Assessment of Collapse Potential of Degrading SDOF Systems

Muzaffer Borekci, Murat S. Kirçil

Abstract—Predicting the collapse potential of a structure during earthquakes is an important issue in earthquake engineering. Many researchers proposed different methods to assess the collapse potential of structures under the effect of strong ground motions. However, most of them did not consider degradation and softening effect in hysteretic behavior. In this study, collapse potential of SDOF systems caused by dynamic instability with stiffness and strength degradation has been investigated. An equation was proposed for the estimation of collapse period of SDOF system which is a limit value of period for dynamic instability. If period of the considered SDOF system is shorter than the collapse period then the relevant system exhibits dynamic instability and collapse occurs.

Keywords—Collapse, degradation, dynamic instability, seismic response.

I. INTRODUCTION

THE major source of injuries, mortalities and financial losses is the collapse of buildings during earthquakes, and therefore one of main goals of earthquake engineering is to predict the collapse potential of different types of structures [1]. In earthquake engineering, collapse refers to the loss of ability of a structural system to resist gravity loads in the presence of seismic effects [2]. Collapse may be either local or global. The fail of a component of a structure or connection refers to local collapse. The spread of local failure from element to element, excessive displacement of an individual story or deterioration of structural components subjected to cyclic loading may result in global collapse. There are many studies for the assessment of the seismic response of the RC structures and most of them interest in the RC structures using the elastic-perfectly plastic hysteretic behavior without degradation because of its simplicity; however, experimental studies showed that all materials degrade and hysteretic response of the RC structures under cyclic loadings does not match with the bilinear hysteretic behavior but has a good fit with the peak-oriented model [3]–[5]. Thus, it is important to use a hysteretic model which is similar to the real seismic response of the RC structure. Furthermore, not only degradation effect but also softening in the hysteretic behavior should be considered. The softening branch is the branch of skeleton curve of the hysteretic behavior which has a negative stiffness. This negative stiffness can be observed because of the P-delta effect or the strength degradation (described as in-cycle degradation in FEMA 440 [6]) occurred after reaching the maximum strength of the system. The branch which has a negative stiffness is also called post-capping branch as is seen in Fig. 1. On condition that the post-capping branch reaches a residual strength, dynamic instability occurs and system collapses. The structure subjected to a certain input is stable if small increase in the magnitude of the excitation results in small changes in the response [7]. Otherwise, structure will not be stable and it is called dynamic instability. Same assumption is also made by [8]. Several methods have been suggested or used in research studies in which structures are modeled as SDOF system to directly assess their collapse capacity. Bernal [9] developed a simplified method to check the safety against dynamic instability of equivalent single-degree-of-freedom (SDOF) system of 2D buildings considering stiffness degrading elastic-perfectly plastic behavior.

The method was based on the derivation of statistical expressions to correlate the required minimum base shear to prevent instability. MacRae [10] proposed a method for considering P-Δ effect with different post-yield stiffness ratios and observed that post-yield stiffness ratio is a major parameter that affects the system's stability. Miranda and Akkar [11] proposed an equation as a function of natural period and post-yield stiffness to estimate the lateral strength that is required to prevent collapse by dynamic instability of SDOF systems. Adam et al. [12] proposed a procedure for the determination of the collapse capacity of a MDOF structure through the use of equivalent SDOF system. References [7], [9], [11], [13] have shown that study of the dynamic instability of SDOF systems provides significant insight to the assessment of collapse of multi-degree-of-freedom (MDOF) structures subjected to earthquakes. Chenouda and Ayoub [14] investigated inelastic displacement ratio considering energy based stiffness and strength degrading hysteretic behavior (same model used in this study). They showed that all degrading systems with a period less than a certain value collapse and that collapse occurs because of the dynamic instability. However, their study includes only limited degradation cases. If a hysteretic model with degradation effect and softening branch is used to consider a more realistic behavior in the estimation of seismic response, dynamic instability should be considered and checked. In this study an equation is proposed for the estimation of a limit period at which a SDOF system exhibits dynamic instability. This limit value is called as collapse period (T_{col}) of the relevant SDOF system. If period of the considered structure is shorter than the collapse period (T<T_{col}) then the relevant structure exhibits dynamic instability and collapse occurs. In this study,
nonlinear time history analyses were performed for strength
reduction factor $R_3 = 1.5, 2, 3, 4, 5, 6$ and post-yield stiffness
ratio $\alpha_c = 0\%$, $3\%$, $5\%$ considering $5\%$ damping ratio. 53
natural vibration periods were used ranging from $T = 0.1$ s. to
$T = 3$ s. ($T = 0.1:0.02:0.2, 0.22:0.03:1, 1.1:0.1:3$). The main
objective of this study is to determine collapse period ($T_{col}$)
which is a limit value for the dynamic instability and to
propose an equation for the estimation of the collapse period.

II. GROUND MOTION RECORDS

A total of 160 earthquake acceleration time histories were
used in this study. 80 records were considered with two
horizontal components at each station and magnitude of the
records ranges from 6 to 7.9. Although there are different
limitations on the fault distance defined in the literature to
describe the near fault effect, minimum fault distance
considered in this study is 30 km, so that near fault effect can
be eliminated. The earthquake acceleration time histories were
divided into four groups according to local soil conditions at
the recording station. Each group consisted of 40 ground
motions. Locations of stations in the first group correspond to
site class A, second group corresponds to site class B, third
group corresponds to site class C and the last group
corresponds to site class D according to USGS [15]
classification.

III. HYSTERETIC MODEL

A. Peak-Oriented Hysteretic Model

Modified-Clough model with energy based stiffness and
strength degradation was used as hysteretic model in this
study. Although it considers the pinching effect in addition to
degradation; pinching effect was neglected for this study since
[2] showed that the collapse capacities of peak- oriented
model with and without pinching is very close.

This model keeps basic hysteretic rules proposed by [16]
and later modified by [17], but the backbone curve was
modified by [3] to include strength capping and residual
strength as shown in Fig. 1 [3].

The basic idea of the model is that the reloading path
always targets the previous maximum displacement where $K_e$
is the elastic (initial) stiffness, $f_y$ is the yield strength, $f_r$
is the residual strength, $f_c$ is the maximum strength, $K_s$
is the post – yield stiffness, $u_y$ is the yield displacement, $u_r$
is the beginning of a softening branch which is called cap displacement, $K_c$ is
the post – capping stiffness which usually has a negative
value.

When the loading path reaches the horizontal axis, the
loading goes through reloading path. The basic idea of the
peak-oriented model is that the reloading path always targets
the previous maximum displacement. The basic rules of Peak-
Oriented Model can be seen in Fig. 2.

Rahnama and Krawinkler [18] adopted a rule in the
Modified-Clough model to account for degradation effects.
Four different deterioration modes can occur after the loading
path reaches the yielding point at least in one direction. These
deterioration modes are basic strength deterioration, post –
capping deterioration, unloading stiffness degradation and
reloading stiffness degradation.

\[
\beta_i = \left( \frac{E_i}{R_3 - \Sigma E_j} \right)^{\frac{1}{c}}
\]  \hspace{1cm} (1)

$E_i$ is the hysteretic energy dissipated in excursion $i$, $E_t$ is the
hysteretic energy dissipation capacity, $\Sigma E_j$ is the hysteretic
energy dissipated in all previous excursions and $c$ is a
component which defines the rate of deterioration. Reasonable
range of $c$ is between 1.0 and 2.0 [18]. Although the parameter
$c$ affects the cyclic deterioration, [3] suggested a constant
value of 1 for $c$ and this suggestion is followed in this study.

\[
E_t = \gamma F_y u_y
\]  \hspace{1cm} (2)

$\gamma$ expresses the hysteretic energy dissipation capacity as a
function of twice the elastic strain energy at yielding ($f_y u_y$).
The parameter $\gamma$ can have different values for each
deterioration mode. Different indices are used for different
modes; $\gamma_i$ is for basic strength deterioration, $\gamma_c$ is for post-capping strength deterioration, $\gamma_u$ is for unloading stiffness deterioration and $\gamma_r$ is for accelerated reloading stiffness deterioration. However the results determined by using the same value of $\gamma$ for all deterioration modes are sufficient for the effect of cyclic deterioration [3]. Deterioration modes are described briefly below, however detailed information can be seen in [3].

The parameters effect on the cyclic degradation $\gamma$, $u_c/u_y$, $\alpha_c$. $\gamma$ is parameter of the rate of the degradation and it is assumed in this study $\gamma = 50, 100$ and 150 as severe, moderate and low degradation, respectively [14]. $u_c/u_y$ is denoted as ductility capacity however the term ductility is not used as its traditional meaning. In this study $\alpha_c$ is the ratio between corresponding displacement of peak and yield strength. $u_c/u_y = 2, 4, 6$ represent non-ductile, medium ductile and very ductile structures, respectively [2]. $\alpha_c$ that is used to define post-capping stiffness ratio are -6% [14], -14% and -21% [11] which represent small, medium and large slope, respectively. -14% is assumed as the medium slope in this study. 27 combinations of degradation parameters are used in this study to define the all possibilities of degradation and these combinations are given in Table I.

<table>
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<tr>
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<th>$\alpha_c$</th>
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IV. ANALYSIS
The global collapse was considered within the scope of this study. There are two main criteria to define the collapse: when

- the post-capping branch intersects the horizontal axis (dynamic instability occurs) or when the parameter $\beta_i$ exceeds 1 (that means hysteretic energy capacity has been exhausted) system collapses. According to results of this study, post-capping branch reaches the horizontal axis before hysteretic energy capacity exhausts. That means collapse occurs only because of the dynamic instability.

Nonlinear time history analyses were performed via MATLAB using Newmark-Beta method based on hysteretic behavior mentioned above. Analyses were performed for SDOF systems with previously mentioned values of $R_y$, $u_y$ and T. The damping ratio is 5% for all systems. With 27 degradation combinations and 160 ground motion records, 4121280 nonlinear time history analyses were performed to determine the collapse period ($T_{col}$) for each considered system. If the structure collapses under the effect of more than 50% of the considered records then it is assumed that its period is median collapse period [14].

V. RESULTS
Collapse periods of the considered systems for all site classes with different combinations of degrading parameters are given in Fig. 3. It is clear from Fig. 3 that collapse period $T_{col}$ increases while strength reduction factor $R_y$ increases. According to the results of this study, considering only elastic-perfectly plastic system ($\alpha_c = 0\%$) yields results conservative enough in the estimation of $T_{col}$. Site class has significant effect on $T_{col}$ thus site class should be considered individually.

Cyclic degradation is the function of the parameters $\gamma$, $u_c/u_y$, $\alpha_c$. Significance of the effect of the degradation parameters on $T_{col}$ is not same for each degradation parameters.

$u_c/u_y$ and $\alpha_c$ have significant effect on $T_{col}$ while the effect of $\gamma$ is not significant as much as $u_c/u_y$ and $\alpha_c$. Detailed information on the effect of each parameter can be seen from [19].

VI. CONCLUSION
Nonlinear regression analysis was made using least squares method and an equation was proposed for $T_{col}$ as a function of $R_y$, $u_c/u_y$ and $\alpha_c$. The proposed equation is given in (3). Some combinations of the considered parameters were excluded from regression analyses so that more realistic results can be obtained. For example, a system with severe degradation and large post-capping slope is assumed not to be ductile.

$$T_{col} = 0.1 + x_1 R_y^{x_2} \left( \frac{u_c}{u_y} \right)^{x_3} + \alpha_c^{x_4}$$  (3)

The observed and predicted values of $T_{col}$ are given in Fig. 4 for each site class. It is clear from figure that the results of the proposed equation for $T_{col}$ have a good agreement with the theoretical values of $T_{col}$. 
Fig. 3 Collapse period of all degradation combinations for mean of all site classes

Fig. 4 Observed and predicted $T_{col}$ for different site classes and moderate degradation ($\gamma = 100$)

Coefficients of (3) are given in Table II.

<table>
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<th>Site Class</th>
<th>Degradation Level</th>
<th>$x_1$</th>
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REFERENCES


