Seismic Design Accelerations for the LSST Telescope

Douglas R Neill[a], Mike Warner[b], Jacques Sebag[a]
[a]National Optical Astronomy Observatory, 950 N Cherry Ave., Tucson, AZ, USA 85719
[b]Cerro Tololo Inter-American Observatory, Colina El Pino S/N, La Serena, Chile

ABSTRACT

The Large Synoptic Survey Telescope will be located on a seismically active Chilean mountain. Seismic ground accelerations produce the telescope's most demanding load cases. Consequently, accurate prediction of these accelerations is required. These seismic accelerations, in the form of Peak Spectral Acceleration (PSA), were compared for site specific surveys, the Chilean building codes and measured seismic accelerations. Methods were also investigated for adjusting for variations in damping level and return period. The return period is the average interval of time between occurrences of a specific intensity.

Keywords: telescope, earthquake, seismic, accelerations, PSA, Peak Spectral Acceleration

1. INTRODUCTION

The LSST will be built on Cerro Pachón, Chile, a 2,682 meter high mountain. This location is seismically active, consequently the telescope and all its components must be designed to withstand the potential seismic accelerations. These seismic accelerations are the most demanding load cases the telescope must be designed to withstand. Consequently, the choice of seismic design loads greatly affects the design of the telescope and all its components. Overly conservative design accelerations increase the cost and mass of the telescope. Non-conservative design accelerations produce unacceptable risk of seismic damage. Accurate estimates of the likely seismic accelerations of the telescope are necessary to produce a safe and cost effective telescope design. Since the LSST support facility, lower enclosure, etc., will be designed and fabricated to the well established Chilean seismic standards, this investigation was principally intended to provide design accelerations for the LSST telescope and its components.

Previously, the LSST project has utilized the seismic design requirements produced for the Gemini Telescopes by Dames and Moore[1]. The Gemini Telescopes are similar in design and size to the LSST telescope. The Gemini South Telescope is located at 1.4 km distance from the LSST telescope site on the same mountain in Chile. The Gemini North Telescope in Hawaii, which was designed to the same seismic requirements, has experienced a significant seismic event[14] without significant damage. However, more recent seismic analysis from other telescope projects[8-11] have predicted larger accelerations than previously utilized by the LSST project. This has led to this review of the LSST seismic design accelerations. In this study, the Dames and Moore seismic design accelerations were compared to the seismic accelerations in the Chilean standards, GMT (URS) seismic accelerations and actual measured accelerations from the Punitaqui and Cobquecura seismic events in Chile.

Most commonly, seismic design accelerations are provided that correspond to the most extreme event expected over a 500 year period. This is equivalent to an event with an average 500 year return period, 20% chance over 100 years or a 10% chance over 50 years. A building can easily last for 50 years and seismic damage to a building also endangers personnel, therefore a 500 year event (10% chance over 50 years) provides reasonable design accelerations for buildings.

To facilitate comparison, except where it specifically refers to another return period, all the analysis in this report refers to 500 year return events. A 500 year event (10% chance over 50 years) provides excessive design accelerations for a component with a limited lifetime and for which seismic failure would produce negligible threats to personnel. This study also investigates the accelerations for shorter (300, 200, 150 and 100 year) return events. Limited lifetime equipment, such as a telescope, should be designed to seismic accelerations reflecting their design lifetimes. Following the previous example of buildings implies that the LSST telescope should utilize shorter return periods:

- Telescope design life: 30 years (telescope return event 300 years).

The purpose of this investigation is to provide design accelerations for a seismic analysis of the LSST telescope. Although this study determined that the most applicable reference for determining the peak spectral accelerations (PSA) is, "Chilean Standard NCh2745-2003 – Earthquake Resistant Design of Base-Isolated Buildings,"[2] the follow up

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analysis will be conducted according to the requirements of, "Chilean Standard NCh2369-2003 – Seismic Design of Industrial Structures and Facilities,"[3] which provides the analysis guidelines appropriate for a telescope structure, however, it does not provide the detailed spectral accelerations required for the actual analysis, where [2] provides this information. A separate standard, "Chilean Standard NCh 433-1996, 2009 Edition – Earthquake Resistant Design of Buildings,"[4] is utilized for normal buildings.

2. PSA: PEAK SPECTRAL ACCELERATIONS

Although the accelerations from a seismic event are very erratic, the expected accelerations produced by a seismic event are most often provided in the form of a Peak Spectral Acceleration (PSA) plot. The PSA can be used to provide either horizontal or vertical accelerations. The PSA provides the response (output) accelerations for a single degree of freedom resonator. The response is the result of the interaction of the ground acceleration and the dynamic properties of a structure. The PSA is normally plotted with the peak acceleration (Ac peak) in gravitational units (G peak) versus the fundamental period (inverse of natural frequency) in seconds (s). The seismic accelerations are commonly shown as envelopes (shown in Figure 1 below as thick solid green lines that approximate the peak values).

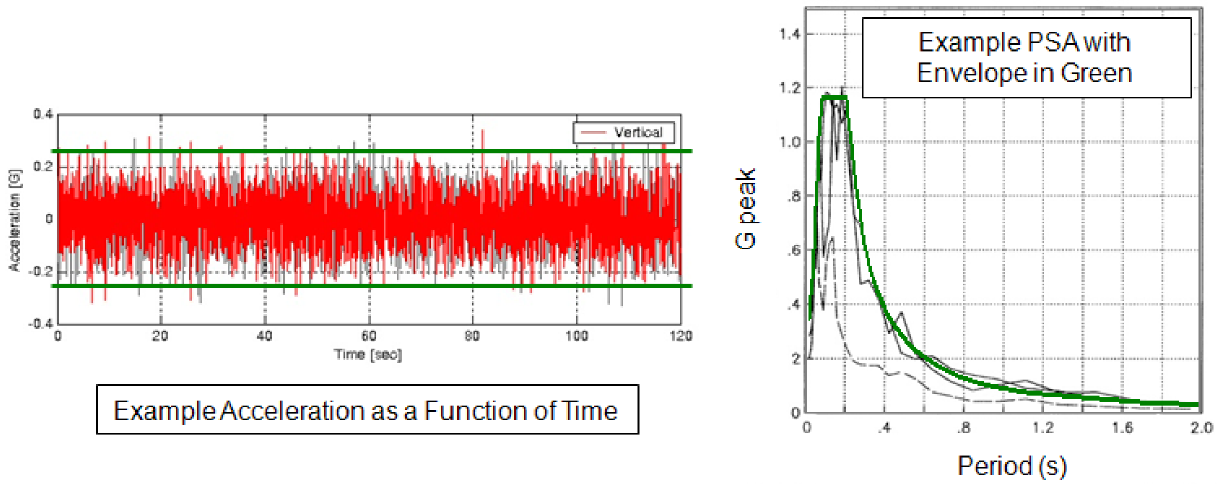


Figure 1. Example Seismic Accelerations and Corresponding PSA.

Two forms of the PSA are common: linear acceleration (G peak) vs. linear time (seconds) or logarithmic acceleration (G peak) vs. logarithmic time (seconds). Other than the plotting scales these graphs are identical. The more common linear vs. linear form will be principally used throughout this document.

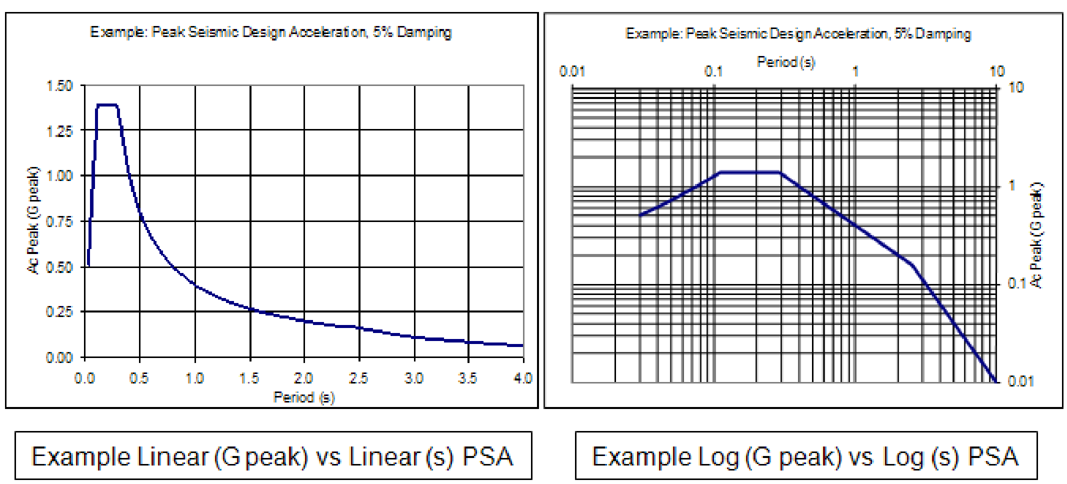


Figure 2. Example of Linear vs. Linear and Log vs. Log PSA.

If the natural frequency of a structure is known then the maximum seismic acceleration can be read directly off the PSA. For the example PSA in Figure 3, a single degree of freedom resonator with a fundamental period of 0.5 seconds (natural frequency of 2.0 Hz) would experience an acceleration of 0.8 G peak. Since a zero period corresponds to an infinitely stiff structure, on a PSA the asymptotic short period value is equal to the peak ground acceleration (PGA). An infinitely stiff structure would follow the input accelerations exactly.

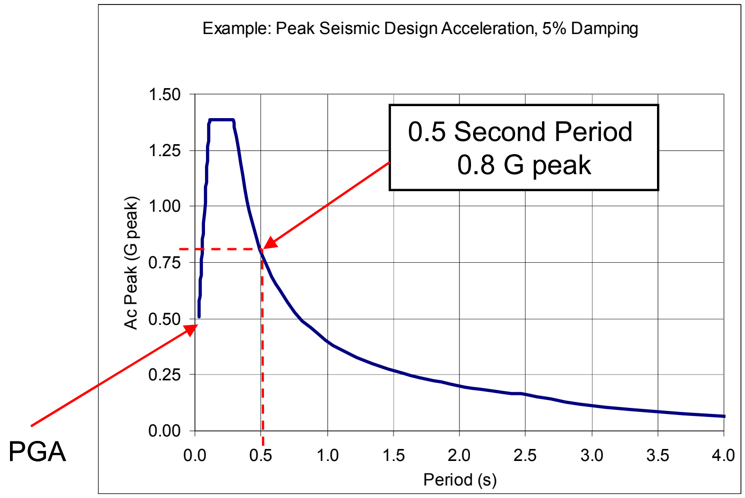


Figure 3. Determination of acceleration from a PSA.

The PSA provides the maximum (peak) response (output) acceleration (Ac_{out}) from a seismic event for a single degree of freedom resonator as a function of its fundamental period and for a specific damping level. Every point on the curve represents the response acceleration for a single resonator with that specific fundamental period, Figure 4.

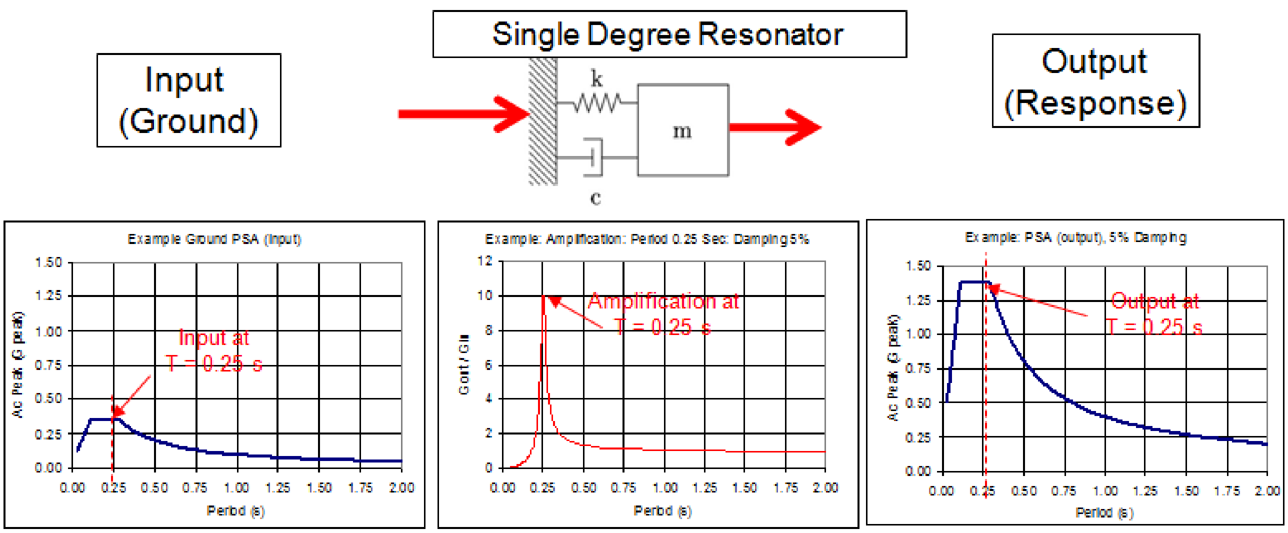


Figure 4. Illustration of PSA Determination – This is a Simplification for Explanation Purposes.

The amplification (A) is the ratio of the output acceleration (Ac_{out}) to the input acceleration (Ac_{in}). For a single degree of freedom isolator the amplification (A) can be calculated by[7]:

$$A(f) = \frac{1}{\sqrt{\left[1 - \left(\frac{f}{f_n}\right)^2\right]^2 + \left[2R\frac{f}{f_n}\right]^2}}$$

Where f = frequency, f_n = natural frequency, R = damping (e.g. R = 0.05 for 5% damping).

At the natural frequency $f = f_n$. The amplification simplifies to the amplification at resonance ($A(f_n) = Q$).

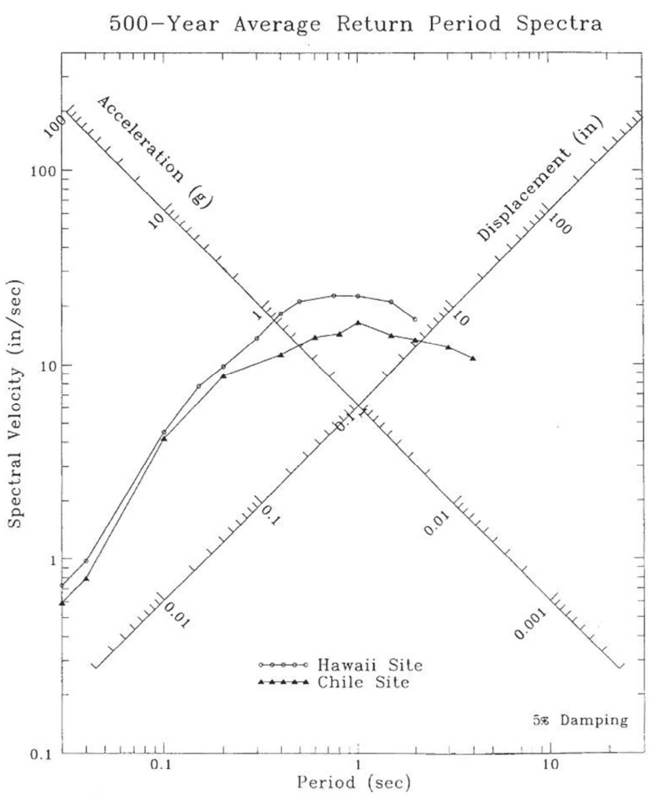
$$A(f_n) = \frac{1}{2R}$$

Consequently, there is a direct inverse relationship between the maximum amplification which occurs at resonance (Q) and the damping (R), and both these values are commonly used as measures of damping.

The relationship between the input (ground) acceleration and the output (response) is significantly affected by the level of damping. Greater levels of damping reduce the acceleration near the fundamental period. Most seismic PSA available utilize 5% critical damping. This common damping level is a reasonable assumption for most buildings. However, the natural damping of telescopes is significantly less than for buildings. Effective telescope operations require high repeatability. Maximizing repeatability minimizes hysteresis which produces damping. As verified by preliminary measurements on the SOAR telescope, telescopes typically have damping levels of order 2%. However, the LSST telescope will have an additional damping system which is needed to meet its stringent slew and settling time requirements [15]. This damping system is expected to increase the damping to approximately 5%.

3. 500 YR PSA: DAMES AND MOORE

Dames and Moore[1] produced a site specific seismic analysis for the Gemini telescope project. Since the Gemini South site is adjacent to the LSST site, the results of this study were assumed adequate for the LSST telescope project. The Gemini project encompasses two telescopes, one on Mauna Kea, Hawaii and one on Cerro Pachón, Chile. The two telescopes are essentially identical and were designed to a single seismic PSA which encompasses both sites. Since the Gemini North site was found to have greater seismic accelerations, the Gemini design PSA should be conservative relative to the actual seismic threat for the LSST Chilean site, Figures 5 and 6.



500-year: $$PSA(T,5\%) = \begin{cases} 0.40 & T \le 0.04 \text{ sec} \\ 4.566\,T^{0.7564} & ,\ 0.04 < T \le 0.10 \text{ sec} \\ 0.80 & ,\ 0.10 < T \le 0.45 \text{ sec} \\ 0.36\,T^{-1} & ,\ 0.45 < T \le 2.0 \text{ sec} \end{cases}$$

Horizontal Acceleration PSA

500-year: $$PSA(T,5\%) = \begin{cases} 0.40 & T \le 0.04 \text{ sec} \\ 4.566\,T^{0.7564} & ,\ 0.04 < T \le 0.10 \text{ sec} \\ 0.08\,T^{-1} & ,\ 0.10 < T \le 2.0 \text{ sec} \end{cases}$$

Vertical Acceleration PSA

Figure 5. Dames and Moore 500 Year PSA – Original Format.

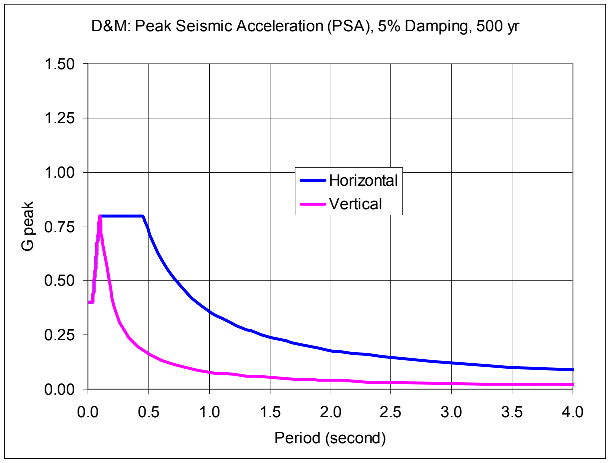


Figure 6. Dames and Moore PSA Reformatted Into the Configurations Provided Earlier For Ease of Comparison.

4. 500 YEAR PSA: URS CORPORATION

URS Corporation produced a site specific seismic hazard analysis for the Giant Magellan Telescope (GMT) [5]. The GMT site is located on the peak of Las Campanas in Chile, approximately 120 km from the LSST site, Figure 7. Although the GMT site is not adjacent to the LSST site, this site specific seismic analysis utilized more modern techniques and data from more recent events than the Dames and Moore Survey. Per [5], it was determined that the GMT site is rock. Consequently, it is similar to the LSST site in both location and geotechnical characteristics.

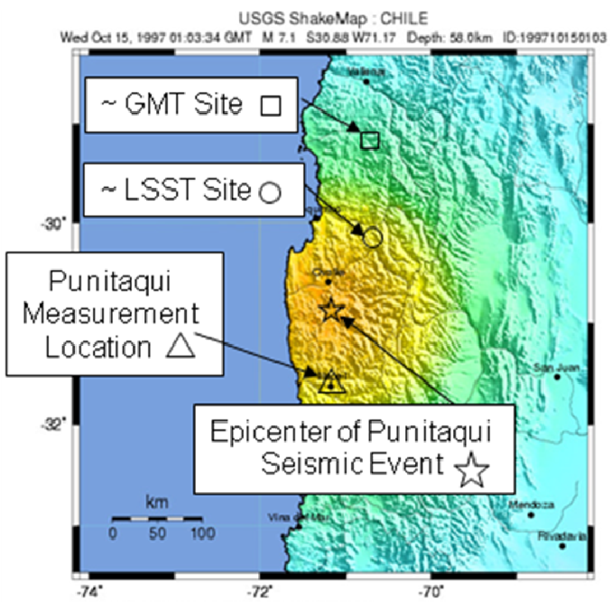


Figure 7. Locations of Telescope Sites in Relation to Punitaqui Seismic Event.

This URS survey produced horizontal PSAs for 100 yr, 200 yr, 475 yr and 2,475 yr return periods, Figure 8. For comparing the PSAs from the various sources, the “475 yr” return period will be used interchangeably with a 500 yr return period. The difference between the two values should be negligible. For the design PSAs, URS determined the vertical accelerations by scaling from the horizontal accelerations. The following scales were used to determine the vertical PSAs:

- $T < 0.3$ s → G vertical = 0.7 x G horizontal.
- $T > 0.4$ s → G vertical = 0.5 x G horizontal.

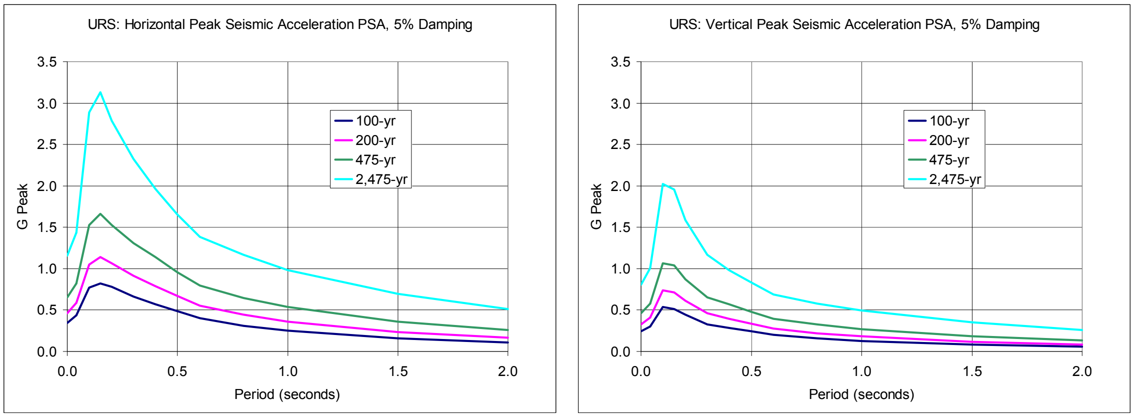


Figure 8. URS PSA.

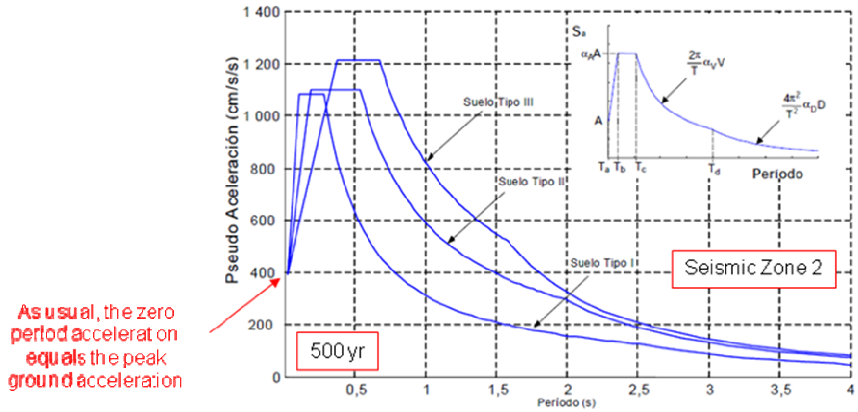
5. 500 YEAR PSA: CHILEAN STANDARD

The Chilean Standard-Isolated[2] is a design reference for the Chilean building construction industry. This provides a design PSA based on a 500 year return period for analyzing civil structures (buildings, bridges etc). Although this reference was developed for buildings with seismic isolation, the intended application does not affect the PSA which provides the acceleration as a function of natural frequency. The isolation modifies the natural frequency of a structure and the PSA is required to determine the effect of this isolation on the resulting accelerations. The other Chilean codes[3,4] are not directed toward seismically isolated buildings. The natural frequencies of these structures are not accurately determined and therefore detailed PSA are not provided.

The PSAs provided by [2] vary depending on ground type and seismic threat zone. Three different ground types are utilized as well as three different seismic threat zones:

- Ground Type:
  I. Rock
  II. Intermediate
  III. Dirt
- Seismic Zone:
  1. Low
  2. Medium
  3. High

The PSAs are determined for the three different soil types according to Figure 9. These PSAs assume 5% damping. The entire PSA is multiplied by a factor Z to account for the seismic zone. The factor Z is 0.75 for zone 1, 1.0 for zone 2, and 1.25 for zone 3. The baseline graphs correspond to zone 2.



Suelo	T_a, s	T_b, s	T_c, s	T_d, s	T_e, s	T_f, s	$\alpha_A A$, cm/s²	$\alpha_V V$, cm/s	$\alpha_D D$, cm
I	0,03	0,11	0,29	2,51	10	33	1 085	50	20
II	0,03	0,20	0,54	2,00	10	33	1 100	94	30
III	0,03	0,375	0,68	1,58	10	33	1 212	131	33

Figure 9. Chilean Standard 500 Year PSA.

The LSST telescope, and most other telescope sites in Chile, are in the higher zone 3 regions and the baseline PSD must be multiplied by 1.25. Consequently, for the rest of this document the Chilean Standard figures will all reference zone 3. Chilean Standard-Isolated[2] recommends vertical accelerations ⅔ of the horizontal accelerations. The Chilean Standard PSA design requirements were reformatted into the configurations provided earlier for ease of comparison, Figure 10.

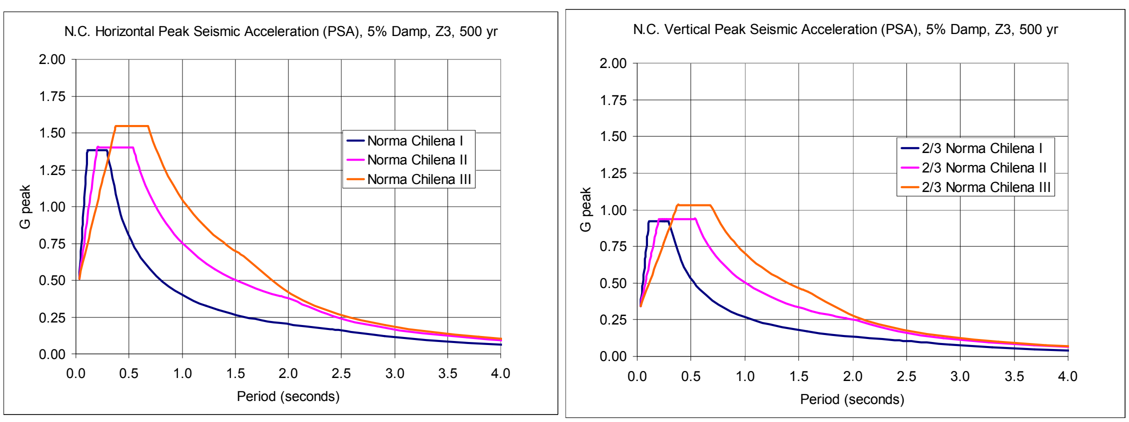
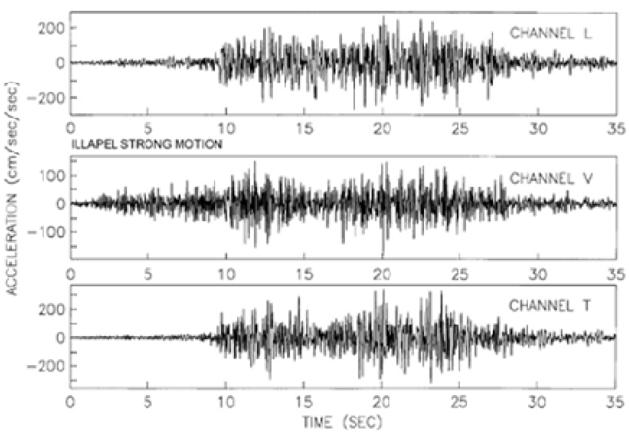


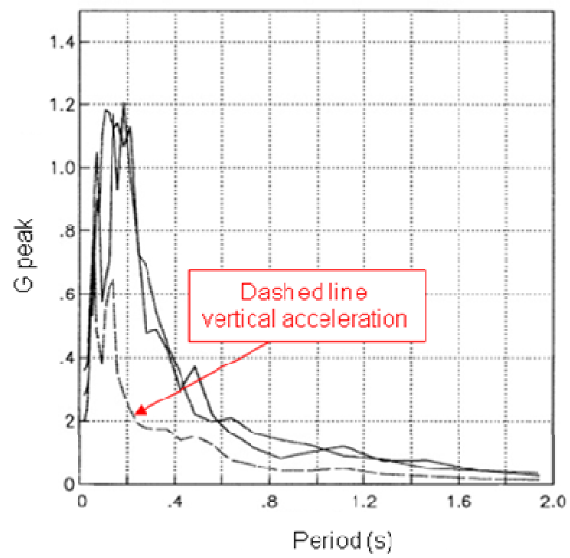
Figure 10. Norma Chilena[2] Zone 3 Acceleration for the Three Soil Types.

6. PUNITAQUI AT ILLAPEL SEISMIC EVENT

The Punitaqui Earthquake[6] of Oct 15th, 1997 (Ms = 7.1) was utilized as a comparison for a possible seismic event that may occur at the LSST site, Figure 11. The location is near the LSST site (Coquimbo Region), and the measurement location site characteristics are similar to LSST site (Ground type I, zone 3). This event was significantly less intense than a design limiting 500 year event.



Three component acceleration of the Punitaqui earthquake
Measured at the city of Illapel
L = Longitudinal, V = Vertical, T = Transverse



Three component PSA of the Puntaqui earthquake
5% Critical Damping

Punitaqui main event

Station	Location	Epicentral distance (km)	Components	Maximum acceleration (%g)
Illapel	31°38′ S 71°10′ W	70	N −20°E N70°E Z	27 35 18

Figure 11. Punitaqui Seismic Accelerations.

Ground accelerations (in units of cm/s^2) were provided in [6] versus time (s). The PSA utilizes 5% damping. The ground accelerations were provided in three directions: Longitudinal (L), Vertical (V), Transverse (T). Only the graphs shown were available. The actual numerical data as a function of time were not available to determine the peak accelerations for this event. Intuitively, the two horizontal accelerations (longitudinal and transverse) should be combined as vectors to determine the ground acceleration. However, for the Cobquecura event, discussed later, the numerical data were available and demonstrated that this vector sum would significantly overestimate the peak accelerations.

The maximum acceleration between the longitudinal and transverse values provides a more accurate estimate of the peak accelerations. This implies that there is sufficient randomness in the direction of the acceleration that the peak accelerations align with one of the two directions. This observation is consistent with the Chilean Standard-Industrial[3], which states that for the accelerations, “it is not necessary to combine these horizontal accelerations. The effects are not concurrent.” An envelope for the PSA was developed for comparison, Figure 12.

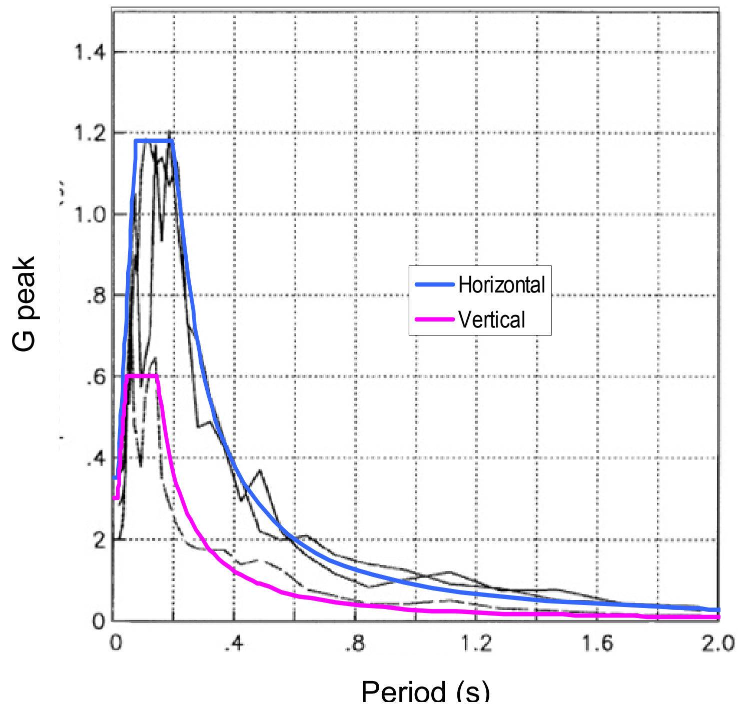
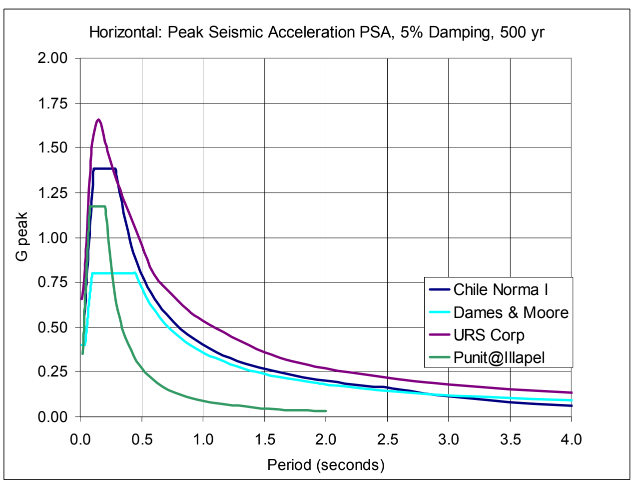


Figure 12. PSA Envelopes for Punitaqui Seismic Event.

The PSA for the Punitaqui event was plotted for comparison to the Dames and Moore PSA, the URS Corp PSA and the Chilean Standard Zone 3, Ground Type I, PSA, Figure 13. In the horizontal direction: For long periods (T > 0.5 s) all the PSAs predicted similar accelerations which were greater than the Punitaqui event. Since the Punitaqui event was of a lesser magnitude than a 500 year event this over-prediction is expected. For short periods Dames and Moore significantly underestimated the Punitaqui event. Chilean Standard-Isolation produced the best representation of the Punitaqui event.



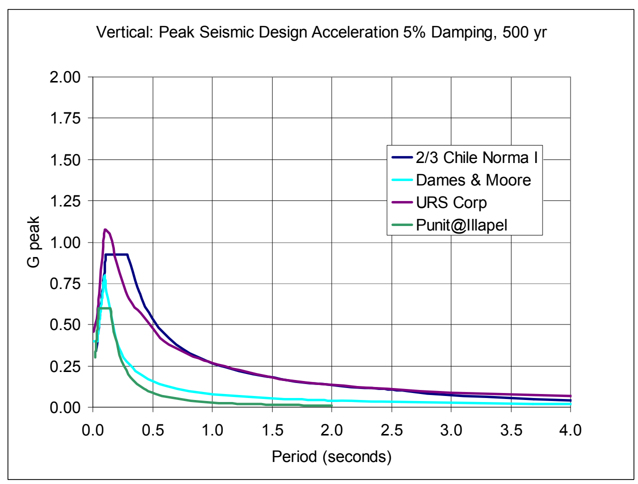


Figure 13. Comparison of various PSA.

Since the Punitaqui event was less than a 500 year event, the vertical motion design PSAs should overestimate the maximum acceleration throughout the spectrum. However, even though the Punitaqui event was less severe than a design limiting 500 year earthquake, for most of the spectrum the vertical acceleration predicted by the Dames and Moore PSA nearly matched the measured accelerations. Consequently, for an actual 500 year event the Dames and Moore PSA would significantly under-predict the vertical accelerations. For both the horizontal and vertical directions, it would appear that both the design PSAs significantly overestimated the long period accelerations.

However, data for the much more powerful Cobquecura event suggest that larger events increase the long period accelerations at a greater rate than the short period accelerations. The ⅔ Chilean Standard-Isolation produced reasonable vertical predictions for this event.

7. COBQUECURA AT CONCEPCION SEISMIC EVENT

The Cobquecura Earthquake of Feb 27th, 2010 (Ms = 8.8) was also used for comparison, Figure 14. Unlike Punitaqui, this event was neither near the LSST location nor measured in a similar ground type. The LSST site is a ground type I while this event was measured in either a ground type II or III. However with a magnitude of 8.8, this event was closer in severity to a 500 year event than the Punitaqui event. The accelerations as a function of time, at a 100 Hz sampling rate, were available. These data were collected at Colegio San Pedro de La Paz, near Concepción, located 110 km from the epicenter.

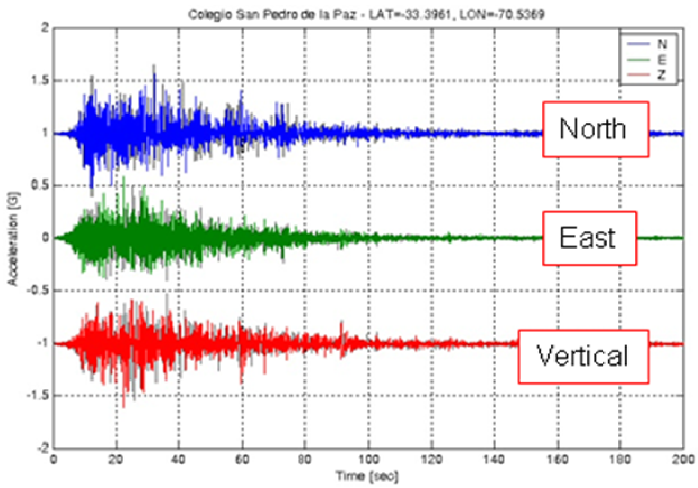


Figure 14. Seismic Accelerations for Cobquecura event.

The ground accelerations were transformed directly into a PSA by numerically applying a 5% damped harmonic oscillator to the data, Figure 15.

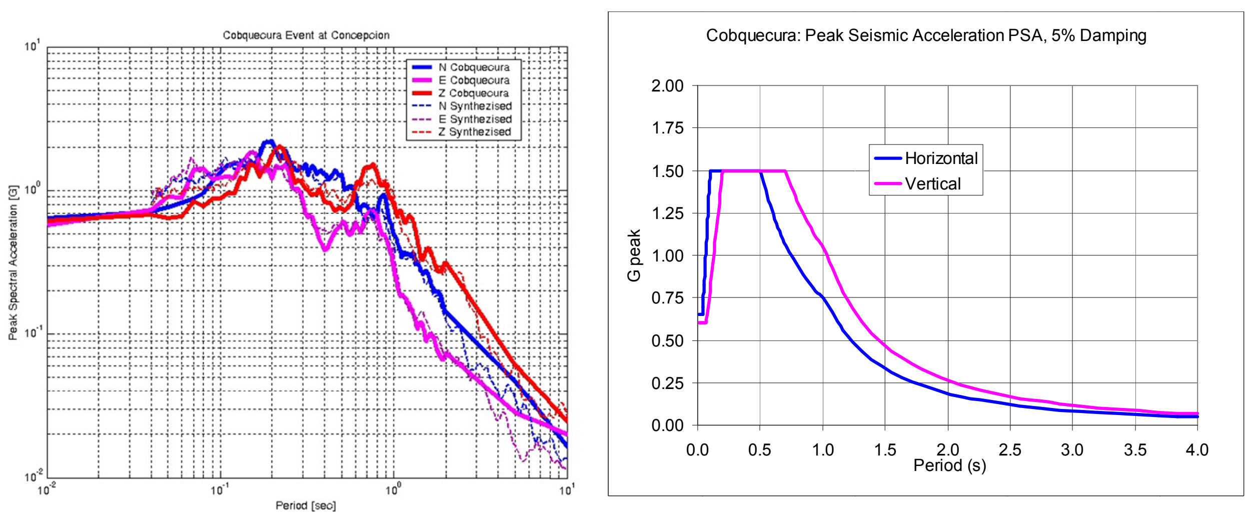


Figure 15. PSA for Cobquecura event.

The peak horizontal accelerations were close to the values predicted by the Chilean Standard ground type II or III, figure 16. The very short period accelerations (T < 0.1 s) were higher than predicted. The actual vertical accelerations were significantly greater than those determined by applying the ⅔ ratio of vertical to horizontal acceleration.

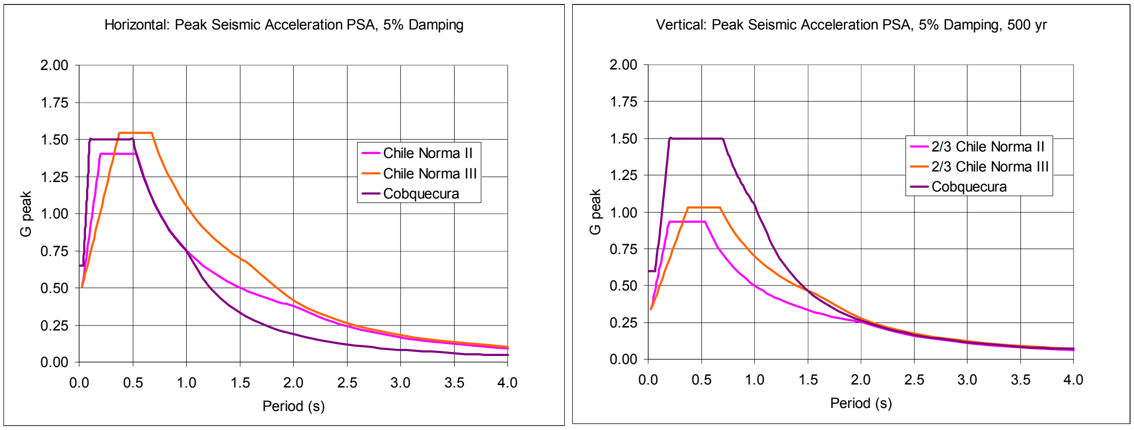


Figure 16. Comparison between Chilean Standard-Isolation and Cobquecura Seismic Event.

In [12] the vertical versus horizontal accelerations were compared for various seismic events and produced the following conclusions: "The ratio of vertical to horizontal response spectra varies as a functional period, distance to the fault, and earthquake magnitude. The ratio is larger in the near-field region and has a peak at a period of about 0.1 second." "In the near-field region, the ratio of vertical to horizontal spectra at short periods is much larger than the ratio of the peak accelerations (vertical peak to horizontal peak). In the high-frequency range of spectra, the commonly used ratio of two thirds grossly underestimates the spectral ratio, especially in the near-field region." "At long periods the vertical to horizontal spectra ratio is less than two thirds."

The V/H acceleration ratio is highest for the high frequency range most relevant to astronomical ground based telescopes (2 to 20 Hz) and highest for the closer and more extreme events. Consequently, utilizing vertical accelerations reduced by a factor of ⅔ would significantly underestimate the accelerations for the extreme (500 year) events. For these more extreme events the vertical accelerations should be similar to the horizontal acceleration.

8. ADJUSTMENTS FOR DAMPING

All the previous design PSAs assumed 5% damping. Since in general telescopes are specifically designed to minimize hysteresis, they have much lower damping. Preliminary measurements on the SOAR telescope suggest damping rates of about 2%. The amplification (Q) of the ground accelerations amplitude is on the order of 25 times. Using the relationship between amplification Q and damping R:

- $Q = 25$;
- $R = 1 / (2 * Q)$;
- $R = 0.02$ or 2%.

Adjustments in a PSA for damping variations are accomplished by multiplying the spectrum by a constant which is a function of the ratio of actual damping to the baseline 5% damping. The asymptotic short period acceleration is simply the peak ground acceleration which is unaffected by the damping. Consequently, this value is not modified. The initial positive slope on the PSA is between the unmodified PGA and the damping modified maximum acceleration.

Both Dames and Moore and Chilean Standard-Isolation provide multiplication factors for variations of damping from the baseline 5% critical damping values. The multiplication factor is applied to the entire spectrum except for values where $T < 0.04$ seconds, which is set to the peak ground acceleration. The Dames and Moore values were determined from averaging separate parameters for acceleration, velocity, and displacement acquired from Newmark and Hall[13]. Since the PSD and PSA are acceleration values, the acceleration parameter should be used. URS Corporation used values identical to Dames and Moore.

An alternative relationship can be determined from the closed form equations (CFE) used for determining the acceleration from a PSD (power spectral density) from [7]. The damping corrections produced by this method are identical to those of the Chilean Standard-Isolation[2]:

$$Ac_{outRMS} = \sqrt{\frac{\pi}{2} P_{in}\, f_n\, Q}$$

$$\frac{Ac_{x\%}}{Ac_{5\%}} = \sqrt{\frac{Q_{x\%}}{Q_{5\%}}}$$

$$\frac{Ac_{x\%}}{Ac_{5\%}} = \sqrt{\frac{R_{5\%}}{R_{x\%}}}$$

According to the above equation, the accelerations (Ac) vary with the inverse square root of the ratio of the damping (R). In Figure 17 below, the "ratio" is the ratio between the PSA for a specific damping value and the PSA for an R = 5% damping value. Consequently, all curves cross and are unity (1) for a 5% damping value (Q = 10).

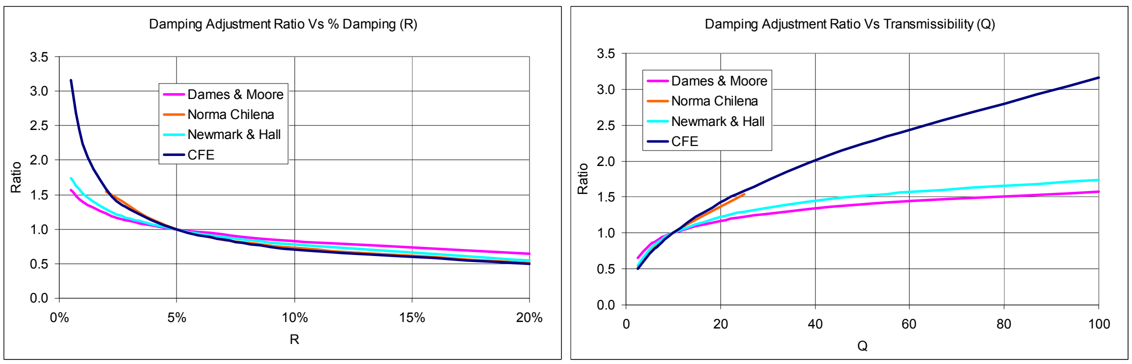


Figure 17. Comparison of damping correction factors.

For damping above 5%, the Chilean Standard-Isolation, Newmark and Hall (N&H) and CFE plots are all similar. The Dames and Moore (D&M) and URS Corporation ratios produce less correction. There is significant disagreement between the D&M and N&H ratios and the other two ratios for damping values below 5%. It is suspected that the D&M and N&H reduced values for low damping are based on limited time events not exciting harmonic isolators to the maximum amplification. Reduced damping (R) increases the amplification at resonance (Q). Greater amplification requires a larger number of cycles to meet the limiting amplification. For example, for Q = 30, it should take more than 30 cycles to meet the maximum amplification of 30. For most structural applications, the natural period is of order of 1 second (1 Hz). Consequently, for a representative seismic event of 20 seconds, for a low damping of Q = 30 the maximum amplification would never be reached as a result of the limited number of possible cycles of 20.

For a ground based telescope application, the fundamental periods are an order of magnitude smaller and are of order 0.1 seconds (10 Hz). Consequently, for a representative 20 second seismic event with low damping of Q = 30, 200 cycles are possible and the maximum amplitude could be reached. The multiplication factors for adjusting the PSA for various damping which are the most appropriate for astronomical telescopes are those derived from the closed form solution which are identical to those of the Chilean Standard-Isolation[2].

9. ADJUSTING FOR RETURN PERIOD

All the previous analysis was in regard to the baseline 500 year return period seismic event. Utilizing the 500 year event would produce excessive design accelerations for components with limited lifetimes and whose failure does not constitute a threat to personnel. Consequently, a less stringent return year event may be chosen for these components and the accelerations for this return period must be determined. The Chilean Standard utilizes a 500 year return period seismic event as its baseline. However, the Chilean Standard-Isolation[2] also investigates a 1,000 year event. To convert from the 500 year event to the 1000 year event it simply multiplies the accelerations by a factor of 1.2. This factor of 1.2 can be determined from the ¼ power of the ratio of the return years:

$$F_{AB} = \left(\frac{Year_A}{Year_B}\right)^{1/4} \Rightarrow \left(\frac{1{,}000}{500}\right)^{1/4} = 1.2$$

Dames and Moore[1] independently determined the PSA for the 200 and 500 year events and then observed that the 200 year event could be closely approximated by simply multiplying the accelerations in the 500 year event by 0.8. Again this factor of 0.8 can be determined from the ¼ power of the ratio of the return years, Figure 18:

$$F_{AB} = \left(\frac{Year_A}{Year_B}\right)^{1/4} \Rightarrow \left(\frac{200}{500}\right)^{1/4} = 0.8$$

For the Dames and Moore, the 200 year event predicted from multiplying the 500 year event by 0.8 does show a small higher prediction of long period accelerations, figure 18. This is expected since the more extreme events have disproportionate long period accelerations.

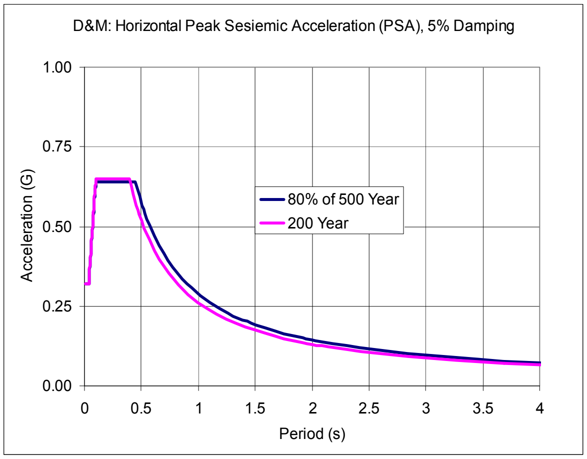


Figure 18. Dames and Moore 200 Year Event Produced by Direct Scaling.

The URS survey independently produced PSAs for 100 yr, 200 yr, 475 yr and 2,475 yr return periods, Figure 19. For these values the variation with return year follows the same pattern as before but with a power of 0.4 rather than 0.25.

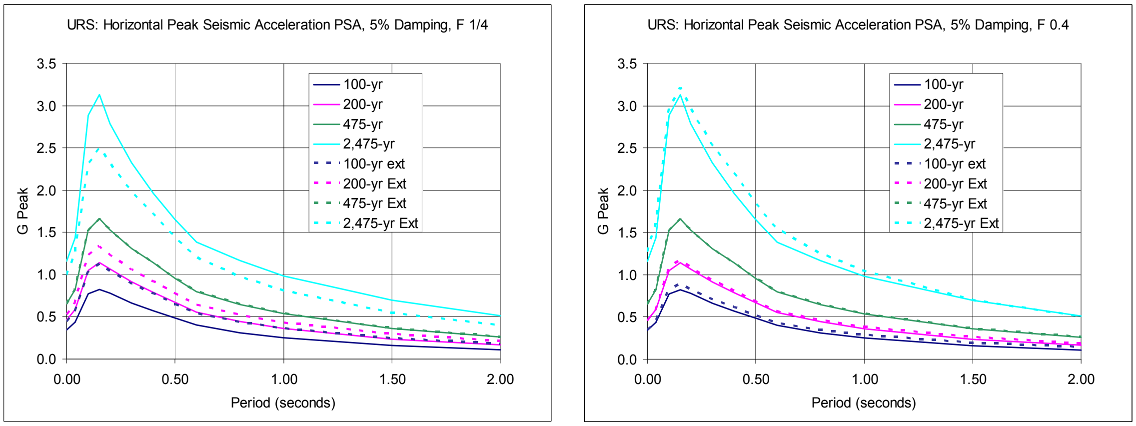


Figure 19. URS Various Return Period PSA Utilizing 0.25 Power and 0.4 Power

The PSA provided by the Chilean Standard-Isolation[2] was shown to more accurately predict the measured seismic accelerations. Since the Chilean Standard-Isolation[2] does not specifically provide a method for determining the accelerations for reduced return period events, this document utilizes the previously discussed method: $F_{AB} = (Year_A / Year_B)^{1/4}$. Scaling factors F_{AB} are applied across the PSA to approximate 100, 150, 200 and 300 year return event.

10. SUMMARY

The Dames and Moore 500 year design PSA, previously used for the LSST project, significantly underestimates the likely accelerations relative to both measured values for similar events and the Chilean Standard design requirements.

The URS Corporation 500 year design PSA predicts slightly larger accelerations than the Chilean Standard-Isolation[2], and appears to overestimate the peak accelerations as compared to measured values. The Chilean Standard PSAs provide accelerations that accurately reflect representative seismic events.

The Chilean Standard[2] recommends a ⅔ ratio for determining the vertical accelerations from the horizontal accelerations. However for the extreme long return period events (500 year and greater), the horizontal accelerations values predicted should also be used for the vertical directions. Measured accelerations from an extreme Chilean event have shown nearly equal vertical and horizontal accelerations. From [12], higher frequency accelerations which are more relevant to ground-based telescopes produce more equal vertical and horizontal accelerations.

The damping values assumed for most seismic analysis of 5% are intended for buildings and may be inappropriate for ground-based astronomical telescopes without added damping. Preliminary measurements have indicated that telescopes have around 2% natural damping. [13] also recommends a damping value of 2% to 3% for "welded steel, prestressed concrete, well reinforced concrete." Telescopes are principally constructed of welded steel and mounted on well reinforced concrete. Their joints that are bolted are designed to minimize hysteresis and behave similarly to welded joints. [3] provides similar damping recommendations. These low natural damping values can lead to large accelerations for astronomical telescopes without added damping.

The horizontal PSA for a specific return period can be used to estimate a PSA of a different return period, Figures 20 and 21, by multiplying all the PSA accelerations by a factor (F_{AB}) determined through:

$$F_{AB} = \left(\frac{Year_A}{Year_B}\right)^{1/4}$$

This method does produce some error in the long period accelerations (T > 0.5 seconds) since they vary with seismic magnitude at a different rate than the rest of the spectrum. However, since telescopes are more affected by short period accelerations (0.5 seconds > T > 0.05 seconds), this error is acceptable. The above relationship was congruent with the predictions of the various references except those of URS Corporation.

11. RECOMMENDED DESIGN PSA FOR 5% DAMPING

LSST: Horizontal Seimic Peak Spectral Acceleration (PSA) Constants									
5% damping: From Norma Chilena, Ground Type 1, Zone 3									
Return	Ta	Tb	Tc	Td	Te	α0	αA	αV	αD
Year	s	s	s	s	s	G	G	Gs	Gs^2
500	0.03	0.11	0.29	2.51	10	0.51	1.38	0.064	0.026
300	0.03	0.11	0.29	2.51	10	0.45	1.22	0.056	0.022
200	0.03	0.11	0.29	2.51	10	0.41	1.10	0.051	0.020
150	0.03	0.11	0.29	2.51	10	0.38	1.02	0.047	0.019
100	0.03	0.11	0.29	2.51	10	0.34	0.93	0.043	0.017

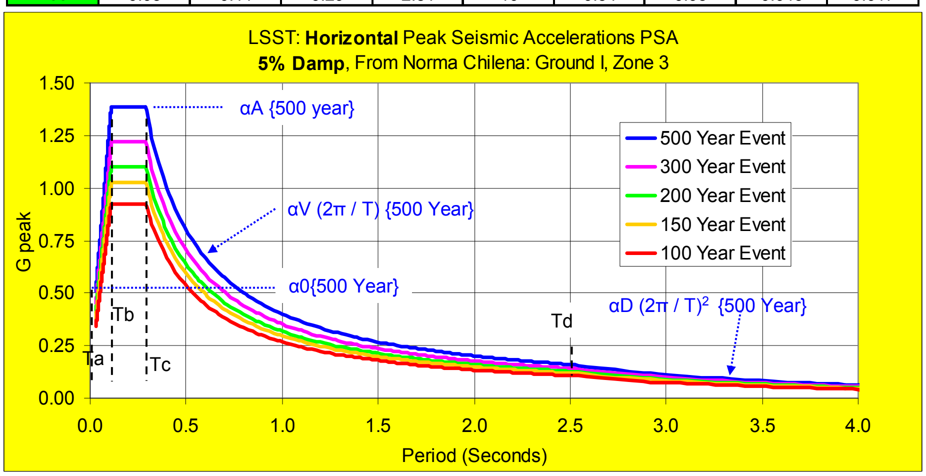


Figure 20. Recommended Horizontal PSA Based on Chilean Standards [2,3].

LSST: Vertical Seimic Peak Spectral Acceleration (PSA) Constants									
5% damping: From Norma Chilena, Ground Type 1, Zone 3									
Return	Ta	Tb	Tc	Td	Te	α0	αA	αV	αD
Year	s	s	s	s	s	G	G	Gs	Gs^2
500	0.03	0.11	0.29	2.51	10	0.51	1.38	0.064	0.026
300	0.03	0.11	0.29	2.51	10	0.30	0.81	0.037	0.015
200	0.03	0.11	0.29	2.51	10	0.27	0.73	0.034	0.014
150	0.03	0.11	0.29	2.51	10	0.25	0.68	0.031	0.013
100	0.03	0.11	0.29	2.51	10	0.23	0.62	0.028	0.011

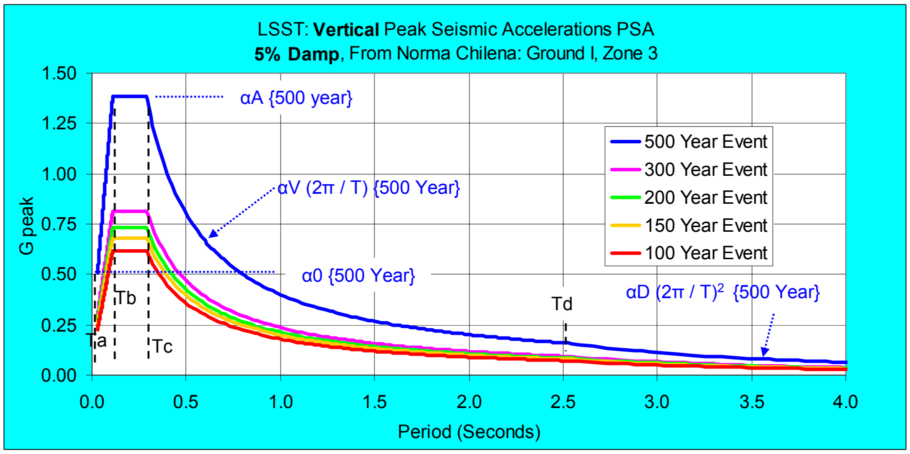


Figure 21. Recommended Vertical PSA Based on Chilean Standards [2,3] .

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