CTAO – South Seismic Risk Specification

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1 Introduction and Scope

1.1 Purpose

The primary purpose of this document is to define the acceptable level of risk associated with the occurrence of earthquakes at the CTAO South site and to define the normative background and methods which must be used to show compliance with this risk. In order to define the risk a distinction is made between the hazard related to the occurrence of earthquakes at the CTAO South site and their resulting effect in terms of damage to equipment and loss of scientific operation.

The effects considered are only those affecting the telescopes. For infrastructure elements like operation and technical buildings or the power distribution system, the level of risk is de-facto implicit in the use of specific seismic norms under consideration of relevant safety factors and geotechnical characteristics of the site. For these reasons, the risk to the infrastructure is not discussed herein.

This document summarizes the seismic studies at the basis of the determination of the hazard and lists to the designer(s) the seismic loadings, the associated norms, and the key parameters to be adopted during the design and verification of both telescope and infrastructure.

The hazard was assessed by means of a geophysical campaign performed at the CTAO South site and the resulting computer modelling and analysis based on the measured parameters. This has complemented probabilistic studies originally undertaken by the European Southern Observatory for the ESO Extremely Large Telescope, presently under construction in proximity of the CTAO South site.

The earthquake risk is then defined in terms of human injuries, loss of operation, level of damage and repair which can be considered tolerable by CTAO. The methods and norms to be applied in the structural analysis to determine the earthquake consequences or risks are also broadly defined herein.

1.2 Scope of Application

This document applies to the CTAO Telescopes (structure and cameras) and to the buildings to be constructed, installed and operated at the CTAO-South site.

1.3 Definitions and Conventions

1.3.1 Abbreviations & Acronyms

Abbreviation	Definition
CCn	Consequence Class n
CTA	Cherenkov Telescope Array
CTAO	Cherenkov Telescope Array Observatory
CTAO-N	CTAO - North
CTAO-S	CTAO - South
DLR	Damage Limitation Requirement
EC	Eurocode
ESO	European Southern Observatory
ELT	Extremely Large Telescope
LST	Large-Sized Telescope
MST	Medium-Sized Telescope
NCR	No-collapse Requirement
NCh	Norma Chilena
PGA	Peak Ground Acceleration (PGa)
PSHA	Probabilistic Seismic Hazard Analysis
SST	Small-Sized Telescope
TBC	To Be Confirmed
TBD	To Be Determined
UHS	Uniform Hazard Spectra

2 Applicable and Reference Documents

2.1 Applicable documents

The document listed herein are complementing the requirements listed in this document.

AD01 CTA Product safety Plan, CTA-PLA-SEI-00000-000, rev 1a

AD02 Eurocode Norms:

EN 1990 Eurocode 0: Basis of Structural Design, including EN 1990:2002/A1:2005,

EN 1998 Eurocode 8: Design of Structures for Earthquake Resistance

AD03 Norma Chilena 433 of 1996 modified in 2012

AD04 Hosting Agreement ESO-CTAO, dated 19.12.2018

2.2 Reference Documents

The documents below are at the basis of the report herein.

RD01 Probabilistic Seismic Hazard Assessment study at Ventarrones Site, report E-TRE-ASD-222-0001, dated 20.07.2010

RD02 Integration of PSHA at the E-ELT Site in Ventarrones/Armazones (northern Chile), report ASDEA *4113 rev*.), 24.10.2013

RD03 CTA Project: Detailed Ground Investigation -Structural Study, Final Report, 18.11.2017, University of Warsaw, Faculty of Geology

RD04 ARUP: Seismic Hazard Assessment E-ELT Project, report E-TRE-ARU-222-0002 issue 1, rev. D

RD05 Geophysic Exploration and Seismic Amplification Study, report IDIEM 1564962, Rev. 0, 31.12.2021

RD06 Cherenkov Telescope Array Observatory - Seismic Amplification Study Report, report ASDEA 2124 rev. 1, dated 1.03.2022

3 Seismic Hazard

3.1 CTAO Array Site Locations

The sites of the Cherenkov Telescope Array Observatory have been selected based on environmental characteristics, like air transparency, percentage of clear nights, low humidity, distance from light sources, amongst others, which are relevant for the observation of the extremely faint Cherenkov showers caused by the high energy gamma rays reaching the earth atmosphere. Based on these and on other operational criteria, the CTAO array sites are the island of La Palma, in the Canary Island for the array located in the North hemisphere, and the Atacama Desert, in the North of Chile, close to the ESO Paranal observatory for the array located in the South hemisphere.

The CTAO-South is located on ESO Land. For this reason, once delivered to CTAO, the components of CTAO-South shall be regarded as equivalent to ESO infrastructure and hence benefiting of the immunities and privileges granted by the Government of Chile. This implies also that rules and regulations applied to the ESO equipment can be applied to the CTAO South telescopes and infrastructure.

Both La Palma and Chile are subject to seismic risk. The island of La Palma is of volcanic nature and subject to moderate earthquakes, while the Atacama Desert is a very seismic region where strong earthquakes occur rather frequently. For this reason, it is necessary to study the effect of earthquakes on the array elements and design them to guarantee a predetermined level of protection. This document treats the seismic risk for the CTAO South Site only.

3.2 Seismic Zones and associated PGA

Chile presents a high level of seismicity caused by the subduction convergence of the Nazca plate toward the South American plate. In Europe earthquakes are generated by the convergence of the Eurasian Plate toward the African Plate. The type of earthquakes generated by the two convergence effects are different, and this also explains the sensible differences between the seismic codes adopted in Europe and Chile.

In general, each national code describes the seismic hazard which must be taken into account when designing structures or buildings in seismic zones. There is a sensible difference between the seismic code adopted in Europe (Eurocode 8) and in Chile (NCh433, and NCh 2369, or NCh 2745). In the case of Eurocode 8 (AD02) it is sufficient to know the value of Peak Ground Acceleration (PGA) and the soil type to determine the seismic loading, expressed in terms of seismic response spectra for a specific damping. The approach used by the Chilean Norms is based largely on the zoning criteria. In the definition of the seismic input data to a structure or building the peak ground acceleration to be used depends on the classification of the specific seismic zone where the structure will be erected. However, the PGA is the minimum level to be used in absence of more detailed geotechnical studies related to the area of interest. In 2011, because of the major earthquake of February 2010 in the center-south of Chile, a ministerial decree requested that the soil type is assessed in-situ with specific geophysical measurements of the shear wave velocity. Consequently, the norm NCh433 (AD03) was duly updated.

3.3 CTAO-South Seismic Hazard

CTAO benefits from the seismic hazard studies initially performed by ESO for the construction of Paranal Observatory, and successively extended to the nearby Armazones mountain where the Extremely Large Telescope is presently being built. Initial studies date back to 1990. Successively studies have been performed in the period 2009 to 2014, date at which the seismic requirements for the ELT were finalized.

Being the seismicity of the area under examination not closely dominated by one specific source, the Probabilistic Seismic Hazard Analysis (PSHA) method for the determination of the seismic hazard was used, rather than the Deterministic Seismic Hazard Analysis (DSHA) method. The PSHA method relies on various information and hypothesis, like geological conditions, knowledge of tectonics and sources, historical seismicity records, recurrence rates w.r.t earthquakes magnitude, estimation of attenuation with distance, amongst others.

The PSHA provides a yearly probability of exceedance of a given seismic parameter, typically the Peak Ground Acceleration (PGA). The seismic hazard for a given site is therefore linked to the probability of exceedance of a specific PGA in a period of interest, usually linked to the lifetime of the facility being designed.

The most widely used analysis method in earthquake resistant design of structures is the Response Spectrum Method which is based on two parameters of interest, namely the spectral period and the damping ratio. This method neglects the duration aspects of a strong motion as well as non-linearity aspects but is adopted for its simplicity and because it is generally considered conservative. For this reason, the most useful output of the PSHA is the Uniform Hazard Spectra (UHS), providing for specific return rates the spectral acceleration as a function of the period in seconds. The UHS is generated for a given damping ratio by combining the response generated by many strong motion accelerograms suitable for the site of interest.

Central to the definition of the seismic hazard for the CTAO-South is the Probabilistic Seismic Hazard Analysis (PSHA) performed by the company ASDEA for the initially selected ELT site, namely Cerro Ventarrones (RD01) concluded in 2010[1]. Later the initial analysis was extended by ASDEA to the Armazones site (RD02), finally selected by ESO for the ELT. The two sites are separated by app. 30 km, and it was shown that the difference in the UHS is negligible. It can be extrapolated that a similar conclusion applies also to the CTAO-South site, located at app. 40 km from Cerro Ventarrones and less than 20km from Armazones.

In the case of Cerro Armazones, a Topographic Amplification Factor was introduced to take into account reflective waves inside the mountain. For the case of CTAO such a factor is not needed, due to the rather flat orography of the site and the importance class assigned to the CTAO (see Section 3.5.3.4), but the relevant soil conditions and the resulting spectral amplification needs to be considered. It shall be reminded that the UHS or the associated PGA is determined for the ground base rock. For determination of the response spectra to be used for structures positioned at the surface it is necessary to obtain the amplification factor(s) caused by the columns of soil above the base rock.

3.4 Soil Amplification factor

The location of the CTAO-South extends over an area of a few km^2 and is within a basin with a direction NNW-SSE and a width of around 2 km. Over geological times the basin has been filled with material, so that at least four types of ground layers can be identified:

A1 subsurface deposits of sands, silt and weathered granite extending to around 1 to 2m depth.

A2 colluvial deposits, consisting of dense deposits with gravel and cobbles of a thickness around 10-20 m but in some cases higher than that.

B1 a relatively thin layer of weathered and soft rock of a thickness 2-5 m.

B2 the bedrock proper which, in the central and southern area of the basin is at a depth of 30m or more.

The above data was initially gathered as results of a field campaign performed by the Faculty of Geology of Warsaw University in 2017 (RD03). During the campaign numerous boreholes where done and various geophysical tests were performed to ascertain the geological characteristics of the rocks. Although the main objective of the campaign was to characterize the site in view of the construction of telescope foundations and access roads, a non-negligible variability of the soil conditions in the area of the telescope array and of the buildings was also detected.

In 2021 a contract was awarded to the Chilean Company IDIEM to carry out an extensive geophysical exploration with stratigraphic and geotechnical characterization of the site, and subsequent 3D modelling to obtain site specific seismic response spectra for the telescope array area and the CTAO-South buildings area. Preliminary study results were available in July 2021, and in their final version at end of December 2021 (RD05).

In terms of stratigraphy the study confirmed the results of the campaign of 2017, whereby this time more information was collected. For details beyond this summary, reference is made to the report itself. In total 35 boreholes were drilled up to 30 m depth. Penetration tests were performed at the boreholes , showing deposit of dense soil above the base rock. Samples collected from the boreholes were sent to a laboratory for study of the rock characteristics. Other geophysical tests were also performed, including seismic profiles to obtain compressional and shear waves velocity maps. Stratigraphic information has also been obtained.

[1] At least two independent PSHA analysis were contracted by ESO and subjected to various independent reviews.

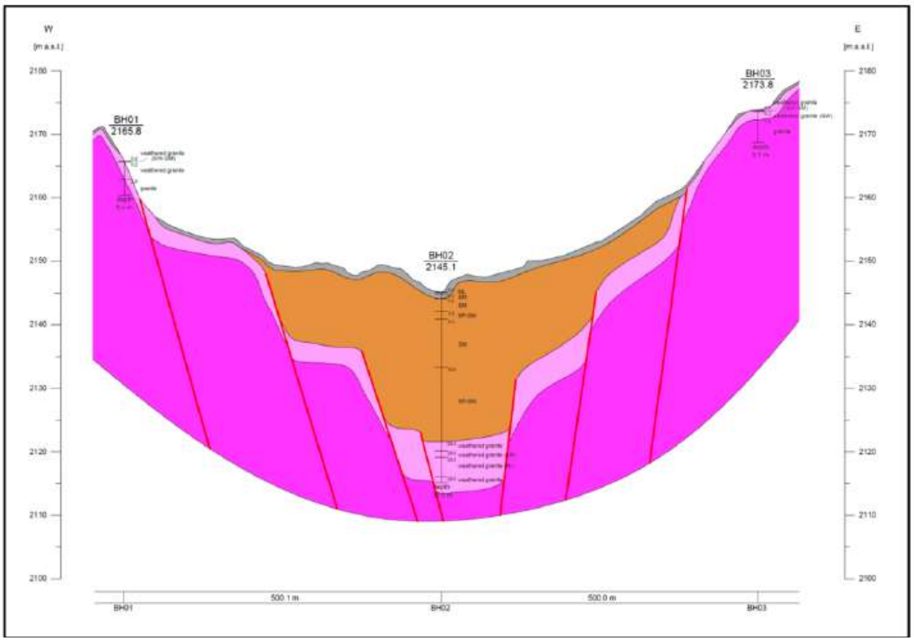


Figure 3.4-1: – Example of a stratigraphic profile W-E identifying layer A1, A2, B1, B2

Geophysical profiles were obtained by IDIEM with the seismic MASW (Multi-channel Analysis of Surface Waves), ReMI (Refraction Microtremor MASW) and Nakamura methods. Maps of the shear velocity (V_{s30}) were obtained at the surface and at the critical depth of 30m, with interpolation between the various geophysical profiles. The Nakamura tests have been used to assess the first fundamental frequency of the soil, this being the first frequency where sensible soil amplification is recorded.

For the determination of the soil amplification and of the surface acceleration response spectra, a time history analysis is used. The selection of which earthquake accelerogram(s) is (are) to be used was based by IDIEM on the spectral matching with the UHS generated in the original ESO ELT seismic hazard studies by ASDEA (RD02) for the No-Collapse Requirement (NCR) and by ARUP (RD04) for the Damage Limitation Requirement (DLR). The Tocopilla Puerto 2007 earthquake accelerogram was selected by IDIEM as providing a good spectral match. The spectral match was also verified in a simplified modelling for two additional real accelerograms of recent earthquakes in Chile. The study used identical records in N-S and E-W directions based on averaging over 10 Chilean records.

To evaluate the amplification behaviour of the soil in the CTAO-South area (telescope array and Operation and Technical building area) the commercial software package *FLAC 3D* from ITASCA was used. The modelling of the area has been based on characteristics assessed with the field campaign and laboratory tests. Verification with other software (DeepSoil) from University of Illinois were performed by IDIEM, to validate their modelling.

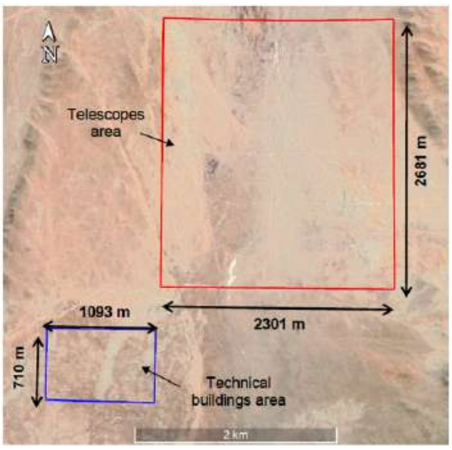


Figure 3.4-2: Geographical areas used for the computer modelling of the site by IDIEM

The IDIEM study proposed significant amplification factors, especially in some site areas resulting in elastic accelerations response spectra in horizontal direction in excess of 3g in the relevant frequency range of the telescopes. This level of accelerations is sensibly higher than what initially assumed and some doubt emerged about possible conservatism in the analysis. It was therefore decided to double check these initial results with additional analyses and to adopt a multiple analysis approach. An additional study by the company ASDEA (RD06) was carried out in order to cross-check and eliminate possibly excessive conservatism in the analysis. The ASDEA study is based on the model generated by IDIEM, but with some modification of the assumptions of the previous analysis (non-simultaneous and in–phase vertical and horizontal excitation, different shear modulus degradation, more spectral records used for deriving the amplification factor).

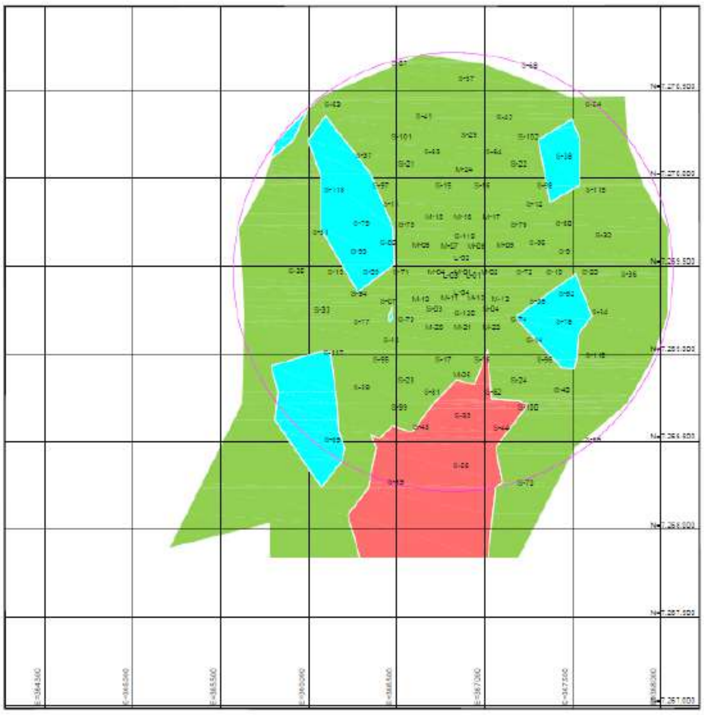
The ASDEA study was completed in December 2021 and the final response spectra were available at the time of writing of this report. While the fundamental validity of the IDIEM study was confirmed by ASDEA, the amplification factors, and hence the acceleration response proposed by ASDEA (and herein adopted) for the telescope array are lower than those of IDIEM. This is linked to two main reasons:

- The average among three earthquakes output[2] was used in lieu of the one output from IDIEM;
- The average among the responses for the same type of ground (spatial) was used, rather than the maximum.

We shall note that always using the maximum of the approaches is considered excessively conservative. The amplification factors initially obtained by IDIEM are higher than those generally assumed by the codes.

3.4.1 Soil Amplification Factor at Telescope locations

In determining the final elastic response spectra, an averaging of the soil amplification factor was obtained averaging over all the telescope locations located on each of the three soil types, namely *Hard soil, Medium soil, and Soft soil.* The distinction of the soil is based on the shear wave velocity ranges ($V_{s,30}$) defined in Eurocode 8[3].



3.4-3: Ground type classification (red soft, green medium, blue hard) in the telescope area

[2] For the determination of the soil amplification the codes/norms do not specify the number of histograms to be used. For structural analysis based on time-histories rather than on response spectra EC8 demands the use of 7 accelerograms.

[3] Table 3.3. Ground types, equivalent also to definition in Chilean norms.

Figure 3.4-3 above reports also the various position of the telescopes as they were at the time of the study by IDIEM and ASDEA. The position of the telescopes in the presently retained Alpha configuration of the CTAO South Array is well covered by the above positions. In the Alpha configuration the Large-sized and Medium-sized telescopes are located in the medium soil area, whereby the Small-sized telescopes are located on all three types of soil. For this reason the response spectra for the Small-sized telescopes are higher than the ones of the Large-sized and Medium-sized telescopes, as defined in Section 3.6.2.

It shall be noted that the amplification factor computed by ADEA even exceed the initial values computed by IDIEM at specific frequencies, but rather than taking the maximum value for the whole spectrum, the local peaks have been averaged by ASDEA.

The response spectra were then extended with corner frequencies to generate the maximum acceleration plateau based on the frequency of interest of the soil amplification, as demanded by Eurocode 8.

The vertical component of the response spectra has been chosen to be 2/3 of the horizontal response based on the result of the soil amplification study and on the studies performed in RD01, RD02, and RD03. It shall be noted that until now no reliable models have been generated to assess the vertical response by means of an accurate and complete vertical PSHA.

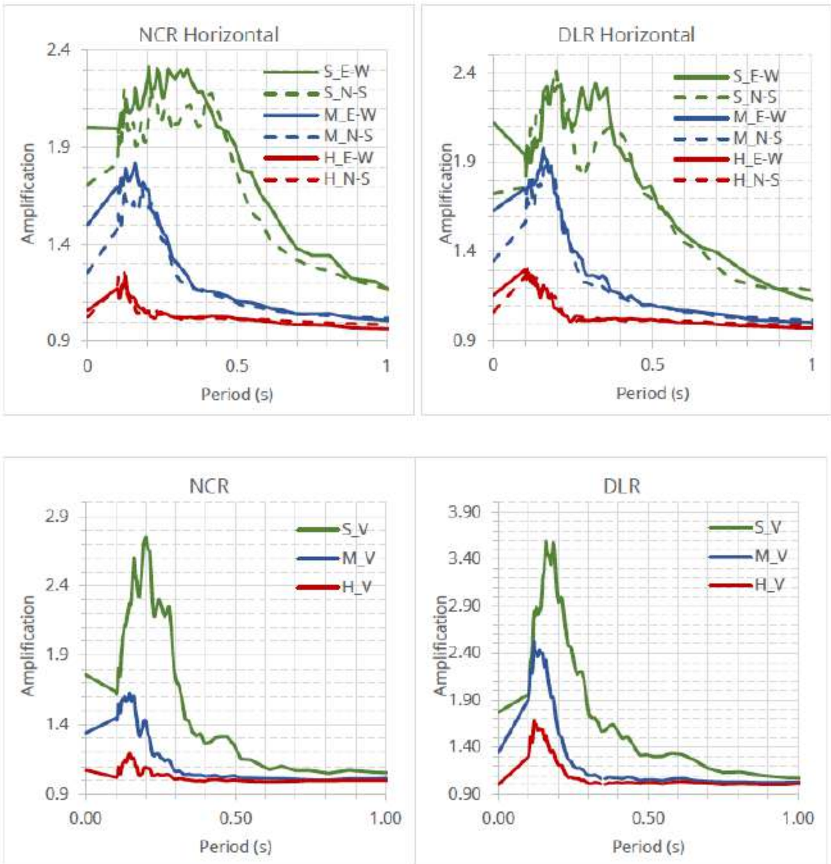


Figure 3.4-3: Soil Amplification factors between 0 s and 1 s (∞ and 1 Hz)

3.4.2 Soil Amplification Factor at CTAO-South Buildings Location

Also in the case of the CTAO-South buildings the key parameter for the response of the soil is the V_{s30} shear wave velocity. Within the geophysical campaign by IDIEM (RD05) the shear wave velocity has been measured at various control points of the building location area, and it is always in excess of 350m/s.

As such the amplification characteristics of the *medium soil* can be used for the soil amplification factor at the Operations and Technical buildings.

3.5 Structural Design and Incorporation in Seismic Protection Codes

3.5.1 Seismic Codes Applicability (Eurocode vs. NCh)

The definition of seismic hazard and even more seismic risk cannot be done without considering which seismic structural code is applicable. The installation of CTAO-South will be located on the land of the European Southern Observatory, as per Hosting Agreement signed by CTAO with ESO in December 2018 (AD04). The agreement does not specifically treat which seismic code has to be applied for the design and construction of CTAO equipment, apart generically requiring that CTAO respects safety rules and regulations in force at ESO.

Specifically, ESO is not strictly bound to use Chilean seismic norms for structural verification, and the Chilean norms represent the baseline standard unless justified reasons exist to deviate. One justification can be that the design, tendering and building of components of the observatory in Europe using the Chilean standard could be associated to larger expenses and risk of errors. This is surely the case for the telescopes designed and built in Europe according to the Eurocode compendium of norms, of which the Eurocode 8 is only one of the elements. Based on the Hosting Agreement the possibility of using different norms and standards is also extended to the CTAO telescopes.

For recent procurements associated to the Extremely Large Telescope ESO has specified the use of Eurocode 8 for equipment designed and procured in Europe (like the ELT telescope structure) and decided to use Chilean Norms for technical building designed and procured in Chile. A similar approach is proposed here for CTAO-South, and in particular it is chosen:

a. To specify the application of Eurocode 8 as the seismic code to be used for the design of the telescopes (telescope structure and cameras) as well as for similar equipment like Lidar;

b. To specify the application of Chilean seismic codes for the technical buildings.

This has various advantages, like:

I. it guarantees the same level of seismic safety as presently required by ESO for all its recent installation.

II. it represents an efficient (and likely economic) solution avoiding the design authorities to venture into seismic codes other than their national one (EC8 for telescope and NCh for technical buildings).

III. it justifies, for buildings which are designed, procured and erected in Chile, the application of an independent verification authority as demanded by Chilean legislation (despite this not being mandatory in the case of CTAO).

It shall be noted that the validity of this approach is in line with the ESO approach.

3.5.2 Limit States according to Eurocode and Chilean Seismic codes

Based on Section 3.5.1 above the structural design of the CTAO telescopes shall be based on Eurocode normative. The Norm EN-1990 (Eurocode 0) defines the basis of structural design, whereby the Norms EN-1991 to EN-1999 (Eurocode 1 to 9) enter in specific aspects of structural design. EN-1998 (Eurocode 8) treats the Design of structures for earthquake resistance.

The Eurocode set of norms is based on achieving a minimum (or specified) value of structural reliability despite the unknowns associated to the design process, to the materials characteristics and the large unknowns about the loadings which may be experienced in the lifetime of the structure. In particular, the concept of reliability within specific *limit states* is defined. A *limit state* is a condition in which the structure ceases to fulfil its relevant design criteria, and consequently its intended function. In general, structural reliability is achieved if the design value of the effect caused by the load on the structure is lower than the design value of the resistance of the structure.

As an example, the physical value of the effect observed could be the internal stress generated in the structure by a load, which is confronted against the design stress (example yield stress) reduced by factors covering the scatter caused by the material and size uncertainty.

EC divides the loads in permanent actions (G), variable actions (Q), accidental actions (A) and seismic actions (A_E). Both accidental and seismic actions can have significant magnitude and have a certain (limited) probability to occur during the design life of the structure. For actions which are of statistical nature and for which there is sufficient information their "*characteristic*" value is prescribed by the Eurocode to be associated to an upper value with an intended probability of not being exceeded[4].

Two limit states are prescribed for structures designed and constructed according to Eurocode[5], and namely:

- *The Damage Limitation Requirement (DLR)* corresponding to a seismic action with a probability of exceedance P_{DLR} = 10% within 10 years, corresponding to an earthquake with a return rate T_R = 95 years. This limit state is also referred to as a Serviceability limit state, which means that the structure has not yielded and retained its strength and stiffness. In this case it can be serviced (repaired) and put back in operation with a very limited effort (cost and time). The structure has behaved to a maximum extent or entirely in an elastic manner. This limit state is in general associated to the intrinsic stiffness built into the structure.

I. *The No-Collapse Requirement (NCR)* corresponding to a seismic action with a probability of exceedance P_{NCR} = 10% in 50 years, corresponding to an earthquake with return rate T_R = 475 years. This limit state is also referred to as a *Damage Control limit state*, which means that the structure has yielded to a certain extent, but the damage is contained so that the structure has retained its structural integrity (no local or global collapse) and has a residual load bearing capability after the seismic event. Due to its permanent deformation and other damages, it may be repaired but at a non-trivial cost. This limit state is in general associated to the strength of the structure, which is based on its ability to sustain internal stresses without becoming ductile.

Based on the above requirement the Uniform Hazard Spectra (UHS) determined by the PSHA mentioned in the previous paragraph are associated to earthquakes with return of T_R = 95 years (DLR) and T_R = 475 years (NCR).

3.5.3 Additional Elements and Parameters

3.5.3.1 CTAO Lifetime vs Probability

It shall be noted here that the probability of exceedance for the NCR case is associated to a 50-year period, which usually corresponds to the lifetime of ordinary buildings[6].

For CTAO the specified design lifetime is presently set at 30 years. The use of lifetime shorter than 50 years with the earthquake of the same return rate (T_R=475y) results in a lower probability of failure, according to the law:

$$\ln(1-P_{30}) = -30/475$$

which leads to a probability of exceedance of the earthquake of P_{30} = 6,12%. Conversely, a 10% probability of exceedance in 30 years would result in the verification against an earthquake with return rate T_R = 792 years. The associated peak ground acceleration of such earthquake could be scaled from the one used for T_R = 475 years with approximate formulas, found in literature, also used for scaling between the NCR and the DLR when the DLR case has not been otherwise determined (which is not the case for CTAO).

3.5.3.2 Partial Factors

As detailed in Eurocode 0, for the verification of the Limit States the seismic action (A_E) must be combined, via partial factors, with other permanent actions (G, like deadweight, additional masses), variable actions (Q,

4 Eurocode 0, Section 4.1.2, paragraph 7

5 In other codes as well as in EC EN-1998-3 related to existing structures also the Near Collapse prevention limit state is defined corresponding to a probability of failure of 2% in 50 years for an earthquake of return rate of 2475 years.

6 This is also the lifetime that ESO has specified for the Extremely Large Telescope.

like snow, wind....) and accidental actions (*A*, like emergency stop…). Partial factors must follow the Eurocode specification for structures designed according to Eurocode.

Similarly in the case of Chilean Norms additional regulation applies which specifies the load combinations and the associated coefficients. [7]

3.5.3.3 Consequence Classes

In terms of reliability, Eurocode 0 specifies Consequence Classes (CC1 to CC3) in terms of failure of the structure. The parameter used in the decision of which consequence class need to be applied are the loss of human life, economic and social consequences, and environmental consequences. For each consequence class a target reliability index β is provided. For the 50 years lifetime reference period and the ultimate limit state (NCR) the target value of β must be at last 3.8. The reliability index is linked to the probability of failure by the formula:

$$P_f = \Phi(-\beta)$$

where Φ is the cumulative distribution function of the standardised Normal distribution[8]. The target reliability index β of 3.8 corresponds to a probability of failure of 7.23e-5.

To achieve the target reliability index both design aspects and the level of quality control during execution (ex. welds) must be considered. The reliability index corresponds to a Consequence Class 2.

3.5.3.4 Importance Class and Factor

Eurocode 8 as well as other national seismic codes including the Chilean ones, are written with the objective to save human life, and to safeguard integrity of key infrastructure for the operation of governmental institutions in a post-earthquake period (hospitals, fire station, power plants, police department offices, amongst others). To this purpose an Importance factor γ_I is defined[9] linked to the importance class of the building or infrastructure under examination. This factor is recommended to be between 0.8 (agricultural sheds) and 1.4 (building vital for operations after a major earthquake). The importance factor influences the reference seismic action used in the verification of the limit state by multiplying the characteristic value of the seismic action (A_E). Therefore, it leads to lower or higher values of the seismic action corresponding to lower or higher return rates. If $\gamma_I = 1$ the event under consideration corresponds to the reference return rate. Higher importance factors ($\gamma_I > 1$) imply protection for earthquake with higher return rate. Similarly, the importance factor can be related to the probability of failure. In the case of Eurocode, four (4) classes are considered (I to IV). Note that Importance classes relate to Consequence classes. Specifically, Importance class II corresponds to Consequence class CC2.

In the Chilean Norm NCh433 applicable to buildings an equivalent classification is used. The Chilean Norm Nch2369 which applies to industrial structures and installations uses three (3) classes (C1, C2, C3).

3.5.3.5 Behaviour Factor

For the ultimate limit state (NCR) the Eurocode[10] admits that seismic energy can be dissipated by the non-linear response of a structure if this is exploited. This is performed by introducing a behaviour factor q which takes into account specific ductility classes. For steel structures the limiting value of q is usually between 1,5 and 2.0. To avoid complex non-linear structural analysis, but still considering the inelastic effects dissipating energy during a strong motion earthquake, the elastic response spectrum is reduced by specific formulas by using the behaviour factor q.

For the case of CTAO a behaviour factor $q = 1$ must be used which corresponds to a fully elastic behaviour of the structure. This is justified by the serious consequences that extensive plasticity in the structure would produce, likely preventing further use of the telescopes, without massive capital investment, or even the loss of the complete CTAO South asset. This therefore reflects the fact that originally the Eurocode is written with

[7] NCh 3171, Diseño estructural – Disposiciones generales y combinaciones de cargas

[8] Eurocode 0, Annex C.

[9] Eurocode 8, Section 2.1.3.

[10] Eurocode 8, Section 2.2.2.

the primary view of saving life and allowing prosecution of operation of key governmental institutions, rather than protecting capital intense scientific assets.

3.5.4 Summary of Relevant Parameters

The following importance classes (and factors) are hereby proposed for CTAO installations in Chile with consideration of the Seismic code to be applied:

Seismic Code	Telescopes				Operation Building		Technical Building		Power Station[11]	
	Imp. Class	**Factor γ_I**	**CC Class**	**q**	**Imp. Class**	**Factor *I***	**Imp. Class**	**Factor *I***	**Imp. Class**	**Factor *I***
EC8	II	1.0	CC2	1.0						
NCH433					III	1.2	II	1.0		
NCh2369							C2	1.0	C1	1.2

Notes:

1) The Operation Building is expected to host tens of people and occasionally more (conferences, meetings). This justifies a baseline Importance factor >1.0.
2) For the technical building it will be decided at a later stage if NCh433 or NCh2369 will be applied
3) The power station is of vital importance for the safety of the telescopes because power must be available to reposition the telescopes to a sun-safe position in case of an earthquake happening in the night or when telescopes are not parked.

[11] The Chilean Norm 2369 is under revision to incorporate power stations. Until that time ETG-1.020 of Endesa is likely to be applied in Chile. The Factor *I* is likely going to be called I_E, but without change of values.

3.6 CTAO South Telescope Response Spectra

3.6.1 Acceleration Response Spectra Expression

The equations here below represent the ground acceleration elastic response spectra. The corresponding parameter, as defined by Eurocode 8 are defined in the following subsections for horizontal and vertical direction for both DLR and NCR seismic cases.

It shall be noted that based on the detailed geophysical campaign performed on site and based on the subsequent modeling and analyses the corner frequencies have been adapted from the values proposed in the Eurocode. Similarly, rather than assigning for the vertical acceleration a value which is 0.90 of the horizontal one, the value used is in this case is 0.67 based on the analyses performed.

The equations governing the elastic response spectrum are provided in table 3.6 -1 below.

Period range	S_e (T)
$0 \le T \le T_B$	$a_g \cdot S\,[1 + T/T_B \cdot (\eta \cdot c - 1)]$
$T_B \le T \le T_C$	$a_g \cdot S \cdot \eta \cdot c$
$T_C \le T \le T_D$	$a_g \cdot S \cdot \eta \cdot c \cdot [T_C/T]$
$T_D \le T \le 4s$	$a_g \cdot S \cdot \eta \cdot c \cdot [T_C{\cdot}T_d/T^2]$

Table 3.6 -1 Formulas for the determination of the elastic response spectrum

$\eta = [10 / (5 + \xi)]^{1/2}$ (see also EC 8, Section 3.2.2.2), where:

Se (T) is the elastic acceleration response spectrum in [g]
T is the vibration period in [s]
a_g Peak Ground Acceleration in [g]
c is the ratio between the maximum and the peak ground acceleration
T_B is the lower limit of the constant spectral acceleration branch in [s]
T_C is the upper limit of the constant spectral acceleration branch in [s]
T_D is the value defining the beginning of the constant displacement response range in [s]
S is the soil factor (amplification factor)
η is the damping correction factor
ξ is the damping ratio in percent

3.6.2 Summary Table of Applicable Spectra

Considering the above the following acceleration response spectra shall be used for the CTAO telescopes:

Telescope type	Spectra DLR $T_{R\,DLR}$ = 95y, P=10%/10y	Spectra NCR $T_{R\,NCR}$ = 475y, P=10%/50y
LST, MST	Section 3.6.3.1	Section 3.6.4.1
SST	Section 3.6.3.2	Section 3.6.4.2

Table 3.6-2. Summary of response spectra for analysis of the various telescope types

3.6.3 Damage Limitation Requirements (DLR) Spectra

3.6.3.1 Damage Limitation Requirement (DLR) – LST and MST

The LST and MST type telescopes of CTAO shall meet the Damage Limitation Requirement (DLR) as defined in Eurocode 8, based on an earthquake excitation at ground level having the following characteristics:

Parameters	a_g [g]	S	T_B {s]	T_C [s]	T_D [s]	C
Horizontal	0.25	1.80	0.10	0.35	2.0	2.0
Vertical	0.15	2.10	0.05	0.30	2.0	2.2

The graphic representation of the response spectra above for a damping ratio of 5% and 2% is shown in Figures 3.6-1 and 3.6-2, (DLR Medium).

3.6.3.2 Damage Limitation Requirement (DLR) – SST

The SST type telescopes of CTAO shall meet the Damage Limitation Requirement (DLR) as defined in Eurocode 8 based on an earthquake excitation at ground level having the following characteristics:

Parameters	a_g [g]	S	T_B {s]	T_C [s]	T_D [s]	C
Horizontal	0.25	2.20	0.10	0.35	2.0	2.0
Vertical	0.15	3.40	0.05	0.30	2.0	2.2

The graphic representation of the response spectra above for a damping ratio of 5% and 2% is shown in Figures 3.6-1 and 3.6-2, (DLR Hard).

3.6.4 No-Collapse requirements (NCR) Spectra

3.6.4.1 No-Collapse Requirement (NCR) LST - MST

The LST and MST type telescopes of CTAO shall meet the No-Collapse Requirement (NCR) as defined in Eurocode 8, based an earthquake excitation at ground level having the following characteristics:

Parameters	a_g [g]	S	T_B {s]	T_C [s]	T_D [s]	C
Horizontal	0.43	1.80	0.10	0.35	2.0	2.0
Vertical	0.26	1.60	0.05	0.30	2.0	2.2

The representation of the formulas and parameters above for a damping ratio of 5% and 2% is shown in Figures 3.6-1 and 3.6-2, (NCR Medium).

3.6.4.2 No-Collapse Requirement (NCR) SST

The SST type telescopes of CTAO shall meet the No-Collapse Requirement (NCR) as defined in Eurocode 8, based on the an earthquake excitation at ground level having the following characteristics:

Parameters	a_g [g]	S	T_B {s]	T_C [s]	T_D [s]	C
Horizontal	0.43	2.10	0.10	0.35	2.0	2.0
Vertical	0.26	2.50	0.05	0.30	2.0	2.2

The representation of the formulas and parameters above for a damping ratio of 5% and 2% is shown in Figures 3.6-1 and 3.6-2, (NCR Soft).

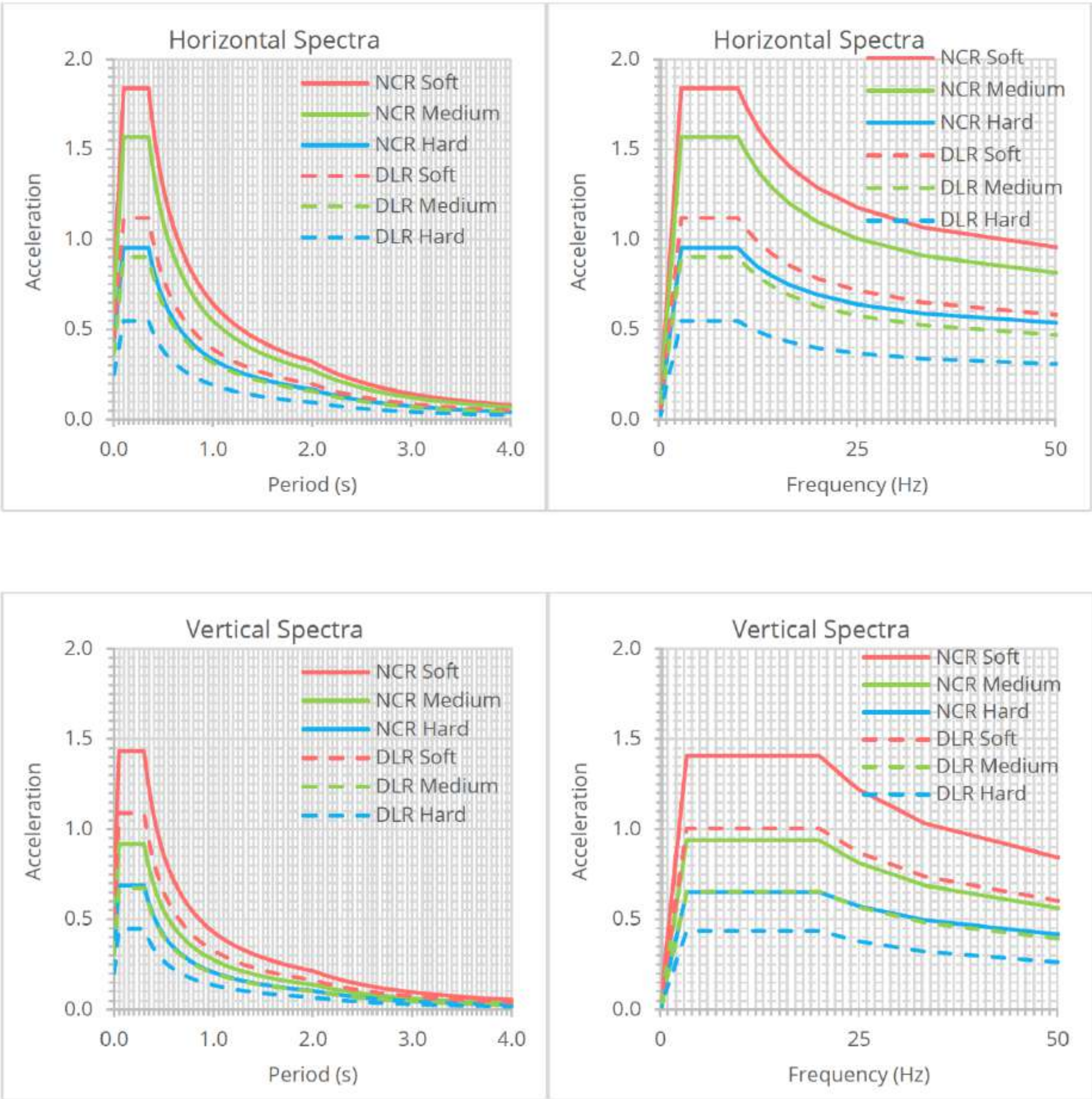


Figure 3.6-1: DLR and NCR Horizontal and Vertical Acceleration Response Spectra for 5% damping

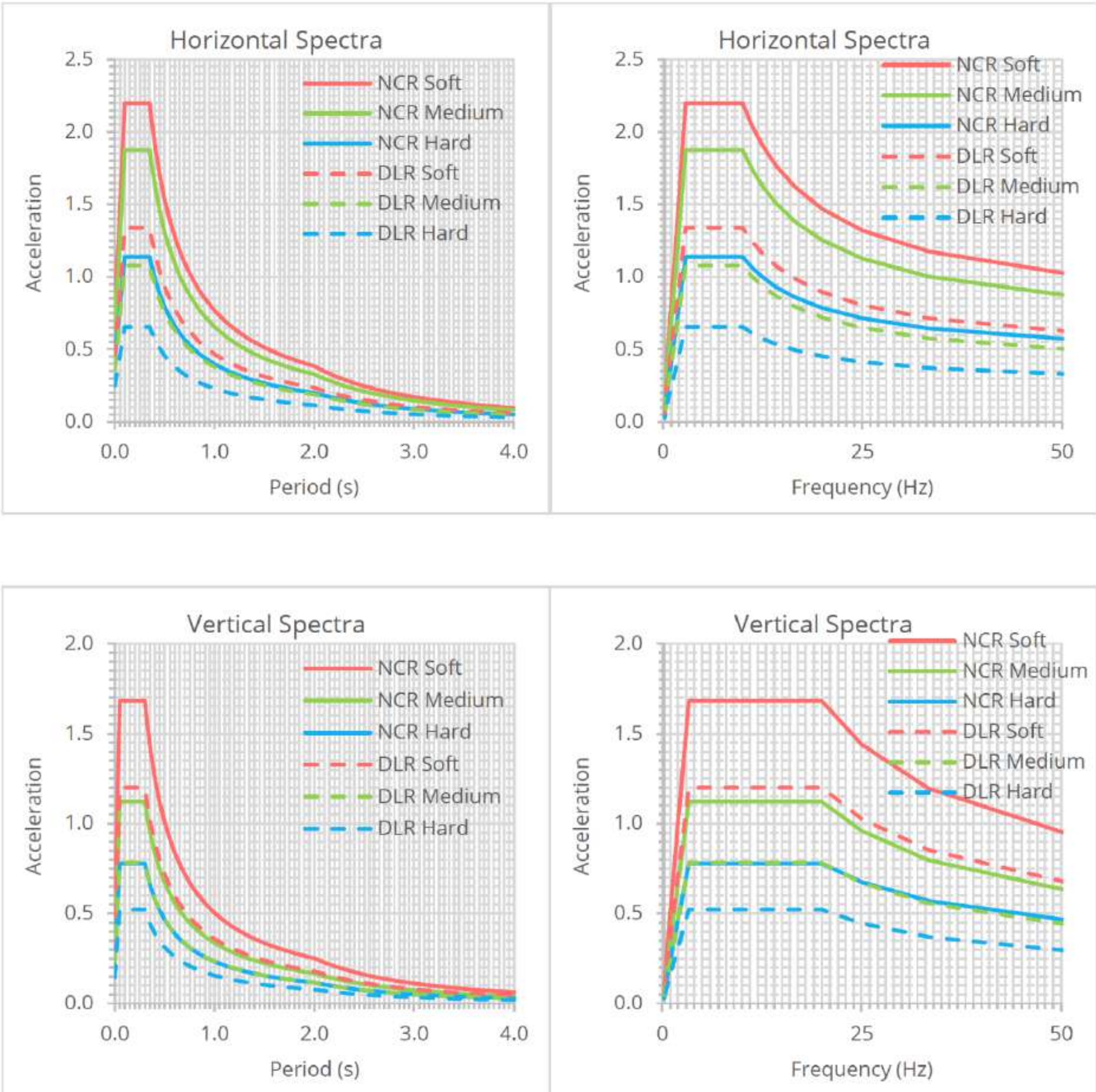


Figure 3.6-2: DLR and NCR Horizontal and Vertical Acceleration Response Spectra (2% damping)

3.6.4.3 Reduced Requirement for Temporary Conditions

For temporary operational scenarios and after explicit approval by the CTAO Project Office, reduced earthquake characteristics can be considered for the telescopes. This is particularly important for intermediate states of construction[12].

The reduction factors of the acceleration values of the Response Spectra are indicated in Figure 3.6-3:

[12] This is based on the Gutenberg-Richter equation linearly linking the earthquake magnitude to the logarithm of the probability of occurrence.

annual exposure time	Acceleration reduction factors	
	NCR	**DLR**
[days]	[-]	[-]
365	1.00	1.00
250	1.00	1.00
200	1.00	1.00
183	1.00	1.00
100	0.83	1.00
50	0.66	1.00
30	0.55	0.94
14	0.43	0.73
10	0.38	0.66
2	0.22	0.38
1	0.18	0.30

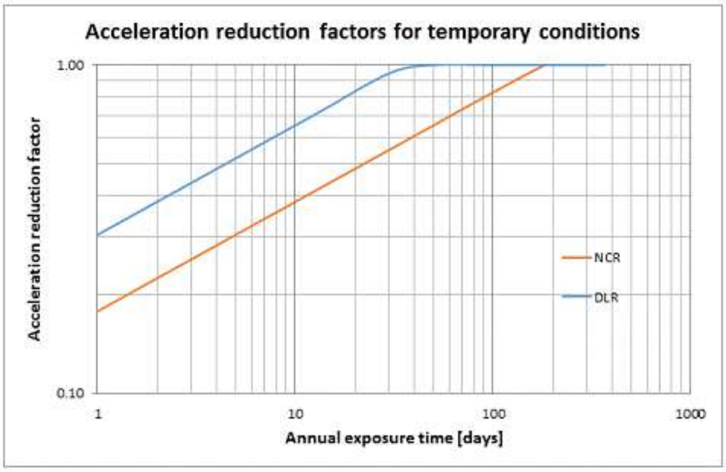


Figure 3.6-3: Acceleration reduction factors for temporary conditions

3.7 CTAO Buildings Response Spectra

As explained in Section 3.5 above the two norms which can be applied for the CTAO buildings are the NCh433 and the NCh2369. Both norms are based on the zoning concept, where a peak ground acceleration is defined as a function of the geographic location of the installation. For CTAO South this would lead to a PGa = 0.4g for the 475 years return rate earthquake (NCR).

The norms allow to consider standard characteristic of amplification based on soil characteristics. While this general approach is valid in absence of detailed evaluation of the site, it may not be conservative for all sites. In the case of the CTAO location, the detailed studies in RD05 and RD06 have provided more refined data which lead to slightly modified acceleration response spectra characteristics. It is noted that the soil type to be assumed in the case of the CTAO buildings corresponds to the "*medium soil*".

The acceleration response spectra are defined by the formulas 6-8 and 6-9 from NCh433:

$$S_a = \frac{SA_o\alpha}{(R^*/I)}$$

$$\alpha = \frac{1 + 4{,}5\left(\frac{T_n}{T_o}\right)^p}{1 + \left(\frac{T_n}{T_o}\right)^3}$$

where:

S_a is the spectral acceleration

A_0 is the PGa

T_n is the period of the mode n

T_0, p are parameters depending on the soil

R^* is a reduction factor depending on the material of the structure

I is the importance factor

S is the soil factor (amplification factor)

The following table provides the parameters for the the horizontal and vertical NCR spectra suggested by NCh433, and also those to be adopted on the basis of the geotechnical studies RD05 and RD06:

Parameters	NCh433 (soil C, baseline)				NCh433 (soil medium, proposed value)			
	A_0 [g]	S	T_n {s]	p	A_0 [g]	S	T_n {s]	p
Horizontal	0.43	1.05	0.40	1.60	0.43	1.30	0.15	2.0
Vertical	0.29	1.05	0.40	1.60	0.29	1.20	0.15	2.0

10% probability of exceeding these figures within 50 years. Reference return period of earthquake T_R = 475 years.

The difference between the spectra is outlined in the picture below computed for the case I =1 and R=1. The spectra proposed have a higher maximum amplitude at a lower period.

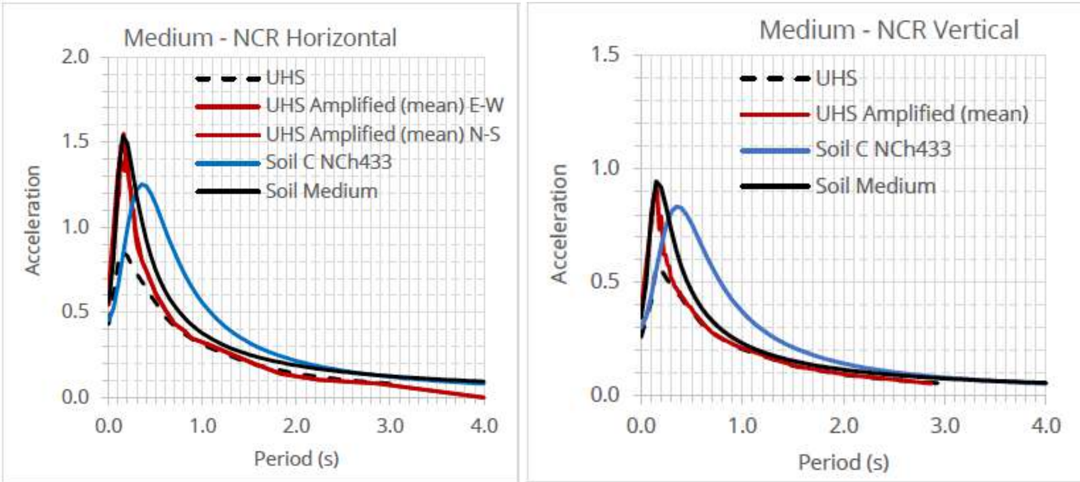


Figure 3.7-1: NCR Horizontal and Vertical Acceleration Response Spectra according to NCh433 (5% damping)

4 Seismic Risk

4.1 General

CTAO represents a unique investment in terms of economical cost, human effort to build and scientific endeavour. Common mode failures associated to weakness in earthquake resistance could potentially knock out large part of the telescopes. The intrinsic value of CTAO-South and the virtual impossibility to replace it demands that such an asset is protected against adverse consequences of natural events. The CTAO South site location, primarily chosen based on scientific and operational reasons, is affected by frequent and important seismic activities. The occurrence of strong earthquakes during the operational life of CTAO has to be expected. The magnitude of the earthquake and their probability are statistically dependent, as shown by the PSHA analysis.

In a simplified way one can state that higher levels of protection against earthquakes can be designed and built into the system, but at an economic and scientific cost. As an example, such cost could be caused using larger cross sections of structural materials, resulting in heavier structures, but reducing the ability of the highly dynamical system to acquire scientific targets. Conversely, the extensive use of lighter but sensibly more expensive materials like Carbon Fiber Reinforced Plastics (CFRP) or sophisticated metal cross sections could recover scientific performance but at non-negligible cost.

The design of the telescopes and their level of seismic protection is therefore a balance between conflicting scientific and economical requirements. The level of protection against earthquakes is therefore associated to the level of risk which can be tolerated by the observatory during its operational lifetime.

When dealing with seismic risk one must consider the damages and the scientific losses which can be caused by the seismic hazard itself. The limit state definitions which are at the basis of the seismic hazard and reported in national norms, have been defined according to criteria associated to civil buildings and infrastructure and the consequences of the onset of specific structural failure criteria in terms of human life, social consequences, and economic cost to society. A similar principle has to be applied to CTAO equipment and telescopes whereby the criteria, beyond the obvious protection against human death and injuries, are of course different than those for residential or public buildings and can be globally linked to a) cost of repair of the product, and b) time loss of scientific operation.

in line with the general requirement of AD01, the quantification of the criteria a) and b) above should be based on classification of hazard severity, their probability and classification as reported in the next Sections[13].

4.2 Risk Estimation

4.2.1 Severity scale

Human safety, cost of repair of the product and loss of operation are listed below as (H), (P) and (O) respectively.

Description	Severity	Operational criteria
Catastrophic	I	(H) Potential fatality (death) (P) Equipment cannot be recovered at a reasonable cost, and/or (O) Equipment is more than three months out of operation
Critical	II	(H) Severe injury, severe occupational illness, in particular with irreversible consequences

[13] The table presented here was originally proposed by ESO in their Risk assessment procedure, not applicable to CTAO, but used as guidance.

		(P) Equipment can be repaired but support from the supplier/industry is necessary, and/or (O) Equipment is up to three months out of operation
Marginal	III	(H) Minor injury, minor occupational illness (P) Equipment can be repaired by ESO staff, and/or (O) Equipment is up to one week out of operation
Negligible	IV	(H) Less than minor injuries, less than minor occupational illness, irritation, no loss of work-days (P) Spare part available on site (O) Equipment is less than one day out of operation

Table 4.2-1 Severity scale classification

4.2.2 Probability scale

Description	**Level**	**Probability of occurrence**	
		Qualitative description	**Quantitative description/year**
Frequent	A	Likely to occur often in the life of an item	$>10^{-1}$
Probable	B	Will occur sometime in the life of an item	10^{-2} - 10^{-1}
Occasional	C	Unlikely, but possible to occur in the life of an item	10^{-4} - 10^{-2}
Remote	D	Very unlikely to be expected in the life of an item	10^{-6} - 10^{-4}
Improbable	E	Extremely unlikely, so that it can be assumed occurrence may not be expected in the life of an item	$<10^{-6}$

Table 4.2-2 Probability scale classification

4.2.3 Risk acceptability

The risk score associated with a hazard combines the severity and the probability of the hazard.

Risk	**Severity**			
	Catastrophic	**Critical**	**Marginal**	**Negligible**
Likelihood (per item per lifetime)	I	II	III	IV
Frequent (A)	IA	IIA	IIIA	IVA
Probable (B)	IB	IIB	IIIB	IVB
Occasional (C)	IC	IIC	IIIC	IVC
Remote (D)	ID	IID	IIID	IVD
Improbable (E)	IE	IIE	IIIE	IVE

Table 4.2-3 Risk acceptability scoring

Risk scores are classified as follows:

- An “unacceptable” risk score (indicated in red in the table above) denotes a serious risk above the limits tolerated by CTAO.
- An “undesirable” risk score (indicated in orange in the table above) shall be lowered or only accepted after written approval by CTAO
- A risk score “acceptable with review” (indicated in yellow in the table above) denotes a medium risk, which can be considered acceptable after CTAO evaluation.
- An “acceptable” risk score (indicated in green in the table above) denotes a low risk within the limits accepted by CTAO.

4.2.4 Application to DLR and NCR for the CTAO Telescopes

4.2.4.1 DLR Case

The case of DLR is classified to have a probability of exceedance of 10% every 10 years for an earthquake with return rate T_R = 95 years. Accordingly the probability of its occurrence over 30 years is P_{30} = 27,1% , and the yearly probability is 1,1% (being ln (1-P_n) = - n/95). As such this event can be classified as an event of probability Level B.

As such, the only acceptable level of risk is *IVB*. To take into account this the limits of table 4.2- 4 below are to be considered as upper limits. Damages beyond these must be agreed by the CTAO Project Office.

Type of risk	Maximum tolerable consequences (after end of earthquake)
Structural damage	• No structural damage. Telescope structure must behave fully elastic. • Camera structure and its support points shall not suffer permanent deformation • No damage to stow pin, if seismic event occurred with telescope parked
Optics damage	• No damage to optics due to collision, or support detachment
Camera damage	• No damage to Photomultiplier or electronics and cabling
Operability	• Camera shutter remaining operational after end of the seismic event, and can be closed remotely • Telescope can be moved on both axes and can be parked with parking script remotely • Brakes can be opened and closed (remotely), stow pins can be inserted (remotely) • Mirror actuators operational and defocusing command can be executed
Breakage	• No system or subsystem breakage. Electrical continuity maintained
Loss of operation	• Maximum loss of operation of one week per telescope due to a) visual inspection and checks, minor realignment *(day-time)*, and b) re-establishment of pointing model *(night-time)*
Injuries	• No injury due to parts falling or detachment of optics or part of it, or others

Table 4.2 - 4: Limit of consequence of a DLR type earthquake

4.2.4.2 NCR Case

The case of NCR is classified to have a probability of exceedance of 10% every 50 years for an earthquake with return rate T_R = 475 years. Accordingly the probability of its occurrence over 30 years is P_{30} = 6,12% , and the yearly probability is 0.21% (being ln (1-P_n) = - n/475]. As such this event can be classified as an event of probability Level C.

As such, the only acceptable level of risk is *IVC*. The level *IIIC* can also be applied, after review and approval by CTAO of the specific analysis of the consequences. To take into account this, the limits of Table 4.2 - 5 below are to be considered as upper limits. Damages beyond these must be agreed by CTAO Project Office.

Type of risk	Maximum tolerable consequences (*after end of earthquake*)
Catastrophic damage	• No overturn or derailing of the structure, no loss of control position on axes, no damage to foundation, no risk of structural buckling
Structural damage	• No sensible structural damage. Telescope structure must behave largely elastically. Localized area of overstresses beyond yield can be tolerated as long as a) not producing any plastic hinge, and b) can be recovered either by structural realignment or local substitution of flanged beams and parts. • Camera structure and its support points shall not suffer permanent deformation • No damage to stow pin if seismic event occurred with telescope parked
Optics damage	• Localized and limited damage to optics, not involving support detachment or falls of mirrors. Maximum damage must be recoverable via existing mirror spares at observatory, (typically < 5% optics)
Camera damage	• No damage to Photomultiplier or electronics and cabling
Operability	• Camera shutter remaining operational after end of the seismic event, and can be closed remotely • Telescope can be moved on both axes and can be parked with parking script remotely • Brakes can be opened and closed (remotely), stow pins can be inserted (remotely) • Mirror actuators operational and defocusing command can be executed • Electrical power to essential services (axes, brakes, stow pins…) must be guaranteed after an earthquake
Breakage	• Minor malfunction of subsystems or parts, as long as spares are available on site. Electrical continuity largely maintained
Loss of operation	• Maximum loss of operation of 6 weeks per telescope, assuming availability of parts on site[14], and available manpower.
Injuries	• No injury due to parts falling or detachment of optics or part of it

Table 4.2 - 5: Limit of consequence of a NCR type earthquake

[14] It is recognized that if parts must be procured (example structural beams) and they have to be shipped to the site this cannot be done within the 6 weeks limit.

5 Concluding Remarks

This document defines:

The seismic loadings to be expected to occur at the CTAO-South site, based on modern geophysical studies, state-of-the-art earthquake engineering, including risk analysis, modelling and computational techniques. Due to the variability of the geotechnical conditions across the site the seismic excitation causes different loadings for the various telescope designs, bases on their planned location[15] and is in particular more demanding for the SST type telescopes.

– The maximum tolerable damage that the various telescopes (structure and cameras) can suffer when exposed to the expected seismic loading has been defined in this document. Deviations from these tolerable damages must be discussed with and specifically agreed by CTAO.

This document does not define:

– The tolerable damage for the technical buildings of CTAO-South. For these buildings only the seismic loading is treated herein. The level of seismic protection (and hence the risk to the CTA Observatory) derives from the application of the relevant Chilean norms. Proposals of relevant parameters influencing the seismic protection have been presented here, and they will need to be endorsed by the final designer.

Other considerations:

This document cannot be considered as a stand-alone document, and its application demands that the computation of the structural effects is performed according to structural normative rules in force and industry-wide accepted methodologies.

– The normative rules associated to the design of telescopes is the set of Eurocode 0 to 9, (Eurocode 8 covering the "Design of structure for earthquake resistance"). The Eurocode set has to be applied in its entirety, which implies application of proper partial factors, and other relevant provisions. For structural analysis methods and partial factors covering the combination of the seismic loading with other loadings (permanent, accidental or variable) reference is made to the CTAO Engineering Analysis standard (document to be issued at the time of writing). The application of the specific importance class (CC2) specified herein constitutes a link to the Norm EN-1090, which therefore become applicable for the execution of welds and the material of welded structures.

– Chilean normative in force shall be applied for the CTAO–South buildings, taking into account the importance factors specified herein.

[15] This is based on the Alpha Configuration of the CTAO South Array