EFFECTS OF LONG-PERIOD PROCESSING ON COLLAPSE PREDICTIONS

K. Buyco¹, B. Roh², and T. H. Heaton³

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We investigate the extent to which applying high-pass filters to ground motion records affects the collapse capacity of building models when subject to these ground motions. We use 23 biaxial tilt corrected ground motions recorded from six large earthquakes with magnitudes ranging from M7.0 to M7.9 and filter them with acausal high-pass 4th order Butterworth filters with corner periods, $T_c$, ranging from 10s to 60s. With these ground motions, we perform incremental dynamic analysis on 9-, 20-, and 55-story steel moment frame building models with fundamental periods, $T_1$, of 1.88s, 3.50s, and 6.10s, respectively, in order to calculate their collapse capacities. We also consider a simple two-degree-of-freedom model of a base-isolated building. For the considered ground motions, we find that filters with $T_c \geq 20$s have only a small effect on the collapse capacity of the building models. If $T_c = 10$s, the collapse capacities of the 20- and 55-story models increase on average by more than 5% and 15%, respectively. For a few ground motions, we find that collapse capacities can increase by more than 50% if $T_c = 10$s or 15s, even for the 9-story models for which $T_1 = 1.88$s. We find that the collapse capacities of the building models with respect to the demeaned, uncorrected raw records are on average the same as the tilt corrected versions, indicating that applying high-pass filters to remove long-period noise usually do more harm than good regarding the collapse predictions of buildings unless $T_c \geq 20$s.

¹Ph.D. Candidate, Dept. of Civil Engineering, Calif. Inst. of Tech., Pasadena, CA 91125 (email: buyco@caltech.edu)
²Ph.D. Candidate, Dept. of Civil Engineering, Calif. Inst. of Tech., Pasadena, CA 91125
³Professor, Dept. of Civil Engineering, Calif. Inst. of Tech., Pasadena, CA 91125

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We investigate the extent to which applying high-pass filters to ground motion records affects the collapse capacity of building models when subject to these ground motions. We use 23 biaxial tilt corrected ground motions recorded from six large earthquakes with magnitudes ranging from M7.0 to M7.9 and filter them with acausal high-pass 4th order Butterworth filters with corner periods, $T_c$, ranging from 10s to 60s. With these ground motions, we perform incremental dynamic analysis on 9-, 20-, and 55-story steel moment frame building models with fundamental periods, $T_1$, of 1.88s, 3.50s, and 6.10s, respectively, in order to calculate their collapse capacities. We also consider a simple two-degree-of-freedom model of a base-isolated building. For the considered ground motions, we find that filters with $T_c \geq 20s$ have only a small effect on the collapse capacity of the building models. If $T_c = 10s$, the collapse capacities of the 20- and 55-story models increase on average by more than 5% and 15%, respectively. For a few ground motions, we find that collapse capacities can increase by more than 50% if $T_c = 10s$ or 15s, even for the 9-story models for which $T_1 = 1.88s$. We find that the collapse capacities of the building models with respect to the demeaned, uncorrected raw records are on average the same as the tilt corrected versions, indicating that applying high-pass filters to remove long-period noise usually do more harm than good regarding the collapse predictions of buildings unless $T_c \geq 20s$.

Introduction

Proper assessment of collapse risk to seismic hazards is fundamental to both the design of new buildings and safety evaluation of existing buildings. For most collapse risk assessment procedures, the underlying methodology, after some simplifications, can be summarized by the following integral [1]:

$$\lambda[C] = \int_{IM} IM \cdot G[C|IM] d\lambda[IM]$$ (1)

where $C$ represents collapse, $IM$ is a ground motion intensity measure (IM) value, $G[x|y]$ is a

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¹Ph.D. Candidate, Dept. of Civil Engineering, Calif. Inst. of Tech., Pasadena, CA 91125 (email: buyco@caltech.du)
²Ph.D. Candidate, Dept. of Civil Engineering, Calif. Inst. of Tech., Pasadena, CA 91125
³Professor, Dept. of Civil Engineering, Calif. Inst. of Tech., Pasadena, CA 91125

probability density function denoting the probability that $x$ will occur given $y$, and $\lambda(x)$ is the mean frequency of exceeding $x$ over some time interval. Thus, for a building at a given site, Eq. 1 relates the seismic hazard to the mean frequency of collapse for the building.

In Eq. 1, $G[C|IM]$ is usually estimated by performing nonlinear time history analysis with a mathematical model of the given building when subjected to a suite of ground motions in order to estimate the building’s collapse capacity. In this paper, we define a building’s collapse capacity to be the shaking intensity (measured either by an IM or by a scale factor for a particular ground motion) required to induce collapse in the building. From nonlinear time history analyses, a median and lognormal standard deviation for the collapse capacity of a given building are calculated and $G[C|IM]$, specified as a lognormal probability density function, is fit to these statistics. In order to conduct time history analyses, ground motions are most commonly selected from the NGA-West2 database [2], which contains processed records from past earthquakes. To remove long-period noise from raw recorded ground motions, each ground motion in the NGA-West2 database is high-pass filtered with a record-specific corner period. Long-period noise can include a tilt of the instrument during shaking, which introduces a static acceleration offset into the record that is not physically present in the true ground motion. It should be noted that the purpose of the NGA-West2 database is to provide ground motion records for generating ground motion prediction equations, not necessarily for nonlinear time history analysis. Decisions with regards to record processing thus reflect this distinction.

Applying high-pass filters to remove long-period noise from the raw record can have unintended consequences with regards to the calculation of $G[C|IM]$. For example, [3] and [4] showed that high-pass acausal filters with corner periods that are too low can affect the inelastic displacement and collapse capacity, respectively, of nonlinear single-degree-of-freedom systems. To reflect the concerns associated with high-pass filters, the NGA-West2 flatfile reports a maximum useable period for each ground motion component [2]. For collapse-prevention assessments in performance-based design, it is common to require the maximum usable period of each input ground motion to be greater than $1.5T_1$ to account for the removal of long periods. In some cases, ensuring that periods up to $1.5T_1$ are preserved in the ground motion is sufficient to accurately assess its potential to cause collapse in a building model. However, some ground motions can have a substantial portion of their spectral content at long periods beyond $1.5T_1$, particularly those recorded in large-magnitude events. In this paper, we perform incremental dynamic analysis (IDA) to determine the collapse capacities of different building models to ground motions that have been tilt corrected and high-pass filtered with acausal and causal filters with corner periods ranging from 10s to 60s. We examine the effects of these filters on the collapse capacity of each structure.

Modeling Considerations

Steel Moment Frame Building Models

We consider three designs of steel moment frame buildings with heights of 9, 20, and 55 stories. The 9- and 20-story building designs were developed for the SAC Joint Venture by [5] and designed according to the 1994 Uniform Building Code (UBC). The 55-story building was also designed according to the 1994 UBC with a procedure and floor plan similar to that presented in
Chapter 8 of [6]. The above-ground heights of the 9-, 20-, and 55-story designs are 37.2 meters (122 ft.), 80.8 meters (265 ft.), and 220.0 meters (722 ft.), respectively.

We create two-dimensional finite element models of each building using Frame-2d, a computer program that is specifically designed to calculate the seismic response of steel moment-frame buildings by using fiber elements to model the behavior of beams and columns. The cross-section of each element is divided into fibers that have hysteretic axial stress-strain relationships, equipped with a yield plateau and strain-hardening/softening region. Geometric nonlinearities (e.g. P-Δ) are accounted for by updating the nodal positions at each time step. [7-9] validated the special features of Frame-2d by extensive numerical testing and comparison with experimental data. Boundary conditions, gravity loads, and seismic masses are applied in accordance with the modeling conducted by [6]. We find the fundamental periods of the 9-, 20-, and 55-story models to be 1.88, 3.50, and 6.12 seconds, respectively.

For each of the three building designs, we develop two models: one with “perfect” (P) moment connections and one with pre-Northridge “brittle” (B) moment connections. The brittle connections model the failures of welded moment connections observed after the 1994 Northridge earthquake. In the models with brittle connections, the short fibers at the end of beam elements that are connected to columns with moment connections represent weld fibers and are assigned a random axial fracture strain according to a user-defined probability distribution. The fracture distributions used in this study are the same as those used by [10] and similar to those used by [11], which were calibrated to weld fracture observations in the Northridge earthquake.

We perform pushover analysis for each of the six building models considered in this study, calculated according to the dynamic procedure described in [11]. We do not modify the mass assigned to each story, so the vertical distribution of forces is proportional to the seismic mass of each story. Fig. 1a shows the pushover curves for each building model. Each model is denoted first by the number of stories (9, 20, or 55) and then by the connection type (P or B). It may be surprising that the 55-story model has a higher base shear capacity than the 20-story model. This is in part due to its “tube” structural plan, with perimeter columns spaced only 8 feet apart in comparison to the 30- and 20-foot bays of the 9- and 20-story models, respectively.

Isolation System Model

To represent a modern structure designed near a large fault, we develop a simple two-degrees-of-freedom (2DOF) model of a base-isolated building using SAP2000 [12]. We approximately model one of 69 isolators in the San Bernardino Justice Center, a 3-story podium and 12-story tower whose structural properties are summarized in [13]. The isolator is a triple concave-friction pendulum and is modeled using the Triple Friction Pendulum element in SAP2000, whose element properties are taken from [13]. The force-displacement relationship for the isolation element is given in Figure 1b, calculated in SAP2000 during loading and unloading.

The superstructure is a linear single-degree-of-freedom element whose period is 1.01 seconds without the isolator. The effective stiffness (K_e) of the isolator is calculated from Fig. 1b, which approximates the stiffness of the isolator during strong shaking. This produces an effective period of 4.25 seconds for the complete 2DOF system. The maximum displacement of
the isolator is 1.067 meters (42 inches), defined as the point at which both inner and outer stops in the isolator are impacted. This is the MCE (Maximum Considered Earthquake) maximum displacement limit in design (e.g. Chapter 17 of [14]) and we do not consider analyses that produce isolator displacements exceeding it. We use this limit to determine the “collapse capacity” for the model, even though it does not imply collapse of the superstructure.

![Figure 1](image)

**Figure 1.** (a) Pushover curves of steel moment frame models. (b) Hysteretic behavior of isolator in 2DOF isolation system.

**Ground Motions**

The 23 input ground motions used in time history analysis are processed records from six large-magnitude earthquakes. Six records are taken from the 2016 M7.8 Kaikoura (New Zealand) earthquake, five from the 1999 M7.6 Chi-Chi (Taiwan) earthquake, one from the 2002 M7.9 Denali (Alaska) earthquake, nine from the 2016 M7.0 Kumamoto (Japan) earthquake, one from the 1992 M7.3 Landers (California) earthquake, and one from the 2015 M7.8 Gorkha (Nepal) earthquake.

The ground motion records are processed by [15]. “Tilt corrected” records are generated by applying tilt corrections to raw records and are assumed in this paper to represent the “true” motion of the ground. To investigate the effects of high-pass filters on structural response, the tilt corrected records are filtered with causal and acausal high-pass 4th order Butterworth filters with corner periods, $T_c$, of 10, 15, 20, 30, 40, and 60 seconds. This processing is described in detail in [15]. Like previous researchers (e.g. [3, 16]), we find that causal filters dramatically alter structural responses because they introduce phase distortions in the ground motion record. As such, we only present results from acausal filters in this paper.

**Incremental Dynamic Analysis**

For the 9P, 20P, and 55P models, we perform incremental dynamic analysis (IDA) for each horizontal component of each ground motion. We treat the two horizontal components of each record as two individual ground motions and do not consider vertical shaking. For a single model and ground motion, we perform IDA by multiplying the ground motion by a scale factor of 0.1 and performing nonlinear time history analysis in Frame-2d. We repeat this process by
incrementing the scale factor by 0.1 for each successive analysis. We continue this process until the scaled ground motion causes collapse of the building model. In this paper, we define collapse of the steel moment frame models to occur when a numerical instability arises in simulation. For each individual time history analysis in an IDA, we record the maximum roof drift and the maximum interstory drift ratio for post-processing.

From the aforementioned analysis, we identify the ground motion record and direction that is generally most destructive from each considered event for further study. These six ground motion records are as follows, labeled [event] [station] [component]: Kaikoura WDFS BN1, Chi-Chi TCU 068 NS, Denali PS10 Normal, Kumamoto 93048 EW, Landers LUC Transverse, and Gorkha KATNP 360. For each of these six ground motions and their associated processed records, we also perform IDA on the 9B, 20B, and 55B models in Frame-2d as well as on the 2DOF isolation system model in SAP2000. For the isolation system model, the scale factor is continually increased until the displacement of the isolation system exceeds its maximum limit (1.067 meters) and we record the maximum displacement of the isolator from each time history analysis.

Results

Scale Factor Ratio Statistics

From the results of IDA, we extract for each ground motion the scale factor at which each of four damage measures (DMs) is first elicited in each of the 9P, 20P, and 55P models. The four DMs are maximum interstory drift ratio (MIDR) = 0.03, MIDR = 0.06, MIDR = 0.1, and collapse. We choose MIDR = 0.03 because it is the collapse-prevention limit for many performance-based applications (e.g. [17]). MIDR = 0.06 is approximately the ultimate limit of modern ductile moment connections [18], at which point failure due to local flange buckling may occur. This is an effect that cannot be captured by Frame-2d. MIDR = 0.1 corresponds to a severely damaged building and would be considered by some to be the default global collapse limit. Note that collapse is equivalent to MIDR → ∞.

For a given DM, ground motion record, and building model, the scale factor ratio (SFR) for a filter is defined as the scale factor needed to multiply by the filtered ground motion in order to induce the DM divided by the scale factor needed to multiply by the tilt corrected ground motion in order to induce the DM. For example, for the 20P model and the Chi-Chi TCU084 NS ground motion record, MIDR = 0.06 is first achieved with a scale factor of 4.6 for the $T_c = 10s$ filtered version and with a scale factor of 4.3 for the tilt corrected version. So in this example, $SFR = 4.6/4.3 = 1.07$.

To generate SFR statistics, we consider the IDA results from the 46 ground motion components for each filter and building model, so each statistic is based on 46 SFR values. For each DM, the SFR median, SFR$_{50}$, and 84$^{th}$ percentile value, SFR$_{84}$, are shown in Table 1 for the 9P, 20P, and 55P models and for the $T_c = 10s$, 15s, 20s, 30s, and 40s high-pass filters. Results are not shown for the $T_c = 60s$ filter because they are very similar to those of the $T_c = 40s$ filter. The distribution of SFR values for a given building model and DM is neither normal nor log-normal, but the median and 84$^{th}$ percentile values are nonetheless presented to summarize the
distribution. In the vast majority of cases, the $SFR_{16\text{th}}$ percentile value, $SFR_{16}$, is 1.00.

Table 1. The $SFR$ median, $SFR_{50}$, and 84th percentile value, $SFR_{84}$, of the $SFR$ values for four DMs for the (a) 9P model, (b) 20P model, and (c) 55P model.

(a) 9P

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(c) 55P

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We see three factors that generally lead to larger $SFR_{50}$ and $SFR_{84}$: more severe DMs, taller building models, and filters with lower corner periods. In cases where $SFR_{50}$ is significantly greater than one, there are important implications for collapse risk assessment using the framework summarized in Eq. 1. For example, if $G[C|IM]$ is calculated for the 20P model based on nonlinear time history analyses that use ground motions that have been processed with $T_c = 10s$, then we expect the median collapse capacity would be underestimated by a factor of 1.08. This would, in turn, underestimate the collapse risk.

Furthermore, there are 32 ground motion components for which a raw record is available. After demeaning the raw records to remove static acceleration offsets, we find for these ground motions that $SFR_{50}$ for collapse is 1.00 for each building model and the corresponding $SFR_{84}$ for the 9P, 20P, and 55P models are 1.00, 1.02, and 1.01, respectively. Qualitatively, these results
are somewhat similar to those for the $T_c = 40s$ high-pass filters. This means the drawbacks of leaving in the long-period noise in the raw records are, in some sense, canceled out by the removal of important long-period motion by the $T_c = 40s$ high-pass filters. This also means the $T_c = 10s$ and $T_c = 15s$ filters remove so much of the relevant long-period signal that simply using the demeaned raw record is likely to result in a significantly more accurate building response even though it retains long-period noise.

**Representative Examples**

To show the aforementioned effects of high-pass filters for individual ground motions and building models, we consider the ground motion record from each earthquake that we found to be generally the most destructive and perform IDA for all building models (9P, 9B, 20P, 20B, 55P, 55B, and the isolation system) with the processed versions of these records. We calculate $SFR$ at collapse for each filtered ground motion, here denoted $SFR^{col}$, and the results for each building model are shown in Fig. 2. Recall that “collapse” for the isolation system model occurs when the isolator reaches its displacement limit, which does not necessarily mean the superstructure will experience collapse.

![Figure 2](image-url)

**Figure 2.** Collapse ratios of all considered building models for six representative ground motion records and their filtered versions with different $T_c$.

Fig. 2 shows that $SFR^{col}$ is usually close to one, but in some cases, particularly for $T_c = 10s$ or $15s$, $SFR^{col}$ can be significantly greater than one. The 9B, 20B, and isolation system models appear less susceptible to these effects while the 55B model appears to be the most susceptible. IDA curves for $T_c = 10s$, $T_c = 15s$, $T_c = 20s$, and tilt corrected versions of the Chi-Chi TCU068 NS and Landers LUC Transverse ground motions are shown in Figs. 3 and 4 for all seven building models. IDA curves for $T_c = 30s$, $T_c = 40s$, and $T_c = 60s$ are not shown because for these ground motions, the IDA curves are virtually identical to those of the tilt corrected records. Note that the corresponding $SFR^{col}$ values in Fig. 2 are calculated from these results.
Figures 3 and 4 illustrate IDA curves for all considered building models with tilt-corrected ground motions and their filtered versions with different cutoff times ($T_c$). The curves show a significant increase in collapse capacity for the 55B model when a $T_c = 10s$ high-pass filter is applied, indicating a phenomenon known as "severe hardening" [19].

Severe hardening occurs for the 55B model in both ground motions for the $T_c = 10s$ filtered versions but not in the tilt-corrected versions because its collapse mechanism is different.
for the $T_c = 10s$ filtered ground motion. In addition to the 55B model, we also see this phenomenon in the IDA curve of the 20P model for the Landers LUC Transverse record. This is “unlucky” in a sense and cannot necessarily be known a priori, but is generally more likely to occur in taller buildings, for which there are more potential collapse mechanisms. Another surprising observation is that the collapse capacities of the 9P and 9B models ($T_1 = 1.88s$) to the Chi-Chi TCU068 NS record increase significantly (by more than 50% for the 9P model) after application of the $T_c = 10s$ filter to the tilt corrected ground motion. This is surprising because $T_c$ is more than 5 times greater than $T_1$ in this case and most engineers would assume that removing long-period content at periods so much longer than $T_1$ would not affect building response.

Conclusions

It is assumed in the earthquake engineering community that if high-pass filters are applied to ground motions with a corner period much longer than the period of the building model, then the application of the filter to the ground motion will not affect the response of the building. We investigated the validity of this assumption, with particular attention paid to the effects on collapse capacity. We find that the application of high-pass filters to input ground motions tends to moderately increase the collapse capacity of building models when compared to the corresponding unfiltered tilt corrected motions. Not surprisingly, this increase is more significant for taller building models and for filters with shorter corner periods. Although this effect usually becomes insignificant for corner periods longer than 20 seconds, applying a high-pass filter with $T_c = 10s$ increases the collapse capacity of the 20P model by an average of about 8 percent. This is perhaps surprising because $T_1$ for the 20P model is only 3.50s, about one third of $T_c = 10s$. For some ground motions and buildings models (even the 9P and 9B models with $T_1 = 1.88s$) the collapse capacity can increase by 50 percent or more if a $T_c = 10s$ high-pass filter is applied. We find that these effects on are usually insignificant for a 2DOF model of a base-isolated building.

When the raw, uncorrected, ground motion record is available, we find that building response to the demeaned raw ground motion is barely different than that of the tilt corrected record. This implies the benefits of removing long-period noise using filters with $T_c < 20s$ do not outweigh the negative effects of removing real long-period content from the ground motion. To ensure accurate collapse predictions and calculation of $G[C|IM]$ for collapse risk assessment, we thus recommend that, if the input ground motions are processed with high-pass filters, $T_c$ should be $\geq 20s$, even if the structure’s fundamental period is much less than 20 seconds. For reference, of the 50 ground motion records in the ATC-63 suite [20] sometimes used for IDA, 54% have a high-pass filter corner period of 10s or less in at least one of the two horizontal components [2].

It should be noted that the ground motions investigated in this study are taken from sites where strong ground motion was recorded during large-magnitude events, so the conclusions made here may not hold for ground motion records from smaller events. Furthermore, the NGA-West2 processing methodology is done on a record-by-record basis and the corner period for each record is determined by visually inspecting its Fourier spectrum. As such, the high-pass corner period should reflect the presence, or lack thereof, of long-period content in the unprocessed ground motion record. Regardless, caution should be exercised when calculating the collapse capacity of a building model with respect to a processed ground motion if $T_c < 20s$, even if $T_1$ is much less than $T_c$. 
References


