Seismic Hazard: Analysis and Design of Large Ground Based Telescopes

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ABSTRACT

This paper will discuss analysis and design of large ground based telescopes for seismic hazard. Seismic hazard is an important issue for both the observatory and the telescope structure. Properly defined seismic specifications are vital. These specifications should include performance objective that matches performance levels and probabilistic based hazard levels for operational and survival conditions. The paper will discuss specific tools that utilize results of existing seismic hazard assessment programs and can be used for initial seismic assessment during site selection. In the final stage of site selection, site specific probabilistic seismic-hazard studies that account for local geological settings and active faults should be used. The results of these site specific studies usually include response spectra and time history records in horizontal and vertical directions for operational and survival conditions. Different methods to analyze the telescope structure for seismic loadings, such as, equivalent static analysis, response spectrum analysis, linear and nonlinear time history analysis, are discussed. Devices that mitigate seismic forces and/or deformations are also presented.

Keywords: Seismic Hazard; Telescope Structure; Seismic Analysis; Seismic Design

1. INTRODUCTION

On Sunday October 15 at 7:07 AM local time, Hawaii experienced a 6.7 magnitude earthquake centered about 10 miles west of Waikoloa. This is the largest earthquake to strike Mauna Kea after the deployment of the telescopes on the summit. Lessons learned during this earthquake [1] reinforce that seismic hazard is an important issue for both the observatory and the telescope structure. Properly defined seismic specifications are vital for design of large ground based telescopes. Section 2 describes performance based seismic requirements that include performance objective matching performance levels and probabilistic based hazard levels for operational and survival conditions. Section 3 discusses specific tools that can be used for initial seismic assessment during site selection and site specific probabilistic seismic-hazard studies that are needed in final stages of site selection. Different methods to analyze telescope structure for seismic loadings are discussed in Section 4. Section 5 presents different devices that can mitigate seismic forces and/or deformations.

2. PERFORMANCE BASED SEISMIC REQUIREMENTS

In order to properly convey the amount of acceptable risk for seismic hazard, telescope/observatory project specifications should include performance based seismic requirements. This includes defining a design performance objective that matches performance levels and design earthquake levels for operational and survival conditions. Design earthquake levels in the form of probabilistic based ground motion levels are described in Section 2.1. Four performance levels, namely: fully functional, operational, life safe, and near collapse, are defined in Section 2.2. A design performance objective suitable for telescope/observatory project is presented in Section 2.3.

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2.1 Probabilistic Based Ground Motion Levels

Design ground motion levels are typically expressed in terms of a probability of exceedance or a return period. The probability of exceedance (e.g. 10% in 50 years) is the chance of an earthquake exceeding a given magnitude within a specified period of time. The return period (e.g. 475 years) is the mean recurrence interval between the occurrences of earthquakes with the same, or greater, magnitude. Return period (T years) is directly related to probability of exceedance (P% in Y years) with the following equation:

$$T = -Y / \ln(1-P)$$

The probabilistic based ground motion levels given in Table 1 can be used for the performance based design of telescopes and observatories. Suitable design parameters, for example, peak ground acceleration, horizontal and vertical response spectra with appropriate damping, and suite of appropriate time histories should be calculated for each design event.

Table 1 – Design Ground Motion Levels

Ground Motion Level	Probability of Exceedance	Return Period	Comments
Operational Level Earthquake			
Frequent Earthquake	50% in 30 years	43 years	
Occasional Earthquake	50% in 50 years	72 years	
Survival Level Earthquake			
Rare Earthquake	10% in 50 years	475 years	Typical "Design Earthquake" for buildings and other structures
Very Rare Earthquake	2% in 50 years	2475 years	"Maximum Considered Earthquake" (MCE)

2.2 Performance Levels

A performance level is a limiting damage state. Damage to structural elements, non-structural elements, building contents, and site utilities should be considered in the performance level definitions. Design performance levels are typically expressed in terms of the suitability of the structure or building for function and occupancy, the extent to which life-safety is protected, and the repairs required to restore the structure or building to service.

The following four design performance levels, based on Structural Engineers Association of California (SEAOC) Vision 2000 definitions [2], can be used in design of telescopes and observatories:

- Fully Functional – Essentially no damage has occurred to structural and non-structural components. Structure/building is suitable for intended use. Telescope/observatory can return to operation in hours.
- Operational – Only minor damage has occurred to structural components. Structure/building retains nearly all its pre-earthquake strength and stiffness. Most non-structural components are secure and most would function if utilities are available. Structure/building may be used for intended purpose, although may be in an impaired mode. Telescope/observatory can return to full operation in days or weeks.
- Life Safe – Significant damage has occurred to structural elements, with substantial reduction in stiffness, however, margin remains against collapse. Nonstructural elements are secured but may not function. Occupancy may be prevented until repairs can be made. Telescope/observatory can return to operation in weeks or months.
- Near Collapse – Substantial structural and nonstructural damage has occurred. Structural strength and stiffness are substantially degraded. There is little margin against collapse. Some falling debris hazards may have occurred. Telescope/observatory is no longer safe to operate or occupy.

2.3 Design Performance Objective

A design performance objective is an expression of the desired performance level for the structure/building for each design ground motion level. The red dots in Figure 1 represent the recommended design performance objective for typical structure/building. Depending on the desired level of protection, telescope/observatory designer should consider specifying a design performance objective, shown as the blue squares in Figure 1, which results in less damage at all the design ground motion levels.

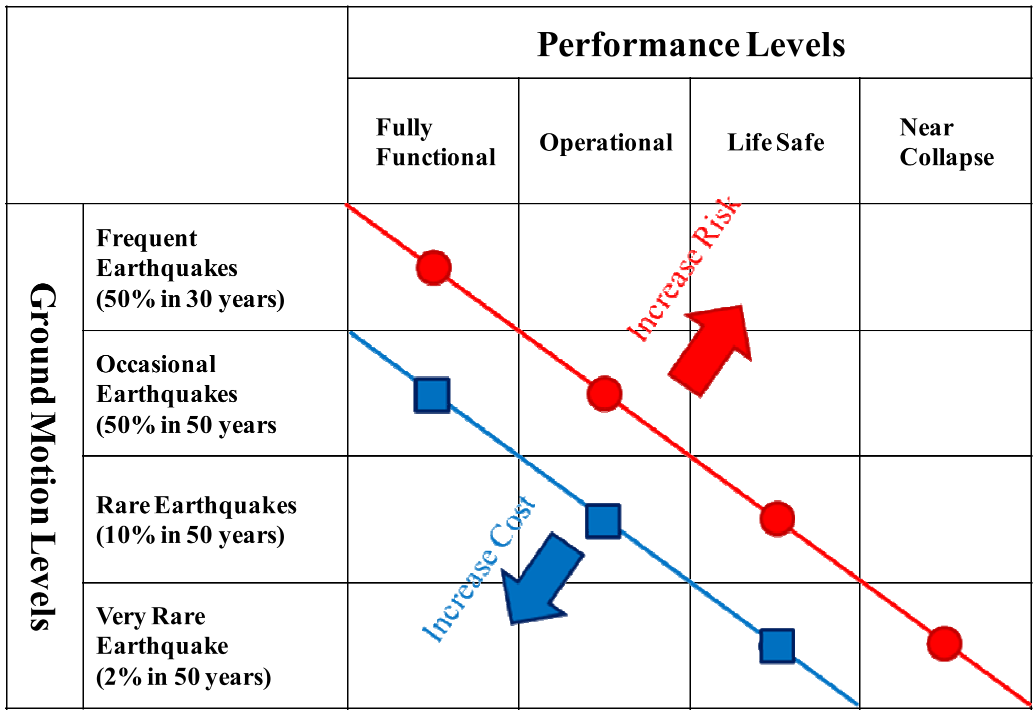


Figure 1 – Design Performance Objectives

3. DEFINING PROBABILISTIC BASED GROUND MOTION LEVELS

During the different stages of the site selection process, different levels of seismic hazard assessment are required. In the early stages of site selection, an initial seismic assessment is needed to compare the severity of seismicity at the different sites. Specific tools that utilize results of existing seismic hazard assessment programs can be used for this purpose. In the final stages of site selection, site specific probabilistic seismic hazard studies, which account for all sources of seismic activities and faults, their predicted activities, and the range of attenuations of stress waves, should be performed. The results of these site specific studies usually include response spectra and time history records in horizontal and vertical directions for operational and survival conditions.

3.1 Initial Assessment for Seismic Hazards

Figure 2 shows the Global Seismic Hazard Map by the Global Seismic Hazard Assessment Program (GSHAP) launched by the International Lithosphere Program in 1992. The primary goal of GSHAP was to create a global seismic hazard map in a harmonized and regionally coordinated fashion, based on advanced methods in probabilistic seismic hazard assessments (PSHA). Regional centers were established to coordinate and to realize of the four basic elements of modern PSHA:

1. Earthquake catalog

2. Earthquake source characterization
3. Strong seismic ground motion
4. Computation of seismic hazard

The resulting GSHAP data is one of the most comprehensive set of PSHA data around the globe. Peak ground accelerations (PGA) for 10% in 50 years are tabulated against latitude and longitude in 0.1 deg intervals. The entire data set is available on the internet on the link listed in Ref. [3]. A simple tool can be written to look up the peak ground acceleration for the four closest grid points for any given latitude and longitude.

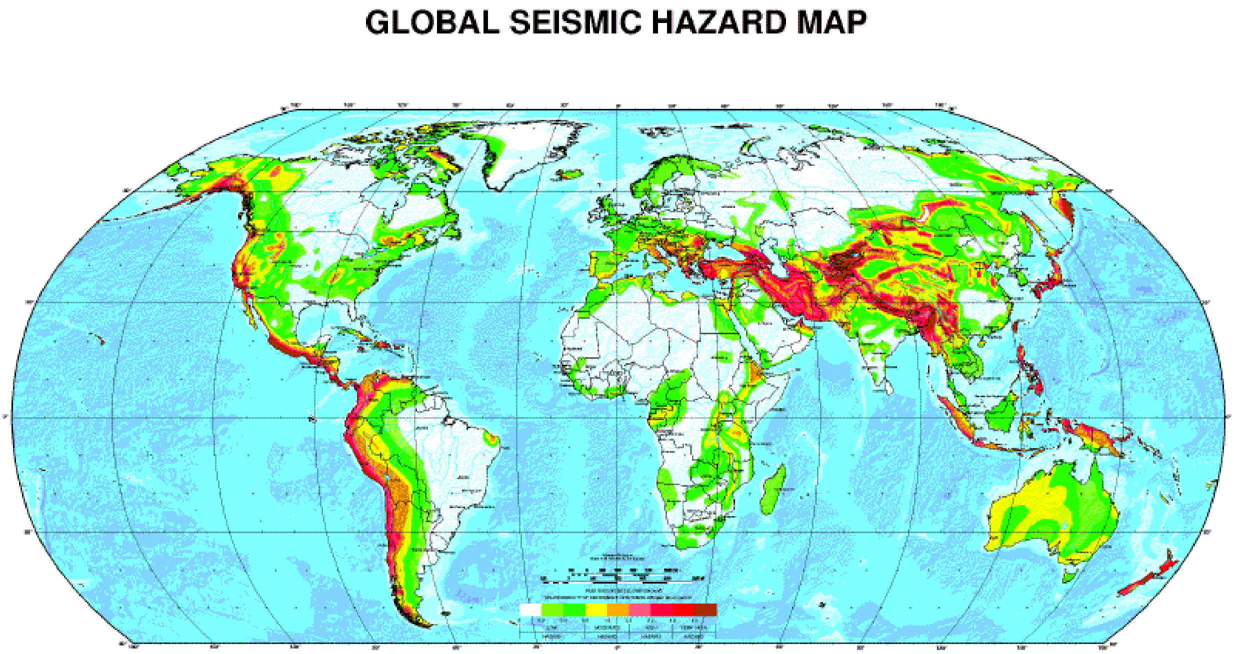


Figure 2 – Global Seismic Hazard Map from Global Seismic Hazard Assessment Program (GSHAP) [3]

GSHAP data can be used for a quick preliminary comparison of the seismic hazard severity among different candidate sites. Table 2 shows the peak ground acceleration for 10% for 50 years at bedrock of the candidate sites for Thirty Meter Telescope (TMT) and Giant Magellan Telescope according to GSHAP data.

Table 2 – Peak Ground Acceleration (PGA) for 10% in 50 years at Bedrock Based on GSHAP Data

Site	Latitude (deg N)	Longitude (deg E)	PGA 10%/50 yr (g)	Comment
Cerro Tolar	-21.9639	-70.0995	0.335	TMT candidate site
Cerro Armazones	-24.5893	-70.1917	0.457	TMT candidate site*
Cerro Tolonchar	-23.9363	-67.9769	0.237	TMT candidate site
San Pedro Mártir	31.0456	-115.4691	0.253	TMT candidate site
Mauna Kea	19.8326	-155.4818	0.485	TMT candidate site*
Las Campanas	-29.0100	-70.6930	0.338	GMT site

*Final two TMT candidate sites

There are other seismic data available for specific regions in the world. For example, the U.S. Geological Survey (USGS) website contains seismic hazard maps for forty-eight contiguous states, Alaska, Hawaii, and Puerto Rico. The USGS Earthquake Ground Motion Parameter Java Application [4] gives probabilistic hazard curves, uniform hazard response spectra for 10% in 50 years and 2% in 50 years earthquake, and seismic design values for buildings for several building codes. The parameters are searchable by zip code or latitude and longitude.

For sites in Chile, the Chilean building codes NCh433.Of96 "Seismic Design of Buildings" and NCh2745.Of2003 "Analysis and Design of Buildings with Seismic Isolations" should be consulted.

3.2 Site Specific Seismic Hazard Assessment

Once the site selection process narrows down to one or two sites, site specific seismic hazard assessment should be performed for the final candidate sites. Typically, the following tasks are included in such assessment:

- Evaluate regional seismicity
    - Review regional tectonic setting
    - Compile master catalog of historical earthquakes
- Characterize regional seismic sources in terms of
    - Spatial distribution
    - Earthquake recurrence rates (including uncertainty)
    - Maximum magnitudes (including uncertainty)
- Establish attenuation relations (including uncertainty) between seismic sources and site given source distances, source depths, and geological conditions
- Perform probabilistic seismic hazard analysis (PSHA) using the seismic source characteristics and attenuation equations
- Compute horizontal and vertical response spectra at the bedrock of the site for selected ground motion levels and damping ratios
- Generate sets of time histories (each set with two horizontal and one vertical components) to match response spectra with appropriate recorded time histories as seeds

The local soil conditions over the bedrock and the type of foundation used affect the response of a building/structure. Additional tasks may be needed in assessing the effect of local soil conditions at the site. These tasks include:

- Review geotechnical information (borings) at site
- Modify horizontal and vertical response spectra and/or time history sets based on soil properties using:
    - Code specified site coefficients
    - Wave propagation software, e.g., SHAKE

The response spectra and time history sets for different design earthquake levels will be used in calculating the telescope/observatory performance levels.

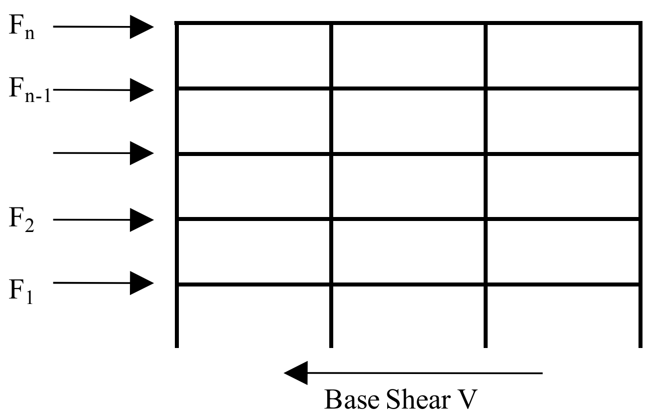
4. CALCULATING PERFORMANCE LEVELS

In the following sections, three different ways of analyzing the performance of the telescope structure and observatory building will be discussed. These methods include (1) Equivalent Static Analysis, (2) Modal Response Spectrum Analysis, and (3) Linear and Non-linear Time History Analysis.

4.1 Equivalent Static Analysis

Equivalent static analysis is one of the code-prescribed procedures for seismic analysis for buildings. Empirical equations are used to estimate the base shear. The lateral forces are then distributed vertically along structure based on mass and distance to ground (see Figure 3).

Since telescope structures typically have significantly different configurations when compared to regular building structures, equivalent static analysis is typically not suitable for analysis and design of large telescopes. Figure 4 shows the finite element model of the Giant Magellan Telescope.



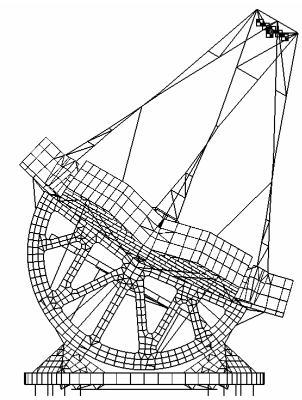


Figure 3 – Distributed Lateral Forces in Typical Building Frame **Figure 4 – Giant Magellan Telescope**

4.2 Modal Response Spectrum Analysis

A response spectrum is a plot of the peak response (displacement, velocity or acceleration) of a series of oscillators (single degree-of-freedom mass/spring systems) of varying natural frequency, which are forced into motion by the same time history ground motion. The resulting plot can then be used to pick off the response of a structure subjected to the seismic ground motion if the natural frequency of the structure is known.

Depending on whether the design response spectra are given at the bedrock level or at the top of the soil cover, the finite element model of the telescope structure may need to include the foundation and the soil stiffness underneath.

Response spectra can also be used in assessing the response of linear systems with multiple modes of oscillation (multi-degree of freedom systems), although they are only accurate for low levels of damping. A modal analysis is first performed to extract the natural frequencies and mode shapes of the structure. For each mode, determine the response from the response spectrum. The response from each mode is then combined to estimate a total response using the following combination methods:

- Square Root of Sum of Squares (SRSS) method if the modal frequencies are not close
- Complete Quadratic Combination (CQC) method
- General Mode Combination Method per ASCE 4-98 (this method is similar to the CQC method)

The result of a modal response spectrum analysis is typically different from that which would be calculated directly by a transient analysis from an input, since phase information is lost in the process of generating the response spectrum. Sufficient modes should be included in the modal response spectrum analysis such that the mass participation factors are over 90% or 95%.

Typically a design response spectrum is with 5% damping. This assumes a certain level of damage. For telescope structure, modal damping values are far less especially when elastic behavior is expected. If possible, one should use damping values measured on the telescope structure.

Response spectra are only suitable for linear systems. Non-linear time history (transient) analysis is needed if any non-linear devices are used in the structure. These devices include base isolators, viscous dampers, seismic restraints, or seismic releases.

Nevertheless, modal response spectrum analysis is a simple and efficient way to estimate the maximum seismic response of a telescope structure with linear behavior.

4.3 Linear and Non-linear Time History Analysis

When the behavior of the telescope structure during the design seismic event is no longer linear elastic, non-linear transient analysis should be used. This is the case when yielding of the telescope structure has occurred or the structure includes non-linear devices. In transient analysis, a set of three time histories (two horizontal and one vertical) should be applied to base of structure or bedrock.

Each time history record sets used in transient analysis should have the following characteristics (see Ref. [5]):

- Two components matching the horizontal design response spectrum and one component matching the vertical design response spectrum
- Generated from seed earthquake time history records with similar magnitude, distance to seismic source, and geological conditions
- Rise time, strong motion duration, and decay time for the given magnitude
- Maximum acceleration matching the design peak ground acceleration
- Statistical independence among the three components

Typically, building codes require a minimum of three sets of time histories to be used in transient analysis. If 3 sets of time histories are used, peak response among the three sets must be used in performance evaluation. If 7 sets are used, average response of the seven sets can be used in evaluation.

The following areas and components should be examined in terms of loads and displacements:

- High stress areas in structure
- Components that are single point failure
- Components that can uplift, for example, wheels or hydrostatic bearing pads
- Mechanical subsystems, for example, bearings, drives, brakes, stow pins
- Fragile components, for example, mirrors and their mounts

5. MITIGATING SEISMIC FORCES AND DEFORMATIONS

For telescopes located in high seismicity areas, there may be a high probability that certain areas or components may experience unacceptable loads or deformations during the design seismic events. Sometimes, modifications to these areas or components may be enough to mitigate such risk. Modifications to the entire system, such as, energy dissipation by supplemental damping or base isolation, may be needed. Devices such as (1) base isolators, (2) viscous dampers, (3) seismic restraints, and (4) seismic releases can be used to reduce the seismic forces or deformations. The behavior of these devices will be discussed in the following sections.

5.1 Base Isolators

The ideas behind the concept of base isolation are very simple. The building or structure is isolated from the earthquake ground motion in the horizontal directions by adding a layer of material with low horizontal stiffness between the structure and the foundation. The resulting fundamental frequency is much lower than the corresponding fixed-base frequency (see Figure 5). The first dynamic mode of the isolated structure involves deformation in the isolation system only, the structure above remains almost completely rigid. The higher modes that produce deformation in the structure are orthogonal to the first mode and thus to the ground motion. Therefore, these higher modes do not participate in the motion. Energy in the ground motion at these higher frequencies cannot be transmitted across the isolators to the structure above.

One type of base isolation system involves the use of elastomeric bearings; the elastomer is made of either natural rubber or neoprene. In this case, the base isolators do not absorb the earthquake energy, but rather they lower the fundamental frequency of the entire system and thus reduce the seismic response. This type of isolation works when the system is linear and even when undamped; however, some damping is beneficial to suppress any possible resonance at the isolation frequency.

Another type of base isolation system involves the use of lead-bronze plates sliding on stainless steel with elastomeric bearings. In addition to lowering the fundamental frequency, this system limits the transfer of shear across the isolation interface. Earthquake energy is dissipated in the base isolators.

The two elastomeric bearings mentioned above commonly used in buildings and bridges. However, they are not suitable for base isolation of telescope structure, because of their low initial stiffness values which significantly affects the operational performance of the telescope. The friction-pendulum system (FPS) is a sliding system that uses a special interfacial material between an articulated friction slider over a spherical steel surface. During an earthquake, the isolated structure moves with small pendulum motions. The characteristics of this pendulum motion lengthen the fundamental period of the isolated structure and reduce the lateral loads transmitted from the ground motion across the isolators to the structure above. Energy is dissipated by friction in the base isolators.

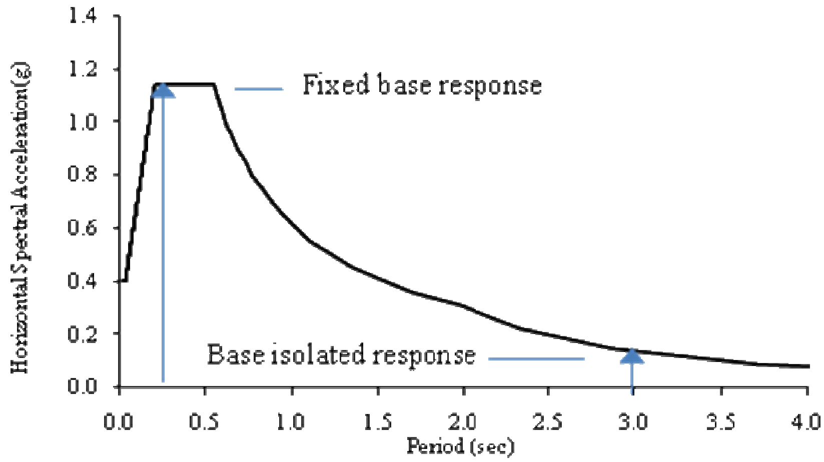


Figure 5 – Response of Fixed Base and Base Isolated Structure

A comparison between FPS bearing and elastomeric sliding bearing is shown in Table 3.

Table 3 – Comparison between FPS Bearing and Elastomeric Sliding Bearing

FPS Bearing	Elastomeric Sliding Bearing
An articulated friction slider over a spherical surface	Multiple layers of steel and rubber bonded together by adhesives
Dissipates energy through friction	Dissipates energy through shear deformation
Essentially rigid under normal operations and does not affect operational frequency	Low initial stiffness and reduces operational frequency
Rated for -100°F to +200°F	Affected by temperature; below glass transition temperature of rubber, bearings can be permanently damaged
Returns to original position	May not return to original position
May not need to be replaced after a significant earthquake	Need to be replaced after a significant earthquake
Lateral and vertical stiffness do not change due to sliding	Lateral and vertical stiffness change due to deformation

In order to base isolate the entire telescope structure, FPS bearings need to be located immediately above foundation mat and below concrete pier/tower. One needs to define the following requirements:

- Minimum horizontal and vertical stiffness before sliding

- Minimum break-free load
- Maximum displacement

In designing the base isolation system with FPS bearings, the following design parameters can be used to tune the seismic performance:

- Period of base isolation system
- Dynamic coefficient of friction
- Weight on FPS bearings

Earthquake Protection Systems, Inc. (EPS) [6] manufactures single pendulum FBS bearings and triple pendulum FPS bearings.

5.2 Viscous Dampers

Another way to reduce the seismic forces and displacements in a telescope structure is the use of viscous dampers. Viscous dampers are applicable to both fixed base and base isolated structures. Fluid Viscous Dampers operate on the principle of fluid flowing through orifices. A stainless steel piston travels through chambers filled with silicone oil, which flows through an orifice in/around the piston head. During a seismic event, the seismic energy is transformed into heat, which dissipates into the atmosphere.

Typically the output of the viscous damper is linear, where force is proportional to velocity. This allows damping levels as high as 50% of critical, offering dramatic reduction of seismic forces in the structure.

One of the most important considerations in the use of viscous dampers on telescope structure is that the viscous dampers cannot affect the telescope performance during operation

5.3 Seismic Restraints

Seismic restraints are devices which serve to limit the movement of equipment and to keep the equipment captive during a seismic event. This is applicable to mechanical, electrical, and electronic equipment or instruments mounted on the telescope structure and inside the observatory building. Seismic restraints are also needed on major components of the telescope, for example, the elevation structure and the azimuth structure, to prevent them from overturning or walk off the support.

Earthquake damage to inadequately restrained mechanical and electrical systems mounted on the telescope structure and inside the observatory building can be extensive. Mechanical and electrical equipment knocked off its supporting structure due to earthquake-related building movement can threaten both life and property. Seismic restraint systems limit the movement of equipment and keep the equipment captive during a seismic event. Proper utilization of these systems can reduce the threat to life and minimize long-term costs due to equipment damage and associated loss of service.

Many telescope structures are supported by hydrostatic bearing pads or wheel/track systems. During a seismic event, the overturning moment on the telescope structure can cause the hydrostatic pads or wheels to lift off from the journal or track. In both cases, seismic restraints are needed to prevent such uplift from happening. In some telescope systems, the elevation structure is free to move along the elevation axis. In these cases, restraints are needed along the elevation axis to prevent the elevation structure from walking off the support.

Other components on the telescope structure may also need to be restrained during an earthquake. For example, M1 mirrors supported by hydraulic actuators may require the use of seismic restraints to prevent the mirror from lifting off and from hitting the mirror cell.

In designing the seismic restraints, the restraints and their attachment interfaces need to have sufficient strength to withstand the imposed seismic forces. Also, the restraints must not interfere with the normal operations of the telescope.

5.4 Seismic Releases

Seismic releases limit the amount of forces that can be transmitted to fragile components of the telescope. For example, displacement controlled mirror supports (hard points) typically have very little forces in them during normal operations because the mirror weight is supported by hydraulic actuators; however, during an earthquake, excessive forces may develop at these hard points because of their high stiffness. Therefore, seismic releases may be needed to ensure no excessive forces are being transmitted to the mirror. Seismic releases are typically force based; that is, the release is triggered with a certain amount of force is exceeded in the device.

In designing each seismic release, one must consider the amount of displacement that may occur to the component during the seismic event after it has been released. Similar to the seismic restraints, the seismic releases must not interfere with the normal operations of the telescope.

6. CONCLUSIONS

Analysis and design of large ground based telescopes for seismic hazard were discussed in this paper. Seismic hazard is an important issue for both the observatory and the telescope structure. Properly defined seismic specifications are vital. Performance based seismic requirements that include performance objective matching performance levels and probabilistic based hazard levels for operational and survival conditions are needed. Specific tools that can be used for initial seismic assessment during site selection are discussed. Site specific probabilistic seismic-hazard studies are described. Modal response spectrum analysis and non-linear time history analysis are discussed as ways to analyze telescope structure for seismic loadings. Base isolators, viscous dampers, seismic restraints, and seismic releases, which mitigate seismic forces and/or deformations, are also presented.

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