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EFFECT OF DAMPING ON DISPLACEMENT DEMANDS FOR STRUCTURES SUBJECTED TO NARROW BAND GROUND MOTIONS

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Abstract

Soft soil sites have produced especially large lateral displacement demands that resulted in significant damage or collapse to medium and high rise buildings in past events such as the 1977 Vrancea, Romania earthquake, the 1985 Michoacan, Mexico earthquake, and more recently the 2010 Maule, Chile earthquake. However, in addition to large displacement demands these ground motions are characterized by narrow band spectra in which these demands exhibit a much larger sensitivity to damping ratios. This is especially true when the fundamental period of the structure is close to the site's predominant period. Seismic provisions include displacement modification factors to account for structures having damping ratios smaller than 5% (e.g., high rise buildings) as well as structures having damping ratios larger than 5% (e.g., structures incorporating viscous dampers). However, most previous studies and seismic provisions are based on structures subjected to ground motions recorded on rock or firm soil and are typically period-independent and therefore may not be adequate for structures built on very soft soil deposits. This paper summarizes a statistical study of displacement modification factors (DMF) which have to be used to adjust 5% elastic spectral ordinates to those with the desired damping. Results of this study suggest that, using the seismic provision's currently recommended DMF, displacement demands can be significantly underestimated for structures with low damping ratios and with fundamental periods close to the predominant period of the site, whereas the opposite holds true for structures with supplemental damping where displacement demands may be smaller. Finally, an equation to estimate the mean DMF as a function of the ratio between the fundamental period of the structure and the soil's predominant period is proposed and a study on the variability of this factor is also analyzed and discussed.

Keywords: damping ratio, displacement modification factors, structures on soft soil deposits, elastic displacement response

1. Introduction

It is widely known that site effects have an important influence on the ground motion intensity that a given site experiences when an earthquake occurs. Soft soil deposits generate narrow band ground motions that can impose important displacement demands in structures. Previous research has shown an important difference in design spectra in this type of soils [1, 2]. This is especially true when the structure's fundamental period of vibration is close to the ground motion's predominant period. Important examples of damaging soft soil ground motions are the 1977 Vrancea, Romania earthquake [3], the 1985 Michoacan, Mexico earthquake [4] and, more recently, the 2010 Maule, Chile earthquake [5].

Ground motion prediction equations (GMPEs) are used to characterize the intensity of earthquake ground motions. These equations are usually developed for a 5%-damped single-degree-of-freedom (SDOF) system. However, several structures can have damping ratios that are higher or lower than this value. For example, high rise buildings often have damping ratios below 5%, and in some cases they can even be as low as 1% [6, 7, 8]. On the other hand, structures that incorporate damping devices are designed using damping ratios higher than 5%. It is therefore a common practice to use displacement modification factors (DMFs) to adjust 5% spectral ordinates to the corresponding ones for other damping ratios. The pioneering work of Newmark and Hall [9] recognized that DMFs are period-dependent and proposed some of the first equations to estimate them in the acceleration-, velocity- and displacement-sensitive regions. Since then, several other studies have continued focusing on the development of these factors [10-14]. Moreover, US codes and provisions [15, 16], and the Eurocode (EC8) [17] incorporated findings from some of the previous studies to recommend period-independent DMFs.

There are only few studies which have addressed the influence of soft soils on DMFs. Pavlou & Constantinou [18] evaluated them for damping ratios between 10% and 100% and concluded that the NEHRP 2000 recommendations, which were developed mainly based on far-field ground motion records on firm soils, were adequate. Note that they used 14 records from NEHRP site class E as representative cases. Hatzigeorgiou [19] selected 10 NEHRP site class D records as soft soil cases and concluded that DMF values from very dense, stiff and soft soils were similar. Sheikh et al. [20] used soft soil simulated ground motion records to point out that the response spectra at soil sites is significantly dependent on the site period and that there are important discrepancies in the recommended DMF from several design codes for damping ratios greater than 5%.

As previously discussed, there has been much research in DMFs for structures built on firm soils, however, its effect in soft soils has not received sufficient attention. In the few cases where it has been studied, researchers have drawn contradictory conclusions which have caused some uncertainty among structural engineers as to the validity of current methodologies in the design of structures built on soft soil sites. Therefore, the main purposes of this study are: (1) to further clarify the effect of soft soil deposits on displacement modification factors via a statistical study using 80 recorded accelerograms, and explicitly considering the site's predominant period, and (2) to propose a simplified equation that will enable an accurate estimation of elastic displacements demands in structures built on this type of soils.

2. DMF for Structures Built on Soft Soil Sites

In this study the displacement modification factor, termed C_ζ, is defined as the ratio of the peak displacement of a linear SDOF with damping ratio ζ to the peak displacement of a linear SDOF having the same period of vibration but with a 5% damping ratio, as shown in Eq. (1).

$$C_\zeta = \frac{S_d(\zeta)}{S_d(\zeta = 5\%)} \tag{1}$$

$$C_\zeta = \frac{\omega^2 \cdot S_d(\zeta)}{\omega^2 \cdot S_d(\zeta = 5\%)} = \frac{S_a(\zeta)}{S_a(\zeta = 5\%)} \tag{2}$$

It should be noted that, from the definition of the pseudo-acceleration spectral ordinate, the displacement modification factor is also equal to the ratio of the pseudo-acceleration spectral ordinate with a damping ratio ζ to the 5% damped pseudo-acceleration spectral ordinate as expressed in Eq. (2).

Fig. 1 presents the 5% damped pseudo-acceleration spectra of three different recorded time histories at stations in the lake bed zone of Mexico City in the April 25, 1989 earthquake. From this figure we can see a clear difference in the period at which each spectrum reaches its maximum ordinate. The periods at which this peak occurs roughly correspond to the predominant period of the ground motion (T_g) which is directly affected by the soil deposit properties. In soft soils, the common approach used to estimate mean DMFs using a suite of ground motions has an important shortcoming. When the C_ζ variation with period from different records is averaged, the enhanced damping effect in the C_ζ value at $T=T_g$ tends to disappear as the main peak in each site occurs at different periods.

Displacement modification factors computed from those same three recordings are shown in Fig. 2. Here we can observe that each station attains its maximum value of C_ζ at a different period. Furthermore, we see a C_ζ value that oscillates around 1.6 for periods between 0.5 and almost 4s. Again, the period at which the C_ζ factor attains its maximum value is considerably different in each record.

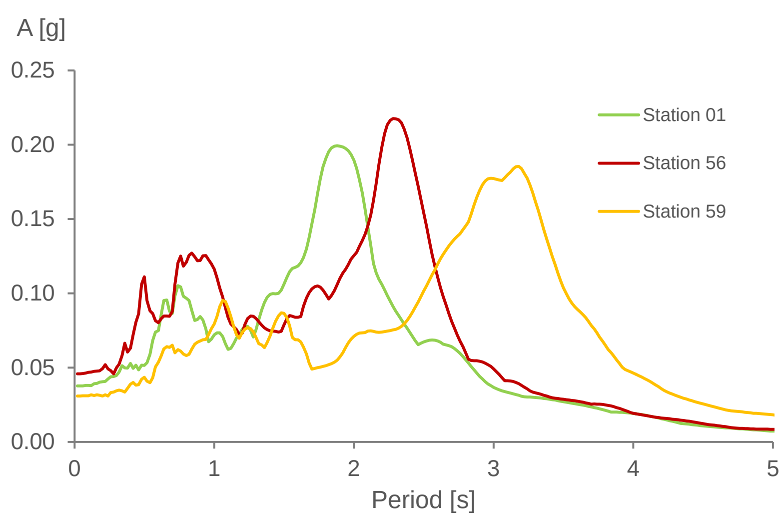

Fig. 1 – Pseudo acceleration spectra (ζ=5%) for three ground motions recorded in the lake bed zone of Mexico City.

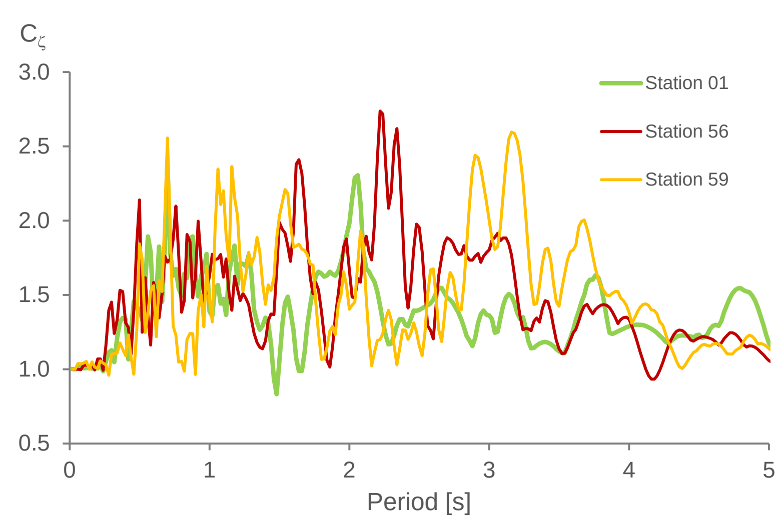

Fig. 2 – C_ζ factors for ζ=1% for three sites and its mean presented as a function of period of vibration.

Miranda [21-23] pointed out that a more suitable alternative for this problem is to characterize the predominant period of the ground motion in order to adequately assess seismic demands on linear systems built on soft soils. This study will use Miranda's proposal to characterize this period as the one at which the 5%-damped relative velocity spectra reaches its maximum ordinate. Fig. 3 shows the 5% damped relative velocity spectrum for the December 10, 1994 EW component of the Xochipilli station record. Also shown in this figure is the predominant period of the ground motion. Using this information the C_ζ factor is computed against a normalized period (T/T_g), and a very different variation is obtained when compared with Fig. 2. From Fig. 4 it is evident that a peak appears in the spectrum of each record, and in their average, at a ratio of T/T_g=1.0. At this period ratio, the mean DMF reaches its maximum value of 2.35 and it clearly starts decreasing at higher period ratios reaching a value close to unity after 2.5s. The mean trend resembles more adequately the trend of each one of the records, even for period ratios less than T/T_g=1.0. This study will use this approach in the computation of all the C_ζ values in order to improve its estimation. By doing this, we reduce the probability of missing important spectral features at certain period ratios which correspond to the first vibration periods of the soil deposit (e.g. T/T_g=1.0, T/T_g=0.33). A statistical evaluation of the C_ζ factors computed using different definitions of the predominant period of the ground motion is presented in [24].

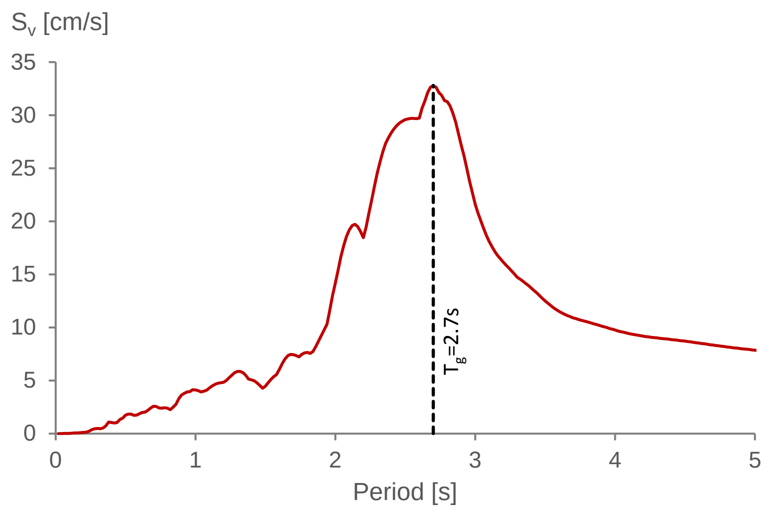

Fig. 3 – Relative velocity spectrum (ζ=5%) for the EW component of the December 10, 1994 Xochipilli record indicating the predominant period of the ground motion, T_g.

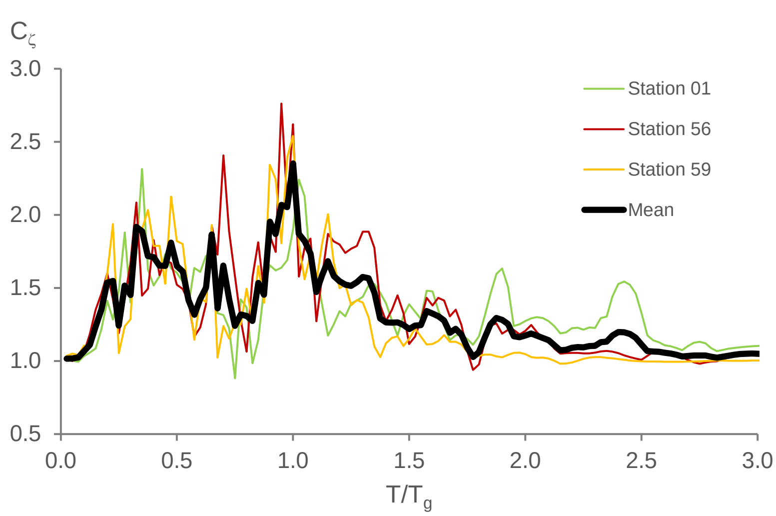

Fig. 4 – C_ζ factors (ζ=1%) for three sites and its mean presented as a function of periods of vibration normalized by the predominant period of the ground motion, T_g.

3. Earthquake Ground Motions

This study includes a total of 80 acceleration time histories which occurred during five major earthquake events recorded in the lake bed zone of Mexico City and corresponding to clay deposit sites with shear wave velocities as low as 40m/s. Table 1 lists general information of all the records used in the computation of the C_ζ values. These ground motions were obtained from the region with the most extensive damage during the 1985 earthquake [4].

Table 1 – Ensemble of ground motions

Date	Magnitude [Ms]	Station name	Station No.	Comp. 1	PGA [cm/s^2]	Comp. 2	PGA [cm/s^2]
09/19/85	8.1	SCT	SC	EW	167.9	NS	97.9
04/25/89	6.9	Alameda	01	EW	37.4	NS	45.5
04/25/89	6.9	C.U. Juárez	03	EW	37.4	NS	40.2
04/25/89	6.9	Xochipilli	06	EW	64.9	NS	49.3
04/25/89	6.9	Villa Gómez	09	EW	45.6	NS	42.9
04/25/89	6.9	P.C.C. Superficie	25	EW	42.5	NS	28.9
04/25/89	6.9	Jamaica	43	EW	31.2		
04/25/89	6.9	Balderas	45			NS	42.6
04/25/89	6.9	Rodolfo Menéndez	48			NS	27.7
04/25/89	6.9	Tlatelolco	55			NS	44.9
04/25/89	6.9	Liverpool	58	EW	40.0	NS	40.6
04/25/89	6.9	Candelaria	59	EW	45.2	NS	28.6
10/24/93	6.6	Xochipilli	06	EW	9.9	NS	8.3
10/24/93	6.6	Villa del Mar	29	EW	11.4	NS	13.6
10/24/93	6.6	Jamaica	43	EW	8.4	NS	12.1
10/24/93	6.6	Buenos Aires	49	EW	17.1	NS	14.4
10/24/93	6.6	Tlatelolco	55	EW	9.7		
10/24/93	6.6	Roma-B	RO-B	EW	8.5	NS	6.5
10/24/93	6.6	Roma-C	RO-C	EW	7.9	NS	10.5
10/24/93	6.6	SCT	SC	EW	10.5	NS	10.9
12/10/94	6.3	Xochipilli	06	EW	15.3	NS	16.4
12/10/94	6.3	Tlatelolco	08	EW	14.4	NS	14.8
12/10/94	6.3	Jamaica	43	EW	10.6	NS	12.1
12/10/94	6.3	Balderas	45	EW	13.7	NS	11.3
12/10/94	6.3	Buenos Aires	49	EW	15.7	NS	16.4
12/10/94	6.3	Tlatelolco	55	EW	12.8	NS	9.8
12/10/94	6.3	Córdova	56	EW	17.4	NS	17.2
12/10/94	6.3	Candelaria	59	EW	14.1	NS	14.1
12/10/94	6.3	Garibaldi	62	EW	15.1	NS	13.9
12/10/94	6.3	Roma-A	RO-A	EW	16.5	NS	19.4
12/10/94	6.3	Roma-B	RO-B	EW	13.7	NS	10.3
12/10/94	6.3	SCT	SC			NS	11.0
09/14/95	7.1	Alameda	01	EW	37.4	NS	45.5
09/14/95	7.1	C.U. Juárez	03	EW	25.9	NS	24.9
09/14/95	7.1	CUPJ	04	EW	26.8	NS	24.5
09/14/95	7.1	Tlatelolco	08	EW	28.5	NS	26.5
09/14/95	7.1	P. Elías Calles	10	EW	30.0	NS	29.7
09/14/95	7.1	Jamaica	43	EW	24.3	NS	27.7
09/14/95	7.1	Tlatelolco	55	EW	19.4	NS	29.7
09/14/95	7.1	Córdova	56	EW	45.2	NS	44.1
09/14/95	7.1	Garibaldi	62	EW	37.4	NS	30.1
09/14/95	7.1	Roma-B	RO-B	EW	25.0	NS	23.6
09/14/95	7.1	Roma-C	RO-C	EW	28.9	NS	31.1

4. Statistical Results

A total of 57,600 C_ζ factors were computed in this study. They correspond to 120 normalized periods of vibration (T/T_g) at equally spaced intervals from 0.025 to 3 and for 6 damping ratios (ζ=1%, 2%, 10%, 15%, 20% and 30%). The following two sections present a quantitative information about the central tendency and dispersion of the proposed factor C_ζ .

4.1 Central tendency of C_ζ

It was observed that the geometric mean and the mean of the C_ζ at all damping ratios and all normalized periods followed practically the same trend. Thus, we decided to use the mean to quantify its central tendency. Fig. 5 shows the mean values of all six studied damping ratios against the normalized period of vibration. It can be seen that the C_ζ factor decreases more rapidly for T/T_g>1.0 than for T/T_g<1.0. In the case of the recordings under study, the latter occurs due to two main reasons: the high frequency content of the ground motion amplifies spectral ordinates at periods usually lower than T_g, causing the C_ζ to decrease at a lower rate for T/T_g<1.0, and the influence of the second and third modes of the soft soil deposit.

An important feature is that, as a general trend, the effect of damping is increased in two clear regions. The first and most important one is at T/T_g=1.0. At this period ratio, the C_ζ value equals to 2.17, 1.63, 0.36, and 0.25 for damping ratios of 1%, 2%, 20%, and 30% respectively. The second important region is at around T/T_g=0.35 which roughly corresponds to the second period of vibration of the soil deposit. At this period ratio, the C_ζ value is less sensitive to damping than at T/T_g=1.0 but it still stands out. Its value corresponds to 1.71, 1.35, 0.60, and 0.53 for damping ratios of 1%, 2%, 20%, and 30% respectively.

4.2 Variability of C_ζ

This study used the logarithmic standard deviation ($\sigma_{\ln C\zeta}$) to quantify the dispersion in the estimation of the C_ζ factor. As it was done for the central tendency, this statistical parameter was computed for each normalized period of vibration and for each damping ratio. Figure 6 shows the $\sigma_{lnC\zeta}$ against the period ratio for the six damping ratios. As expected, the dispersion increases as the damping ratio moves away from ζ=5%. In the most the extreme cases analyzed, the maximum value of dispersion reached 0.25 and corresponded to ζ=30%. A slight reduction in the dispersion is achieved at T/T_g=1.0 which is a beneficial result of the normalization strategy. An important benefit of these small dispersion values is that they are smaller than the ones determined in common S_a GMPEs [25, 26], thus, making the dispersion of the final spectral ordinate (i.e. dispersion in the S_a value from GMPEs and the dispersion in the C_ζ factor) to marginally increase.

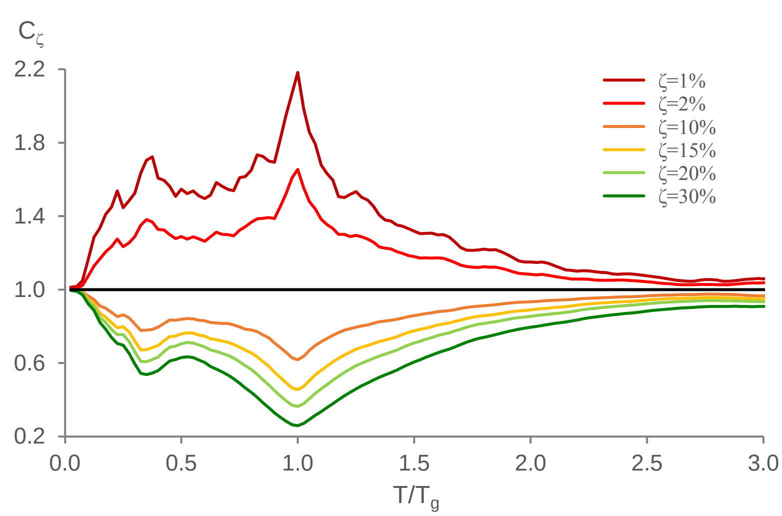

Fig. 5 – Mean values of the C_ζ factor for six damping ratios as a function of periods of vibration normalized by the predominant period of the ground motion, T_g.

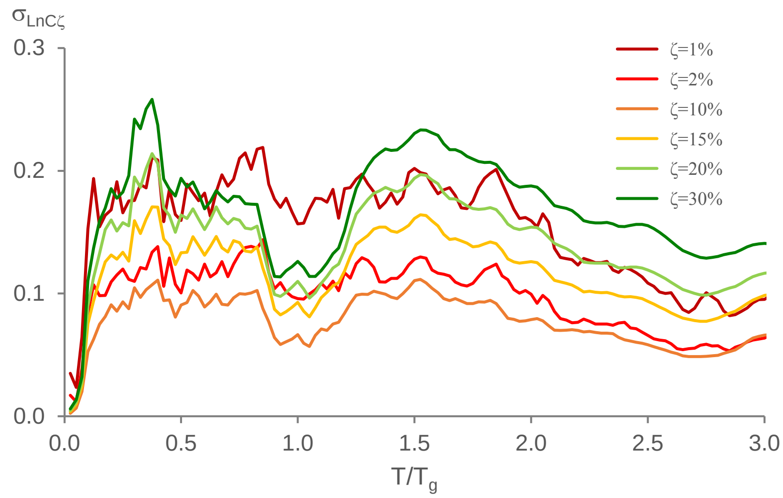

Fig. 6 – Logarithmic standard deviation of the C_ζ factor for six damping ratios as a function of periods of vibration normalized by the predominant period of the ground motion, T_g.

5. Nonlinear Regression and Proposed Equation

This study proposes a simplified nonlinear equation to estimate the mean value of C_ζ for damping ratios ranging from ζ=1% to ζ=30%. Most importantly, it is a function of the normalized period of vibration. Based on the observations of Section 4.1, the proposed model is given by Eq. 3-6

$$\tilde{C}_\zeta = 1 + a\left[\frac{\exp\left(-\frac{(\ln(T_r))^2}{2}\right)}{2.5\cdot T_r} + \exp\left(-b\cdot(\ln(T_r))^2\right) + \frac{\exp\left(-200\cdot(\ln(T_r+0.65))^2\right)}{3}\right] \tag{3}$$

$$T_r = \frac{T}{T_g} \tag{4}$$

$$a = 0.15\cdot\zeta - 1.025 \tag{5}$$

$$b = 2.4\cdot\zeta^{-0.35} \tag{6}$$

In the previous equations, ζ is the damping ratio, T is the first mode period of the structure and T_g is the period of the soil deposit. The first and second term capture the general variation of C_ζ with T/T_g, while the third and fourth terms account for local amplifications or reductions (depending on ζ). These take place at periods close to the fundamental period of vibration of the soil deposit ($T/T_g\approx1$) and at periods close to the second mode of vibration of the soil deposit ($T/T_g\approx1/3$).

This equation was obtained by conducting a non-linear least square regression analysis that minimized the difference between the computed C_ζ ordinates and the estimated responses from Eq. (3). A final conservative adjustment was made in the amplitude of the peaks and valleys at T/T_g=1.0 in order to produce estimates closer to the mean trend at that normalized period ratio. Fig. 7 shows the fitted mean of C_ζ as a function of T/T_g for the six damping ratios used. It appropriately captures the general trend and the enhanced effect of damping expected at the first and second mode periods of the soil deposit.

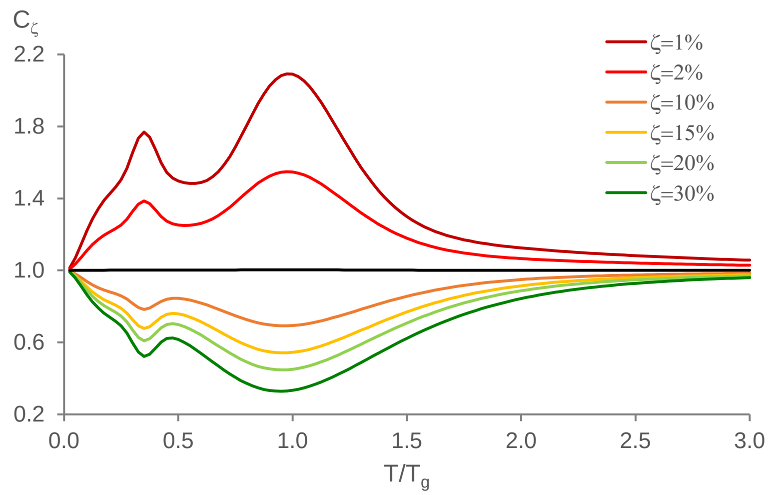

Fig. 7 – C_ζ factors computed using Eq. (3-6) as a function of periods of vibration normalized by the predominant period of the ground motion, T_g.

7. Discussion of Results

This study showed that response spectra from soft soils records exhibit important features that must be adequately quantified. The methodology implemented in this study accomplishes this and enables to propose a simplified expression that estimates the C_ζ factor as a function of two main variables, ζ and the normalized period of vibration.

Important differences must be emphasized between the C_ζ trend from ASCE 7-10 [15] and the one computed in this study for T/T_g=1.0. Fig. 8 shows that for damping ratios lower than 5%, the C_ζ values are larger in soft soil sites when compared to the ones recommended by ASCE 7-10. The opposite holds true for damping ratios larger than 5%. The differences in the former case can be as large as 76%, while in the latter they can also reach a considerable 55%. It can be also be seen that for T/T_g=1.0, the proposed equation seems to adequately capture the mean variation of C_ζ with damping ratio in soft soils.

The rate at which the C_ζ factor increases with decreasing damping, for three T/T_g values is shown in Fig. 9. It is seen that this general trend is a function of the normalized period. It is important to note that, besides the T/T_g=1.0 case, damping is especially effective at $T/T_g\approx 0.33$. This normalized period corresponds approximately to the second mode of vibration of the soil deposit. This second-mode effect can cause differences in the C_ζ of a factor of 1.37 in structures with damping ratios of 1%, and 1.1 for a damping ratio of 30% when compared to the factor proposed by the ASCE 7-10.

Results from this study corresponding to damping ratios greater than 5% are in agreement with [19] as the significant importance of T/T_g on C_ζ is also observed. This previous observation is also applicable for damping ratios lower than 5%. In both cases, it is extremely important to use this period normalization when estimating displacement demands in structures having damping ratios different than the usual 5%.

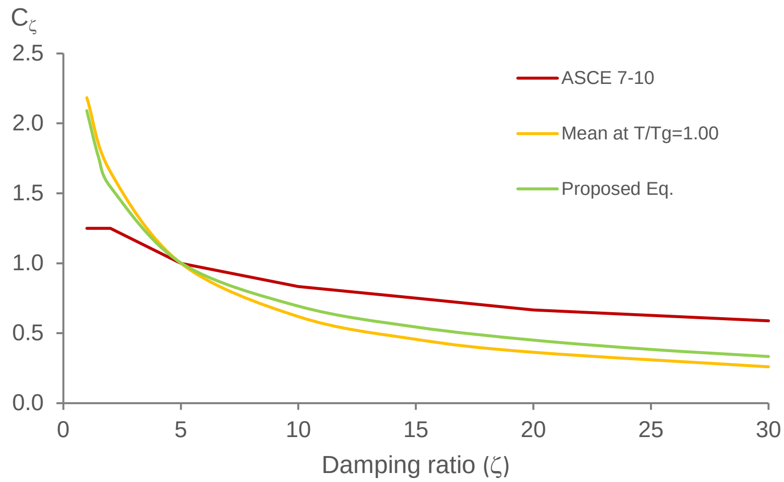

Fig. 8 – Comparison of C_ζ values from the proposed equation, from ASCE 7-10 and from the mean of SDOF systems at T/T_g=1.0.

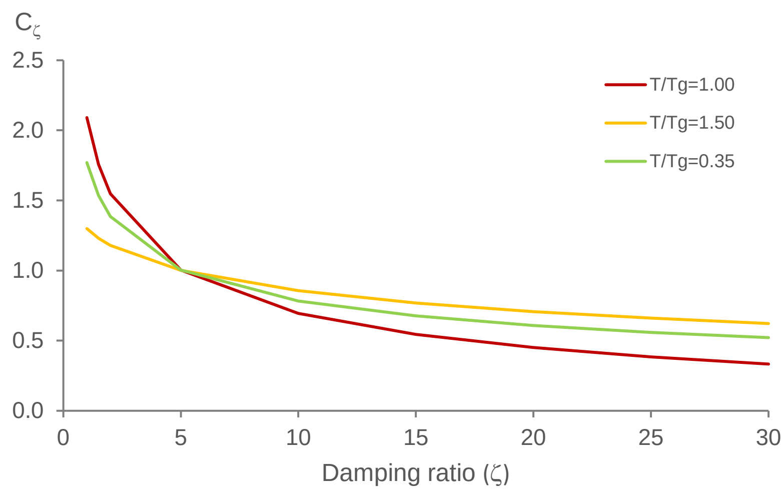

Fig. 9 – Variation of mean C_ζ values with damping ratio for several T/T_g ratios using the proposed equation.

7. Conclusions

The primary objective of this research was to evaluate the effect that soft soils have on displacement modification factors which are used to estimate the elastic design spectrum for damping ratios other than the 5%. In this study, we expressed the variation of this factor as a function of the fundamental period of vibration of the structure normalized by the predominant period of the ground motion, T_g. The statistical analysis was conducted using a total of 80 earthquake ground motions recorded in the soft soils of Mexico City during five major events. The following conclusions can be drawn from the results of this study.

1. For all the damping ratios analyzed, the value of C_ζ for structures in soft soils like the ones in the lake bed zone of Mexico City exhibits a different behavior than its corresponding one for firm soils. This is especially true when the structure has a period closer to the predominant period of the ground motion (T/T_g=1) and close to the second mode of the soil deposit (T/T_g=1/3). This makes of paramount importance to adequately characterize the C_ζ variation in order to have a better estimate of displacements in the design process.

2. Damping ratios of 1% and 2% have a mean C_ζ values of 2.2 and 1.65 which corresponds to an increase of 76% and 32% respectively, when compared to those recommended by current codes. On the other hand,

damping ratios greater than 5% produce reductions in the C_ζ values that range between 25% and 55%. The rate at which the C_ζ increases is more pronounced as the damping ratio is reduced. This trend also decreases as the T/T_g ratio deviates from unity.

3. A statistical study on the dispersion of the C_ζ factor is presented. It was seen that the minor effect that this uncertainty will add to the final computation of the adjusted spectral ordinate using current GMPEs is almost negligible.

4. We proposed an equation to estimate the C_ζ factor as a function of T/T_g and the damping ratio. It is recommended that this equation should be used to estimate elastic displacement demands for structures in soft soils instead of equations specifically developed from studies conducted on rock or firm soils.

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