17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

RESPONSE MODIFICATION FACTOR FOR SHORT PERIODS OBTAINED FROM A SET OF PERUVIAN SEISMIC ACCELERATION RECORDS

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Abstract

Most earthquake-resistant design codes include a response modification factor that simplifies the calculation of equivalent inelastic lateral seismic force and that are used in the seismic design of the structures. In this paper, the evaluation of resistance reduction factors is presented with the purpose of estimating the demand of inelastic resistance from the elastic resistance demand and for different ductility values. The processing was done from twelve records of seismic accelerations measured in several places of the Peruvian coast.

From a model of a degree of freedom that has elastic and elastic-perfectly plastic behaviors, the spectral responses of the selected records were obtained for different critical damping ratios and ductility demands. The elastic and inelastic responses were processed, in order to obtain the resistance modification values for each selected record.

For each of the acceleration records it was observed that the resistance modification factor is strongly influenced by the displacement ductility demand and by the vibration period of the system. A simple expression of the response modification factor has been proposed to estimate a reasonable response spectrum of inelastic design for this type of records.

Finally, the results obtained were compared with the pseudo-acceleration design spectrum from Peruvian seismic code (E.030) and from Chilean seismic code (NCh433). This comparison provided satisfactory results.

Keywords: Response reduction factor; ductility; spectral response; seismic Peruvian records.

1. INTRODUCTION

Most seismic design provisions employ philosophy and principles of seismic design where is recognized that it is not feasible to reach complete protection for all severe earthquakes. One of these principles of earthquake-resistant engineering design is to allow acceptable damage levels to buildings according to the intensity of the seismic event, which implies inelastic incursions of structural components, and they are associated with a certain level of global ductility of the structure.

On the other hand, one of the widely accepted seismic analysis methods is the Modal Response Spectrum Analysis (MRSA) using a reduced elastic design spectrum, which consists of performing an elastic linear analysis of the structure and subsequently adjusting the lateral force and displacement values by factors that modify the response [1, 2]. The MRSA Method is very attractive due to its simplicity and because it allows to obtain results that are considered acceptable.

The Strength Reduction Factor R, also known as Response Modification Factor [3, 4, 5] is the most important factor in the design or seismic evaluation of buildings since no other parameter affects the design shear force demand [6]. The Shear force demand for design is obtained dividing the elastic base shear demand by R factor [3, 4, 5]. This R factor depends mainly on the ductility demand, the fundamental vibration period of the structure, the structural damping, the site soil conditions, among others [2, 6, 7]. Riddell et al [8] have realized a statistical study of the spectral response of several ground motion records and have found that the shape of the function $R=R(T)$ is approximately the same for the different ductility factors, and there is a build-up for R at $T<0.5$ seconds up to a certain value that remains essentially constant for periods larger than 0.5 seconds.

Miranda [9] have made a study with a large number of recorded ground motions in order to study the effects of the influence of local site conditions on strength reduction factors, which were classified as rock, alluvium and very soft soil, and concluded that soil conditions may influence significantly the reduction factor, particularly the soft soil sites. Similar studies [9, 10] also concluded that magnitude and epicentral distance have a negligible effect on strength reduction factors.

The study realized by Riddell y Newmark [11] has concluded that peak responses of elastoplastic, bilinear and stiffness degrading system are very similar, and what the use of an elastoplastic system for inelastic analysis is generally conservative.

The present study aims to show the results obtained from evaluating the response modification factor R with a single degree of freedom SDOF systems with perfect elastoplastic behavior and 5% critical damping ratio, subjected to 12 pairs of ground motion recorded along the Peruvian coast. The results showed typical amplification of the pseudo-acceleration response in the range of short periods of the system, declining as the system becomes more flexible.

The statistical results, which were computed with ductility ratios between 1.5 and 10 and the 12 pairs of ground motion records, showed that Strength reduction factors R tends to grow as the vibration period increases until a certain value is reached, and from a determined period value, the value of the modification factor has a more stable and almost constant response. This behavior has also been exhibited in other studies [8, 9, 10, 11].

2. METHODOLOGY

2.1. GROUND MOTION RECORDS CONSIDERED IN THIS STUDY

The two horizontal components of 12 earthquake events measured in various events that occurred on the west coast of Peru and for different types of soil (rock or alluvial) were used. It should be noted that all records are caused by the tectonic activity of the subduction between the Nazca Plate and the South American one. The characteristics of the records used are given in Table 1. Each one of the 24 seismic signals were scaled to a PGA value equal to 1·g (gravity acceleration, 9,808 m /s^2) before they were used in the analysis. Such records correspond to events that occurred along the coast of Peru (Fig. 1), due to the subduction mechanism caused by the mentioned plates.

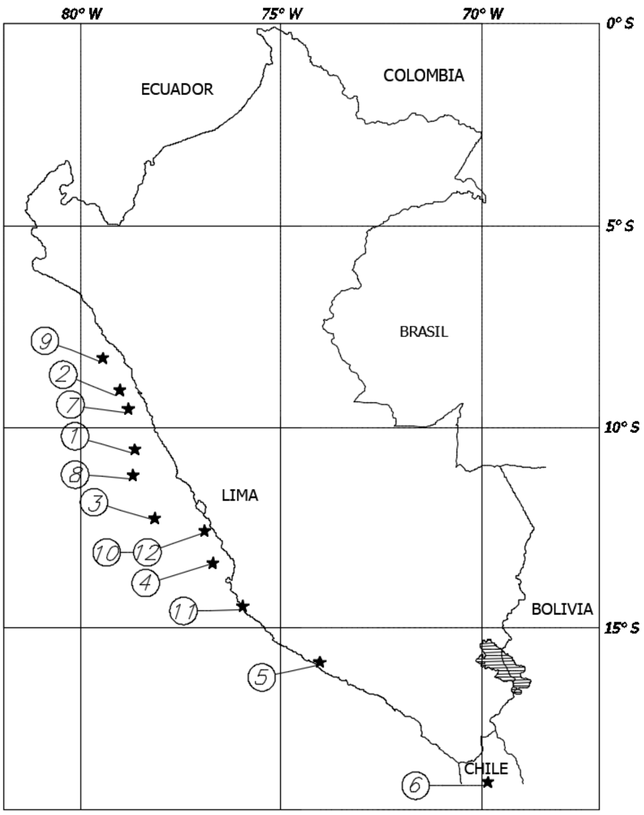

Fig. 1: Epicentral of Eartquake motions used in this study.

2.2. SYSTEM AND LOAD DEFORMATION MODEL

A simple single degree of freedom SDOF system was considered with an elastoplastic load-deformation function without stiff degrading or strength deterioration (Fig. 2). A reasonable 5 percent of critical damping ratio (ξ) was used. Besides, the spectra were computed for linear and inelastic responses associated with ductility factor values of 1, 1.5, 2, 3, 4, 5, 6, 8 and 10. In addition, the vibration period value (T^j) was varied from 0.01 to 5 seconds in three equally spaced groups (50 period values between 0.008 and 0.020 seconds, 200 between 0.020 and 2.00 seconds; and, 30 between 2.00 and 5.00 seconds).

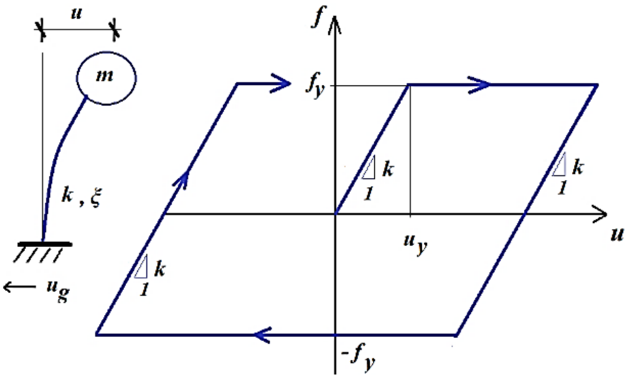

Fig. 2: SDOF system for analysis and elastic-plastic behavior considered.

Table 1: Earthquake and record data for ground motions used in this study.

Id	Station	Epicenter coordinates	Earthquake Date and Time	Focal Deep (km)	Epicentral Distance (km)	Magnitude	Station Coordinates	PGA W-E (g)	PGA N-S (g)
1	Parque de la Reserva (PRQ)	10.70° S 78.70° W	17/10/1966 16:41 local	24	237	7.5 Ms (USCGS)	12.06° S 77.05° W	0.275	0.184
2	Parque de la Reserva (PRQ)	9.36° S 78.87° W	31/05/1970 15:23	64	361	7.8 Ms (USCGS)	12.06° S 77.05° W	0.100	0.107
3	Parque de la Reserva (PRQ)	12.50° S 77.98° W	3/10/1974 9:21	13	114	7.6 Ms (NEIS)	12.06° S 77.05° W	0.182	0.196
4	Asamblea Nacional de Rectores (ANR)	13.67° S 76.89° W	2/02/2009 17:53	35	172	5.8 Ml (IGP)	12.13° S 76.98° W	0.005	0.005
5	CISMID – Lima (CISMID)	16.08° S 73.77° W	24/08/2011 12:46	90	575	7.0 Ml (IGP)	12.01° S 77.05° W	0.010	0.005
6	Ciudad Nueva – Tacna (CNMC)	18.76° S 69.76° W	22/03/2015 23:51	125	100	6.2 Ml (IGP)	18.00° S 70.20° W	0.082	0.077
7	Sayan-Lima (SAYH)	9.74° S 78.73° W	1/04/2016 14:01	36	228.9	5.1 Ml (IGP)	18.00° S 70.20° W	0.00043	0.00041
8	Carquin-Lima (CRQN)	11.49° S 78.58° W	6/01/2017 17:55	36	113.8	5.0 Ml (IGP)	11.1° S 77.6° W	0.015	0.016
9	Trujillo - La Libertad (TRUJ)	8.44° S 79.36° W	1/02/2018 0:35	49	52.5	5.0 Ml (IGP)	8.1° S 79.0° W	0.007	0.007
10	Mala - Lima (MALA)	12.79° S 76.87° W	17/05/2018 11:07	49	30	5.5 Ml (IGP)	12.7° S 76.6° W	0.101	0.102
11	Pucusana - Lima (PUCU)	14.73° S 75.69° W	1/02/2018 0:35	49	52.5	6.0 Ml (IGP)	12.5° S 76.8° W	0.003	0.004
12	Pucusana - Lima (PUCU)	12.78° S 76.89° W	22/03/2019 7:50	33.9	43	4.9 Ml (IGP)	12.5° S 76.8° W	0.025	0.021

The ground motion records used in this study were scaled to a PGA equal to $1{\cdot}g$. Table 2 shows the scale factors used for each one of the 24 signals, and the corresponding Arias intensity (I_A), where N-S component of scaled earthquake 3 has the highest I_A value.

Table 2: Characteristics of the scaled signals, and Arias Intensity values.

Id	Scale factor		Arias Intensity I_A ($\pi/2{\cdot}g$)	
	N-S	W-E	N-S	W-E
1	5.430	3.641	1.20E+06	7.70E+05
2	9.355	10.032	1.73E+06	1.68E+06
3	5.094	5.480	2.20E+06	1.77E+06
4	190.408	193.412	1.13E+06	1.16E+06
5	92.509	102.466	1.60E+06	1.71E+06
6	12.916	12.203	8.01E+05	6.23E+05
7	2,338.50	2,465.15	1.21E+06	1.36E+06
8	65.230	62.211	6.50E+05	4.30E+05
9	142.950	140.607	9.10E+05	7.49E+05
10	9.832	9.906	2.77E+05	2.74E+05
11	280.342	293.672	1.33E+06	1.83E+06
12	48.573	39.385	3.11E+05	2.65E+05

2.3. ANALYSIS OF THE DATA

The 24 scaled signals were processed for each SDOF associated to each vibration period considered T^j. Subsequently, elastic responses (μ=1) were obtained for spectral pseudo-acceleration S_A, lateral displacement u, and lateral demand F_y. Similarly, inelastic responses ($\mu = \mu_i$) for S_A, u, and F_y were also obtained. Finally, the spectral pseudo-acceleration S_A responses were normalized ($S_{AN} = S_A/PGA$), in this manner, 24 normalized pseudo-acceleration responses $S_{AN}(\mu = \mu_i)$ were obtained.

The normalization of the responses with respect to the maximum acceleration allows the data to become independent in absolute terms, and to visualize the amplification of the response in terms of the maximum acceleration of the soil (PGA).

3. RESULTS

The Normalized Elastic Spectral Acceleration (pseudo-acceleration) Responses $S_{AN}(\mu=1)$ are shown in Fig. 3. The Average Normalized Spectral Acceleration Responses for different ductility values $\hat{S}_{AN}(\mu = \mu_i)$ are shown in Fig. 4. The Response Modification Factor R is defined as the ratio between the elastic strength demand to the inelastic strength demand (Eq. 1).

$$R(\mu, T) = \frac{F_y(\mu = 1)}{F_y(\mu = \mu_i)} \tag{1}$$

For our purpose, the Average Response Modification Factor R is defined from the average normalized spectral acceleration $\hat{S}_{AN}$ as shown in Eq. 2 [8].

$$R(\mu, T)_{AVG} = \frac{\hat{S}_{AN}(\mu = 1)}{\hat{S}_{AN}(\mu = \mu_i)} \tag{2}$$

The average normalized spectral acceleration values presented in Fig. 4 have a smooth shape than the individual responses; and, because they are normalized values, this figure exhibits the behavior of the amplification of the ground motion, which is concentrated at the short period zone.

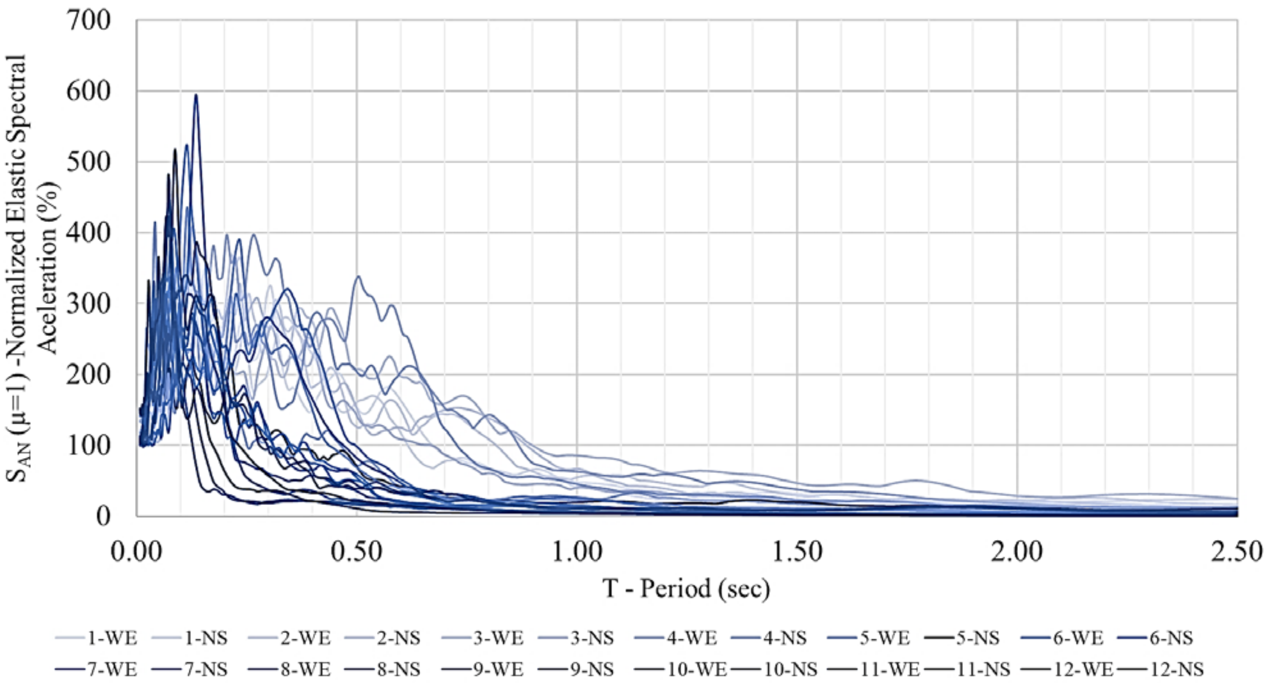

Fig. 3: Normalized Elastic Spectral Acceleration Responses for the 24 signals processed $S_{AN}(\mu=1)$.

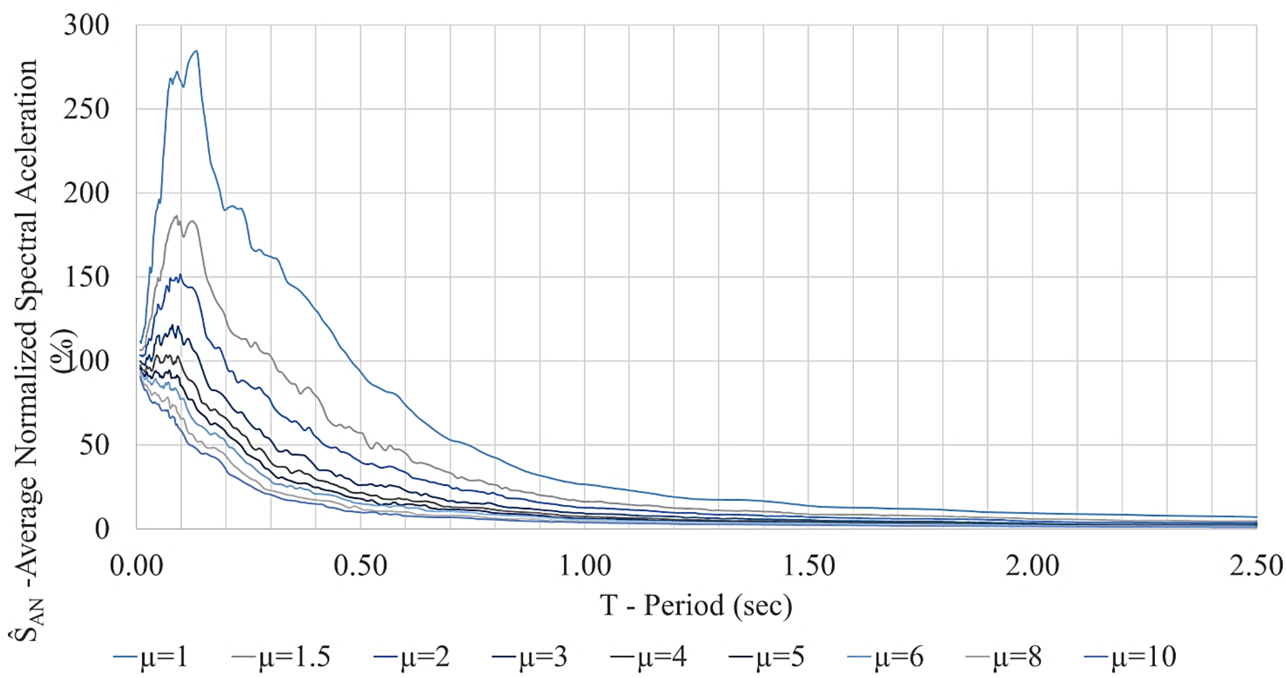

Fig. 4: Average Normalized Spectral Acceleration associated with the predetermined ductility factor values $\hat{S}_{AN}(\mu=\mu_i)$.

The Average Response Modification Factors *R* obtained from Eq. 2 are shown in Fig. 5, the results for the first 2.50 seconds are presented. In the short period zone, the Response Modification Factor has a growing and almost erratic behavior, which increases with the period and ductility. There are not important variations of the factor *R* for curves when $\mu < 3$; however, for higher ductility demands a significant increase of the R factor is observed, especially in the short periods zone ($T^j < 0.4$ sec). These observations are in accordance with what has been concluded by other researchers [8, 10, 11].

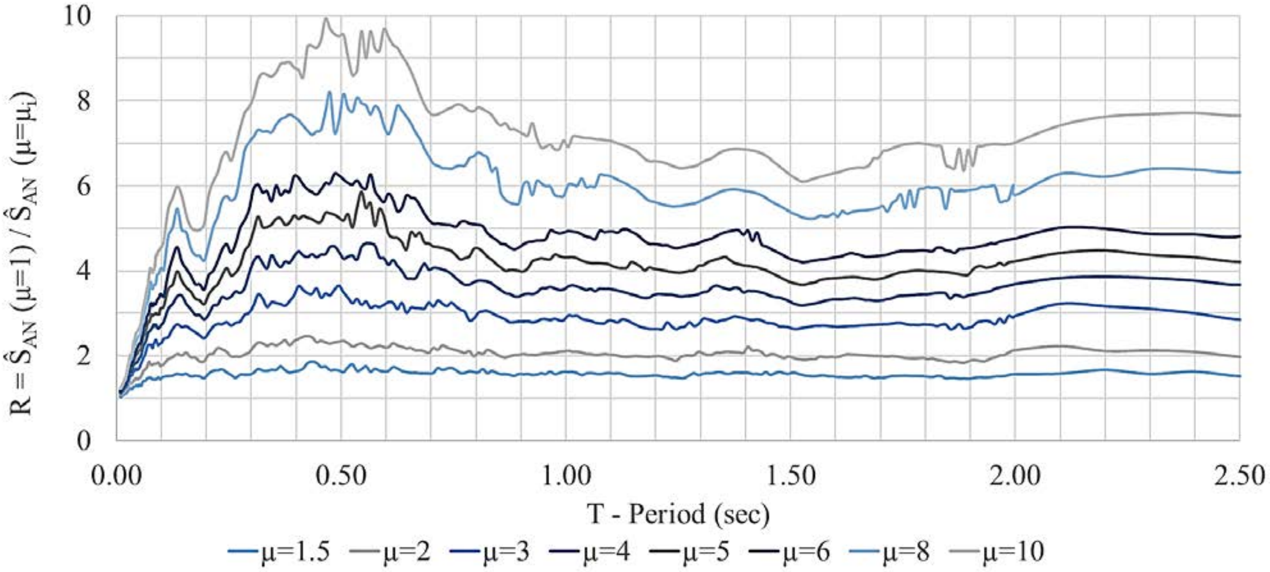

Fig. 5: Average Response Modification Factors obtained for various ductility factors demand.

The behavior of the Response Modification Factor *R*, which is exhibited in Fig. 5, is highly sensible at short periods zone ($T < 0.5\ sec$), specially for ductility values relativity high ($\mu > 4$). Paulay and Priestley [12] had expressed their concern in finding an appropriate expression for *R* that is expressed in terms of *T* and μ. This aspect is discussed in the following paragraphs.

4. EVALUATION OF THE RESPONSE MODIFICATION FACTOR *R(T, μ)*

In order to propose an expression to evaluate the response modification factor *R*, expressions based on the proposal of Nassar and Krawinkler [10] was adjusted, which are formulated in terms of the period of vibration *T* and the demand for global ductility μ.

$$R(\mu, T) = [1 + c \cdot (\mu - b)]^{1/c} \tag{3}$$

$$c = \frac{T^a}{1 + T^a} + \frac{T^*}{T} \tag{4}$$

The *R* factor proposed in Eqs. 3 and 4 is a function of *T* and μ, in addition to the parameters *a, b* and T^* whose values are shown in Table 3. Fig. 6 shows the idealized curves for the *R* factor, obtained from these Equations, in the range of periods *[0.0-1.00] secs* and for the predetermined ductility values.

Table 3: Proposed values for the parameters of the *R* factor idealized curve.

μ	*a*	*B*	T^*
1.5	4.5	1.00	0.250
2	4.0	1.25	0.225
3	3.5	1.50	0.200
4	3.0	2.00	0.200
5	2.5	2.50	0.200
6	2.0	3.00	0.200
8	1.5	4.50	0.150
10	1.0	6.00	0.125

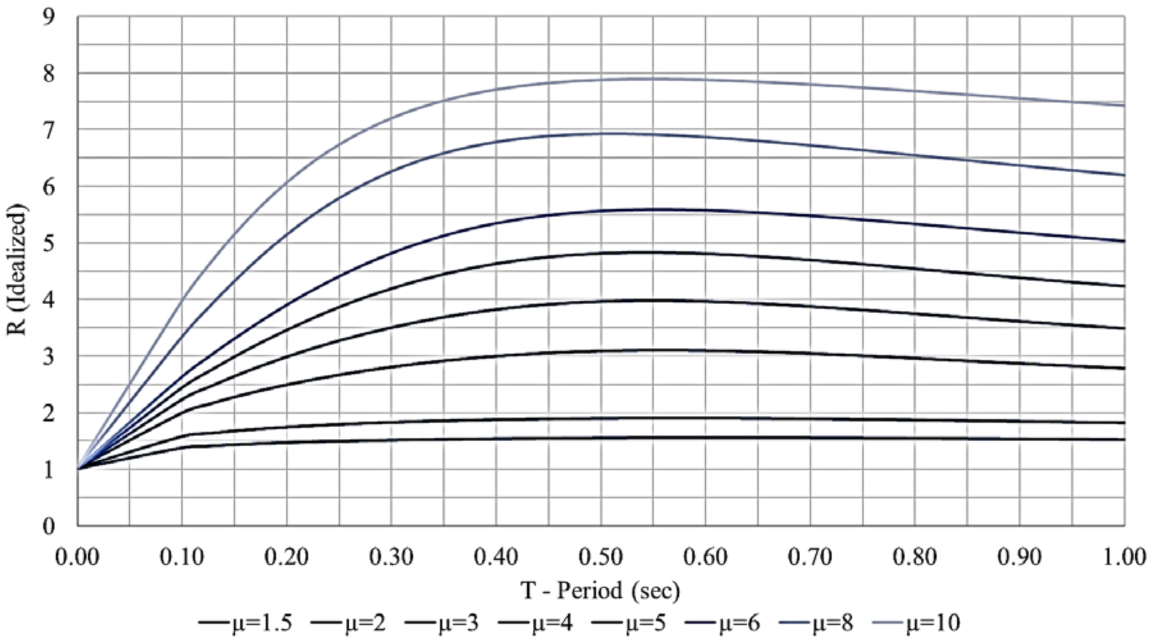

Fig. 6: Idealized Curves proposed for Response modification factor *R*.

The comparison between the idealized (Eqs. 3 and 4) and the average curve (average spectral responses discussed in item 3) for the modification factor *R* with different global ductility values μ is shown in Fig. 7. There is no clear tendency in the average data for the value of *R* in cases of $\mu > 3$; Furthermore, it is appreciated that the corresponding idealized curves provide conservative values of *R*.

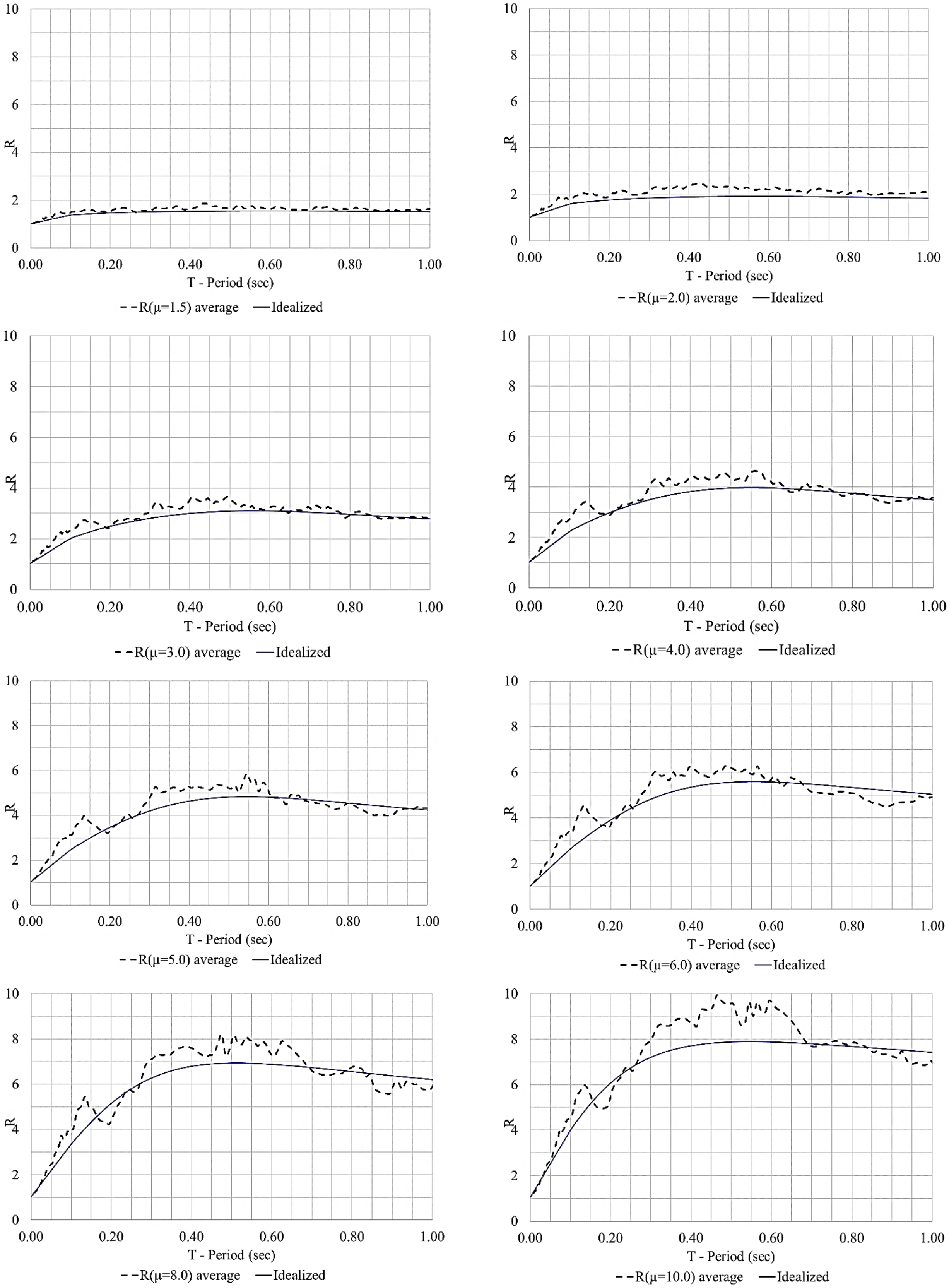

Fig. 7: Comparison of strength reduction factors between the average data and the idealized proposal for different ductility demand values.

5. INELASTIC DESIGN SPECTRUM WITH PROPOSAL RESPONSE MODIFICATION FACTOR *R(T, μ)*

For practical purposes, the inelastic design spectrum has been generated from the elastic spectrum of the Peruvian code, rather than from the ground motion records. This practical design spectrum (Eqs. 5 and 6) has been developed in order to evaluate the effect of the idealized modification factor proposed in this study $R(\mu, T)$.

For $\mu \leq 2.5$:

$$S_{AN.I}(T) = 1.00 + \frac{(S_{AN.E}(T)/R_o - 1.0) \cdot T}{T_a} \qquad \text{For: } T \leq T_a$$

$$S_{AN.I}(T) = \frac{S_{AN.E}(T)}{R_o} \qquad \text{For: } T_a \leq T \leq T_p \tag{5}$$

$$S_{AN.I}(T) = \frac{S_{AN.E}(T)}{R(\mu, T)} \qquad \text{For: } T > T_p$$

For $\mu > 2.5$:

$$S_{AN.I}(T) = 1.00 + \frac{(S_{AN.E}(T)/R_o - 1.0) \cdot T}{T_p} \qquad \text{For: } T \leq T_p$$

$$S_{AN.I}(T) = \frac{S_{AN.E}(T)}{R(\mu, T)} \qquad \text{For: } T > T_p \tag{6}$$

Where: $S_{AN.E}$, is the normalized elastic spectral acceleration from the Peruvian code NTPE030 [13] ($R=1$); $S_{AN.I}$, the calculated normalized inelastic spectral acceleration; R_o, the idealized response modification factor computed for $T=T_p$ and the respective ductility; T_a, a very short period of reference ($T_a=0.10$ sec); and T_p, the short period that defines the platform of the Peruvian spectrum NTPE030 ($T_p=0.40$ sec).

6. DISCUSSION

A comparison of proposal design spectrum and response spectrum obtained from the data for different ductility values is presented in Fig. 8. In general, the proposed design spectrum has a good relationship with the shape of the response spectrum. However, there is also a disagreement between the spectrum values in the area of very short periods ($T < T_a$), especially for ductility less than 4.

A comparison of inelastic design spectrums computed by the Peruvian Code NTPE030 [13], the Chilean code NCh433 [14] and the spectrum proposed in this study for ductility values of 2.0, 3.0 and 5.0 is presented in Fig. 9. The seismic parameters used in this figure corresponds to firm soil sites and the higher seismic risk zones. It may be concluded that, for $\mu < 2.5$, the Peruvian code is conservative only at very short periods zone ($T < T_a$). In addition, the proposed design spectrum is generally the most conservative in almost all vibration period ranges. Finally, Fig. 9 shows that The Peruvian Code could be unconservative at the short period zone ($T_a<T<0.40$ sec), which comes from the use of a flat design spectrum and constant R factors, this is evidenced for curves width $\mu = 5$.

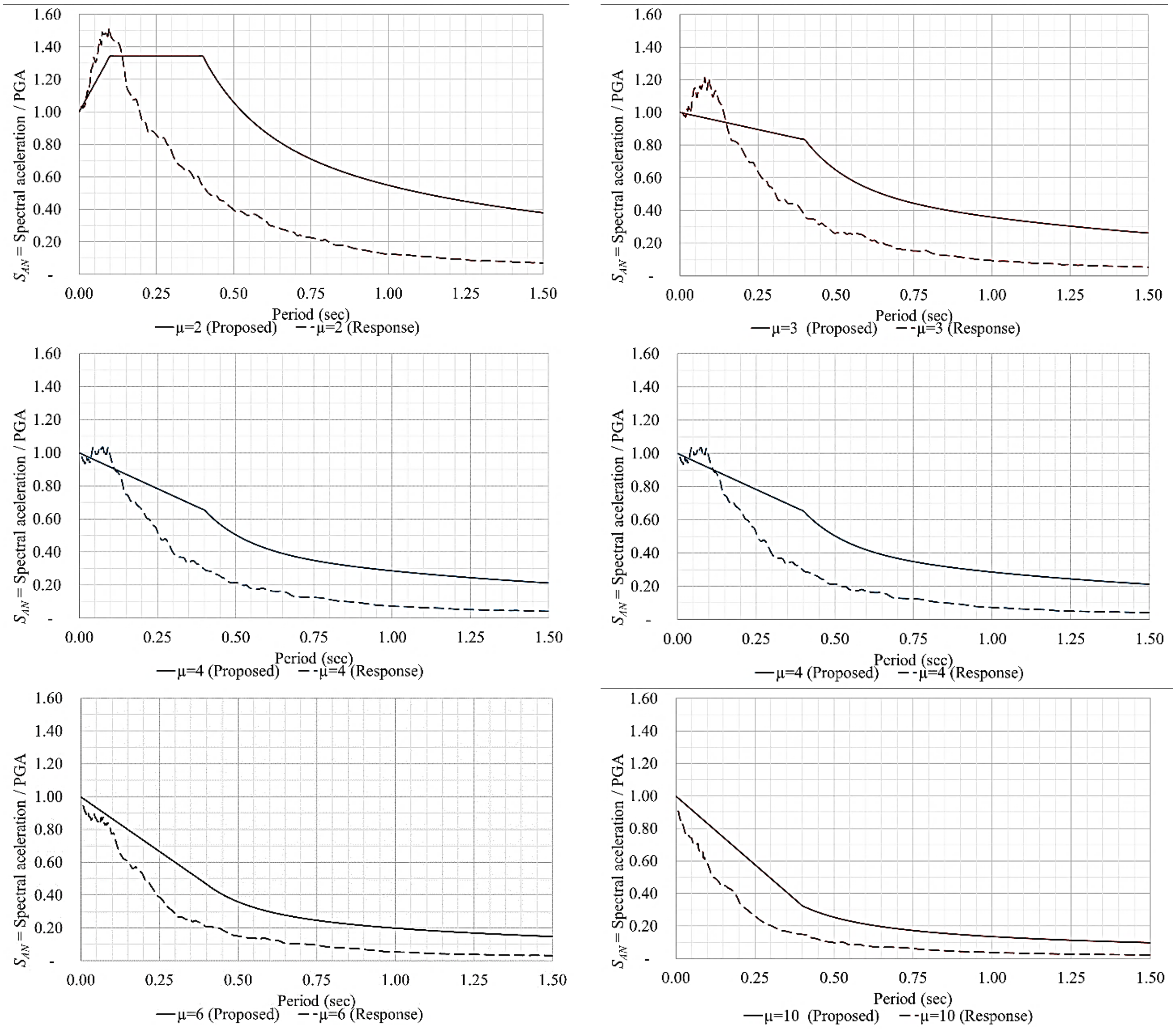

Fig. 8: Comparison of proposal design spectrum and response from data for different ductility values.

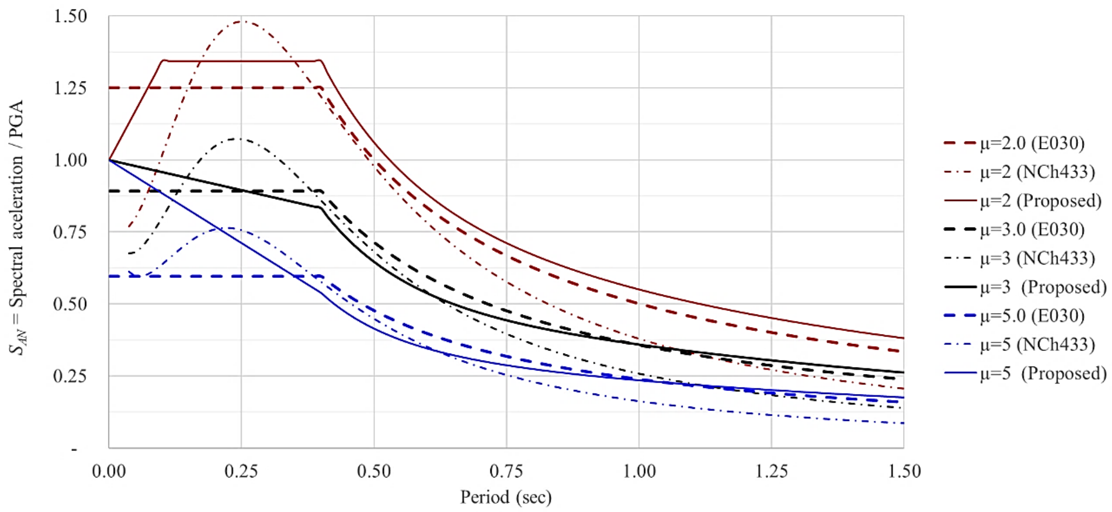

Fig. 9: Comparison of inelastic design spectrum of Peruvian Code (E030), Chilean code (NCh433) and spectrum proposed for ductility values of 2.0, 3.0 and 5.0.

7. CONCLUSIONS

Elastic and inelastic response spectrums for SDOF's (with perfect elastoplastic behavior and 5% critical damping ratio) were processed using 12 pairs of ground motions recorded along the Peruvian coast and with several ductility ratios, in order to study the Response Modification Factor *R*. The following conclusions can be drawn from this study:

a) The Response Modification Factor *R* grows irregularly with the period approximately until $T=0.40$ *sec* and then decreases softly as the period increases. This becomes more evident as global ductility μ increases (Fig. 6 and 7).
b) In the short period zone ($T <0.4$ *sec*), using a response modification factor R, depending on the T and μ, could result in a more conservative and representative spectrum of the response spectrum than the current design spectrum of Peruvian code NTPE.030, which uses a constant *R* factor.

It is recommended to propose an inelastic design spectrum considering a robust local ground motion data, where a variable response modification factor *R* is used as it was in this study. This in order to improve the current spectrum of Peruvian seismic code.

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