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Assessment of specific structural and ground-improvement seismic retrofitting techniques for a case study RC building by means of a multi-criteria evaluation

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ABSTRACT

Existing reinforced concrete (RC) structures might not comply with current seismic codes due to their aseismic design and construction date. By seismically retrofitting them, it is possible to improve their seismic performance to resist the expected seismic loads. However, selecting the best solution is challenging since social and economic issues can affect the choice. Multi-criteria decision making (MCDM) provides an opportunity to overcome the challenge but there are some drawbacks in the available MCDM techniques. This paper reports an improved MCDM-based seismic retrofit: Additional criteria have been included and weighted according to their importance (ductility improvement and damage reduction); Finite element modelling of the case study building has been carried out instead of following methods based on different simplifications; iii) Structural performances have been assessed by determining the damage in local elements instead of following global assessment procedures; Effects of soil-structure interaction (SSI) have been taken into account to ultimately compare different structural and ground-improvement techniques. Consistency and sensitivity analyses have proved the stability of the results and the robustness of the method. It is shown that SSI can increase the seismic damage up to 17%, and regarding the seismic safety verification, the building needs to be retrofitted. Adding fibre reinforcement polymers and steel bracings are the best solutions due to the minimum architectural impact and the outstanding structural improvement, respectively. Nevertheless, the solution preferred is the addition of single steel braces in beam-column joints despite its high maintenance costs. The sensitivity analysis indicates that the most sensitive criteria are the functional compatibility and the reduction of the collapse risk.

1. Introduction

Existing reinforced concrete (RC) structures may not comply with current seismic requirements. This can be due to the fact that: i) they were built prior to earthquake resistant building codes; ii) they were designed to resist horizontal loads but without restricted designing principles; or, iii) they are located in places where the seismic hazard has been reassessed. Nevertheless, by seismically retrofitting them, it is possible to improve their seismic performance to resist the expected seismic loads [1]. Moreover, from a social and economic point of view, the seismic upgrading of structures (before the event) is more convenient than demolishing or reconstructing buildings [2]. However, it should be pointed out that if the repairing costs (after the event) of a building are 50% or more higher than the replacement costs, then, the repairing is not feasible [3].

The seismic retrofitting of buildings is a complex task studied in numerous works. A broad analysis concerning the different retrofitting strategies available for RC buildings was presented in [4]. This was based on the well-known classification proposed by the American ATC-40 [5]. Most of the studies on the effects of adding these solutions were performed by just considering the improvement of the structural performance [6]. However, these strategies can be significantly different if some other aspects, such as social and economic, are borne in mind [7]. Therefore, choosing the most optimal retrofitting solution is subjected to other aspects rather than only the structural safety assessment. In fact, these aforementioned aspects become highly important when referring to buildings of strategic importance, such as schools [8]. In these cases, aspects like the disruption of the use, the architectural impact and the construction and the maintenance costs affect the decision [9]. Hence, it has been highly recommended that selecting the best solution should be

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based on a consistent assessment of various aspects through a comprehensive and integrated comparison of the solutions [10].

Multi-criteria decision making (MCDM) methods can be helpful to evaluate retrofitting solutions. They can allow making informed decisions regarding whether or not the solutions are advantageous and/or appropriate for a specific building considering different criteria [11]. MCDM procedures have been widely used in different research fields [12]. Among these, the TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) [13] has been defined as the most appropriate for the assessment of upgrading buildings. This is due to the clarity of the results and the capability of the method to adapt the judgement [7].

The TOPSIS method was originally proposed by [13] and first applied to the seismic retrofitting of buildings in [14]. In this latter work, the authors took into account economic/social and technical criteria to assess different retrofitting solutions. For the technical part, only the seismic safety was analysed. However, some other aspects can affect the structural performance, such as ductility. In fact, in RC buildings, this can allow structures to undergo major deformations without a substantial reduction in strength [15]. In some cases, by increasing the ductility, it is possible to prevent the brittle collapse mechanisms. These are typical in buildings designed without seismic design [16–18]. Moreover, in certain cases, ductility can lead to a reduction of the seismic damage [19]. Therefore, it is a parameter that needs to be taken into account in order to propose specific retrofitting solutions. Additionally, since what is intended is to reduce the lateral displacement demand by retrofitting the buildings, it is possible to reduce the damage in non-structural elements.

Some examples on the application of the TOPSIS method for the seismic retrofitting of RC buildings can be found. As abovementioned, in [14], the general method was firstly adapted to the upgrading of a very simple RC structure. Four traditional retrofitting techniques were added to the structure and a first ranking was proposed. These authors continued applying MCDM procedures to account for the expected losses [20], to be implemented in Building Information Models (BIM) [21] or for the risk mitigation [22]. In [23], the method, adapted in the first work, was simply applied to a case study building to compare its results with other multi-criteria methods. It was concluded that the TOPSIS method could provide a robust rank of the retrofitting solutions. In fact, it was pointed out that the method can provide a consistent basis for the construction management and the decision-making. In [24], the retrofitting solutions were experimentally assessed and compared with the MCDM method. It was concluded that assigning the weights to the criteria is one of the most critical decisions to select the optimal solution.

In these works, the retrofitting solutions have not been carefully selected considering either the effect on the aesthetics of the building or analysing their efficiency. Regarding the first concern, the architectural impact that these solutions might have on the building has not been assessed. In this sense, non-invasive retrofitting techniques can help to overcome the space limitations, to prevent the fragile failure and to improve the strength of the elements while being minimally invasive [25]. Such is the case of the addition of fibre reinforcement polymers (FRP) wrapping or steel braces in beam-column joints [26]. Concerning the second issue, in most of the works, these authors believe that the solutions were just added randomly, without a previous analysis of the deficiencies of the building. Therefore, the solutions were not added in the most optimal positions to obtain the highest performance improvement and damage reduction.

Ground-improvement techniques can allow minimising their impact on the functionality and the configuration of RC buildings [27]. Nonetheless, the soil-structure interaction (SSI) is often omitted in seismic vulnerability analyses of buildings [28]. Yet, it has been proved that this can worsen the seismic performance of RC buildings under certain circumstances [29]: nonlinear modelling of the systems, soft soils and medium to high-rise buildings. Solutions like adding micropiles in footings [30] or improving the soil properties by means of injections have been widely used in the retrofitting of RC buildings [31].

In this context, despite the availability of many retrofitting strategies, either based on the structural or ground improvement, they have not been quantitative compared by means of different criteria. Also, these interventions must be thoroughly analysed in order to select the most efficient one for a specific case [32]. In this sense, research on the retrofitting of RC buildings was, to some extent, based on artificial and fuzzy models instead of real case study buildings [33]. It has been proved that in order to obtain a realistic behaviour of the buildings, they should be numerically modelled properly [29]. Fuzzy models do not provide this kind of information since they are based on general models that can be to some extent significantly different to the real case. Moreover, for the sake of easiness, most of the studies did not bear in mind specific modelling of the structures apart from [34]. In fact, these works were mainly based on the global behaviour enhancement instead of analysing the failure of local elements [25]. This all leads to a lack of studies on the seismic retrofitting of RC buildings founded on specific, integrated and thorough assessments.

The aim of this paper is to comparatively assess and to rank different seismic retrofitting techniques by means of an improved multi-criteria method based on the TOPSIS procedure. This method is focused on the relative closeness to ideal solutions to select the most suitable alternative. The main novelty of this paper is that: i) additional criteria have been included and weighted according to their importance (ductility improvement and damage reduction); ii) the specific modelling of a real case study building has been carried out using the finite element method (FEM), instead of following methods based on different simplifications; iii) the structural performance has been assessed by determining the damage in local elements instead of following global assessment procedures; iv) the SSI effects have been taken into account to ultimately compare different structural and ground-improvement techniques. The stability of the results and the robustness of the method have been assessed through a consistency checking and a sensitivity analysis. The different retrofitting solutions examined have been added to a pre-code RC mid-rise case study school. This typology of buildings is sensitive to social and economic criteria rather than just the structural assessment. This building is affected by the SSI effects and it is strongly deficient in terms of seismic performance. Therefore, it must be retrofitted.

2. Definition of the research steps

In this work, the TOPSIS method has been used to comparatively assess and rank the retrofitting solutions contemplated. This is based on the relative closeness to ideal solutions to select the most suitable alternative. The research process is based on the following steps (Fig. 1):

1. Definition of the case study building (Section 3): structural configuration and soil. Numerical modelling using the FEM. This is one of the main novelties of this paper compared to previous works. In this case, the retrofitting solutions have been applied to a real case study building, which is representative of a considerable amount of similar buildings in the area under study. Moreover, the main parameters needed to numerically model the SSI have been presented.
2. Characterisation and evaluation of the retrofitting techniques (Section 4). Design and numerical modelling of the set of alternatives considering structural and ground-improvement techniques. In this section, guidance regarding the numerical modelling of the retrofitting solutions is provided for the readers.
3. Definition and description of the evaluation criteria chosen for the MCDM method to rank the alternatives (Section 5.1). In this work, additional criteria to [14] have been borne in mind based on the work developed by [35]. These are the ductility improvement and the damage reduction. These criteria can be modified as well as selected according to the type and the configuration of the building under study.

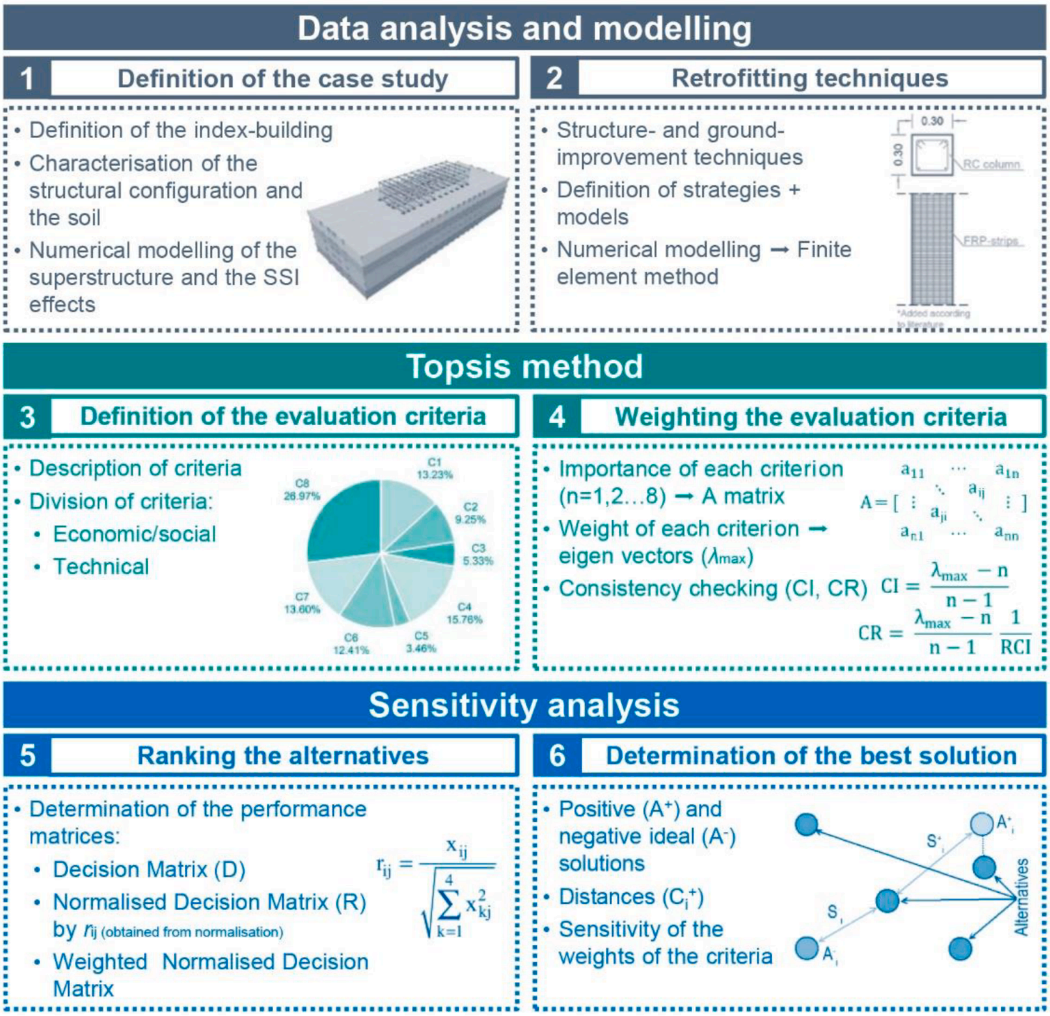


Fig. 1. Steps of the research procedure.

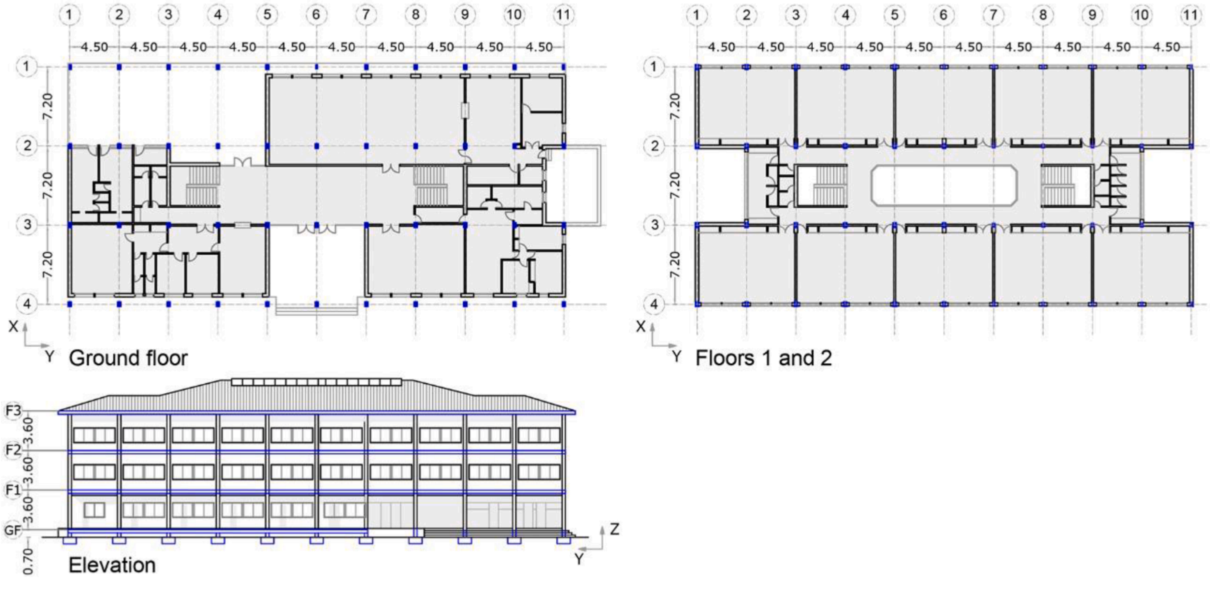


Fig. 2. Configuration of the case study building. Depicted by the authors according to the available blueprints.

4. Weighting and evaluation of the criteria (Sections 5.2 and 5.3). The eigenvalue approach has been used to give overall consistency to the subjective choices taken by the Decision Maker (DM)'s judgement. Additionally, the structural performance and the seismic safety assessment are described. The main steps to assess each configuration are presented in this section, which can be followed and implemented in future works by researchers or engineers.
5. Ranking the alternatives through performance matrices (Section 6.3). Unlike the rest of the related works, in this case the retrofitting elements have been added after a previous analysis of the deficiencies of the building (Section 6.2). Therefore, these solutions have been added in the most efficient positions.
6. Determination of the best choices by defining the positive and the negative-ideal solutions (Section 6.4). Sensitivity analysis of the relative importance on the final decision of the criteria (Section 6.5).

Additional results have been presented to analyse the effects of the SSI in the seismic performance of the case study building (Section 6.1).

3. Case study

3.1. Characterisation of the case study

3.1.1. Building

The structure studied for the application of the method is a four-storey RC building (Fig. 2) located in *Huelva*, (southwestern Spain). This area is characterised by a considerable seismic hazard due to the proximity to various faults able to generate very large earthquakes of catastrophic consequences [36]. According to the work developed in [37], on the characterisation of the primary schools buildings in the area under study, this building is representative of 34% of the RC schools identified in the region. Therefore, owing to this, it has been selected as a case study building or 'index-building', representative of a notable portion of the buildings of the area. Moreover, it is a pre-code building since it was constructed in the 1970 s while the first restrictive seismic code in Spain was introduced in 1994 [38]. Therefore, it presents typical seismic vulnerabilities: insufficient rebar ratio, wide-beams, irregularities in plan and in height and low-quality structural materials. In this work, it has been proved that this building is strongly deficient in terms of seismic performance.

Data regarding the configuration of the building has been obtained through the available blueprints and the constructive codes of application in this period. The structural system is composed of RC infilled frames: columns, wide-beams and 25 cm thick ribbed slabs (Table 1). Different gravitational loads have been taken into consideration: dead (self-weights, in total 5.5 kN/m^2) and live loads (defined according to Part-1 of Eurocode 8 (EC8-1) [39]). The total mass of the structure is 1550 Tons.

3.1.2. Soil

The characterisation of the soil underneath the building has been carried out according to 8 nearby geotechnical surveys that included 17 boreholes. The information has been compiled from laboratory tests as well as in situ geotechnical prospections. Based on this information, an interpretation of the soil layering at the site has been performed. In this work, the most probable soil profile has been contemplated for the analyses. As shown in Fig. 3(a), four different geotechnical strata have been identified. After classifying the soil, it has been obtained that it is mainly clayey. In Fig. 3(b), the N_{spt} from standard penetration tests (SPT) has been shown for each stratum. According to the Spanish building code [40], the shallow layers can be classified as low-dense soils (N_{spt} ≈11-30) while the deepest layers are dense (N_{spt} ≈31-50).

Table 1
Geometrical characteristics of the structural elements of the case study building.

Characteristic	Columns	Load beams	Tie beams
Dimensions (cm)	30 × 40	60 × 30	30 × 30
Cross-section (cm^2)	1,200	1,800	900
Longitudinal rebar (cm^2)	1.572	Top: 0.786 Bottom: 3.495	Top: 0.786 Bottom: 0.786
Transversal rebar (cm^2)	0.196	0.196	0.196
Spacing of stirrups (cm)	15	20	25

The shear wave velocity (V_s) (Fig. 3(c)) and the Poisson ratio (ν) are needed to numerically model the soil in 3D. These have been attained from laboratory tests performed on soil samples, selecting the most probable results (pointed out with an 'X' in the plot). The soil behaviour has been defined according to three parameters: shear (G), elastic (E) and bulk (B) modulus and the unit weight (γ). These have been obtained according to the widely-known geotechnical correlations available in [41]. In Fig. 3(d), the shear modulus has been plotted as a function of depth to represent the rigidity of the soil.

3.2. Numerical modelling

The numerical modelling of the case study building has been carried out in OpenSees [42], using the FEM. The results have been handled in STKO [43] and in MATLAB [44].

3.2.1. Superstructure

The nonlinear behaviour of the RC frames has been simulated by means of the distributed plasticity approach to allow a faster modelling. Nonlinear beam-column elements and nonlinear structural materials ('Concrete04′ and 'Steel02′) have been used. In order to reflect excessive lateral displacement and forces, the p-Δ effects have been taken into account by using '3Dforcebeam' elements. Infills have been simulated by means of hysteretic materials following the two-trusses approach [45]. Owing to the rigidity of the system, the effects of the rigid slabs have been noted. The masses have been applied at the centre of each floor. The ageing effects in RC, the presence of smooth rebars and the rebar slippage have accounted for as proposed by [46]. Similarly to [46], the RC frames have been divided according to their level of exposure to the environment: medium (within the façades of the building) and totally (not covered by infills) exposed. According to this type of exposure, two aspects have been considered: the reduction of the longitudinal and transversal rebar section; and, the degradation of the concrete cover. For more information on the ageing effects simulation, the readers are referred to the previous work. The characteristics of the structural parameters are listed in Table 2.

3.2.2. Soil-structure interaction

The exhaustive modelling of the soil can be carried out following the direct or the substructure method [47]. In this work, the direct method has been followed since it can allow determining the response of the soil and the structure simultaneously, leading to faster and simpler analyses [48]. Several features are able by using this method: the soil and the structure can be modelled by means of the FEM method, the boundaries can be specially treated, the stress in the soil can be easily assessed and 3D nonlinear analyses are possible. The underlying soil of the building has been modelled with a mesh of 65x135x34 m in the X, Y and Z directions, respectively. It has been defined and discretised according to the V_s and to the soil-frequency (ω), obtained from a modal analysis and following the procedure established in the STKO manual. 'SSPbrick' brick elements have been applied to the solid elements to capture the small soil deformations. The mesh is characterised by 24 902 nodes and 75 941 brick elements. The lateral boundaries have been fixed in the corresponding direction and the base in all directions. Since the soil is clayey, the 'PressureIndependMultiYield' (PIMY) material has been used to simulate its nonlinear behaviour. This material has been used for this type of soil since it is independent from the gravitational confinement. 'EqDOF''s (Equal Degree of Freedom) has been applied to the interaction between the surfaces of the soil and the footings to allow faster

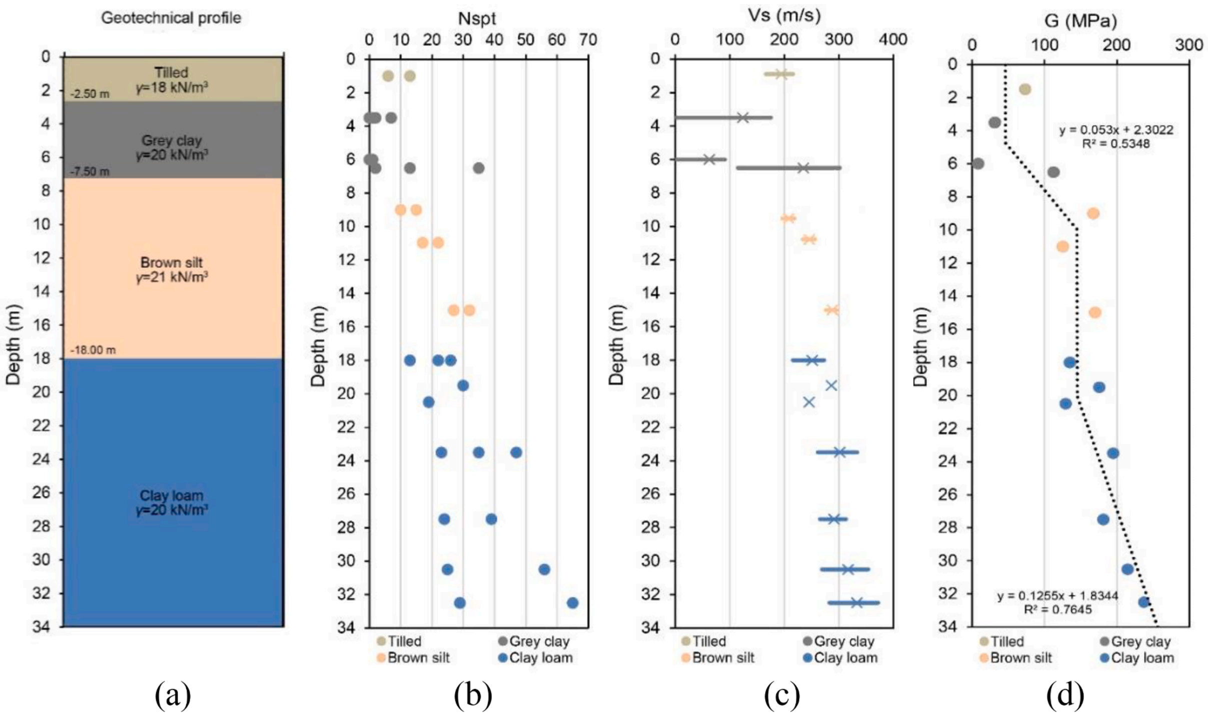


Fig. 3. Soil characterisation. (a) Soil profile, (b) N_{spt}, (c) V_s and (d) G according to depth.

Table 2
Characteristics of the structural parameters of the existing building.

Concrete		Steel		Infills	
f_c (MPa)	17.5	f_y (MPa)	220	G_w (GPa)	1.240
E_c (GPa)	30	E_s (GPa)	310	α	0.05
ε_c (%)	0.2			τ_{cr} (MPa)	280
ε_{cu} (%)	4			E_w (GPa)	4.092

Where: concrete compressive (f_c) and Young's modulus (E_c); concrete strain at maximum (ε_c) and ultimate strength (ε_{cu}); steel yielding strength (f_y); steel modulus of elasticity (E_s); infills shear modulus (G_w); post-capping degrading branch coefficient (α) (defined following the suggestions of the referred work); shear cracking stress (τ_{cr}); masonry elasticity modulus (E_w).

calculations in X, Y and Z. The 'beamsolidCoupling' constrain has been applied to the interaction between the footings and the superstructure to allow rigid linking. As aforementioned, four soil layers have been defined.

4. Retrofitting solutions

4.1. Description of the retrofitting solutions

In this work, five different retrofitting solutions have been selected (Fig. 4). They have been divided into structural and ground-improvement solutions. The first group is composed of the addition of FRP-wrapping (FRP) and single steel braces (SB) in beam-column joints. These solutions can be classified as non-invasive techniques. FRP has been widely used while adding SB has obtained satisfactory results when upgrading RC structures [35]. Additionally, X-bracings (XB) have been added since it is the most implemented retrofitting solution for this type of structures [49]. The ground-improvement solutions selected are jet-grouting (JG) and micropiles (MP) in footings.

Regarding the design of the retrofitting solutions, some approaches are available in the literature such as the risk-targeted approach. In [50], the retrofitting solutions were designed with the same nominal performance, therefore, the seismic performance criterion could be omitted. Considering the use of the case study building, there are others such as the economic and social that are important to be weighted and

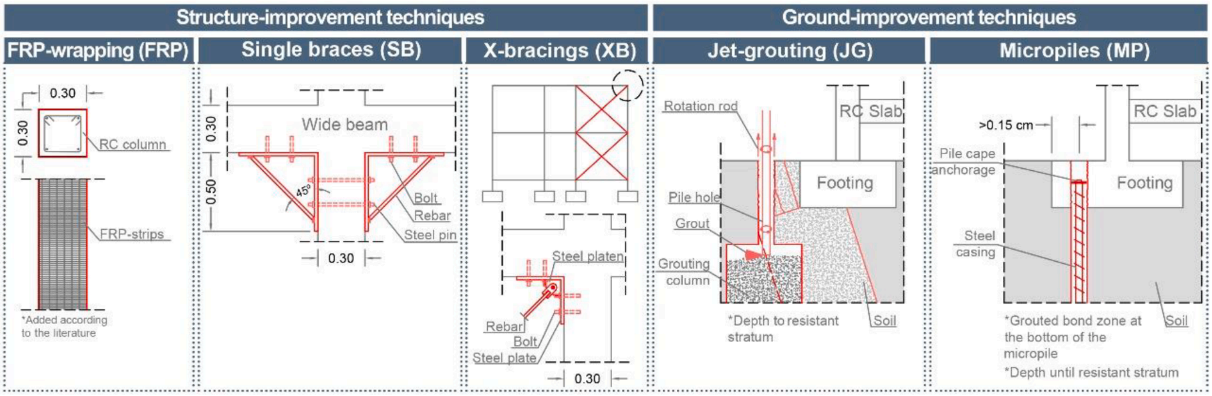


Fig. 4. Constructive details of the retrofitting solutions considered.

compared. Therefore, in this work, it has been opted to maintain the seismic performance criterion. Hence, the retrofitting solutions have been designed according the analysis of the seismic deficiencies presented in Section 6.2 and the results obtained in a previous work [35]. The ground-improvement techniques have been designed considering the previous knowledge of the authors.

In Fig. 5, the position of the retrofitting elements is shown. In total, ten different retrofitting alternatives (A) have been assessed. Some parameters have been varied: the amount and the position of the reinforcement material and the number of elements retrofitted. For the FRP, the reinforcement material has covered 1/3 of the length of the columns. They have been added in 25% (25) (A_1) or 50% (50) (A_2) of the firstly damaged vertical elements. This also applies to the addition of SB: 25% (A_3) and 50% (A_4) of columns have been retrofitted. In the case of XB, the retrofitting elements have been added in all floors as follows: two XB in X-corners (X) (A_5), four XB in Y-corners (Y) (A_6) and four XB in Y and two XB in X-corners (XY) (A_7). Ground-improvement techniques have only been added in the footings of the perimeter of the building to avoid extra constructions costs and to reduce the duration of the works. Only one configuration of JG has been selected (A_8), adding the retrofitting material in the perimeter. In the case of MP, one (1) (A_9) or two (2) (A_{10}) MPs have been added in the middle or the corners of the footings, respectively. Additional description of the characteristics of each strategy can be found below.

4.2. Numerical modelling

4.2.1. Structure improvement

4.2.1.1. FRP-wrapping (FRP). The FRP-wrapping has been simulated through the uniaxial material 'ConfinedConcrete01' [51] designed for rectangular columns. The mechanical properties of the FRP are defined according to [52], the modulus of elasticity (E_{FRP}) and the ultimate strain ($\varepsilon_{j,rup}$) being 231 GPa and 0.0072, respectively. The characteristics of the wraps are: width, 50 mm; spacing, 30 mm; and thickness, 1.3 mm. This configuration was concluded to be the most efficient one among the different FRP-wrapping techniques analysed in [35].

4.2.1.2. Steel braces (SB). The steel braces have been added using Φ16 mm trusses forming 45° in the beam-column joints. Furthermore, they have been separated from the bottom of the RC beams by at least 50 cm. They have been added in both directions (X and Y). The trusses have been linked to the superstructure with 'EqDOF' interactions in the X, Y and Z directions. The structural steel selected presents the following characteristics: yield stress (f_y) 275 MPa, modulus of elasticity (E_s) 210 GPa and weight 76.98 kN/m^3.

4.2.1.3. X-bracings (XB). The X-bracings have been added within the bays of the building using trusses. The modelling procedure and the structural characteristics are the same as for the single steel braces.

4.2.2. Ground improvement

4.2.2.1. Jet grouting (JG). The JG has been simulated by modelling solid grouting columns using the 'ElasticIsotropic' material. In order to define the mechanical characteristics of the concrete grouting, a literature review has been carried out based on the work developed by [53]. In Table 3, different values compressive strength (f_{jg}) of the JG have been listed according to the type of soil. For the case study, a clayey soil, a medium value of 30 kPa has been selected as f_{jg}. The elastic modulus (E_{jg}) has been calculated following Eq. (1) from the Spanish concrete code [54]. The area of the columns was 0.85 m^2. The depth of the concrete columns was 11 m in order to embed them 3 m in the brown silt, a moderate resistant stratum.

$$E_{jg} = 8500\sqrt[3]{f_{jg}} \tag{1}$$

4.2.2.2. Micropiles (MP). The MPs have been simulated by means of beam elements. They have been linked to the solid elements with 'EqDOF' to perform faster analyses and to avoid convergence problems. The depth and the diameter of the MP have been defined so that its bearing resistance (R_{cd}) is 3 times higher than the gravitational loads, as recommended by the Spanish construction code [40]. In order to calculate the characteristic bearing resistance (R_{ck}), the characteristic

Table 3
Analysis of the compressive strength of the jet grouting concrete in kPa.

Reference	Clay	Silty-clay	Lime	Sandy
[55]	25–45		40–60	+100
[56]	20–40	50–70		80–120
[57]	5–50			10–100
[58]	5–50	10–70	30–80	50–150
[59]	100			170

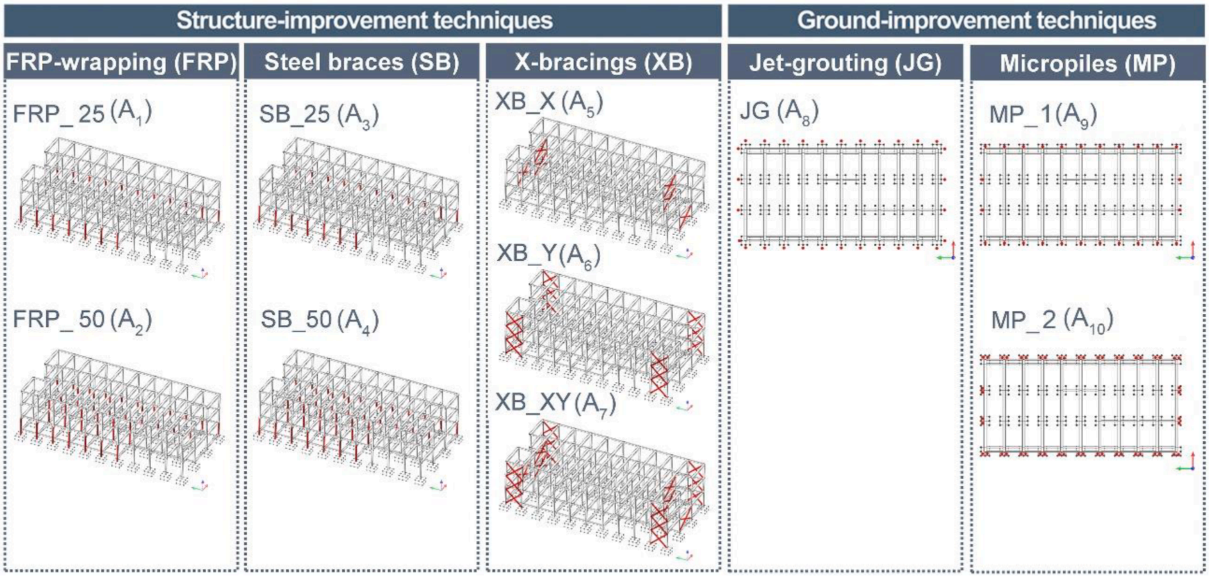


Fig. 5. Configuration of the retrofitting alternatives proposed.

skin friction (R_{fk}) and the end-bearing resistance (R_{pk}) have been computed in function of the soil properties. Additionally, the ultimate bearing capacity ($\sigma_{ultimate}$) of the pile has been calculated according to the Spanish construction code and the characteristics of the pile. The depth and diameter have been defined according to the lowest value of resistance. In this case, it has been obtained that the depth of the MP should be 19 m, embedding it 1 m in the clay loam, which represents 5 times the diameter of the pile i.e., the diameter has been 20 cm.

5. Application of the Multi-criteria method to evaluate the retrofitting techniques

5.1. Definition of the evaluation criteria

The TOPSIS method has been applied to rank the solutions. It is based on the relative closeness of the positive (A^+) (best) and negative (A^-) (worst) ideal solutions. The criteria examined to assess the alternatives have been divided into economic/social and technical. The selection has been based on the work developed by [14] and improved considering new criteria that affect the case study building under examination. These criteria have been selected from the work developed by [35]: the ductility improvement and the damage reduction. The definition and the description of the criteria (C) considered in the assessment are listed in Table 4.

5.2. Weighting the evaluation criteria and consistency checking

A qualitative evaluation of the relative importance (weight) (w_i) of each criterion (i) to the final decision is firstly carried out using the approach proposed by [60]. This is based on comparing the importance (a) of pairs of criteria (named as i, j, k, etc.) by means of the DM's judgement. The scale to quantify the importance is listed in Table 5.

After comparing all the criteria, they can be arranged to the decision matrix (A), which is the array of all the alternatives and the criteria. It turns out to be symmetric: when comparing the same criterion, the importance is equal (a_{jj} is 1). Some specific considerations for the case study building have been taken into account to weight the criteria, i.e., defining a_{jk}. It is assumed that the installation costs (C_1) are moderately more important than the maintenance costs (C_2). However, they are highly important compared to the duration of works (C_3) and the technical capability (C_5). C_1 is equally important to the functional compatibility (C_4) due to the use of the building. The structural performance has been assumed moderately important compared to the installation costs and some of the rest of the criteria. Owing to the building typology, the reduction of the collapse risk (C_8) has been considered more important than the other criteria. The maintenance costs (C_2) have been essentially important compared to the duration of works and the functional compatibility. Nevertheless, the duration and the compatibility have been moderately to essentially important with regards the technical capability (C_5). The ductility improvement (C_6) has been equal to the significant damage reduction (C_7).

Table 4
Evaluation criteria adapted from [14].

Group	Symbol	Definition	Description
Economic / Social	C_1	Installation cost	Total cost of the solutions
	C_2	Maintenance cost	Economic cost during the life of the building
	C_3	Duration of works/ disruption of use	Time of construction
	C_4	Functional compatibility	Architectural impact of the solutions
	C_5	Required technical level	Skilled level needed to implement the solutions
Technical	C_6	Ductility	Improvement of the ductility factor
	C_7	Significant Damage	Reduction of the seismic damage ratio
	C_8	Near Collapse	Reduction of the collapse risk ratio

Table 5
Scale of relative importance [60].

Intensity of Importance	Definition
1	Equal importance
3	Moderate importance of one to another
5	Essential or strong importance
7	Demonstrated importance
9	Extreme importance
2, 4, 6, 8	Intermediate values between the two adjacent judgements
Reciprocal of above	If criterion j compared to criterion k gives one of the above, then k, when compared to j, gives it reciprocally. Where: j and k range from 1 to 8.

$$A = [a_{ij}] = \begin{bmatrix} 1 & 2 & 6 & 1 & 5 & 1/2 & 1/2 & 1/3 \\ 1/2 & 1 & 3 & 1/4 & 6 & 1/2 & 1/2 & 1/2 \\ 1/6 & 1/3 & 1 & 1/5 & 3 & 1 & 1/3 & 1/4 \\ 1 & 4 & 5 & 1 & 4 & 1 & 1 & 1/3 \\ 1/5 & 1/6 & 1/3 & 1/4 & 1 & 1/3 & 1/3 & 1/3 \\ 2 & 2 & 1 & 1 & 3 & 1 & 1 & 1/3 \\ 2 & 2 & 3 & 1 & 3 & 1 & 1 & 1/3 \\ 3 & 2 & 4 & 3 & 3 & 3 & 3 & 1 \end{bmatrix}$$

To obtain acceptable pairwise judgements, a consistency checking has been carried out. To do so, the right eigenvector (W) of decision matrix A is determined. This defines the relative importance weight of each variable. The consistency checking verifies that the maximum eigenvalue (λ_{max}) of matrix A is close to the total number of decision variables ($n = 8$). The consistency index (CI) is obtained and normalised by the random consistency index (RCI) as proposed by [13]. The pairwise comparison is viewed as perfectly consistent if the CR is lower than 10% and more than four decision variables are used. In this case, for matrix A, λ_{max} is equal to 8.976 and the CR is 10%. Therefore, the weights can be considered consistent.

$$W = [w_i] = \{13.23, 9.25, 5.33, 15.76, 3.46, 12.41, 13.60, 26.98\}$$

In Fig. 6, the shares of importance defined by the pairwise comparison are plotted, highlighting the possible variation of the results. In Table 6, the criteria have been ranked according to the weights. For the case study building, it has been obtained that the most important criterion is the reduction of the collapse risk (C_8), followed by the functional capability (C_4), the significant damage (C_7) and then, the installation costs (C_1). The collapse risk and the functional capability have been selected as two of the utmost criteria. This is due to the fact that for the retrofitting of the building, it is considered that: i) children can suffer adverse effects after earthquakes and in this type of buildings there is a low adult-child ratio, which is important in case of emergency evacuation; and, ii) the retrofitting solutions should present a minimum architectural impact in order not to disrupt the use of the building. The installation costs have been also important since a lot of buildings similar to that of the case study can be found in the area; these will need to be retrofitted as well. The reduction of the seismic damage (C_7) and the improvement of the ductility (C_6) follow these criteria. The technical capability (C_5) and the duration of works (C_3) have been the least important criteria. As can be observed, the structural performance criteria (C_6, C_7 and C_8) represent just 50% of the importance in selecting the most optimal solution.

5.3. Evaluation of the retrofitting solutions

In this section, the procedure to assess each of the criteria appraised in the MCDM is described. It is divided into economic/social and technical criteria.

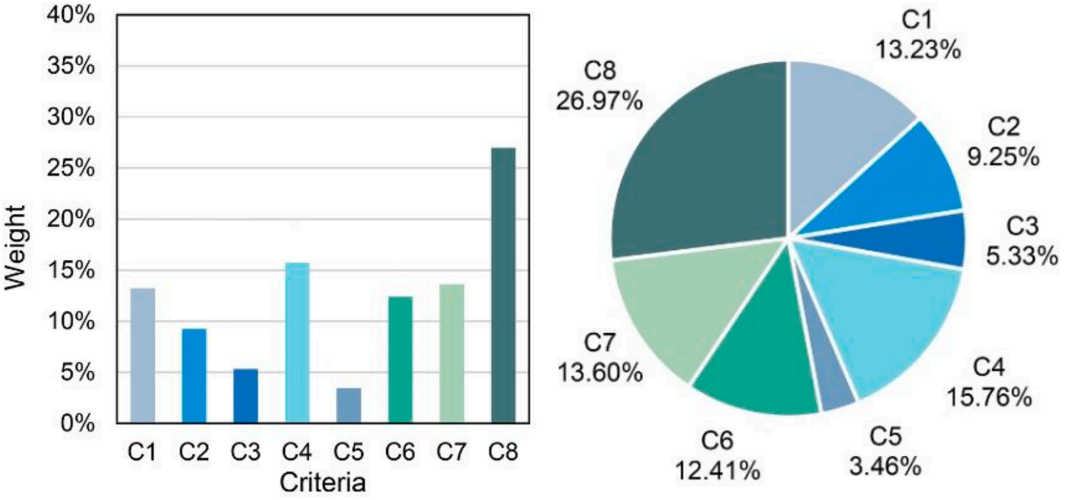


Fig. 6. Weights obtained for the criteria and shares.

Table 6
Ranking of criteria according to their weight.

Ranking order	Weights (w_i)	Symbol	Description
I	26.98%	C_8	Near Collapse
II	15.76%	C_4	Functional compatibility
III	13.60%	C_7	Significant Damage
IV	13.23%	C_1	Installation cost
V	12.41%	C_6	Ductility assessment
VI	9.25%	C_2	Maintenance cost
VII	5.33%	C_3	Duration of works/disruption of use
VIII	3.46%	C_5	Required technical level

5.3.1. Specific evaluation of the solutions according to the economic/social criteria

The installation costs (C_1) have been calculated for each of the alternatives by means of a detailed measurement of a bill of quantities. A Spanish construction cost database [61] has been used, which takes into account the costs of the materials, the labour and indirect costs and the industrial benefit. The demolishing and reconstructing activities have been borne in mind in the measurement.

The maintenance cost (C_2) has been assessed considering the economic life of the building. According to the Spanish building code [40], the durability of these buildings should be 50 years. During this time, different monitoring activities have been noted for each alternative to guarantee the health of the building. It has been considered that inspections of the retrofitting elements will be carried out every 10 years according to the Spanish building code. For the FRP, every 10 years, 5% of the columns should be additionally reinforced. The SB and XB should be reviewed every 10 years and an anticorrosive should be applied if required. For JG and MP, an instrumental examination every 10 years has been taken into consideration.

The duration of the works (C_3) represents the time needed to implement each of the solutions. It is calculated from the start of the demolition works to the final decoration stage. It is assumed that each working day has 8 h.

In order to assess the functional capability (C_4) (Table 7) and the required technical level (C_5) (Table 8), a quantitative analysis has been carried out using the TOPSIS method. Therefore, a pairwise comparison and the eigenvalue approach have been applied to rank the solutions considering these criteria. The consistency checking has also been performed to prove the validity of the analysis. Briefly, it has been assumed that the ground-improvement techniques are the least invasive techniques followed by the solutions adding FRP. The solutions of very strong to extreme importance are those adding XB. For all the strategies, it has been considered that the importance is higher if additional retrofitting elements or materials are added. In the case of the technical level, it has been assumed that the similar retrofitting strategies have been of equal importance, i.e., $a_{jj} = 1$. The implementation of JG has been the solution needing a higher technical level followed by the addition of MP, therefore, they present lower values of importance. FRP has been the next important solution followed by the XB and the SB.

5.3.2. Specific evaluation of the solutions according to the technical criteria

The technical criteria are based on the seismic performance assessment of the different models considered. In this work, nonlinear static analyses have been carried out to determine the capacity of the models. These analyses obtain consistent results for low to mid-rise buildings in a relatively short period of time compared to dynamic analyses. The results will only reference the modal load pattern since this has been the most restrictive. For this load pattern, worse results in terms of seismic capacity and, therefore, seismic performance, have been obtained for all the configurations compared to the uniform load pattern.

Table 7
Quantitative evaluation of the alternatives according to the functional capability (C_4). $\lambda_{max} = 10.896$. CR = 6.7%.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	Priority
A_1	1	2	3	4	7	7	9	1/4	1/4	1/4	0.102
A_2	1/2	1	2	3	6	6	8	1/5	1/5	1/5	0.075
A_3	1/3	1/2	1	2	3	5	7	1/6	1/6	1/6	0.051
A_4	1/4	1/3	1/2	1	3	4	6	1/7	1/7	1/7	0.039
A_5	1/7	1/6	1/3	1/3	1	1	3	1/8	1/8	1/8	0.021
A_6	1/7	1/6	1/5	1/4	1	1	3	1/8	1/8	1/8	0.019
A_7	1/9	1/8	1/7	1/6	1/3	1/3	1	1/9	1/9	1/9	0.012
A_8	4	5	6	7	8	8	9	1	1	1	0.227
A_9	4	5	6	7	8	8	9	1	1	1	0.227
A_{10}	4	5	6	7	8	8	9	1	1	1	0.227

Table 8

Quantitative evaluation of the alternatives according to the technical skill needed (C_5). $\lambda_{max} = 10.268$. CR = 2.0%.

	A_1	A_2	A_3	A_4	A_5	A_6	A_7	A_8	A_9	A_{10}	Priority
A_1	1	1	1/2	1/2	1	1	1	8	5	5	0.119
A_2	1	1	1/2	1/2	1	1	1	8	5	5	0.119
A_3	2	2	1	1	1	1	1	7	4	4	0.149
A_4	2	2	1	1	1	1	1	7	4	4	0.149
A_5	1	1	1	1	1	1	1	7	4	4	0.126
A_6	1	1	1	1	1	1	1	7	4	4	0.126
A_7	1	1	1	1	1	1	1	7	4	4	0.126
A_8	1/8	1/8	1/7	1/7	1/7	1/7	1/7	1	1/4	1/4	0.018
A_9	1/5	1/5	1/4	1/4	1/4	1/4	1/4	4	1	1	0.034
A_{10}	1/5	1/5	1/4	1/4	1/4	1/4	1/4	4	1	1	0.034

The extended version of the N2-method established in the EC8-1 has been examined to define the idealised bilinear curve [62]. The ductility improvement (C_6) has been assessed by determining the ratio between the displacement ductility factor (μ-factor) obtained for the retrofitted (i) and the un-retrofitted building (u). The μ-factor represents the ratio between the ultimate displacement (δ_{ult}) and the yielding displacement (δ_y).

The significant damage (SD) (C_7) and the near collapse (NC) (C_8) reduction have been calculated according to the Capacity Demand Ratio (CDR). To do so, the ratio between each damage state (DS) displacement (δ_{DS}) and the corresponding seismic demand (δ_{demand}) obtained has been calculated. Each DS displacement has been obtained according to Part 3 of Eurocode 8 (EC8-3) [63]. As established in this code, buildings should comply with the SD limit state (ultimate limit state). Therefore, in this case, it has been selected to perform the seismic verification. As concluded in [35,46], in this type of RC structures, damage is usually concentrated in the vertical frames. Therefore, for the sake of simplicity, in this work, only the damage in the vertical elements has been assessed. The $\delta_{DS\text{-}NC}$ is calculated considering the fragile and the ductile failures. The shear resistance (V_R) and the ultimate chord rotation (θ_{um}) have been studied for each failure, respectively. The $\delta_{DS\text{-}SD}$ has been calculated considering 75% of the $\delta_{DS\text{-}NC}$. Additionally, the damage limit (DL) state has been calculated by obtaining the yielding chord rotation (θ_y). For this case study building, a PGA of 0.1 g and a return period of 475 years and the EC8-1 response spectrum have been appraised to define the δ_{demand}.

6. Analysis of the results

6.1. Comparison between the fixed-based and the SSI model

In this section, the SSI effects on the case study building under examination are presented. To do so, two models have been firstly assessed for the un-retrofitted situation: without considering the SSI effects, fixed-based (FB), and considering the SSI effects by directly modelling the soil (CS) as previously indicated. Fig. 7 shows the single-degree-of-freedom (SDOF) curves of the FB and CS models. All the capacity curves of this work have been normalised by the total mass (W) and height of the building (H_t). It can be observed that the initial stiffness of the system can decrease by up to 25% when the SSI is borne in mind. The maximum strength of the building can decrease by up to 10%. This all leads to an increase of the expected seismic damage of 17% and 7% in X and Y, respectively. Regarding the modal analyses, the fundamental period of vibration for the FB model has been 0.38 and 0.28 in the X and Y direction, respectively. For the CS model, it has been 4.09 and 3.92 in the X and Y direction, respectively. These results cannot be directly compared, but they can be useful to check that the system with the surrounding soil presents higher values of periods.

Concerning the geotechnical analysis, the local failure of the footings has been checked. To do so, the allowable bearing capacity of the soil (q_a) has been calculated considering the Brinch-Hansen formulation. The short-term condition has been selected since the soil is clayey and this is the most conservative situation for this type of soils. In this case, q_a equals to 512 kPa, which represents a considerable rigid soil. Then, it has been checked that the capacity of the soil is not surpassed by any of the footings by obtaining the normal and shear stress components of each of the footings. It has been obtained that q_a is not surpassed in any of the directions. Therefore, it can be assumed that the failure of the structure is governed by the behaviour of the elements of the superstructure. In this case, it has been obtained that they will not comply with the seismic requirements.

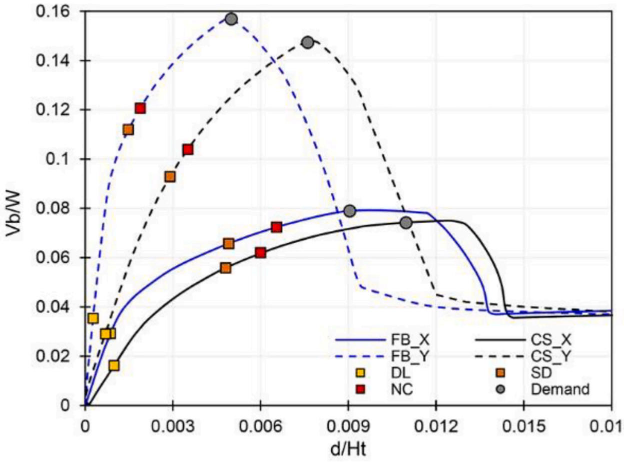


Fig. 7. SDOF capacity curves in the X and Y direction considering the SSI effects. Where: V_b and d refers to the shear at the base of columns and the displacement of the control node at the rooftop, respectively.

6.2. Determination of elements damaged

The weakest or first damaged vertical elements have been identified to define the most efficient position for the addition of the retrofitting elements. This has been carried out through the seismic safety verification. It should be mentioned that all the analyses considering the retrofitting alternatives have been carried out bearing in mind the direct modelling of the soil.

In Fig. 8, the estimated damage considering the SSI effects has been plotted for each of the directions. It can be seen that this will be concentrated in the ground floor, more elements being damaged in the Y direction. The columns in the perimeter will fail due to excessive shear force owing to the lack of infills confinement. In fact, these columns even present excessive stresses just due to gravitational loads. The columns in the centre will present ductile failure. These groups are the first ones to be rehabilitated. Additionally, some columns located in the irregularities of the building (in the atriums at the ground floor) will be close to yielding.

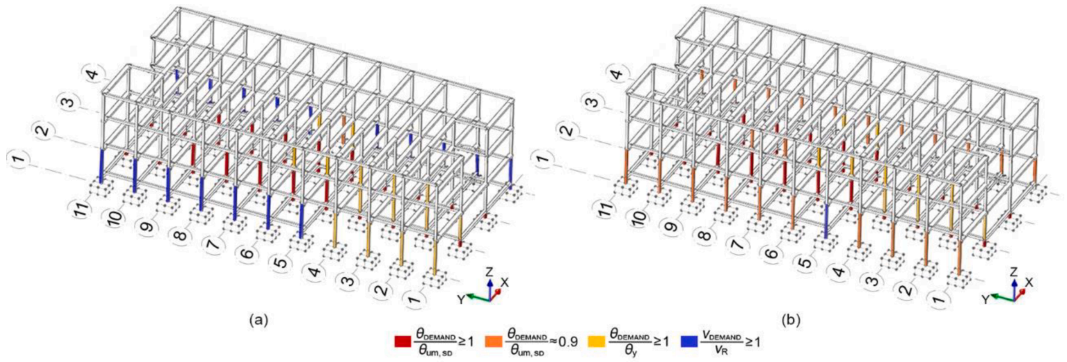
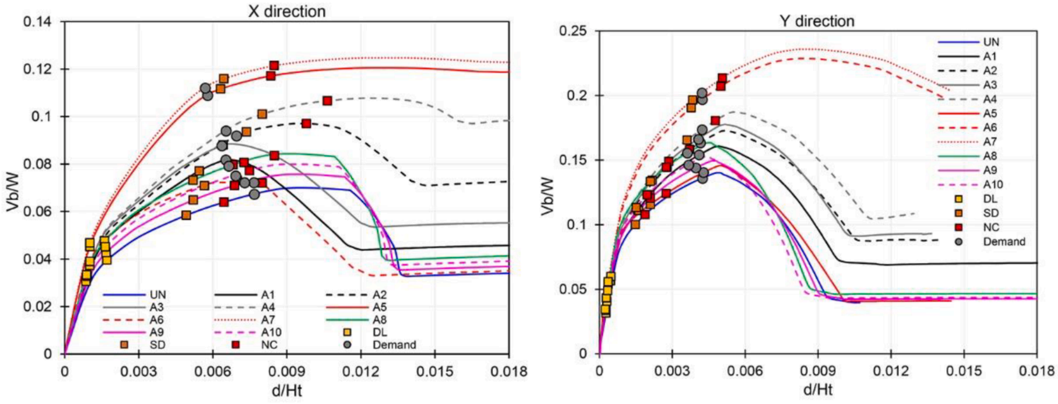


Fig. 8. Damage in the vertical elements of the un-retrofitted building considering the SSI in the X (a) and Y (b) directions.

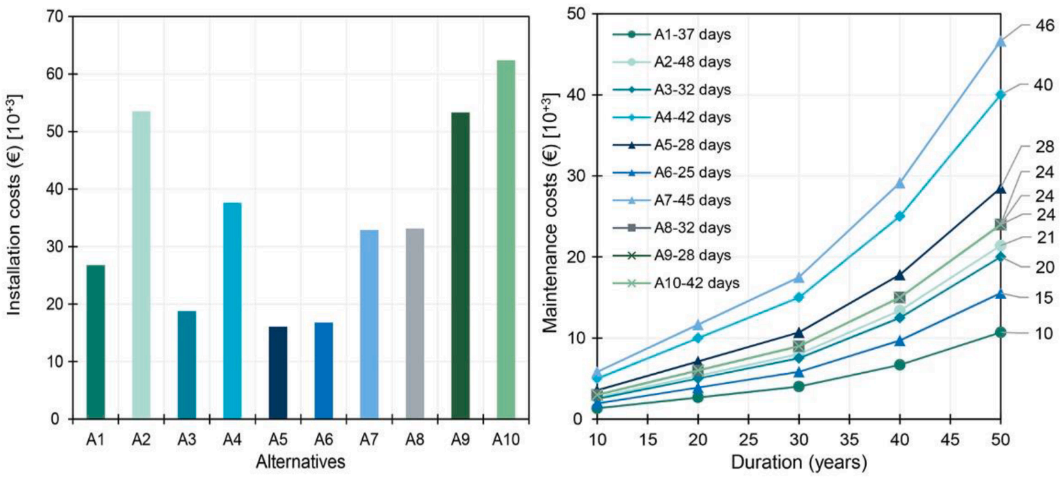


(a) (b)

Fig. 9. SDOF capacity curves for all the alternatives in the X (a) and Y (b) direction, highlighting the un-retrofitted situation and plotting the DS's and the seismic demand.

6.3. Ranking of solutions

In this section, the solutions are ranked according to the different criteria. In Fig. 9, the results from the nonlinear static analyses and the seismic safety verification have been plotted for all the alternatives in the X and Y directions. It can be seen that, from the structural performance point of view, the best solutions are adding XB (depending on the direction) and SB. They increase the initial stiffness of the system, resulting in an improvement of the capacity and a reduction of the seismic damage expected. Solution A_7 has highly improved the performance since XBs were added in both directions. The alternatives adding retrofitting elements in at least 50% of the columns have also resulted in moderately high performance ratios. However, the ground-improvement techniques have merely increased the displacement capacity in the horizontal direction and the resistance has been scarcely increased. The best ground-improvement solution in the horizontal directions has been implementing the JG system or adding two MPs.



(a) (b)

Fig. 10. Installation (a) and maintenance (b) costs of each of the alternatives examined. The duration of the construction works is pointed out.

According to the assessment of the construction costs (C_1) (Fig. 10(a)), the most expensive solutions are those adding MPs, A_9 and A_{10}. The addition of FRP in at least 50% of columns (A_2) has also been quite expensive compared to the rest of solutions. The cheapest ones have been the addition of XB in the X (A_6) and SB in only 25% of the columns (A_3) due to the reduced number of elements to be retrofitted. Regarding the maintenance cost (C_2) (Fig. 10(b)), the most expensive solution has been A_7 owing to the high amount of retrofitting elements needed, followed by the addition of other SBs and XBs, A_4 and A_5, respectively. Contrariwise, the cheapest solutions to be maintained are those adding fewer FRP, XB and SB, A_1, A_6 and A_3. Regarding the duration of the works (Fig. 10(b)), it has been assumed that the solutions adding retrofitting elements in columns last longer than ground-improvement techniques.

6.4. *Selection of the best retrofitting solution*

In Table 9, the decision matrix D is shown. This represents the performance measure (x) of each of the alternatives according to the criteria defined (i, j…). The normalised decision matrix R is presented in Table 10. It has been obtained by normalising the measures in D, x_{ij}, by r_{ij} that relates the measurements as established in [14].

The final preferences and the ranking of the alternatives are obtained through the weighted normalised decision matrix V (Table 11). V is attained by weighting R, which has been calculated by multiplying each value by the weight (w) of each criterion. In this case, the most preferred solution is alternative A_4, the addition of SB in 50% of the columns. This is due to their reduced construction costs and outstanding structural performance improvement. It is followed by A_8 and A_6, adding JG and XB just in the Y direction. Conversely, the implementation of FRP in only 25% (A_1) of the columns and MPs (A9 and A10) are the least preferred solutions owing to their higher costs and reduced structural improvement despite their reduced architectural impact.

In order to define the best solution, the relative closeness procedure has been applied. This is based on calculating two opposite, positive- A^+ and negative- A^-, ideal alternatives. A^+ and A^- represent the ideal best and worst solution and they are calculated by selecting the “best” and “worst” measurements of each criterion (Table 12). Next, the distances (S) of each alternative (i) to these ideal solutions have been calculated (Table 13): the distance from A_i to A^+ (S_i^+) and from A_i to A^- (S_i^-). Additionally, the coefficient of closeness (C_i^+) has been assessed: the best alternative will be the one with highest C_i^+.

It can be observed that the solutions of highest C_i^+ have been A_2 and A_7, the addition of FRP in 50% of the elements and the addition of XB in the X and Y directions, respectively. In the first case, this solution has presented shorter distances, S_i^+ to the best ideal positive solution, A^+, while presenting a moderate value of S_i^-. This is mainly due to the minimum architectural impact of this strategy compared to other structural-improvement techniques and the moderate structural performance. However, it is not very separated from the worst solution given its considerable construction costs. The addition of XB in both directions has been the next best solution, mainly because of its highest distance from A^-. It has been that well located because it has obtained the highest structural performance improvement. The preferred solution, A_4, adding SB in 50% of the columns, has not been the best solution owing to its low S_i^+. This is basically because of its high construction and maintenance costs. As the ground-improvement techniques have been ranked as the worst alternatives as they have had the highest distances from the best solution. These have not presented a high reduction of the expected seismic damage despite their minimum architectural impact. This might be due to the fact that, for this type of buildings, the failure is mainly because of that of the vertical elements: they present brittle failure owing to the lack of transversal reinforcement and the characteristics of the structural elements.

6.5. *Sensitivity analysis*

A sensitivity analysis following the work developed in [10] has been performed to prove that the final decision sounds logical and that the ranking is not a result of a random prioritisation. To do this, all the possible combinations of criteria and pairs of alternatives have been computed, resulting in 360 possible combinations. After performing that comparison, the absolute values lower that the w_i for each criterion are considered for the analysis (Table 14). It has been obtained that C_4 has been the most critical criterion since it has had the lowest value of the criticality degree of each criterion (D'_k), 14.23%. This is also known as the lowest percentage top (PT) as referenced in [10]. The next most sensitive decision criteria are C_1, C_8, C_2 and C_7. It can be seen that if three of the criteria (C_3, C_5 and C_6) vary, the existing ranking will not be changed.

7. Conclusions

This study has aimed to comparatively assess and to rank different seismic retrofitting techniques by means of a rational MCDM method named TOPSIS. It is based on the relative closeness assessment procedure to positive and negative -ideal solutions. The main novelty of this work is the comparison of structural and ground-improvement techniques by means of different and additional criteria to the available literature: social, architectural impact, economic, ductility improvement and damage reduction. The preliminary conclusions obtained during this research were:

- The case study building could be affected by the SSI and it will not comply with the seismic safety requirements. Therefore, it needs retrofitting.
- For its refurbishment, the minimum architectural impact was important (in order not to disrupt the use of the building) as well as the construction costs (numerous similar buildings to be retrofitted). Ground-improvement techniques present the lowest architectural impact and could be used as a solution to retrofit the buildings. Therefore, the authors believed that it was interesting to test their effects compared to other retrofitting solutions that have already been tested in different RC buildings.

Table 9
Decision Matrix ($D = [x_{ij}]$).

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.601	1.000	0.676	0.102	0.119	1.212	0.610	0.810
A_2	0.300	0.500	0.520	0.075	0.119	1.289	0.864	1.149
A_3	0.855	0.535	0.781	0.051	0.149	1.317	0.769	1.016
A_4	0.428	0.268	0.601	0.039	0.149	1.452	1.038	1.377
A_5	1.000	0.375	0.893	0.021	0.126	1.359	0.790	1.042
A_6	0.957	0.688	1.000	0.019	0.126	1.236	0.903	1.111
A_7	0.489	0.229	0.555	0.012	0.126	1.511	1.018	1.343
A_8	0.485	0.446	0.781	0.227	0.018	1.293	0.682	0.893
A_9	0.302	0.446	0.893	0.227	0.034	1.126	0.561	0.737
A_{10}	0.258	0.446	0.595	0.227	0.034	1.200	0.614	0.808

Table 10
Normalised Decision Matrix ($R = [r_{ij}]$).

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A_1	0.304	0.590	0.286	0.243	0.339	0.294	0.241	0.244
A_2	0.152	0.295	0.220	0.179	0.339	0.312	0.341	0.346
A_3	0.432	0.316	0.331	0.122	0.425	0.319	0.304	0.306
A_4	0.216	0.158	0.255	0.093	0.425	0.352	0.410	0.415
A_5	0.505	0.222	0.378	0.050	0.359	0.330	0.312	0.314
A_6	0.484	0.406	0.424	0.045	0.359	0.300	0.356	0.335
A_7	0.247	0.135	0.235	0.029	0.359	0.366	0.402	0.405
A_8	0.245	0.263	0.331	0.542	0.051	0.314	0.269	0.269
A_9	0.153	0.263	0.378	0.542	0.097	0.273	0.221	0.222
A_{10}	0.130	0.263	0.252	0.542	0.097	0.291	0.242	0.243

Table 11
Weighted Normalised Decision Matrix V.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	Priority	Preferred
A_1	4.017	5.458	1.527	3.835	1.174	3.648	3.273	6.586	443.75	IX
A_2	2.009	2.729	1.174	2.820	1.174	3.877	4.638	9.336	469.66	VII
A_3	5.719	2.920	1.765	1.918	1.470	3.962	4.129	8.258	475.52	V
A_4	2.860	1.460	1.358	1.466	1.470	4.370	5.572	11.193	518.78	I
A_5	6.688	2.049	2.017	0.790	1.243	4.090	4.240	8.467	471.77	VI
A_6	6.401	3.757	2.259	0.714	1.243	3.719	4.844	9.028	502.66	III
A_7	3.271	1.252	1.254	0.451	1.243	4.547	5.466	10.916	498.22	IV
A_8	3.246	2.435	1.765	8.535	0.178	3.892	3.658	7.254	503.77	II
A_9	2.018	2.435	2.017	8.535	0.335	3.387	3.010	5.986	440.13	X
A_{10}	1.724	2.435	1.345	8.535	0.335	3.610	3.297	6.564	454.91	VIII

Table 12
Positive- A^+ and negative- A^- ideal solutions.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
A^+	1.724	1.252	1.174	0.451	0.178	3.387	3.010	5.986
A^-	6.688	5.458	2.259	8.535	1.470	4.547	5.572	11.193

- The SSI affects the seismic performance of the case study building to a certain extent due to the hard properties of the soil and the foundation configuration. However, for a soft or very soft soil, the results would have notably differed. Hence, the main novelty of this work is the method developed, the modelling approaches and the criteria followed.

Considering this preliminary conclusions, this work uses as a reference previous research papers on the application of multi-criteria methods to assess different retrofitting techniques. These works perform the comparison among techniques that were added to prototypes. However, in this manuscript, they have been applied to a real case study building. It provides information regarding its seismic behaviour (which is representative of a considerable amount of similar RC school buildings in the area) as well as information regarding the assessment of the retrofitting strategies following the available method.

Table 13
Distances S_i^+ S_i^- and relative closeness C_i^+ to the ideal solution of each alternative.

	S_i^+	S_i^-	C_i^+	Ranking
A_1	6.001	7.561	0.558	VII
A_2	4.793	8.248	0.632	I
A_3	5.446	7.903	0.591	V
A_4	6.222	9.025	0.592	IV
A_5	5.949	9.008	0.602	III
A_6	6.577	8.372	0.560	VI
A_7	5.934	9.791	0.623	II
A_8	8.467	6.520	0.435	X
A_9	8.220	8.205	0.500	VIII
A_{10}	8.202	7.961	0.493	IX

Regarding the effects of the SSI and the performance of the building, it has been obtained that:

- For this case, the initial stiffness of the system and the maximum strength can decrease by up to 25% and 10%, respectively, if the SSI is borne in mind by means of the direct modelling of the soil. This turns into an increase of the seismic damage of up to 17%.
- The seismic safety verification has been carried out by demining both the brittle and shear failures according to the European seismic code. It has been observed that the seismic damage will be concentrated in the ground floor mainly due to the irregularities of the building. Also, the columns in the perimeter (un-confined with infills), will be firstly damaged due to excessive shear. Columns in the centre of the building will present ductile failure.
- This work can improve the knowledge on the quantification and consideration of the SSI effects on the seismic behaviour given the lack of works on this issue. Furthermore, the comparison among structural and ground-improvement retrofitting techniques has not been widely carried out. Therefore, the authors believe that this manuscript can provide some insight into how both types of retrofitting techniques can affect the case study building.

Concerning the application of the MCDM method, the functional compatibility (architectural impact), the construction costs and the

Table 14
Calculation of the most sensitive criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
D'_k	35.290	84.200	0	14.239	0	0	93.870	62.780
Sens (C_k)	0.028	0.012	0	0.070	0	0	0.011	0.016

reduction of the near collapse damage have been the most important criteria. The maintenance costs, the duration of works and the required technical level have been the least important aspects. The consistency checking has shown stable results regarding the consistency of the criterion weighting. The sensitivity analysis has concluded that the most sensitive criterion is the functional compatibility followed by the installation costs and the reduction of the collapse damage. It can be assumed that the rest of the criteria they will not be affected if the measurements of the criteria vary.

For the case study building, the retrofitting solutions have improved the seismic behaviour of the building, obtaining different conclusions:

- The structural-improvement solutions behaved better than the ground-improvement ones. In fact, the ground-improvement techniques have had the highest distances from the best solution. Therefore, they have been ranked as the worst alternatives and they have not presented a high reduction of the expected seismic damage despite their minimum architectural impact. This might be due to the fact that this building is not very affected by the SSI owing to its mid-height and the hard properties of the soil.
- Structural-improvement techniques tend to avoid the excessive concentration of the local damage of these elements, resulting in the most efficient alternatives. However, the authors would like to point out that, despite the moderate effect of the ground improvement techniques in this case study, they should be considered as they can be notable in some cases. Moreover, they present the advantage of having no architectural impact and allowing the building to be kept in use. Finally, in certain cases, only ground improvement techniques could be applied in order to fulfil the seismic safety requirements.
- The results show that confining columns with FRP is the best solution due to its minimum architectural impact and to the moderate construction costs.
- This has been followed by the addition of steel X bracings in both directions. Although this alternative presents the highest architectural impact, it has the highest structural performance improvement ratios and the lowest construction costs.
- The solution preferred has been the addition of single steel braces in 50% of the beam-column joints. It has not been the best solution due to its high distance from the best-ideal alternative basically due to its high maintenance costs. It can be suggested that if these elements were stainless, they would not need maintenance, resulting in the best solutions. Therefore, it can be concluded that increasing the installation costs to reduce the maintenance ones can lead to more optimal solutions.

8. Future work and limitations of this study

One of the most critical aspects of MCDM is that they are based on a very subjective point of view. To identify the best solution, the choice is mainly based on the weighing of the criteria carried out by the decision maker. Tools such as the consistency index and the sensitivity analyses can provide control and disaggregate the process. Nevertheless, if the technical criteria were more relevant, the ranking of solutions would have considerably differed.

This case study building can be affected by the SSI, which can worsen the behaviour of the building, leading to higher values of damage. These statements have been provided in this research work. Therefore, the authors believe that testing ground-improvement techniques to improve the seismic behaviour of buildings could be useful in cases in which the architectural impact is significant or when it is mandatory for the building to be kept in use. In this work, it has been concluded that it is possible to do that up to a certain extent.

In future works, the assessment of hybrid configurations could be an opportunity to design more efficient solutions. They can obtain better results by minimally changing some of the aspects. Additionally, in the assessment of the seismic performance of the other types of buildings aspects such as the local failure of the foundations should also be borne in mind. In this case, the failure is mainly due to that of the vertical elements: they present brittle failure owing to the lack of transversal reinforcement and the characteristics of the structural elements. However, for more complex systems of foundations or other types of analyses, these results are limited.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] O'Reilly GJ, Sullivan TJ. Probabilistic seismic assessment and retrofit considerations for Italian RC frame buildings. Bull Earthq Eng 2018;16(3): 1447–85. https://doi.org/10.1007/s10518-017-0257-9.
[2] Aslani H, Miranda E. Probabilistic earthquake loss estimation and loss disaggregation in buildings. Stanford University, Department of Civil and Environmental Engineering; 2005.
[3] Federal Emergency Management Agency (FEMA). FEMA P-58-1: Seismic Performance Assessment of Buildings-Methodology. USA: 2018.
[4] Requena-Garcia-Cruz M-V, Morales-Esteban A, Durand-Neyra P, Zapico-Blanco B. Influence of the constructive features of RC existing buildings in their ductility and seismic performance. Bull Earthq Eng 2021;19(1):377–401. https://doi.org/10.1007/s10518-020-00984-z.
[5] Applied Technology Council (ATC). ATC-40: seismic evaluation and retrofit of concrete buildings. USA: 1996.
[6] Alam Shahria M, Moni M, Tesfamariam S. Seismic overstrength and ductility of concrete buildings reinforced with superelastic shape memory alloy rebar. Eng Struct 2012;34:8–20. https://doi.org/10.1016/J.ENGSTRUCT.2011.08.030.
[7] Caterino N, Iervolino I, Manfredi G, Cosenza E. Comparative analysis of multi-criteria decision-making methods for seismic structural retrofitting. Comput Civ Infrastruct Eng 2009;24:432–45. https://doi.org/10.1111/J.1467-8667.2009.00599.X.
[8] Requena-García-Cruz MV, Morales-Esteban A, Durand-Neyra P, Estêvão JMC. An index-based method for evaluating seismic retrofitting techniques. Application to a reinforced concrete primary school in Huelva. PLoS One 2019;14:e0215120. 10.1371/journal.pone.0215120.
[9] O'Reilly GJ, Perrone D, Fox M, Monteiro R, Filiatrault A. Seismic assessment and loss estimation of existing school buildings in Italy. Eng Struct 2018;168:142–62. https://doi.org/10.1016/j.engstruct.2018.04.056.
[10] Triantaphyllou E, Sánchez A. A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. Decis Sci 1997;28(1): 151–94. https://doi.org/10.1111/j.1540-5915.1997.tb01306.x.
[11] Formisano A, Mazzolani FM. On the selection by MCDM methods of the optimal system for seismic retrofitting and vertical addition of existing buildings. Comput Struct 2015;159:1–13. https://doi.org/10.1016/J.COMPSTRUC.2015.06.016.
[12] Mardani A, Jusoh A, MD Nor K, Khalifah Z, Zakwan N, Valipour A. Multiple criteria decision-making techniques and their applications – a review of the literature from 2000 to 2014. Econ Res 2015;28(1):516–71. https://doi.org/10.1080/1331677X.2015.1075139.
[13] Hwang C-L, Yoon K. Methods for Multiple Attribute Decision Making. Mult. Attrib. Decis. Making. Lect. Notes Econ. Math. Syst., Springer, Berlin, Heidelberg; 1981, p. 58–191. 10.1007/978-3-642-48318-9_3.
[14] Caterino N, Iervolino I, Manfredi G, Cosenza E. Multi-criteria decision making for seismic retrofitting of RC structures. J Earthq Eng 2008;12(4):555–83. https://doi.org/10.1080/13632460701572872.
[15] Park R. State-of-the-art report: ductility evaluation from laboratory and analytical testing. Proc. 9th World Conf. Earthq. Eng., Kyoto: 1998, p. 605–616.
[16] Pampanin S. Towards the "ultimate earthquake-proof" building: development of an integrated low-damage system. Geotech Geol Earthq Eng 2015;39:321–58. https://doi.org/10.1007/978-3-319-16964-4_13.
[17] Pampanin S. Reality-check and renewed challenges in earthquake engineering. Bull New Zeal Soc Earthq Eng 2012;45:137–60. https://doi.org/10.5459/BNZSEE.45.4.137-160.

[18] Nuzzo I, Caterino N, Pampanin S. Seismic design framework based on loss-performance matrix. J Earthq Eng 2020. https://doi.org/10.1080/13632469.2020.1828201.

[19] Masoero E, Wittel FK, Herrmann HJ, Chiaia BM. Progressive collapse mechanisms of brittle and ductile framed structures. J Eng Mech 2010;136(8):987–95. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000143.

[20] Caterino N, Cosenza E. A multi-criteria approach for selecting the seismic retrofit intervention for an existing structure accounting for expected losses and tax incentives in Italy. Eng Struct 2018;174:840–50. https://doi.org/10.1016/J.ENGSTRUCT.2018.07.090.

[21] Caterino N, Nuzzo I, Ianniello A, Varchetta G, Cosenza E. A BIM-based decision-making framework for optimal seismic retrofit of existing buildings. Eng Struct 2021;242:112544.

[22] Nuzzo I, Caterino N, Novellino A, Occhiuzzi A. Computer-aided decision making for regional seismic risk mitigation accounting for limited economic resources. Appl Sci 2021;11:5539. https://doi.org/10.3390/APP11125539.

[23] Gallo WWC, Gabbianelli G, Monteiro R. Assessment of multi-criteria evaluation procedures for identification of optimal seismic retrofitting strategies for existing RC buildings. J Earthq Eng 2021:1–34. https://doi.org/10.1080/13632469.2021.1878074.

[24] Formisano A, Mazzolani FM. Multi-Criteria Decision Methods for Structural Modification Interventions: Vertical Addition and Seismic Retrofitting. 13th Int. Conf. Civil, Struct. Environ. Eng. Comput., Stirlingshire, UK: Civil-Comp Press; 2011. 10.4203/ccp.96.173.

[25] Vielma-Perez J-C, Porcu MC, Gómez MA. Non-linear analyses to assess the seismic performance of RC buildings retrofitted with FRP. Rev Int Métodos Numéricos Para Cálculo y Diseño En Ing Non-Linear 2020;36:1–7. 10.23967/j.rimni.2020.03.009.

[26] Ahmad N, Masoudi M. Eccentric steel brace retrofit for seismic upgrading of deficient reinforced concrete frames. Bull Earthq Eng 2020;18(6):2807–41. https://doi.org/10.1007/s10518-020-00808-0.

[27] Requena-Garcia-Cruz MV, Morales-Esteban A, Segovia Verjel ML, Romero Sánchez E, de Miguel RJ, Estêvão JMC. Seismic performance comparison between structure-improvement techniques and ground-improvement techniques: application to a reinforced concrete school building. WIT Trans Built Environ 2019:99–108. https://doi.org/10.2495/ERES190081.

[28] Nasab MSE, Chun S, Kim J. Soil-structure interaction effect on seismic retrofit of a soft first-story structure. Structures 2021;32:1553–64. https://doi.org/10.1016/j.istruc.2021.03.105.

[29] Requena-Garcia-Cruz MV, Bento R, Durand-Neyra P, Morales-Esteban A. Analysis of the soil structure-interaction effects on the seismic vulnerability of mid-rise rc buildings in lisbon (Under Review). Structures 2022.

[30] Falcone R, Carrabs F, Cerulli R, Lima C, Martinelli E. Seismic retrofitting of existing RC buildings: a rational selection procedure based on Genetic Algorithms. Structures 2019;22:310–26. https://doi.org/10.1016/J.ISTRUC.2019.08.006.

[31] Kazemian S, Huat B. Assessment and comparison of grouting and injection methods in geotechnical engineering. Eur J Sci Res 2009;27:234–47.

[32] Ferracuti B, Savoia M, Zucconi M. RC frame structures retrofitted by FRP-wrapping: a model for columns under axial loading and cyclic bending. Eng Struct 2020;207:110243. https://doi.org/10.1016/j.engstruct.2020.110243.

[33] Di Trapani F, Malavisi M, Marano GC, Sberna AP, Greco R. Optimal seismic retrofitting of reinforced concrete buildings by steel-jacketing using a genetic algorithm-based framework. Eng Struct 2020;219:110864. https://doi.org/10.1016/j.engstruct.2020.110864.

[34] Anelli A, Vona M, Santa-Cruz Hidalgo S. Comparison of different intervention options for massive seismic upgrading of essential facilities. Buildings 2020;10(7):125.

[35] Requena-Garcia-Cruz M-V, Morales-Esteban A, Durand-Neyra P. Optimal ductility enhancement of RC framed buildings considering different non-invasive retrofitting techniques. Eng Struct 2021;242:112572. https://doi.org/10.1016/j.engstruct.2021.112572.

[36] Amaro-Mellado JL, Morales-Esteban A, Martínez-Álvarez F. Mapping of seismic parameters of the Iberian Peninsula by means of a geographic information system. Cent Eur J Oper Res 2018;26(3):739–58. https://doi.org/10.1007/s10100-017-0506-7.

[37] Morales Esteban A, Romero Sánchez E, Zapico Blanco B, Requena García de la Cruz MV, de Miguel Rodríguez J, Estêvão J. Schools, seismicity and retrofitting (PERSISTAH project). Universidad de Sevilla; 2020.

[38] Spanish Ministry of Public Works [Ministerio de Fomento de España]. Spanish seismic code 1994 (NCSE94). 1994.

[39] European Union. Eurocode 8: Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings. Belgium: 2004.

[40] Spanish Ministry of Public Works [Ministerio de Fomento de España]. Spanish Technical Code of Buildings [Código Técnico de la Edificación (CTE)]. Spain: 2006.

[41] Requena-Garcia-Cruz MV, Morales-Esteban A, Durand-Neyra P, Romero-Sánchez E. Soil-structure interaction in the seismic vulnerability analysis of RC buildings. Application to a case study building located in southwestern Spain. 8th Int. Conf. Comput. Methods Struct. Dyn. Earthq. Eng., Athens, Greece: Eccomas Proceedia; 2021.

[42] McKenna F, Fenves GL, Scott MH. OpenSees: Open system for earthquake engineering simulation. Pacific Earthquake Engineering Research Center 2000.

[43] Petracca M, Candeloro F, Camata G. STKO User Manual. Pescara, Italy: ASDEA Software Technology; 2017.

[44] The MathWorks Inc. MATLAB and Statistics Toolbox Release 2018b 2018.

[45] Celarec D, Ricci P, Dolšek M. The sensitivity of seismic response parameters to the uncertain modelling variables of masonry-infilled reinforced concrete frames. Eng Struct 2012;35:165–77. https://doi.org/10.1016/j.engstruct.2011.11.007.

[46] Couto R, Requena-García-Cruz MV, Bento R, Morales-Esteban A. Seismic capacity and vulnerability assessment considering ageing effects. Case study: three local portuguese RC buildings. Bull Earthq Eng 2021;19(15):6591–614. https://doi.org/10.1007/s10518-020-00955-4.

[47] Maslenikov 0. R., Chen AJC, Johnson JJ. Uncertainty in Soil-Structure Interaction-Analysis Arising from Differences in Analytical Techniques. CA (USA): Lawrence Livermore National Lab; 1982.

[48] Khatibinia M, Salajegheh E, Salajegheh J, Fadaee MJ. Reliability-based design optimization of reinforced concrete structures including soil–structure interaction using a discrete gravitational search algorithm and a proposed metamodel. Eng Optim 2013;45(10):1147–65. https://doi.org/10.1080/0305215X.2012.725051.

[49] Noureldin M, Memon SA, Gharagoz M, Kim J. Performance-based seismic retrofit of RC structures using concentric braced frames equipped with friction dampers and disc springs. Eng Struct 2021;243:112555.

[50] Gentile R, Galasso C. Simplified seismic loss assessment for optimal structural retrofit of RC buildings. Earthq Spectra 2021;37(1):346–65. https://doi.org/10.1177/8755293020952441.

[51] D'Amato M, Braga F, Gigliotti R, Kunnath S, Laterza M. A numerical general-purpose confinement model for non-linear analysis of R/C members. Comput Struct 2012;102–103:64–75. https://doi.org/10.1016/j.compstruc.2012.03.007.

[52] Zhou Y, Chen X, Wang X, Sui L, Huang X, Guo M, et al. Seismic performance of large rupture strain FRP retrofitted RC columns with corroded steel reinforcement. Eng Struct 2020;216:110744. https://doi.org/10.1016/j.engstruct.2020.110744.

[53] Covil CS. Jet grouting, a state of the art review. London: Imperial College; 1991.

[54] Spanish Ministry of Public Works [Ministerio de Fomento de España]. Structural concrete code [Instrucción de Hormigón Estructural (EHE-08)] 2008.

[55] Biosca García de Tejada F. Aplicaciones del Jet-Grouting en la mejora de suelos. 2018.

[56] Covil CS, Skinner AE. Jet grouting: a review of some the operating parameters that form the basis of the jet grouting process. Thomas Telford publishers; 1996.

[57] Keller. Soilcrete. Jet-grouting process. Brochure 67- 03 E. 2006.

[58] TekTracker. Jet grouting. Technology overview n.d. http://www.jet-grouting.com.

[59] Essler R, Yoshida H. Ground improvement. Jet Grouting: The Cromwell Press Ltd publishers; 2004.

[60] Saaty RW. The analytic hierarchy process-what it is and how it is used. Math Model 1987;9(3-5):161–76. https://doi.org/10.1016/0270-0255(87)90473-8.

[61] CYPE Ingenieros S.A. Construction costs database [Generador de precios] n.d.

[62] Dol?ek M, Fajfar P. Simplified non-linear seismic analysis of infilled reinforced concrete frames. Earthq Eng Struct Dyn 2005;34(1):49–66. https://doi.org/10.1002/eqe.411.

[63] European Union. Eurocode-8: Design of structures for earthquake resistance. Part 3: Assessment and retrofitting of buildings. Brussels, Belgium: 2005.