MEDEA

Multidimensional seismic risk assessment through explainable artificial intelligence

Deliverable 3.1.: Benchmark structures, their classes, and EDPs

MULTIDIMENSIONAL SEISMIC RISK ASSESSMENT COMBINING STRUCTURAL DAMAGES AND PSYCHOLOGICAL CONSEQUENCES USING EXPLAINABLE ARTIFICIAL INTELLIGENCE

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Abstract	This deliverable provides criteria used to define classes of structures (masonry and reinforced concrete structures, and geotechnical systems). For each class, technical parameters are defined to describe the reference structures. The technical parameters are geometrical and mechanical properties and those related to seismic analysis. In addition, Engineering Demand Parameters (EDPs) are defined for the reference structures in order to have a representative overview of the effect of the seismic action on the structural elements. Typical EDPs are the chord rotation, inter-story drift, and internal forces of the structural elements. EDPs are used to obtain the peak ground acceleration corresponding to the attainment of predefined levels of damage. Finally, after identifying the reference structure and consequently its technical parameters, the range of variation of the technical parameters was defined in order to generate the dataset related to the chosen classes of structures.
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ABBREVIATIONS

MEDEA	**Multidimensional Seismic Risk Assessment Combining Structural Damages And Psychological Consequences Using Explainable Artificial Intelligence**
EDP	Engineering Demand Parameter
PGA	Peak Ground Acceleration
RC	Reinforced concrete
IO	Immediate Occupancy
LS	Life Safety
DC	Damage Control
CP	Collapse Prevention
XAI	eXplainable Artificial Intelligence

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1. INTRODUCTION

The overarching goal of the MEDEA project is to enhance cross-border disaster risk management by focusing on prevention and preparedness in Europe and neighboring EU countries. Specifically, the project aims to mitigate the impact of seismic events and enhance resilience, defined as the capacity to withstand, absorb, adapt to, and recover from earthquakes efficiently and promptly. To achieve this objective, the project proposes developing an intelligent system for multidimensional seismic risk assessment in cross-border regions. Using artificial intelligence, this system aims to estimate earthquake-induced losses by predicting structural damage, such as building collapses, while also forecasting the psychological ramifications for affected individuals. Integrating psychological consequences, the project will investigate familial and individual factors and relational and contextual aspects that may exacerbate psychological distress among family members in the aftermath of seismic events. By assessing potential medium and long-term psychological effects on those involved in earthquakes, the project seeks to identify high-risk families susceptible to psychological distress, thereby anticipating and preventing the onset of post-traumatic stress disorder (PTSD).

Within the framework of the MEDEA project, the specific objectives Work Package 3 "*Benchmark structures, EDPs, and representative families*" are: i) Identification of benchmark structures; ii) Selection and calculation of the best EDPs to quantify the effect of seismic actions on structures; iii) Identification of the representative families. This deliverable focuses on the definition of classes of structures having similar characteristics in terms of materials and geometry, the definition of the EDPs used to quantify the effects of seismic actions, and the criteria used to define benchmark structures and to determine the values of their EDPs.

This deliverable is organized as follows: Section 2 presents the structural approach used; Section 3 presents the criteria used to define classes of structures; Sections 4-6 presents the masonry, reinforced concrete, and geotechnical benchmark structures, respectively. For each type of structure, three sub-Sections focusing on the technical parameters, the engineering demand parameters, and the datasets of benchmark structures, respectively, are included. Section 4 draws the conclusions.

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2. APPROACH FOR THE EVALUATION OF DAMAGES

Referring to buildings, the response of a structure subjected to a seismic event of a given intensity is usually evaluated by means of Engineering Demand Parameters (EDPs). Typical EDPs are the internal forces on structural elements and relative displacements measuring the deformation of individual structural elements or the entire structure. Based on the values of the EDPs attained during a seismic event, the level of damage of the structure can be estimated.

Typically, four level of damage, D1, D2, D3, and D4 [1] are considered for building structures (Figure 1):

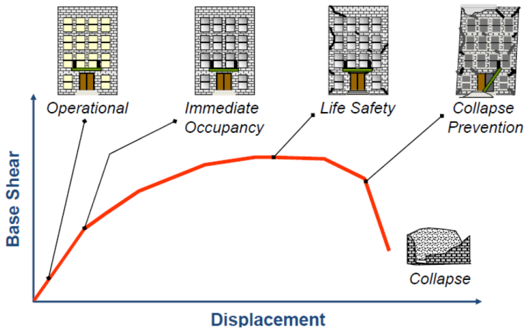

Figure 1. Effect of seismic action [2].

- <u>D1 - Immediate Occupancy (IO)</u>

  In this state, the structure experiences minimal to no damage during the seismic event. The building remains fully functional and safe for occupancy immediately after the earthquake. The structural response tends to be linearly elastic, meaning that the structure behaves within the elastic range of its materials. No immediate repair is required for the building to resume normal operations.

- <u>D2 - Life Safety (LS)</u>

  The structure exhibits moderate damage and is still safe for occupancy. Occupants can evacuate safely during the earthquake. Some repair work may be needed to non-structural elements even though the structural integrity remains intact.

- <u>D3 - Damage Control (DC)</u>

  The structure exhibits significant damage and is temporarily unusable. Occupants must evacuate the building due to safety concerns. Extensive repair work is required before reoccupation.

- <u>D4 - Collapse Prevention (CP)</u>

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The structure has incurred severe damage that compromises its integrity. There's a high risk of imminent collapse, and the building needs to be evacuated. Repair may not be feasible, and demolition or significant reconstruction is necessary.

The approach used within MEDEA project is based on the determination of the peak ground accelerations (PGAs) producing the aforementioned levels of damage. These PGAs are referred to as capacity PGAs and denoted with PGA_{D1}, PGA_{D2} PGA_{D3}, and PGA_{D4}, respectively. The capacity PGAs can be determined based on the EDPs which can be evaluated by means of nonlinear finite element pushover analysis. In pushover analyses, the displacement of a control point (typically the center of mass of the upper floor, named top displacement) is monotonically increased and the total lateral force, named base shear, associated with any displacement is computed. Figure 2 shows a typical base shear-top displacement response. The points corresponding to the levels of damage considered are determined based on the values of the EDP during the increase of the top displacement.

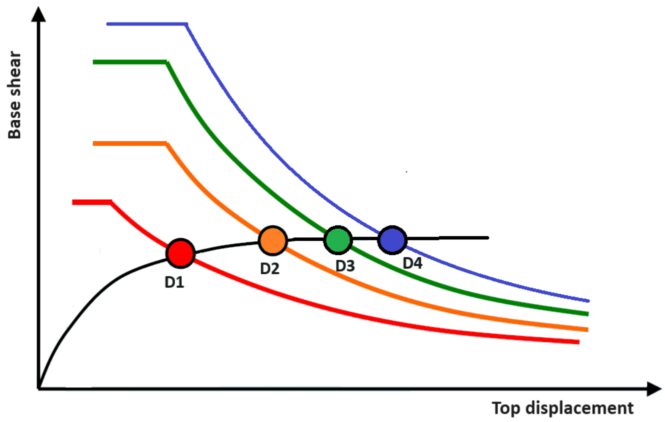

Figure 2. Base shear-top displacement response.

Levels of damage are associated with limit the states defined by construction codes [3], as shown in Table 1 [4].

Table 1. Limit states and corresponding levels of damage.

Level of damage	Limit state	Type of limit state
D1	SLO (limit state of operation)	Serviceability limit states
D2	SLD (damage limit state)	
D3	SLV (life-saving limit state)	Ultimate limit states
D4	SLC (collapse limit state	

For geotechnical systems, only the collapse PGA was considered. It was obtained using the equilibrium method considering the horizontal seismic acceleration corresponding to the full

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mobilization of the strength of the system in limit equilibrium conditions. The collapse PGA was determined as the soil acceleration which generates pseudo–static inertia forces capable of bringing the soil–retaining structure system in a limit equilibrium condition. When the seismic soil acceleration exceeds the critical value, a collapse mechanism of the system develops and permanent displacements occur.

The numerical evaluation of the capacity PGAs for a significant number of structures is computationally demanding and requires a complete knowledge of each structure in terms of geometrical and mechanical parameters. The approach used in the project consists in the definition of classes of structures and, within each class, the identification of a number of benchmark (representative) structures. The capacity PGAs are determined via structural nonlinear analysis for benchmark structures, whereas eXplainable Artificial Intelligence (XAI)-based procedures are used to estimate the capacity PGAs for the remaining structures of each class.

This requires the following steps:

1. Identification of classes of structures with similar characteristics;
2. Definition for each class of a set of technical parameters whose values identify the structures of the class;
3. Definition of representative (benchmark) structures of each class;
4. Computation of the capacity PGAs of benchmark structures via structural nonlinear analysis;
5. Use of XAI to estimate the capacity PGAs of non-benchmark structures based on similarity criteria with benchmark structures, as described in Deliverable 4.1.

3. CLASSES OF STRUCTURES

Classes of structures are defined based on construction technology, structural configuration, material properties, age, and detailing.

Construction technology strongly influences the seismic response in terms of dynamic characteristics and failure mechanisms (ductile or fragile failure, local failures, etc.).

Structural configuration refers to the regular or irregular distribution (either in plan and in elevation) of the structural elements. It affects the distribution of masses and stiffnesses and therefore the seismic response. In the MEDEA project, the regularity criteria provided by Eurocode 8 [2] are used.

Constrictions of different *ages* typically differ for construction techniques, design criteria, and materials used. In addition, the mechanical property of the materials usually decreases with time

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due to degradation phenomena.

Structural details such as steel bars arrangements in structural elements, connections between structural elements, and floor slab configuration strongly affects the seismic capacity since un-appropriate detailing may cause local failure mechanisms leading to premature collapse.

Based on the mentioned parameters, the following classes were defined:

- Buildings with masonry structure
- Buildings with reinforced concrete (RC) structure
- Masonry buildings with a limited number of RC elements;
- Steel structures;
- Geotechnical systems.

For buildings with masonry structure, in this deliverable focus was put on single regular structures typical of the period between 1945 and 1990 having rigid flat floors, with up to four storeys, and made of masonry with regular textile.

For buildings with reinforced concrete structure, in this deliverable, focus was put on single regular structures typical of the period between 1970 and 1990 with multilevel bidirectional frame system, and flat floors.

For geotechnical system, in this deliverable focus was put on earth retaining flexible structures.

For each class of structures, a set of technical (geometrical and mechanical) parameters was defined.

4. MASONRY STRUCTURES

4.1 Technical parameters

The technical parameters used to describe masonry benchmark structures (Table 2) were divided into three categories: mechanical parameters, used to characterize the materials, geometrical data, used to describe the shape of the structure, and seismic analysis parameters (seismic floor mass). Figure 5 shows examples of benchmark structures. Mechanical parameters are the masonry elastic (E_m) and shear (G_m) moduli, unit weight (w_m), compressive (f_m) and shear (τ_m) strength. If structural analysis of a real structure is performed and a real structure is used as benchmark structure, these parameters can be obtained from direct measurements or design documents. Geometrical parameters are divided in two categories: global parameters, which refer to the whole structure, and local parameters, which refer to each individual floor. Global parameters are the number of

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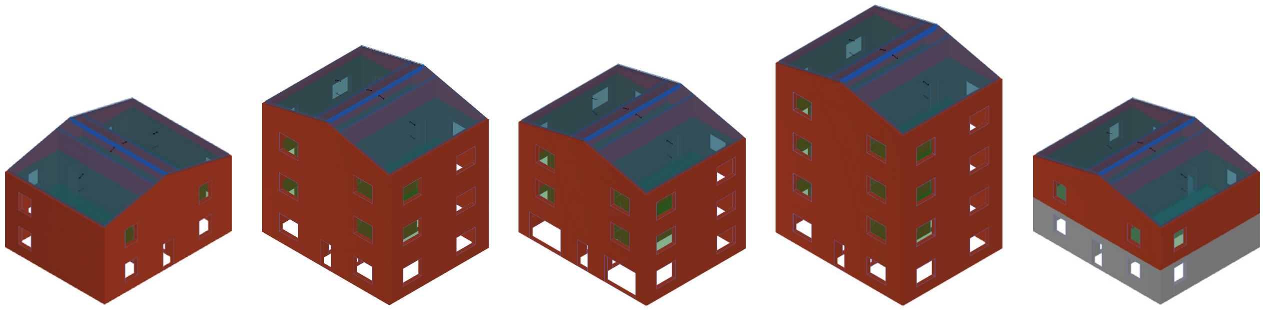
floors of which the masonry structure is composed (n_f), the average value of the height of the individual floors (h_f), the lengths of the sides of building along the X- and Y- directions (L_x and L_y), the number of internal shear walls (evaluated in both main directions), and the floor area. Local parameters are evaluated on a floor-by-floor basis.



a) Two levels structure b) Three levels structure c) Four levels structure d) Structure with two types of masonry

Figure 3. Examples of benchmark masonry structures.

Specifically, they are the average value of the thickness of the individual (internal and external) shear walls (t_m), the area of the openings (doors and windows) on each level, and the effective shear area, obtained by subtracting the area of the openings from the cross-sectional area of the walls.

Table 2. Technical parameters for masonry structures.

ID	Description
F0	Number of levels
F1	Average floor height
F2	Sides ratio (x-length / y-length)
F3	Floor area
F4	Number of internal alignments of masonry wall in X-direction
F5	Number of internal alignments of masonry wall in Y-direction
F6	Area of the openings of the external masonry walls
F7	Area of the openings of the internal masonry walls
F8	Average thickness of external masonry shear wall
F9	Average thickness of internal masonry shear wall
F10	Average shear strength of masonry
F11	Average compressive strength of masonry
F12	Masonry gross density
F13	Elastic modulus
F14	Shear modulus
F15	Effective shear area
F16	Seismic floor mass
F17	Ratio seismic floor mass / Effective shear area

The number of technical parameters for masonry structures depends on the number of floors, since some parameters, such as openings, average shear wall thickness, etc., must be evaluated

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individually for each floor. Each building is described by 6 global technical parameters (from F0 to *F5*), and each level of a masonry structure is described by 12 technical parameters (from F6 to F17). Table 2 summarizes the 18 technical parameters considered.

4.2 Engineering Demand Parameters

For masonry benchmark structures, the capacity PGAs were determined by pushover analysis based on EDPs representing the consequences of a seismic action on each individual structural element. The selected EDPs were the forces and bending moments at the ends of the masonry panels, the chord rotation of the masonry panels, and the interstory drift, according to the criteria defined in [2].

4.3 Construction of the dataset of benchmark structures

Based on technical parameters shown in Table 2, 1176 benchmark masonry structures were defined. These structures are typical of masonry constructions built between 1945 and 1990. The basic configuration used to generate the benchmark masonry structures (Figure 4) had a rectangular plan with sides equal to 12.4 m and 9.7 m and the same floor height at each level, equal to 2.85 m. The structural system includes two internal walls along the shorter dimension. The thickness of the masonry wall is equal to 0.3 m. Each masonry wall has openings (doors and windows). The slabs is made of reinforced concrete and clay elements.

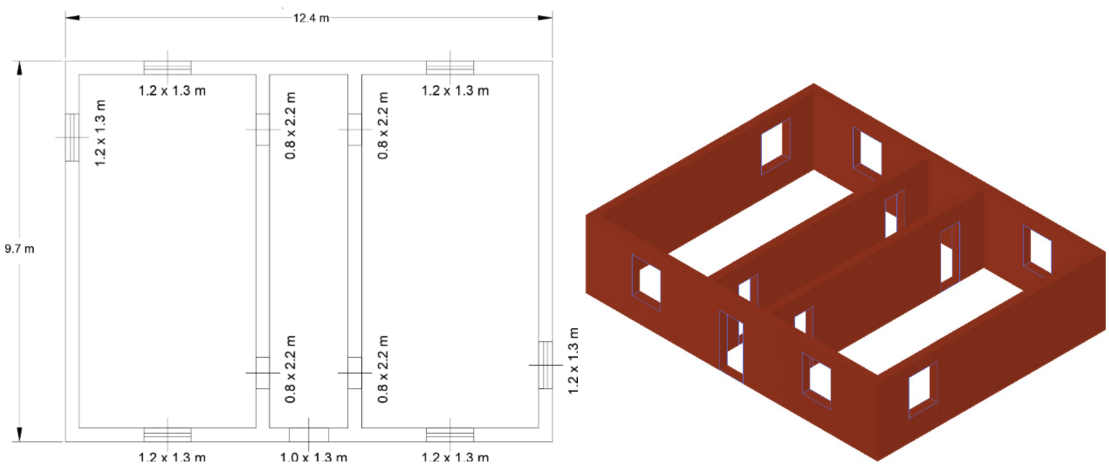

Figure 4. Basic structural configuration used to generate masonry benchmark structures.

Starting from the basic configuration, the benchmark structures were generated by varying the main geometrical parameters in the ranges reported in Table 3. In addition, for any geometrical configuration, different mechanical properties of the masonry were considered, representing the

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masonry types mentioned in Table 3.

Table 3. Ranges of parameters for benchmark masonry structures.

Parameter	Range	Unit
Number of levels	2-4	-
Average floor height	2.85-3.40	m
Number of internal alignments of masonry wall	1-2	-
Area of the openings of the masonry walls	6.2-21.6	m^2
Average thickness of masonry shear wall	0.30 -0.45	m

Table 4. Masonry mechanical parameters used for benchmark masonry structures.

Type of masonry	Mechanical Parameter	Value	Unit
Disordered stone masonry	Average shear strength of masonry	0.028	MPa
	Average compressive strength of masonry	1.4	MPa
	Masonry gross density	16	kN/m^3
	Elastic modulus	1080	MPa
	Shear modulus	360	MPa
Regular ashlar masonry of soft stone	Average shear strength of masonry	0.04	MPa
	Average compressive strength of masonry	2.0	MPa
	Masonry gross density	16	kN/m^3
	Elastic modulus	1410	MPa
	Shear modulus	450	MPa
Squared stone blocks masonry	Average shear strength of masonry	0.09	MPa
	Average compressive strength of masonry	5.8	MPa
	Masonry gross density	22	kN/m^3
	Elastic modulus	2850	MPa
	Shear modulus	950	MPa
Clay brick and lime mortar masonry	Average shear strength of masonry	0.05	MPa
	Average compressive strength of masonry	2.6	MPa
	Masonry gross density	18	kN/m^3
	Elastic modulus	1500	MPa
	Shear modulus	500	MPa

5. REINFORCED CONCRETE STRUCTURES

5.1 Technical parameters

The technical parameters used to describe the reinforced concrete benchmark structure were divided into three categories: mechanical parameters, used to characterize the materials, geometrical parameters, used to describe the shape of the structure, and seismic analysis parameters. Figure 5 shows an example of benchmark reinforced concrete structure. Geometrical global parameters are the number of floors underground (number of underground levels) and the number of floors in elevation (number of floors), the total height (building height), the total length of the building in the X- and Y-direction (total length X-side and total length Y-side). Based on the geometrical parameters of individual structural elements and material properties, parameters from F_5 to F_13 were obtained.

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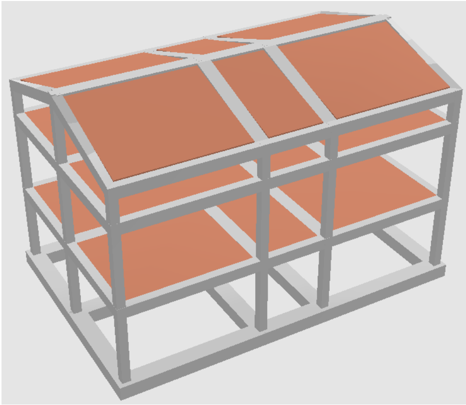

Figure 5. Typical reinforced concrete benchmark structure.

The choice of the parameters allowed to obtain a number of technical parameters independent of the number of storeys (Table 5).

Table 5. Masonry technical parameters used for benchmark masonry structures.

ID	Description
F0	Number of underground levels
F1	Number of floors
F2	Building height
F3	Total length X-side
F4	Total length Y-side
F5	Seismic floor mass MAX / Seismic floor mass MIN
F6	Parameter between the max and the min (Ratio of Seismic floor mass/ Concrete area)
F7	Average stress in the columns in the corner at the ground floor
F8	Average stress in the external column at the ground floor
F9	Average stress in the internal columns at the ground floor
F10	Ratio between maximum/minimum eccentricity
F11	Ratio between maximum/minimum stiffness X direction
F12	Ratio between maximum/minimum stiffness Y direction
F13	Period of the structure

5.2 Engineering Demand Parameters

For reinforced concrete benchmark structures, the capacity PGAs were determined by pushover analysis based on EDPs representing the consequences of a seismic action on each individual structural element. The selected EDPs were the forces and bending moments at the ends of beams and columns, the chord rotation of the columns, the interstory drift, the state of stress of beam-column joints, according to the criteria defined in [2].

5.3 Construction of the dataset of benchmark structures

Based on the technical parameters shown in Table 5, 1200 benchmark reinforced concrete structures representing typical buildings built between 1970 and 2000 were defined. The basic configuration used to generate the reinforced concrete benchmark structures represents a building

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with a rectangular plan of dimensions 15.5 m and 8 m and a constant interstory height (Figure 6). The structure comprises two internal frames parallel to the shorter dimension and one internal frame parallel to the longer direction. Slabs are made of reinforced concrete and clay elements. Concrete has a characteristic (cylindrical) compressive strength of 16 MPa, whereas steel bars have a yielding stress of 320 MPa. Typical dimensions of the structural elements are shown in Table 6.

Table 6. Dimensions of structural elements for benchmark reinforced concrete buildings.

Structural element	Dimension	Unit
Columns	0.3x0.3	m
Beams in floor thickness	0.50x0.24	m
Beams lowered	0.30x0.40	m

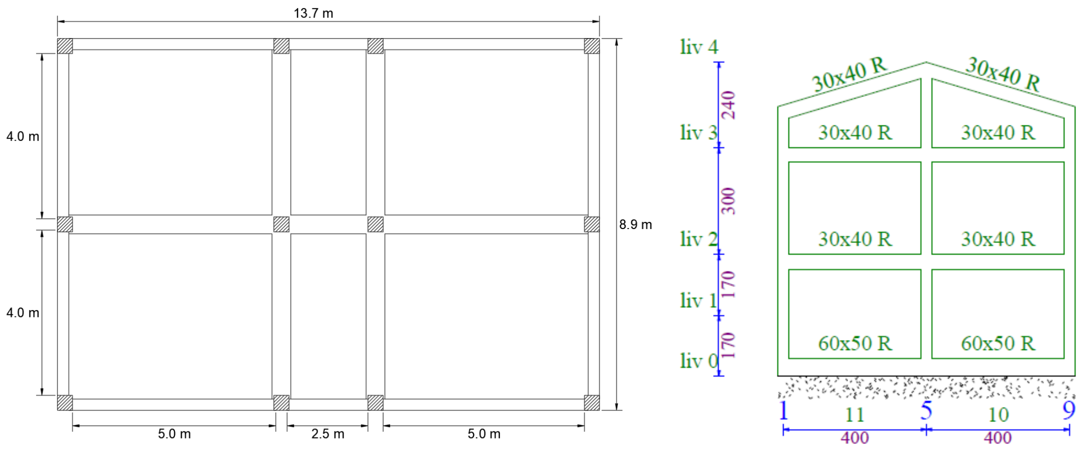

Figure 6. Basic structural configuration used to generate reinforced concrete benchmark structures.

Starting from the basic configuration, the reinforced concrete benchmark structures were generated by varying the main geometrical and mechanical parameters in the ranges reported in Table 7.

Table 7. Ranges of parameters for benchmark reinforced concrete structures.

Parameter	Range	Unit
Concrete characteristic compressive strength (cylindrical)	16-28	MPa
Floor height	2.60-3.50	m
Length of the frame in the major direction	3.25-4.0	m
Length of the frame in the major direction	4.25-5.0	m

6. GEOTECHNICAL SYSTEMS

A class of earth retaining flexible walls was defined. It includes:

i) cantilever wall (Figure 7a);

ii) propped wall at the top (Figure 7b);

iii) anchored wall with one level of anchor (Figure 7c).

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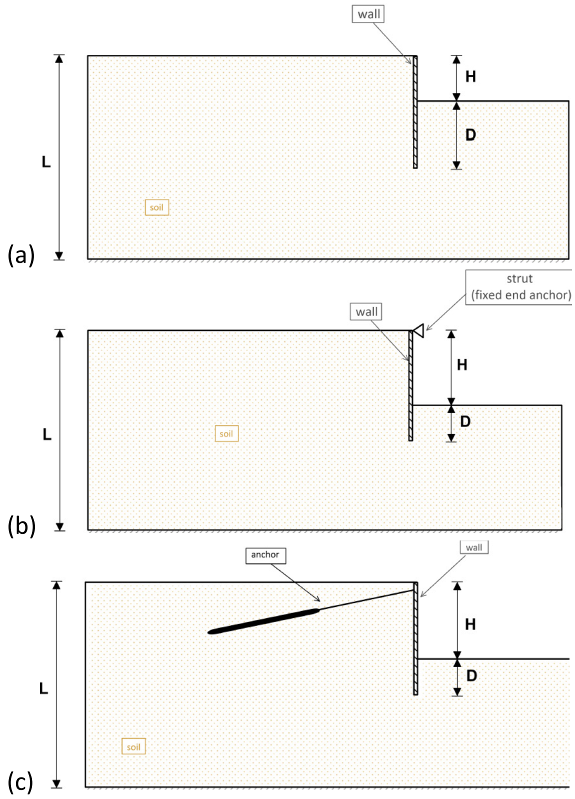

Figure 7. Geometrical parameters of the earth retaining flexible walls. (a) Cantilever wall; (b) Propped wall at the top; (c) Anchored wall with one level of anchors.

The diaphragm walls are characterized by thickness t, and embedment length D and support an excavation of height H on a layer of dry sand of thickness L.

6.1 Technical parameters

Technical parameters chosen to identify each diaphragm wall can be divided in geometrical parameters, mechanical parameters, and anchor parameters. Geometrical parameters (Figure 7) are the excavation height (H), the thickness of the layer (L), the thickness (t) of the diaphragm wall, and the embedment length (D). The material and mechanical parameters describe the soil properties, the mechanical properties of the wall, and the soil-wall interaction. Chosen parameters are: soil unit mass (ρ), effective friction angle (ϕ), soil–wall interface friction angle (δ), and yielding bonding moment of the wall (M_y). Parameters for propped wall also include the and strut limit compression load (R_y). For anchored walls, further geometrical parameters are the depth the connection between the anchor and the wall (a), the active length of the anchor (L_a), the grouted length (L_f), and the inclination angle (α), whereas, further mechanical parameters represent the properties of the anchor: equivalent strength of the anchor in plane strain conditions (T_{lim}), and pull-out strength (R_f). Table 8 summarizes the technical parameters used to identify the benchmark flexible earth retaining walls.

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Table 8. Technical parameters for flexible retaining walls.

ID	Description	Used for caltilever walls	Used for propped walls	Used for anchored walls
F0	Excavation height (H)	✓	✓	✓
F1	Thickness of the soil layer (L)	✓	✓	✓
F2	Thickness (t) of the diaphragm wall	✓	✓	✓
F3	Embedment length (D)	✓	✓	✓
F4	Depth of the anchor connection (a)			✓
F5	Anchor active length (L_a)			✓
F6	Anchor grouted length (L_f)			✓
F7	Anchor inclination angle (a)			✓
F8	Soil unit mass (r)	✓	✓	✓
F9	Soil effective friction angle (f)	✓	✓	✓
F10	Soil–wall interface friction angle (d)	✓	✓	✓
F11	Wall yield bending moment (M_y)	✓	✓	✓
F12	Strut limit compression load (R_y)		✓	
F13	Anchor equivalent strength in plane strain conditions (T_{lim})			✓
F14	Anchor pull-out strength (R_f)			✓

6.2 Engineering Demand Parameters

For earth retaining flexible walls, only the PGA producing the collapse of the wall was considered. It was determined by nonlinear finite element analysis based on the velocity fields associated with different levels of seismic action. When the seismic soil acceleration exceeds the collapse PGA, a collapse mechanism of the system develops and permanent displacements occur. It should be noted that the procedure adopted accounts for different failure mechanisms (Figure 8).

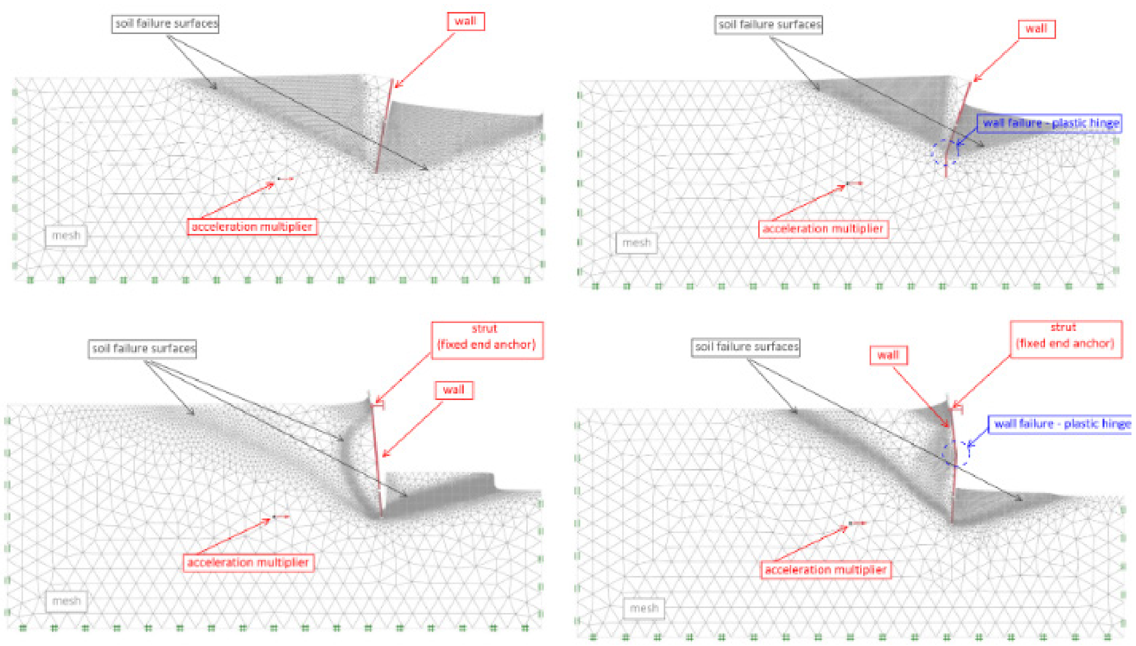

Figure 8. Collapse mechanisms of earth retaining flexible walls. (a) Overturning of a cantilever wall; (b) flexural failure of a cantilever wall; (c) overturning of a propped wall; (d) flexural failure of a propped wall.

In particular, Figure 8a shows a collapse mechanism associated with the overturning of a cantilever wall,

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Figure 8b shows a collapse mechanism caused by the attainment of the flexural strength of the cantilever wall (bending moment equal to M_y and formation of a plastic hinge), Figure 8c shows a collapse mechanism associated with the overturning of a propped wall, and Figure 8d shows a collapse mechanism caused by the attainment of the flexural strength of the propped wall.

6.3 Construction of the dataset of benchmark structures

Referring to the schemes in Figure 7, a total of 984 benchmark earth retaining flexible walls was obtained by varying the technical parameters shown in Table 8. In particular, 9 dimensionless parameters were defined. For each dimensionless parameter, typical ranges were considered to represent a wide class of retaining walls. Five values of the friction angle ϕ in the range [30°, 38°] (loose to dense sands), three values of the normalized friction angle at the soil–wall interface δ/ϕ (0.5, 0.67, and 1.0), four values of yielding bending moment M_y from 800 kNm/m (slender sheetpiles) to 3200 kNm/m (relatively thick reinforced concrete walls), two values (1m and 2m) of the depth (a) of the connection between the anchor and the wall, and two values (10° and 20°) of the inclination angle a of the anchor were considered. The ratio D/H was considered in the ranges [0.32, 0.63], [1.2, 1.6], and [0.42, 0.63] for propped, cantilever, and anchored walls, respectively. Finally, the ratio $T_{lim}/(rgH^2)$ was considered in the range [0.14−0.19] (from weak to strong anchor resistance), whereas the ratio $R_f/(rgH^2)$ was considered in the range [0.11 − 0.22] (from weak to strong foundation). Table 9 summarizes all the ranges of the parameters adopted for the construction of the dataset of benchmark structure.

Table 9. Ranges of parameters for benchmark reinforced flexible retaining walls.

Parameter	Unit	Cantilever wall	Propped wall	Anchored wall
F	[°]	30-38	30-38	30-38
d/f	[--]	0.5-0.67	0.5-1	0.5-0.67
D/H	[--]	1.2-1.6	0.32-0.63	0.42-0.63
$M_y/(\rho gH^3)$	[--]	0.32-1.28	0.05-0.21	0.05-0.19
$T_{lim}/(\rho gH^2)$	[--]	--	--	0.14-0.19
a/H	[--]	--	--	10-20
L/L_a	[--]	--	--	2.0-2.4
$R_f/(\rho gH^2)$	[--]			0.11-0.22

5. CONCLUSION

This deliverable reports the criteria adopted for defining structure classes based on construction technology, structural configuration, material properties, age and details. Technical parameters were then defined for each class of structures in term of mechanical parameters, geometric data and seismic parameters. In addition, a range of variation was defined for each technical parameters and used to generate the dataset of structures in each class. Finally, engineering demand parameters (EDPs) were defined to be evaluated after performing nonlinear analyses on the reference structure in order to evaluate the consequences of a seismic

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action on each structural element. The choice of the technical parameters for describing the reference structure and EDPs for evaluating the effects of seismic action are of fundamental importance for a correct estimation of the seismic capacity of structures.

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