Assessment of the Soil Structure Inertial Interaction Effect on the Behavior Coefficient Using Simplified Methods

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Received: 18 August 2022 | Revised: 29 August 2022 | Accepted: 31 August 2022

Abstract-This study aims to assess the effect of the Soil Structure inertial Interaction (SSI) on the behavior coefficient (R). For this purpose, R was estimated with and without SSI. The pushover N2 method and its extension SSI-N2 method were applied to the plain Reinforced Concrete (RC) frame structures. For calculating the SSI effect on R, four shear wave velocities V_s, representing rocky soil, firm soil, loose soil, and very loose soil, with three soil damping ratios ζg% for each soil type were considered. The estimated values of R using the N2 method were 4.1, 4.97, 5.75, and 6.96 for rocky soil, firm soil, loose soil, and very loose soil respectively. For the SSI-N2 method, R values were in the range of 3.67-3.97 for rocky soil, 4-4.69 for firm soil, 4.01-5.09 for loose soil, and 4.14-5.81 for very loose soil. In the Algerian code, R was kept constant for each soil type, and its value is 3.5 and 5 with and without infill masonry respectively. Soil shear wave velocity and the soil damping ratio must be taken into account in calculating R. The redundancy, overstrength, and ductility reduction coefficients were determined by taking into account the SSI. The SSI effect can change the values of R, so it must be taken into account when calculating R.

Keywords-behavior coefficient; N2 method; SSI-N2 method; RPA 99 v 2003; redundancy; overstrength; ductility

I. INTRODUCTION

An earthquake-resistant structure is designed to be subject to structural and non-structural damage during a strong seismic event without sudden collapse. This can be achieved by non-linear time history analysis [1] which is rather complicated and the responses depend on the registration component. Seismic codes have simplified this task by using inelastic response spectra. For this purpose, the elastic response spectra values are divided by the reduction coefficient or behavior coefficient (R) [2-4]. There are also many approaches to assessing inelastic performance using the pushover method [5-7]. The N2 method [8], the displacement coefficient method [9], and the capacity spectrum method [10] are included in many seismic codes (ATC40 [11], FEMA 356 [12], and EC8 [3]). These methods are used in the estimation of the ductility reduction coefficient. The behavior coefficient is also determined by a product of the ductility reduction coefficient, the redundancy coefficient, and the overstrength coefficient [13, 14]. In the Algerian seismic code RPA 99 v 2003 [2] and Eurocode 8 [3], the behavior coefficient value depends on the typology of structure and the ductility without accounting for overstrength. The ductility reduction coefficient also depends on the interaction between the structure and the soil (SSI). Authors in [15] proposed a simplified approach to consider the inertial SSI effects on the ductility reduction coefficient by the combination of the non-linear replacement oscillator method [16] and the N2 method. In [17], the effect of the height of Reinforced Concrete (RC) frames on overstrength, redundancy, and ductility response modification coefficients were estimated by the pushover method and nonlinear incremental dynamic analysis. The effect of vertical geometric irregularity on the R values of RC structures with Moment Resisting Frame (MRF) systems was studied in [18]. In this analysis, the capacity spectrum method according to ATC 40 was used.

In this paper, the behavior coefficient of a 2d RC frame structure is estimated by two simplified methods: the N2 method [8] and the SSI-N2 method [15]. In this study, 4 soil types and 3 soil damping ratios for each soil type were considered when taking into account the soil structure inertial interaction effect on the behavior coefficient value.

II. BEHAVIOR COEFFICIENT

In this study, the behavior coefficient is calculated by considering the 3 reduction coefficients (redundancy, ductility, and overstrength), according to [13, 14]:

$$R = R_{\mu} . R_{\rho} . R_{\Omega} \quad (1)$$

where R_{μ}, R_{ρ}, and R_{Ω} are ductility, redundancy, and overstrength reduction coefficients. Based on the pushover capacity curve in Figure 1 of [17], the above coefficients can be expressed as:

$$R_{\mu} = \frac{F_e}{F_y}, R_{\rho} = \frac{F_y}{F_1}, \text{and } R_{\Omega} = \frac{F_1}{F_d} \quad (2)$$

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III. N2 AND SSI-N2 METHODS

The SSI-N2 method is an extension of the N2 method [5] proposed in [15, 19], where the SSI is introduced in the N2 method by using the replacement oscillator concept [16]. The replacement Single Degree Of Freedom (SDOF) system has the same effective values for the first mode of vibration of the structure (height h_{eff}, mass m, lateral stiffness k, and damping c), and 3 degrees of freedom (Figure 2). The stiffness k_u and k_θ, the damping C_u and C_θ represented in Figure 1, were expressed by the impedance function as follows:

$$K_u = \alpha_u k_u \quad (3)$$

$$C_u = \beta_u \frac{k_u r_u}{V_s} \quad (4)$$

$$K_\theta = \alpha_\theta k_\theta \quad (5)$$

$$C_\theta = \beta_\theta \frac{k_\theta r_\theta}{V_s} \quad (6)$$

where V_s is the mean shear wave velocity representing the site effects. The quantities α_u, α_θ, β_u, and β_θ are adimensional parameters that take into account the influence of the excitation frequency on the impedance and k_u and k_θ represent the static stiffness of a half-space disk and are defined as follows:

$$k_u = \frac{8}{2-V} G_{ru}\ ,\ k_\theta = \frac{8}{3(1-V)} G_{r\theta} \quad (7)$$

$$a_u = 1, \beta_u = b_1 \quad (8)$$

$$a_\theta = 1 - b_1 \frac{(b_2 a_0)^2}{1+(b_2 a_0)^2} - b_3 a^2{}_0 \quad (9)$$

$$\beta_\theta = b_1 b_2 \frac{(b_2 a_0)^2}{1+(b_2 a_0)^2} \quad (10)$$

The coefficients a_0, b_1, b_2, and b_3 are functions of Poisson coefficient Ʊ [2], r_u, r_θ are the equivalent radii of foundation and are expressed as: $r_u = \sqrt{\frac{A_f}{\pi}}$, $r_\theta = \sqrt[4]{\frac{4I_f}{\pi}}$, where A_f and I_f are the area and inertia moments of the foundation. From the above expressions, the period and the damping ratios of the equivalent system with soil-structure interaction are calculated by the following expressions:

$$\tilde{T} = T\sqrt{1 + k\left[\frac{1}{K_u} + \frac{h^2{}_{eff}}{K_\Theta}\right]} \quad (11)$$

$$\tilde{\zeta} = \frac{T^2}{\tilde{T}^2}\zeta + \left[1 + \frac{T^2}{\tilde{T}^2}\right]\xi_g + \left[\frac{T_u{}^2}{\tilde{T}^2}\xi_u + \frac{T_\Theta{}^2}{\tilde{T}^2}\right]\xi_\theta \quad (12)$$

where h_{eff} is the distance from the base to the fundamental mode inertial forces gravity center.

$$T = 2\pi\sqrt{\frac{m\, d_y}{F_y}}, = \frac{2\pi}{T}, \zeta = \frac{c}{2m\omega}, m = \sum_{i=1}^{n} m_i \emptyset_i \quad (13)$$

T and ζ are the fundamental mode period and the damping ratios of the equivalent system on a rigid base. m_i and $\emptyset_i$ represent the mass and the modal value of the fundamental mode for the floor I, d_y and F_y represent the yield displacement and the actual strength of the equivalent SDOF [8].

$$\omega_u{}^2 = \frac{K_u}{m}, T_u = \frac{2\pi}{\omega_u}, \zeta_u = \frac{c_u}{2m\omega_u} \quad (14)$$

where ω_u, T_u, and ζ_u represent the natural frequency, the period, and the damping ratios of the equivalent soil structure system where the structure is assumed to be perfectly rigid and the rotation of the foundation is blocked.

$$\omega_\Theta{}^2 = \frac{K_\Theta}{m}, T_\Theta = \frac{2\pi}{\omega_\Theta}, \zeta_\Theta = \frac{c_\Theta}{2m\omega_\Theta} \quad (15)$$

where ω_Θ, T_Θ, and ζ_Θ represent the natural frequency, the period, and the damping ratios of the equivalent soil structure system where the structure is assumed to be perfectly rigid and the translation of the foundation is blocked.

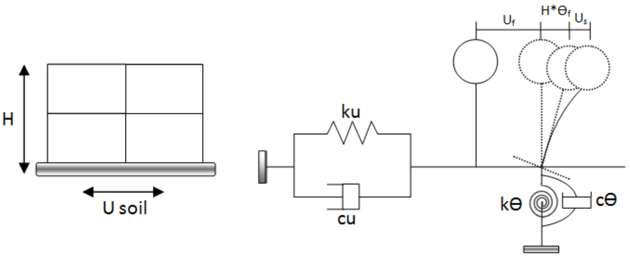

Fig. 1. The replacement SDOF for SSI.

The N2 method was used to determine the ductility μ of the equivalent system (without SSI).To take into account the inelastic interaction effects, an equivalent ductility coefficient is defined according to [13]:

$$\tilde{\mu} = 1 + (\mu - 1)\frac{T^2}{\tilde{T}^2} \quad (16)$$

The strength reduction coefficient proposed in [21] has been used in the case of soil-structure interaction:

$$\tilde{R}_\mu = (\tilde{\mu} - 1)\frac{\tilde{T}}{T_c} + 1 \qquad \tilde{T} \le T_c \quad (17)$$

$$\tilde{R}_\mu = \tilde{\mu} \qquad \tilde{T} > T_c \quad (18)$$

The $\tilde{R}_\mu$ allowed to plot the new demand spectrum ($S_{ay}(\tilde{T},\tilde{\zeta})$, $S_{dy}(\tilde{T},\tilde{\zeta})$), based on the elastic spectrum, and the following relationships:

$$\tilde{S}_{ay}(\tilde{T},\tilde{\zeta}) = \frac{\tilde{S}_{ae}(\tilde{T},\tilde{\zeta})}{\tilde{R}_\mu(\tilde{T})} \quad (19)$$

$$\tilde{S}_{dy}(\tilde{T},\tilde{\zeta}) = \frac{\tilde{T}^2}{4\pi^2}\tilde{S}_{ay}(\tilde{T},\tilde{\zeta}) \quad (20)$$

The displacement demand $\tilde{S}_d$ of the replacement SDOF on a flexible base is obtained by the intersection between the new capacity spectrum and the new inelastic demand spectrum (($S_a(T, \tilde{\zeta})$, $S_d(T, \tilde{\zeta})$). Thus the global displacement demand on a flexible base is calculated by the relationship: $\tilde{U} = \Gamma\tilde{S}_d$ where Γ is the modal participation coefficient.

IV. DESCRIPTION OF THE STUDIED RC FRAME STRUCTURE

The studied 2d RC frame structure is shown in Figure 2. The columns and beams are calculated to satisfy the strong column weak beam condition (collapse through global mechanism) according to the Algerian code [2]. The design load Fd is 300.14kN, calculated with S_a/g equal to 0.197 using the inelastic response spectrum (S_a/g, $T(s)$) of the Algerian code for rocky soil (*Tc*=0.3), where 5% damping ratio and 3.5 behavior coefficient, were considered. The frames were characterized by a span length of 5.5m, 6 spans, inter-story height of 3.0m, and 6 stories. The columns had a rectangular section of 400×300mm^2; the beams had a rectangular section of 300×200mm^2 and the reinforcement details are represented in Figure 3. The material characteristics are F_{ck} = 35MPa, E_c = 30GPa for the concrete and F_{yk} = 450MPa, E_s = 210GPa for the reinforcing bars. The used loads in the pushover analysis and floor masses are presented in Figure 3.

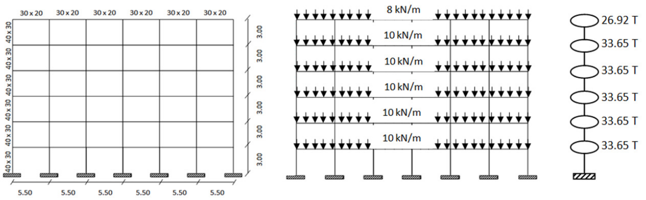

Fig. 2. Studied 2d RC frame structure.

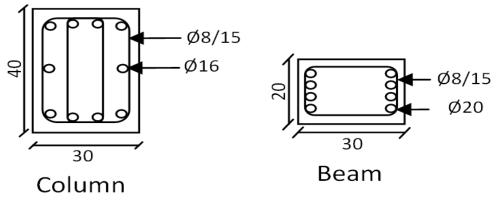

Fig. 3. Reinforcement details of the studied structure.

The period, the linear displacement shape, and the modal mass participating ratio for the fundamental mode of vibration are T = 1.02s, ϕ^T = [1 , 0.91 , 0.77 , 0.57 , 0.34 , 0.12], and Γ = 0.795 respectively.

V. METHODOLOGY

Our study focused on the evaluation of the site effect on the behavior (reduction) coefficient. For this reason, 4 soil types (four shear wave velocities V_s) were considered: rocky, firm, loose, and very loose soil (Table I). For each soil type, 3 damping soil ratios ζg% had been taken into account: 5%, 10%, and 20% [22]. The lateral load pattern used in the pushover analysis is uniform [16]. The capacity curve is determined by Sap 2000 software [12]. The generalized force-deformation curves used in the FEMA-356 standard were adopted [16].

TABLE I. SOIL CHARACTERISTICS

Soil type	Shear modulus G (kN/m^2)	Poisson coefficient	Shear wave velocity V_s (m/s)
Rocky soil	648000	0.28	1000
Firm soil	180800	0.39	600
Loose soil	75000	0.45	300
Very loose soil	33500	0.5	150

The elastic response spectrum (S_a/g, $T(s)$) is that of the RPA99 v 2003 seismic code. For each soil type, damping ratio of 5%, peak ground acceleration of 0.5g, and behavior coefficient of 1 were considered (Figure 4).

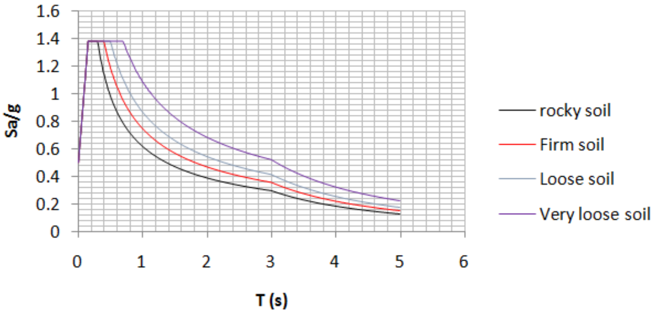

Fig. 4. The elastic response spectrum for each soil type.

Ductility μ is estimated by [8]:

$$\mu = R_\mu \qquad T > T_c \quad (21)$$

$$\mu = (R_\mu - 1)\frac{T_c}{T} + 1 \qquad T \le T_c \quad (22)$$

$$R_\mu = \frac{S_{ae}}{S_{ay}} \quad (23)$$

S_{ae} represents the acceleration value corresponding to the period T of the equivalent SDOF, in the elastic response spectrum (Sa/g, $T(s)$). The acceleration S_{ay} is determined by:

$$S_{ay} = \frac{F_y}{m} \quad (24)$$

where F_y and m are the actual strength of the equivalent SDOF and its mass respectively.

VI. RESULTS AND DISCUSSION

The pushover curves (base shear versus roof displacement for global structure (F(kN), U(m)), the equivalent model (F_y(kN), u(m)), and the bilinear idealization of the equivalent model, are presented in the Figure 6 with F_y=F/Γ and u=U/Γ [5]. The transformation constant (modal participation coefficient) is Γ = 1.31 and the equivalent mass amounts to m = 118.58 T. Figure 6 shows the pushover curves of the global structure on a fixed base with the necessary forces to calculate the reduction coefficients.

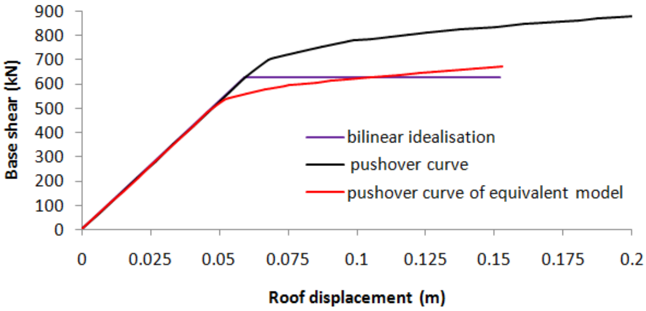

Fig. 5. Pushover curves and bilinear idealization.

For each soil type and damping soil ratio, the design strength Fd, the first yielding strength F_1, and the actual strength Fy are shown in Figures 7 – 10. Fy5, Fy10, and Fy20 represent the actual strength of the global structure with 5%, 10%, and 20% of the damping soil ratios ζg% respectively. The values of the redundancy coefficient (Rρ = Fy/F1) are in the range 1.05-1.48 and close to Rρ = 1.3 prescribed by Eurocode 8 [3]. The overstrength coefficient (RΩ = F1/Fd) is 2.1 which is in good agreement with the values found in [23]. The ductility reduction coefficient (Rμ = Fe/Fy) values were determined with the N2 method (without SSI) and the SSI-N2 method (with SSI) (see Figure 11).

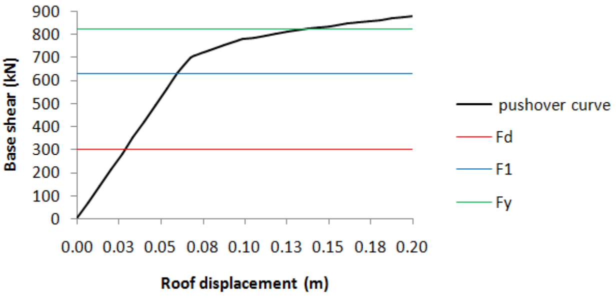

Fig. 6. Pushover curve of global structure on the fixed base.

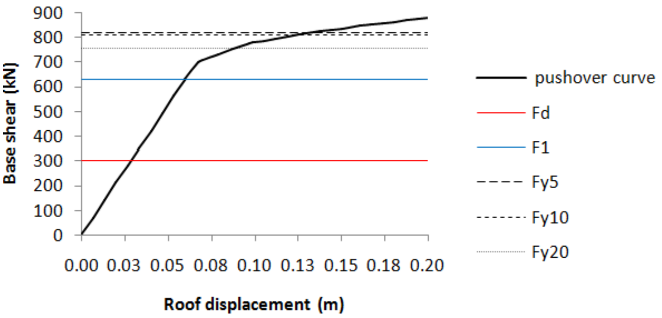

Fig. 7. Pushover curve of global structure: rocky soil.

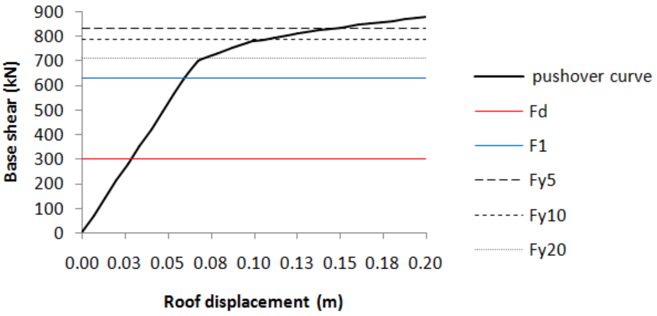

Fig. 8. Pushover curve of global structure: firm soil.

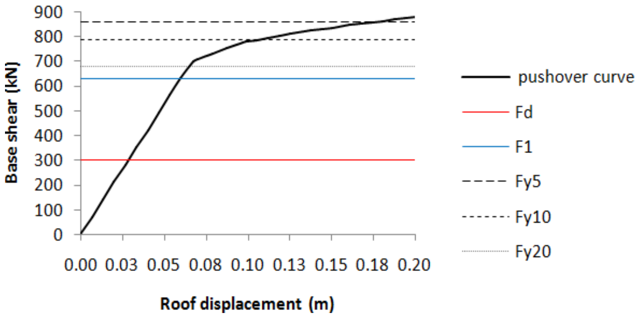

Fig. 9. Pushover curve of global structure: loose soil.

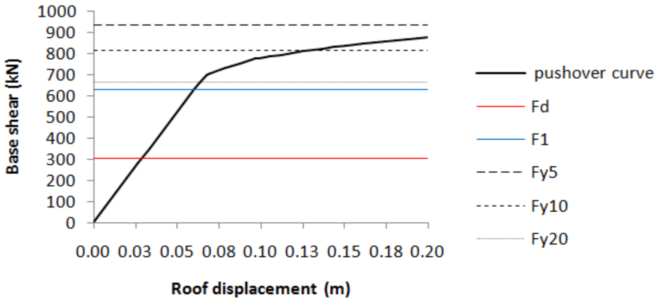

Fig. 10. Pushover curve of global structure: very loose soil.

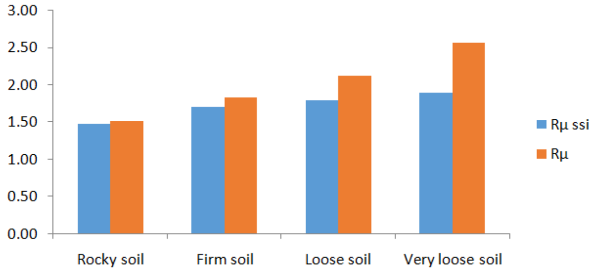

Fig. 11. Rμ (N2) and Rμssi (SSI-N2).

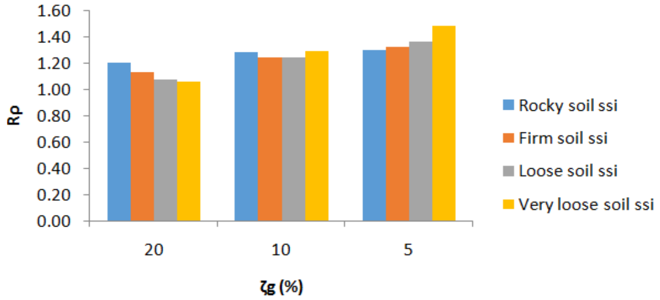

Fig. 12. Rρ VS ζg% and soil type.

We noted that Rμ values with SSI (1.47-1.88) are lower than those estimated without SSI (1.51-2.56). In Figures 7-10, Fy varies with ζg% and soil type. To clarify this relationship, the variation of the redundancy coefficient (Rρ = Fy/F1) versus ζg% and soil type is represented in Figure 12. This Figure shows the decrease of Rρ when ζg% is increased in all soil types. Indeed, the damping ratio $\tilde{\zeta}$ of the equivalent system is proportional to ζg% (12), thus the decrease of $\tilde{S}_{ay}(\tilde{T},\tilde{\zeta})$. The behavior coefficient, estimated for each soil type with the N2 method, is shown in Figure 13. According to RPA 99 v 2003 seismic code, the behavior coefficient in RC frame structure is 3.5 and 5 for infill and without infill masonry respectively. The estimated R values using the N2 method are 4.1, 4.97, 5.75, and 6.96 for rocky soil, firm soil, loose soil, and very loose soil respectively (Figure 13). The calculated R values with the SSI-N2 approach are shown in Figure 14 and are in the range 3.67-3.97 for rocky soil, 4-4.69 for firm soil, 4.01-5.09 for loose soil, and 4.14-5.81 for very loose soil. These values are lower than those of R without SSI (Figure 13) and depend on both ζg% and the type of soil (shear wave velocity V_s). Therefore, damping soil ratios ζg% and soil type should not be neglected when calculating the behavior coefficient R.

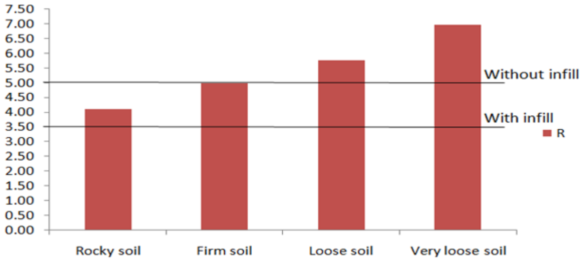

Fig. 13. Behavior coefficient without SSI (N2).

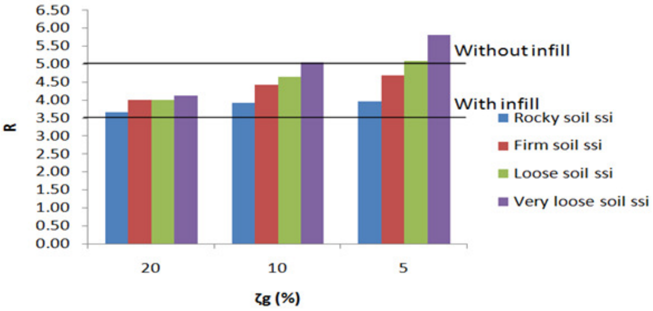

Fig. 14. Behavior coefficient with SSI (SSI-N2).

Table II summarizes the variation in the period T and ductility μ. $\tilde{T}$ and $\tilde{\mu}$ are the period and ductility taking into account the SSI. According to (7), when decreasing shear modulus G, k_u and k_Θ decrease therefore $\tilde{T}$ in (11) increase and $\tilde{\mu}$ in (16) increase.

TABLE II. VARIATION OF PERIOD AND DUCTILITY VS. SHEAR WAVE VELOCITY V_S

Soil type	$T(s)$	$\tilde{T}(s)$	μ	$\tilde{\mu}$
Rocky soil	0.66	0.69	1.51	1.47
Firm soil	0.66	0.73	1.83	1.68
Loose soil	0.66	0.79	2.12	1.79
Very loose soil	0.66	0.9	2.65	1.89

The behavior coefficient for the studied frame structure has been estimated by different methods quoted in [24] and shown in Table III.

TABLE III. BEHAVIOR COEFFICIENT WITH DIFFERENT METHODS

Soil type	Newmark & Hall [24]	Giuffre &Giannini [24]	Krawinkler & Nassar [24]
Rocky soil	1.51	1.57	1.51
Firm soil	1.83	1.85	1.80
Loose soil	2.12	2.10	2.09
Very loose soil	2.07	2.39	2.62

For each soil type, the estimated behavior coefficients R in Table III are close to each other. Compared to the R of the Algerian code (3.5 and 5), the estimated R using the N2 method or the calculated R using the SSI-N2 method, the R values in Table III are conservative. The mentioned methods in Table III did not take into account the effect of the shear wave velocity and the damping soil ratio on the R value [23]. Due to the big difference between the R values calculated by the methods in Table III and the R values calculated by the N2 and SSI-N2 methods, the effect of V_s and ζg% on R values cannot be neglected.

VII. CONCLUSIONS

In this study, the behavior coefficient R has been estimated with and without soil structure inertial interaction. For this purpose, the pushover N2 method and its extension SSI-N2 method were applied in plan RC frame structures to evaluate the effect of SSI on R value. Four shear wave velocities representing rocky, firm, loose, and very loose soil, with three soil damping ratios for each soil type, were considered. The obtained values of R were compared with the values in the Algerian code and with those calculated by 3 other methods. Based on the obtained results, the following can be concluded:

- The N2 simplified method enabled us to estimate the reduction coefficients for each soil type, and thus the behavior coefficients. Their values were 4.1, 4.97, 5.75, and 6.96 for the rocky soil, firm soil, loose soil, and very loose soil respectively
- The SSI-N2 simplified method allowed us to estimate the reduction coefficients for each soil type and soil damping ζg%. Their values were in the range of 3.67-3.97, 4-4.69, 4.01-5.09, and 4.14-5.81 for rocky soil, firm soil, loose soil, and very loose soil respectively. These values are lower than those calculated by the N2 method for each soil type.
- The redundancy reduction coefficient increased with decreasing the soil damping ratio.
- The ductility reduction coefficient increased with decreasing soil shear wave velocity.
- The R values must be calculated while taking into account the shear wave velocity and the soil damping ratio.
- The estimated R values without taking into account the SSI effect are conservative.
- The N2 and SSI-N2 methods allow us to calculate the behavior coefficient only in buildings where the first mode is predominant and therefore it must be developed to take into account all the modes that have a significant contribution to the response of the building. The effect of torsion also cannot be neglected in the seismic response and therefore on the behavior coefficient, so it must be taken into account in these methods.

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