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PRELIMINARY STUDY FOR SEISMIC ASSESSMENT OF THE UNDERGROUND FACILITIES AT POINT 5 OF THE LARGE HADRON COLLIDER (LHC) AT CERN

Ugo Carmando[1], Ahmed Mubarak[2], Antonio Bilotta[1], Emilio Bilotta[3], Jonathan Knappett[2], Saverio La Mendola[4], Martin Gastal[4], Pieter Mattelaer[4], Luca Sironi[4], Davide Merlini[5], Matteo Falanesca[5], Gianluca Bella[5], Filippo Gianelli[5], Marco Andreini[4]

[1] University of Napoli Federico II
Department of Structures for Engineering and Architecture
via Claudio, 21 - Naples, Italy
ugo.carmando@unina.it; antonio.bilotta@unina.it

[2] University of Dundee
School of Science and Engineering
Dundee, United Kingdom
a.mubarak@dundee.ac.uk; j.a.knappett@dundee.ac.uk

[3] University of Napoli Federico II
Department of Civil, Architectural and Environmental Engineering
via Claudio, 21 - Naples, Italy
emilio.bilotta@unina.it

[4] CERN - European Organisation for Nuclear Research
Geneva, Switzerland
saverio.la.mendola@cern.ch; martin.gastal@cern.ch; pieter.mattelaer@cern.ch; luca.sironi@cern.ch; marco.andreini@cern.ch

[5] Pini Group SA
Switzerland
matteo.falanesca@pini.group; filippo.gianelli@pini.group; gianluca.bella@pini.group; davide.merlini@pini.group

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Abstract

The European Organisation for Nuclear Research (CERN) is continuously upgrading its extensive underground facilities to cope with the need for new and more complex experiments. The Large Hadron Collider (LHC) houses the Compact Muon Solenoid (CMS) detector at its Point 5, where there are two large shafts, two 100 m deep major parallel caverns, with a total span of 50 m, separated by a 7 m wide and 28 m high concrete pillar, and a system of secondary tunnels and caverns. Such a complex underground infrastructure lies in a sedimentary rock formation (red molasse) of the Geneva basin, with a low rock cover of about 20 m to the overlying 50 m thick layer of water bearing moraine. The site is classified as a zone of moderate seismicity and the underground structures were designed against a "standard" seismic risk, that corresponds to the importance category II according to Eurocode 8. To study the dynamic response of the caverns to seismic waves, a series of Finite Element (FE) full dynamic analyses have been carried out, where the non-linear behavior of the underground layers has been carefully modelled. A suite of input signals that comply with the design spectrum has been applied to the model. The preliminary results are commented in the paper to define the seismic safety requirement for the sensitive infrastructures and installations located inside the tunnels and caverns.

Keywords: Finite Element Model, Underground Tunnels, Seismic Input Motion, Damping, Dynamic Analyses.

1 INTRODUCTION

In recent years, several researchers carried out analytical and numerical studies concerning various aspects of the behavior of underground structures under seismic excitations in different ground conditions. In parallel, there is a need to properly quantify the structural safety and operativity of the underground facilities of CERN (European Organisation for Nuclear Research), an international research laboratory site at the Franco – Swiss border, in the Geneva basin: more specifically, consisting of linear and circular accelerators, including the Large Hadron Collider (LHC), representing particle physics experiments of international relevance. This paper shows the preliminary results of a study aiming to model and simulate the behavior of two deep caverns of the LHC Point 5, hosting the Compact Muon Solenoid (CMS) experiment, under plane-strain conditions. Stratigraphic and lithological profiles have been simplified on the basis of previous studies [1]. Different seismic input motions were applied to the bedrock.

This study aims to assess the amplification of the ground shaking through the layers up to ground level, as well as to identify the effect of seismic excitations on the cavities' boundaries, to provide a tool to check the seismic safety of the sensitive equipment and installations located inside the mentioned tunnels and caverns.

2 SITE LOCATION AND RELATED SEISMIC HAZARD

The Geneva basin is characterized by crystalline basement rocks and formations of Triassic, Jurassic and Cretaceous ages. It is filled with sedimentary deposits, the so called Molasse, which is overlain by Quaternary glacial moraines. The Molasse comprises horizontally bedded sedimentary deposits layers of marls, limestones, sandstones, sandy marls and marly sandstones, with varying strengths, material properties and layer thickness. The moraine deposits essentially comprise gravels and sands, with varying amount of silt and clay [2]. Located on the border between France and Switzerland, the seismic classification of the site is based on the indications given in the "*Décret no 2010-1254 du 22 octobre 2010 relatif à la prévention du risque sismique*" [3], which subdivides French territory into five seismic zones from very low seismicity (zone 1) to strong seismicity (zone 5). According to the "*Arrêté du 22 octobre 2010 relatif à la classification et aux règles de construction parasismique applicables aux bâtiments de la classe dite 'à risque normal*" [4], LHC point 5 is in zone 3 ("*sismicité modérée*"), Figure 1, and the seismic action, defined in terms of reference peak ground acceleration on type A ground, is about 0.090g, 0.112g, 0.135g and 0.159g respectively for return periods of 243, 475, 821 and 1303 years.

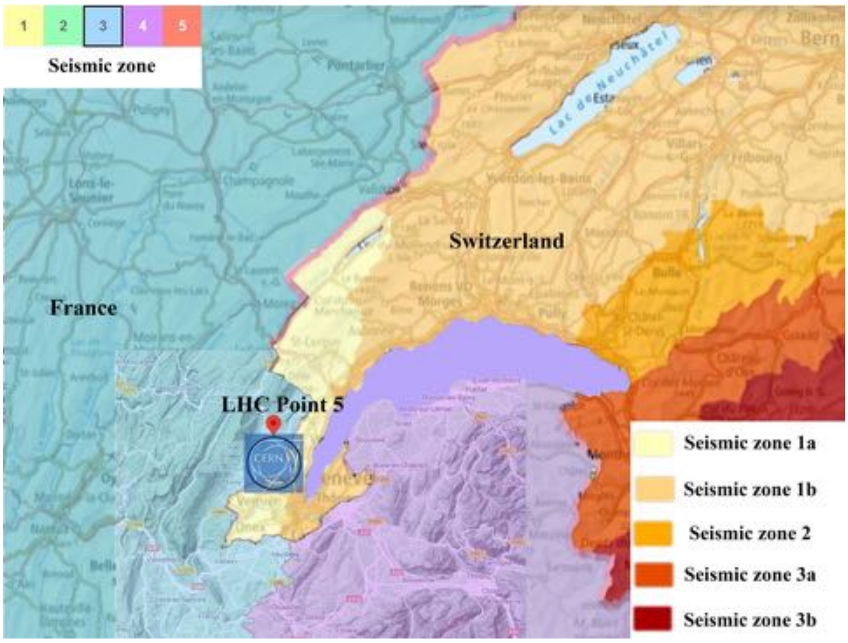


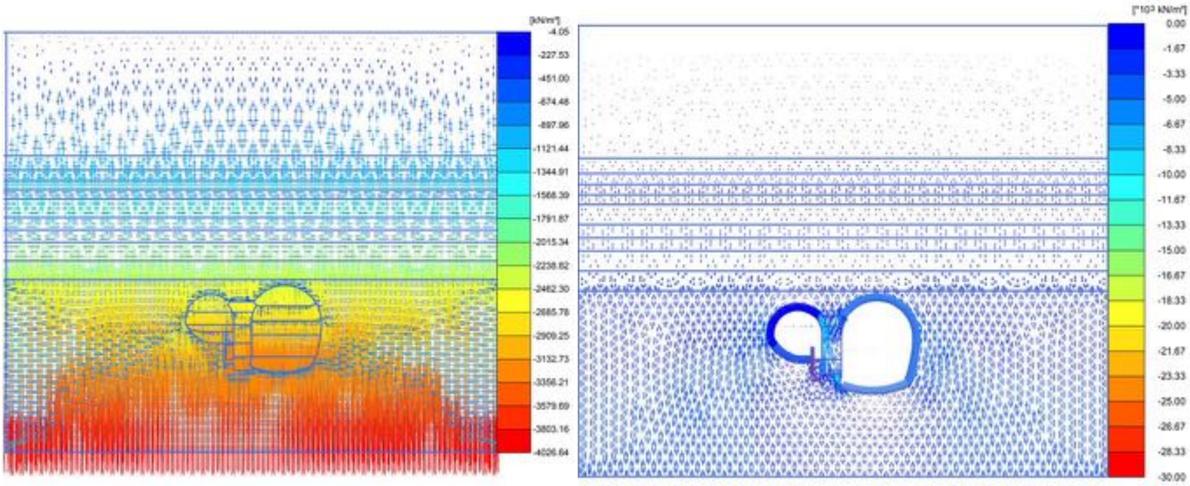
Figure 1. LHC ring: seismic classification and identification of Point 5 where CMS experiment is located.

3 DESCRIPTION OF THE NUMERICAL MODEL

To estimate the response of the large underground cavities under seismic excitations, several fully dynamic analyses have been carried out through the software PLAXIS v20 [5], where non-linear material properties for each soil layer were assigned. The caverns' lining was modelled with elastic plate elements. The vertical boundaries of the model were set at five times the caverns' depth to reduce the effect of boundary wave reflection in the area of interest [6]. This leads the total width of the model to 1 km.

The seismic input signals were retrieved from the Engineering Strong-Motion Database (ESM) [7], in order to be compatible with the horizontal design spectrum foreseen by the Eurocode 8 for a type-A ground, assuming nominal life of 100 years. Hence, the reference peak ground acceleration was scaled to 0.15g.

Once the materials models were defined, a mesh of 15-noded elements was generated (Figure 3) in conformity with the most common element sizing criteria [8]. Five preliminary plastic calculation stages were computed to achieve a realistic stress state in the ground, which included cavities excavation and supports, simulated according to the available documentation (Figures 2a-2b).



a) b)

Figure 2. Stress state in the ground: a) free-field lithostatic conditions and b) post cavities excavation.

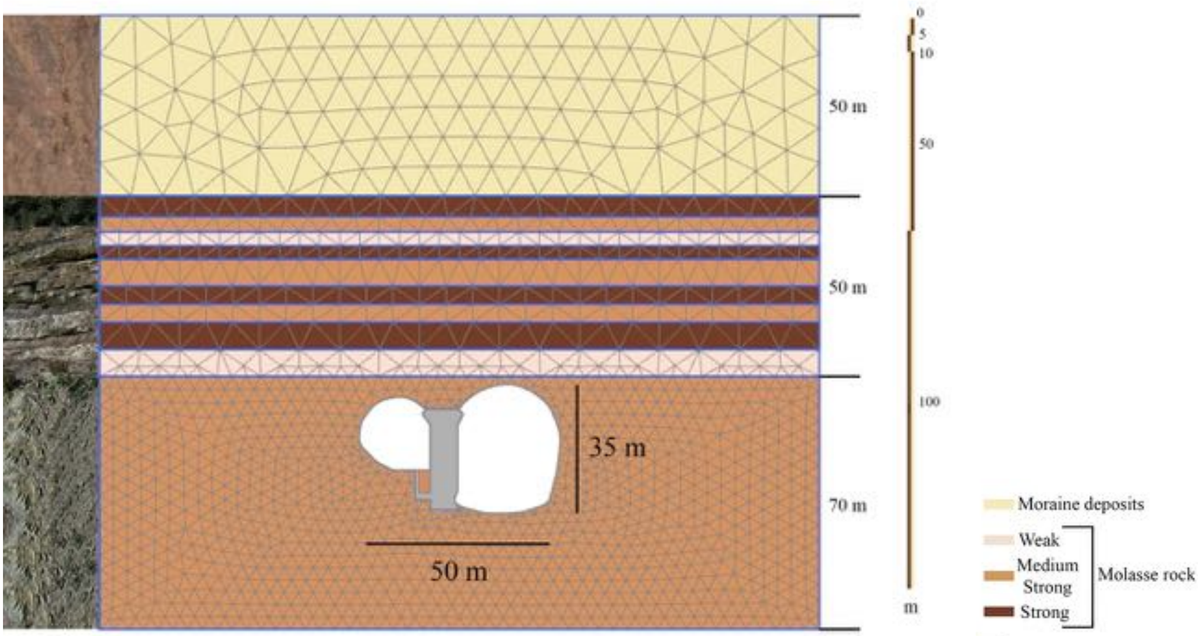


Figure 3. LHC Point 5: stratigraphic and mesh layout.

3.1 FE Model Description

The model is ideally divided into three major layers, starting from the top: a Moraine deposits layer, extending from ground level to 50 m depth; an underlying Molasse rock layer, extending to 100 m depth, divided into sublayers by stiffness; and a medium stiff Molasse rock layer extending a further 50 m to the base of the model. Static boundary conditions were defined restraining the horizontal and vertical displacements at the base and the horizontal displacements at both sides. During the dynamic stages, the input acceleration time history was applied at the base of the model and the lateral boundary conditions were set as equivalent to a free-field condition. The stress-strain behavior of the various materials was modeled using the non-linear elasto-plastic isotropic hardening hysteretic model, known as Hardening Soil model with small strain stiffness (HS small) [9]. HS small model parameters used for the different geotechnical units are: γ_{sat} ,the saturated unit weight; $E_{50}{}^{ref}$, $E_{oed}{}^{ref}$, $E_{ur}{}^{ref}$ the reference secant normal, oedometer and unloading-reloading stiffness moduli respectively, defined at mean effective reference confining pressure of 100 kPa; $G_o{}^{ref}$, the reference shear modulus; $\gamma_{0,7}$, the shear strain at G = 0.7 G_o; ν, the Poisson's ratio; *m*, the exponent for stress – level dependency of stiffness; c'_{ref}, the cohesion; φ', the friction angle; ψ, the dilatancy angle. The model incorporates the increase of damping ratio with strain, D(γ) through its hysteretic formulation, while the damping at very small strain level (D_0) has been modelled using a Rayleigh approach with double frequency control. Tables 1 – 2 report the adopted on the basis of available ground investigation data of previous studies [1].

Parameter	Unit	Moraine	Molasse rock		
			Weak	Med.-strong	Strong
γ_{sat}	kN/m^3	23	24	24	24
E_{50}^{ref}	kN/m^2	30 x 10^3	340 x 10^3	1.2 x 10^6	2.42 x 10^6
E_{oed}^{ref}	kN/m^2	30 x 10^3	340 x 10^3	700 x 10^3	1.8 x 10^6
E_{ur}^{ref}	kN/m^2	60 x 10^3	680 x 10^3	2.4 x 10^6	4.84 x 10^6
G_0^{ref}	kN/m^2	92 x 10^3	2.24 x 10^6	2.72 x 10^6	4.1 x 10^6
$\gamma_{0.7}$	[-]	0.09 x 10^{-3}	1.2 x 10^{-3}	1.2 x 10^{-3}	1.2 x 10^{-3}
c'_{ref}	kN/m^2	0	140	792	1660
φ'	[^{o}]	35	18	50	53
ψ	[^{o}]	0	0	0	0
ν	[-]	0.3	0.25	0.25	0.25
m	[-]	0.5	0	0.7	0.7

Table 1. LHC Point 5: mechanical properties and model parameters for the different layers.

Parameter	Unit	Shotcrete C35/45	Concrete C50/60
γ E	kN/m^3 kN/m^2	25 34.63 x 10^6	25 37.24 x 10^6
EA	kN/m	45 x 10^6	230 x 10^6
EI	kN m^2/m	6.34 x 10^6	739 x 10^6

Table 2. LHC Point 5: mechanical properties for UXC55 cavity walls.

3.2 Seismic Input Motion and Analyses Setup

Table 3 lists the five accelerograms selected from the ESM database. The Newmark time integration scheme was used in the simulations where the time step was constant. A critical time step for dynamic analyses was estimated in order to accurately model wave propagation and reduce the error due to the integration of time history functions, based on the material properties and the element size [5]. The calculation time step is adjusted to this value through sub-stepping. As an example, the first adopted input time history is shown in Figure 4a and the related Fourier spectrum in Figure 4b.

Accelerogram	Event date	Accelerometer registration component	Peak Ground Acceleration [g]	Arias Intensity [m/s]	Bracketed Duration [s]
Friuli	15/09/1976	HNN	0.128	0.095	2.85
Centre Italy	30/10/2016	HNE	0.146	0.183	7.255
Iceland_1	17/06/2000	HN2	0.123	0.165	3.595
Iceland_2	17/06/2000	HN3	0.155	0.192	3.795
Iceland_5	29/05/2008	HN2	0.13	0.112	3.935

Table 3. Selected seismic records.

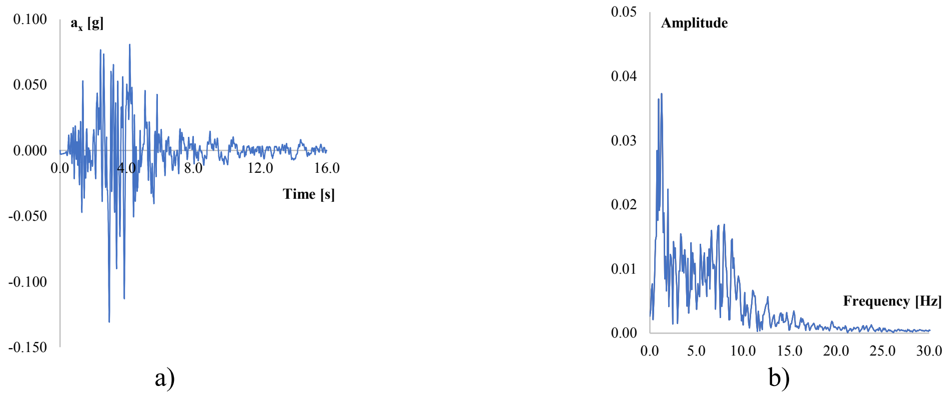


Figure 4. Friuli earthquake input signal: a) time history of the acceleration and the related b) Fourier spectrum.

4 RESULTS

For the sake of brevity, we set a limit herein in presenting the details of the first seismic input considered in this study (i.e., Friuli earthquake of 1976) in Section 4.1. A comparison with the results obtained using the other inputs is presented in Section 4.2.

4.1 Friuli earthquake (1976)

Figure 5 shows a comparison in terms of Pseudo-Spectral Acceleration (PSA) computed along three vertical axes: across the main experimental cavern, 90 m away and 300 m away from it. Acceleration amplification, compared to the bedrock, is calculated towards the ground surface, within the underlying molasse layer (see "Bottom border molasse-molasse"), the layered molasse sequence (see "Upper border moraine-molasse") and the uppermost moraine layer (see "Ground level). The two central axes (0 and 90m) are affected by the presence of the caverns. The basement of the UXC55 cavern shows larger amplification than the surrounding rock at very low periods (peak at 0.15s). Comparing with the point at the roof of UXC55 it seems clear that the response spectra change with the position along the perimeter of the cavern cross-section.

Figure 6 shows the PSA along horizontal axes (ground level, upper border of the layered molasses, bottom border of the layered molasses). It confirms that amplifications larger than under free-field conditions are generally computed around the cavities, within a horizontal distance from the cavern wall of at least two times the value of the cavity height.

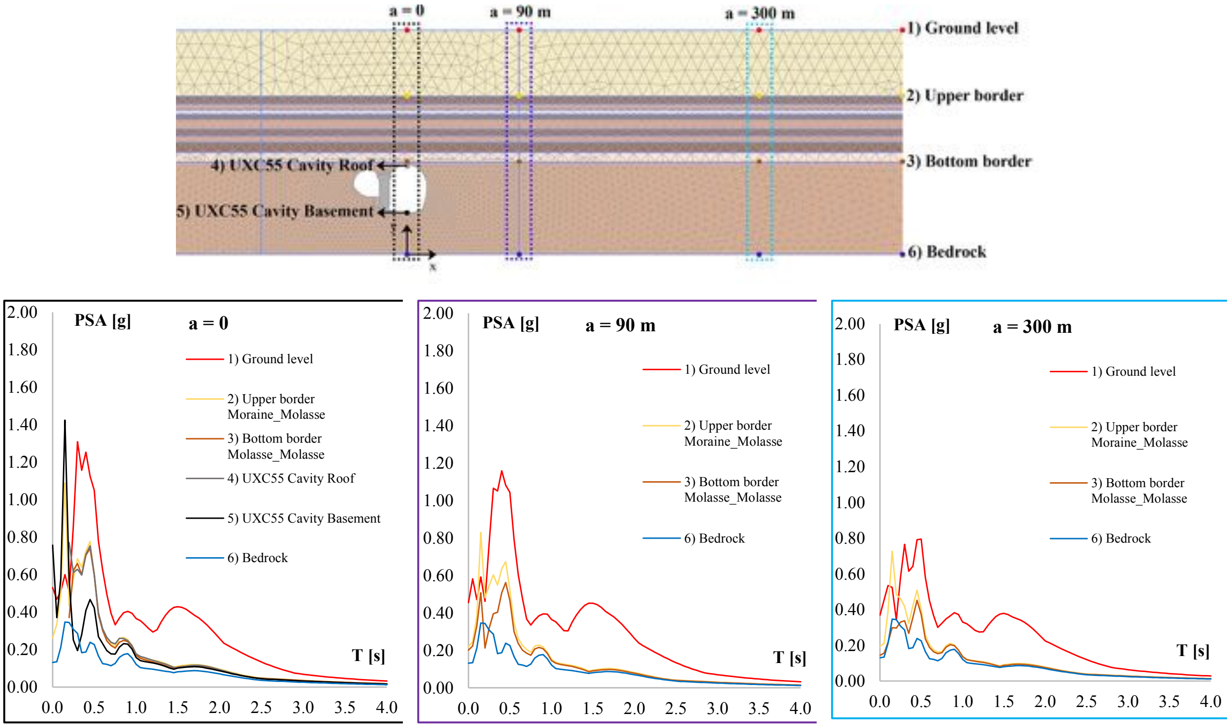


Figure 5. PSA values along vertical arrays, related to Friuli signal, in significative points of the model.

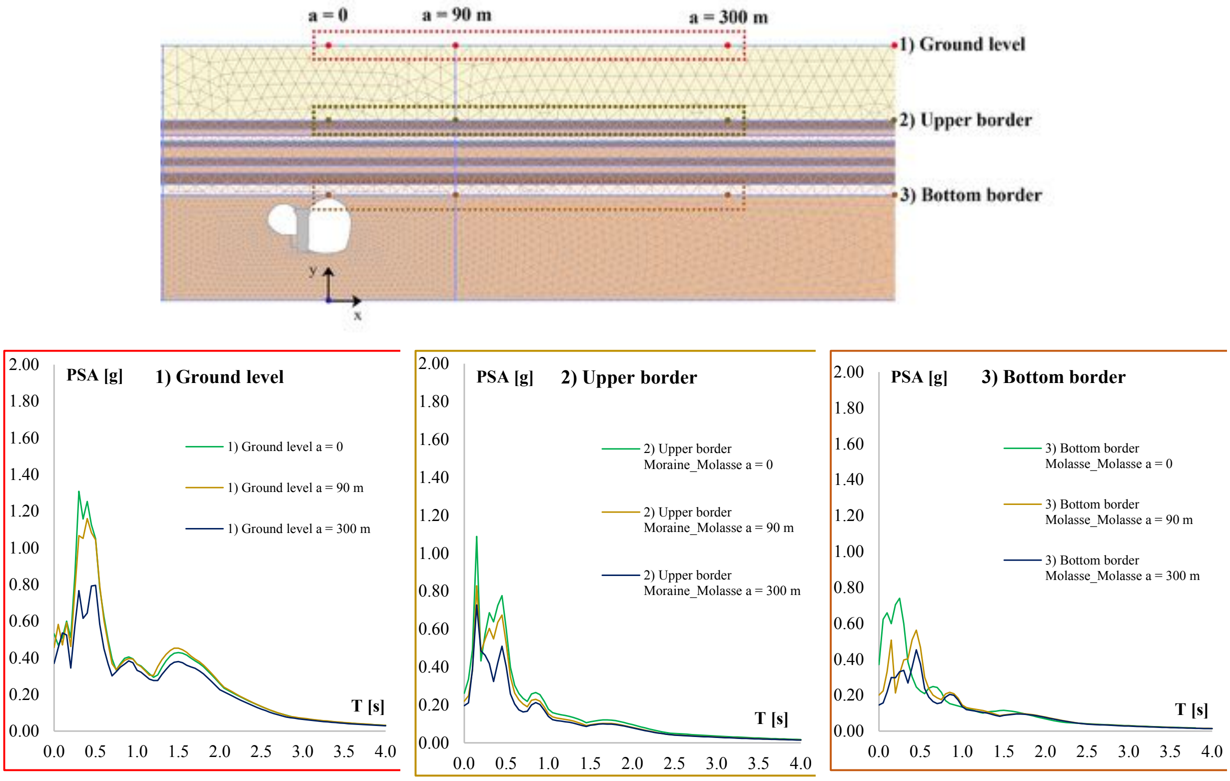


Figure 6. Friuli earthquake PSA values along horizontal axes, computed in significative points of the model.

4.2 Other input motions

The results using the whole set of input signals are plotted in Figure 7 in terms of response spectra. On the cavity perimeter (both basement and roof) the response spectra show a larger peak at around 0.15s, which corresponds to the predominant period of the input signals; a second peak, around 0.5s, appears predominant in the response of the rock layers ('upper border' and 'bottom border'). This seems to indicate a rather rigid response of the cavern system, that could be influenced by the stiff behavior of the 7 m wide / 28 m high concrete pillar that separates the two cavities.

A direct comparison between the mean spectra for the cavity basement and the cavity roof confirms that the spectral response is affected by the position along the perimeter of the cavity cross-section.

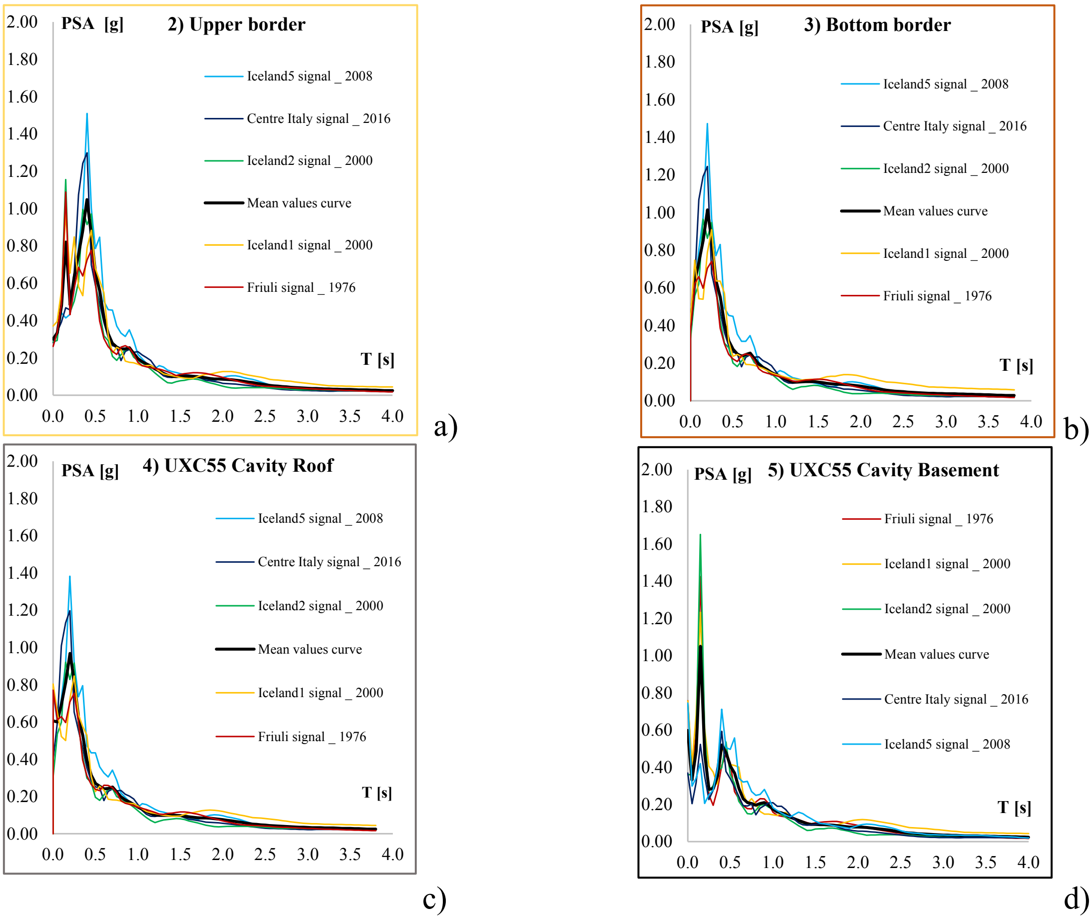


Figure 7. PSA values for the considered seismic inputs at different locations.

5 CONCLUSIONS

The application of a numerical methodology to the main LHC Point 5 underground infrastructures is presented. Several seismic inputs were applied to the bedrock and propagated up to ground level. The effects on the underground cavities in terms of plane-strain conditions have been assessed.

The results of non-linear dynamic analyses show how the seismic response may vary along the perimeter of the cavern cross-sections. Therefore, a thorough assessment of the seismic response of the underground cavities contributes to more accurate estimations of the structural safety and the functional integrity requirements of the hosted equipment and installations, which are unique in their kind and permit a continuous improvement of the human understanding of how the nature of the universe works. Future developments will consider the use of a larger number of input signals to take in due consideration the uncertainties of the seismic hazard in the area. Furthermore, three-dimensional FE analyses will be carried out to investigate possible non-uniform response of the cavities along the longitudinal axis.

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