Suggested Changes to the non-conservative low frequency criteria for the seismic design spectrum used in intraplate regions

John M. Nichols
Department of Construction Science, Texas A&M University, USA.

Abstract

The shape and the amplitude of the design spectrum are critical to the safe design of structures. This paper presents suggested changes to the shape constraints for the design spectrum in the 0.5 to 3 Hz range for large intraplate earthquakes. The main recommendation arises because of the impact on a large pulse loading within an intraplate earthquake with a frequency of 1 to 2 Hertz. Newmark and Hall in 1978 establish the seismic criteria for the design of nuclear power plants. This criteria still forms an integral part of the legal framework in the United States for the design of nuclear facilities. The earthquake spectrum developed for the nuclear power plant design was based on an extensive analysis of the seismicity of interplate regions and a rigorous mathematical review of the wave and pulse constraints on the limits of the design spectrum. The shape of the 0.5 to 3 Hertz region of this design spectrum was based on a number of mathematical assumptions in the analysis that were known in 1978 to be non-conservative and requiring review with the collection of additional seismic traces. Recent earthquake data from the secret Russian database held in the Lamont Doherty Observatory database, data from the New Madrid Seismic Zone, other large intraplate events and the recent 2004 Sumatra earthquake provides sufficient data to reconsider the wave and pulse constraints used by Newmark and Hall in the original mathematical review of the design spectrum. The recommendations about the spectrum shape change for major intraplate are applicable to other major structures with a low natural frequency.

Keywords: Intraplate earthquakes, nuclear power plants, design spectrum
1 Introduction

The derivation of the normally accepted seismic design spectrum used in interplate regions can be traced to analysis of data from the Californian seismic work of the 1950s and 60’s [1]. Newmark and Hall [2] derived the engineering characterization of ground motions for nuclear power plants, with significant emphasis on the impact of pulse loading, and the averaging effects in the low frequency range to establish the shape of the design spectrum that should be used for the design of nuclear power plants. There have been no identifiable changes in the literature or US Legislative requirements for this Nuclear Design Standard since 1978. The National Science Foundation and the United States Geological Service have embarked on a seismic data collection and post earthquake evaluation program since the 1950’s as part of the general US governments’ observations on ground movements caused by earthquakes. The issue that remains after this period of data collection and analysis is the method used to handle the impact of large low frequency pulses in the seismic design of structures in intraplate regions. This issue was briefly considered by Newmark and Hall in 1978. This study of the impact of large low frequency pulses on intraplate design spectra looks at the mathematical aspects of harmonic loading of structures from earthquake loading, reviews the conceptual basis for the various existing spectra in use around the world. This research identifies a set of criteria for the earthquake design spectra allowing for low frequency pulses.

2 Literature Review

Five or six earthquakes will cause vast devastation of infrastructure and loss of life in this century [3] causing approximately 75% of all earthquake deaths and probably half the economic losses. Limited near field seismic data are available for large intraplate earthquakes [4] and for the recent 2004 Sumatra earthquake [5]. The 2001 Gujarat Earthquake (moment magnitude 7.9) occurred near the Rann of Kachchh in north-western India. The damage in the town of Bhuj was consistent with a felt intensity of MM X or greater. The earthquake occurred in an area of known seismic activity with a great event having occurred early in the 19th century in this state of India. One area of interesting damage occurred with the re-collapse of a historic masonry wall in Ahmedabad, at a distance of 250 km from the epicentre (Figure 1). The recent southern Italian earthquake on October 31, 2002 measured 5.6 on the Richter scale and represents the worst death toll for that size earthquake in several centuries. A 50-year-old two-storey school building collapsed in the centre of town killing 24 people mainly children (Figure 1), whilst other nearby centuries old buildings were still standing [6]. A shaking table study of small masonry dwellings in Italy also showed the potential impact of a frequency match between a harmonic loading and the building’s natural frequency [7, 8], although this observation can not be proven conclusively for these three types of structures. The limited earthquake database provides little insight into the probable location of these events and there is great reluctance in the community at large to design for such events [9].
A number of earthquakes for historical reasons have been used as primary seismic study tools (Table 1). Some of the earthquakes listed have been used in the development of the current US design spectrum, and in the development of theoretical frequency spectra [10]. These listed earthquakes are intraplate unless noted, and have been used in this analysis of large pulse loads in understanding the change in the shape of the design spectrum from small to large events, unlike the average spectrum assumed by Sanchez-Silva and Arroyo [11].

Table 1: Significant Earthquakes

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Date</th>
<th>Magnitude</th>
<th>Location /Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imperial Valley</td>
<td>May 18, 1940</td>
<td>6.4</td>
<td>California / Interplate</td>
</tr>
<tr>
<td>Kern County</td>
<td>July 21, 1952</td>
<td>7.6</td>
<td>Taft / Interplate</td>
</tr>
<tr>
<td>Nahanni</td>
<td>Dec. 23, 1985</td>
<td>6.8</td>
<td>St. 1 Iverson Creek</td>
</tr>
<tr>
<td>Saguennary (1)</td>
<td>Nov. 25, 1988</td>
<td>5.9</td>
<td>St 8 La Malbaie, CA</td>
</tr>
<tr>
<td>Marked Tree</td>
<td>Synthetic</td>
<td>7.25</td>
<td>Arkansas - NMSZ</td>
</tr>
<tr>
<td>Newcastle</td>
<td>Dec. 28, 1989</td>
<td>5.4</td>
<td>Newcastle, AU</td>
</tr>
<tr>
<td>Irpinia, Calatrini</td>
<td>Nov. 23, 1980</td>
<td>6.9</td>
<td>Italy /</td>
</tr>
<tr>
<td>Eureka</td>
<td>Dec 21, 1954</td>
<td>6.6</td>
<td>St 22, / Interplate</td>
</tr>
<tr>
<td>Miramichi</td>
<td>Jan 9, 1982</td>
<td>5.7</td>
<td>Loggie Lodge</td>
</tr>
<tr>
<td>Bros</td>
<td>May 27, 1995</td>
<td>&lt; 4</td>
<td>Tennessee</td>
</tr>
<tr>
<td>Parkfield</td>
<td>June 27, 1966</td>
<td>5.6</td>
<td>Parkfield / Interplate</td>
</tr>
<tr>
<td>Sumatra</td>
<td>Dec 26, 2004</td>
<td>9</td>
<td>Largest 40 yrs, inter.</td>
</tr>
</tbody>
</table>

Brune [10] developed a model for estimating the spectra of seismic shear waves from earthquakes, which is used in the study of theoretical earthquakes. The form of the Brune function is:

$$
\Omega(\omega) = \frac{\sigma \beta}{\mu} \frac{1}{\omega(\omega^2 + \tau^{-2})^{0.5}}
$$

where $\omega$ is the frequency (Hz), $\sigma$ is the effective stress (Pa), $\beta$ is the shear wave velocity (m/s), $\mu$ represents the rigidity, and $\tau$ (sec) represents the dimensional order of the fault divided by $\beta$. Brune provides a range of values used in his 1970 analysis based on the limits presented for a number of interplate
earthquakes. Brune noted that the frequencies of interest were from 0 to 10 Hertz for seismic studies.

### 3 Earthquake Analysis

The 1989 Nahanni earthquake provides one example of a time signal for a large intraplate earthquake containing pulses [12]. The Fast Fourier transform (FFT) for the spectral amplitude has been calculated and the change in the phase angle (Figure 2) plotted for the Nahanni earthquake. The results show that the phase angle is not distributed randomly as is commonly assumed for the derivation of spectra using the Brune model, but the phase angle rotates at a reasonably characteristic rate for each earthquake, with a reduction in amplitude with frequency. The FFT results provide a more generalized method to undertake the type of mathematically based pulse analysis used by Newmark and Hall in considering the impact of the pulse load at low seismic frequency.

![Figure 2: Nahanni Phase Angle.](image)

Jacobs [13] of the Lamont – Doherty observatory supplied a copy of the Marked Tree time trace for a M7.25 earthquake in the New Madrid Seismic Zone. The development of this time trace was based on the Brune model, although Jacobs noted that the conditions in the Mississippi valley make the smooth Brune spectra into a ‘holy’ event with a significant peak at about 1 Hz. The interesting feature is that the Maximum Credible Event (MCE) for the NMSZ is at least a great event (M8) [1], as there has been no credible research to show the warranted application of a lower standard to the 1811-1812 events [4]. The historical earthquakes listed in Table 1 have been plotted on a tri-part...
logarithmic chart with the various standard spectrums developed by Richter, Newmark and Hall and the USGS over the last 50 years (Figure 3). Figure 3 also shows the general limits recommended by Richter [1], and the Maximum Credible Earthquake from the New Madrid Seismic Zone (NMSZ) [12, 14].

Figure 3: Earthquake FFT Plots and Limits

The results of this FFT analysis of a range of earthquakes with magnitudes from M3 to 7.25 shows that the observation made by Richter in 1958 about relative paucity of data and that low seismicity zones may not be seismically quiet over a long period were prophetic. In this case, we are looking at about 43 years of additional data and forensic investigation as to the characteristics and geology of historical events providing data on events outside the reach of the earlier seismic networks and the analysis at the time. The plotted results on Figure 3 demonstrate the gradual increase in the expected size of the design events in the continental USA from 1958 until 2002. The plotted FFT results on Figure 3 demonstrate the banded nature of the energy in any earthquake from the Bros event in TN to the 1985 Nahanni event, and the change in shape of the banding function from the low events to the higher magnitude earthquakes. The
change in shape of the banding function can be attributed to increase in length of
the fault rupture, which generates a rupture path long enough to create
the wavelengths to sustain the low frequency waves, and the increased rupture
length is likely to include an increased stress change or drop which increases the
available energy for all frequencies. The FFT results on Figure 3 show that a
theoretical M7.25 Marked Tree and the Nahanni events generate elements in the
frequency domain that exceed the MCE design spectrum recommended by the
USGS.

Three observations were made from the data used to prepare Figure 3. The
first observation that can be made from the data plotted on Figure 3 is the
gradual increase in the maximum design velocity expected from earthquakes
from Richter in 1958 to the USGS in 2003. The second interesting feature is the
relative stability of the upper corner frequency on the design spectrum at about
1.6 to 2 Hertz. However the critical third observation is that there is no
physically based mathematics nor evidence from the large plotted earthquake
events that requires the standard tent form of the spectrum shape to be the
limiting criteria for all earthquakes, and the bandwidth criteria of
\[ \frac{\text{acceleration} \times \text{displacement}}{\text{velocity}^2} < 6 \]
for the maximum values in an
earthquake used by Newmark and Hall is only approximately correct, as was
Sumatra – Andaman earthquake matches the observations on the large intraplate
events, and given the 1200 kilometre length of the rupture the observation of
large pulses in the time trace are as expected for such an event.

4 SDOF Analysis using Laplace and Fourier Transforms

Newmark and Hall [2] and Craig [16] provide slightly different defining sketches
for a single degree of freedom (SDOF) operator (Figure 4).

![Figure 4: SDOF Defining Sketch](image)

The symbols are defined as the mass, \( m \) (kg), spring stiffness, \( k \) (N/m),
damping coefficient, \( c \) (kg.m), applied loading function, \( p(t) \) (N), and
distances, \( x, y, u \) (m). Newmark and Hall define \( u = x - y \). The equation of
motion derived from Newton’s second law assuming that the base can be
excited, i.e. \( \ddot{y} \neq 0 \), and where \( u = 0 \) implies an unstretched spring is:

\[
m\ddot{u} + c\dot{u} + ku = p(t) - my
\]  
(2)
The Laplace transform provides a mathematical method to transform a differential equation into the frequency domain thus providing an analytical solution. The convolution integral that forms the basis for the Duhamel integral [2] used in the standard solution method for Newton’s second equation is:

\[ h(t) = \int_{0}^{t} f(t-\tau) g(\tau) d\tau \]  

(3)

where \( t \) is the time, \( h(t) \) is the system response or convolution product at time \( t \), \( \tau \) is a dummy argument, \( g(\tau) \) is the signal input function, and \( f(t-\tau) \) is a function that weights the output in response to the input function. The Laplace transform for the homogenous differential equation is:

\[ (m[s^2Y(s) - s\dot{y}(0) - \ddot{y}(0)]) + (c[sY(s) - y(0)]) + kY(s) = 0 \]  

(4)

where \( Y(s) \) is the Laplace transform of the unknown function \( u(t) \). Eqn (4) can be rearranged using the relationships that \( 2\eta = c/m \) and \( \lambda^2 = k/m \) to yield:

\[ Y(s) = \frac{as + b}{s^2 + 2\eta s + \lambda^2} \]  

(5)

with the constants for each initial value problem which are termed \( a \) defined as \( y(0) \), and \( b \) defined as \( \dot{y}(0) + \eta \ddot{y}(0) \). The complex roots for the denominator are \( s_{1,2} = -\eta \pm \sqrt{\eta^2 - \lambda^2} \). The form of eqn (5) suggests a relatively straightforward convolution product solution, which is termed the Duhamel Integral for a non-homogenous differential equation such as for eqn (3). The solution for \( u(t) \) for a SDOF operator that is underdamped can be found in Craig [16]. The analysis demonstrates the development of the transfer function \( Y(s) \) that relates the analytical frequency domain to the time domain. The equation \( p(t) - m\ddot{y} \) provides the loading pattern, depending upon the movement of the base and the force function applied to the mass.

The clear mathematical observation from eqns (5) and the solution to the Duhamel integral is the impact of a low frequency pulse that will significantly alter the velocity function at the time of the pulse, even allowing for the exponential die-off of the output function for each pulse. This finding on pulses matches the analysis of the earlier results presented by Newmark and Hall, with the caveat as to the limited amplitude of the pulses considered in their work. The final observation is the structural similarity between the Laplace Transfer function (5) and Brune’s eqn (1), although the phase angle assumption of a random angle for eqn (1) is not based on reality.

Brune has used a Fourier transform to generate the transfer function. Brune’s model provides for a linear relationship between the effective stress and the spectrum amplitude for a constant frequency, and thus the critical value in the model is the time of rupture \( \tau \). Brune estimated the Parkfield earthquake as having a rupture time of 0.5 seconds for a 2km long fault. The 1915 Abruzzo earthquake has been shown to have a fault length of about 25 km. This provides
an estimate for the time of rupture at 6 seconds, and the 2004 Sumatra
earthquake had a rupture length of 1200 km and a rupture time of 8 minutes.

The increase in length of the rupture plane for an increasing size of
earthquake has two impacts, the first is the potential increase in the energy
release, and the second is the increased duration of the rupture time. Brune’s
model provides an opportunity to consider the ‘theoretical’ difference in the
amplitude spectrum for an event on a short rupture plane and an event on a long
rupture plane. The results for competent bedrock have been shown by Nichols
[12] to match the standard spectrum shape for short duration events but to have a
significantly increased energy at low frequencies in the long duration events. The
curvature introduced to the short rupture-plane frequency spectrum means that
for a 0.01 second event the ratio of the energy at 1 Hertz is less than 8 percent of
the infinite value, whereas at 10 Hertz the difference is only 60 percent.

Veletsos and Newmark [17] have used an analysis of various velocity and
acceleration pulses based on the known characteristics of the typical Imperial
Valley events of the 1940’s. These results and analysis techniques support the
method developed by Brune, but suggest a change in the spectrum to allow for
the size of the low frequency pulse expected in a large intraplate earthquake.

5 Spectrum Shape Review

5.1 Static Analysis

The definition of a static loading assumes a finitely small frequency for the
loading. A simple analysis assuming constant mass and normal values for
stiffness and damping shows that a frequency of loading of less than about 0.3
Hz (3.3-second period) provides an error of less than 1 percent in using the static
form of Newton’s second law to the full differential equation. The value of the
acceleration measured using a FFT at a 0.6 to 1 Hertz range provides a
reasonable guide as to the equivalent static acceleration. The common
assumption in the low frequency region is that the displacement is constant
below 0.3 Hertz.

5.2 Low Frequency – 0.3 to 10 Hz

The USGS in the common design method are implicitly accepting the 1 Hz peak
as the critical maximum for the velocity component, and a corner frequency of
about 1.7 Hz for the acceleration limit. This result matches the observed
bounding function for the medium range Californian events such as the 1940’s
Imperial Valley events, and conforms to the estimated impact of small pulses in
these types of events [2]. The Laplace transfer function established from
Newtons’ second law and the Fourier transform method used by Brune do not
support the theory of a region of constant velocity where the fault displacement
length is long enough to provide for the generation of low frequency waves. The
observation by Jacobs [13] that extreme damage often occurs to individual
buildings in a group because of frequency matching illustrates the real difficulty
in designing structures for large earthquakes, and the difficulty in studying the failures in Italy and India that have a high probability of being caused by a frequency matched effect.

5.3 High Frequency – 10 to 100 Hz

The high frequency elements of the current design spectrum match the observed data. The interesting observation relates to the findings from the Borovoye Digital Seismogram Archive of harmonic components in one seismic trace [18]. Kim et al., [18] attribute the harmonics to a wave of 2.7 Hertz generated by a multiple source with a time difference of 0.4 seconds, although the series actually represents a decaying series of odd numbered sine pulses with a first pulse at about 1.3 Hz. The use of decaying sine pulses provides a potential method to identify large pulses from the harmonics.

6 Conclusions

This paper reviewed the form of the standard seismic design spectrum to consider the impact of 1 Hertz pulses in larger earthquakes. The historical seismic data analysis used Fast Fourier transforms for a range of historical earthquakes including the El Centro, Eureka, and Parkfield, and the Nahanni earthquake. The criteria for the seismic design spectrum have been developed over the last 50 years, are essentially from interplate data. These criteria were developed from a statistical analysis of the available seismic data, with the adoption of a three-part standard in the spectrum having three constant regions of displacement (< 0.3 Hz), velocity (0.3 to 2Hz), and acceleration (> 2 Hz). Richter, and Newmark and Hall commented on the limitations of the seismic data available for this type of statistical analysis and the associated development of seismic standards. Hall further noted in 2001 that some of the earlier seismic data did not support the assumption of constant velocity for large events. The theoretical analysis using the standard Laplace transform of Newton's second law for a single degree of freedom operator, and the Fourier transform to generate the Brune frequency spectrum show the dependence of these transfer functions on the frequency range of the input function. Analysis of a range of historic events suggests that the criteria for the standard design spectrum are non-conservative for large intraplate events for the lower frequency elements. This corner frequency should approach the limit of about 0.3 Hz for an M8 or great earthquake, from a maximum of 2 Hz for an M5 intraplate event.

References