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Effect of ground motion duration on earthquake-induced structural collapse

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ABSTRACT

Although the influence of ground motion duration on liquefaction and slope stability is widely acknowledged, its influence on structural response is a topic of some debate. This study examines the effect of ground motion duration on the collapse of reinforced concrete structures by conducting incremental dynamic analysis on nonlinear multiple-degree-of-freedom models of concrete frame buildings with different structural properties. Generalized linear modeling regression techniques are used to predict the collapse capacity of a structure, and the duration of the ground motion is found to be a significant predictor of collapse resistance. As a result, the collapse risk of the analyzed buildings is higher on being subjected to longer duration ground motions, as compared to shorter duration ground motions having the same ground motion intensity. Ground motion duration affects the collapse capacity of highly deteriorating (non-ductile) and less deteriorating (ductile) concrete structures. Therefore, it is recommended to consider the duration of the ground motion in addition to its intensity and frequency content in structural design and assessment of seismic risk.

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1. Introduction

Earthquakes that have occurred in recent years, including those in Tohoku, Japan (M_w 9.0, 2011), Maule, Chile (M_w 8.8, 2010), and Sumatra, Indonesia (M_w 9.1, 2004), continue to remind us that very long duration ground shaking may occur at some sites [1]. In the Tohoku earthquake, sites across Japan experienced ground motions lasting for 40–270 s [2], compared to, for example, ground motion durations on the order of 6–30 s experienced in the Loma Prieta earthquake (M_w 6.93, 1989) [3]. Although the effect of shaking duration on structural damage is not always clear, reconnaissance teams investigating damage in past events have repeatedly attributed damage in some events and at some sites to long duration shaking, and the associated high number of load reversal cycles. Ground motions generated from large magnitude events, such as the recent earthquakes listed above, and recorded at sites situated some distance away from the epicenter, are particularly likely to be of long duration. The buildings constructed at these sites should therefore be capable of withstanding the expected long durations in addition to the expected ground motion intensities. Present building codes and analysis procedures are based on the probabilistic site-specific design spectra that do not directly consider duration [4].

It is well-known that ground motion duration and the number of cycles have an important influence on some types of earthquake damage, such as inducing liquefaction and slope instability [5,6]. Yet, there remains disagreement in the research community on the effect of ground motion duration on structural response [7]. For example, experimental studies of reinforced concrete and steel elements or frames have typically concluded that duration or number of cycles of loading is positively correlated to structural damage. The damage observed in connections of steel moment resisting frames in the Northridge and Kobe earthquakes was attributed to low cycle fatigue (*i.e.* many cycles). In addition, analytical studies adopting cumulative damage measures, like plastic strain, have generally found duration to be important in quantifying structural damage. However, analytical studies using maximum drift or displacement as a measure of damage in the structure contradict these findings, and generally have found no correlation between ground motion duration and increasing damage. Even in these types of studies, though, research employing structures with degrading characteristics and allowing for destabilizing effects of gravity loads shows that longer duration ground motions may in fact increase maximum structural responses. In summary, the relationship observed between ground motion duration and structural response is heavily dependent on the definition of ground motion duration and structural response parameter used and whether significantly nonlinear behavior and destabilization effects are considered [7].

This paper explores the influence of ground motion duration on structural collapse risk, which is a critical metric of life safety. Structural collapse occurs due to a combination of large amplitude demands (which past research suggests is not strongly duration dependent) and damage accumulated over multiple cycles during the earthquake (which past research indicates is significantly dura-

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tion dependent). Previous studies have shown how ground motion intensity and frequency content affect structural collapse risk and failure mechanisms [8–11]. However, the influence of duration, or the number of cycles imposed on the structure, is not well understood. One possible hypothesis is that long duration motions impose larger energy demands on the structure and therefore may cause collapse at lower ground motion intensities. This hypothesis is supported by work by Ruiz-Garcia [12] and Iervolino et al. [13], which suggests that duration may be more important for collapse than other, more linear limit states, but it has not been directly explored. To further complicate matters, the ground motion duration itself is related to earthquake features like magnitude, distance to site, and fault type [14], so it is difficult to decouple the effects of duration from other earthquake and ground motion characteristics. Understanding the effect of ground motion duration on structural collapse risk and failure mechanisms will bring us one step closer to preventing future earthquake-induced collapses.

This study quantifies the influence of ground motion duration on the predicted collapse response of concrete frame structures. Incremental dynamic analysis is carried out on a set of 17 archetypical reinforced concrete buildings representative of modern and older construction in high seismic regions of the U.S. Each of the analytical building models is subjected to a database of 76 ground motion time histories with varying duration. The simulations use nonlinear multiple-degree-of-freedom models, which are capable of capturing strength and stiffness deterioration, along with destabilizing effects of gravity loads. The collapse capacity of each structure is quantified by the median ground motion intensity causing collapse, measured in terms of inelastic spectral displacement. Once these results are obtained, the inelastic spectral displacement at collapse for all the buildings is studied as a function of duration, and the structure's fundamental (first-mode) period and ductility capacity using general linear modeling (GLM) regression techniques. In doing so, we expand on previous research by quantifying the correlation between duration and structural collapse resistance, which is a combined mechanism of different damage and response measures that have been studied independently before, utilizing nonlinear analysis models representing realistic building designs.

2. Ground motion duration

A ground motion time history or accelerogram, recorded from a particular earthquake at a particular site, can be characterized by a number of parameters including amplitude, frequency content, energy, and duration of shaking. There are many definitions for ground motion duration available in literature [15]. Bracketed duration considers the amplitude of the ground motion to measure the duration and is defined as the length of the time between which the absolute accelerogram exceeds some threshold acceleration (*e.g.* 0.1g) for the first and last time. The significant duration, on the other hand, is defined based on the energy of the ground motion record. Several measures serve as proxies for the total energy of the accelerogram, including the integral of the square of the acceleration history over time $a(t)$, which is known as the Arias intensity (AI) and is calculated as

$$AI = \frac{\pi}{2g}\int_0^{T_r} a^2(t)dt \tag{2.1}$$

where T_r is the total recorded time of the accelerogram and g is the acceleration due to gravity. Among the different definitions of significant duration present in the literature, the 5–95% significant duration [16] is employed here, as it has been used and recommended by a number of other studies [7,17]. The 5–95% significant duration, denoted *5–95%* D_s, is calculated as the interval between the times at which 5% and 95% of the Arias intensity of the ground motion have been recorded, representing the duration of time over which 90% of the energy is accumulated. Although the total length of the accelerogram may vary depending on the recording device, the *5–95%* D_s quantifies the length of the strongest part of the ground motion time history, *i.e.* that part of the motion which may damage a structure. This duration definition is also independent of the scaling of the record, as the rate of accumulation stays the same, and also does not vary with ground motion frequency content. Fig. 1 shows two recorded ground motions having the same peak ground accelerations (*PGA*), but different durations. The Arias intensity plot (Fig. 1(b)) shows that the energy accumulates over more time for the longer duration ground motion as compared to the shorter duration ground motion. The time histories in Fig. 1(a) also illustrate the greater number of load reversal cycles for the longer duration record.

3. Ground motion database

To consider a broad range of ground motion duration values, 76 ground motion records with *5–95%* D_s varying between 1.1 s and 271.3 s are used in the dynamic analysis. The distribution of duration values in the record set is illustrated in Fig. 2(a). Details of the records are provided in Appendix A. These ground motion records are obtained from the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation database [3], the COSMOS Virtual Data Center [18], and the USGS National Strong-Motion Project [19]. The records are from 24 different earthquakes with M_w 4.8 and above, with the maximum number of the records from a single event being limited to eight. Due to lack of availability of recordings for large long duration ground motions, particularly those from potentially large magnitude subduction events, this study also uses eight simulated records from Yang [20], in addition to the 68 strong motion recordings. Among short duration records, of which there are many ground motion recordings available, records with the largest *PGA*s were selected. To avoid any near site effects or effects of rupture directivity, only ground motions without large pulses in the velocity time history are used in dynamic analysis [21]. The record selection process did not consider spectral shape, but this is not expected to have a critical influence on the fragility predictions, due to the use of an inelastic ground motion intensity measure (described later in Section 5).

The significant duration of a ground motion at a site depends on various factors, such as earthquake moment magnitude, distance to the fault rupture, depth to the top of rupture, soil type and the type of earthquake [14]. Seismological theory and models predict that duration of shaking at the source increases with an increase in seismic moment or earthquake magnitude [22]. As the magnitude of the earthquake increases, so does the length and area of the fault rupture, which increases the time taken for the strain energy to release, resulting in longer strong motion durations at the source. The ground shaking duration modifies further as waves travel to a particular site, due to the factors such as soil and distance [14]. In general, as seismic waves scatter with distance between the source and site, the duration of ground shaking tends to become larger because of the increased difference in time between the arrivals of different seismic waves. Ground motion recordings from soil sites usually exhibit longer durations than rock sites [14].

This study uses ground motion records from crustal and subduction events (M_w 4.8–M_w 9.2), and the increase in duration with magnitude for these ground motions can be seen clearly in Fig. 2(b). The relationship between site epicentral distances and duration is also apparent in the record set, as shown in Fig. 2(c). Record *PGA*s vary between 0.02g and 0.73g. Fig. 2(d) shows that most of the long duration records have low *PGA* because they are re-

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