GMT Telescope Seismic Isolation System Design and Validation

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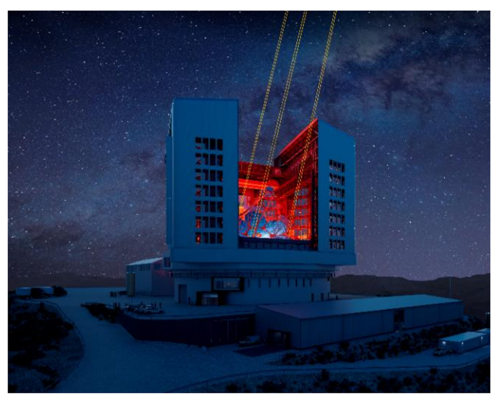
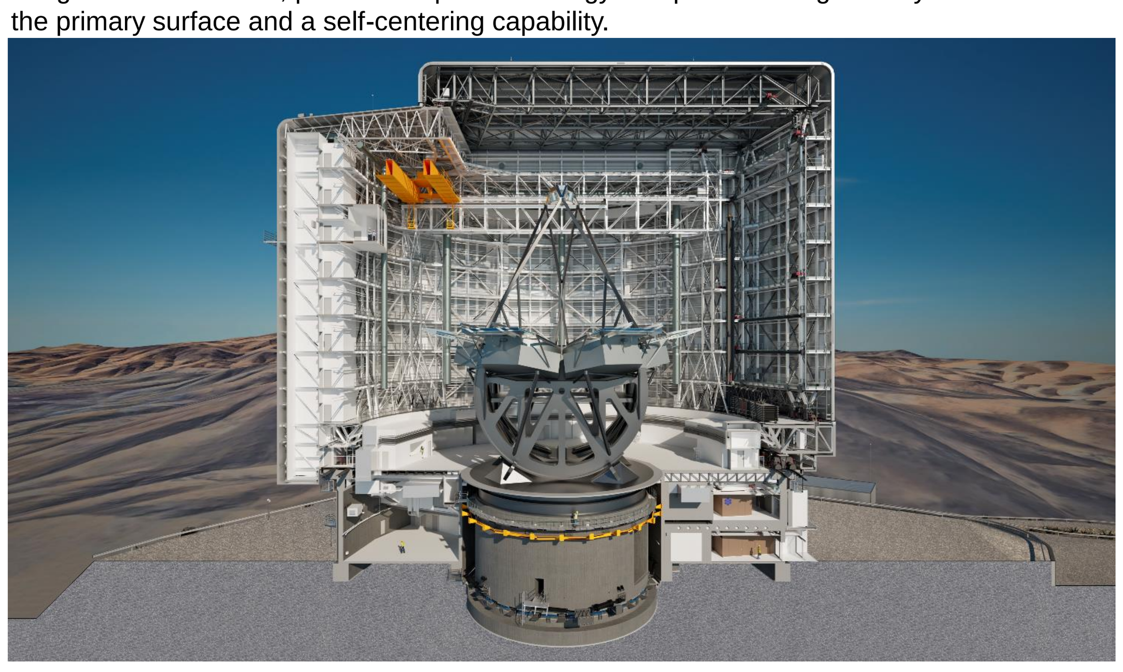
INTRODUCTION

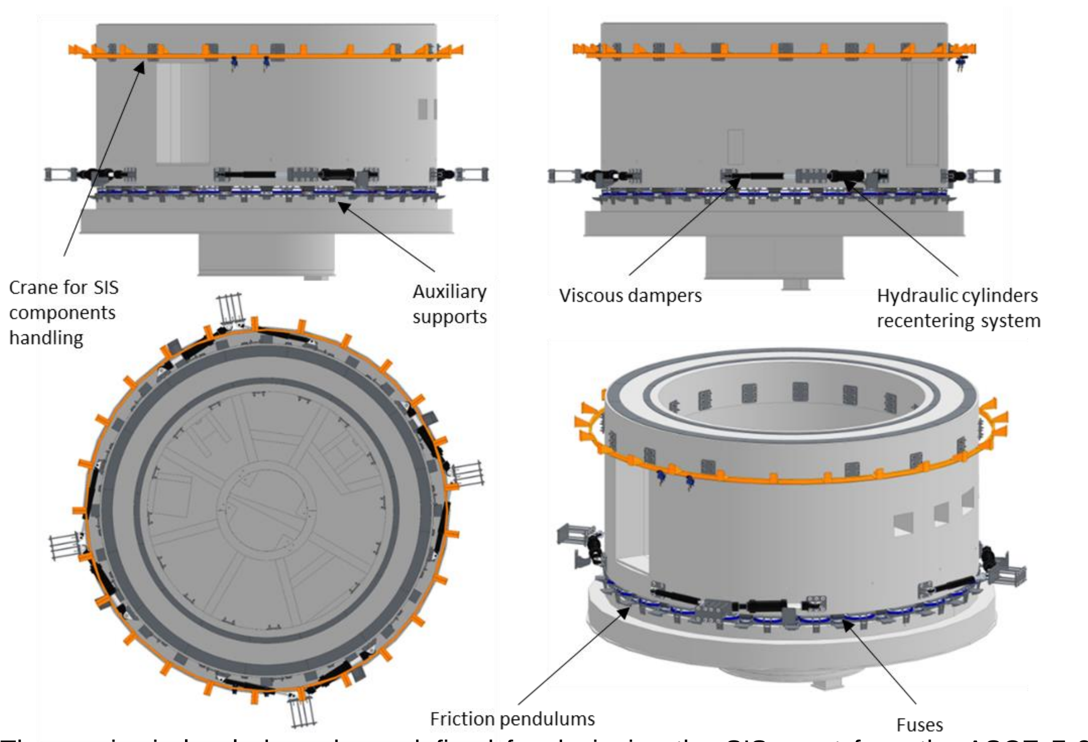
The Giant Magellan Telescope (GMT) will be the second largest ground-based telescope with a height of ~65 m and an outer diameter of ~66 m and one of the largest movable structures ever built. The GMT has seven mirrors of 8.4 m diameter each with a resolving power of a 24.5 m primary mirror. The GMT will be installed at Las Campanas summit in the Atacama Desert (Chile), one of the highest seismicity areas worldwide. To protect the telescope high value optical systems and instrumentation a seismic isolation system (SIS) has been devised An enclosure protects the telescope from adverse environmental conditions allowing the observation during nighttime.



The telescope, with a weight of 2.300 tn, is supported on a massive concrete cylindrical pier of 22 m outer diameter, 13 m heigh, 1.9 m wall thickness and 5.500 tn weight providing enough inertial mass to minimize vibrations at the telescope tracking and optical mechanisms The SIS is installed at the bottom of the pier isolating the telescope from the ground motions during an earthquake. The SIS shifts the telescope and pier frequency to a long period of 4 seconds using single friction pendulums to decouple de structure from the ground. Friction pendulums transmit the vertical loads from the telescope to the bedrock while providing the necessary lateral flexibility through the primary sliding surface decoupling accelerations from the ground. In addition, pendulums provide energy dissipation through the dynamic friction of the primary surface and a self-centering capability.



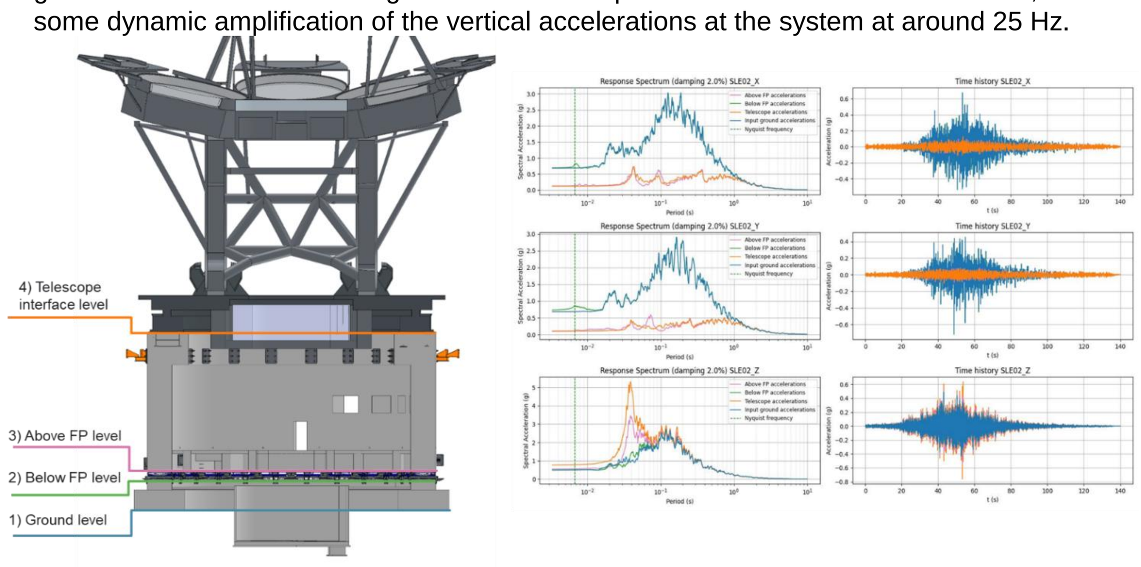
During the observation, the telescope must provide a high horizontal and vertical stiffness to reduce mainly the Abbe error effects at the telescope mirrors. The stiffness is provided by the combination of friction pendulums and fuses distributed around the perimeter of the pier.
The main subsystems of the pier SIS are 24 single friction pendulums (FPs) to decouple the seismic ground motions from the telescope, 4 viscous dampers to increase the seismic energy dissipation capacity and 24 fuses to provide the horizontal stiffness and the breakaway force during the observation. In addition, a pier re-centering system (PRS), based on 4 servo-hydraulic cylinders is added together with a health monitoring system to measure accelerations and displacements of the system during an earthquake.



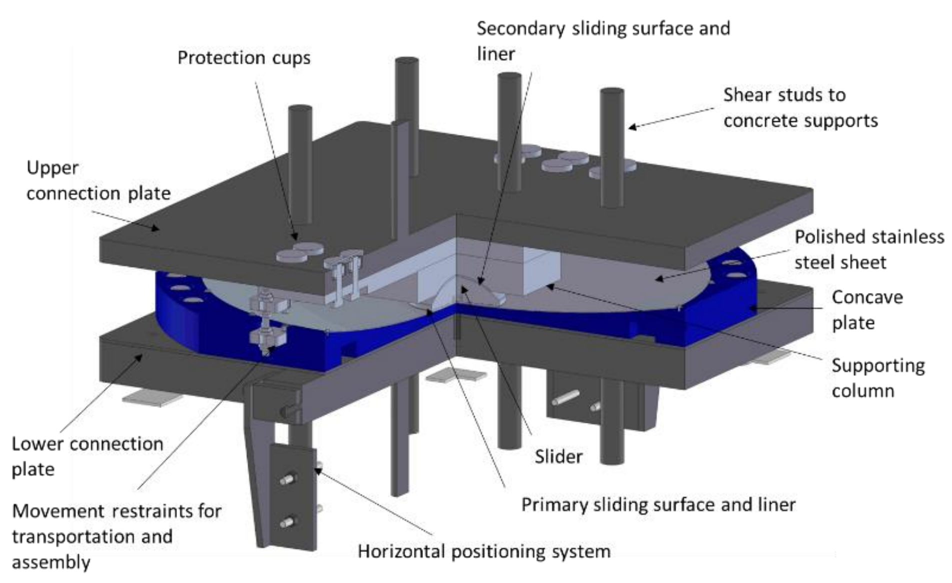
Three seismic levels have been defined for designing the SIS apart from the ASCE 7-22 MCE_R. A Rigidity Level Earthquake (RLE) with a return period of 2 years below which the telescope SIS does not have to activate. This prevents that the telescope accurate nominal position must be re-calibrated because of minor seismic movements frequently. An Operational Level Earthquake (OLE) with a 500-return period activating the SIS where no damage should appear in any part of the structure. And a Survival Level earthquake (SLE) of a 2475-year return period where no onerous to replace equipment must be damaged.

FRICTION PENDULUMS DESIGN AND EARLY PROTOTYPES VALIDATION

The main function of the friction pendulums bearings is to isolate the telescope from the ground accelerations. The pendulums are designed to keep the accelerations transmitted to the telescope to an acceptable level that does not compromise the telescope integrity. The pendulums are evenly distributed around the pier annular section.
Single pendulums bearings are selected to minimize the number of sliding contact surfaces, while maximizing the vertical stiffness.
Each single friction pendulum is composed of a polished stainless steel spherical backing plate surface of 4 m radius, providing an isolation frequency of 0.25 Hz, with a maximum horizontal displacement capacity of +/- 700 mm, a vertical load capacity of 10 MN and a vertical stiffness of 10 MN/mm.
As shown in the next figure only the horizontal in-plane movements are decoupled from the ground motion. Due to the high stiffness of the pendulums in the vertical direction, there is some dynamic amplification of the vertical accelerations at the system at around 25 Hz.



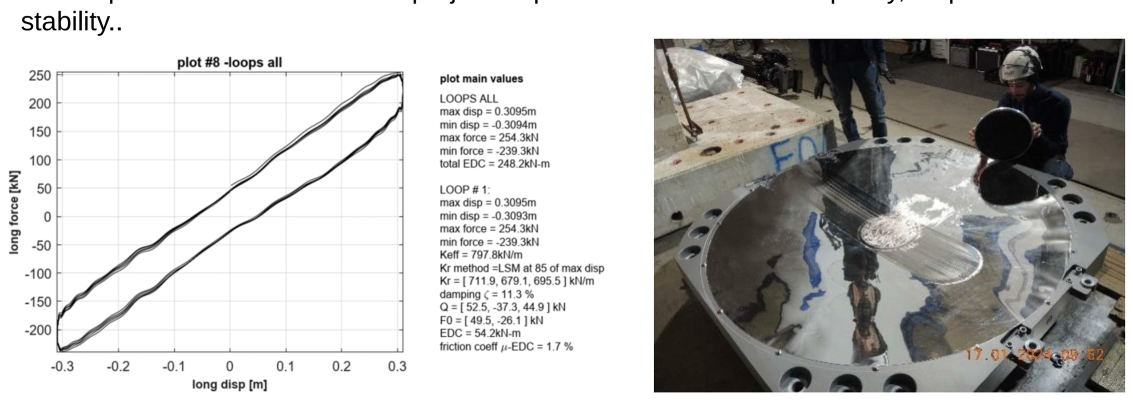
The pendulums are lubricated, and the liner has dimples where lubrication grease is hosted to reduce the dynamic friction of the primary sliding surface to around 2% improving the isolation from ground accelerations.



A prototype test campaign has been performed to accurately obtain the FP properties to be used in the SIS analyses. During this test campaign two design validation test setups have been performed. An initial one to verify the compliance with the required stiffness and breakaway force (GMTO requirements), using simplified prototypes of the pendulum core to define the best combination of liner dimensions, thickness, recess depth and at the TU München and at the Structural Testing Laboratory (KIB-KON) of the Ruhr Universität Bochum (Germany). The tests resulted in the optimization of the slider primary and secondary contact surfaces geometry and material. The sensitivity of the stiffness and breakaway force under different load rates and load levels was also analyzed.

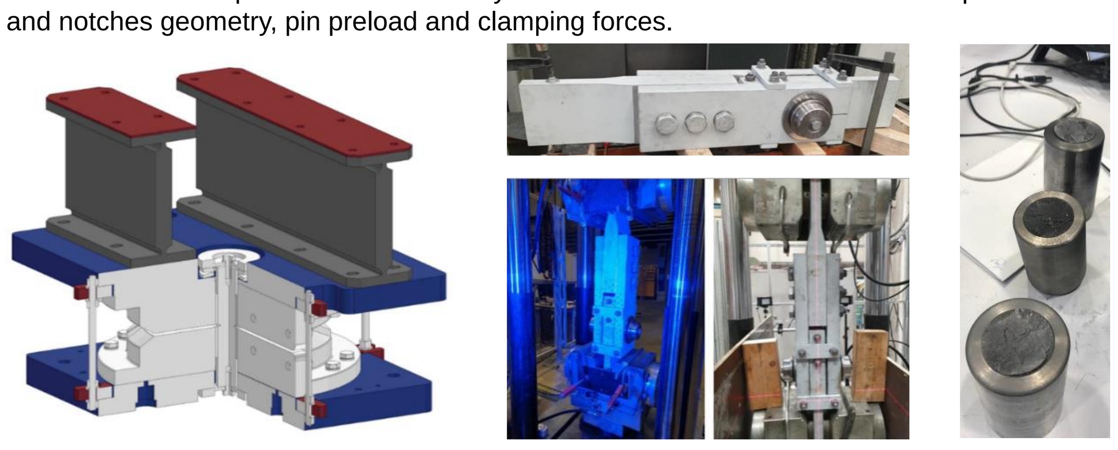
A second campaign of full-scale friction pendulums tests was conducted at the EUCENTRE at Pavia (Italy). During this campaign, the vertical and horizontal stiffness results were confirmed and the test sets according to the ASCE 7-22 Chapter 17 were conducted. These tests included fully reversed dynamic cycles of loading to confirm the design hysteretic curves defining the effective stiffness and damping and the dynamic friction to different levels of displacement ($0.25 \cdot D_M$, $0.5 \cdot D_M$, $0.67 \cdot D_M$, and $1.0 \cdot D_M$) and vertical forces and overload and stability tests at the maximum capacity of 10 MN and horizontal displacement of 700 mm.

Four FPs prototypes, two lubricated and two non-lubricated, were manufactured and tested showing consistent results. These tests together with the manufacturer previous project knowledge provided information about the FPs property modification factors. The tested friction pendulums met with the project requirements in terms of capacity, displacement and stability..

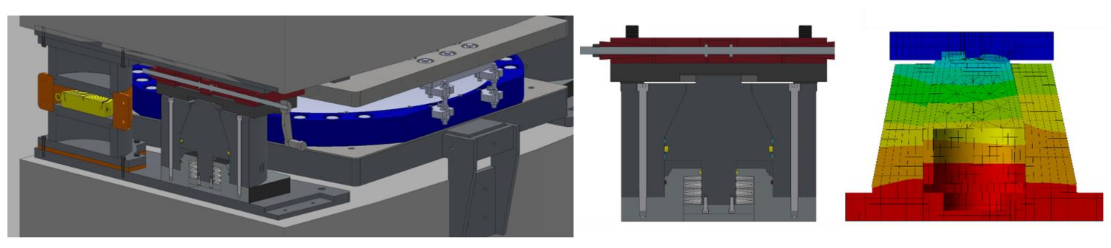


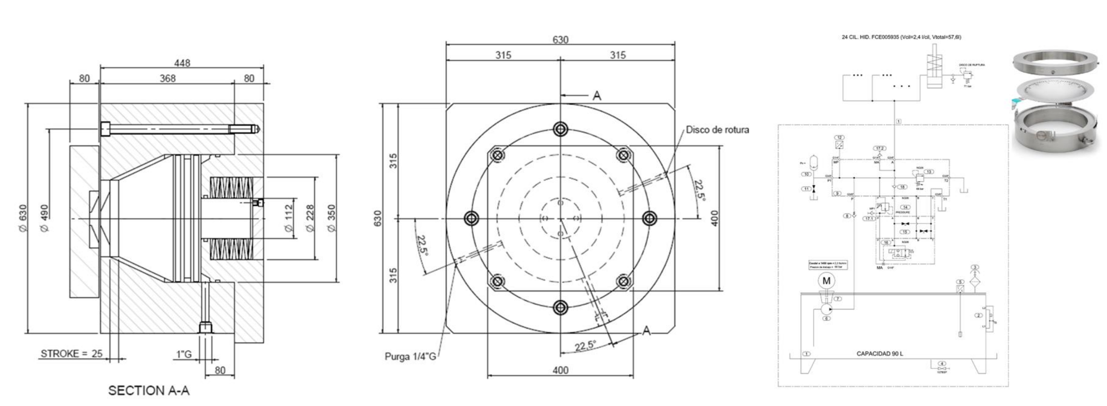
FUSES DESIGN AND EARLY PROTOTYPES VALIDATION

The fuses fix the isolated pier during the telescope normal operation conditions and are only released when the earthquake exceeds a defined level (Rigidity Level Earthquake). The SIS does not have to be activated neither because of the operational wind loads, up to 20.5 m/s wind speed, telescope mechanisms operation or emergency braking of the azimuth or elevation axes movements. In addition, the fuses provide a high horizontal stiffness to the telescope during the observation.
The fuse design is based on pins designed to break at a specific shear load coincident with the maximum RLE load. They are manufactured in grey cast iron, so the failure is fragile and instant. A disk springs stack frees the vertical movements, so the element does not take vertical force, and allow to introduce some axial load to fine adjust the breaking force.
The shear pins are stiff and thus sensitive to break due to even thermal deformations caused by the seasonal temperature variation, between -4 ºC and 20.5 ºC, during the year. To prevent this failure the shear pins are installed in conjunction with planar flexures.
Early prototypes of the shear pins have been tested at the Ruhr Universität Bochum to verify the stiffness of the pin and the breakaway force under different combinations of pin diameter and notches geometry, pin preload and clamping forces.



The shear pin fuses break randomly during the initial stages of an earthquake, around the first 10 seconds, when their shear capacity is reached.
A second design has been developed based on a hydraulic friction fuse concept to overcome the necessity of replacing all the broken pins once they are activated. The fuse exerts a preload against a retaining mating steel counter plate with a wedge where the system climbs. The hydraulic oil pressurizes a chamber at 60 bar generating a force to a conical piston surface, to avoid any horizontal backslash or stiffness dead band close to the zero-load position, in the wedge and friction counter plate and against a loaded disk springs stack. Once the fuse starts sliding and climbing the wedge an overpressure is generated in the chamber that provokes the break of a tuned hydraulic rupture disk and the evacuation of the fluid releasing the pressure and causing the retraction of the piston due to the disk springs. The safety and reliability of the system is increased installing two redundant rupture disks in parallel. The hydraulic pressure can be passively maintained in the system in the long-term, more than two years, using 3 litres piston hydraulic accumulators that supply the oil that could be leaked through the hydraulic seals during the operation. As the pressure chamber volume is small the amount of oil required to maintain it pressurized is not significant. A wedge-based levelling mechanism installed over the counter plate is used to adjust the preload of the system through a leadscrew and to eliminate the backslash.



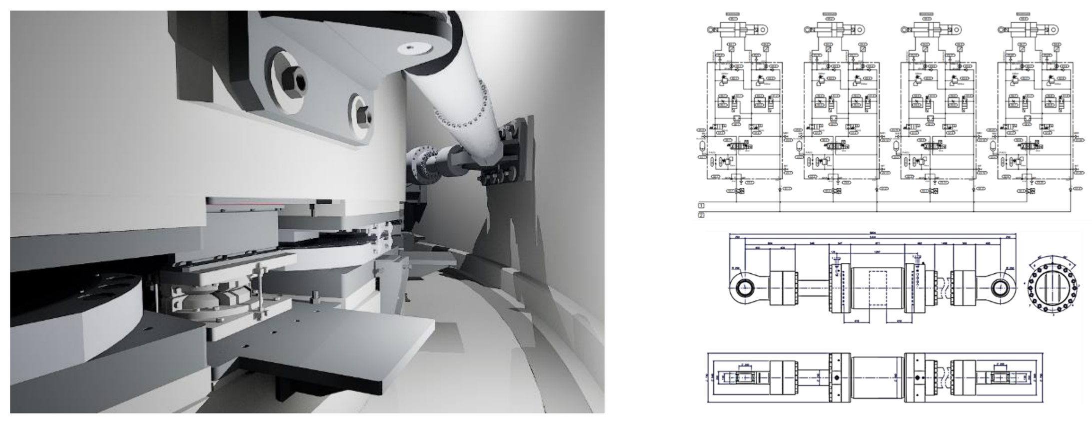


VISCOUS DAMPER DESIGN

Four large viscous dampers are installed orthogonally tangential to the telescope pier cylindrical wall in horizontal position. These dampers increase the SIS seismic energy dissipation already provided by the friction pendulums limiting the maximum horizontal displacement during an earthquake. The viscous dampers have a capacity of 1,500 kN with displacement of +/-700 mm. The total dissipated energy of the whole system is the sum of the energy of the four viscous dampers and the twenty-four friction pendulums. The property variations are of the VDs have been considered in the SIS design analyses.

PIER RECENTERING SYSTEM DESIGN

The pier recentering system (PRS) positions accurately the telescope within a +/-10 mm radially and 3.4 arc min rotationally tolerance using four 5,000 kN capacity servo-hydraulic actuators after the activation of the SIS. The actuators are installed orthogonally tangential to the pier in horizontal position and are disengaged during the normal operation of the observatory.
The hydraulic actuators are equipped with a control block including the servo-valves, LVDTs and pressure transducers to allow a fine recentering control overcoming the frictional and inertial forces of the pier.



SEISMIC DETECTION AND PIER MONITORING SYSTEM

The seismic detection and pier monitoring system (SDPMS) is a real time monitoring system. It functions as a warning alert of a seismic event and records the performance of the SIS during an earthquake to evaluate its behavior acting as a health monitoring system of SIS.

The SDPMS measures the ground accelerations, and the accelerations transmitted to the telescope using triaxial accelerometers. The displacements of the isolated structure are also measured using LVDTs.

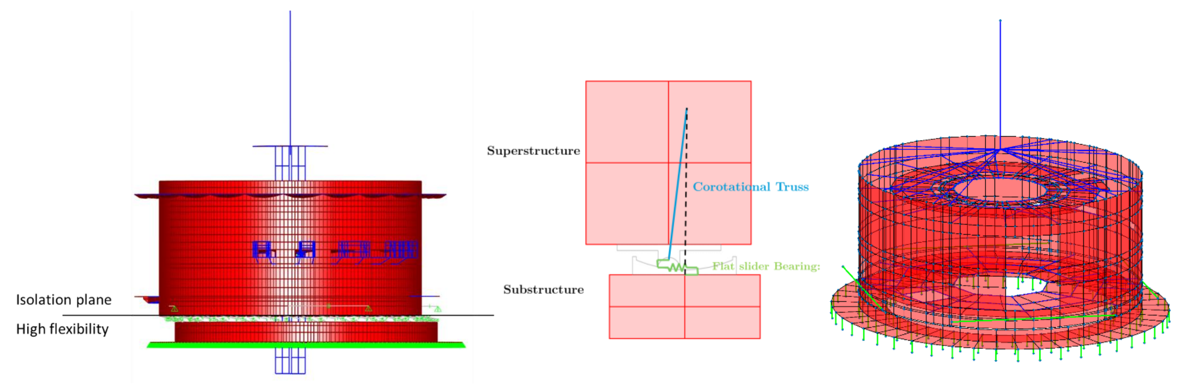
SIS PERFORMANCE FEM VALIDATION

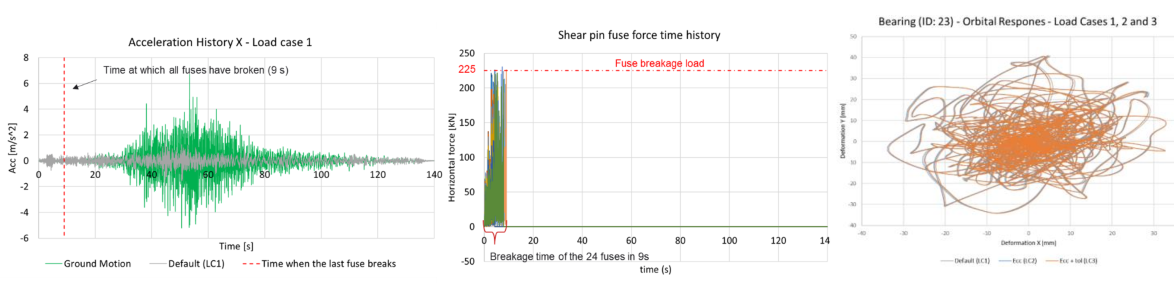
A site-specific seismic hazard analysis (SSSHA) has been developed for the project. The SSSHA comprises a selection of a representative set of eleven subduction earthquake records, three components each, and spectrally matched to the site-specific, 5%-damped, MCER response spectra following the procedure and scaling requirements of Chapter 16 of ASCE 7-22, and the additional requirements of the GMT project.

Two finite element models of the seismic isolation system and the Pier have been developed. A SAP2000 model using the common industry models of the pendulums, fuses, and viscous dampers and a more sophisticated and accurate model in OpenSees, developed in collaboration with the UC San Diego. The SAP2000 and OpenSees model results have been compared for the nominal case, showing only marginal differences that have been included in the calculations through the use of safety factors.

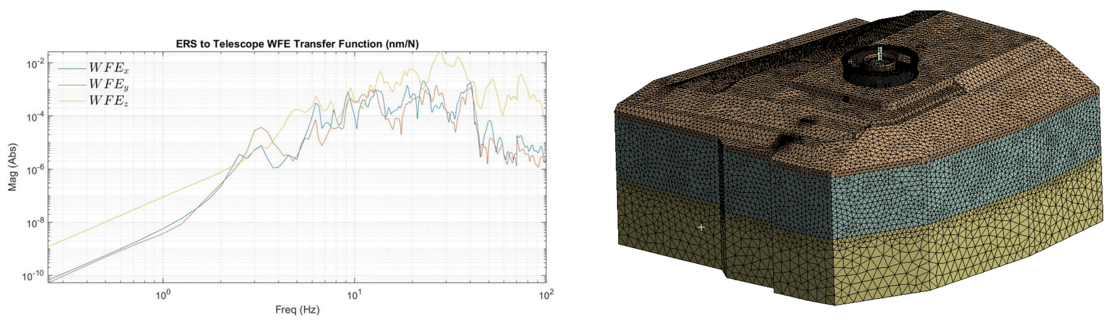
The OpenSees model has a more accurate mathematical definition of the friction pendulum bearing model capturing the variation in the dynamic friction coefficient as a function of the temperature, velocity, and pressure using the element called 'FPBearingPTV'. Additionally, an innovative mathematical approach has been used to model the bearing's vertical pendulum motion in relation to the horizontal one, and the uplift and the consequent impact force. A flat slider element is coupled with a coronational truss element with the same radius as the friction pendulum, generating the pendular movement. The Opensees model includes the following effects:

- A possible accidental torsion.
- Construction tolerances considering a non-uniform vertical force distribution at the pendulums due to construction tolerances and a possible tilting of the friction pendulum connection plate that generates a displacement of the pivot point.





Additionally, an ANSYS model has been developed to analyze the vibrations transmitted to the telescope through the pier system and SIS. The primary objective of this study is to quantify the wavefront error (WFE) at the focal plane of the telescope induced by the vibration generated by rotating or reciprocating machinery, bogies tracking and travelling, wind buffeting, transformers and large electrical equipment and pipework, pumps and valves turbulences.

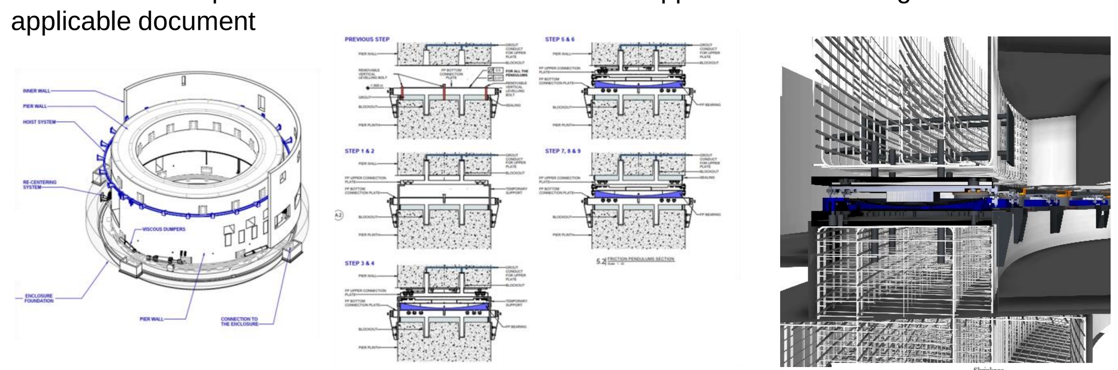


SIS CONSTRUCTION CHALLENGES

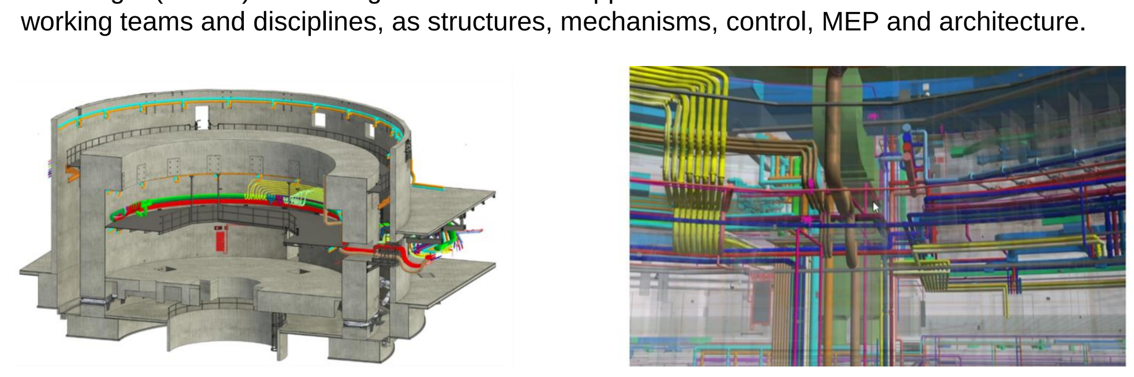
The GMT is constructed at Las Campanas summit in the Atacama desert (Chile). As such it has the complexities associated of a construction at a remote site with scarce resources and extreme environmental conditions.

The friction pendulums must be installed accurately within tight tolerances for a proper function. The installation process has been defined to guarantee the achievement of this design tolerances.
The concrete shrinkage has been analyzed and included into the construction program, so it has a minor impact on the accurate positioning of the friction pendulums and the activation of the fuses. The pendulums are installed once the remaining pier concrete cylindrical wall radial shrinkage is only marginal and thus it does not affect their accurate positioning.

There is a fine leveling system for the FPs has been developed to reduce construction tolerances at the system. The compatibility of the pendulums and fuses shear studs, rebars, reinforcements and anchorages of the viscous dampers and pier re-centering system has been studied through a complete modulization in 3D of all the rebars, concrete structures and steelwork of the pier in Revit and Tekla that will be supplied to the building contractor as an applicable document



Pipework, electrical and control cables connect the enclosure fixed part with the telescope through the SIS components moving horizontally +/-700 mm, so it is necessary to use displacement compliant supports and elements. The access to the pier through the portal using a bridge and the telescope observing level have been designed to be compliant with the SIS maximum horizontal displacements. To manage the complex integration work at the telescope pier and enclosure, Building Information Modelling (BIM) with LODs between 300 and 450, depending on the specialty, and Construction Operations Building Information Exchange (COBie) technologies have been applied for the coordination of the different working teams and disciplines, as structures, mechanisms, control, MEP and architecture.



All the design, analyses and early prototype activities summarized in this entry has allowed to demonstrate the validity of the telescope pier SIS design to comply with the stringent GMT project requirements.