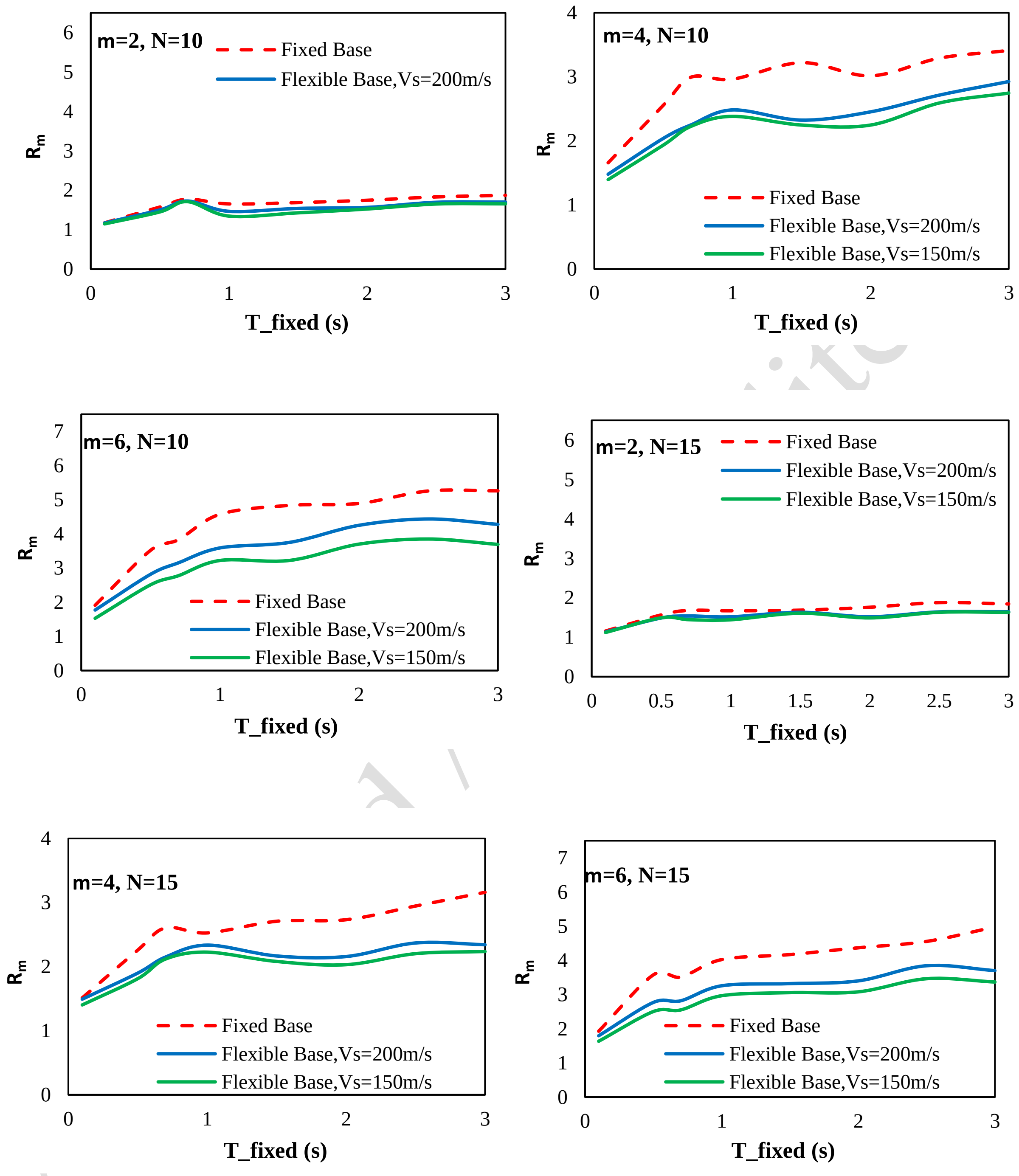


Fig. 10. The effect of ductility demand ratio on Ductility Strength reduction factor for 3, 5, 10 and 15 story structures on soil type D and E

3.4. Effects of number of stories

It was found that as the number of stories increased, the seismic strength reduction factor R_μ of multi-story buildings constructed on various soft soil types in accordance with **Figs 9-10** decreased. This decrease was especially remarkable when it came to increased levels of ductility. This indicated that the soil-structure interaction had a greater impact on the strength demand of shorter buildings with less floors.

Short buildings (3 and 5 floors) experienced a greater reduction in R_μ values compared to tall buildings (10 and 15 floors). In simpler terms, as the number of stories in tall buildings increased, the rate of decrease in reduction of R_μ was not as significant as in shorter buildings, resulting in a similar value in 10- and 15-story buildings. This refers to the fact that SSI had a greater impact on structures of shorter to medium lengths.

3.5. Effects of Aspect Ratio

Fig. 11 demonstrated how the aspect ratio (*H*/*r*) impacts R_μ. The aspect ratio equaled the structure's effective height divided by the foundation's equivalent radius. As the aspect ratio grew, so R_μ did the increase. Based on the previous sections, a higher ductility ratio resulted in increased variations in R_μ. In fact, the effect of soil-structure interaction in reducing the strength demand of slender structures was less than that of squat structures (*H/r*=1). However, in slender structures, the lateral displacements may be amplified by the translational and rocking displacements of the foundation due to kinematic interaction and P-delta effects, thus demonstrating the destructive effect of soil-structure interaction in slender structures.

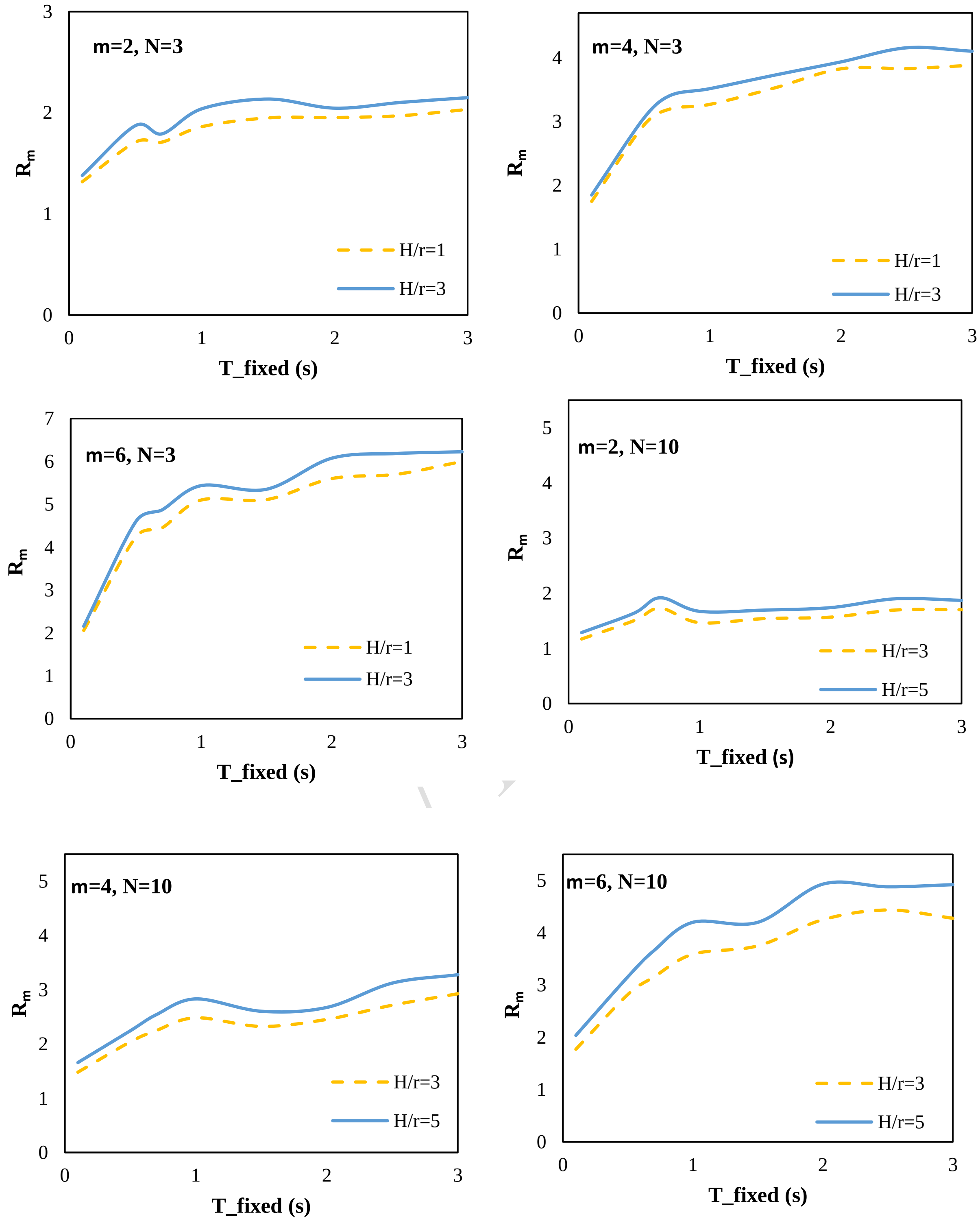
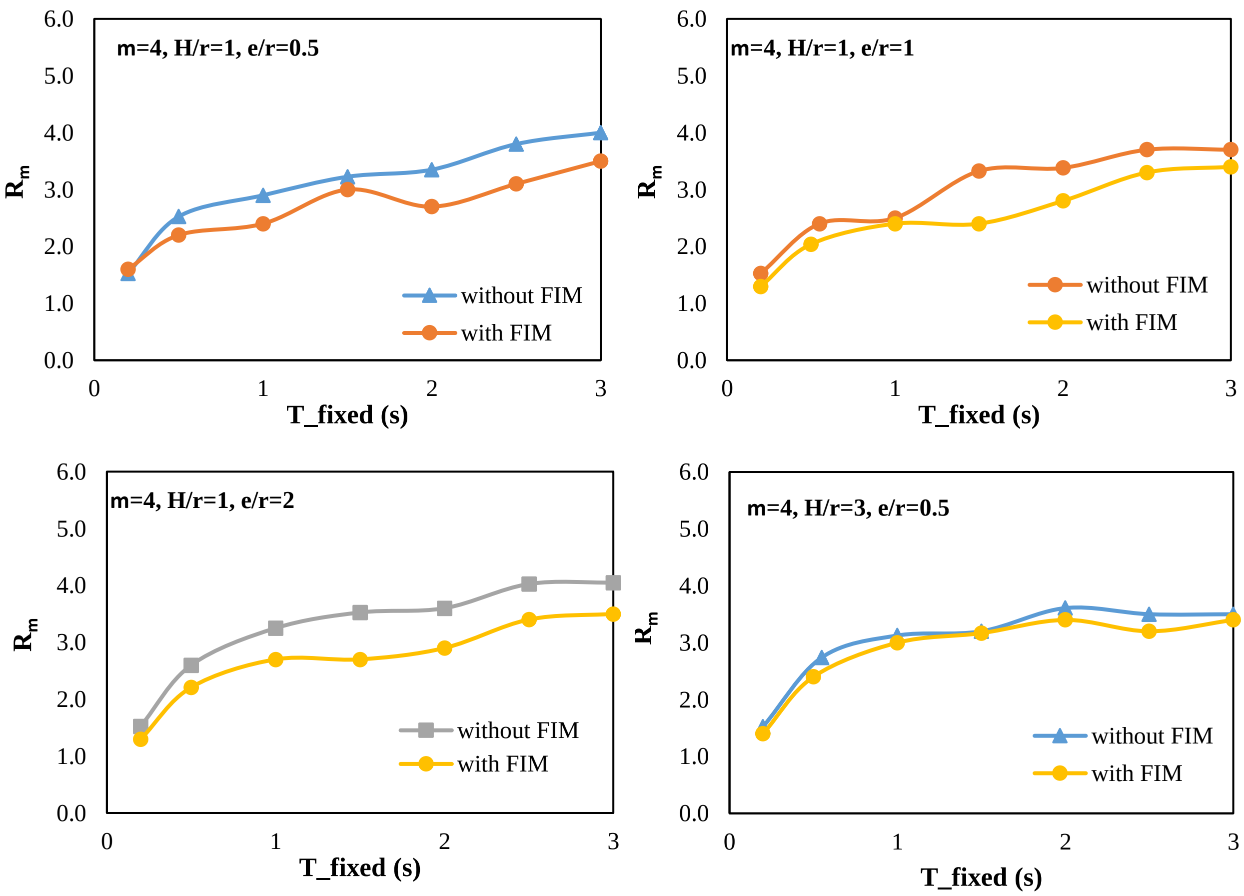


Fig. 11. The effect of aspect ratio on Ductility Strength reduction factor for 3 and 10 story structures

3.6. Effects of Kinematic Interaction

Fig. 12 illustrated the influence of the foundation embedment depth and kinematic interaction on 10-story structures. According to this diagram, it was observed that for the squat structure (*H/r*=1), the kinematic interaction decreased the strength reduction factor for all three types of foundation embedment. Less reduction in R_μ was achieved as the embedment ratio increased. Yet, in slender structures ($H/r = 3.5$), a decrease in foundation embedment depth ($e/r = 0.5.1$) did not impact on R_μ, and with an increase in embedment depth ($e/r = 2$), there could even be an increase in R_μ. Based on the research by Mahsuli and Ghannad (2009), foundation embedment was advantageous for squat structures while it might increase ductility demands for slender buildings. The primary factor in this phenomenon was the rocking motion caused by KI.



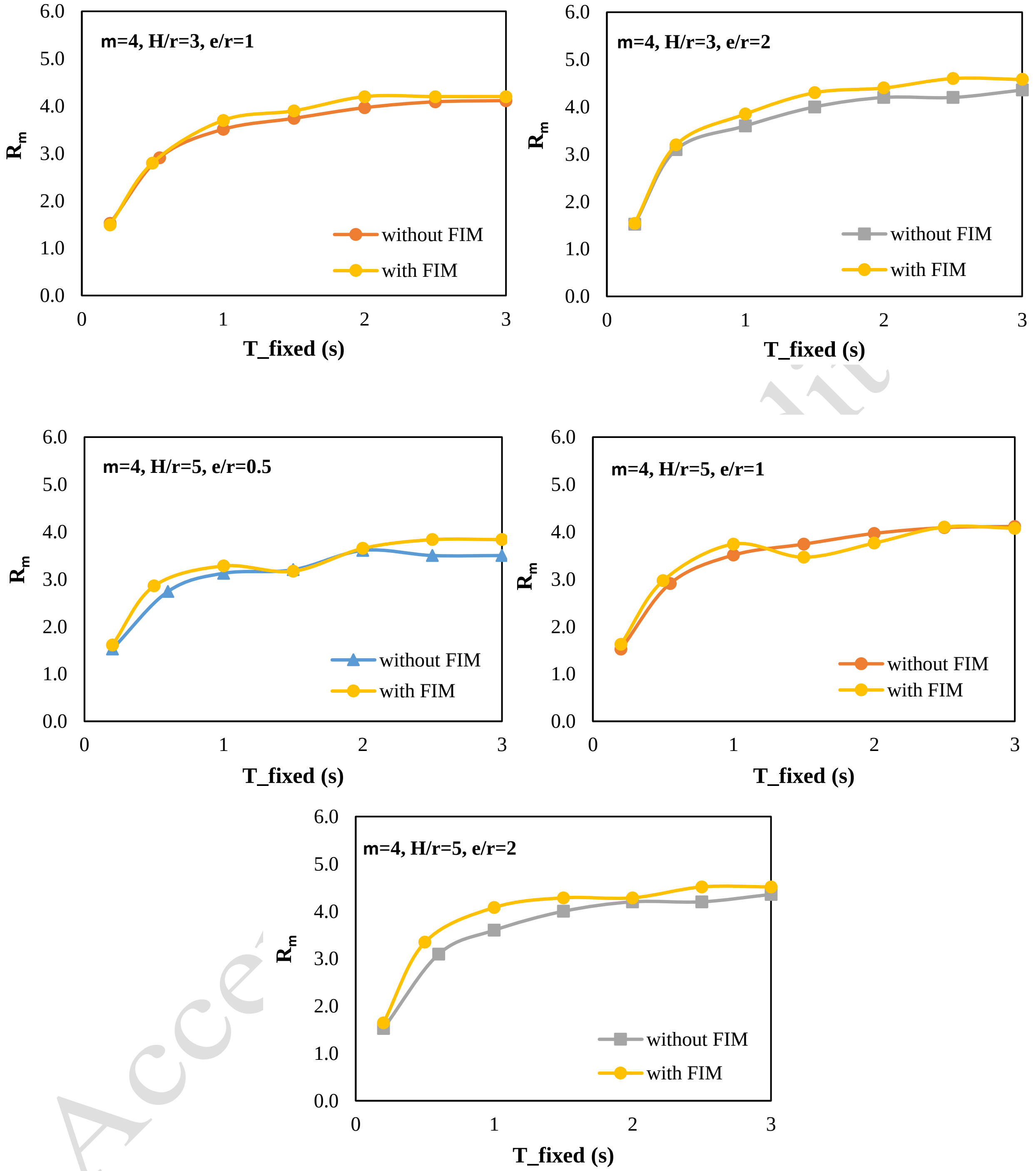


Fig. 12. The effect of kinematic interaction on Ductility Strength reduction factor for 10 story structures

4. Suggested Expression for Strength Reduction Factor of Soil-Structure Systems

As mentioned before, the strength reduction factor of the soil-structure systems decreased because of the soil-structure interaction effect. Therefore, the suggested reduction factor in design guidelines could lead to a significant underestimation of inelastic strength needs and lateral displacement of soil-structure systems, particularly when the ductility ratio is high.

Hence, it is essential to have a simple formulation for evaluating strength reduction factors for soil-structure systems in seismic design. Using the information shown in the previous pictures (**Figs. 7-11**), it was determined that nonlinear dynamic analyses resulted in suggesting a fundamental equation for soil-structure systems that considers the flexibility of the soil.

$$R_{\mu-SSI} = \left(\alpha \ln T_{fixed} + \beta\right)/\delta \leq \mu \tag{9}$$

Where α and β parameters were established based on the ductility ratio and the number of stories in the building, as seen in the findings of **Fig. 9**. Based on the results shown in **Fig. 10**, soil type E, which had a lower shear wave velocity ($V_s = 150\,\mathrm{m/s}$), also had lower R_μ compared to the soil D. Thus, the δ parameter was utilized to modify **Eq. 9** for soil type E, originally designed for soil type D. α, β and δ were formulated by **Eqs. 10-18** which were classified based on ductility ratios ($\mu = 2.4.6$).

- For $\mu = 2$**:**

$$\alpha = 0.0011N^2 - 0.0247N + 0.2671 \tag{10}$$

$$\beta = \frac{2.119}{n^{0.136}} \tag{11}$$

$$\delta = \frac{1.0933}{n^{0.022}} \tag{12}$$

- For $\mu = 4$:

$$\alpha = 0.0013N^2 - 0.0527N + 0.7459 \tag{13}$$

$$\beta = \frac{4.335}{n^{0.289}} \tag{14}$$

$$\delta = \frac{1.21}{n^{0.057}} \tag{15}$$

- For $\mu = 6$:

$$\alpha = -0.0005N^2 - 0.0385N + 1.2711 \tag{16}$$

$$\beta = \frac{6.894}{n^{0.315}} \tag{17}$$

$$\delta = \frac{1.36}{n^{0.076}} \tag{18}$$

The equations previously given were obtained under the assumption of an aspect ratio of 1 (*H*/*r*=1). It is advisable to use a modification factor, γ, as **Eqs. 19-20**, when the aspect ratio is greater than one.

$$1 < \frac{H}{r} \leq 3 \rightarrow \gamma = 0.0013\mu^2 - 0.0075\mu + 1.07 = 0.75\left[17\left(\frac{\mu}{100}\right)^2 - \left(\frac{\mu}{100}\right)\right] + 1.07 \tag{19}$$

$$\frac{H}{r} > 3 \rightarrow \qquad \gamma = -0.0025\mu^2 + 0.03\mu + 1.05 = 3\left[\frac{1}{12}\left(\frac{\mu}{100}\right)^2 - \left(\frac{\mu}{100}\right)\right] + 1.05 \tag{20}$$

Based on the literature, kinematic interaction resulted in an added rocking component in the foundation input motion, leading to increased lateral displacement of buildings, particularly tall slender buildings.

According to **Fig. 12**, it was noted that the kinematic interaction did not cause a major impact on the strength reduction factor of the buildings. It decreased the factor in squat structures by 10 percent, yet the changes may not be easily noticeable. Conversely, in slender embedded structures, kinematic interaction rose the strength reduction factor by 5 percent.

5. Results and Discussion

Based on the findings mentioned above, the strength reduction factors for soil-structure systems were less than those for fixed-base structures. Therefore, it would not be suitable to utilize fixed-base factor recommendations from the design code. A deficiency in research and design guidelines has been identified regarding the recommendation of a comprehensive approach to predict the strength reduction factor of multi-story buildings with consideration of SSI. Hence, it is necessary to examine how SSI impacts the strength reduction factor and suggest an appropriate method for calculating the factor in light of SSI effects. To reach this objective, various structures ranging from 3 to 15 stories were subjected to numerical time history analyses with ductility ratios of 2, 4, and 6 and the elastic and inelastic demand of each structure were calculated. Then a novel formulation was created based on the findings. The formulation was determined by considering the ductility ratio, fixed-base period, aspect ratio, soil type, and number of stories. This section assessed the credibility and precision of the obtained relationships and their parameters through numerical and existing experimental data.

5.1. Verification

This section verified the accuracy of the formulation by comparing it to numerical findings from Eser *et al*. (2011) and Ganjavi and Hao (2014). The results from both the proposed model and previous research were presented in **Fig. 13**.

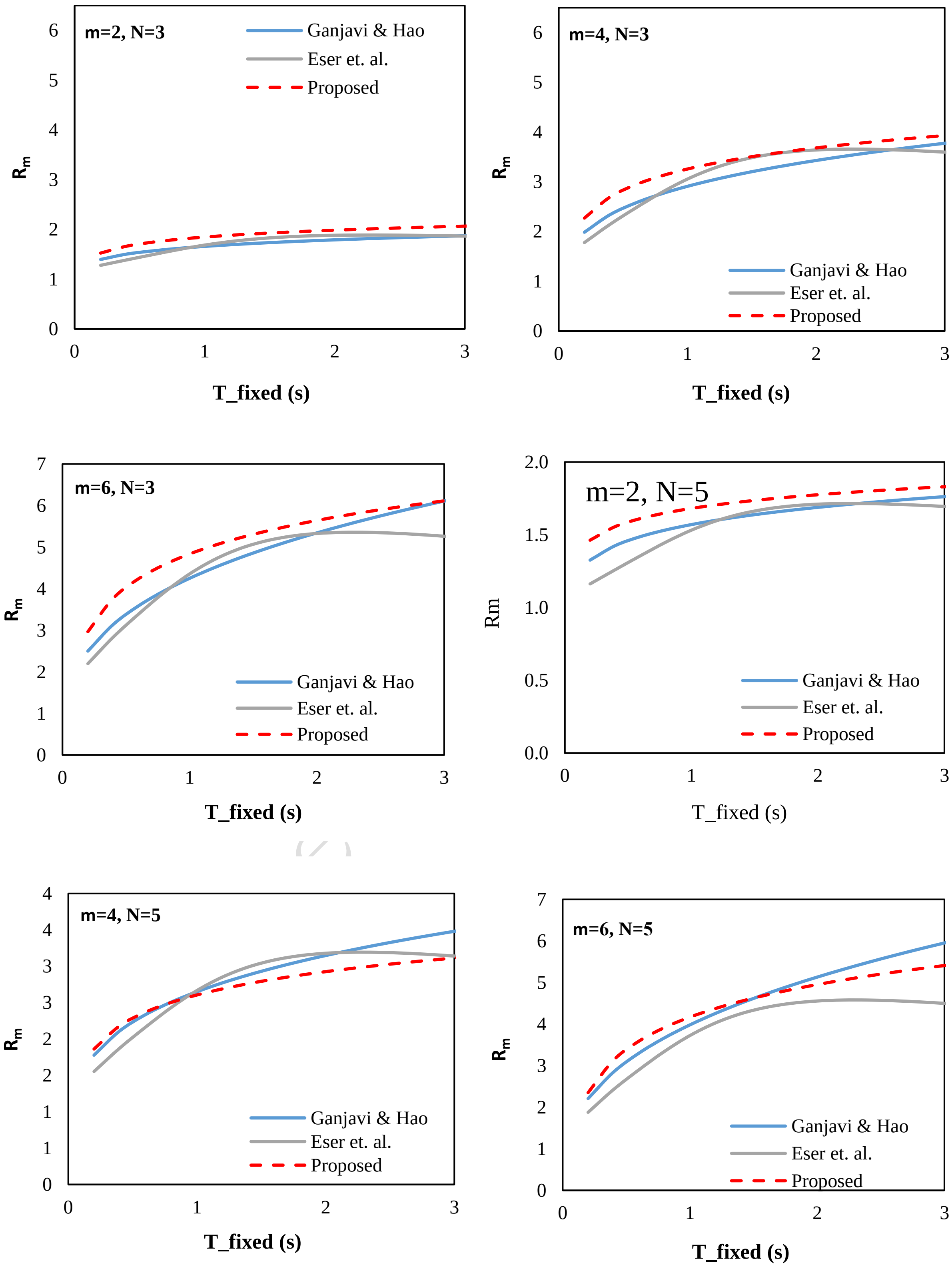
Eser *et. al*. utilized effective period, effective damping, and effective ductility values in their study of soil-structure interaction systems. They proposed a formula for the strength reduction factors of SDOF systems with periods between 0.1 and 3.0 seconds showcasing elastoplastic behavior. To account for the impacts of multiple degrees of freedom (MDOF), the equation proposed by Lu *et. al*. (2016) was utilized. This formulation was developed based on several analyses of shear building models involving soil represented as a cone model.

Ganjavi and Hao (2014) examined different Multiple Degrees of Freedom (MDOF) systems and their Equivalent Single Degree of Freedom (E-SDOF) systems in shear-beam models subjected to earthquake ground motions. They presented a formula for estimating strength reduction factors for MDOF soil–structure systems. The soil–foundation element is represented by a cone model-based equivalent linear discrete model.

Based on **Fig. 13**, it was found that the R_μ calculated in the new method utilized a similar approach to previous research formulas. For instance, a decrease in R_μ was noticed with an increase in the number of stories. Increasing both the ductility ratio and the fixed period of structures results in an increase in R_μ.

The methods suggested in this research and Ganjavi and Hao (2014) were similar in approach. As *n* increased, the difference between these two formulations also increased. This showed that the proposed formulation was greater than Ganjavi and Hao's recommendation for fewer stories, and lesser for more stories. Since Ganjavi and Hao's study inaccurately modeled the effects of SSI by using a simplified cone model instead of a full continuum modeling of soil. In addition, the impact of SSI typically rose as the number of stories (*n*) increased. Consequently, the suggested expression for R_μ demonstrated a reduction in a greater number of stories.

On the other hand, the suggestion R_μ put forward by Eser *et. al*. mirrored two other approaches for a smaller number of stories. Nevertheless, as *n* grew, the difference between this method and two others also grew wider. It could be seen that using the MDOF modification suggested by Lu *et. al*. (2016) is not appropriate for the SDOF system introduced by Eser *et. al*. Hence, Eser *et. al*.'s method would not be considered suitable for MDOF buildings


m=2, N=3
m=4, N=3
m=6, N=3
m=2, N=5
m=4, N=5
m=6, N=5
Ganjavi & Hao
Eser et. al.
Proposed
R_m
Rm
T_fixed (s)

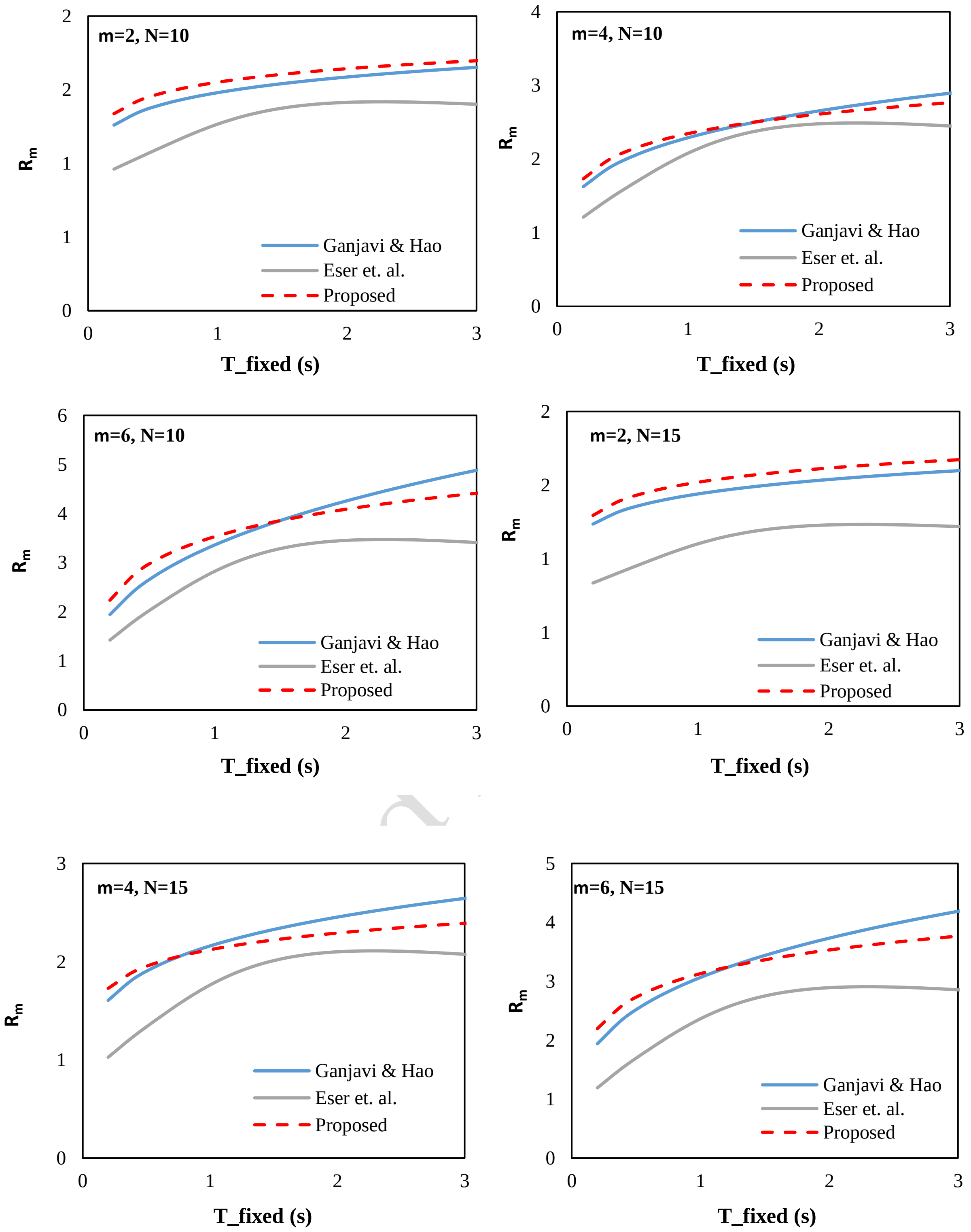


Fig. 13. The comparison between the proposed formulation and the previous studies

5.1. Sensitivity Analysis

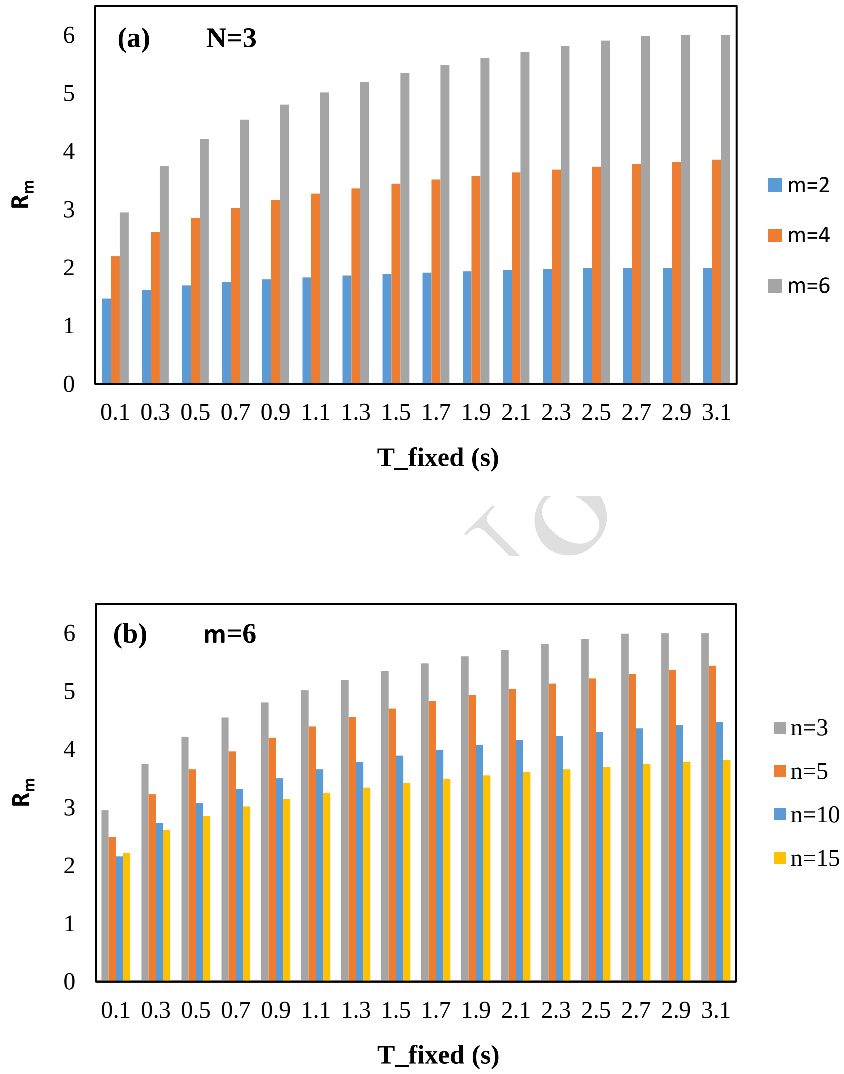
According to **Eq. 9**, the SSI strength reduction factor relied on certain variables. In this section, variations in every parameter were analyzed in correlation with one another. The sensitivities of each variable were shown in the **Fig. 14**, assuming all other variables stayed the same. **Fig. 14a** illustrated the proposed alterations in SSI R_μ related to the desired ductility ratios ($\mu = 2.4.6$). According to the diagram, it was noted that there was a rise in R_μ as μ increased. This implies that in order to achieve higher target ductility ratios, elastic demand must be decreased further.

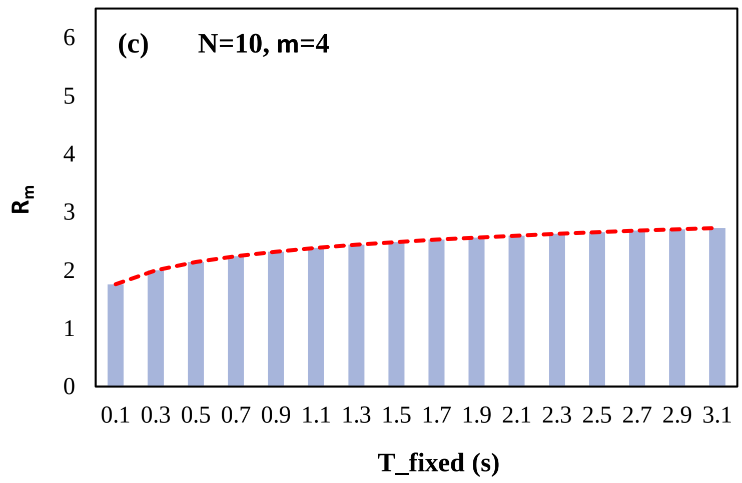
As previously stated, the strength reduction factor could be influenced by the number of stories. Based on **Fig. 14b**, it was determined that R_μ rose as the number of stories parameter increased. Thus, as the number of stories grew, the effect of SSI became more pronounced and the strength reduction factor deviated further from the rigid base case. In tall slender buildings, the strength required decreases, but the maximum displacement increases due to kinematic interaction, which may disrupt the structure's performance.

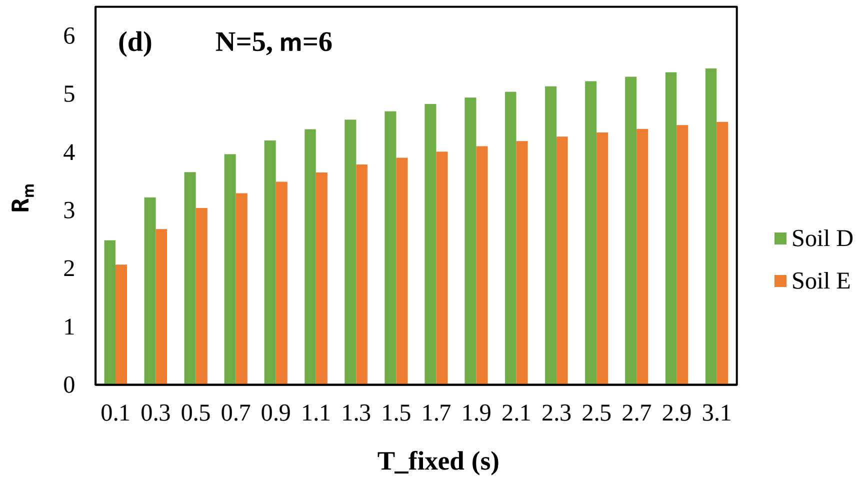
Fig. 14c depicted the relationship between the strength reduction factor and the fixed-base period of the structure. The findings concluded that R_μ increased as the fixed-base periods of structures increased. Nevertheless, the graph's incline reduced over prolonged time periods. Thus, in structures with short periods, the impact of SSI on altering the R_μ factor was abrupt and greater.

It was noted that with a higher soil shear velocity, there was a decrease in the strength reduction factor, as depicted in **Fig. 14d**. The diagram showed that soil type E experienced a decrease in strength reduction value.

According to **Fig. 14e**, it could be seen that as long as all variables remained unchanged, the correlation between H/r and was R_μ directly linked. As the slenderness of the structure increased, R_μ increased and the base shear force decreased. But as mentioned, due to the secondary effects of P-delta in slender structures, the amount of maximum lateral displacement in the structure increased.







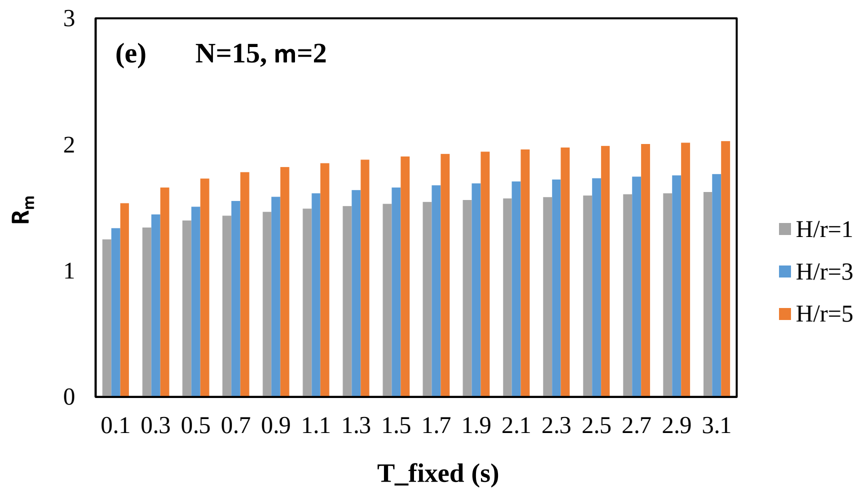


Fig. 14. Sensitivity analysis of the ductility strength reduction factor compared to (a) ductility ratio, (b) number of stories, (c) fixed-base periods, (d) soil type and (e) aspect ratio

6. Conclusion

Design codes determined strength reduction factors based on fixed-base structures. Using the *R* values provided in design codes for soil-structure systems results in incorrect inelastic strength and ductility demands. Hence, it is crucial to take into account soil-structure interaction when determining strength reduction factors.

Most previous research on soil-structure interaction focused on studying the effects of SSI on the *R* factor without providing calculation guidance for design codes. Only a few studies have been done to propose a mathematical formula for estimating the strength reduction factor of soil-structure system as a solution to this issue. These studies were carried out on either single-degree-of-freedom systems or by representing soil using independent vertical spring methods. Spring models do not reflect the soil's true behavior due to the shear behavior observed in the soil, which is not accounted for in the vertical springs modeling.

Hence, it has been found that there is a need for more research and design recommendations when it comes to determining the appropriate relationship for estimating the strength reduction factor of multi-story buildings considering SSI. The goal of this research is to tackle problems related to modeling highlighted in previous studies and to introduce a comprehensive new relationship to be used in design codes.

By conducting numerical studies on multi-story buildings with periods ranging from 0.1 to 3 seconds and ductility ratios of 2, 4, and 6, strength reduction factors were computed and compared in the fixed base conditions and with consideration of the soil environment.

This research investigated the effects of different parameters ductility strength reduction factor of the soil-structure systems. Strength reduction factors were determined and contrasted in fixed-base and flexible-base conditions through numerical analyses of multi-story buildings with periods ranging from 0.1 to 3 seconds and ductility ratios of 2, 4, and 6. In this regard, OpenSees software was used to dynamically analyze 22 earthquakes recorded on soil types D and E. Structures were depicted as 2D beam-column elements while soil was portrayed as plane strain elements.

The findings of this study can be summarized as follows:

- A novel formulation for estimating the ductility strength reduction factor was introduced, which, based on validation findings, could provide an accurate estimation of R_μ in multi-story buildings on soft soil for design process.
- In general, the strength reduction factor was reduced by the soil-structure interaction. Put simply, the strength required for a structure on soil differs from that of a structure with a fixed base. The use of code behavior coefficients in structural design, especially for structures affected by soil-structure interaction, led to designs that were not conservative.
- For the squat structure (H/r=1), the kinematic interaction decreased the strength reduction factor for all three types of foundation embedment. As the embedment ratio increased, the reduction in R_μ became smaller.
- In slender structures ($H/r = 3.5$) with shallow embedment depth ($e/r = 0.5.1$) kinematic interaction did not affect R_μ. Alternatively, kinematic interaction in a deeper embedment depth ($e/r = 2$) could potentially lead to a rise in R_μ by five percent.
- The strength reduction factor increased with the increase in the level of target ductility in both the fixed-base and flexible-base structures. Soil-structure interaction had a more pronounced impact in instances with higher ductility ratios.
- The strength reduction factor decreased as the number of stories in the building increased. This issue was present in fixed-base and flexible-base structures, but the

decrease was more significant in the structure with a flexible base. Likewise, a greater ductility ratio resulted in a more pronounced decrease in strength reduction factor.

- Decreasing the shear wave velocity of the soil resulted in a greater impact on the soil-structure interaction and led to a decrease in the strength reduction factor. Therefore, the decrease in the strength reduction factor correlated with an increase in stiffness disparity between the structure and soil.
- Given a fixed number of stories, the strength reduction factor saw an increase with a greater aspect ratio. Generally, the strength reduction factor rose higher as the ductility ratio increased.

Statements and Declarations

- The authors declare that no funds, grants, or other support were received during the preparation of this manuscript.
- **Declaration of interest statement**: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
- All authors contributed to the study's conception and design. Conceptualization, methodology, software, investigation, and review and editing were performed by …. and ….. The first draft of the manuscript was written by …., and all authors reviewed and edited previous versions and approved the final manuscript.
- All authors approved ethical standards and consented to participate in and publish this manuscript.
- Data availability statement: The supplementary data is available upon the respected editor's request.

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