Prediction of Collapse from PGV and PGD

S. Song & T.H. Heaton
California Institute of Technology, Pasadena, CA, USA

SUMMARY:
We propose a collapse prediction model described in peak ground velocity (PGV) and peak ground displacement (PGD) for steel and reinforced concrete moment-resisting frame buildings. Olsen (2008) simulated the seismic response of eight steel frame buildings to over 60,000 simulated seismic motions; the simulations showed that collapse can be predicted from PGV and PGD. Song and Heaton (2012, also in this proceeding) showed that collapse of the same buildings can also be predicted from the peak amplitude of low-pass Butterworth filtered accelerations (PFA) and knowledge of the pushover curve. This study maps the collapse threshold of PFA's into the PGD and PGV space. As expected, the PFA-derived curve for PGD and PGV does an excellent job of fitting the collapse data of Olsen.

Keywords: Collapse, PGV, PGD

1. INTRODUCTIONS

This study is a continuation of an accompanying study (Song & Heaton, 2012) that describes a simple method to predict the P-delta collapse of moment-resisting frame buildings (steel and reinforced concrete) that are subject to a wide range of ground motions. In the previous study, we proposed a collapse prediction method based on a new parameter, peak filtered acceleration (PFA). To predict whether a building will collapse in response to a given ground motion, we first estimate the maximum lateral capacity of the building. We then filter the ground acceleration time history using a low-pass 2^{nd}-order Butterworth filter (4^{th} order for ramp-like and pulse-like motions) and with a cutoff frequency that is typically lower than the first mode frequency. If the amplitude of the filtered acceleration record (given as a fraction of g) exceeds the building's pushover maximum strength (given as a fraction of the building weight) then P-delta instability is expected.

While PFA is simple and effective for predicting collapse, it is a new parameter and hence it is, as yet, unfamiliar. The elastic response spectral acceleration at the first modal period, $S_a(T_1)$, is widely used to describe the intensity of ground motion in studies of collapse (Champion & Liel, 2012; Krawinkler, Zareian, Lignos, & Ibarra, 2009; Liel, Haselton, & Deierlein, 2011). Baker (2008) proposed a vector intensity measure, spectral acceleration and ε; where ε measures the difference between an observed spectral acceleration and the expected spectral acceleration from a ground motion prediction equation.

Olsen and Heaton (2012) studied the collapse of eight steel frame buildings by nonlinear finite element simulations of more than 60,000 ground motions. They found that the vector (PGD, PGV) seems to predict simulated collapse more reliably than spectral acceleration and ε.

The purpose of this report is to demonstrate the relationship between the new unfamiliar PFA parameter and the vector parameter (PGV, PGD). In particular we show how to convert our PFA model for collapse into an equivalent (PGV, PGD) model for collapse. We also show a good agreement between our predicted results with Olsen and Heaton's (2012) computational results.

2. DEVELOPING COLLAPSE PREDICTION MODEL IN PGV AND PGD

2.1. Collapse Prediction Model Using PFA

In a companion study (Song & Heaton, 2012), we assumed a suite of sinusoidal ground motions and used nonlinear finite-element analysis to determine the minimum collapse PGA (MinCPGA) for 10 buildings (both steel and RC). This study of collapse caused by simple harmonic motion helps us to understand the conditions that can cause collapse. Even though real ground motions that cause collapse may not be harmonic, the collapse can typically be understood by approximating the record with a predominant frequency that captures the most important part of the building excitation. To obtain the MinCPGA spectrum, a series of sinusoidal ground motions of different periods and durations are generated. Incremental dynamic analysis (IDA) is applied to determine the threshold of collapse. For all the studied buildings, collapse is defined as the point where a building starts to lose P-delta stability. We plot MinCPGA versus period of sinusoidal input for each building (example is shown in Figure 1 for U20B). The main conclusion is that the accelerations that cause collapse are much smaller than the accelerations that cause collapse at shorter periods. Furthermore, the amplitude of the long-period acceleration that causes collapse is close to the maximum lateral strength calculated in a pushover analysis. Motivated by this observation, we remove mostly irrelevant short-periods from a ground motion record using a low-pass Butterworth filter; the peak time domain amplitude of the filtered acceleration (PFA) seems to predict collapse quite well.

2.2. Collapse Prediction Model Using PGV and PGD

Although the proposed prediction method in previous study is straightforward in concept, peak filtered acceleration (PFA) is a brand new concept which might not be adopted by engineers easily. In this section, we describe the same method in alternative measures, PGV and PGD, which are more widely used in measuring ground motion intensities.

To obtain PGV and PGD, we first need to integrate ground acceleration time history with respect to time once and twice to get ground velocity and displacement time history. Since we use sinusoidal ground motion in computing MinCPGA, to obtain the corresponding PGV and PGD, simply multiply the amplitude by $T_s/2\pi$ once and twice (T_s denotes the period of sinusoidal ground motion).

However, in the PFA model, we measure the size of a real ground motion record by the ½ peak-to-peak value (except in the case of long-period motions when we use the peak value). Hence, to convert ½ peak-to-peak values into peak values (PGV and PGD), we need to multiply the PFA's by coefficients c_V and c_D, where c_V denotes the average ratio of peak ground velocity to ½ peak-to-peak ground velocity and c_D denotes the average ratio of peak ground displacement to ½ peak-to-peak ground displacement. From the statistical results in the companion study (Song & Heaton, 2012), c_V is chosen as 1.08 and c_D is chosen as 1.57. Then, the collapse threshold in terms of PGV and PGD could be obtained as a function of period from Eqn. 1 and Eqn. 2.

$$PGV_{threshold} = c_V \cdot \frac{T_s}{2\pi} \cdot MinCPGA \tag{1}$$

$$PGD_{threshold} = c_D \cdot (\frac{T_s}{2\pi})^2 \cdot MinCPGA \tag{2}$$

After obtaining $PGV_{threshold}(T_S)$ and $PGD_{threshold}(T_S)$, we eliminate the common variable, T_S, and plot the collapse threshold in Log (PGV)-Log (PGD) space where T_S is now a parameter along the collapse curve. An example is shown in Figure 2 for U20B, a 20-story steel building with brittle welds. To predict whether a building will collapse when subjected to a given ground motion, first compute PGV and PGD of the record, then plot the point (PGV, PGD) in the corresponding collapse prediction chart (e.g. Figure 2). If the point falls into region B, it is expected to collapse. Otherwise, it is expected to survive the ground motion when it is located in region A.

Using the simple relationship between velocity and displacement for a sinusoid, we can use equations (3) and (4) to plot lines of constant period T_S in Figure 2. Generally, most real data that is classified as strong shaking has periods between ½ and 5 seconds. Therefore most (PGV, PGD) points fall into a banded region (between black solid lines in Figure 2).

$$PGV = 2\pi PGD/T_s \tag{3}$$
$$Log(PGV) = Log(PGD) - Log(T_s) + 0.8 \tag{4}$$

3. VERIFICATION OF THE DEVELOPED MODEL

Olsen collected 64,765 synthetic, seismic ground motions and applied them to eight finite element models of welded, steel moment-resisting frame buildings. Each ground motion is characterized with a vector intensity measure (PGV, PGD), and the building model response to each ground motion is characterized as “collapsed” or “standing”. Among the eight finite element models, four are identical with what we used in the previous study. They are U6P, U6B, U20P and U20B, respectively. In this section, we predict collapse thresholds of the four building models using PGV and PGD prediction model derived from the PFA prediction model. We then compare the predicted collapse thresholds with the computational results Olsen has obtained.

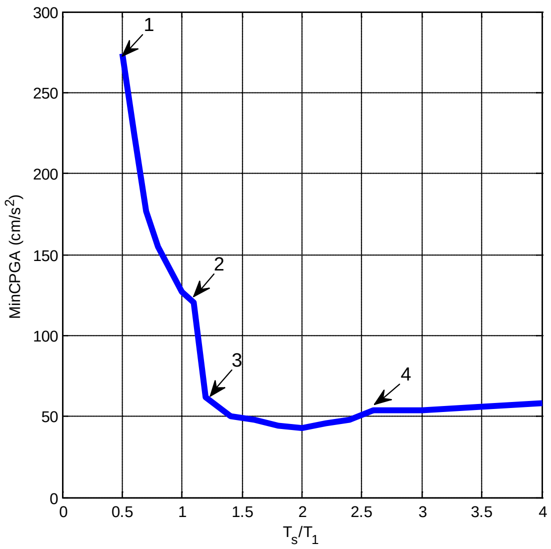

Figure 1. Example of minimum collapse PGA for U20B. The motion is sinusoidal with duration of 40s and period T_S. T_1 is the period of the 1st mode, which is 3.47 s for this building.

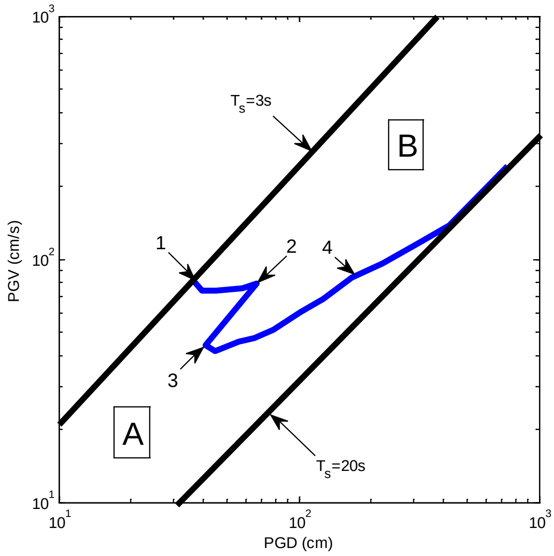

Figure 2. Example of collapse threshold in terms of PGV and PGD of the same building in Figure 1.

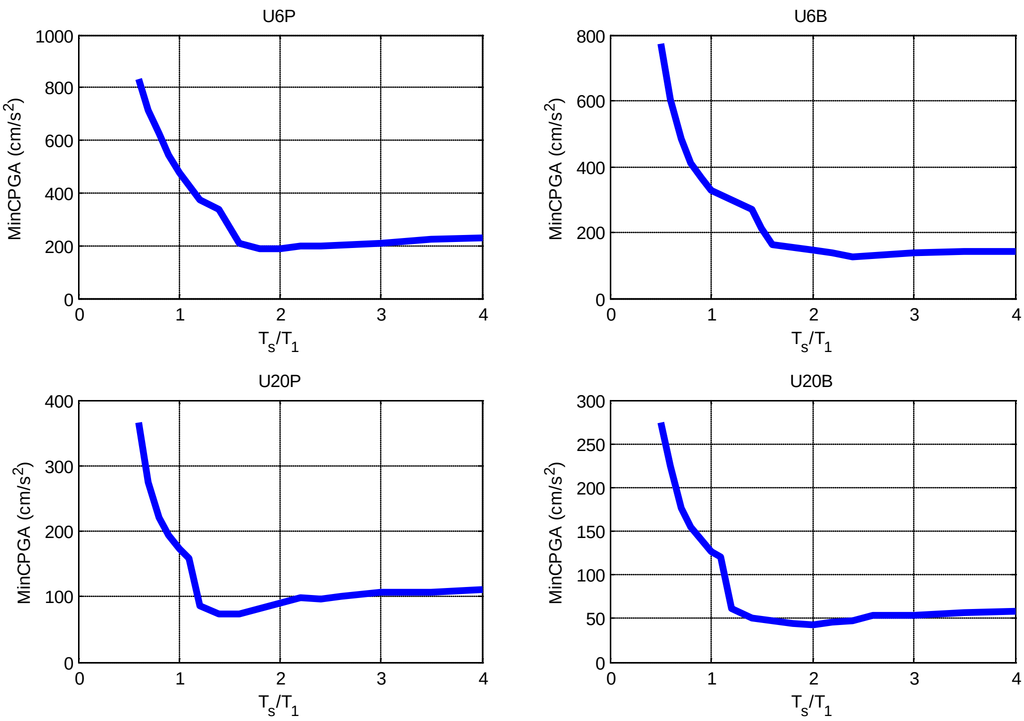

Figure 3. Minimum collapse PGA spectra in sinusoidal ground motions for U6P, U6B, U20P and U20B

3.1. MinCPGA Spectra of the Studied Buildings

In section 2.1, we have discussed the procedure to generate minimum collapse PGA (MinCPGA) spectrum. Figure 3 shows the computed MinCPGA spectra for U6P, U6B, U20P and U20B; a 40s duration of sinusoidal ground motions is used in each case.

3.2. Comparison of the Predicted and Computational Results

After obtaining collapse thresholds in term of PGA, we convert them into collapse thresholds in terms of PGV and PGD using Eqn. 1 and Eqn. 2. The predicted collapse thresholds based on our proposed model and the computational results obtained by Olsen are plotted in Figure 4. The first mode of the U20P and U20B is 3.47s and Olsen was able to use simulated records that had a 2s cutoff frequency that was dictated by the grid size in finite element models used to simulate ground motions. However, the first period of U6P and U6B is only 1.54s and so Olsen was forced to use records broad-band simulated motions; unfortunately, there were far fewer of these available to study. To ensure enough data points, results for U6P and U6B from our companion study are also included in Figure 4. In Figure 4, black dots represent the ground motions that cause collapse of the corresponding building while gray dots are those that do not. The predicted thresholds are plotted in red solid lines. Since our proposed model is developed based on the minimum ground motions that cause collapse of buildings, the threshold we predict is actually the lower boundary of collapse. In Figure 4, the predicted thresholds and lower boundaries of collapse show good agreement. Especially for U20P and U20B, the predictions captured the features of the collapse boundaries. However, the predictions work slightly worse for U6P and U6B, especially when they are subjected to high frequency ground motions (high PGV to PGD ratios). One possible explanation is that when computing collapse thresholds, we assumed the ground motions to be harmonic. However, high frequency ground motions are quite different from harmonic motions, which leads to the poor performance in predicting collapse of buildings subjected to high frequency ground motions.

Olsen and Heaton (2012) proposed a collapse prediction model based on the regression from the computed results. However, it is difficult to capture the features of collapse threshold using this method since it needs a complicated regression equation.

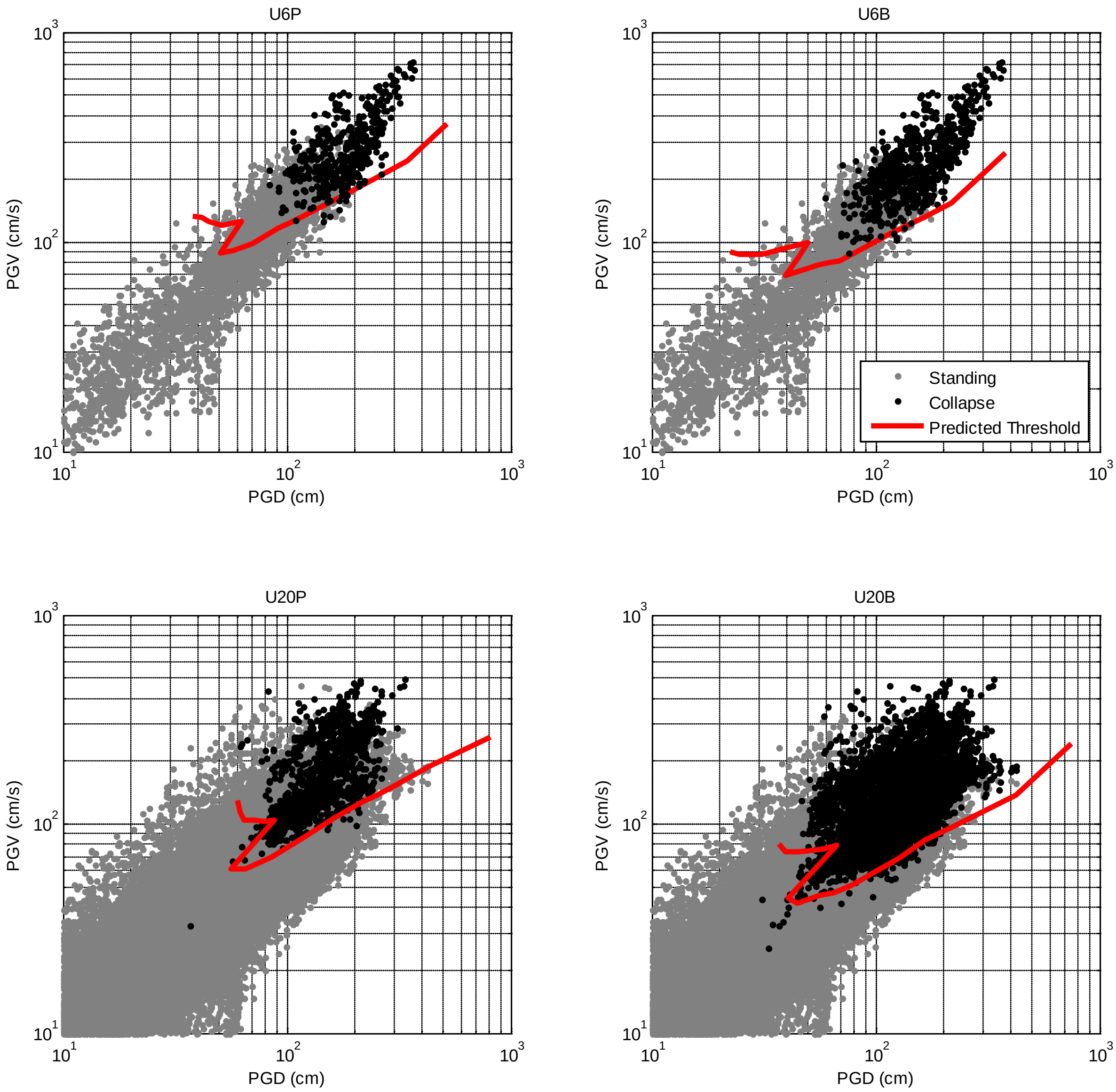

Figure 4. Comparison of predicted collapse thresholds and Olsen's computed results

4. COMPARISON BETWEEN PROPOSED METHOD AND ORIGINAL METHOD

We developed two models to predict the collapse of moment-resisting frame buildings. One model predicts collapse with peak filtered acceleration (PFA), while the other one does it with PGV and PGD. Both models assume that the long-period component of a ground motion controls the collapse of buildings. Hence, to predict collapse of buildings, we neglect unnecessary short-period components and only consider the long-period components

The first model extracts long-period component from a ground motion record with a Butterworth filter, while the second model does it with integration. The log-log gain functions of 2nd-order Butterworth filtering, time integration (acceleration to velocity) and double integration (acceleration to displacement) are plotted in Figure 5.

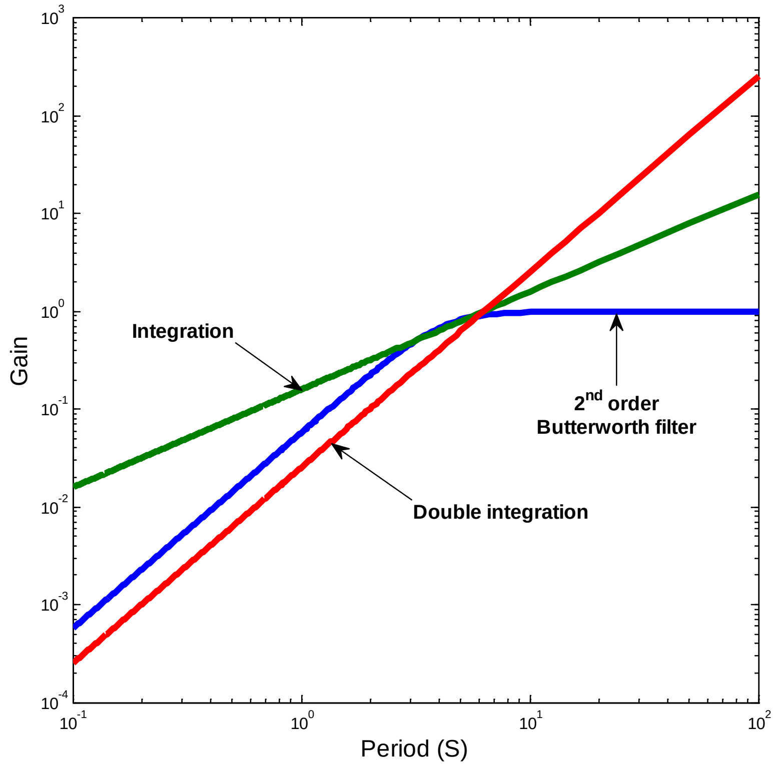

Figure 5. Gain function of 2nd order Butterworth filter and integration

Although integration can be viewed as a type of filter that enhances long periods linearly with period (or as period squared in the case of double integration), integration has no inherent scale. This is different from the Butterworth filter where we use the natural period of the building in the formula to define the corner in the filter. That is, the PFA collapse methodology explicitly includes the building properties, whereas the (PGV, PGD) parameter cannot reflect the difference between buildings. The (PGV, PGD) model solves this problem by introducing a different 2D collapse threshold for each building. PFA model only has a 1D collapse threshold (a constant derived from pushover analysis).

In summary, the PFA model of Song and Heaton (2012, this volume) and the (PGV, PGD) model of Olsen and Heaton (2012) represent the same physics, but they are stated in different ways. The PFA model filters out extraneous high-frequency motions using a Butterworth filter whose parameters are determined by the dynamic characteristics of building. Alternatively, the (PGV, PGD) model ignores the extraneous high frequencies by integration and then considers the difference among buildings to be given by a threshold curve that is determined from nonlinear analysis of a broad range of ground motions.

5. CONCLUSION

In this work, we developed a collapse prediction model in terms of peak ground velocity (PGV) and peak ground displacement (PGD). The model covers steel and reinforced concrete moment-resisting frame buildings.

We derive the (PGV,PGD) collapse threshold based on the minimum collapse amplitude of low-pass filtered accelerations, PFA, that is described in our companion study that predicts collapse of steel and reinforced-concrete frame buildings in different types of ground motions. We map the PFA collapse threshold into (PGV, PGD) space by approximating the key part of the collapse motion with a simple sinusoid of the appropriate period. To predict whether a building will collapse in response to a ground motion, simply plot the ground motion in (PGV, PGD) space, if the resultant point is above the building's collapse threshold, collapse is expected, otherwise, the building is expected to survive the ground motion.

The proposed prediction model is verified by comparing to Olsen's (2008) simulation results and they show good agreement.

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