A POTENTIAL PROBLEM IN ESTIMATING THE DRIFT RESPONSE OF LONG-PERIOD STRUCTURES

S. Pujol¹, A. Irfanoglu², P. Gülkan³, T.H. Heaton⁴, M.A. Sozen⁵, and L. Laughery⁶

ABSTRACT

During the last two decades, dozens of ground motion records that differ from the types assumed in developing design spectra appear to have gone mostly unnoticed by the structural engineering community. These motions have occurred for a wide range of faulting mechanisms, and have been recorded at stations ranging from 0.3 to 90 km from the fault on sites with a wide range of properties. The records result in large spectral amplifications at periods as long as 5 s., with spectral displacements approaching 4 meters for damping ratios between 2 and 5 percent of critical. These displacements are 3 to 4 times what would have been expected on the basis of a standard design spectrum with a “nearly constant” displacement range starting at 2 to 3 s. Differences between the consensus approaches used in codes for drift demand at long periods and those that have been observed should make us wonder what drift demands these ground motions, rich in long-period components, could produce in tall buildings and structures with base isolation. In this note, we discuss the features of “long-period” ground motions and their potential consequences in an attempt to invite examination of the problem by the engineering community.

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ABSTRACT

During the last two decades, dozens of ground motion records that differ from the types assumed in developing design spectra appear to have gone mostly unnoticed by the structural engineering community. These motions have occurred for a wide range of faulting mechanisms, and have been recorded at stations ranging from 0.3 to 90 km from the fault on sites with a wide range of properties. The records result in large spectral amplifications at periods as long as 5 s., with spectral displacements approaching 4 meters for damping ratios between 2 and 5 percent of critical. These displacements are 3 to 4 times what would have been expected on the basis of a standard design spectrum with a “nearly constant” displacement range starting at 2 to 3 s. Differences between the consensus approaches used in codes for drift demand at long periods and those that have been observed should make us wonder what drift demands these ground motions, rich in long-period components, could produce in tall buildings and structures with base isolation. In this note, we discuss the features of “long-period” ground motions and their potential consequences in an attempt to invite examination of the problem by the engineering community.

Introduction

Long-period ground motion features extreme spectral displacements at periods as long as 10 s. Figure 1 shows a comparison between displacement spectra for a record obtained in Kathmandu Nepal in 2015 and a record from the 1995 Kobe Earthquake that became a common reference for its destructive power. The comparison is made between responses of linear oscillators with modest damping. Tall and base-isolated structures are bound to enter their nonlinear range of response (achieving increased effective damping) during strong ground motion. Nevertheless, the comparison in Figure 1 shows clearly the crux of the problem: in long-period ground motion, seismic demands for long-period structures can be two or more times larger than what has been experienced in most of the earthquakes that form the bulk of our professional experience. Publicly available video gives a raw qualitative perspective of the amount of ground displacement that took place in Nepal in 2015 [1]. If one pictures a base-isolated structure in the type of motion illustrated by this video, it becomes clear that the

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isolation system would experience extreme demands. The effect is alleviated partly by increased damping and nonlinearity. Nevertheless, linear demands as large as those in Figure 1 are unlikely to become trivial because of damping and nonlinearity, and this problem is not unique to the record obtained in Nepal, as discussed in sections below.

![Linear SD, 2% Damp. Ratio](image)

**Figure 1.** Displacement spectra illustrating long-period ground motion.

### Examples of Long-Period Ground Motion and Its Damage Potential

Since the 1999 Chi-Chi Taiwan Earthquake, at least four other earthquakes have generated records indicating large demands for long-period (T>3s) structures (Table 1). It is difficult to find commonalities among the earthquakes listed. The records that are worrisome seem to occur in a wide range of soils, at different distances from the inferred fault (ranging from 300 m to 90 km), for different types of faults, and for a rather wide range of magnitudes (7 to 7.8).

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Year</th>
<th>Fault-Station* Dist.</th>
<th>Fault Type</th>
<th>Dip</th>
<th>PGA Range* g</th>
<th>PGV Range* cm/s</th>
<th>Vs30 m/s</th>
<th>Mw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi-Chi (Taiwan)</td>
<td>1999</td>
<td>0.3-90 km</td>
<td>Oblique</td>
<td>33 deg</td>
<td>0.1-0.7</td>
<td>30-250</td>
<td>200-600**</td>
<td>7.6</td>
</tr>
<tr>
<td>El Mayor (Baja CA)</td>
<td>2010</td>
<td>11-55 km</td>
<td>Strike-Slip</td>
<td>63 deg</td>
<td>0.2-0.3</td>
<td>30-70</td>
<td>200-240</td>
<td>7.2</td>
</tr>
<tr>
<td>Darfield (New Zealand)</td>
<td>2010</td>
<td>1.5-8 km</td>
<td>Strike-Slip</td>
<td>82 deg</td>
<td>0.2-0.4</td>
<td>50-80</td>
<td>250-300</td>
<td>7.0</td>
</tr>
<tr>
<td>Kumamoto (Japan)</td>
<td>2016</td>
<td>40 km</td>
<td>Strike-Slip</td>
<td>66 deg</td>
<td>0.35</td>
<td>80</td>
<td>270</td>
<td>7.0</td>
</tr>
<tr>
<td>Nepal (or Gorkha)</td>
<td>2015</td>
<td>20 km</td>
<td>Reverse</td>
<td>7 deg</td>
<td>0.1-0.2</td>
<td>40-110</td>
<td>180-300</td>
<td>7.8</td>
</tr>
</tbody>
</table>

*For stations generating record “rich” in low frequencies, **Except for one station at 125 m/s
In the Kumamoto, Japan, Earthquake in 2016 observations indicated large demands occurred in base-isolated structures resulting in recorded relative displacements exceeding 40 cm, damage to poorly detailed connections to base isolators, and damage to nonstructural elements within the range of motion of the structures (Figure 2). These observations warn us of what may occur to long-period structures during long-period ground motion. Fortunately these occurrences have not really affected many long-period structures, but that is bound to change when long-period ground motion occurs in a large, modern urban area.

Figure 2. Damage in base isolated structures in Kumamoto, Japan (Courtesy of BRI)

Figure 3 compares displacement spectra for selected records from the mentioned earthquakes and spectra for other earthquakes that have caused widespread damage in cities in the past 20+ years (marked with asterisks). The plot stresses that earthquakes that have created much chaos such as Northridge, Kobe, and Christchurch cannot be taken as a point of reference at all in design and evaluation of long-period structures. Notice that at $T>5s$ the ground motion from Kumamoto (that caused the damage illustrated in Figure 2) is the least demanding of the
long-period motions in the plot. Other than moderately tall buildings in Taiwan, we have limited experience with ground motion exciting structures with long periods (T>3s).

One thing is clear: as Westergaard [2] observed, in these records peak ground acceleration (PGA) was not a good indicator of damage potential especially at T>2s. Most of what we do today in earthquake engineering still revolves around PGA. Dealing with long-period ground motions requires a new way of thinking about earthquake demand [3,4,5].

Seismological Aspects

Long-period motions start at the fault and are related to its slip. Large fault slips produce motions with long periods [6]. This can be exacerbated by “resonances,” large amplifications in both soils and basins. While there are techniques to identify potential for resonance or large amplification, there are not yet reliable means to anticipate when and where large fault slips may occur. What is known is that while large fault slip often occurs over large areas in large magnitude earthquakes, it also occurs over small areas in moderate magnitude earthquakes explaining the wide variation in magnitude in Table 1 and creating uncertainty about the effects of relatively frequent earthquakes [7].

Geotechnical Aspects

The problem of long-period ground motion is not related to site amplification alone. Figure 4 shows a comparison of linear spectra for the main shock and aftershocks recorded at the same station in Kathmandu Nepal (on deep alluvial deposits). Dual vertical scales for main- and aftershocks are used to facilitate comparing amplification. The plot shows that the level of amplification for long periods was much larger during the main shock. Two plausible explanations are nonlinear soil response and differences in fault slip, implying that identification of places where long-period ground motion may take place may require us to consider more factors than soil type and soil depth.

Figure 4. Comparison of mainshock and aftershock spectra from Nepal.
**Structural Aspects**

A combination of damping changes, nonlinearity, and modified design spectra is likely to lead to reductions in the damage that could be caused by long-period ground motion in a modern urban area. Figure 5 shows that increased damping helps reduce long-period amplification, but it does not eliminate it. Nonlinearity has a similar effect as damping does at long periods. Figure 6 shows that nonlinearity causes a large decrease in response. Yet, the displacement demand for a nonlinear system with a period exceeding 4 s and for ground motion similar to that recorded in Kathmandu is still 2 to 4 times what would be obtained for “conventional” ground motion with a “range of nearly constant displacement” starting at 2 to 3 seconds [8,9]. If spectral displacement can reach 2 m as suggested by this plot, then many base-isolated structures are vulnerable to damage during long-period ground motion (similar to the one in Kathmandu) as building isolators can seldom accommodate more than 1 m of displacement. This rather pessimistic prediction needs testing because of the lack of sound data from the field and because of the magnitude of potential consequences.

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**Figure 5. Effect of damping on reducing long-period amplification.**

If the period of the structure (isolated or tall) falls in the range Newmark [8,9] called “range of nearly constant displacement,” one could idealize spectral displacement as peak ground displacement (PGD) times an amplification factor. But estimating PGD is difficult because it requires correct removal of instrument error from acceleration records, and this challenge is not simple and there is no consensus on how to address it. Nevertheless, for long-period ground motion this does not seem to be an issue. Figure 7 shows a comparison of spectra obtained from “raw” and “corrected” acceleration records from Kathmandu, Nepal. Of course, estimates of PGD obtained from raw records often border the absurd and Kathmandu was not an exception. Yet, in this case the spectra obtained are nearly identical, suggesting that in the range of periods considered peak ground velocity (PGV), not PGD, controls response. That is, in long-period ground motion the boundary between the regions of constant velocity and displacement is
long, making most long-period structures of interest fall in the range of nearly constant velocity. Fortunately, in this range the profession has experience and it should be possible to produce estimates of deformation. The accuracy of these estimates needs to be evaluated in future investigations.

Figure 6. Effect of nonlinearity on reducing long-period amplification.

Figure 7. Comparison of spectra obtained from raw and processed records.
Current Practice

In 2006 Crouse et al. proposed changes to U.S. practice. Since then, design spectra in the U.S. feature spectral displacements increasing linearly with period up to 8 and 12 s [10]. These periods are the so-called “long-period transition periods” now mapped in USGS hazard maps. They lead to spectra similar to those shown in Figure 8 in red. This plot shows that the use of “long-period transition periods” is likely to help reduce the vulnerability of structures to long-period ground motion. But at least three questions remain: Are the changes made by Crouse et al. enough in light of new evidence? What about structures built or retrofitted before 2006? And what about structures in countries that have not adopted changes similar to those proposed by Crouse et al.?

![Figure 8. Comparison of design spectra corresponding to U.S. practice and long-period ground motions. Note that the factor 1.4 is used to project from a damping ratio of 5% to 2%.](image)

Conclusions

Long-period ground motions are defined by large amplifications in response at periods as long as 5 s. They lead to linear response spectra with displacements 3 to 4 times as large as what would be obtained using a standard design spectrum, which can cause problems with high-rise and base-isolated structures. The events that produce these motions are not isolated: they have been observed during earthquakes caused by a wide range of faulting mechanisms and on sites between 0.3 to 90 km from the fault with Vs30 values ranging from 180 to 600 m/s. The goal of this note has been to bring this phenomenon to the attention of the earthquake engineering community so that it can work to understand what causes it and develop strategies to avoid potentially dire consequences. Here, we introduce five earthquakes that led to long-period motion, describe salient features of the stations and sites where the motions were recorded, and show how structural nonlinearity and damping can help to mitigate – but not eliminate – the effects. A more comprehensive examination is required to ensure that tall and base-isolated
buildings subjected to long-period ground motions will have the same level of safety as the rest of the building stock.

References


