INELASTIC RESPONSE OF STRUCTURES UNDER MULTI-COMPONENT GROUND MOTIONS

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Abstract

This paper presents an extensive study on inelastic displacement ratios (IDR) to estimate the performance of the structure by taking into account soil-structure-interaction (SSI), degradation of the materials, repeated earthquakes and both translational and rotational acceleration components of the ground motion. The aim is to quantify the performance of the structures by including significant aspects that have not been considered in the current seismic provisions yet.

A database of 100 ground motion records were collected to conduct the analysis of degrading single degree of freedom systems (SDOF). First, the study has been carried out for two different foundation assumptions, fixed-based and resting on soft soil respectively, for investigating SSI. Second, the impact of single ground motion and repeated earthquakes on the system has been examined. Modified Clough model has been used to signify the degradation on the hysteresis of reinforced concrete structures. Third, a multi component ground motion spectrum has been developed to demonstrate structural damage due to the vertical and rotational component of ground motion. For this purpose, a SDOF oscillator has been subjected to coupled horizontal and rotational excitations of ground motion.

It has been found that not only material degradation affects the (IDR) of the systems but also repeated earthquakes have a significant effect on them. It is believed that measuring structural performance by means of coupled translational and rotational component of acceleration is a breakthrough achievement with regards to designing new structures as well as existing ones.

Keywords: repeated earthquakes, rotational acceleration, degradation, inelastic displacement ratio, SSI

1. Introduction

Currently, seismic provisions for structural design do not account for repeated earthquakes and soil-structure interaction (SSI). Some of the sophisticated seismic design approaches contain SSI, but for most of the engineering problems, simplified methods are used. Widely assumed, fixed-base foundation neglects the impact of SSI. Moreover, in current seismic design, the effect of a single earthquake is taken into account. It is claimed that the structure will behave likewise under repeated earthquake loading. But this assumption, then, gives up the effect of degradation. Parameters such as stiffness and strength (for both the structure and soil) are reduced under every load cycle. Therefore, soil augments the ground motion acceleration as well as the structure undergoes highly inelastic range of motion and could end up with collapse. This implies that repeated earthquakes can be more damaging to the structure in comparison to a single earthquake [1].

Even if seismic design standards permit structures to undergo inelastic deformations under strong ground motions, practically linear elastic analyses are used to estimate the maximum response of the structure. On the other hand, to estimate the maximum inelastic response, and particularly the maximum lateral inelastic displacement demands, the results from a linear elastic analysis are used. One of the first studies was done by Veletsos [2] who pointed out to the relation between maximum deformation of elasto-plastic system to an elastic system, which by then is referred to as “the equal displacement rule”. Miranda [3] worked on a correlation study to show that in the high and moderately high frequency regions, the inelastic displacements are higher than their elastic ones.

An inelastic displacement ratio (IDR) is defined as the ratio of the maximum lateral inelastic displacement demand of a structure to the maximum lateral elastic displacement demand [3]. IDR values in the study, have been calculated for SDOF systems undergoing different levels of inelastic deformation when subjected to several recorded earthquake ground motions.

During recent earthquakes, the vertical component of the ground motion found to be exceeding the horizontal component, which opposes the current provisions that assumes the value of the vertical ground motion to be 1/2 to 2/3 of the horizontal component. As recently shown, the vertical motion may increase the bending moment in longitudinal bridge girders. Efforts have been made for development of vertical ground motion spectra by focusing mostly on near fault accelerograms [4].

The consequences of rotational earthquake ground motions on structural response are still under investigation. Synchronised six-component earthquake measurements are being gathered gradually. A ring laser installed in Germany, which considers plane transverse wave propagation, has been developed to measure acceleration and rotation rate, which should be in phase and their amplitude ratio proportional to the horizontal phase velocity. It should be noted that the impact of torsion component of ground motion acceleration is being under examination and the results will be presented only in the conference session.

2. Degradation

Structural systems show stiffness degradation when subjected to reverse cyclic loading. Furthermore, this is more evident for reinforced concrete components under large cyclic load reversals. Stiffness degradation in reinforced concrete components is the product of cracking and high shear or axial stresses [5]. Not only the material properties, geometry, level of ductility and connection characteristics of the structure are proportionate to the stiffness, but also the loading history does.

Many studies have been done to assess the effects of stiffness degradation. In addition, the peak response of stiffness degrading systems and elasto-plastic and bilinear strength hardening systems have been compared [6-7-8]. These studies sum up that, despite the reduction in lateral stiffness and hysteretic energy dissipation capacity, systems with stiffness-degrading action for moderate and long-periods experience peak displacements that are like those of structures with elasto-plastic or bilinear strength-hardening hysteretic behaviour. Variances in peak displacements between stiffness-degrading and non-degrading systems rise as the period decreases and as the lateral strength decreases. By exploring the stiffness degradation on structures subjected to ground motions recorded on especially soft soil sites, it has been concluded that stiffness degradation is more significant [9]. This conclusion is one of the many reasons to choose soil type C as soft soil for the paper.

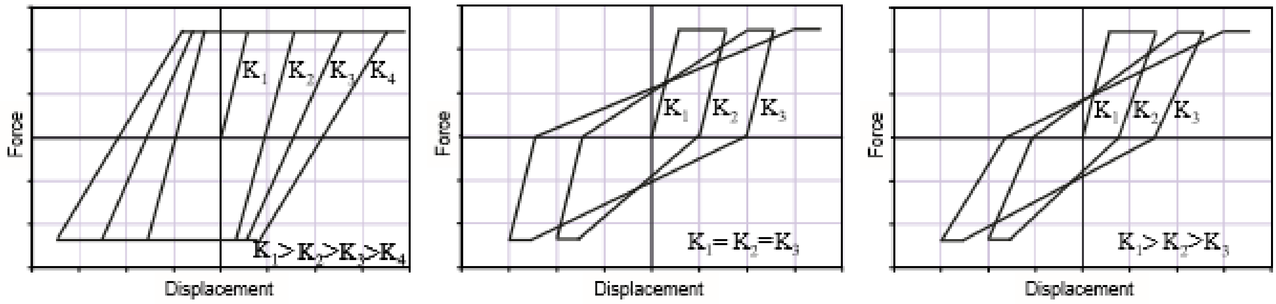

Fig. 1- Different stiffness degrading hysteretic models- adopted from FEMA P440A Chapter2.

Figure 1 above exemplifies three different stiffness-degrading models. They all show change on the stiffness as a function of displacement. As a result, to contain the degradation in the system, material modeling has been chosen carefully as the Modified Clough Model. This model includes three parameters: an elastic branch, a strain-hardening branch and a softening cap branch as mentioned by [10]. A residual strength is considered in all models.

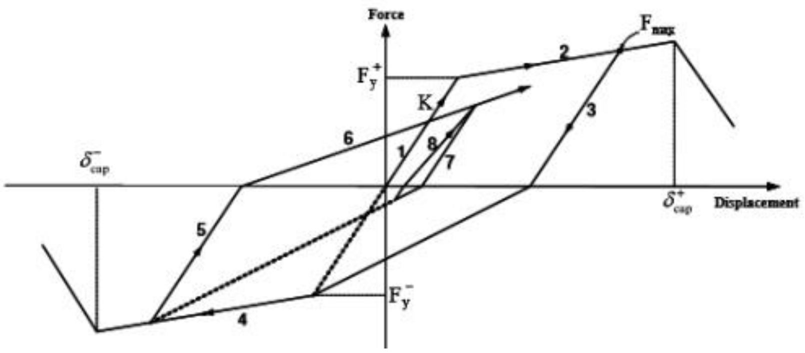

Fig. 2- Modified Clough Model adopted from [10].

This approach is based on the above mentioned Krawinkler's method [7] that consists of eight parameter energy-based criteria. Four parameters simulate the rate of deterioration, while the other four simulate the degradation capacity. As per the latter, four types of cyclic degradation are considered.
As seen in Fig.2, the Modified Clough model has been used to imply the degradation on the hysteresis of reinforced concrete structures by following four degradation types:

1. Yield degradation, that refers to the decrease of the yield strength as a function of the loading history.
2. Unloading stiffness degradation, that refers to the decrease in unloading stiffness as a function of the loading history.
3. Accelerated stiffness degradation, that refers to the decrease in reloading stiffness.
4. Cap degradation, that is observed as a result of cumulative damage.

In this study, four types of degradation are simultaneously implemented for modified Clough models. The structural system's collapse is assumed if the following conditions are satisfied: when the displacement becomes bigger than the cap slope intersection point with the residual strength line resulting in a cap failure and when β (scalar parameter) exceeds a value of 1 resulting in degradation failure.

3. Models and Analyses

A set of hundred earthquake data have been taken from different strong ground motion data centers around the world. Based on different parameters, the analyses have been performed. Those parameters are SSI, Sequence of repeated earthquake and vertical and rotational component of ground motion acceleration. The impact of those various parameters on the inelastic structural response has been investigated. Analysis was conducted for different strength reduction factors R=2,4, and 8.
Earthquake records have been scaled to analyse the seismic behaviour of a SDOF system. The scaling confirms that the earthquake records have comparable magnitudes.
Real tested column data have been used to simulate column behaviour under earthquake loading accurately. Five reinforced concrete columns with similar beam column parameters have been picked from the PEER Report 2007/03 [11].

3.1. Repeated Earthquakes

Different (SDOF) systems have been examined under selected ground motions as well as artificially generated repeated earthquake series associated to those ground motions. The repeated model simulates fore shock, main shock and after shock. A factor of the main shock was assumed to replicate the after shock. Empirical relationships were used to accomplish the scale factor [1].

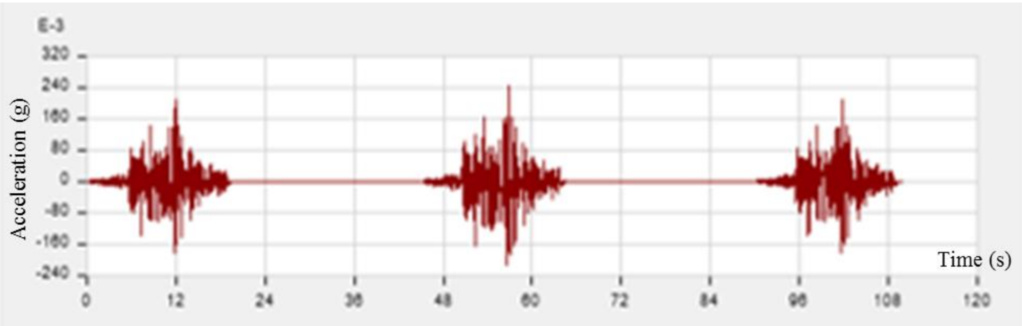

Fig.3- Northridge Earthquake Repeated Sequence

Fig.3 shows generated artificial earthquake sequences, consisting of foreshock, main shock, and after shock. For the fore and after shock the main shock has been downscaled. The data belong to the Northridge Event, recorded in Pasadena-N Sierra Madre Villa.

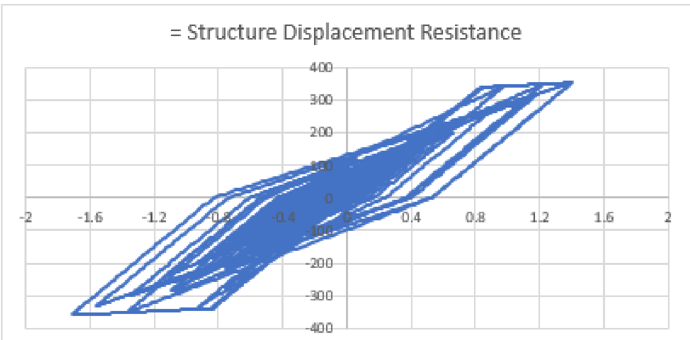

Fig.4- Northridge Earthquake Repeated Sequence Normalized Displacement-Force History

Fig.4 demonstrates the hysteresis for normalized displacement values on the x-axis versus normalized load values on the y-axis that belongs to the same event shown in the former figure.

3.2. SSI

One of the core objectives is comparison of fixed based systems vs soil interacting systems. Moreover, the fixed-base case also serves as a benchmark for comparing results against repeated earthquakes.

A SDOF oscillator is commonly used to take into account SSI. The substitute oscillator is governed by the $\tilde{T}$ (effective period) and $\tilde{\beta}$ (effective damping). Soil type C has been chosen because it is believed to be more critical than solid soils. All required parameters are obtained from [12]:

$$\tilde{T} = T\sqrt{1 + \frac{k}{K_x}\left(1 + \frac{K_x h^2}{k_\Theta}\right)} \quad (1)$$

$$\tilde{\beta} = \beta_0 + \frac{0.05}{\left(\frac{\tilde{T}}{T}\right)^3} \quad (2)$$

Eq.1 and Eq.2 above are given to demonstrate the calculation of effective period and effective damping. Different damping ratio and foundation size are assumed for every analysis. The aspect ratio (h/r) has been defined as the ratio of the height of the element to the foundation radius length. The analyses have been performed for a ratio of 1.

The results of analyses have been given below with the parameters mentioned in 3.1. and 3.2.

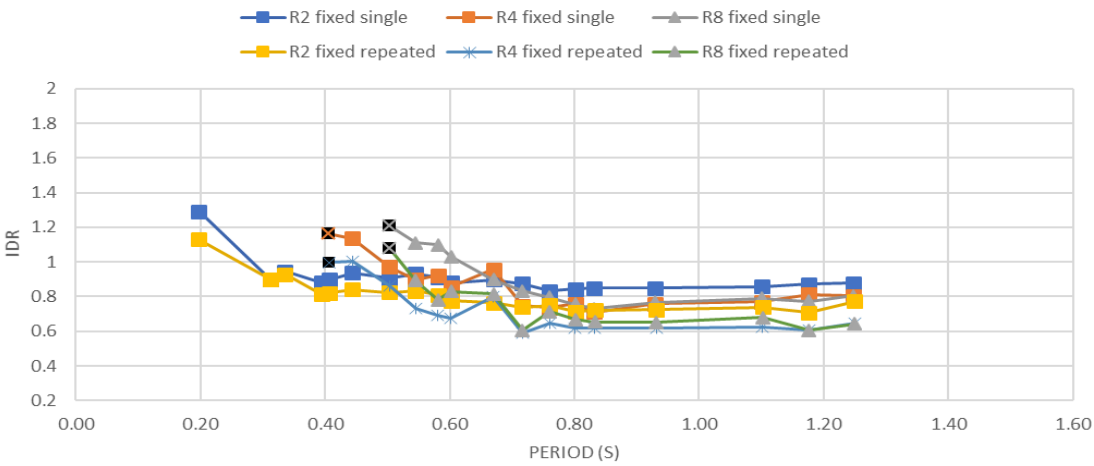

Fig.5 IDR for Fixed Based single earthquake vs Fixed Based repeated earthquake for R=2,4,8

Fig. 5 shows the IDR curves for single and repeated earthquake case for fixed-based foundation with a period range of 0.20 - 1.40 second. The plots have been drawn for different strength reduction factors of R=2, R=4, R=8, respectively. The (x) points indicates failure. It should be highlighted that the drop in the IDR is more dramatic in Fig.5 compared to Fig.6 for the whole period range. At the long period range, IDR values drop down to 0.6 for R=8 for both single earthquake and repeated earthquake. This already approves that fixed and soil interacting systems may behave differently to accommodate earthquake energy. Another noteworthy difference is that repeated earthquake IDR curves have lower values with respect to single earthquakes regardless of R values.

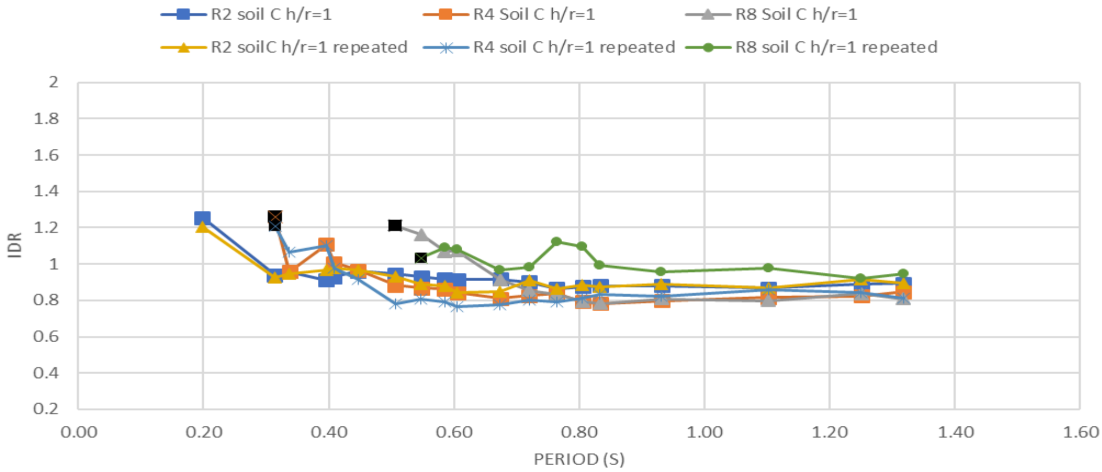

Fig.6 – IDR for SSI (Soil C) single earthquake and SSI (Soil C) repeated earthquake for R=2,4,8

Fig.6 displays the IDR curves for single and repeated earthquake cases for foundation laying on soft soil, Soil type C. The plots have been drawn for different strength reduction factors, R=2, R=4, R=8 respectively and the period range varies from 0.20 second to 1.40 second. The aspect ratio of the foundation is assumed as h/r=1 to account for SSI effect when calculating effective damping and effective period. The points with (x) shaped markers in black indicate failure. According to the plots, each single and repeated earthquake follows the same trend for the same R value. However, increasing R value results in failure of the structure at higher periods and this happens at even higher periods when R is higher. At the short period region, the drop of IDR is more significant as the range of IDR values tend to be stable at the long period. For R=8, the difference in the IDR values between single and repeated earthquake is the most distinct. The IDR values for R=2 at 0.20 second is around 1.2 and it decreases to 0.9 between 0.60-1.40 second.

3.3. Multi Component Spectra

Similar to vertical component, rotational components of ground motion due to SV waves and surface waves are often neglected whilst evaluating the structural inelastic response. Though, many structural failures and the damage caused by earthquakes cannot be associated only with horizontal components, the impact of different components on the structures was confirmed by, for instance, the San Fernando, 1971 California Earthquake.

Coupling of different components of ground motions can significantly boost the seismic demand by rising lateral forces and P-Δ effects. A SDOF oscillator has been subjected to coupled horizontal, angular accelerations and tilt excitations of ground motion. These coupling effects has been introduced through an equivalent fixed-base system. The derived Eq. (3) has been used to represent a SDOF oscillator with three components of ground motion acting on the base of the oscillator as presented in [13].

$$m\ddot{u} + c\dot{u} + [k_0 - k'_G]\ u = -m\ddot{u}_g + m(g - \ddot{z}_g)\alpha_g + m\ddot{\alpha}_g l \tag{3}$$

Eq. (3) is the modified form of equation of motion to be able to compute the response of a SDOF oscillator under multi-component ground motion excitation. The equation also contains the second order component linked to tilt and vertical component of ground motion. The preliminary results of analyses for multi components of records has been given below. Fig.7 has been plotted for R=4 to capture the distinction coupled behaviour of the system. It displays the normalized displacement on the x-axis and normalized force on the y-axis of a system accounting for tilt and vertical ground accelerations. The hysteresis has been related with a long period (T=1.12 sec.) for the sake of the study.

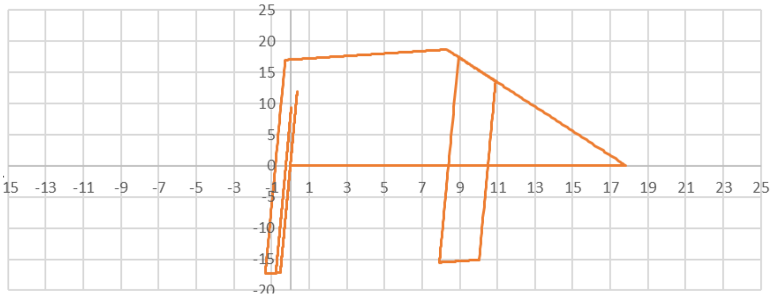

Fig.7 – Structural normalized resistance due to translational and rotational component of ground excitation.

The Pacoima Dam – Upper Left Abutment record for Northridge Earthquake, 1994, has been used to obtain the hysteresis as it was investigated earlier by [13] who found out that the residual tilt reached high degrees. The hysteresis achieved by using only the translational component of the record on the other hand, did not show high displacement values.

4. Conclusion

In this study, the soil-structure interaction, repeated eartquake, translational and vertical component of ground acceleration have been examined for SDOF systems for a period range of 0.2–1.40 second in order to comprehend how various parameters differentiates the structural response. RC columns, which had been tested, have been subjected to 100 ground motions. Dynamic analyses have been conducted through numeric runs.

The study can be expanded further by adding different parameters to the structural system; however, the following results can be drawn from this study's results:

1. Deterioration occurs in all types of materials due to the application of load. Moreover, damage accumulation resulted by inelastic excursions is in proportion to the number of the excursions.
2. Degradation should be taken into consideration when modelling hysteretic activity.
3. Stiffness and strength degradation play a vital role on the inelastic response of the structures.
4. IDR values generally decrease as the period increases.
5. Collapse occurs at higher periods. Also, as the strength reduction factor rises, collapse is more likely to occur.
6. The effect of foundation type, aspect ratio, and SSI to inelastic response of the structures is not negligible at short period range.
7. The effect of SSI and repeated earthquake phenomena should be considered in the design of complex buildings. This provides a reduction in hazard.
8. Multi-components effects should be considered for records which tend to have high intensity of vertical shaking and ground tilting. This effect should be considered for performance based seismic design or seismic performance assessment.

5. Copyright

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