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Evaluation on Definition of Strength Reduction Factor for Soil Structure Interaction of Multistoried Buildings

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***Abstract:** The determination of strength reduction factor of MDOF structures is essential to study soil structure interaction. International codes ATC, FEMA,UBC,IBC and Current codes {IS1893(PART1&2)} etc emphasize the need for evaluating ssi if the structure is resting on other than rocky or rock like material having SPT -N value less than 50. The current SRF in seismic codes is based on fixed base structure. Subsoil flexibility is to be investigated for accurate evaluation of SRF. However SRF were not well defined by various authors and contribute in different way without uniformity among various researchers. It is also noticed that researchers are sticking on their own definitions to verify their results in the academic world. The typical values given in codes of developed countries can not be applied to developing countries irrespective of ground motion, site conditions, ductility demand etc. The various codes provide values for strength reduction factor depending on type of structure, namely moment resisting frames with or without shear wall/ load bearing, steel, rcc/masonry structure. In this paper, the definitions of different authors are compared in order to interpret SRF These will allow structural and geotechnical engineers to quickly and accurately establish the actual SRF for multistorieyed building structures due to ssi.*

Keywords: MDOF, fixed base, strength reduction factor (SRF), soil structure Interaction, soil flexibility, multistorieyed buildings.

Introduction

The first well known studies on strength reduction factors were conducted by Veletsos and Newmark and Newmark and Hall They proposed formulas for strength reduction factors as functions of structural period and displacement ductility to be used in the short, medium and long period regions. Alternative formulas were proposed by Lai and Biggs and Riddell et al. The first study that considered the effects of soil conditions on the strength reduction factors was conducted by Elghadamsi and Mohraz. Another study which considered the site effects on the strength reduction factors was conducted by Nassar and Krawinkler, also considering the effects of yield level, strain hardening ratio and the type of inelastic material behavior.(1) More recently, Miranda studied the influence of local site conditions on strength reduction factors, using a group of 124

The values of the strength reduction factor are determined by:
a) the strength characteristics of the materials;
b) the use of the response spectrum in the seismic computations;

ground motions classified into three groups as ground motions recorded on rock, alluvium and very soft soil. During last decade, soil-structure interaction effects on strength reduction factors have been the topic of some investigations. Aviles and Perez-Rocha studied on strength reduction factors using the great 1985 Michoacan earthquake recorded at one site representative of the lakebed zone in Mexico City. Also Ghannad et al. studied on strength reduction factors for two different aspect ratios (h/r = 1, 3) two values of non-dimensional frequency (a0=1,3) and three levels of nonlinearity (ε=2,4, 6). It is common to characterize seismic hazard at a site and to estimate the design forces or displacements of a linearly behaving single-degree-of-freedom (SDOF) structure, with specified period and damping, through elastic design spectrum

2. Reduction Factor -A General Guideline

(2)In design codes the considered seismic force used to dimensioning the structural elements is multiplied by several coefficients, in order to simplify the design process. One of them is the reduction factor. In the following are presented different ways to evaluate the seismic force, as well as the values for the behavior factor in some seismic design codes. The behavior factor of the response is computed as a product of three factors

R = RS Rε Rɜ

where: *RS* is the strength reduction factor; *R*ε ī the ductility reduction factor; *R*ɜ ī the damping reduction factor. In the ATC-19 meeting from 1995 the damping reduction factor was not taken into consideration, being replaced by the redundancy reductionfactor,*RR*

R =RS Rε RR

The strength reduction factor, *RS* , is computed as the difference between the seismic force at the bottom, *Vb* , and the ultimate shear force at the bottom, *Vu* . The values of this factor, depending on the height of the structure, are presented in Table 1.

Table 1 The Strength Reduction Factor for Reinforced Concrete Structures

Structural type	RS
Rc structures medium and high in elevation	1.6é 4.6
Rc structures with irregularities in elevation	2.0é 3.

c) column design to the seismic action on two directions; along one is applied 100% of the seismic force, and along the orthogonal one only 30% of the seismic force.

3. L E Perez Rocha and j Aviles Lopez (2008) explained (5) SRF based on ductility demand. It is common in design criteria the use of strength reduction factors to account for the non-linear structural behavior. They come from the ratio between the strength required for elastic behavior, Sa (1) , and the one for which the ductility demand equals the target ductility, Sa (ε) , that is

Sa (1) /Sa (μ) = R (T) (7)

The shape of the Rε (Ð) factor, at the fixed-base condition, has been extensively studied in the last years using recorded motions and theoretical considerations. In particular, Ordaz and Pérez-Rocha (1998) observed that, for a wide variety of soft soils, the strength reduction factor depends on the ratio between the elastic displacement spectrum, Sd (Te ,ͼe) ,and the peak ground displacement, Ugmax , in the following way

Ŭ (Ð)=1+(μe-1) Sd(Te,úe)Ugmax (8)

where Ŭ å 0.5 This expression has correct limits for very short period and long periods of vibration.

Opposed to what happens with available reduction rules, the values provided by eq (8) can be larger than ε e , specially at the resonant condition, where the structural period is close to the site period. This reduction rule is more general than others reported in the literature, because its period and damping dependence is properly controlled by the actual shape of the elastic displacement spectrum, and not by a smoothed shape obtained empirically. As it is explicit in eq (7), the strength reduction factor depends not only on the natural period Te and the ductility factor ε e , but also on the soil flexibility measured by the shear wave velocity ϐs . As in the fixed-base condition, this factor has irregular shape that is inadequate to be incorporated in building codes. Avilés and Pérez-Rocha (2005) have proposed a smooth reduction rule based on the a work of Ordaz and Pérez-Rocha (1998) and the replacement oscillator approach. This reduction rule may be readily obtained by replacing in eq (8), and regarding that Ŭ å 0.5 , that is

~ ~ ~ ~ 1/

Rμ(ϐs) = 1+(μe-1)TeSd(Te,úe)Te Ugmax (9)

Eq. (8) will yield the same result as Eq. (9) if the elastic displacement spectrum without SSI appearing in the former is replaced by the one with SSI. The two spectra Sd (Te ,ͼe) and Sd (Te ͼe) are used to emphasize the fact that the former corresponds to the actual structure, whereas the latter to the replacement oscillator. Avilés and Pérez-Rocha (2005) have shown that the use of the factor based on the later provides excellent results. A more accuracy results can be obtained if the reference displacement Ugmax , in the fixed-base condition, is conceived as the total displacement of the structure discounting the deformation of the structure. For elastically supported structures, this new reference displacement becomes ~ ~ 2

Ugmax =Ugmax TeTe (10)

In view of the many uncertainties involved in the definition of this factor, it is judged that Eqs. (8) and (10) are appropriate for design purposes.

4. Effect Of Ssi On Ductility Reduction Factor

B Ganjavi & H Hao (4) studied the effect of number of stories and dimensionless frequency on DRF ($R\mu$) for fixed-base and flexible-base structures, shear buildings of 3, 5, 10, 15 and 20 stories as well as the corresponding ESDOF systems are considered which represent the common building structures from low to high rise models..It is observed that for fixed-base systems, regardless of the level of Nonlinearity, increasing the number of DOFs (stories) always results in a reduction in the averaged values of $R\mu$. For soil-structure systems, the effect of the number of stories are, however, very different from the fixed-base models. For the cases with significant SSI effect, $R\mu$ spectra become less sensitive to the variation of the number of stories. This is more apparent in cases with low level of inelasticity. In addition, an interesting point can be observed for the case of E-SDOF soil-structure systems with severe SSI effect ($a0$ = 3) in which $R\mu$ values are significantly lower than those of the MDOF systems in almost all ranges of period. Therefore, it can be concluded that the modifying factors for DRFs of MDOF soil-structure systems could be completely different from those of the fixed-base systems. For fixed-base structures, it has been proposed to multiply $R\mu$ of SDOF systems by a modifying factor that takes into account the possible concentration of displacement ductility demands in specific floors (Miranda, 1997; Santa-Ana and Miranda, 2000) for use of the reduction factor in seismic analysis of MDOF systems. This factor was defined by Santa-Ana and Miranda (2000) for fixed-base systems as:

$$RM=\frac{VSDOF(\mu=\mu i)}{VMDOF(\mu=\mu i)}$$

where *SDOF V* and *MDOF V* are the strength demands of SDOF and MDOF systems subjected to a given ground motion and presumed target ductility demand, respectively. Also RM represents a modification factor to the DRF of SDOF systems so it can be applied to MDOF structures. Therefore, the DRF of MDOF systems (Rμ MDOF) can be computed from the following equation:

Rμ(MDOF)= R(SDOF) RM

As seen, this modification factor just considers the difference between the inelastic demands of MDOF and the corresponding SDOF systems. Santa-Ana and Miranda (2000) and Moghaddam and Mohammadi (2001) showed that for fixed-base systems the values of this factor are approximately equal to one regardless of the number of stories. This means that for ε =1 the lateral strength of the MDOF systems is, on average, nearly equal to that of the SDOF system. However, results of this study indicate that this finding is not correct for soil-structure systems. To show the importance of this problem, the averaged ratios of strength demands on MDOF to those on E-SDOF systems for different ranges of nonlinearity are computed and the results are depicted in Figure 3 for both the fixed-base and soil-structure systems of a 10-story building.

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5.1 Effect of Aspect Ratio

In order to examine the effect of aspect ratio on DRF of MDOF-soil structure systems a 10-story building with three values of aspect ratio (*H/ r*= 1, 3, 5) and with three ductility ratios (*μ*= 2, 4, 8) as well as two dimensionless frequencies (a0 = 1, 3) is considered and analyzed subjected to the selected ground motions. It is clear that for the case of less SSI effect, the values of averaged *R*μ are insensitive to the variation of aspect ratio but significant for SDOF systems as reported by Ghannad and Jahankhah (2007). For the case with severe SSI effect and high inelastic response, except in short period ranges, the values of mean *Rμ* increase with the aspect ratio, which is completely different from the results obtained for the SDOF system by Ghannad and Jahankhah (2007) , where increasing the aspect ratio is always accompanied by decreasing the *Rμ* values. This finding indicates that SSI affects the strength reduction factors of MDOF and E-SDOF systems in a different manner. The same results have been observed in this study for MDOF soil-structure systems with different number of stories.

5.2 Estimation of the ductility reduction factors for mdof soil-structure systems

In earthquake resistant design and, in general, for practical purpose it is desirable to have a simplified expression to estimate strength reduction factors of MDOF systems. Here, based on nonlinear dynamic analyses of 10800 MDOF soil-structure systems the following simple equation is proposed:

$$R\mu(MDOF)=aT_{fix}^{b}$$

where is the fundamental period of the corresponding fix-based structure; and are constants depending on the inter story displacement ductility ratio, number of stories, aspect ratio, and dimensionless frequency and can be obtained from the Tables reported by Ganjavi and Hao (2012). .

6. Mohammad Ali GHANNAD, and Hoossein JAHANKHHAH(2004) (3)studied SRF considering SSI. The current seismic design philosophy is based on non-linear behavior of buildings during moderate and strong earthquakes. As a result, the design base shear provided by seismic codes is usually much lower than the lateral strength required to maintain the structure in the elastic range. The ratio of the structural strength demand, to stay elastic, to the provided lateral strength is known as Strength Reduction Factor (SRF) in the literature. Considering an idealized elasto-plastic SDOF system, this factor is defined as follows.

$$R\mu= f_e / f_y \quad (1)$$

7. M. ORDAZ, AND L. E. PE¨ REZ-ROCHA (1998)(12)proposed a new approach to find SRF of elasto-plastic systems .Contemporary seismic design of buildings requires, among many other things, the estimation of various structural response parameters in the inelastic range. For instance, since enough strength must be furnished to limit ductility demand, k, to a specified value, and thus prevent collapse, estimation of k for a given strength is essential in the design process .Estimation of required strengths, ductility demands or inelastic displacements is usually done using strength-reduction factors, Rμ. For an elasto plastic single-degree-of freedom oscillator subjected to a given ground motion, Rμ is the ratio between the strength required for elastic behavior and the strength for which ductility demand equals μ. If F(T,μ) is the spectrum of required strengths, then

$$R\mu(^1)=F(T, 1)/F(T,\mu)$$

where T is the structural period. Thus if Rμ(T) is known, then the required strength to attain a ductility demand μ can be obtained dividing the corresponding elastic force spectrum by Rμ(T).

Also, it can be shown that the inelastic displacement for given ductility and period, D(T, μ), can be computed with

$$D(T, \mu) =\frac{D(T)\mu}{R\mu(T)}$$

where D(T) is the elastic relative displacement spectrum. Therefore, determination of Rμ(T) allows also computation of inelastic displacements from their elastic counterparts. In this paper, a new rule to estimate Rk(T) is presented, that can be applied to a wide variety of site conditions. With this rule, Rμ(T) is not an explicit function of structural period as in all the rules previously published in the literature but a function of elastic spectral displacement. This implies that the variation of Rμ(T) with T is mainly controlled by the shape of the displacement spectrum and not by a standard shape obtained empirically. The effect of site conditions, recognized as a crucial factor in determining Rμ(T), is therefore automatically included in the rule by means of the shapes of the elastic displacement spectra

7. Yang LU, Imam HAJIRASOULIHA and Alec M MARSHAL studied SRF of shear buildings and SSI (9)For a SDOF system, is a factor which reduces the elastic base shear to that required to avoid the maximum ductility larger than the design target ductility μi

$$V_{sdof}(\mu=1)/V_{sdof}(\mu=\mu_1) = R\mu$$

where $V_{sdof}(\mu=1)$ and $V_{sdof}(\mu=\mu_1)$ are the base shear demands of SDOF structures to remain elastic (μ=1) and to limit their maximum ductility ratios to the target value (μt), respectively. In the present study, factors are calculated from constant ductility spectra obtained for given and values. The mean factors are calculated by averaging the reduction factors obtained from the six spectrum compatible earthquakes. ao is a factor that controls the severity of the SSI phenomena, and is the slenderness of the building. It is observed that in general, regardless of and for nearly rigid structures (i.e.TnŸ 0) tends to one and increases with increasing the flexibility of the buildings. For fixed-base structures (ao=o) having a long natural period (i.e. very flexible structure), approaches the target ductility ratio. These observations are consistent with the evidence presented by Miranda and Bertero (1994). It also shows that increasing a0(including SSI) reduces Rμ of flexibly-supported structures when compared to their fixed-base counterparts. The reduction is more obvious when the value is smaller than 2, and is up to 75% for a structure with predominant SSI effects (ao=3). Unlike the rigidly-supported structures whose Rμ factors are not affected by the slenderness ratio in SSI systems, for slender structures is smaller than squatty structures. However, the strength reduction factor Rμis mainly influenced by the relative stiffness, and to a lesser degree, by the slenderness of the structures. This indicates that using fixed-base Rμ to design a slender building considering SSI can be un conservative. It should be noticed that the Rμ factor is not only a function of the dynamic properties of the SSI system, but also related to site condition and the ground input motion. However, the mean Rμ factor for a SSI system subjected to a given set of earthquake ground motions (ignoring any strength hardening or softening) can be expressed as a function of the effective system period T , damping ratio ɛ and the target ductility demand μ . The period T and damping ratio of SSI systems can be calculated from their fixed-base counter ɛ parts and using the modified expressions based on the work of Veletsos and Meek (1974)

7.1 Modification Factor or multi-storey buildings, it is proposed that the Rμ factor in above Equation be multiplied by a modification factor to account for the possible concentration of the ductility in certain floors. This modification factor, denoted by Rm is proposed as:

Earth-quake	site class	StationName location	Epicentral Distance	Mg	a-max
Loma Prieta	426.6 A,B	Gilroy1,Gavillan	10.90	7.1 90	433.6 360

Table 2. Set of ground motions recordedon rock and firm sites.

This modification factor was evaluated for six target ductility ratios: 1, 1.5, 2, 3, 4 and 5. It was evaluated using the following methodology1. VMDOF(ε = εi) was computed by scaling the intensity of the ground motion until the maximum story displacement ductility ratio in the MDOF structure was, within a 1% tolerance, equal to the target ductility. The scaling factor was obtained by an iterative procedure using Drain 2DX . VSDOF(ε = εi*)* was computed by iteration on the lateral strength of the SDOF system when subjected to the same ground motion and scale factor of the previous step until the Displacement ductility ratio in the MDOF structure was, within a 1% tolerance, equal to the target ductility.

10.Strength Reduction And Amplification Factors Of 15-Story Building

E.Ahmadi F Koshnoudian (2013) studied ssi subjected to idealized pulses of multi-story buildings. The 15-story structure under SSI effects described and artificial pulses explained are employed to investigate the variations of strength reduction and amplification factors. Figure 3 delineates variations of strength reduction factors for aspect ratio, S, of 3 and structural ductility ratio μ, of 2. The black and red plots correspond to the 15-story building without (a0=0) and with dominant soil-structure interaction effects (a0=3), respectively. This Figure illustrates that Rε plots shift down and to the right as a0 increases. The shift in graphs toward right is due to the period elongation resulting from the soil structure system with increasing a0. Also,

Vsdof(μ=μi)/Fsdof(μmax=μi) = Rm

where Fsdof(μmax=μi) is the base shear strength that is required to limit the maximum inter-storey ductility of a MDOF system to the target ductility μi .

8. **Perla R SANTA- ANA (2004**) (10) performed analysis on SRF and modification factors for elasto plastic structures The base shear yield strength required for a SDOF system to not exceed the maximum allowable ductility is estimated as

$$\text{VSDOF}(\mu=\mu i)=\frac{\text{V SDOF}(\mu=1)}{R\mu}$$

where VSDOF(ε = 1) is the base shear yield strength required to maintain the SDOF system elastic and *R*ε is the strength reduction factor derived from SDOF systems. For multistory buildings the lateral strength required to avoid story displacement ductility demands larger than the maximum allowable ductility, ε *i* can be estimated from

$$\text{VSDOF}(\mu=\mu i)=\frac{\text{VSDOF}(\mu=1)}{Rm}$$

the plots downward shift emanates from an increase of damping ratio of the overall system due to the damping ratio of the soil. Another important point is that Rε is so close to 1 in the case of soil-structure system particularly for low Tp/Tfix ratios and forward directivity pulse which shows that the behavior of structure is elastic for these cases. Figure 3.(a) (b) Another important parameter in soil-structure systems is aspect ratio. Figure 4 illustrates Rε for non dimensional frequency, a0, of 2 and structural ductility ratio, ε, of 4. The black and red plots correspond to the squatty (S=1) and slender (S=4) 15-story buildings, respectively. Before the threshold period ratio of 1, the required strength of structure for a specific structural ductility demand decreases with increasing of aspect ratio. However, the trend is reversed for period ratio greater than 1. For fling step pulse, not only the maximum required lateral strength increases due to the increase in the aspect ratio, but the plot peaks are gradually shifted towards right. The reason lies in the greater elongation of the overall system s period that occurs due to the increase of the structure s aspect ratio. In addition, slenderizing the structure leads to significantly lower values of radiation damping for the soil structure system which explains the upward shift of plot s peak values. In previous Figures, Rε was associated with low structural ductility ratios (2 and 4). In Figure 5, Rε of 15-story building is depicted for aspect ratio of 4 and structural ductility ratio of 8. Unlike low str To detect higher-mode effects in the soil-15 story structure system, the amplification factor, adopted by Santa-Ana and Miranda (2000), is used to clarify higher-mode effects in the studied soil structure system. Amplification factor is defined as the shear base associated with 15-story building to the base shear of its equivalent single degree of freedom system and is marked by Rm. Figure 6 illustrates the results of amplification factor for aspect ratio, S, of 4 and structural ductility ratio, of 2 as a function of Tp/Tfix ratio. It is confirmed that for 15-story fixed-base structure (a0=0), this factor possesses great values at lower Tp/Tfix ratios where the higher modes effects are significant. This means that the lateral strength of the soil-15 story structure system is approximately greater than that of the equivalent soil-SDOF system. An increase of Tp/Tfix ratio causes the higher

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mode effects to reduce. In the case of SSI effects, amplification factor increases with the intensification of SSI effect at lower Tp/Tfix ratio. It implies that SSI effect activates higher modes more than fixed-base structures. Moreover, the trend of plots is inverse at higher Tp/Tfix ratios and SSI effect decreases this factor. Effects of forward directivity pulse on this factor is more notable than that of fling step at lower Tp/Tfix ratio and SSI effect amplifies this phenomenon. Figure 7 illustrates amplification factors as a function of Tp/Tfix ratio for aspect ratio, S of 4 and structural ductility ratio, of 8. The influence of structural ductility can be obtained by comparing the plots of Figure 6 and 7.structural ductility ratios (2 and 4), the SSI effect causes the reduction of Rε almost for all Tp/Tfix ratios. It can be seen that the amplification factors for high structural ductility (8) are smaller than those obtained for low structural ductility ratio (2) which means that increase of structural ductility ratio reduces the higher mode effects and amplification factors reduce at lower Tp/Tfix ratios It can be seen that the amplification factors for high structural ductility (8) are smaller than those obtained for low structural ductility ratio (2) which means that increase of structural ductility ratio reduces the higher mode effects and amplification factors reduce at lower Tp/Tfix ratio.

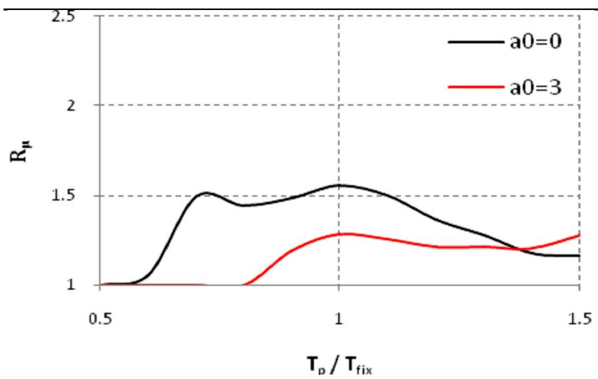
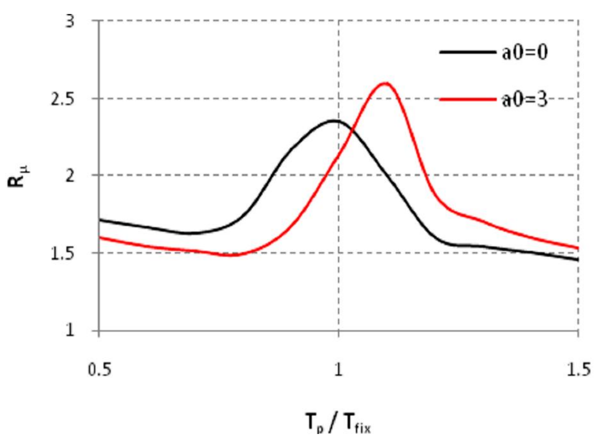


Figure 3 : R of 15-story building with structural target ductility of 2 for (a) fling (b) forward directivity



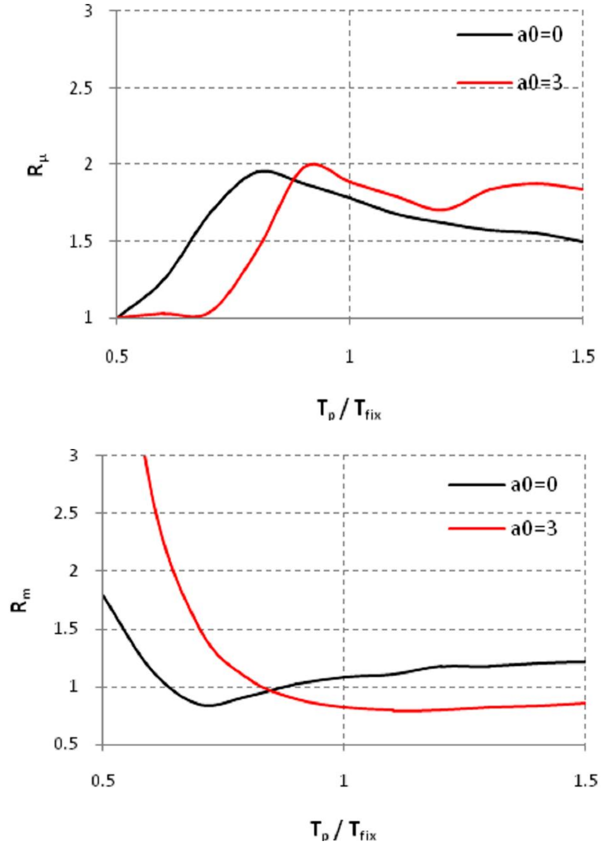


Figure 4 : R of 15-story building with structural target ductility of 4 for (a) fling (b) forward directivit

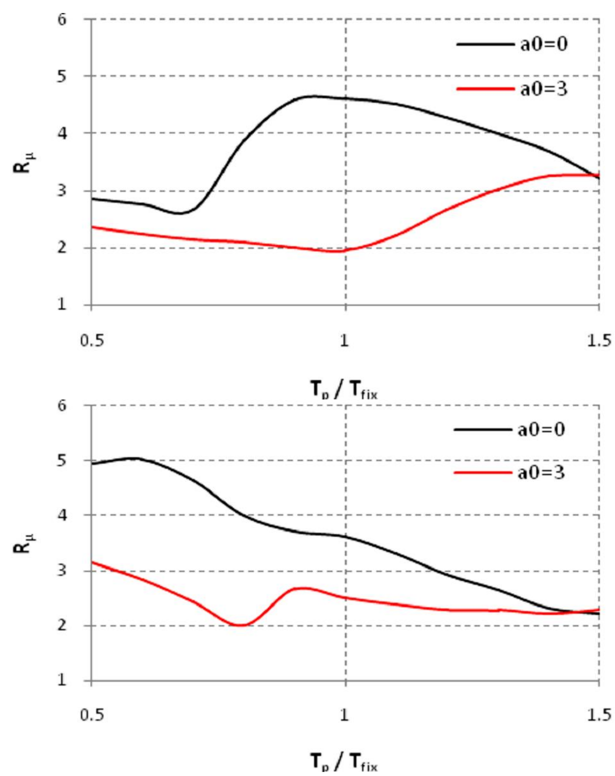


Figure 5 : R of 15-story building with structural target ductility of 8 for (a) fling (b) forward directivity

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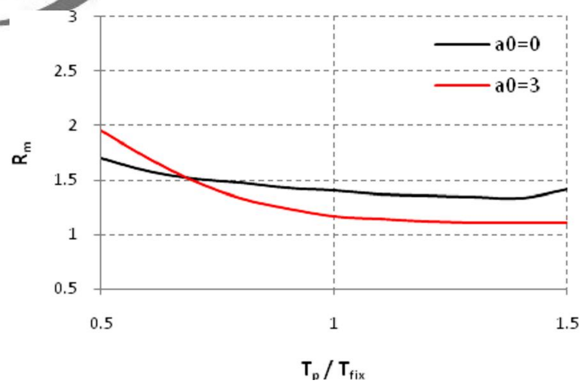

Figure 6 : Rm of 15-story building with structural target ductility of 2 for (a) fling (b) forward directivity

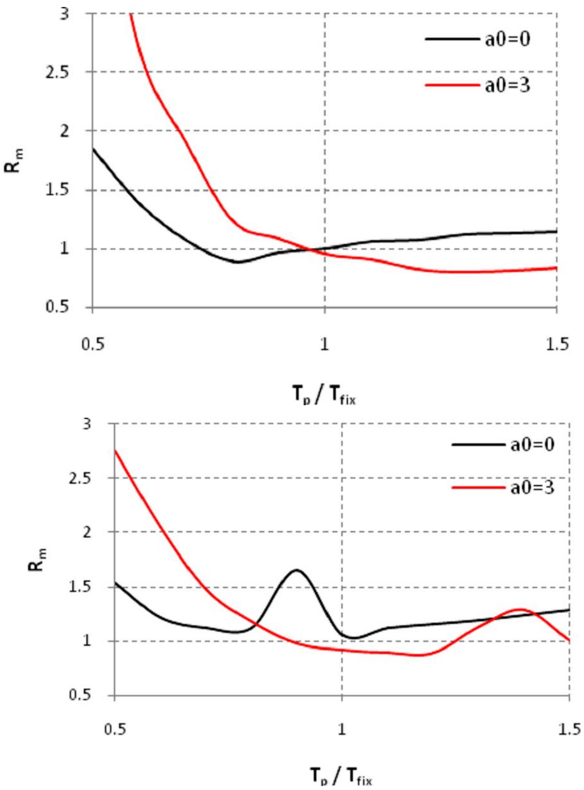

Figure 7 : Rm of 15-story building with structural target ductility of 8 for (a) fling (b) forward directivity

11. Conclusions

The structural design taking into account the ductility concept leads to an increase of the strength and the quantity of dissipated energy. It also ensures a global plastic mechanism of the structure before collapse. The design of structures located in seismic areas uses the dissipative behavior principle. According to this substantially reduced seismic loads are used instead of those corresponding to the elastic response of the structures through the behavior factor. The reduction of the seismic design forces is realized based on the ductility, redundancy and the strength excess of the structure. Among these, the most significant reduction of the design forces is based on the ductility of the structure that depends on the chosen structural type and the material characteristics.

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