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SEISMIC VULNERABILITY ASSESSMENT OF CONCRETE BLOCK CONFIGURATIONS FOR RADIATION SHIELDING

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Abstract. *This paper describes the methodology, related steps and results of a research project on the seismic vulnerability assessment for configurations of radiation shielding blocks. The project was mainly carried out in the decade 2012-2022, with the collaboration of several research institutions (i.e., LMGC, EPFL, EUCENTRE and Caltech). First, the research was oriented to calibrate discrete element software for the dynamic behaviour simulations of blocks' configurations by means of full-scale experimental tests. In a second stage, a methodology based on the Incremental Dynamic Analysis (IDA) for the seismic risk assessment was developed. The paper presents also the results of the application of such a methodology to a real case study at CERN.*

Keywords: Concrete Blocks, Discrete Element Models, Incremental Dynamic Analysis, Radiation Shielding, Seismic Vulnerability.

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1 INTRODUCTION

Particle physics research laboratories like the European Organisation for Nuclear Research (CERN) have a duty to protect and shield personnel, equipment and high-technology devices from radiation produced during daily operations, such as those of particle accelerators. The most widespread approach used to achieve the required level of shielding implies the use of concrete blocks with a significant mass [1]. Among similar research centres around the world (i.e., Fermilab and KEK), CERN appears as one of the few that uses these blocks without any joint-connection or any additional metallic bracing system resistant to lateral forces (Figure 1). In this context, if on one hand there are radiation protection safety requirements to be met, on the other hand there is the need to guarantee an adequate level of structural safety of stacked block assemblies under static and dynamic loads, i.e., seismic actions. Although simple block piles might be analysed by means of analytical procedures, more complex block configurations require advanced numerical Discrete Element Models (DEMs) [2] to be assessed. These DEMs shall account for the non-smoothness tied to the frictional contacts between the blocks and the energy dissipation due to friction and eventual shocks, which can occur in case of earthquakes of a certain magnitude. A validation of these models against the results of experimental tests is needed.

This paper deals firstly with the calibration procedure that has been adopted to define the variables of two DEM software applications: the "*Logiciel de Mécanique Gérant le Contact 90*" (LMGC90) [3, 4] and the Level Set Discrete Element Method (LS-DEM) [5], developed respectively at the University of Montpellier and at California Institute of Technology (Caltech). This calibration is based on the results of an experimental campaign carried out on full-scale samples at the European Centre for Training and Research in Earthquake Engineering (EUCENTRE) [6, 7]. In addition, the paper shows the developed methodology for the seismic assessment of complex block configurations based on Incremental Dynamic Analyses [8]. The application of such a methodology to a case-study in a CERN experimental area is finally presented.

2 RESEARCH PROJECT ON THE SEISMIC BEHAVIOUR OF CONFIGURATIONS OF RADIATION SHIELDING BLOCKS

2.1 Standard CERN shielding blocks

The blocks used in the shielding configurations at CERN are made of concrete, steel, or lead. The most used ones are made of precast concrete, having a weight of 77 kN and a standardized parallelepipedal shape of these dimensions: 2.40 x 1.60 x 0.80 m. Several multiples or sub-multiples of this standard shape are used for specific installations on CERN sites. These blocks have been designed according to the norms EN 206-1 [9] and Eurocode 2 [10]. Referring to the nomenclature adopted by such norms, the main characteristics are: concrete quality C40/50, exposure class XC4-XD3-XF3, maximum diameter of the aggregate equal to 32mm, chloride content equal to 0.20, metallic formwork type IV, edge chamfers of 2 cm, and reinforcement steel grade B500B.

2.2 The experimental test campaign at EUCENTRE

The dynamic response of four different configurations of full-scale stacked concrete blocks has been investigated conducting an experimental campaign consisting of shaking table tests. Four different configurations of blocks, whose height varied from 4.8 m to 7.6 m have been assembled in EUCENTRE laboratory and tested (Figure 2). The first and the second configura-

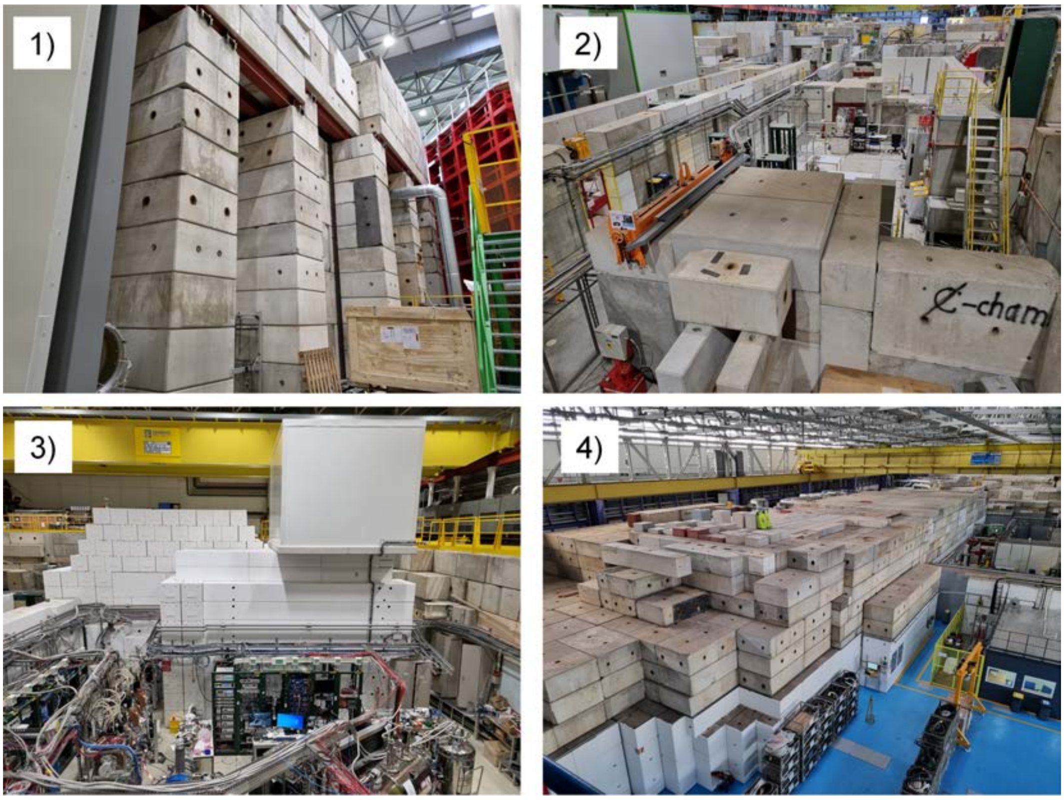

Figure 1: Examples of concrete block configurations at CERN: 1) Beam line shielding in the Neutrino Platform Trenches, 2) Experimental Hall North 1 (EHN1), 3) Bunker of the Gravitational Behaviour of Antimatter at Rest (GBAR) experiment and 4) Proton Synchrotron East Area Facility.

tions consisted of simple piles of respectively three and four stacked blocks. The third and the fourth ones consisted of two piles of four stacked blocks, with a block on the top. The latter was supported by four steel profiles in the fourth configuration.
All configuration specimens were assembled on a base concrete slab, fixed to the platform of the testing shaking table. Two acceleration time-histories, called Alkion and Basso Tirreno, typical of the Mediterranean region, have been applied at the base of the configuration specimens with increasing amplitude levels. The full description of this experimental test campaign is available in [6].

2.3 Calibration of numerical model variables

2.3.1 Brief introduction to LMGC90 and LS-DEM

LMGC90 is an open-source software, developed by the Mechanical and Civil Engineering Laboratory (LMGC) of the University of Montpellier and of the French "*Centre National de la Recherche Scientifique*" (CNRS). The software implements the Non-Smooth Contact Dynamic Discrete Element Method.
"*The LMGC90 software is dedicated to the modelling of large object collections in interaction. It enables to simulate complex systems thanks to sophisticated and very detailed models. Each object modelled is defined throughout its own geometry and a proper behaviour is associated to each body. A wide range of models (rigid, elastic, viscoelastic, etc.) may be used to model objects behaviours. Moreover, behaviours between objects are modelled by using many contacts*

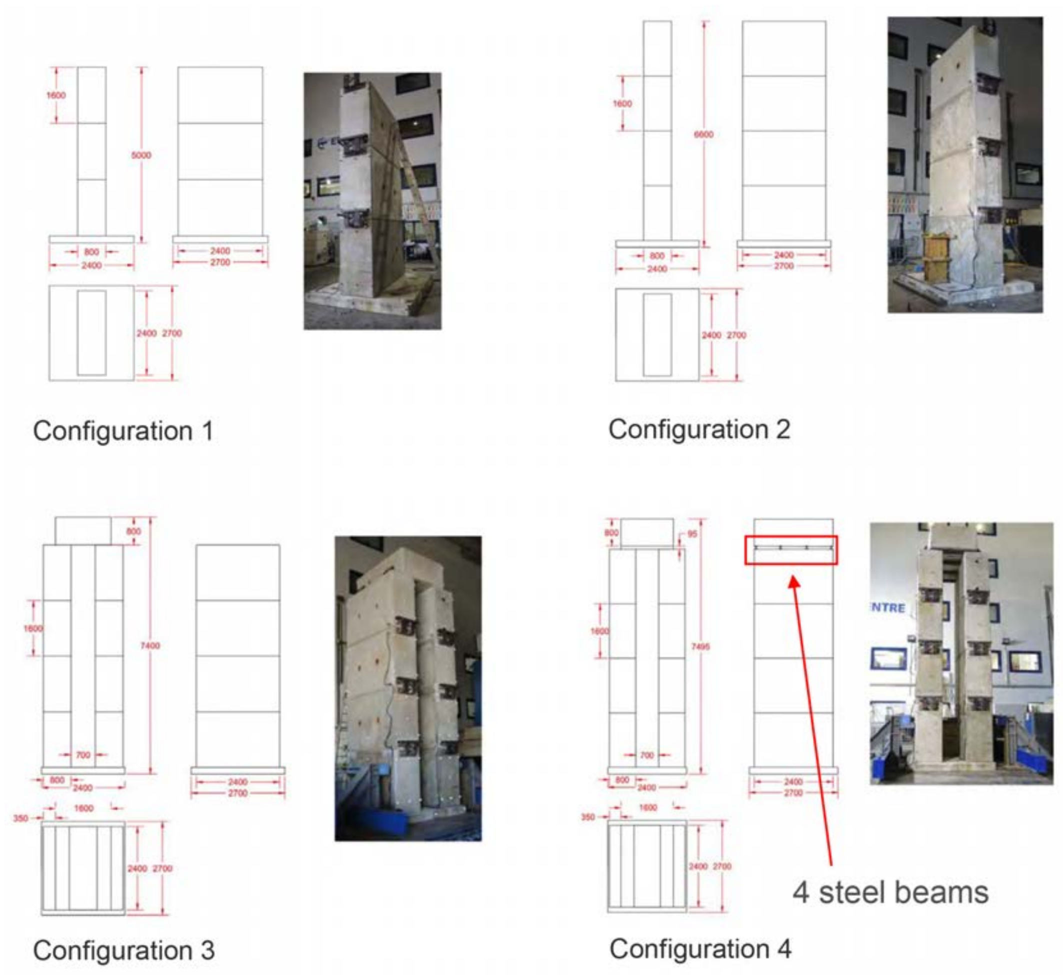

Figure 2: The four blocks' configurations tested at EUCENTRE, Pavia-Italy in 2019

laws"[3, 4].
LS-DEM is a software developed by the Cosymo Laboratory of Caltech.
"*LS-DEM is a discrete element method variant able to simulate systems of particles with arbitrary shape using level set functions as a geometric basis. LS-DEM is similar to the classic discrete element method (DEM) in that it simulates the kinematics and mechanics of a system of discrete particles, with the only difference being its ability to capture arbitrary shape as opposed to only spheres as in DEM*" [5].

2.3.2 Calibration procedure

A semi-probabilistic approach was adopted to calibrate the input variables of numerical models developed with LMGC90 and LS-DEM. Models of the tested configuration specimens have been generated with both software applications. The geometrical variables have been treated as deterministic while the main mechanical ones (e.g., friction coefficients, material densities, moduli of elasticity, etc.) have been considered as random and, therefore, described by distribution models. This approach was chosen mainly because of the large variation of the friction coefficients of concrete-concrete and steel-concrete presented in the technical literature. A Correlation Controlled Latin Hypercube Sampling methodology [11] was used to sample values from the mechanical variables' distributions. Such a methodology was chosen because it's effi-

cient and accurate for small sample sizes. Indeed, in the preliminary analyses, it was observed that 20 samples would have been reasonably acceptable in terms of achieving an appropriate level of accuracy. The calibration procedure consisted in tuning the mechanical variables' distribution parameters (i.e., the mean, the standard deviation (SD) and, consequently, the coefficient of variation (C.o.V.)) and checking whether the numerical models' analyses results, in terms of maximum and minimum block displacements, were compatible with those observed experimentally for the four tested configurations.
The final set of variable distribution parameters that provided the most satisfactory results are shown in Table 1.

Variable	Distribution Model	Mean	SD	C.o.V.
Friction Concrete/Concrete [-]	Log-normal	0.75	0.075	0.1
Friction Concrete/Foundation [-]	Log-normal	0.75	0.075	0.1
Friction Steel/Concrete [-]	Log-normal	0.3	0.03	0.1
Concrete Density [kg/m^3]	Log-normal	2400	96	0.04
Concrete Young's Modulus [Pa]	Log-normal	3.45E+10	5.175E+09	0.15
Concrete Viscous Modulus [Pa]	Log-normal	1.5E+08	2.25E+07	0.15
Steel Density [kg/m^3]	Log-normal	7700	77	0.01
Steel Young's Modulus [Pa]	Log-normal	0.21E+12	6.3E+09	0.03
Steel Viscous Modulus [Pa]	Log-normal	0.21E+10	6.3E+07	0.03

Table 1: Model variables' distributions and related parameters obtained after the calibration process [7].

3 SEISMIC VULNERABILITY ASSESSMENT OF BLOCK CONFIGURATIONS

3.1 Introduciton to Seismic hazard and design requirements for CERN

3.1.1 Seismic hazard models for CERN territory

Seismic hazard identification is the subject of continuous updates. Considering the scope of this paper, we define a limit by referring to the web-platform developed by the European Facilities for Earthquake Hazard and Risk (EFEHR), which is accessible at `http://hazard.efehr.org/en/home/`. Such a platform provides access to interactive tools such as seismic hazard models, products and information. Distributed data, models, products and information are based on research projects carried out by academic and public organisations. For instance, Figure 3a shows the map of the CERN region indicating the spectral horizontal acceleration at 5 Hz as per the European Seismic Hazard Model 2020 (ESHM2020)[12], for a seismic event having a Probability of Exceedance (POE) of 10% in 50 years (POE 10%50years). Figure 3b shows the seismic hazard curve for the CERN Globe of Science according to ESHM2020.

3.1.2 Seismic Design and Assessment Requirements

According to the French "*Décret n°2000-892 du 13 septembre 2000*" [13], new constructions or constructions submitted to important modifications in seismic regions shall comply with the applicable seismic design requirements. CERN does not have a specific internal seismic safety rule in force at present and, consequently, regulations of Host States (France and Switzerland) are considered as applicable. In particular, the French "*Décret no 2010-1254 du 22 octobre 2010*" [14] foresees that buildings, equipment and installations "à risque normal" are those for

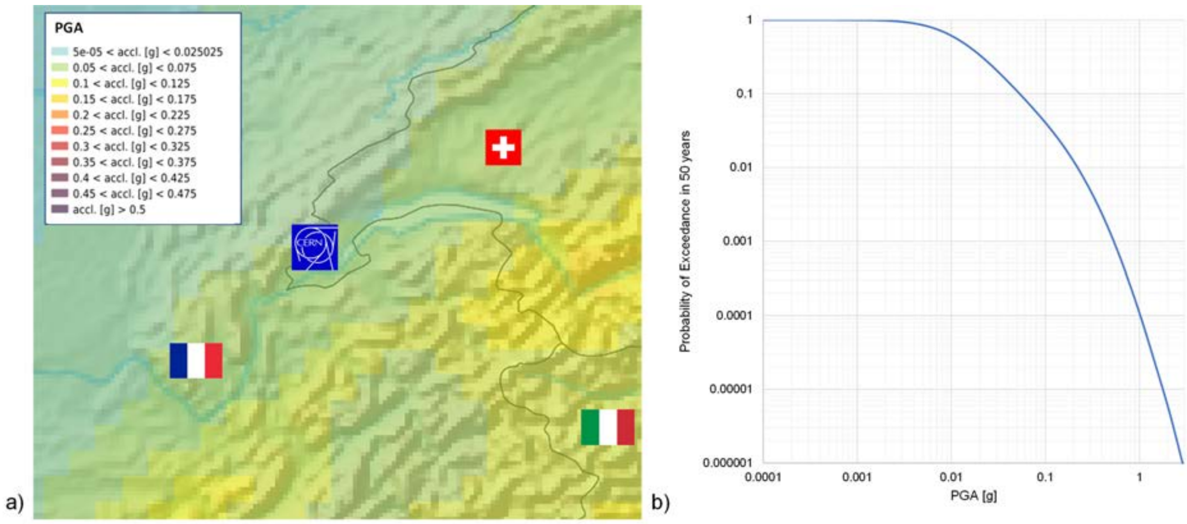

Figure 3: a) Seismic Hazard Map for CERN region: spectral horizontal acceleration at 5 Hz as per ESHM2020, for a seismic event having a POE 10%50years. b) Seismic Hazard Curve for the CERN Globe of Science and Innovation: Peak Ground Acceleration (PGA) versus O in 50 years as per ESHM2020.

which the consequences in the event of an earthquake are limited to an area within the vicinity. Buildings, equipment and installations for which the consequences in case of an earthquake may have an impact outside the vicinity, due to explosions, pollution or fire, are classified as being "*à risque special*". According to [14], French territory is divided in five seismic zones from very low seismicity (seismic zone 1) to strong seismicity (seismic zone 5). CERN is included in seismic zone 3 ("*sismicité modérée*"), according to the French "*Arrêté du 22 octobre 2010*" [15]. For such a zone, Peak Ground Acceleration (PGA) values to be used in the structural design and assessment at the Ultimate Limit State (ULS) are given. For the sake of example, the PGA for buildings belonging to the Importance Class II (e.g. residential buildings, office and commercial purpose buildings, etc.), realised on type-A ground soil, is equal to 1.10 m/s^2. Such a value corresponds to a seismic event having a POE 10%50years and represents the life-safety requirement foreseen for this kind of buildings.

In case of buildings or infrastructures having more (or less) severe consequences in case of failure, the mentioned value of the PGA shall be magnified (or reduced) by a so-called Importance Factor γ_I, which allows to account for POE and reference periods different to those mentioned above. The role played by the different ground soils is also accounted for, applying a PGA multiplication factor *S*. To account for the different vibration frequencies/modes, it is prescribed to use the shapes of the elastic response spectra of the horizontal and vertical accelerations as defined in the norm Eurocode 8 [16]. As the Eurocode 8 (together with the related National Determined Parameters [17]) is also applicable in the Swiss territory of CERN and for the sake of brevity, the description of the Swiss regulation seismic assessment approach is omitted in this paper. The reader is invited to refer to the SIA 260 and 261 [18, 19] for all the related information.

3.2 Seismic Vulnerability Assessment of Block Configurations by IDA

IDA is a computational analysis method of earthquake engineering to achieve an assessment of the dynamic behaviour of structures, with respect to a time-history input [8]. IDA methodology requires to perform multiple nonlinear dynamic analyses of a structural model, under a series of ground motion records, each of them scaled to several levels of seismic intensity. The scaling levels are selected to force the structure through the entire range of behaviour, from rigid to dynamic instability and collapse. The seismic risk assessment procedure for shielding block configurations consists essentially in selecting the basic accelerograms, generating the mechanical models, running the IDA, post-processing the obtained results and comparing with the acceptance thresholds. These phases are described in the following sub-sections.

With the intention to be as compliant as possible with the French "*Arrêté du 22 octobre 2010*" [15], we refer to the shapes of the Type-I elastic response spectra of the acceleration indicated in the Eurocode 8 [16]. We retrieve from the European Strong Motion (ESM) database (`https://esm-db.eu/#/rexel`) [20] 7 sets of 3-component accelerograms (2 horizontal and 1 vertical) compatible with such spectra.

It is worth mentioning that, with regards to section 2.3.2 of this paper, the mechanical variable distributions and the 20 related samples have to be considered to create the same number of models with LMGC90 or LS-DEM.

The process to run IDA on block configuration models involves the following stages:

1. Identify the blocks to be monitored, representative of the most probable failure mechanism.
2. Select a 3-component accelerogram among the 7 compatible with the elastic response spectra foreseen for the location of interest.
3. Normalize such an accelerogram to the PGA of the main horizontal component .
4. Create a range of Scale Factors (SCFs), e.g. [0.02, 0.04, . . . , 1], and generate as many sets of scaled 3-component accelerograms as the number of the considered SCFs.
5. Run a non-linear dynamic analysis for each model (generated for every sample – see section 2.3.2) subjected to every scaled 3-component accelerogram (point 4).
6. Collect the results in terms of Damage Measure (DM) (i.e., maximum relative and residual displacement vector) for every generated model and each monitored block.
7. Display on the same graph the DM results in function of the earthquake Intensity Measure (IM) (e.g., PGA) corresponding to the related SCF for each model (IDA curves).
8. Calculate the DM median and relevant percentiles for any considered IM value.
9. Repeat the procedure from point 2 for each of the other 6 accelerograms.

Referring to section 3.1, the overall seismic risk assessment of a block configuration can be carried out comparing the IDA curves for the monitored blocks with the hazard curve, expressed in terms of the same IM for the related reference period (e.g., the lifetime of the experiment/equipment to be shielded) and location. This way one can link the respective DM value to a frequency of occurrence or a POE and see whether this is acceptable or not. In case one or more couples DM – POE/frequency are unacceptable, one can either decide to modify the block configuration or reduce the lifetime of the concerned experiment/equipment.

4 CASE STUDY: BUNKER AT THE EXPERIMENTAL HALL NORTH 2 (EHN2) OF CERN

EHN2 hosts the Apparatus for Meson and Baryon Experimental Research (AMBER). In particular, the measurements of the so called Drell-Yan processes requires an experimental setup that concerns the use of a significant radiation shielding mass. A bunker concerning 155 blocks in concrete and steel is foreseen to be realised. Its dimensions in plan are 7.1m x 6.4m, the maximum height is 7.2m and the total mass is 727.7 tons (see Figure 4).

EHN2 appears as an ordinary industrial building. As foundation, EHN2 has a shallow concrete slab laying on a type-E soil, according to the Eurocode 8 [16], for which an amplification

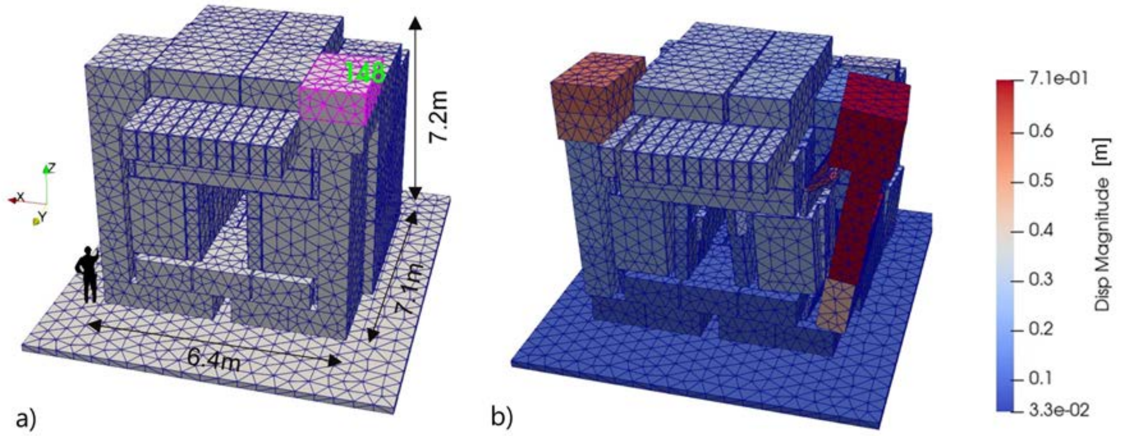

Figure 4: The EHN2 Bunker: a) The LMGC90 rigid block mechanical model, indicating dimensions and the monitored Block #148; b) Block configuration kinematisms expected for one of the earthquake among the 7 considered scaled up to a PGA = 1g, using the median value of the mechanical properties indicated in the Table 1.

factor S=1.8 is adopted. Keeping this normative reference, we considered earthquakes having a POE 10%50years, which corresponds to the ULS requirement for buildings of Importance Class II, as per French "*Arrêté du 22 octobre 2010*" [15]; this is linked to an Importance Factor γ_I=1 [16]. Figure 5 shows the resulting elastic response spectrum of the horizontal acceleration and those of the natural acceloragrams obtained by the ESM [20], related to the 7 earthquakes (sets of 3 accelerograms) considered in this seismic assessment.

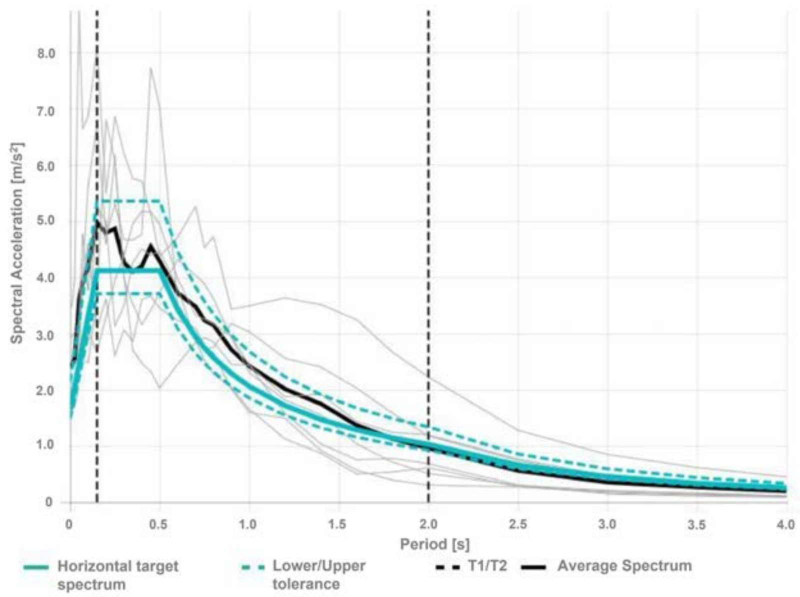

Figure 5: Response spectra of the horizontal acceleration conisdered in the EHN2 bunker assessment: Aqua-color continous line represents the shape of the elastic spectrum given by Eurocode 8 considering a PGA = 1.98 m/s^2, value obtained by amplifying the PGA(POE 10%50years for type-A soil) 1.1 m/s^2 by the factor S(type-E soil) = 1.8. Gray lines are the compatible spectra of the 7 earthquakes obtained by ESM [20] and considered in the assessment.

The IDA curves for the first set of 3 accelerograms are shown in Figure 6, where the horizontal axis shows the DM expressed in terms of maximum relative displacement of a monitored block along a certain direction; the vertical axis shows the IM in terms of PGA; the 20 IDA

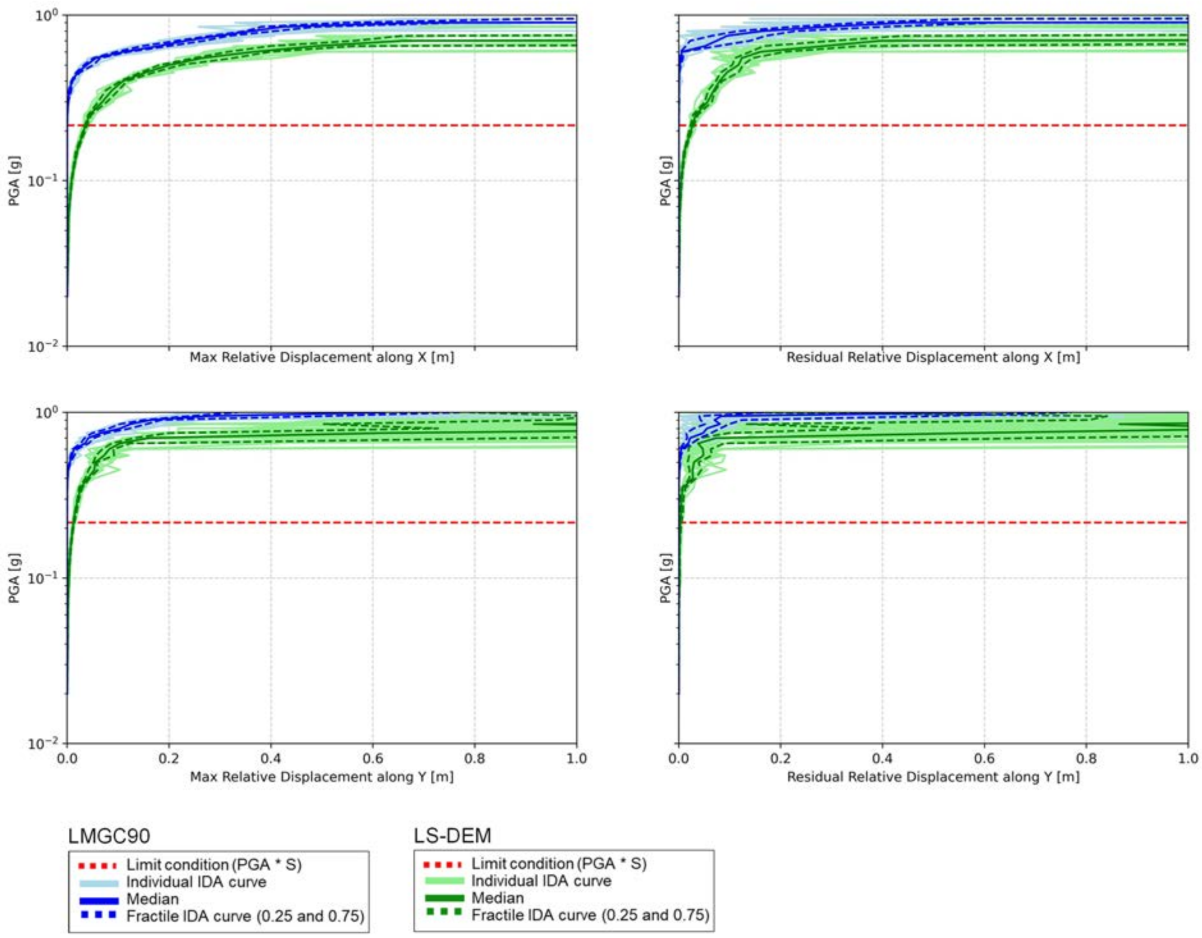

Figure 6: IDA curves for the Block #148 of the EHN2 bunker, subjected to the first set of scaled accelerograms among the 7 considered.

curves for each analysed model with the related variable sample are respectively in light blue for LMGC90 and green for LS-DEM. The darker continuous lines are the median value while the dashed-lines correspond to the 25th and 75th percentiles; the horizontal red dashed-line is the reference PGA (POE 10%50years).

From the comparison plot of IDA curves between LMGC90 and LS-DEM, it can be seen that LS-DEM model yields the same relative displacement at a lower PGA value. Given the different nature of the two simulation methods, differences between results can be expected. Compared to tested configurations with a maximum of 9 blocks in [7], the system simulated here has over 100 blocks, which significantly increases the modeling complexity and hence results in greater deviations between the two simulation methods. Furthermore, LMGC90 implements non-smooth contact. Shear force is zero in the static friction regime and jumps instantly to some value upon sliding. In the contrary, in LS-DEM, shear force increases linearly until sliding starts, resulting in non-zero shear force even in the static friction regime. Consequently, a small distance in shear direction could be present even at low PGA.

5 CONCLUSIONS

This research project aimed to define a seismic risk assessment methodology for configurations of radiation shielding blocks carried out during 2012-2022, with the collaboration of several institutions (i.e., Université de Montpellier, EPFL, EUCENTRE and Caltech). Starting from the seismic hazard defined for CERN territory, the variables of advanced numerical models for the seismic analyses were calibrated by experimental tests. A seismic risk assessment procedure based on IDA was developed. The case study of the AMBER bunker in the Experimental Hall North 2 (EHN2) of CERN has been finally presented, highlighting the difference in results obtained by using LMGC90 and LS-DEM.

REFERENCES

[1] M.F. Kaplan, *Concrete Radiation Shielding: Nuclear Physics, Concrete Properties, Design and Construction*. John Wiley Sons, 1989.

[2] P.A. Cundall, Formulation of a three-dimensional distinct element model—Part I. A scheme to detect and represent contacts in a system composed of many polyhedral blocks. *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, **25(3)**, 107–116, 1988.

[3] M. Jean, The non-smooth contact dynamics method. *Computer Methods in Applied Mechanics and Engineering*, **177(3)**, 235–257, 1999.

[4] F. Dubois, V. Acary, M. Jean, The Contact Dynamics method: A nonsmooth story. *Comptes Rendus Mécanique*, **346(3)**, 247–262, 2018.

[5] R. Kawamoto, E. Andò, G. Viggiani, J.E. Andrade, Level set discrete element method for three-dimensional computations with triaxial case study. *Journal of the Mechanics and Physics of Solids*, **91**, 1–13, 2016.

[6] L. Sironi, M. Andreini, C. Colloca, M. Poehler, D. Bolognini, F. Dacarro, P. Lestuzzi, F. Dubois, Z. Zhou, J.E. Andrade. Shaking table tests for seismic stability of stacked concrete blocks used for radiation shielding. *Paper currently under review*.

[7] Z. Zhou, M. Andreini, L. Sironi, P. Lestuzzi, E. Andò, F. Dubois, D. Bolognini, F. Dacarro, J.E. Andrade. Discrete Structural Systems Modeling: Benchmarking of LS-DEM and LMGC90 with Seismic Experiments. *Paper currently under review*.

[8] D. Vamvatsikos , C.A. Cornell, Incremental Dynamic Analysis. *Earthquake Engineering and Structural Dynamics*, **31(3)**, 491–517, 2002.

[9] European Committee for Standardization (CEN). EN 206-1:2000 - Concrete - Part 1: Specification, performance, production and conformity.

[10] European Committee for Standardization (CEN). EN 1992-1-1:2004 - Eurocode 2 - Design of concrete structures - Part 1-1: General rules and rules for buildings.

[11] M. Vořechovský, D. Novák, Correlation control in small-sample Monte Carlo type simulations I: A simulated annealing approach. *Probabilistic Engineering Mechanics*, **24(3)**, 452–462, 2009.

[12] L. Danciu, S. Nandan, C. Reyes, R. Basili, G. Weatherill, C. Beauval, A. Rovida, S. Vilanova, K. Sesetyan, P-Y. Bard, F. Cotton, S. Wiemer, D. Giardini, The 2020 update of the European Seismic Hazard Model: Model Overview. *EFEHR Technical Report 001, v1.0.0*, 2021.

[13] *Décret n° 2000-892 du 13 septembre 2000 portant modification du code de la construction et de l'habitation et du décret n° 91-461 du 14 mai 1991 relatif à la prévention du risque sismique* (in French).

[14] *Décret n° 2010-1254 du 22 octobre 2010 relatif à la prevention du risque sismique* (in French).

[15] *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* (in French).

[16] European Committee for Standardization (CEN). EN 1998-1:2004 - Eurocode 8 - Design of structures for earthquake resistance - Part 1 : General rules, seismic actions and rules for buildings.

[17] Swiss Society of Engineers and Architects. SN EN 1998-1:2019 - Eurocode 8 - Design of structures for earthquake resistance - Part 1 : General rules, seismic actions and rules for buildings - National Annex to SN EN 1998-1:2004.

[18] Swiss Society of Engineers and Architects. SIA 260. Basis of Structural Design. 2013.

[19] Swiss Society of Engineers and Architects. SIA 261. Actions on Structures. 2020.

[20] S. Sgobba, R. Puglia, F. Pacor, L. Luzi, E. Russo, C. Felicetta, G. Lanzano, M. D'Amico, R. Baraschino, G. Baltzopoulos, I. Iervolino. REXELweb: a tool for selection of ground-motion records from the Engineering Strong Motion database (ESM). *7th International Conference on Earthquake Geotechnical Engineering (ICEGE)* 17 - 20 June 2019, Roma, Italy.